Article

A Comparative Analysis of Root Growth Modules in HYDRUS for SWC of Rice under Deficit Drip Irrigation

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Abstract: Root distribution during rice cultivation is a governing factor that considerably affects soil water content (SWC) and root water uptake (RWU). In this study, the effects of activating root growth (using growth function) and assigning a constant average root depth (no growth during simulation) on SWC and RWU for rice cultivation under four deficit drip irrigation treatments (T_{90} , T_{80} , T_{70} , and T_{60}) were compared in the HYDRUS-2D/3D model version 3.03. A secondary objective was to investigate the effect of applied deficit irrigation treatments on grain yield, irrigation water use efficiency (IWUE), and growth traits of rice. The simulated DI system was designed to reflect a representative field experiment implemented in El-Fayoum Governorate, Egypt, during two successive seasons during 2017 and 2018. The deficit treatments (T_{90} , T_{80} , T_{70} , and T_{60}) used in the current study represent scenarios at which the first irrigation event was applied when the pre-irrigation average SWC within the upper 60 cm of soil depth was equal to 90%, 80%, 70%, and 60% of plant-available water, respectively. Simulation results showed that as water deficiency increased, SWC in the simulation domain decreased, and thereby, RWU decreased. The average SWC within the root zone during rice-growing season under different deficit treatments was slightly higher when activating root growth function than when considering constant average root depth. Cumulative RWU fluxes for the case of no growth were slightly higher than for the case of root growth function for T_{90} , T_{80} , and T_{70} accounting for 1289.50, 1179.30, and 1073.10 cm², respectively. Average SWC during the growth season (24 h after the first irrigation event, mid-season, and 24 h after the last irrigation event) between the two cases of root growth was strongly correlated for T_{90} , T_{80} , T_{70} , and T_{60} , where r^2 equaled 0.918, 0.902, 0.892, and 0.876, respectively. ANOVA test showed that there was no significant difference for SWC between treatments for the case of assigning root growth function while the difference in SWC among treatments was significant for the case of the constant average root depth, where p -values equaled 0.0893 and 0.0433, respectively. Experimental results showed that as water deficiency decreased, IWUE increased. IWUE equaled 1.65, 1.58, 1.31, and 1.21 kg m⁻³ for T_{90} , T_{80} , T_{70} , and T_{60} , respectively. Moreover, higher grain yield and growth traits of rice (plant height, tillers number plant⁻¹, panicles length, panicle weight, and grain number panicles⁻¹) were obtained corresponding to T_{90} as compared with other treatments. Activating the root growth module in HYDRUS simulations can lead to more precise simulation results for specific dates within different growth stages. Therefore, the root growth module is a powerful tool for accurately investigating the change in SWC during simulation. Users of older versions of HYDRUS-2D/3D (version 2.05 and earlier) should consider the limitations of these versions for irrigation scheduling.

Keywords: rice cultivation; HYDRUS-2D/3D model; root growth module; SWC; drip irrigation

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1. Introduction

Rice is the most widely consumed staple food in the world, feeding approximately 50% of the world's population [1]. It is cultivated in an area of more than 165 million ha in 125 countries worldwide [2]. Egypt is the largest producer of rice in Africa and has the most productive farms [3]. In Egypt, rice ranks as the second most consumed staple food and is mainly cultivated in the North Delta and coastal areas. Annually, rice consumes about 10 billion m³ of Nile River water (approximately 18%) [4]. Egypt faces several challenges related to its increasing water demand [5]. The sustainability of rice production in Egypt is becoming threatened by limited water resources [6,7]. Thus, during the past ten years (2008–2018), Egypt reduced the allotted area for rice cultivation by 59% from 745,000 ha to 304,080 ha [8].

The traditionally used method for rice cultivation is the transplanting of rice (TPR) [9]. Other methods of rice cultivation, such as direct-seeded rice (DSR), dry, and wet have also emerged [10]. Similar to many countries worldwide, rice is commonly cultivated in Egypt under continuous flooding, with about 5 cm of water during the growing season [11]. Rice cultivation by this method involves salt leaching from the root zone. Subsequently, poorly drained parts (thick clay layers) of the Nile Delta are used for rice and berseem (Egyptian clover) production only and are not suitable for other alternatives of crop rotations [12]. The irrigation water requirement of rice under continuous flooding is more than 20,000 m³ ha^{−1} [13], meanwhile, rice biologically needs only 6000–8000 m³ ha^{−1} [14]. A drip irrigation (DI) system has been highly recommended for increasing irrigation water use efficiency and crop productivity [15].

Recently, many researchers (e.g., references [16–19]) recommended using DI instead of flood irrigation for watering rice to save irrigation water. Sharda et al. [16] investigated the performance of drip irrigated DSR in South Asia through a two-year field experiment. They found that a higher grain yield and higher root density at the top 30 cm soil layer occurred under DI as compared with flood irrigation. The grain yield ranged from 7.34 to 8.01 ton ha^{−1} and from 6.63 to 7.60 ton ha^{−1} under DI and flood irrigation, respectively. Moreover, higher water use efficiency was achieved under DI as compared with flood irrigation, with more than 40% of water conserved. He et al. [17] stated that by using drip irrigation, 60% of irrigation water needed for watering rice through conventional methods can be conserved. Zhu et al. [18] recommended applying small water amounts by means of emitters to keep the soil at 90% of its water-holding capacity to improve rice yields under drip irrigation. Guo and Chen [19] stated that with good management the rice yield under DI can be as high as paddy rice. Coltro et al. [20] explored the environmental impact of using DI instead of flood irrigation for watering rice. They concluded that by converting irrigation from flood to drip many environmental benefits can be achieved, such as 50% less water consumption with 15% higher yield, 66% less acidification, 30% less eutrophication, and 66% lower GWP.

Water flow in paddy fields involves interaction with complex processes, and their observation and evaluation under field conditions are relatively difficult, costly, and time-consuming [21]. HYDRUS-2D/3D software packages [22] are widely used to simulate water and heat, and solute transport in one-, two-, and three-dimensional, variably saturated porous media. The governing equation for water flow (Richard's equation) that is solved in the model incorporates a macroscopic sink term to account for root water uptake (RWU) [23], which may be reduced due to salinity and drought stress. Water flow is greatly affected by RWU [24] and the pattern of RWU is determined by the root distribution [25]. The RWU model in the standard versions of the HYDRUS-2D/3D model [26] does not consider root growth [27]. Later, a root growth module was adapted and incorporated into the HYDRUS-2D/3D software packages to model root growth as a function of different environmental factors [28].

Compared with traditional transplanting rice (TPR), direct-seeded rice (DSR) requires different water management, particularly during its seedling stage. During the first two weeks after seeding, rather than being flooded as with TPR, the topsoil needs only an

adequate amount of soil water content (SWC) to allow for seed germination [29]. As a result, the root mass of DSR is distributed shallower than that of traditional TPR, which consequently produces different vertical profiles of water content [30]. Thus, the root distribution of rice entirely depends on the method of cultivation and on environmental factors. These processes and the way they are reflected in HYDRUS 2D/3D are not yet fully understood. Thus, to improve this knowledge, there are needs to compare model results with representative field applications. Consequently, the main aims of the current study were to (i) compare observed environmental factors in a representative field drip irrigation setup with model simulations, (ii) simulate root water uptake (RWU) and SWC for the representative paddy field setup under different deficit drip irrigation treatments using the HYDRUS 2D/3D model, and (iii) compare soil water content (SWC) along the soil vertical profile while considering root growth (using growth function) with the results of assigning a constant average root depth (no growth) during irrigation season. As secondary objectives, the effects of deficit irrigation treatments on grain yield (kg ha^{-1}), irrigation water use efficiency (IWUE), and growth traits of rice were investigated. The assumption of constant average root depth (no growth) is the only available option in the oldest version of the HYDRUS-2D/3D model (e.g., version 2.05). Thus, simulations with newer model versions need to be evaluated using field observations. Moreover, the effect of assigning constant average root depth (no growth) on SWC and RWU will be better understood. Results of the current study are important for sustainable use of irrigation water, especially in areas where water resources are scarce and under threat of salinization.

2. Materials and Methods

The HYDRUS-2D/3D model was used for simulating water flow and solute transport in 2D/3D variably saturated porous media. The old version of HYDRUS software (version 2.05) does not contain a root growth module, but has been incorporated in the newest versions (e.g., version 3.03). As these processes have not yet been evaluated for different soil types and environmental factors it is important to compare observations of root growth with simulations. It is important to examine the limitations (if any) of older versions of HYDRUS (version 2.05 and earlier) with newer model versions. In the current study, a comparison between the results obtained from HYDRUS (version 3.03) while deactivating and activating the root growth module was conducted. The comparison included SWC at different dates throughout the soil profile during the rice-growing season in sandy loam soil under surface deficit drip irrigation (DI) and different irrigation treatments. Moreover, the cumulative RWU, evaporation, free drainage, and variable flux (emitter discharge) were investigated at the end of the growing season.

2.1. Experimental Design and Model Setup

The simulated DI system was designed to reflect a representative field experiment carried out in El-Fayoum Governorate, Egypt, on a private farm ($29^{\circ}7'28''$ N, $30^{\circ}43'20''$ E) during two successive seasons (2017–18), growing rice under surface deficit drip irrigation in sandy loam soil. The average salinity of the field soil was 2.4 dS m^{-1} (soil paste extract), while soil pH was 7.85. The groundwater was observed at 2.0 m below the ground surface. Four deficit irrigation treatments (T_{90} , T_{80} , T_{70} , and T_{60}) were applied during the experiment. These treatments represent the scenarios at which the first irrigation event was applied when the pre-irrigation average SWC within the upper 60 cm soil depth was equal to 90%, 80%, 70%, and 60% of plant-available soil water capacity ($=FC-PWP$), respectively. The experimental layout was designed in a randomized complete block with three replications. The irrigation system was designed so that the distance between drip lines was 60 cm while the distance between emitters along the drip line was 30 cm and the emitter discharge was 2 L h^{-1} . On 19 June 2017, and 17 June 2018, seedlings (37 days old) of the rice variety Giza 179 were transplanted to the field (3–4 seedlings/hill) and the harvesting date was on 27 September 2017, and 24 September 2018, respectively (100 days after transplanting). The same procedure was approximately applied in the field

experiments during the two successive agricultural seasons (2017 and 2018); the irrigation schedule of 2018 was only considered while using the HYDRUS-2D/3D model. In 2018, the number of irrigation events was 25, 22, 19, and 15 for T₉₀, T₈₀, T₇₀, and T₆₀, respectively. This led to a total amount of applied water of 5000, 4400, 3800, and 3000 m³ ha⁻¹ for T₉₀, T₈₀, T₇₀, and T₆₀, respectively. Table 1 shows the dates of irrigation events for the different irrigation treatments and the day of irrigation (in the model simulation) from the transplanting date (17 June 2018).

Table 1. Day and date of irrigation events in model simulations for different treatments.

Irrigation Event	Day and Date (in Simulations) of Irrigation Events from the Transplanting Date (17 June 2018)			
	T ₉₀	T ₈₀	T ₇₀	T ₆₀
1st	3 (19 Jun)	6 (22 Jun)	9 (25 Jun)	13 (29 Jun)
2nd	6 (22 Jun)	9 (25 Jun)	12 (28 Jun)	17 (3 Jul)
3rd	9 (25 Jun)	12 (28 Jun)	16 (2 Jul)	21 (7 Jul)
4th	12 (28 Jun)	16 (2 Jul)	20 (6 Jul)	25 (11 Jul)
5th	15 (1 Jul)	19 (5 Jul)	23 (9 Jul)	30 (16 Jul)
6th	18 (4 Jul)	22 (8 Jul)	27 (13 Jul)	34 (20 Jul)
7th	21 (7 Jul)	26 (12 Jul)	31 (17 Jul)	38 (24 Jul)
8th	24 (10 Jul)	29 (15 Jul)	35 (21 Jul)	43 (29 Jul)
9th	27 (13 Jul)	33 (19 Jul)	38 (24 Jul)	48 (3 Aug)
10th	30 (16 Jul)	36 (22 Jul)	42 (28 Jul)	52 (7 Aug)
11th	33 (19 Jul)	39 (25 Jul)	46 (1 Aug)	57 (12 Aug)
12th	36 (22 Jul)	43 (29 Jul)	50 (5 Aug)	63 (18 Aug)
13th	39 (25 Jul)	46 (1 Aug)	54 (9 Aug)	71 (26 Aug)
14th	42 (28 Jul)	50 (5 Aug)	58 (13 Aug)	80 (4 Sept)
15th	45 (31 Jul)	54 (9 Aug)	65 (20 Aug)	90 (14 Sept)
16th	48 (3 Aug)	58 (13 Aug)	72 (27 Aug)	—
17th	52 (7 Aug)	63 (18 Aug)	79 (3 Sept)	—
18th	55 (10 Aug)	68 (23 Aug)	89 (13 Sept)	—
19th	58 (13 Aug)	75 (30 Aug)	96 (20 Sept)	—
20th	63 (18 Aug)	83 (7 Sept)	—	—
21st	68 (23 Aug)	90 (14 Sept)	—	—
22nd	74 (29 Aug)	97 (21 Sept)	—	—
23rd	80 (4 Sept)	—	—	—
24th	87 (11 Sept)	—	—	—
25th	94 (18 Sept)	—	—	—

The climate at the experimental field was arid and characterized by low precipitation (less than 150 mm y⁻¹). From May to September (rice-growing season 2017 and 2018), the minimum and maximum temperatures were 21 and 39 °C, respectively. The relative humidity ranged from 31 to 45% (meteorological station of Fayoum Governorate) [31].

The simulated domain was rectangular, 30 cm wide, and 100 cm deep and represented a vertical plane normal to the drip lines from the emitter to halfway between drip lines. The model domain was spatially discretized by unstructured triangle mesh with 2166 2D elements. As the flux rapidly changed near the soil surface, mesh refinement was applied. To minimize the potential water balance error, the error tolerance for water content and pressure head was set to 0.0002 m³ m⁻³ and 0.2 cm, respectively. In addition, a minimum time step of 10⁻⁷ d was assigned. Twenty-eight observation points were set within the simulation domain (Figure 1). These points were situated at seven depths between the upper boundary of the simulation domain, a depth of 60 cm (at intervals of 10 cm), and four horizontal distances 10 cm apart (starting from the left edge of the simulation domain). These observation points were selected to capture the variation in SWC within the flow domain during the simulation period. The SWC at these points was used while performing the statistical analyses to determine the effect of activating and deactivating the root growth module on simulation results.

Figure 1. Domain geometry used in HYDRUS-2D simulations showing boundary conditions, variable finite element mesh generated for simulations, and location of the twenty-eight observation points.

2.2. Soil Hydraulic Properties

Table 2 shows the soil physical properties obtained from soil samples collected every 20 cm, from the soil surface to 60 cm depth. These properties include particle size distribution, bulk density, hydraulic conductivity, SWC at field capacity (FC), and permanent wilting point (PWP). SWC at FC and at PWP were obtained via a pressure plate apparatus with applied tensions of 0.33 and 15 bar, respectively. Table 3 shows SWC corresponding to different suction pressures varying from 0.001 to 15 bar for soil samples collected at depths from 0–20 cm, 20–40 cm, and 40–60 cm. The ROSETTA software package [32] within the HYDRUS model was used to estimate soil hydraulic properties [33]. To consider variation in soil hydraulic properties, the flow domain was divided into three subregions (Figure 1). Particle size distribution, bulk density, and SWC corresponding to FC and PWP were used in ROSETTA for hydraulic property calculations (Table 4). Table 4 shows estimated soil hydraulic properties for the three subregions in the simulation domain. Soil properties from a 60 to 100 cm depth (3rd layer) were assumed to be similar to the properties of the overlying layer (from 40 to 60 cm depth).

Table 2. Soil physical properties of the experimental site.

Depth (cm)	Particle Size Distribution (%)			Bulk Density (g cm^{-3})	Hydraulic Conductivity (cm h^{-1})	Soil Water Content (SWC) ($\text{m}^3 \text{m}^{-3}$)	
	Sand	Silt	Clay			Field Capacity (FC)	Permanent Wilting Point (PWP)
0–20	70.18	14.32	15.5	1.51	1.79	0.32	0.11
20–40	72.35	14.51	13.12	1.53	2.01	0.31	0.11
40–60	75.17	13.23	11.6	1.55	2.88	0.29	0.10

Table 3. Soil water content (%) versus suction pressure (bar).

Depth (cm)	P (bar)	0.001	0.10	0.33	0.66	1	5	15
0–20	SWC (%)	43.02	34.64	31.88	24.08	23.01	19.47	11.07
20–40		42.26	33.97	30.64	24.39	23.37	19.52	10.79
40–60		41.51	32.40	28.68	23.45	22.42	19.41	10.36

Table 4. Hydraulic parameters of simulated soil.

Soil Depth	θ_r	θ_s	n	α	l	K_s (cm d ^{−1})
0–20 cm	0.0428	0.3918	1.6157	0.0031	0.5	10.70
20–40 cm	0.0399	0.3843	1.5731	0.0037	0.5	11.00
40–100 cm	0.0365	0.3777	1.5045	0.0049	0.5	12.45

θ_r : residual water content, θ_s : saturated water content, K_s : saturated hydraulic conductivity, α : inverse of the air-entry value, n: pore size distribution index, l: pore connectivity parameter.

2.3. Initial and Boundary Conditions

The initial SWC (θ_i) was assumed to be uniform for all simulated irrigation treatments equal to 0.20 m³ m^{−3}. This value represents the average plant-available SWC within the top 60 cm soil layer. Figure 1 illustrates the simulation domain with the imposed boundary conditions. No flux boundary condition (BC) was assigned along the right and left edges of the simulation domain. The left side was assigned as no flux BC due to symmetry. Because of the wide flow domain ($\geq$ the half distance between emitters), the right side was also assumed as no flux BC. As the water table is located 2.0 m below the soil surface, the lower edge of the simulation domain was assumed as free drainage BC. The upper edge of the simulation domain was set as atmospheric BC except for the part that represents the emitter (assigned as variable flux).

Reference crop evapotranspiration (ET_o) was estimated using the CROPWAT 8.0 model [34] and meteorological data (minimum and maximum temperature, relative humidity, wind speed, sun hours, and solar radiation) was used for the study area [31]. Evapotranspiration (ET_c) was estimated by multiplying ET_o by crop coefficient (K_c) for rice. The K_c values equal to 1.00, 1.20, and 0.90 were used corresponding to initial, mid-, and late growth stages, respectively [35]. The growth period of rice was 137 days divided into 37 days in a nursery and 100 days in the field. The growth period was divided into 27, 27, 56, and 27 days for initial, development, mid, and late stages, respectively. These four growing stages correspond to the phenological phases of rice, namely, transplanting, vegetative, reproductive, and maturity [36]. Different methods can be used for monitoring phenological stages, such as field survey, bioclimatic simulation models, or remote sensing. In this study, rice phenology monitoring was not our main objective, we mainly focused on comparing rice grain yield for four different irrigation treatments for two successive seasons considering other factors (e.g., water utilization characteristics) constant. The HYDRUS model requires separation of ET_c into transpiration (T) and evaporation (E). The T was estimated by subtracting ET_c from E values recorded at the meteorological station of El-Fayoum Governorate. Moreover, the surface length associated with transpiration was set to 30 cm during simulations. Figure 2a shows crop coefficients for the different growth stages. Figure 2b displays the estimated evapotranspiration (ET_c), evaporation, and transpiration in mm during the growing season. A variable flux was assigned at the emitter location during irrigation events, which was equal to zero during fallow. The variable flux was calculated based on the emitter discharge and the drip tubing surface area. Irrigation duration was estimated based on emitter discharge, area served by each emitter, and variable flux.

Figure 2. (a) Crop coefficients for the different growing stages; (b) estimated evapotranspiration (ET_C), evaporation, and transpiration in mm during the growing season.

2.4. Root Water Uptake Parameters

Rice is characterized by shallow roots. The root zone occupies about 60 cm of the soil domain while the maximum root density lies 25 cm below the ground surface [37,38]. Root growth function is used to express root evolution during the growing season by specifying given parameters. These parameters can be either initial root growth and harvesting times, initial and maximum rooting depths, and root depth at a specific time or all the previous parameters and replacing root depth at a specific time with the hypothesis that 50% of the rooting depth is reached at the middle of the growing season.

Root distribution parameters were assumed based on Vrugt et al. [39]. Parameters of Vrugt's model used in the simulations of all irrigation treatments were as follows: maximum rooting depth = 60 cm, depth of maximum root density = 25 cm, and $P_z = 1$. However, when considering root growth during the simulation period, initial and harvesting times of zero and 100 days were assigned. Moreover, an initial root depth of 5 cm and a maximum

root depth of 60 cm were assigned. The assigned Feddes parameters [23] were $P_o = 100$ cm, $P_{opt} = 55$ cm, $P_{2H} = -160$ cm, $P_{2L} = -250$ cm, $P_3 = -15,000$ cm, $r_{2H} = 0.50$ cm·d⁻¹, and $r_{2L} = 0.10$ cm·d⁻¹. No solute stress was assumed during simulations.

2.5. Statistical Analyses

The root mean square error (RMSE) was calculated by comparing the measured SWC in the case of an assigned constant average root depth and considered root growth. The RMSE was calculated according to:

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (S_v - S_c)^2} \quad (1)$$

where S_v and S_c are simulated outputs (e.g., pressure heads, water fluxes) for considered root growth (using growth function) and constant average root depth (no growth), respectively. N is the number of observations.

The one-way analysis of variance (ANOVA) test was performed using SPSS (statistical package of the social sciences) 24.0 software (IBM Corporation, New York, NY, USA) to compare SWC obtained from the HYDRUS-2D/3D model for activating and deactivating the root growth module for each treatment. The SWC was compared for the different irrigation treatments to check if the p -value between treatments was significant at a 95% level of confidence. Irrigation water use efficiency (IWUE) and growth traits of rice (plant height, tillers number plant⁻¹, panicles length, panicles weight, and grain number panicles⁻¹) during the two successive agricultural seasons of 2017 and 2018 were determined to investigate the effect from different deficit irrigation treatments. IWUE was estimated to evaluate the productivity of applied irrigation water in the treatments at the level of crop yield production (IWUE = yield/applied irrigation water, where yield is in kg ha⁻¹, applied irrigation water in m³ ha⁻¹, and IWUE in kg m⁻³) [40–42].

3. Results

3.1. SWC at the Middle of the Growing Season

SWC, throughout the simulation domain and 24 h after applying the middle irrigation event for all irrigation treatments (i.e., T_{90} , T_{80} , T_{70} , and T_{60}) when activating and deactivating the root growth module, is shown in Figure 3. The corresponding day for the middle irrigation event of T_{90} , T_{80} , T_{70} , and T_{60} was 39.1, 39.1, 42.1, and 43.1 days from the onset of simulation, respectively. The SWC for the upper two subregions, especially at the upper 20 cm soil depth close to the emitter, was slightly higher in all irrigation treatments when activating the root growth module compared to the case of constant average root depth (no growth). Higher RWU rates occurred when assigning constant average root depth compared to the case of using the root growth module. Figure 3 shows that, for both root growth modules, as applied irrigation water increased SWC increased throughout the entire simulation domain. The SWC was higher in T_{90} compared with other irrigation treatments. Thus, the deficit irrigation greatly impacted the SWC distribution throughout the simulation domain.

3.2. SWC at the End of the Growing Season

The SWC distribution directly after applying the last irrigation event for all deficit irrigation treatments is shown in Figure 4a,b. The last irrigation event ended on day 94.1, 97.1, 96.1, and 90.1 after the transplanting date for T_{90} , T_{80} , T_{70} , and T_{60} , respectively. The figure illustrates that SWC was approximately the same for the simulations in both modules of root distribution under the same irrigation treatment. No obvious difference is noted in SWC, especially in the region close to the emitter and in the region containing maximum root density (upper 25 cm). Conversely, insignificant differences in SWC were observed in the upper 30 cm soil layer far from the emitter for treatments T_{90} , T_{80} , and T_{70} . The SWC was higher when activating the root growth module. However, T_{60} showed no

significant differences in SWC at the upper 55 cm while activating and deactivating the root growth modules.

Figure 3. SWC distribution after 24 h from the middle irrigation event for the four irrigation treatments, (a) considered root growth, and (b) constant average root depth (no growth) during the growing season.

Figure 4. SWC distribution after the last irrigation event for the four irrigation treatments, (a) considering the root growth and (b) constant average root depth during the growing season.

3.3. Spatial Distribution of SWC and Statistical Results

The average SWC 24 h after the three irrigation events (first, middle, and last) for both cases of root growth and no growth, for the upper two subregions, and for the four irrigation treatments is shown in Figure 5a,b. The 40 cm depth represents the two upper

subregions where maximum root density was established and where maximum root water uptake occurred. The results show that the average SWC throughout the upper two subregions was higher when applying the root growth module compared to the constant average root depth (no growth). This can be attributed to higher RWU rates when a constant average root depth is applied. For this case, the root system was constant from the beginning to the end of the simulation period. Thereby, RWU was higher compared to results obtained from the root growth module. Figure 5 shows that SWC was higher in T₉₀ compared to other irrigation treatments, regardless of the root growth module. As irrigation increases, SWC in the upper 40 cm soil depth increases. To investigate and assess the differences between water contents while applying different root growth models, statistical tests were performed.

Figure 5. Average SWC ($\text{cm}^3 \text{cm}^{-3}$) 24 h after the first, middle, and last irrigation events for the four irrigation treatments, (a) constant average root depth, and (b) considered root growth during the growing season.

The correlation analysis for average SWC between root growth and constant average root depth (no growth) is shown in Figure 6a–d for T₉₀, T₈₀, T₇₀, and T₆₀, respectively. Average SWC was calculated at the location of the twenty-eight observation points exactly at the emitter, along the 30 cm domain width with 10 cm apart, and along the 60 cm depth with 10 cm apart. The SWC at each location was calculated as an average of three dates: 24 h after the first irrigation event (during the initial stage), 24 h after the mid-irrigation event (mid-growth stage), and 24 h after the last irrigation event (reflects the late stage). Root mean square error was calculated by which the relationship between the root growth case and constant average root depth was linear. The R^2 was 0.918 for T₉₀, 0.902 for T₈₀, 0.892 for T₇₀, and 0.876 for T₆₀.

Figure 6. Relationship for SWC between the constant average root depth and root growth module for (a) T_{90} , (b) T_{80} , (c) T_{70} , and (d) T_{60} .

The analysis of variance of SWC average between deactivating and activating the root growth module (assigning constant average root depth with no growth and considering root growth during simulation) for each irrigation treatment is shown in Table 5. The results show that there is no significant difference for SWC between the case of constant average root depth and considered root growth for T_{90} and T_{60} treatments where p -values equal 0.1314, and 0.0599, respectively. Results of the ANOVA test show that the difference between SWC for the case of constant average root depth and root growth was significant for the T_{80} and T_{70} irrigation treatments where p -values equalled 0.0492, and 0.0337, respectively.

Table 5. ANOVA test for SWC between constant average root depth and root growth for different irrigation treatments.

(T ₉₀)				
Source of Variation	Sum of Square, SS	Mean Square, MS	F-Statistic	p-Value
Between treatments	0.0012	0.0012	2.35	0.131
Error (within treatments)	0.0271	0.0005		
(T ₈₀)				
Between treatments	0.0021	0.0021	4.05	0.049
Error (within treatments)	0.0283	0.0005		
(T ₇₀)				
Between treatments	0.0026	0.0026	4.75	0.034
Error (within treatments)	0.0299	0.0006		
(T ₆₀)				
Between treatments	0.0022	0.0022	3.70	0.060
Error (within treatments)	0.0323	0.0006		

F-ratio is 2.346, p is 0.1314. Result is not significant at $p < 0.05$. F-ratio is 4.048, p is 0.0492. Result is significant at $p < 0.05$. F-ratio is 4.747, p is 0.0337. Result is significant at $p < 0.05$. F-ratio is 3.695, p is 0.0599. Result is not significant at $p < 0.05$.

3.4. Comparison of Different Cumulative Fluxes

Cumulative RWU, evaporation, free drainage, and variable fluxes for different deficit irrigation treatments are shown in Figures 7 and 8 for the cases of root growth and no growth, respectively. The results show that as irrigation water increased, cumulative RWU increased regardless of root growth [43]. In contrast, cumulative evaporation decreased as irrigation water increased. As the applied water was less than the crop water requirement, no free drainage occurred. Approximately no free drainage occurred during the simulation of the four different irrigation treatments for the two cases of root growth and no growth. The cumulative RWU was slightly higher when applying constant average root depth (no growth) compared with root growth. The cumulative RWU for T_{90} , T_{80} , T_{70} , and T_{60} when using constant average root depth was 1289.50, 1179.30, 1073.10, and 949.86 cm^2 , respectively. These values, when applying the root growth module, were 1263.50, 1177.0, 1072.00, and 955.60 cm^2 . No significant differences in cumulative RWU were obtained when applying different root growth modules, especially in T_{80} and T_{70} . Therefore, activating the root growth module did not affect the cumulative RWU.

Cumulative evaporation was higher when deactivating the root growth module compared with activating this module. Cumulative evaporation for T_{90} , T_{80} , T_{70} , and T_{60} when using constant average root depth was 685.18, 693.84, 771.25, and 911.84 cm^2 , respectively. When applying the root growth module, these values were 599.17, 678.68, 767.34, and 870.71 cm^2 , respectively. The differences in cumulative evaporation when applying two root growth modules were more pronounced in T_{90} and T_{60} compared with T_{70} and T_{80} . The selected cumulative fluxes: RWU, evaporation, free drainage, and variable flux for the cases of constant average root depth (no growth) and considered root growth are shown in Table 6.

Figure 7. Cumulative root water uptake, evaporation, free drainage, and variable fluxes for (a) T_{90} , (b) T_{80} , (c) T_{70} , and (d) T_{60} when activating root growth option.

Figure 8. Cumulative RWU, evaporation, free drainage, and variable fluxes for (a) T_{90} , (b) T_{80} , (c) T_{70} , and (d) T_{60} when deactivating root growth option.

Table 6. Selected cumulative fluxes (cm^2); RWU, evaporation, free drainage, and variable flux for different irrigation treatments (T_{90} , T_{80} , T_{70} , and T_{60}) considering root growth and constant average root depth.

	T_{90}		T_{80}		T_{70}		T_{60}	
	No Growth	Root Growth	No Growth	Root Growth	No Growth	Root Growth	No Growth	Root Growth
Cumulative root water uptake (RWU)	1289.50	1263.50	1179.30	1177.0	1073.10	1072.0	949.86	955.60
Cumulative evaporation	685.18	599.17	693.84	678.68	771.25	767.34	911.84	870.71
Cumulative free drainage	6.94	10.61	6.72	10.00	6.67	9.57	6.67	9.26
Cumulative variable flux	1500.00		1320.00		1140.00		900.00	

The results of Table 7 show that there are significant differences between grain yields among the four irrigation treatments for 2017 and 2018 where p -values equal 0.011 and 0.010 (<0.05), respectively. Also, there are significant differences in IWUE among irrigation treatments for 2017 and 2018 where p -values equal 0.002 and 0.001, respectively.

Table 7. Normality test and *t*-test for difference in grain yield (kg ha^{-1}) and water use efficiency (IWUE) (kg m^{-3}) among the four irrigation treatments for 2017 and 2018.

	Yield (kg ha^{-1})		IWUE (kg m^{-3})	
	2017	2018	2017	2018
Skewness	0.024	−0.015	−0.260	−0.096
Kurtosis	−2.451	−2.405	−3.831	−4.416
t-value	5.733	5.811	9.842	13.630
Sign. (two-tailed)	0.011	0.010	0.002	0.001

Confidence interval is 95%.

3.5. Growth and Yield

Table 8 shows calculations of IWUE (kg m^{-3}) for the collected yield of each treatment during the two successive agricultural seasons. Figure 9 shows the relationship between IWUE and the applied irrigation water (IR). Experimental results show that yield (kg ha^{-1}) is significantly correlated with IR ($\text{m}^3 \text{ ha}^{-1}$). During 2018, IWUE was 1.65, 1.58, 1.31, and 1.21 kg m^{-3} corresponding to T_{90} , T_{80} , T_{70} , and T_{60} , respectively and was 1.70, 1.62, 1.27, and 1.09 kg m^{-3} during 2017. Statistical analysis revealed that yield is correlated to RWU with *p*-values equal to 0.992 and 0.995 at a 0.01 level of significance (two-tailed).

Table 8. Grain yield and irrigation water use efficiency (IWUE) for different irrigation treatments (T_{90} , T_{80} , T_{70} , and T_{60}).

Irrigation Treatments	T_{90}		T_{80}		T_{70}		T_{60}	
Seasons	2018	2017	2018	2017	2018	2017	2018	2017
Grain yield (Kg ha^{-1})	8260	8510	6950	7120	4980	5060	3640	3720
Applied irrigation water ($\text{m}^3 \text{ ha}^{-1}$)	5000	5000	4400	4400	3800	4000	3000	3400
Water use efficiency (IWUE) (kg m^{-3})	1.65	1.70	1.58	1.62	1.31	1.27	1.21	1.09

Figure 9. Relationship between water use efficiencies and applied depth of water (cm).

Table 9 shows the growth and yield of rice plants during the two successive agricultural seasons under different deficit treatments. The table reveals that the growth and yield of rice plants were influenced by the applied deficit irrigation levels. The largest growth traits (i.e., plant height (82.50 cm), tiller number plant⁻¹ (3.40), panicle length (23.25 cm), panicle weight (2.93 gm), grain number panicles⁻¹ (112.50), and grain yield (8.39 ton ha⁻¹)) were obtained under irrigation treatment T₉₀. Growth and yield traits of the paddy were negatively affected and considerably decreased with an increase in the severity of water stress. T₆₀ resulted in a decrease of plant height (24.2%), tiller number plant⁻¹ (29.4%), panicle length (27.5%), panicle weight (24.7%), grain number panicle⁻¹ (36.8%), and grain yield (56.1%) compared with T₉₀. The Pearson correlation between grain yield (ton ha⁻¹) among the four irrigation treatments and other yield parameters for 2017 and 2018 is shown in Table 10.

Table 9. Effect of deficit irrigation treatments on growth and yield of rice crop.

Irrigation Treatment	Grain Yield (ton ha ⁻¹)	Plant Height (cm)	Tiller Number Plant ⁻¹	Panicle Length (cm)	Panicle Weight (g)	Grain Number Panicle ⁻¹
Season 2018						
T ₉₀	8.26 ± 0.22	81.33 ± 1.54	3.15 ± 0.32	23.11 ± 0.54	2.89 ± 0.09	110.01 ± 1.87
T ₈₀	6.95 ± 0.13	74.21 ± 1.30	2.89 ± 0.21	20.12 ± 0.36	2.75 ± 0.13	96.87 ± 1.64
T ₇₀	4.89 ± 0.32	66.41 ± 1.37	2.53 ± 0.41	18.14 ± 0.47	2.36 ± 0.12	82.61 ± 1.83
T ₆₀	3.64 ± 0.14	62.28 ± 1.80	2.39 ± 0.11	16.81 ± 0.55	2.20 ± 0.11	69.60 ± 1.55
Season 2017						
T ₉₀	8.51 ± 0.53	84.02 ± 1.94	3.46 ± 0.43	23.50 ± 0.70	2.97 ± 0.14	115.04 ± 1.67
T ₈₀	7.12 ± 0.44	76.32 ± 1.34	2.88 ± 0.17	20.77 ± 0.36	2.80 ± 0.10	98.54 ± 1.51
T ₇₀	5.06 ± 0.19	70.31 ± 1.66	2.66 ± 0.33	19.16 ± 0.44	2.42 ± 0.11	84.79 ± 1.47
T ₆₀	3.72 ± 0.71	63.15 ± 1.47	2.38 ± 0.21	16.88 ± 0.21	2.23 ± 0.12	72.55 ± 1.63

Table 10. Pearson correlation between grain yield (ton ha⁻¹) among the four irrigation treatments and other yield parameters for 2017 and 2018.

			Plant Height (cm)	Tiller Number Plant ⁻¹	Panicle Length (cm)	Panicle Weight (g)	Grain Number Panicle ⁻¹
2017	Grain yield (ton ha ⁻¹)	Pearson correlation	0.995 **	0.995 **	0.980 *	0.995 **	0.997 **
		Sign. (two-tailed)	0.005	0.005	0.020	0.005	0.003
2018	Grain yield (ton ha ⁻¹)	Pearson correlation	0.992 **	0.963 **	0.985 *	0.997 **	0.994 **
		Sign. (two-tailed)	0.008	0.037	0.015	0.003	0.006

* Correlation is significant at the 0.05 level (two-tailed). ** Correlation is significant at the 0.01 level (two-tailed).

4. Discussion

The high SWC at the top 20 cm soil depth (near the emitters) one day after applying the middle irrigation event during the growing season (Figure 3) for the case of assigning root growth and considering constant root depth can be attributed to the effect of the root system configuration on RWU rates. When activating the root growth module, the roots evolved with time and did not reach their full configuration (maximum root density) at the middle of the growing season. Thereby, RWU rates did not reach their highest values as compared to the case of constant average root depth. Moreover, due to the application of deficit irrigation treatments, SWC did not exceed the initial SWC, which confirms that the plants were always subjected to water stress. The almost similar distribution of SWC at the end of the growing season (Figure 4) confirmed that root length was the same for the two modules (considering root growth function and no root growth) during the late stage of the growing season. This similarity leads to approximately the same RWU rates as the cumulative RWU (Figures 7 and 8). Similar results were obtained by Bufon et al. [44] with high volumetric moisture content near the emitters. The insignificant differences of SWC

along the 55 cm depth between the cases of activating and deactivating the root growth for treatment T_{60} can be attributed to severe water deficiency during T_{60} for both cases of root growth and no growth, compared with the other irrigation treatments (T_{90} , T_{80} , and T_{70}). The SWC was approximately the same throughout the uppermost 50 cm of soil layer directly before the irrigation event; these results are similar to Eltarabily et al. [45].

The minimally cumulative free drainage for treatment T_{60} (Figures 7d and 8d), compared with other treatments, confirms that the plants exploit all applied irrigation water, which proves the existence of plant water stress. Although free drainage fluxes were close to zero, higher values were observed when activating the root growth module. This is due to a higher SWC in the simulation domain when activating the root growth module (Figure 5b) and relatively lower RWU, especially during the initial stage of the growing season. The strong correlation between yield and RWU for the different treatments explains the simulation results of the cumulative evaporation. Cumulative evaporation for T_{60} and T_{70} was relatively high compared to other treatments. When a reduction in cumulative RWU occurs, an increase in evaporation loss prevails. This confirms plant exposure to severe water stress when applying the T_{70} and T_{60} treatments. In this case of drought stress, the root water uptake of rice is affected by the root response, which is highly dependent on the crop genotype, period, and density of stress [46,47]. The reduction in growth and yield of rice caused by water stress may be attributed to the decrease in SWC, resulting in lower water and nutrient uptake by roots, causing a reduction in cell deviation, a cell enlargement decreases in the leaf area [48], stomatal closure, and a reduction in photosynthetic activity [49–52].

5. Summary and Conclusions

The HYDRUS-2D/3D model is considered an effective tool for irrigation management. A precise estimation of the model input leads to successful irrigation scheduling. The SWC distribution within the soil profile depends mainly on applied water (amount and duration) and RWU. However, RWU is greatly affected by the imposed root distribution during simulation. In the current study, two root distribution modules (i.e., constant average root depth and root growth) incorporated with the HYDRUS-2D/3D model (version 3.03) were used during a simulation of drip-irrigated rice in sandy loam soil under different deficit irrigation treatments. These treatments corresponded to the situation in which the first irrigation event was applied when the pre-irrigation average of SWC within the upper 60 cm soil depth was equal to 90% (T_{90}), 80% (T_{80}), 70% (T_{70}), and 60% (T_{60}) of plant-available water. The simulated DI system reflects a representative field experiment that was implemented in El-Fayoum Governorate, Egypt, during two successive seasons in 2017 and 2018. The irrigation schedule in the year 2018 was used to run the HYDRUS model. However, the experimental results of the two successive seasons were considered while comparing the effect of different deficit treatments on grain yield, IWUE, and growth traits. Simulation results showed that both SWC and RWU were correlated with water deficiency. Higher SWC and RWU were observed under T_{90} , while lower values occurred under T_{60} . By activating the root growth module, relatively higher average SWC within the root zone, regardless of deficit treatments, was obtained as compared to constant average root depth (no growth).

Cumulative RWU at the end of the simulation period was slightly higher when assigning a constant average root depth. Results of the ANOVA test showed that there was no significant difference for SWC between treatments when activating the root growth module while it was significant while using constant average root depth. For all deficit irrigation treatments, although SWC and RWU results differed at specific dates during the growing season when activating and deactivating the root growth module, the cumulative fluxes (by the end of the simulation period) were approximately the same. Therefore, the root growth module is recommended as it is a powerful tool for accurately investigating changes in SWC. Experimental results showed that the growth and yield of rice plants during the two successive agricultural seasons was greatly affected by the level of water

deficiency. As the applied water decreased, the grain yield, IWUE, and growth traits (plant height, tillers number plant⁻¹, panicles length, panicles weight, and grains number panicles⁻¹) of rice decreased. Higher yield, IWUE, and growth traits were obtained under T₉₀, while lower values were obtained under T₆₀. Therefore, severe deficit irrigation treatment is not recommended for drip-irrigated rice. We believe that the findings of our study are important for users of older versions of the HYDRUS software (version 2.05 and earlier). Users should consider the limitations of these versions for predicting different fluxes at specific dates during the growing season when scheduling irrigation events. Results are also important for managers in terms of irrigation scheduling to use irrigation water sustainably.

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