Desalination and Water Treatment
www.deswater.com
doi: 10.5004/dwt.2022.28898

275 (2022) 323–338
November

Precision irrigation of five years date palm trees (Majdool variety) by applying Hydrus-2D software: Jericho area/West Bank (occupied Palestinian territories)

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Received 11 April 2022; Accepted 1 September 2022

ABSTRACT

In the West Bank, the agricultural sector accounts for the majority of water demand in the region. Where irrigated agriculture covers only 12% of the cultivated area of the West Bank it consumes around 65% of the total water resources. Most of the irrigated area of the Jordan Valley is under Majdool date palm trees, with a total number of about 250,000 trees, half of whom are younger than 5 y. Despite using drip irrigation, which is considered efficient and reduces water loss, improvement of the irrigation schedule can still be realized by a tailored management of the water demand of plants. In the Jordan Valley, the most important irrigated agricultural area in the West Bank, over-irrigation of the crops and trees is a common practice that causes the degradation of the groundwater aquifer systems. This study aims to use precise irrigation management to balance water demand with irrigation volumes to avoid water spillage. The Hydrus-2D package was used to develop an irrigation schedule for a 5 y date palm old. Model simulations show that farmers can schedule irrigation with less than the recommended volume of 20 m^3/tree·y. By applying around 46% of the currently recommended volume, similar production levels could be obtained in terms of yield and biomass. We conclude that using precision irrigation scheduling, the water demand per tree reduces to a recommended rate of about 12.5 m^3/tree·y increasing crop water productivity up to 2.63 kg/m^3 as opposed to 1.66 kg/m^3 with the traditional irrigation schedule. Additionally, less water drains beneath the root zone.

Keywords: Young date palm; Irrigation scheduling; Hydrus-2D; Jordan Valley

1. Introduction

Efficient water management is a challenging and important issue when confronted with water scarcity, climate change, and deterioration of available water resources [1]. It was estimated, that by 2025, about 1.8 billion people will be living in water-stressed regions. Also, the world will face about a 40% shortfall between the forecast demand and the available supply of water by 2030 [2]. Accordingly, the calls to design strategies that economize the uses of the available water are justified specifically, for the agriculture sector, which wastes around 1,500 trillion liters of water worldwide [3]. The Middle East and North Africa (MENA) are a special case in point. The MENA region is considered the most water-scarce region of the world, due to the rapid population growth, intermittent periods of droughts, limited freshwater reserves, and political conflicts. The region contributed to about 6.3% of the world's population and contains only 1.4% of the world's renewable freshwater [4]. The agriculture sector accounts for the majority of water

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Presented at the 1st Palestinian-Dutch Conference on Water, Sanitation and Hygiene (WASH), and Climate Smart Agriculture (CSA), 5–6 September 2022, Nablus, Palestinian Authority

demand in the MENA region, with around 85% of the total water withdrawals, and only 50% to 60% of water use efficiency [5].

West Bank is already suffering from severe water scarcity, due to various restrictions on water use and other political constraints. This, in turn, leads to over exploitation of the water resources and limits the sustainability of water management in terms of quality and quantity [6]. Irrigated agriculture accounts for about 12% of the total cultivated area in the West Bank, but consumes around 65% of the water sources in the region [7]. In this respect, improving the efficiency of agriculture water management, through innovative irrigation techniques and irrigation scheduling is a necessity to achieve higher agricultural water productivity. Indeed an accurate estimation and conservation of the irrigation water results, simultaneously in reduced water losses and stresses, an increase of farming revenue and preservation of water for other sectors.

One of the irrigation water management strategies that have been adopted in the West Bank is the drip irrigation system. Despite being considered as one of the best methods to reduce water losses and improve water allocation, farmers practicing drip irrigation are still unclear about the exact quantity of water that crops need and the appropriate frequency of irrigation [8]. This leads to over-irrigation and increases the risk of bad drainage conditions and salinization.

Another irrigation water management strategy that has led to a considerable improvement in irrigation management is using modern efficient irrigation technology, such as soil water content probes, tensiometers for soil water status monitoring, and other monitoring techniques. However, installation and operation costs of such instruments are expensive and only few can afford. Additionally, in the case of large fields with spatial variation in soil properties, spendings might further increase due to fine tuning monitoring instrument.

Another solution to increase water use efficiency is a modeling approach to improve the irrigation scheduling. The modeling outputs can help farmers to apply precision irrigation treatment when and where needed using a defined quantity of water. However, sound modeling requires measurement and analysis of several variables related to soil, plant, and external environments such as soil hydraulic parameter sets, boundary conditions, and root water uptake parameters. Therefore, numerical models based on the numerical solutions of the Richards' equation [9] are matching these conditions to represent water movement in the soil profile to fine tune the plant root water uptake and promote efficient water usage [10,11].

One of the most famous tools that are used to create numerical hydrological soil models is the Hydrus (2D/3D) software [12] that was successfully used for predicting and analyzing the water flow in the vadose zone for agricultural purposes under different soil types, different environmental conditions, and different plants constraint [13]. All reviewed studies showed that the Hydrus water dynamic simulation result concurred reasonably with the field measurements, therefore, the software can be applied effectively in the development and management of irrigation systems for several crops [14–18].

For the application of our modelling exercise we focus on the Jericho area a water scarce area that faces several constraints to cultivate and produce date palm [19,20]. Palestinian farmers mostly use fresh groundwater to irrigate their date palm trees. They have mainly relied on springs and groundwater boreholes that become much less reliable due to the over-pumping, most wells consider a private property regime. Due to the high water demand, farmers started to use treated water generated from the wastewater treatment plant in Jericho [21,22] which generates about 600 to 700 m^3 treated wastewater per day for the irrigation of date palms trees [21].

Despite that the date palm tree survives and produces under arid conditions, it requires a sufficient amount of water to reach the potential yield and produce a good quality of fruits [23]. The efficient use of irrigation water in this area is considered as a priority, where Ahmad Fares/ Ministry of Agriculture explained that "unfortunately this sector is facing a real problem resulting from the shortage of water needed for existing projects or future expansions, as large areas of land are available for cultivation, and if we can secure the needed water, we will be able to double the area cultivated with palm trees "If not, we will incur losses". Also, Ismail Deiq, one of the largest investors in the palm sector, said that date palm tree cultivation in Palestine is facing a real threat because of the lack of water. He also anticipates that if a solution is found to the water shortage, the revenue generated by this sector will increase to around $120–150 million within the next 6 or 7 y, in comparison with the current revenue of $35 million [24].

With our research we aim to develop an irrigation water management through new scheduling of irrigated water based on a modeling approach using the Hydrus-2D package for the 5 y-old Medjool date palm trees in Jericho. Although that Hydrus software had been used worldwide to optimize irrigation water efficiency usage, there are no studies available about using such numerical modeling in the agricultural sector in the West Bank. Hence, this study introduces a new concept of irrigation management for the Palestinian date palm farmers by using a combination of soil moisture monitoring and Hydrus-2D modeling to estimate hydraulic properties that can predict soil–water content. This is followed by a model calibration using inverse modeling with field data to estimate the hydraulic properties. In addition we use the Penman–Monteith methods, available in the CROPWAT program (FAO, 1992), to calculate the reference crop evapotranspiration. Hence, we study in sync the effect of the proposed irrigation scheduling on production and its water-saving capacity. In this paper, the materials and methods are presented in section 2, the results are discussed in section 3, and the conclusion is provided in section 4.

2. Materials and methods

2.1. Field experiment

This part of the methodology is dedicated to field data collection, soil samples analysis, soil moisture content measurement, and monitoring through a specified period of 70 d. The collected information is harmonized to build a validated and calibrated base hydrological model using Hydrus-2D software, that accurately represented the experimental site's conditions.

2.1.1. Location

In an agricultural area owned by the Ministry of Agriculture, the experimental study site is situated at 260 m below sea level coordinates of (31° 51′ 26″ °N and 35° 27′ 50″ °E) in Jericho city, east of the Jordan river in the Jordan Valley. The site is about 2.5 dunums in size with 33 date palm trees (Fig. 1). The experimental study site is located in an arid climate with temperatures ranging from 12°C in March up to 50°C between July and October, with average annual humidity of 49.3% [19,25], conditions that are ideal for date palm production as well as for the maturation of the fruit. Accordingly, Jericho governorate is the biggest date producer in the West Bank, with 99% of the total production [26]. An additional advantage of the date palm cultivation is that the crop requires only one-third of the water needed to produce bananas or oranges, so when date palm trees are substituted for banana plants and orange trees, two-thirds of irrigation water can be applied to other crops [19]. Hence, although date palm cultivation sustainability in the Jordan Valley is still controversial, due to the limitation of water resources [21,27].

In our experimental site, water from Ein Sultan spring with a salinity of about 780 uS/cm is used to irrigate the date palm trees. Commonly 20 m^3/tree·y of freshwater is used for irrigation.

2.1.2. Design of field experiment

The experimental site is approximately 2,500 m^2, with 33 date palm trees spaced 9 m apart. In the experimental work, a plot row – line of six 5 y-old Majdool date palm trees were used to build the base calibrated hydrological model. Six fiberglass tubes were inserted into the soil profile at a depth of 83 and 50 cm from the palm tree trunk. These tubs are used to place the probe PR2 tube device that measures soil moisture at five different depths (3, 13, 23, 43, and 83 cm) within the six locations; B_1 to B_6 (Fig. 2).

Drip irrigation was the irrigation technique applied at the target area, where the date palm trees was been irrigated by the farmer in the site, using drip pipes which were wrapped around each tree to form a wetting area of about 9.07 m^2. During the simulation process of 70 d, the irrigation schedule followed in this part of the methodology was the same as that applied by farmers in the experimental site: where, the irrigation volume was monitored through the flow meter (m^3), and the time of irrigation was one time in the first two weeks, then it has been irrigated three times per week until the final day of simulation (This procedure is only to construct the base model, in order to check the ability of Hydrus model to represent the actual condition of the experimental field).

2.1.3. Measurement of soil physical properties and soil moisture

Two soil trenches were excavated in representative locations to a depth of 1.5 m, to represent the root zone of the date palm (Fig. 3). The soil samples were collected horizontally at depths of 0–20, 20–40, 40–60, 60–80, and 80–115 cm with three replications. The undisturbed soil samples were collected manually and transported to the laboratory in closed plastic bags. Sieve analysis and the hydrometer methods were used for the determination of the particle-size distribution for the soil samples, the hydrometer analysis is the procedure generally adopted for the determination of the particle-size distribution in soil for the fraction that is finer than the sieve size of 0.075 mm. The lower limit of the particle-size determined by this procedure is about 0.001 mm, in other words, this analysis was used to distinguish between silt and clay particles, which could not be done by the sieve analysis [28].

The soil samples analysis is important to input data for the Hydrus-2D model, to initially estimate the soil hydraulic parameters: soil van Genuchten's water retention parameters (θ_r, θ_s, m, α, and n) and the saturated hydraulic conductivity (K_s), that were been estimated by using the ROSSETA software that implements pedotransfer functions (PTFs) based on the soil textural information.

Fig. 1. Location of the field experimental site in Jericho.

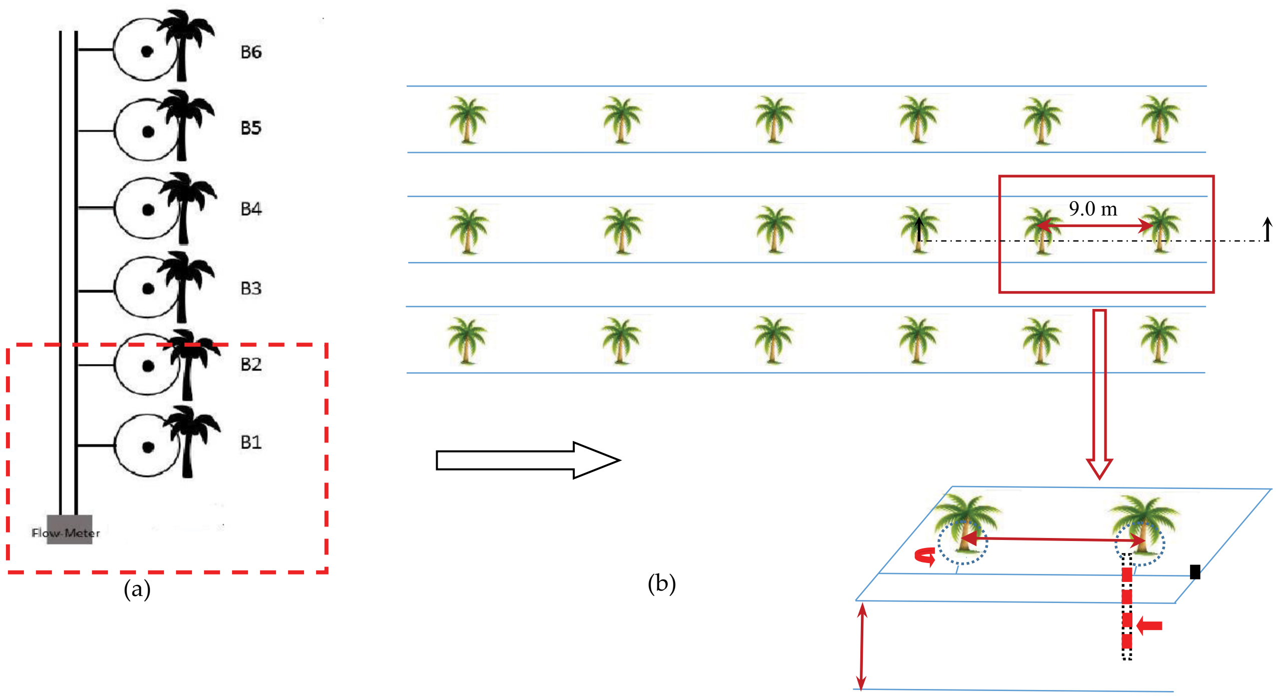


Fig. 2. Schematic of the field experimental site: (a) surface drip pipe, and date palm plants in the experimental field and (b) location of PR2 tube in the root zone.

Fig. 3. Soil trench excavation.

Soil moisture contents were measured at depths of 3, 13, 23, 43, and 83 cm in the six locations from B_1 to B_6. Soil moisture measurement occurred from 24 August 2020 to 1 November 2020. During this time, soil moisture was measured whenever it is possible, especially when there were irrigation events. The soil moisture was measured by using a profile probe type PR2 where the sensor device was been inserted in plastic access tubes preventively installed in the soil and allowed measuring the volumetric water contents in (%) of the soil volume, it measures soil moisture at different depths within the soil profile. The probe sensor device consists of a sealed polycarbonate rod, 25 mm in diameter, with electronic sensors [29]. Table 1 illustrate the methods used to estimate the soil characteristic and hydraulic properties measurements in the research study.

2.2. Numerical modelling

2.2.1. Water flow equations

Soil water movement in the experimental field was simulated as water flow in a 2D vertical plane crosses drip tape wrapped around each date palm tree. The equation governing water flow is as follows: [15,18,33].

$$\frac{\delta\theta}{\delta t}=\frac{\delta}{\delta x}\left[k(\theta)\frac{\delta h}{\delta x}\right]+\frac{\delta}{\delta z}\left[k(\theta)\frac{\delta h}{\delta z}\right]+\frac{\delta k(\theta)}{\delta z}-s \quad (1)$$

where θ is the volumetric water content (cm³·cm⁻³), h is the pressure head (cm), S is a sink term (cm⁻³) which represents the volume of water removed per unit time from a unit volume of soil due to plant water uptake, and $k(\theta)$ is the unsaturated hydraulic conductivity function (cm·d⁻¹).

Soil hydraulic properties were estimated with the van Genuchten–Mualem function as follows:

$$\theta(h)=\begin{cases}\theta_r+\dfrac{\theta_s-\theta_r}{\left[1+|\alpha h|^n\right]^m}; & h<0\\ \theta_s; & h\geq 0\end{cases} \quad (2)$$

$$K(\theta)=K_sS_e^1\left[1-\left(1-S_e^{\frac{1}{m}}\right)^m\right]^2 \quad (3)$$

$$S_e=\frac{(\theta-\theta_r)}{(\theta_s-\theta_r)},\quad m=1-\frac{1}{n},n>1 \quad (4)$$

Table 1
Methods to estimate the soil characteristic and hydraulic properties measurements used in the research study

Parameter	Method	No. of measurements	References
Particle-size distribution (sand percentage)	Sieve analysis	6 soil samples	[28]
Particle-size distribution (fractions that are finer than 0.075 mm)	Hydrometer analysis	6 soil samples	[26]
Initial soil water content	Profile probes types PR2	30 times (one time for each location at the 6 depths)	[29]
Soil hydraulic parameters (θ_r, θ_s, m, α, and n)	The ROSSETA computer program	Manual calibration process	[30]

where θ_s is the saturated water content ($cm^3 \cdot cm^{-3}$), θ_r is the residual water content ($cm^3 \cdot cm^{-3}$), K_s is the saturated hydraulic conductivity ($cm \cdot d^{-1}$), α, m, and n are the empirical parameters affecting the shape of the hydraulic function, S_e is the effective water content, and h is the pressure head.

2.2.2. Domain shapes and geometries, material selection

In this research, 2D – standard version of Hydrus software was used in order to simulate the irrigation water movement through the soil profile. The 'Simple' geometry with "2D-Vertical Plane XZ" was been selected, to simulate the transport domain. The dimensions of 5,400 cm in the x-direction, were chosen to represent the date palm trees in the specified experimental line with a distance of 9 m between every two trees from the center. While, the 200 cm in the Z-direction was been specified to represent the effective root zone of the date palm, while notifying that for the date palm, 40% of all water is being extracted from the first 50 cm, 70% is from the first 100 cm, 90% is from the top 150 cm, and only 10% is from the last layer or 150 to 200 cm and deeper [34]. For material selection, the soil profile was divided into five layers known as "surfaces" in the model, based on the soil analysis done in the laboratory, where each soil layer has different percentages of sand, silt, and clay, that in turn lead to a different soil hydraulic parameters.

2.2.3. Initial and boundary conditions

The initial conditions were defined in terms of the volumetric water contents, that were measured in the field at various depths (i.e., 3, 13, 23, 43, and 83 cm), by using the profile probe device PR2, the measurements were taken at the beginning of the experimental period on 24 of August 2020 after one week of no irrigation.

The two-dimensional transport domain that represents the soil profile has four external boundaries: upper, left, right, and bottom sides. The upper boundary represents the soil surface (Z = 0) and used the atmospheric boundary, which processed daily climatic conditions like precipitation, evaporation, and transpiration by plants, except for the distances from x = 0 to 360 cm, x = 900 to 1,260 cm, x = 1,800 to 2,160, x = 2,700 to 3,060 cm, x = 3,600 to 3,960 cm and x = 4,680 to 5,040 cm, which were defined as a variable flux to represent the drip irrigation with the variable intensity and it was calculated as the volume of applied irrigation water that been flowed into the model domain (reading of the flow meter/number of trees in the line), indicated as a negative value when water flow in the region, in a daily period, through the specified area that was assumed to have a radius of 1.7 m, which had been calculated as 9.07 m^2 around each date palm tree. The variable flux [35] is described as:

$$q = \frac{Q}{A}, \; A = \pi r^2 \tag{5}$$

where, Q = the flow rate measured from the metering device (L^3/T). In the case of the field layout in the present work, Q is calculated as, A = the area of the surface saturated water entry around each date palm tree (L^2), r = saturated water entry radius (L) assumed in this study as 1.7 m. While the left and right sides of the domain have a no-flux boundary because no water flows into or out of the domain through these boundaries. Also, the seepage face boundary condition was imposed at the bottom side of the soil profile (z = 200 cm), which means that the water is freely draining through the boundary, in case the flow domain becomes saturated.

2.2.4. Estimating evaporation and transpiration

The daily potential evaporation from the soil surface (E_p) and potential transpiration by plants (T_p) are both required inputs in Hydrus-2D. These values were considered as time-variable boundary conditions, which both have entered into the simulation model separately. In this situation, the potential crop evapotranspiration that exported from CROPWAT software (computer program used to calculate the potential evapotranspiration (ET_0) with the Penman–Monteith method in mm/d, using the available soil, crop, and climate data for monthly mean values (of 15 y at least) for Jericho weather station), was divided into potential evaporation and potential transpiration by using Beer's law, through 1 y, its concept based on using the average leaf area index (LAI) of the reference grass of height (h) of 0.12 m as a partitioning factor of the potential crop evapotranspiration as follows: [16,36].

$$T_p = \mathrm{ET}_p\left(1 - e^{-k(\mathrm{LAI})}\right) = \mathrm{ET}_p\left(\mathrm{SCF}\right)$$

$$E_p = \mathrm{ET}_p\left(e^{-k(\mathrm{LAI})}\right) = \mathrm{ET}_p\left(1 - \mathrm{SCF}\right) \tag{6}$$

where, ET_p, T_p, and E_p are the potential evapotranspiration, transpiration, and evaporation fluxes [L/T], respectively, LAI is the leaf area index of the reference crop estimated as 2.88, which was calculated as 24 h [16], SCF is the soil cover fraction, and k is the constant governing the radiation extinction by the canopy of the reference grass, it is ranging from 0.5 to 0.75 [36].

2.2.5. Input parameters

The simulation domain was divided into five soil layers: 0–20, 20–40, 40–60, 60–80, 80–200 cm. The values of saturated soil water content, saturated hydraulic conductivity, and parameters θ_r, α, and n were optimized via manual calibration using ROSSETA computer program M.Th. van Genuchten et al. [37].

2.2.6. Root water uptake

The amount of water that is being withdrawn from the root zone by the crop uptake process in the Hydrus-2D simulation is defined by the following equation:

$$S(h)_w = \alpha(h) \times b(x,z) \times S_t \times T_p \quad (7)$$

where α (h) is the soil water stress function of [38]. While, S_t present the length of the soil surface associated with transpiration (L) [33]. $b(x,z)$ is the normalized root water uptake in 2D distribution, which is defined by [39] as follows:

$$b(x,z) = \left(1 - \frac{z}{z_m}\right)\left(1 - \frac{x}{x_m}\right) e^{-\left[(p_z/Z_m)|z^{*} - z| + (p_x/X_m)|x^{*} - x|\right]} \quad (8)$$

where, X_m and Z_m are the maximum rooting lengths in the x and z-directions (L), respectively. The x and z are the distances from the origin of the date palm tree in the x and z-directions (L), as 150 and 1,250 cm respectively [40]; and p_x, p_z, x^*, and z^* are the empirical parameters [33] (Table 2).

2.3. Criteria of model evaluation

The performance and behavior of the hydrologic models are commonly checked and evaluated through the comparison processes made between the simulated and observed values, by using a variety of statistics. It is known, that there is no single statistical efficiency test that could be applied ideally. Therefore, it was suggested to use a combination of different efficiency criteria to determine the volume of error [41]. According to the published literature, the most recommended performance criteria used to evaluate the difference between observed and modeled data, and also being applied in the present work to check the performance of the Hydrus-2D model, were the root-mean-square errors

Table 2
Parameters of the root water uptake distribution function [37]

Z_m (cm)	z^* (cm)	p_z	X_m (cm)	x^* (cm)	p_x
150	110	1	1250	200	1

(RMSE), the coefficient of determination (R^2), mean absolute error (MAE), and Nash–Sutcliffe efficiency (NSE) [42–46]. They are calculated by the following equations:

$$\text{NSE} = 1 - \left[\frac{\sum_i^n \left(Y_i^{\text{obs}} - Y_i^{\text{mean.obs}}\right)^2}{\sum_i^n \left(Y_i^{\text{obs}} - Y_i^{\text{mean.obs}}\right)^2}\right] \quad (9)$$

$$r^2 = \left[\frac{\sum_i^n \left(Y_i^{\text{obs}} - Y_i^{\text{mean.obs}}\right)\left(Y_i^{\text{sim}} - Y_i^{\text{mean.sim}}\right)}{\sum_i^n \left(Y_i^{\text{sim}} - Y_i^{\text{mean.sim}}\right)^2 \left(Y_i^{\text{obs}} - Y_i^{\text{mean.obs}}\right)^2}\right] \quad (10)$$

$$\text{RMSE} = \sqrt{\frac{\sum_i^n \left(Y_i^{\text{obs}} - Y_i^{\text{sim}}\right)^2}{n}} \quad (11)$$

$$\text{MAE} = \frac{\sum_i^n \left(Y_i^{\text{obs}} - Y_i^{\text{sim}}\right)^2}{n} \quad (12)$$

where, Y_i^{obs} and Y_i^{sim} is the observation and simulated soil water content value at time/place i, respectively. While, $Y_i^{\text{mean,obs}}$ is the mean of the observed data, and $Y_i^{\text{mean,sim}}$ is the mean of the simulated data, and n is the total number of the observations.

All these statistical equations were used to compare the simulated and observed values of the soil water content at a specified depth along the soil profile. The MAE and RMSE is considered to be satisfactory when both values are close to zero, while for a better performance of the simulation model, the R^2 and NSE should be close to 1. NSE ranges from −∞ and 1, so it may result in negative values in case the mean square error exceeds the variance of the observed values [47].

2.4. Optimize the best irrigation scenario

Once the Hydrus-2D model was built and validated in the first part of the methodology, it was used to simulate the soil water content through the soil profile under different irrigation scheduling scenarios for 1 y, which was assumed to have 365 d, starting from the initial development stage of date fruit to the harvest or late development stage.

The Hydrus-2D software base model was used to simulate four scenarios, to compare the water distribution results along the root zone of the date palm tree. The scenarios investigated the possibility of improving irrigation management efficiency by comparing root water uptake, water availability in the root zone based on specified water content thresholds, drainage, irrigation amounts, crop water productivity, and yield. Using equations derived from two studies conducted on Medjool date palm in the Jorden valley [48], and [49], respectively. The last two criterias (crop water productivity, and yield) were calculated.

The four irrigation scenarios used to compare processes of the water flow movement through the soil profile are:

- Irrigation scheduling by applying the required irrigation for the crop using CROPWAT 8.0 program.
- Irrigation scheduling suggested by the CROPWAT software using the option of refilling soil to the soil field capacity.
- Irrigation scheduling using actual water amounts by farmers in the experimental field.
- Irrigation schedule using water balance concept.

3. Results and discussion

3.1. Field measurements: measurement of soil physical properties, estimation of soil hydraulic parameters

Table 3 showed the results of the soil samples analysis in the laboratory using sieve analysis, and hydrometer method, these values for the five layered soil profile, are very important inputs in Hydrus-2D, to accurately determine the hydraulic parameters of the soil layers (Table 3). Where, the values of saturated soil water content, saturated hydraulic conductivity, and parameters θ_r, α, and *n* were optimized via manual calibration using ROSSETA computer program. This program implements five hierarchical pedotransfer functions (PTFs) that allow the estimation of van Genuchten water retention parameters and the saturated hydraulic conductivity using textural classes as input data (Table 4).

3.2. Model evaluation

A comparison of the measured moisture content at different soil depths (3, 13, 23, 43, and 83 cm) with the simulated moisture content from the Hydrus-2D basic model was performed at six locations in the test field. Executed in (B_1 to B_6). Comparisons were made in this study at specific time points from August 24 to November 1, 2020.

Based on the results of the four statistical tests, using RMSE, coefficient of determination (R^2), MAE, and NSE, the Hydrus-2D model was successfully able to accurately simulate the temporal and spatial changes in the soil water contents and to be used as a tool to simulate the dynamics of soil water content in a cropped soil with surface drip irrigation technique. Annex. 1 showed the results of the statistical tests.

3.3. Scenarios analysis

Using the Hydrus-2D model, the four different simulated scenarios over 365 d were analyzed and compared based on the following criteria: water availability for plant uptake, crop water productivity, yield amounts, drainage of water, irrigation amounts used, and water stress periods.

3.3.1. Comparison of water distribution patterns among scenarios

This section compares simulations of soil water content fluctuations at depths ranging from 0 to 200 cm with specific soil water thresholds depending on the soil type, including, saturation (*S*), field capacity (FC), permanent wilting point (PWP), and allowable depletion management (MAD), for each scenario over a 365 d simulation period.

These thresholds indicate the water availability for plant consumption and showed if there were any water stress periods or water percolation below the effective root zone, which is for date palm 110 cm. Table 5 summarized the stress period for each depth in each scenario, in other words, it showed the period where the soil water content was smaller than the MAD threshold, an indication that the crop was suffering from water stress in that specified period. Scenario three had the largest stress periods at different depths, compared to other scenarios. Table 6 showed the percolation periods, the time when the water content was above the soil field capacity.

Figs. 5–7 show the daily volumetric water content changes, through the soil profile over 1 y period starting from 15 Aug 2020 to 14 Aug 2021 under the four different irrigation schedules by using the Hydrus-2D model in location B_3 (the middle date palm tree).

Table 3
Properties of the soil profile and particle-size distribution were measured in the laboratory

Soil depth	Sand	Silt	Clay	Texture
(cm)		%		
0–20	38	27	35	Clay loam
20–40	37	27	36	Clay loam
40–60	14	40	46	Silty clay
60–80	24	40	36	Clay loam
80–120	40	38	22	Loam

Table 4
Soil hydraulic parameters of the van Genuchten–Mualem model at the experiment site. Saturated hydraulic conductivity (K_s) and saturated water content (θ_s), *n*, α, and θ_r were estimated values through manual calibration

Soil depth	Sand	Silt	Clay	θ_r	θ_s	α	*n*	K_s
(cm)	%			cm³·cm⁻³		cm⁻¹		cm/d
0–20	38	27	35	0.0817897	0.427136	0.0176151	1.33444	5.05734
20–40	37	27	36	0.0827844	0.429899	0.0176044	1.32947	5.04597
40–60	14	40	46	0.0974478	0.487398	0.0135323	1.34288	15.6868
60–80	24	40	36	0.0872987	0.456763	0.0112528	1.415	11.4795
80–120	40	38	22	0.0660518	0.409665	0.0107407	1.4745	8.31475

Table 5
End date of the stress period for each scenario through a year, for different soil depths along the effective root zone

Scenarios/ Depth	0–40	40–60	70–80	80–110
SC1	30-8-2020	12-9-2020	21-9-2020	24-9-2020
SC2	27-8-2020	3-9-2020	13-9-2020	15-9-2020
SC3	3-9-2020	24-9-2020	13-10-2020	10-10-2020
SC4	19-8-2020	7-9-2020	11-9-2020	14-9-2020

Note: Starting date of stress periods in all scenarios and all depths was on 15 August 2020.

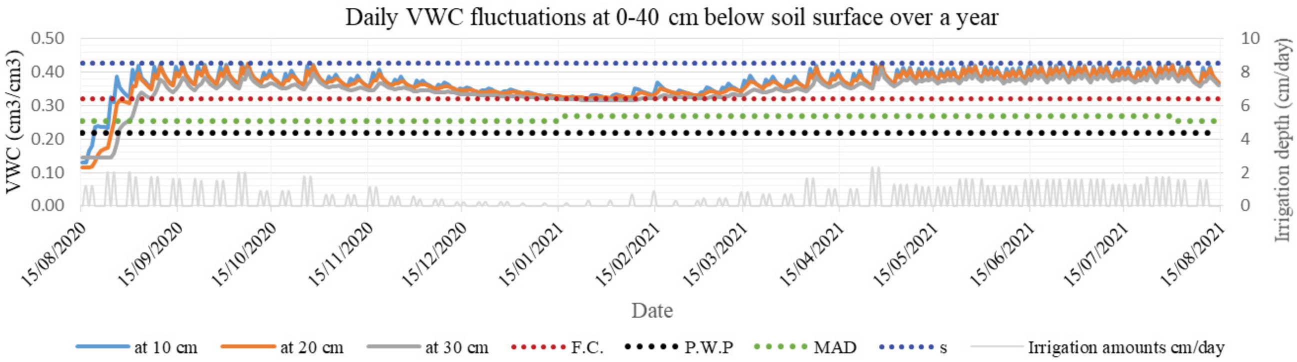
Figs. 4–7) and Tables 5 and 6 show, in most cases, that in scenario three, water started to percolate beneath the root zone earlier than in the other scenarios. While, in the case of scenario four, water starts to percolate beneath the root zone later than in the other scenarios. Moreover, it was very clear, that scenario four had smaller water stress and percolation periods. It could be concluded that scenario four had the longest time period where water was available to crop use.

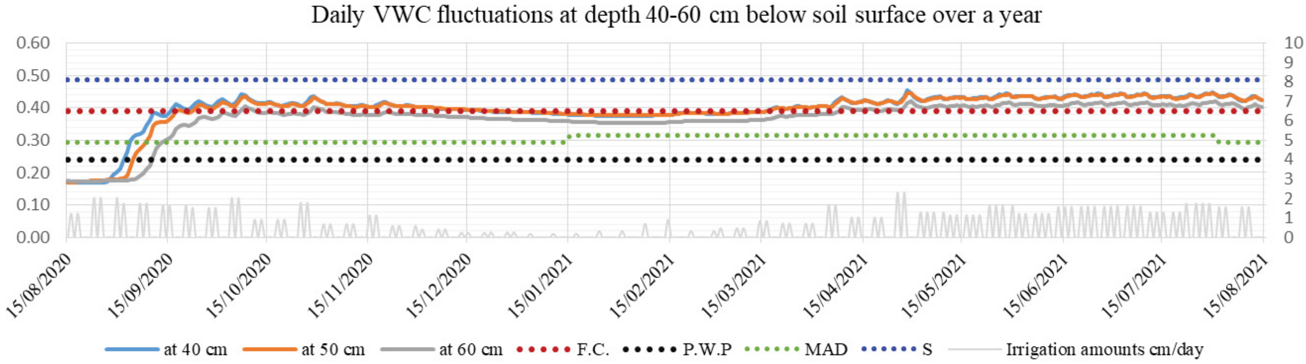
Table 6
Percolation periods for each scenario through a year, for different soil depths along the effective root zone

Scenarios/Depth	0–40	40–60	70–80	80–110
SC1	7-9-2020 to 14-1-2021/11-3-2021	19-3-2021	2-10-2020 to 16-12-2020/20-3-2021	10-4-2021
SC2	3-9-2020	22-4-2021	8-8-2021	15-11-2020
SC3	15-9-2020	31-12-2020	6-5-2021 to 2-8-2021	20-12-2020
SC4	30-8 to 9-11-2020/30-11 to 19-12/20-3-21	3-5-2021	Days – very small periods	23-3-2021

Note: All the dates present the starting date of the percolation period, the ending date of percolation periods in all scenarios and all depths was on 14 August 2021.

3.3.1.1. For scenario one (SC1)





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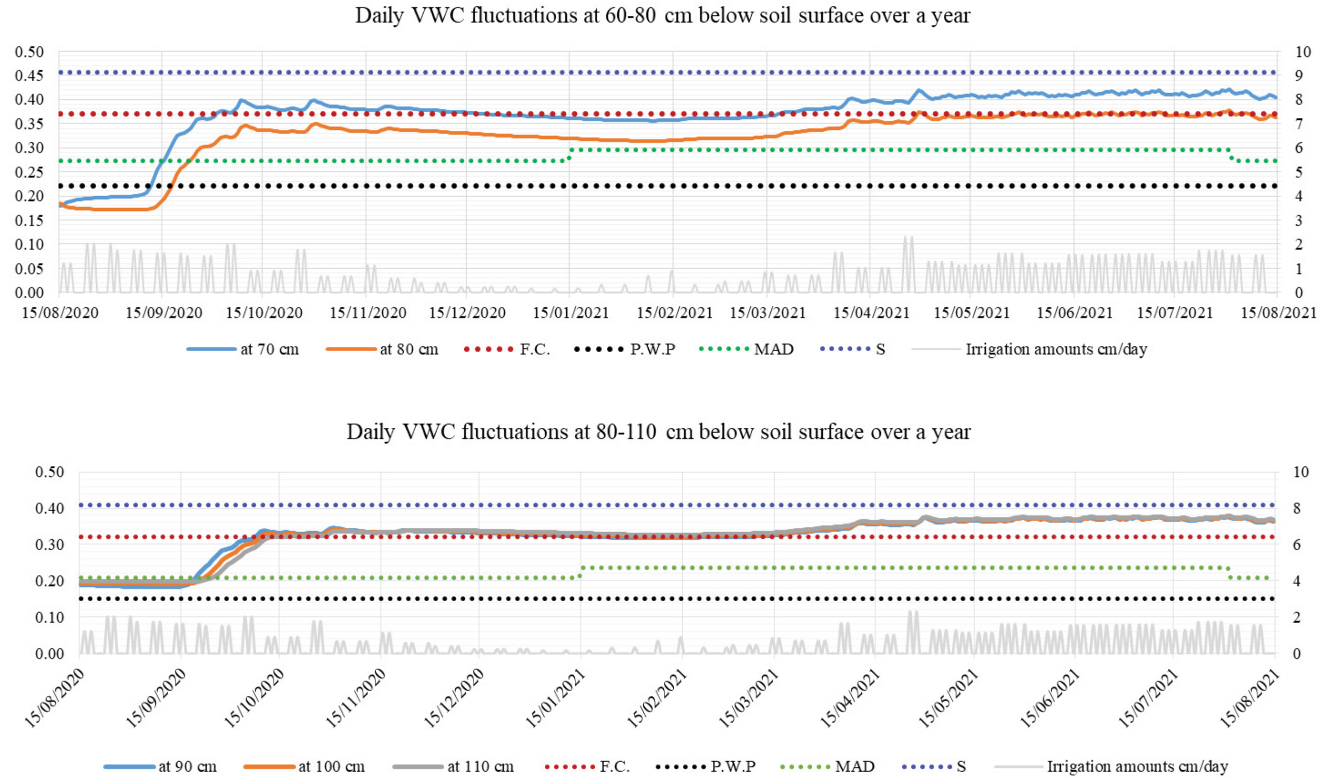
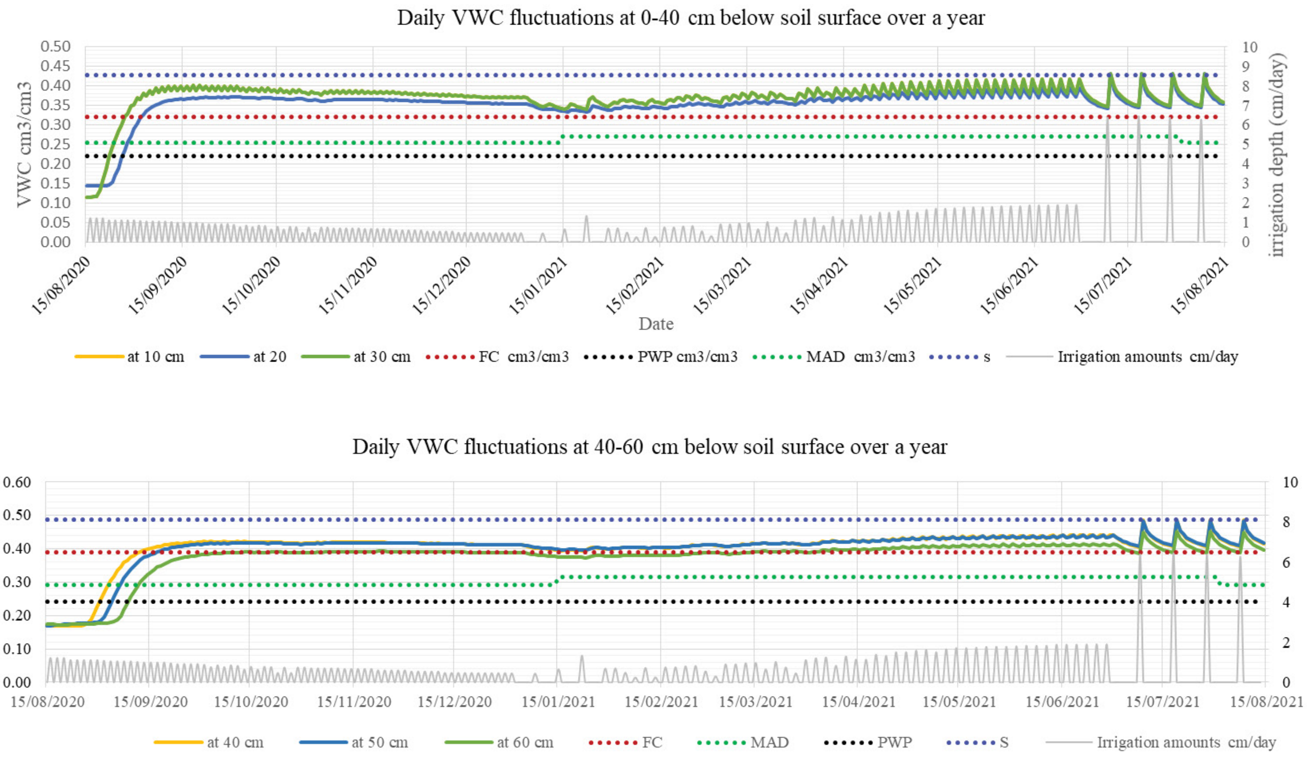
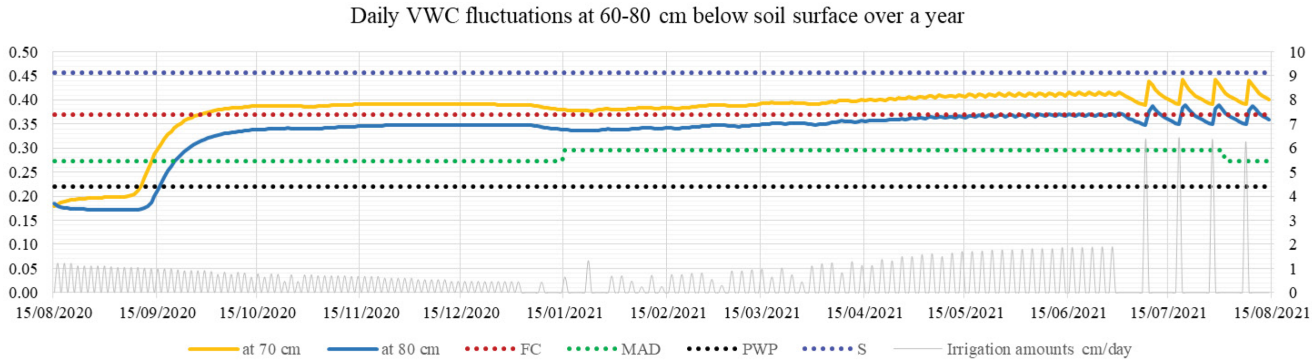


Fig. 4. Scenario one, daily VWC fluctuations along the effective root zone over 1 y.

3.3.1.2. For scenario two (SC2)



(Continued)



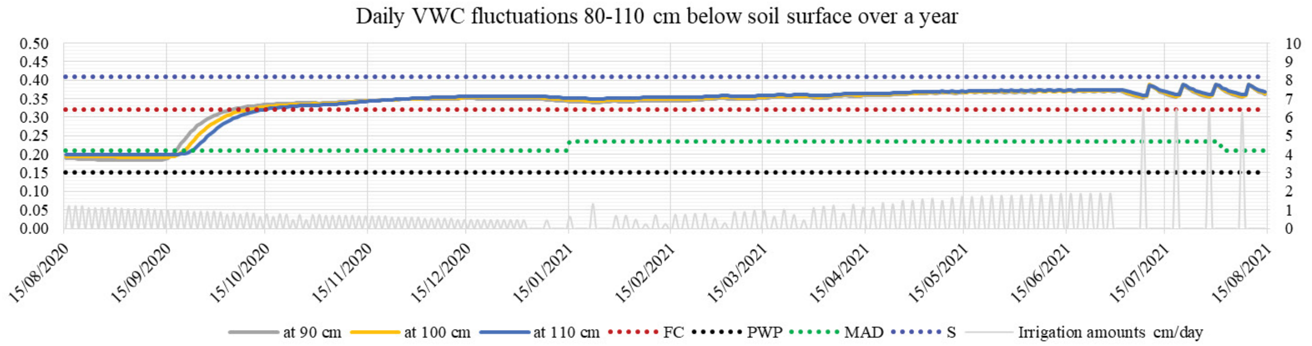
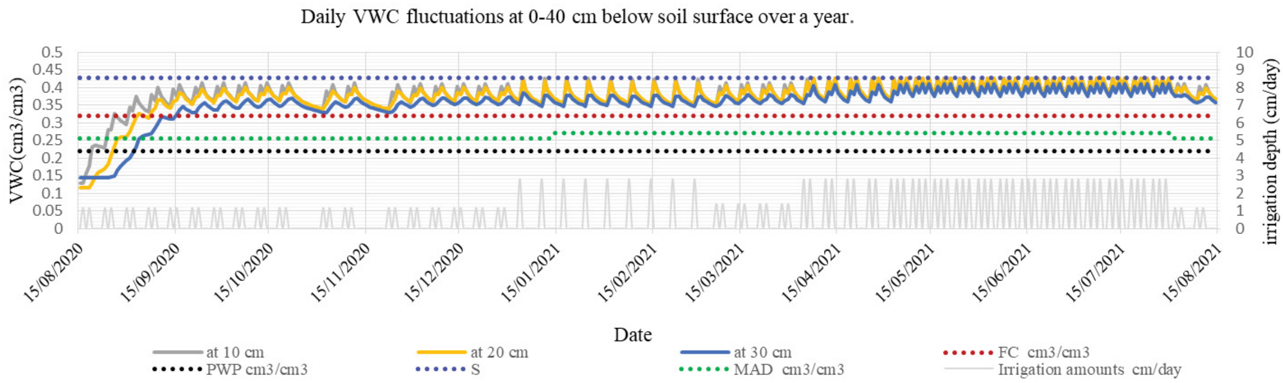
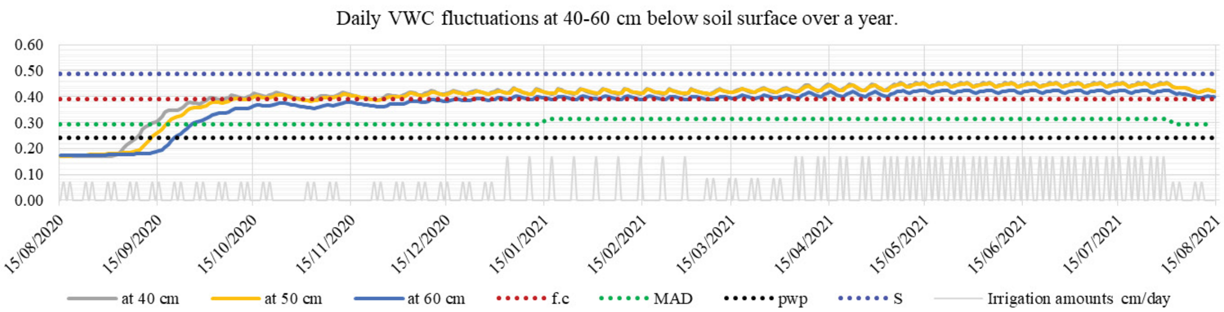


Fig. 5. Scenario two, daily VWC fluctuations along the effective root zone over 1 y.

3.3.1.3. For scenario two (SC3)





Daily VWC fluctuations at 80-110 cm below soil surface over a year.

(Continued)

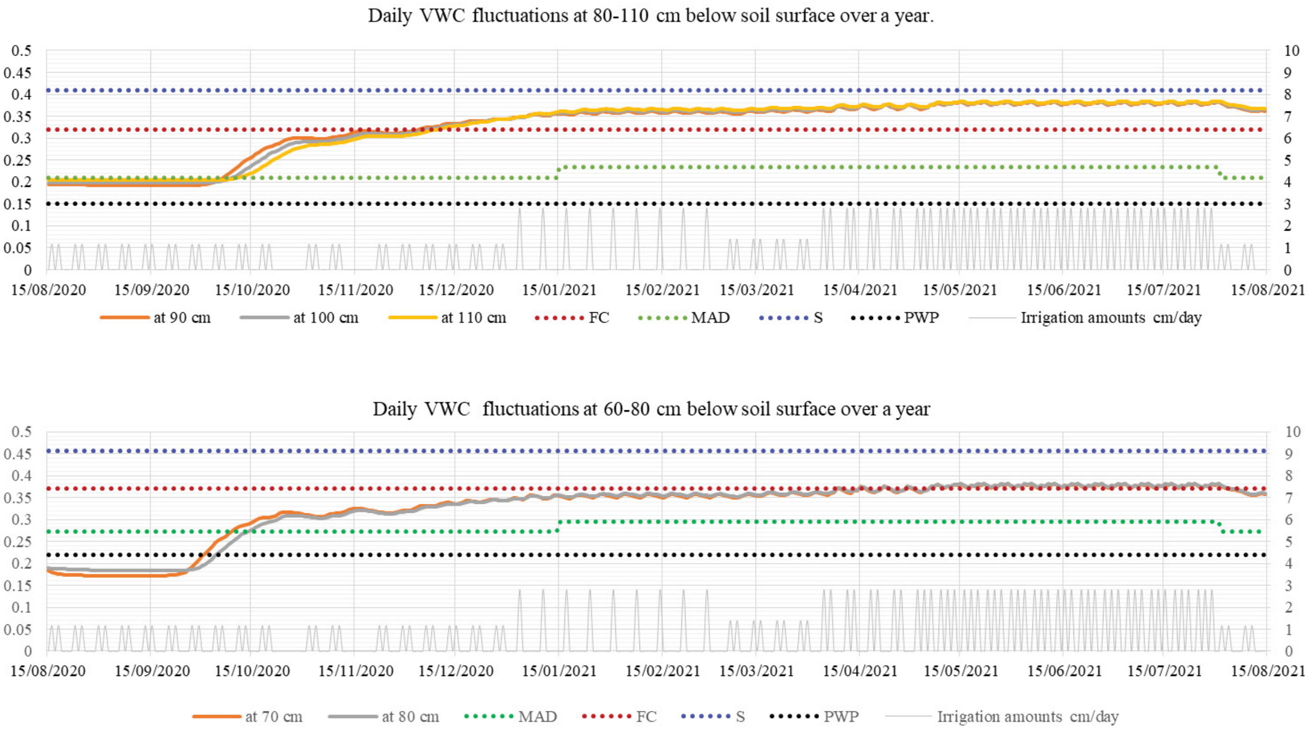
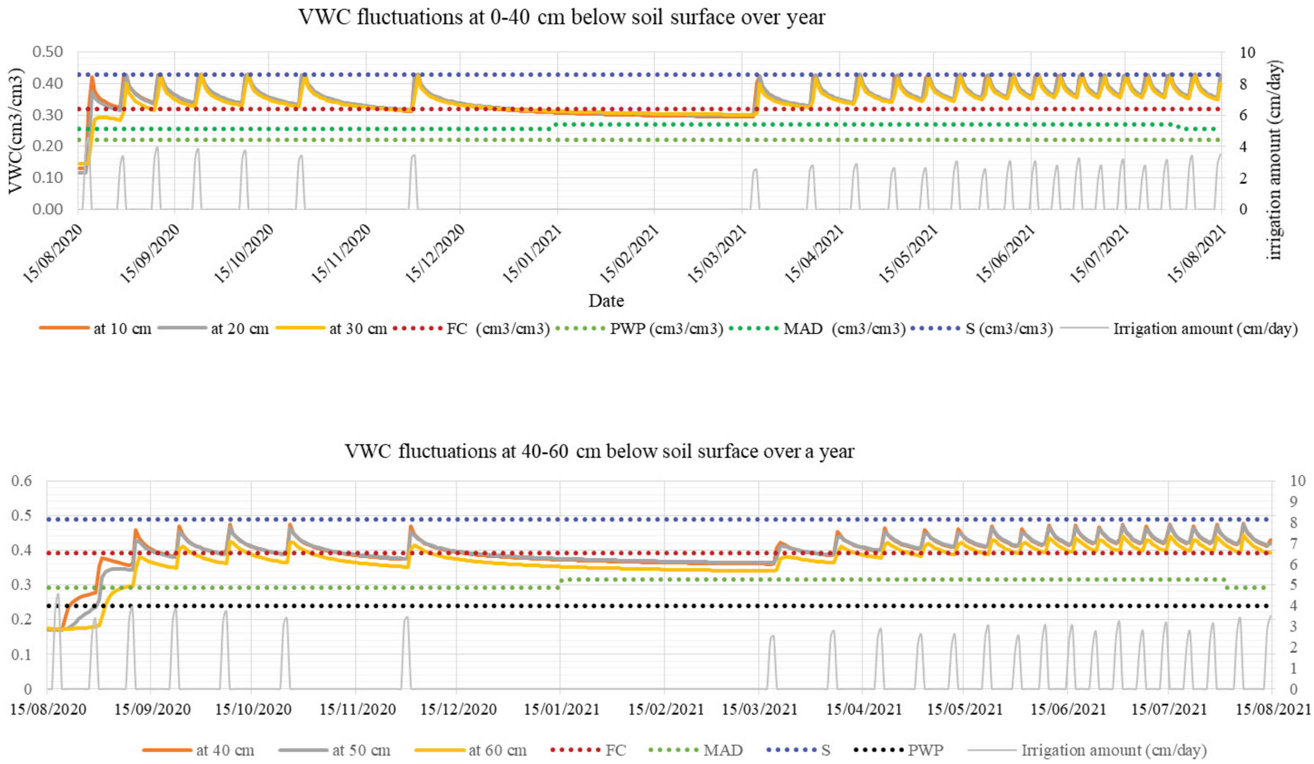


Fig. 6. Scenario three, daily VWC fluctuations along the effective root zone over 1 y.

3.3.1.4. For scenario four (SC4)



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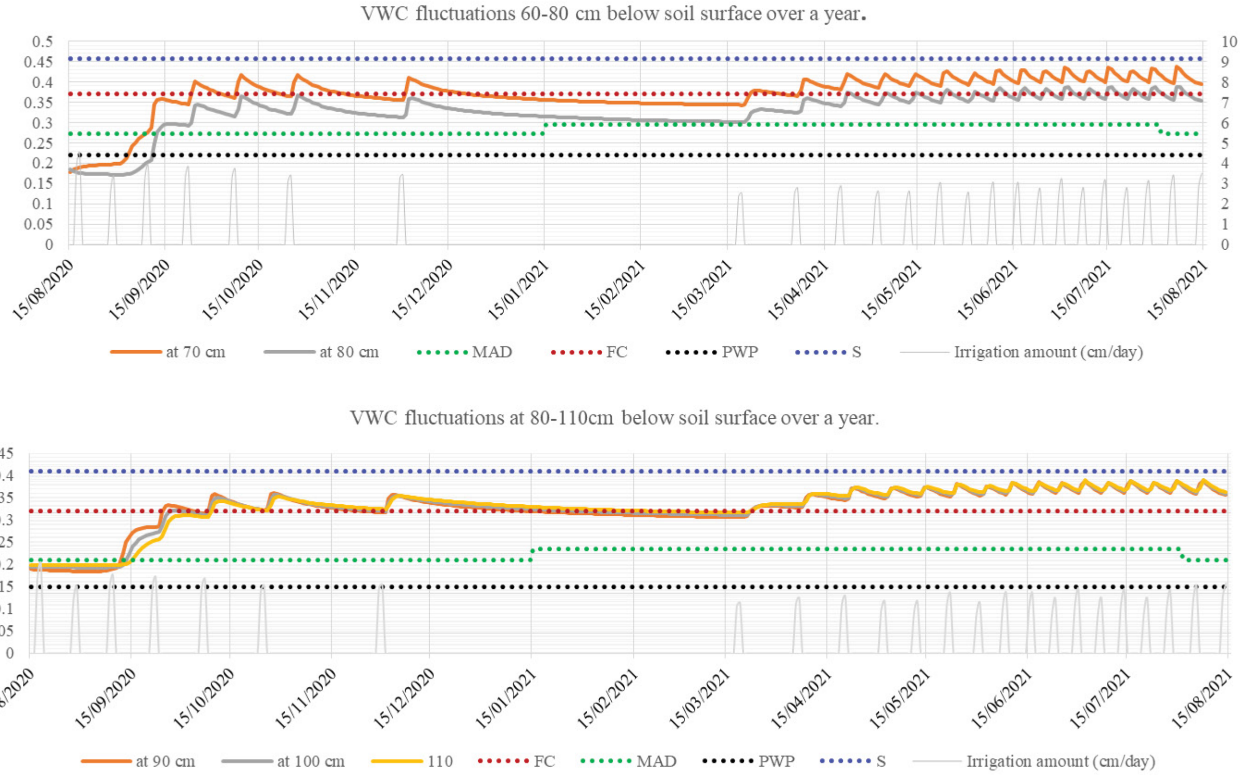

Fig. 7. Scenario four, daily VWC fluctuations along the effective root zone over 1 y.

Table 7
Simulated water balance components and other compression criteria of each scenario from 15 August 2020 to 15 August 2021

Compression criteria/y	Scenario one	Scenario two	Scenario three	Scenario four
Root water uptake (cm/y)	68.25	77.88	98.81	64.56
Irrigation (cm/tree·y)	127.6	144	215.36	137.40
Irrigation (m^3/tree·y)	11.6	13	20	12.5
Yield (kg/tree)	32.90	32.2	33.1	32.91
CWP (kg/m^3)	2.84	2.53	1.66	2.63
Drainage (cm/y)	19.47	27.9	77.5	36.5

3.3.2. Comparison of water balance components, crop yield, and crop water productivity among scenarios

The water balance components in the root zone (depth of 0–110 cm) for all scenarios are shown in Table 7, actual root water uptake (RWU), drainage at a depth of 110 cm, irrigation water volume, crop water productivity, and crop yield, from 15 August 2020 to 15 August 2020, were computed from the simulation study. Regarding the RWU, it was obvious from Table 7 and Fig. 8 (figures exported from the Hydrus model) that scenario three (irrigation scheduling used by farmers in the experimental site) had the maximum RWU values, thus most water loss generated by transpiration.

The second criteria was the amount of water used for irrigation, the results present that farmers used in the actual situation (presented by scenario three) 20 m^3/tree·y, which is about 46.15% more than water needed in scenarios one and four. Yet scenario three will not lead to lower yields. So farmers can use about 46% less irrigation water and have the same crop yield. Moreover, the results showed a higher CWP and smaller water loss by percolation below the root zone for scenarios one and four. So as a result, the farmer is advised to apply either irrigation schedule scenario four or scenario one.

4. Conclusion

Our study conducted a field experiment to evaluate the use of the Hydrus-2D software, in improving the agricultural water management through new proposed irrigation scheduling of fresh groundwater in irrigation schemes of 5 y date palm trees in the Jericho area. The Hydrus-2D was used to simulate and predicting the soil water distribution

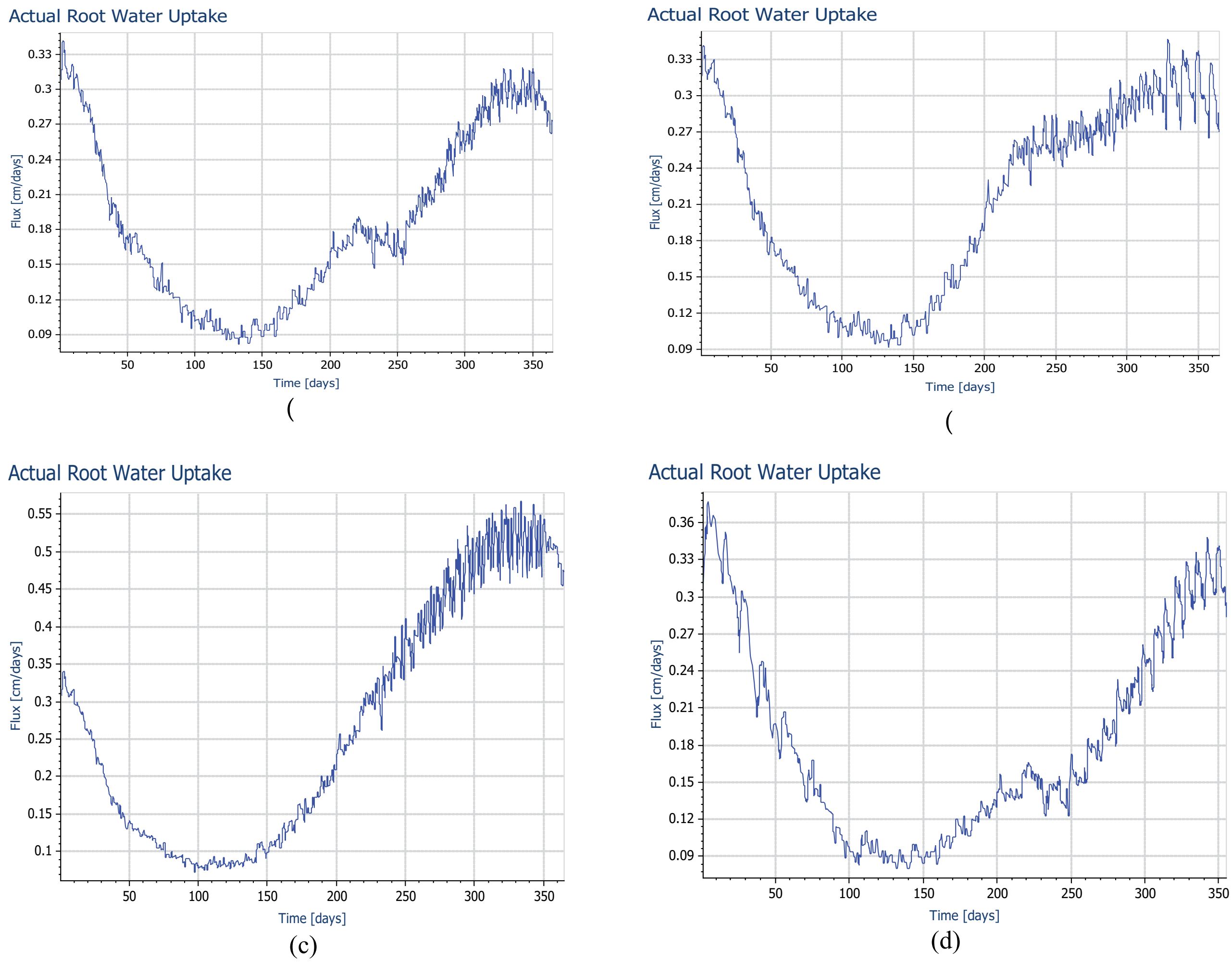

Fig. 8. Actual root water uptake through 1 y for (a) scenario 1, (b) scenario 2, (c) scenario 3, and (d) scenario 4.

through the root zone. The new irrigation scheduling reduces water consumption by 46% of the current water use, without affecting the yield.

A first step in our research was to verify the suitability of the Hydrus-2D simulation-base model in assessing and predicting the soil water distribution through the soil profile. The suitability assessment was based on the comparison between results of Hydrus-2D simulations and experimental observations taken by the profile probe device. For this, the simulation model (Hydrus-2D) was calibrated, and validated, during a specified experimental period of 71 d in each date palm tree location. The model was used to simulate water flow distribution through the five layered soil textures of location of the date palms. Graphical comparison and four well-known statistics (R^2, NSE, RMSE, and MAE), were used to assess model performance. The results suggest that observed soil water content measured by profile probe device and simulated results obtained with Hydrus-2D are generally in good agreement. So, these results support the possibility of using the Hydrus modeling in improving irrigation water efficiency.

The second step was to find the most efficient and saving water irrigation schedule by comparing the actual irrigation schedule used by farmers in the experimental site with three scientifically based irrigation schedules, using the resulted-base model from the first step. In this research, four different and common irrigation schedules were been simulated and analyzed by Hydrus-2D. The results of the simulations of the four water irrigation scenarios for 1 y starting from 15 August 2020 to 15 August 2021 suggest to avoid the commonly used irrigation schedule, which is practiced by the farmers in Jericho. Instead the irrigation schedule of scenarios one and four were mostly been recommended where farmers could have the same annual yield by using 46% less water. Additionally, these scenarios show that irrigation and operation costs also decline and the saved amount of water could be used either to irrigate other crops.

Acknowledgments

This study is one outcome of PIOF-PADUCO II-project. Thanks to GMT-company for their help in using GMT-lab in Ramallah during the Corona epidemic Special thank go to Eng. Anas Haddad from the Agricultural ministry for his help during the closure.

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Anex 1
Statistical tests analysis for each tree location along the soil profile

Date	B_1				B_2				B_3				B_4				B_5				B_6			
	RMSE	MAE	NSE	R^2 (%)	RMSE	MAE	NSE	R^2 (%)	RMSE	MAE	NSE	R^2 (%)	RMSE	MAE	NSE	R^2 (%)	RMSE	MAE	NSE	R^2 (%)	RMSE	MAE	NSE	R^2 (%)
24–8	0.08	0.05	–1.2	20	0.09	0.07	–0.5	85	0.04	0.05	–0.4	55	0.09	0.08	–2.1	15	0.07	0.07	–0.2	86	0.065	0.047	–2.6	40
26–8	0.2	0.16	–1.3	30.2	0.05	0.16	0.06	73	0.14	0.12	0.80	26	0.11	0.09	–0.3	69	0.13	0.10	–0.04	53	0.057	0.053	–1.1	70
16–9	0.12	0.08	0.204	25.9	0.12	0.098	–1.8	86.3	0.15	0.139	–4.7	70	0.108	0.09	–3.5	20	0.139	0.133	–4.9	60	0.16	0.201	–8.4	84
19–9	0.12	0.095	–0.99	74.4	0.136	0.116	–2.4	86.2	0.17	0.161	–6.3	86.2	0.18	0.149	–3.6	50	0.157	0.151	–5.6	61.3	0.20	0.211	–21	65
27–9	0.15	0.166	–0.36	24	0.123	0.121	–0.18	24.8	0.179	0.161	–5.4	48	0.183	0.174	–27	87.5	0.183	0.176	–5.1	81.2	0.21	0.208	–17	68.7
1–10	0.169	0.162	–6.7	57.9	0.198	0.175	–8.5	76.99	0.198	0.182	–8.5	76.9	0.208	0.192	–9	13.5	0.188	0.183	–27	38.9	0.177	0.148	–4.7	81
4–10	0.177	0.154	–7.5	74.5	0.23	0.21	–10.4	89.7	0.252	0.23	–15	79.2	0.192	0.212	–6.8	62.5	0.175	0.157	–10	69.2	0.202	0.181	–9	94.6
11–10	0.186	0.165	–10	83.4	0.303	0.28	–14.8	91.7	0.309	0.278	–9.5	91.9	0.255	0.241	–8	57	0.128	0.105	–1.9	89	0.239	0.233	–20	53
15–10	0.218	0.204	–3.3	80.8	0.119	0.09	–3.38	35.7	0.29	0.252	–5.3	95.2	0.09	0.069	–0.12	69.3	0.158	0.114	–0.89	93.6	0.19	0.179	–7.5	73.5
18–10	0.238	0.232	–8.2	71.3	0.30	0.277	–11.2	86.5	0.32	0.28	–6.4	99.4	0.257	0.244	–9.24	13	0.196	0.189	–12	46.7	0.168	0.16	–10	97.4
25–10	0.04	0.008	0.195	38.11	0.216	0.198	–7.0	56.8	0.311	0.284	–7.8	98.3	0.268	0.26	–17	11.6	0.192	0.184	–11	53.5	0.228	0.222	–19	39.1
1–11	0.19	0.15	–1.9	75.6	0.09	0.03	–0.196	35.3	0.26	0.22	–3.1	93.5	0.048	0.033	–0.02	91.2	0.147	0.113	–0.73	90.5	0.174	0.16	–5.6	78.8