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An Assessment of the Vertical Movement of Water in a Flooded Paddy Rice Field Experiment Using Hydrus-1D

Abdikani Abdullahi Mo'allim¹, Md Rowshon Kamal^{1,*}, Hadi Hamaaziz Muhammed¹, Nasehir Khan E. M. Yahaya², Mohamed Azwan b. Mohamed Zawawe¹, Hasfalina bt. Che Man¹ and Aimrun Wayayok¹

¹ The Department of Biological and Agricultural Engineering, Faculty of Engineering, Universiti Putra Malaysia, Serdang, UPM Serdang 43400, Selangor DE, Malaysia; abdikani51@gmail.com (A.A.M.); hadi.azizm@gmail.com (H.H.M.); mohdazwan@upm.edu.my (M.A.b.M.Z.); hasfalina@upm.edu.my (H.b.C.M.); aimrun@yahoo.com (A.W.)

² National Hydraulic Research Institute of Malaysia, Seri Kembangan, Selangor Darul Ehsan, Selangor 43300, Malaysia; nasehir@nahrim.gov.my

* Correspondence: rowshon@yahoo.com; Tel.: +60-389464339

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Abstract: A quantitative estimation of the major components of the field water balance provides management decisions on how the scheme ought to be operated to ensure better distribution of irrigation water and increased delivery performance. Therefore, in this study, the water balance component in transplanted and broadcasted rice fields with conventional irrigation (flooding irrigation) in the Tanjung Karang Rice Irrigation Scheme (TAKRIS), Sawah Sempadan were observed and then modeled using Hydrus-1D numerical model during two consecutive rice growing seasons. During the off-season, irrigation water accounted for 59.6% of the total water input (irrigation + rainfall), but about 76.2% of total water input during the main season. During the main season, rainfall water only contributed to 23.8% of total water input and 40.4% during the off-season. Drainage water accounted for 37.3% of the total water input during the off-season and 43.7% during the main season, respectively, which was the main path of water losses from conventional rice fields, which indicates that maintaining a high water level and huge rainfall events during both seasons increased drainage water. Simulated ET during the off-season and the main season accounted for 38.1% and 49.5% of the total water input, respectively. Observed and simulated water percolation revealed about 17.1% to 19.2% of total water input during both seasons, respectively. Additionally, the water productivities analyzed from total water input and irrigation water were 0.43 and 0.72 kg m⁻³ during the off-season and 0.60 and 0.78 kg m⁻³ during the main season, respectively. The water productivity index evaluated from observed and modeled evapotranspiration was 1.03 and 1.13 kg m⁻³ during the off-season and 0.98 and 0.94 kg m⁻³ during the main season, respectively. The overall results revealed that Hydrus-1D simulations were a reasonable and effective tool for simulating vertical water flow in both broadcasted and transplanted rice experimental fields.

Keywords: water flow; water losses; water balance; Hydrus-1D; water productivity

1. Introduction

Rice is the main food crop in Malaysia. Rice production of the country has achieved 72% self-sufficiency level (SSL) with an annual production of 3.5 million tonnes a year [1]. The Agriculture and Agro-based Industry Ministry targets the country to achieve a 100 percent self-sufficiency level (SSL) in paddy production by 2020. Irrigation is crucial to the world's food grain production, because 40% of all crops and close to 60% of cereal production comes from irrigated agriculture [2],

even though irrigated lands comprise only 20% of the arable land [3]. In Asia, irrigated agriculture uses 90% of the total freshwater, and more than half of this irrigates rice. About 75% of the global rice volume is produced in the irrigated low lands (Cantrell 2004). There are an estimated 150 million hectares of rice lands worldwide, 50% of which are irrigated, usually with continuous flooding for most of the crop season [4]. In many irrigated areas, rice is grown as a monoculture with two rice crops every year. Global water and food security are two of the most important challenges in the 21st century to supply sufficient food for the increasing population while sustaining a stressed environment threatened by climate change.

Water management is a difficult task for a large rice irrigation system. Different sub-systems, such as soil, water, climate, nutrients, plant, management systems, and their complex dynamics work in the paddy field environment. Furthermore, an individual irrigation scheme has its physical and unique characteristics. The effects of climate change are significant on water demand for irrigation that is continuously being aggravated by unsustainable practices like over-use of chemical fertilizers and poor water management. Excessive irrigation deliveries generate a huge amount of return flows containing fertilizers, insecticides, and pesticides from paddy fields in Malaysia. Eventually, drainage water from paddy fields loses essential agrochemicals and pollutes surface water resources. Poor and uneven water distributions were often criticized as the major bottleneck in attaining efficient water use in rice irrigation systems in Malaysia [5,6].

Deep percolation in water-intensive paddy rice crop field is a major outflow and needs due attention. The rate of deep percolation depends on soil type, puddling intensity, hydraulic conductivity, depth of ponding, etc. It is now well known that the water policies need to facilitate market-based approaches to water allocation and commercialization of agriculture. Only a fraction of irrigation water applied to the fields is utilized by the plants. Some portion of the applied water that is not consumed in agricultural fields flows to streams/drainage canals or is percolated downwards. The movement of water horizontally into the bunds and then vertically downwards to groundwater through the undisturbed soil column within the bunds is termed lateral percolation [7]. Bhuiyan et al. [8] reported that seepage and percolation (S & P) are site-specific and depend on soil texture, water table depth, proximity to drainage outlet, and farmer's field water management status. Ghani [9] reported that in addition to the above factors, seepage and percolation at the field level are affected by puddling and the standing water depth status of the rice fields and the crop growth stages.

With a rising irrigation water requirement and developing competition all around water utilizing areas, the world now faces challenges to convey a great deal more food with less water. This objective will be sensible only if appropriate methodologies are found to get water savings and additionally more effective water uses in agriculture. Rosenzweig et al. [10] assessed alterations in crop water requirement and water availability to determine the reliability of the irrigation system. Over the last few decades, in conjunction with fast population growth and commercial concentration in urban centres, which are affected by financial growth, power shortages have grown to be an issue, particularly in seaside areas, and water shortages have taken place in northern China, mainly in the Yellow River Basin [11].

Quantification of the amount of water used is very crucial for understanding and finding water use efficiency at an irrigation system level. Irrigation return flow consists of surface and subsurface flows. Water balance models, considering both components, can predict the return flow for re-use in paddy fields [12]. Additionally, a field scale investigation of water flow in paddy rice fields involves the interaction of very complex processes, which is, relatively speaking, very difficult, costly, and time consuming. Therefore, numerical modeling is a fast and inexpensive approach with which to study water movement and optimal irrigation management practices. Hydrus-1D [13] is a numerical model that has been widely tested by many researchers to predict water flow in paddy fields under different irrigation and management practices [2,14–17]. However, no work has been done yet to check the accuracy of this model for simulating water flow in broadcasted and transplanted paddy rice fields in Tanjung Karang Rice Irrigation Scheme (TAKRIS), which leads researchers to question the usefulness of this model.

Modeling of water flow in rice field becomes a challenge, as rice is a highly water demanding crop; thus, it poses a greater risk of water loss in both surface and subsurface waters [12]. In addition, rice is a shallow-rooted crop and the domain of the root zone is about 30–40 cm below the soil surface, which can lead to considerable water loss if it leaches under irrigated or high rainfall conditions [18]. As the water movement in a rice field is vertical due to constant ponding water condition, the one-dimensional model can be used effectively [12]. Furthermore, since the seepage in paddy plots is minimized, and water and solute transport can be simplified to a vertical movement [19], thus, the Hydrus-1D model can be used in the present study, even though it has been often used by many researchers to simulate water flow and solute transport in flooded rice fields [18,20]. Indeed, no study is reported yet on this important aspect in Malaysia. Mostly previous studies were based on large-scale estimation of water balance components using multifarious parameters that may not reflect the true condition of paddy fields [21–23]. In order to overcome these challenges, this study was carried out to evaluate and model the water movements and losses through the surface and sub-surface water leaving from a paddy field for better management practices through intensive field observations using modern monitoring devices together with sensors, and data logging and analysis techniques. In most irrigation projects, like any other countries, in Malaysia's agricultural fields, in particular in its paddy rice fields, a huge amount of valuable irrigation water is lost through different processes from rice fields that needs to be quantified to determine the actual water balance component. This study, therefore, wishes to investigate the water movement in flooded paddy rice fields during two consecutive rice-growing seasons and then evaluate it using Hydrus-1D numerical model. We do not only evaluate water losses via subsurface water but also via an intensive investigation of the water balance component and productivity analysis, which were conducted to estimate water losses through surface and subsurface water using modern monitoring devices together with sensors and data logging and analysis techniques.

2. Material and Methods

2.1. Study Area Description

The study region relates to the Tanjung Karang Rice Irrigation Scheme, which is located at 3°25'~3°45' N latitude and 100°58'~101°15' E longitude in the state of Selangor, Malaysia. It is one of the several irrigation compartments in Sawah Sempadan which consists of 1468 lots with the total area at about 2300 hectares, divided into 24 blocks. BLOCK C in Sawah Sempadan compartment had 86 individual farmers and was chosen as a research study area in the present study. The only source for irrigation supply in Sawah Sempadan is the Berman River. Geographically, the study area is located 3°28'10" N 101°13'26.4" E with average altitude 6.2 m above the mean sea level. The area experiences a humid equatorial climate with bimodal rainfall patterns largely influenced by the southwest and northeast monsoons. Rainfall is strongly seasonal, with roughly 70% occurring between the months of October and December during the northeast monsoon, while dry months generally fall from February to March and June to August during the southwest monsoon period. However, rainfall distribution is unreliable from January to August, and therefore the crop has to rely to a large extent on irrigation for sustained yields. The soils, derived from a semi-detailed soil survey of 1967 and 1984, indicate that the greater part of the area is mainly of alluvial origin deposited during the rise in sea level [24]. Based on the soil surveys, a total of 12 soils series were identified derived from (1) marine-derived clays (including, Kranji, Banjar, Sedu, Jawa, Selangor, Bernam, Baku, and Serong), (2) brackish water (which includes brown clays), and (3) organic deposits (which include Briah) and other unclassified soils (such as Sempadan, Karang, and Telok). The physical and chemical properties of the soil at the site are listed in Tables 1 and 2, respectively.

Table 1. Physical properties of the paddy soil in the experimental field.

Depth (cm)	Textural Class	Bulk Density (g cm ⁻³)	Conductivity K _s (cm d ⁻¹)
0–20	Clay loam	1.28	10.25
20–40	Clay loam	1.33	9.34
40–60	Clay Loam	1.38	8.55
60–80	Clay	1.44	8.10
80–100	Clay	1.42	7.20

Table 2. Chemical properties of the paddy soil in the experimental field.

Depth (cm)	pH	EC (ms/cm)	Organic Carbon (g kg ⁻¹)	Total Nitrogen (%)	Extractable P (µg/g)	Extractable K (µg/g)
0–20	5.44	0.40	3.7	0.27	13.72	93.7
20–40	5.58	0.50	3.9	0.24	12.18	201
40–60	5.58	0.80	2.6	0.17	11.95	215
60–80	5.50	0.70	2.5	0.17	11.56	211
80–100	5.50	0.50	2.4	0.16	11.17	222

2.1.1. Experimental Design and Measurements

The experiment was conducted during two consecutive rice growing seasons (January–April 2017 and July–October 2017) at Sawah Sempadan irrigation compartment at IADA Selangor. The experimental plot is 0.5 ha (5000 m²) in size. “BLOCK C” was chosen as a research study area. The experimental plot has a soil texture of clay loam, while the texture of soil surface ranged from clay loam to clay. The soil is classified as Jawa series and was defined as clayey, mixed isohyperthermic sulfic tropaquept. After the land preparation, the seeds were evenly broad-casted by hand on the soil during the off-season and were mechanically transplanted during the main season, respectively. After seeding and transplanting, the field was irrigated until pre-saturation. The harvest dates were on April and October for off and main seasons, respectively. The total growing periods during these two seasons were thus 100 and 105 days, respectively.

In the experimental field, Parshall Flume RBC, drainage sensor, rain gauge, Marriott tube, micro-paddy lysimeter, and water level recorder were installed as shown in Figure 1. The amount of precipitation was measured using a Data-Logging rain gauge. During both seasons, the total amount of rainfall was 47 and 21 cm, respectively. The highest rainfall occurred during the month of January during the off-season (23 January 2017), which was 8.7 cm. The amount of irrigation water and the flow rate was measured by using Parshall Flume RBC with MJK 7070 level sensor with CR200X logger (SZ-CR200X/7070, Eijkelkamp, Germany) whenever an irrigation event occurred. The total amount of irrigation supply was 69.4 and 68.9 cm for both seasons, respectively. During the experimental period, the field water level was maintained from 3 cm to 10 cm depth until one week before harvesting time and every drainage event. The water level was measured using E-water level sensor. In addition, the irrigation water was re-applied in order to maintain the crop water requirement when there was no rainfall (dry period) and the water level fell below a maintained depth. A concrete sump (70 cm × 50 cm × 70 cm) with MJK7060 level sensor (NB-CR200X/7060) was used to estimate the amount of drainage water whenever a runoff event occurred. The total amount of drainage was 43 and 39 cm for both seasons, respectively. The actual evapotranspiration was measured using Marriott tube, micro-paddy lysimeter (Adapted from Tomar and O’Toole 1980). Crop and reference evapotranspiration was modeled using CropWat 8.0. Soil water content was estimated using oven drying method (24 h with 104 degrees). Deep percolation was measured by the difference between two lysimeter tanks (closed bottom and opened bottom) installed in the experimental plot.

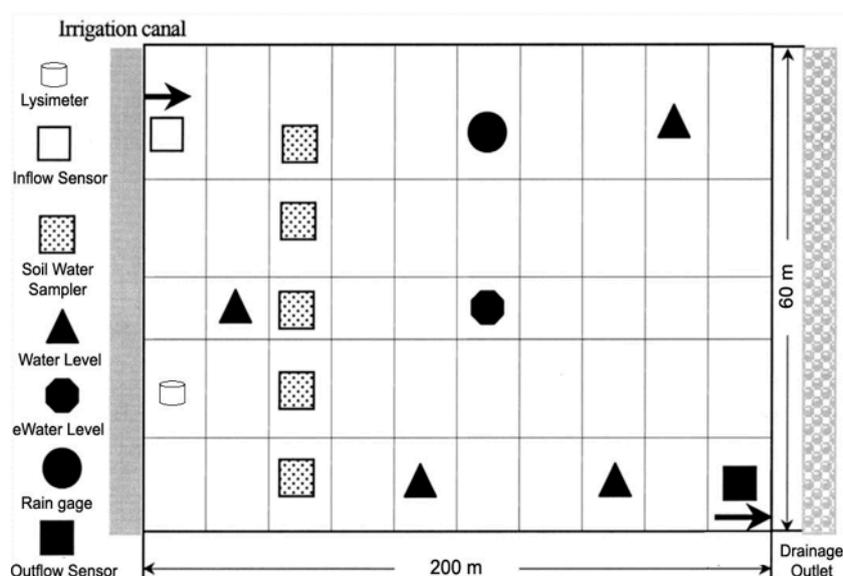


Figure 1. Layout of the equipment installation for the field investigation of water balance components in a paddy field.

2.1.2. Calculation of Irrigation Performance Indices

The water requirement during normal irrigation period can be calculated as follows [11]:

$$NIR = ET + SP + RP - WD - ERF \quad (1)$$

in which, NIR = Net Irrigation Requirement (cm), ET = Evapotranspiration (cm), SP = Seepage percolation (cm), RP = required ponding depth (cm), WD = Standing Water Depth (cm), and ERF = Effective rainfall (cm).

The water productivity index (WPI) is a ratio of yield output to crop water consumptive use. The WPI were calculated as follows:

$$WPI = \frac{Yield \text{ (kg)}}{Total \text{ water consume (m}^3\text{)}} \quad (2)$$

in which, Total water consumed is equal to the total water used (irrigation water + rainfall).

2.2. Hydrus-1D Model

HYDRUS-1D [13] was selected to simulate water flow and solute transport in the experimental field. The governing flow and transport equations are solved numerically using Galerkin-type linear finite element scheme. It has been widely used in applications ranging from water flow to solute and heat transfer in the vadose zones.

2.2.1. Water Flow

The governing flow equation is given by the following modified form of Richard's equation as follows [13]:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left[K \left(\frac{\partial h}{\partial z} + 1 \right) \right] - s \quad (3)$$

in which θ is soil volumetric water content ($\text{cm}^3 \text{ cm}^{-3}$), h is soil water pressure head (cm), t is time, z is spatial coordinate (cm), K is unsaturated hydraulic conductivity (cm day^{-1}), and S is sink term

in the flow equation ($\text{cm}^3 \text{ cm}^{-3} \text{ day}^{-1}$) accounting for root water uptake. In this study, we used van Genuchten's K - h and θ - h relationships [25] to describe soil hydraulic properties of paddy soils:

$$\theta(h) = \begin{cases} \theta_r + \frac{\theta_s - \theta_r}{(1 + |\alpha h|^n)^m} & h < 0 \\ \theta_s h \geq 0 \end{cases} \quad (4)$$

$$K(h) = K_s S_e^1 \left[1 - \left(1 - S_e^{\frac{1}{m}} \right)^m \right]^2 \quad (5)$$

Here, θ_s is saturated water content ($\text{cm}^3 \text{ cm}^{-3}$), θ_r is residual water content ($\text{cm}^3 \text{ cm}^{-3}$), K_s is saturated hydraulic conductivity (cm day^{-1}), and n , α , and l are shape parameters.

In which,

$m = 1 - \frac{1}{n}$; S_e = relative saturation, which is defined as follows:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad (6)$$

2.2.2. Model Parameters

Hydrus-1D requires four main sets of processes; soil hydraulic parameters, solute parameters, solute reaction parameters, and root water uptake.

2.2.3. Estimation of Soil Hydraulic Parameters

The van Genuchten's soil hydraulic parameters θ_r , θ_s , m , α , and l , which are required by the model, were estimated using ROSSETA software package provided by Hydrus-1D regarding soil texture [26]. The pore connectivity (l) was assumed to be equal to 0.5 for many soils [13].

2.2.4. Calculation of Reference Evapotranspiration

In the present study, FAO-56 Penman-Monteith's equation was used to estimate reference evapotranspiration. It is found that this method is one of the best methods to calculate ET_o . The Penman-Monteith equation [27] is given as follows:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (7)$$

in which, ET_o is reference evapotranspiration (mm day^{-1}), Δ is slope of saturation (vapour pressure per temperature curve ($\text{kPa}/^\circ\text{C}$)), γ is psychrometric constant ($\text{kPa}/^\circ\text{C}$), u_2 is wind speed at 2 m height (m s^{-1}), R_n is total net radiation at the crop surface ($\text{MJ m}^{-2} \text{ day}$), G is soil heat flux density ($\text{MJ m}^{-2} \text{ day}$), T is mean daily air temperature at 2 m height ($^\circ\text{C}$), e_s is saturation vapour pressure (kPa), and e_a is actual vapour pressure (kPa). The crop evapotranspiration ET_c under normal conditions can be determined as [27]:

$$ET_c = ET_o \times K_c \quad (8)$$

In this study, the crop coefficient value was taken from the result reported by [28]. They estimated crop coefficient values of rice at Tanjung Karang and listed in Table 3.

Table 3. Crop coefficient K_c values for rice [28].

Days (after Seeding)	7	20	46	105	110	115	117	120	125	130
K_c	1.1	1.1	1.35	1.35	1.2	1	1	1	1	1

2.2.5. Root Water Uptake

The actual rice root water uptake was estimated using the general equation introduced by [29], which was coupled in HYDRUS-1D numerical model. In the present study, the optimized parameter values by Singh et al. [30] for rice crops ($h_1 = 100$ cm, $h_2 = 55$ cm, h_3 (high) = -160 cm, h_3 (low) = -250 cm, and $h_4 = -15,000$ cm) were used to parameterize the water stress response proposed [29]. These parameters were also used by [2,19,20]. The parameters h_1, h_2, h_3 , and h_4 represent different pressure heads. We assume that if $h > h_1$ then, the water uptake is equal to zero. Also, for h_4 , the water uptake is assumed to be equal to zero. However, the water uptake is assumed to be optimal between pressure heads h_2 and h_3 [19].

2.2.6. Initial and Boundary Conditions

For water flow analysis, the initial boundary condition was defined by using the observed soil moisture content under different soil depths. In the present study, an atmospheric boundary condition with surface layer (as most of the time the rice field was under submerged condition, $h_{\max} = 10$ cm) was assigned along the top of the soil surface to allow interactions between soil and atmosphere. These interactions, which included rainfall, evaporation, and transpiration, were given in the time-variable boundary conditions. Seepage was negligible, since the inflows from adjacent plots compensates outflow. Thus, the left and right side boundaries of soil domain were treated as no-flux boundaries. The bottom boundary condition was assigned as free drainage boundary condition, since the water table was far below from the root zone.

2.2.7. Model Evaluation Criteria

In order to check the capability of the model to predict the parameters of water flow and solute transport in paddy field, it is necessary to evaluate the of agreement between the hydrus-1D predicted value and the observed field data. In this regard, two statistical procedures were used: coefficient of determination (R^2) and root mean square error (RMSE), which can be calculated as:

Regression coefficient:

$$R^2 = 1 - \frac{\sum_{i=1}^N (O_i - P_i)^2}{\sum_{i=1}^N (O_i - \bar{O}_i)^2} \quad (9)$$

Root Mean Square Error:

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (P_i - O_i)^2}{n}} \quad (10)$$

in which, P is the predicted values, O_i is the observed values, \bar{O} is the mean of the observed values. The optimum values of R^2 and RMSE are 1 and 0, respectively.

3. Results and Discussions

3.1. Model Assessment

It is well understood that the calibration and validation of complex numerical models are usually difficult due to many parameters that need to be simultaneously checked and well determined. However, in the present study we evaluated the performance of Hudrus-1D model by using the soil hydraulic parameters estimated using RETC shown in Table 4 as initial estimates, the observed values of saturated conductivity and water content are compared with measured data from the experimental paddy plot during off-season for calibration. After the calibration, the field observed data of saturated conductivity, and water content during the main season was used to validate the model. The usefulness

of the model was tested using statistical parameters of determination of coefficient R^2 and Root Mean Square Error (RMSE), as shown in Table 5. High value of R^2 and reliable RMSE indicates that there is good agreement between observed and predicted water fluxes in paddy field.

Simulated water content at depths of 20, 40, 60, 80, and 100 cm well agreed with the measured field data during two rice growing seasons: off-season ($R^2 = 0.80$, $RMSE = 0.048 \text{ cm}^{-3} \text{ cm}^{-3}$) and main season ($R^2 = 0.77$, $RMSE = 0.051 \text{ cm}^{-3} \text{ cm}^{-3}$), respectively. The statistical analysis presented in this study is similar to that reported by [18,19]. Overall, it was reasonable to use the model for vertical movement of water in a real paddy environment. The calibration and validation results for each parameter will be discussed in separate sections below.

Table 4. Optimized values of soil hydraulic parameters.

Soil Depth (cm)	Soil Type	θ_r ($\text{cm}^3 \text{ cm}^{-3}$)	θ_s (cm)	α	n	L	K_s (cm day^{-1})
0–20	Clay loam	0.0792	0.4418	0.0158	1.4145	0.5	10.25
20–40	Clay loam	0.0792	0.4418	0.0158	1.4145	0.5	9.34
40–60	Clay loam	0.0792	0.4418	0.0158	1.4145	0.5	8.55
60–80	Clay	0.0982	0.4588	0.0150	1.2529	0.5	8.1
80–100	Clay	0.0982	0.4588	0.0150	1.2529	0.5	7.2

Table 5. The comparison between simulated and observed soil water content.

Seasons	Depth (cm)	R^2	RMSE ($\text{cm}^3 \text{ cm}^{-3}$)
Off-season	20	0.85	0.06
	40	0.92	0.04
	60	0.57	0.07
	80	0.85	0.06
	100	0.76	0.05
Main season	20	0.88	0.04
	40	0.94	0.04
	60	0.61	0.07
	80	0.84	0.05
	100	0.75	0.06

3.2. Pressure Head

Figure 2 shows simulated pressure head under different soil depths during two consecutive rice growing seasons, respectively. The minimum pressure head was observed during the off-season at a depth of 20 cm, which was -160 cm. During the off-season, the pressure heads showed decreasing pattern with increasing soil depth. All pressure head values below 80 cm soil depth remained negative during the off-season. Pressure heads at 60 and 80 cm reached maximum values of 14.7 and 20 cm during the off-season, respectively.

In contrast to the off-season, due to the lower rainfall period most pressure heads remained mines during the main season. Pressure heads at 20 cm reached a minimum value of -296.6 cm during the main season. During the main season, all pressure head values ranged from -296.6 to 52.8 cm under different soil depths at 20 to 100 cm. Pressure head values are strongly related to hydrological and soil conditions. For example, during the off-season there were continuous rainfall events, and the total amount of rainfall was 4.6 cm, which kept the pressure head values until -160 cm. However, pressure head above -250 cm indicates that the driest water regime occurred during main season experiment (less rainfall as compared to off-season). On the other hand, the rice water uptake was not affected by the water stress as long as the threshold of pressure head was set to -296.6 cm [19].

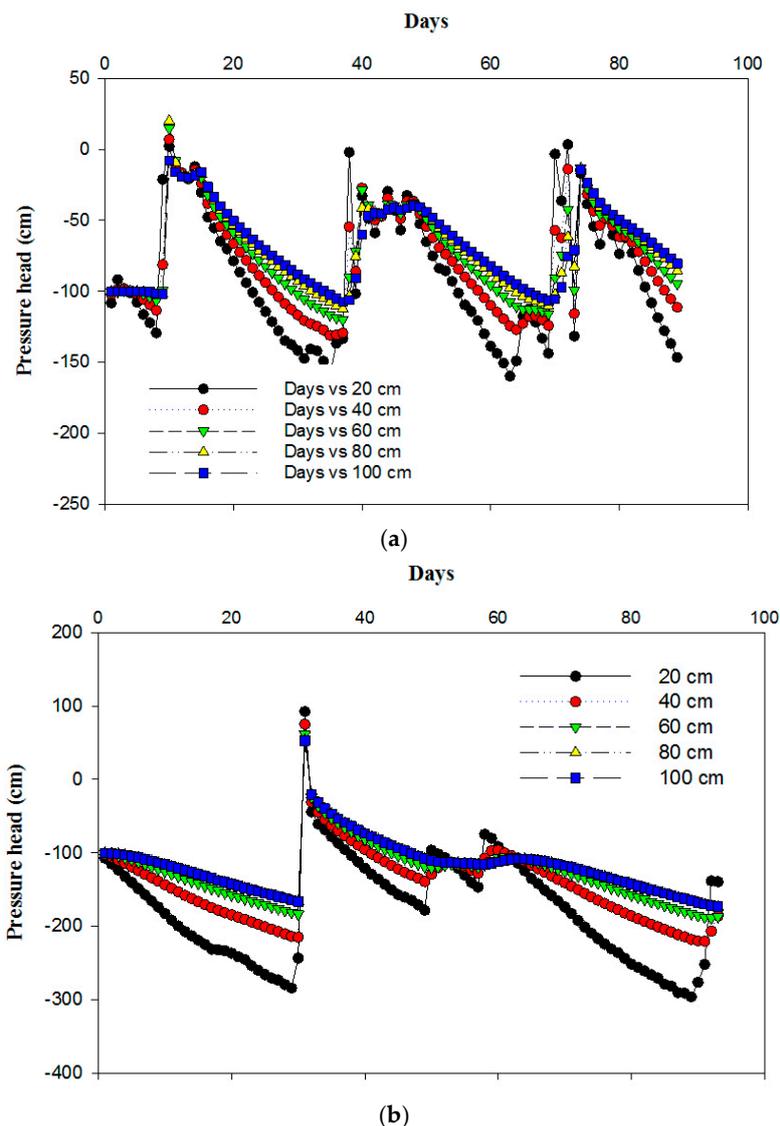


Figure 2. Simulated pressure heads at different soil depths 20, 40, 60, 80, and 100 cm during the (a) off-season (b) main season.

3.3. Evapotranspiration (ET)

Figure 3 shows the daily variation of measured rice evapotranspiration data during two rice growing seasons: (a) off-season and (b) main season, respectively. The modeled evapotranspiration (ET_m) was minimal during the off-season especially. The mean ET_m was 4.7 mm day^{-1} for the off-season and 4.9 mm day^{-1} for main season, respectively. The minimum and maximum ET_m was 1.6 and 6.5 mm day^{-1} during the off-season and 3 and 6 mm day^{-1} during the main season, respectively. The total amount of modeled ET_m was 433.8 and 477.4 mm day during both seasons, respectively. The modeled ET_m was almost similar to those obtained from a field experiment. The minimum ET values were recorded at the end of January 2017 (23–31 January) due to the unpredictable weather condition and storm events. During both seasons, we revealed that ET was low at early stages and then started to increase gradually as rice plant growing into reproductive stage. Generally, during the early stage, the rice plant is young and there is no canopy; thus, the flooding water surface is exposed to wind and radiations. Another reason is that about 30–40% of evapotranspiration is evaporation

during rice growing periods [31]. The measured ET was in the range of 2.8 to 5.8 mm day⁻¹ for the off-season and 4.8 to 7.1 mm day⁻¹ for main season, respectively.

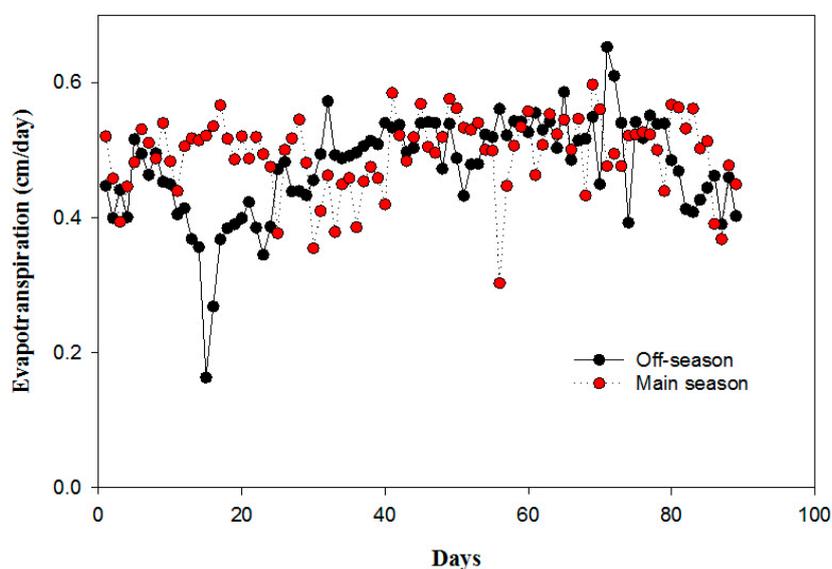
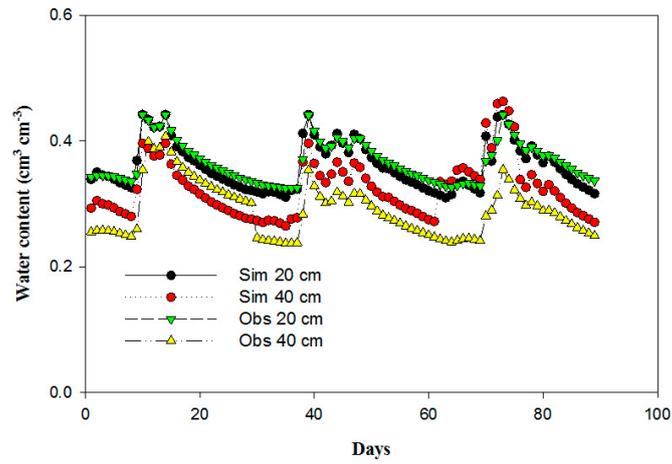


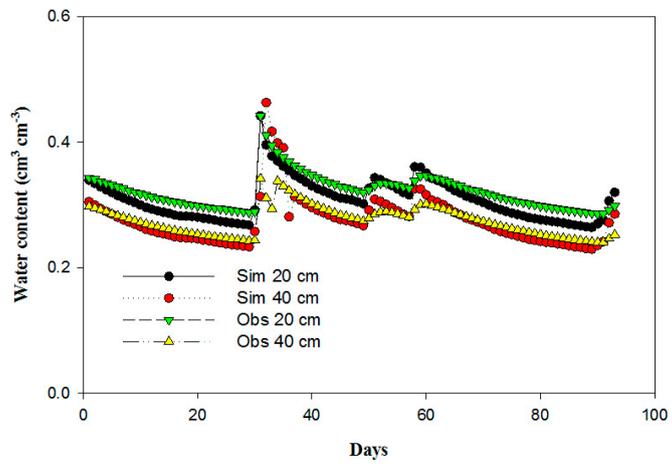
Figure 3. Comparison of daily crop evapotranspiration in a paddy plot during two rice growing seasons (January to October 2017).

3.4. Water Content

Figure 4 shows the comparison between measured and simulated soil water content within root zone (20–40 cm) during two rice growing seasons, respectively. During the off-season, the simulated soil water content at 40 cm soil depth ranged from 0.3 to 0.44 cm³ cm⁻³, with mean value of 0.36 cm³ cm⁻³, while the observed mean soil water content within root zone was 0.49 cm, which ranges from 0.4 to 0.6 cm³ cm⁻³ during off-season. During the main season, the observed soil water content within 40 cm soil depth ranged from 0.23 to 0.46 cm³ cm⁻³, with mean value of 0.3 cm³ cm⁻³. However, the simulated mean soil water content within 40 cm was 0.31 cm³ cm⁻³, which ranges from 0.26 to 0.44 cm³ cm⁻³ during the main season. Figure 5 shows the comparison between observed and simulated soil water content below root zone (60 to 100 cm) during two consecutive rice growing seasons, respectively. The simulated soil water content below root zone ranged from 0.33 to 0.44 cm³ cm⁻³, with mean of 0.36 cm³ cm⁻³ for off-season and 0.3 to 0.44 cm³ cm⁻³ with mean value of 0.33 cm³ cm⁻³ for main season, respectively. The observed mean soil water content below 60 cm was 0.5 cm³ cm⁻³ (range: 0.4 to 0.6 cm³ cm⁻³) for off-season and 0.3 cm³ cm⁻³ (range: 0.25 to 0.46 cm³ cm⁻³) for main season, respectively. In the present study, major differences were found between simulated and observed values of water content at 60 cm depth, which are due to soil condition and other climatic factors. Maintaining 3–10 cm of water level and continuous extreme raining events during the off-season may increase the observed water content at 60 cm soil depth, as shown in Figure 5a. This is also another important reason why large differences between simulated and observed soil water content at 60 cm soil depth were obtained during that period (off-season). On the other hand, irrigation and rainfall caused rapid vertical movement of water at depth of 60 cm, which elevated soil water content. Tan et al. [19] stated that the major difference between observed and simulated soil water content can be due to the inaccurate division of soil layers. However, overall, the model predicted values were well agreed with the observed field data.

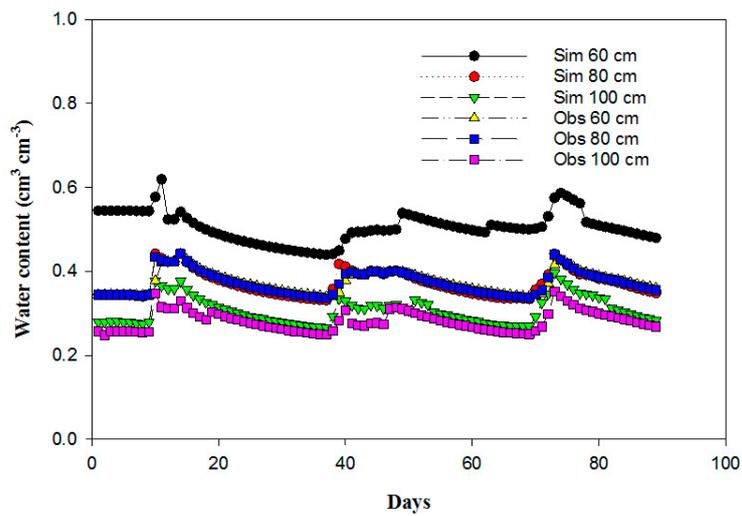


(a)



(b)

Figure 4. Simulated and observed soil water content within root zone (0–40 cm) during the (a) off-season and (b) main season.



(a)

Figure 5. *Cont.*

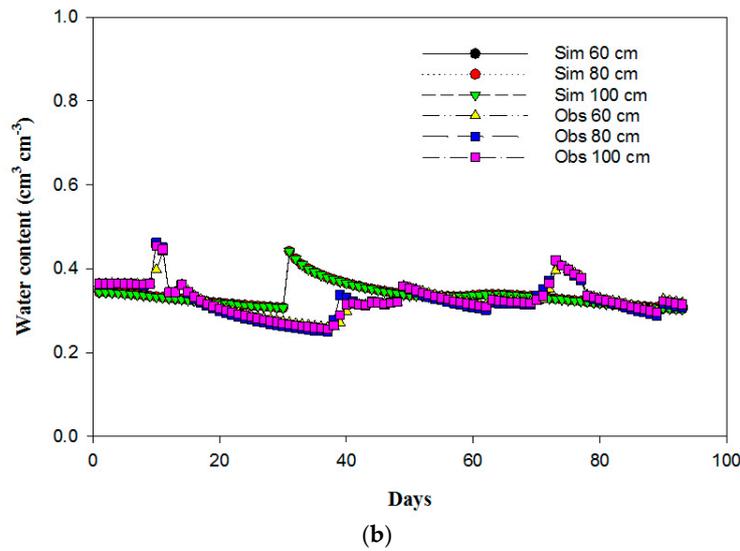


Figure 5. Simulated and observed soil water content below root zone (60–100 cm) during the (a) off-season and (b) main season.

3.5. Root Water Uptake

Figure 6 shows the daily predicted root water uptake by rice during the two rice growing seasons. The simulated results showed that the cumulative root water uptake initially was less and then picked up with the growth of the crop until it reached its maximum. During the off-season, root water uptake started to decline rapidly from 17 to 20 January 2017 until it reached its minimum value of 0.14 cm day^{-1} and then suddenly showed increasing trend. The maximum daily root water uptake was recorded approximately ten days after continuous rainfall (5 February 2017), which was 0.38 cm day^{-1} during the off-season period. During the main season, simulated daily root water uptake reached its maximum value of 0.34 cm day^{-1} on 19 July 2017. The minimum daily rate of root water uptake was recorded on 10th and 14th of September 2017, which was 0.1 cm day^{-1} .

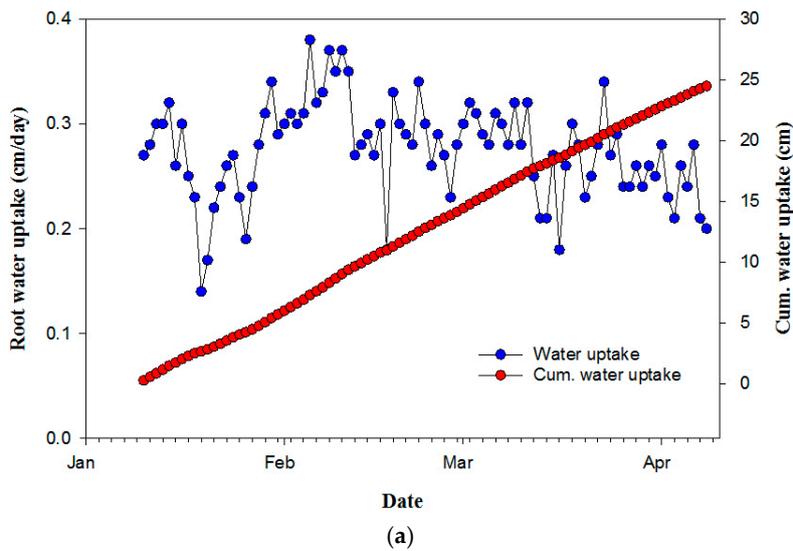


Figure 6. Cont.

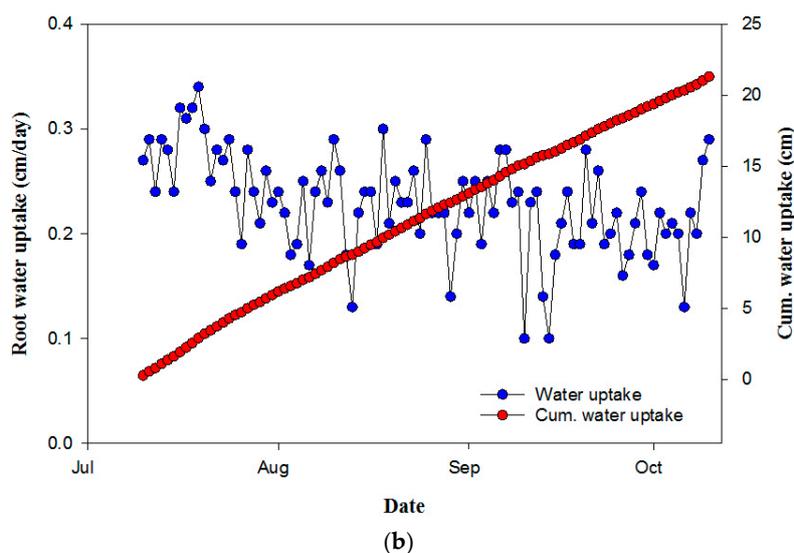


Figure 6. Simulated actual daily root water uptake and simulated cumulative water uptake during the (a) off-season and (b) main season.

The mean daily root water uptake was 0.27 cm day^{-1} for off-season and 0.23 cm day^{-1} during the main season, respectively. We revealed that at the end of rice growing season, the daily root water uptake declined drastically during off-season. However, contrary to off-season, the daily water uptake at the end of rice growing season increased instantly during the main season. The cumulative root water uptake by rice started to increase slowly during initial stages and later increased sharply as the season advances and ultimately reached 24.5 cm during off-season. In addition, during the main season the cumulative root water uptake by rice increased rapidly and showed almost same increasing pattern until it reached 21.3 cm during the rice growing period. The findings of the present study are almost closed compared to those reported by [2,32]. Daily root water uptake by rice at the range of 0.0 to 0.7 cm day^{-1} was reported by [32].

3.6. Water Flux

In the present study, the vertical movement of water under different soil depths was simulated and then compared with the observed percolation data collected during two rice growing seasons. Figure 7 shows the characteristics of water movement within root zone (0–40 cm) for both seasons, respectively. During the off-season, the mean rate of water fluxes within root zone was 0.23 cm day^{-1} , which ranges from 0.02 to 0.6 cm day^{-1} . During the main season, it ranges from 0.06 to 0.78 cm day^{-1} , with mean value of 0.21 cm day^{-1} .

Figure 8 shows downward water percolation below the root zone (60–100 cm) during two consecutive rice growing seasons. During the entire off-season, the mean percolation rate was 0.21 cm day^{-1} , which varies between 0.04 to 0.65 cm day^{-1} . The percolation rate during main season ranged from 0.1 to 0.66 cm day^{-1} , with mean rate of 0.22 cm day^{-1} . The cumulative water percolation fluxes at 0–40 cm depth were 21.1 cm for off-season and 20.5 cm during main season, respectively. However, the cumulative bottom fluxes of percolation water below root zone (60–100 cm) were 20.3 cm for off-season and 19.5 cm for main season, respectively.

The vertical movement of water in paddy fields is related to climatic factors such as rainfall and also irrigation events. Frequent rainfall after rice broadcasting (22–26 January 2017) resulted in relatively continuous high percolation rates during off-season, as shown in Figure 7. In fact, cumulative flux of percolation water in paddy fields mainly depends on soil condition, field management, and hydrological conditions. Bouman et al. [33] insisted that excessive loss of water by surface runoff, seepage, and percolation is about 25–50% of all water used in heavy soils, with shallow water

tables of about 50 cm depth. However, in this study we estimated percolation losses of 17.1 to 19.2% of the total water applied during entire both seasons, respectively.

A comparison between model-simulated and observed deep percolation fluxes for two seasons was made. The total simulated and observed deep percolation rate was 21.8 and 19.9 cm during off-season. During the entire main season, the total deep percolation simulated by Hydrus-1D was 20.4 cm, and the observed value was 17.3 cm. Overall, the correspondence between simulated and field-observed deep percolation fluxes during both seasons was very good. The minor differences between simulated and observed values could be due to the lateral seepage, soil cracks, and root [34]. The modeled values of deep percolation matched well with the observed data. This result indicates that Hydrus-1D model can be perfect tool with which to predict water balance components in paddy fields.

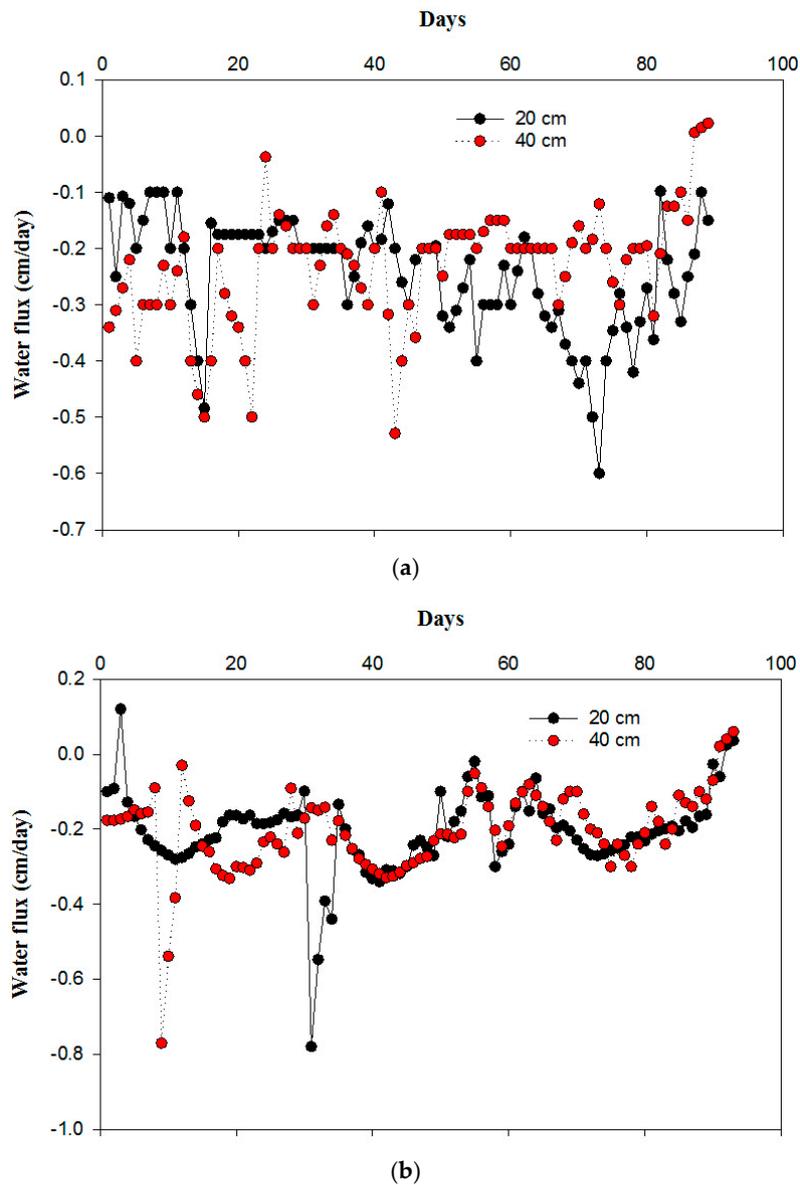


Figure 7. Simulated water fluxes within root zone (0–40 cm) during the (a) off-season and (b) main season.

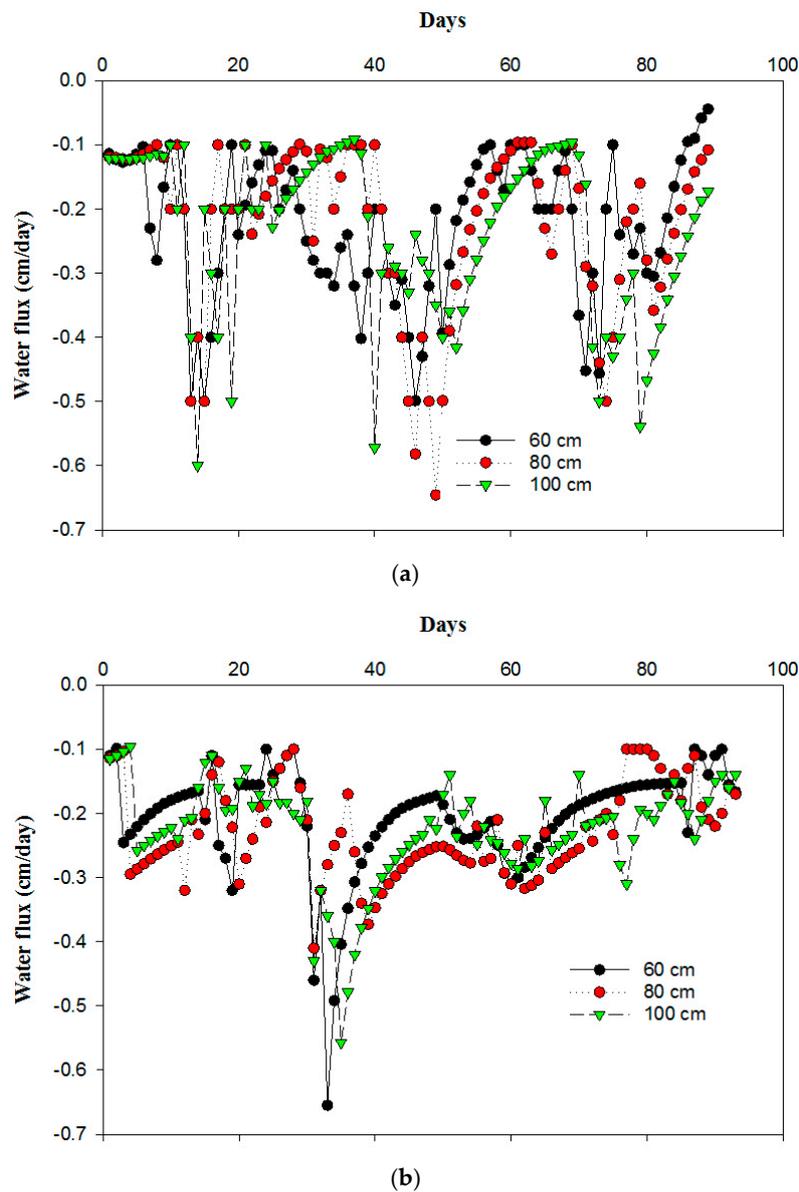


Figure 8. Simulated water fluxes below root zone (60–100 cm) during the (a) off-season and (b) main season.

3.7. Water Balance and Productivity

In this study, the water balance components, namely, irrigation water (IR), rainfall (RF) and effective rainfall (ER), crop evapotranspiration (T), seepage-percolation (SP), drainage water (DR) and fluctuation of field standing water depth (SW) were monitored through intensive field observations and analysed recorded data successfully. The observed values of ET in the present study were within 0.28–0.71 cm day⁻¹ during both seasons, respectively, which are usually quoted values for major rice producing areas in Asia. The standing water depth during both seasons was high (7–10 cm), especially during reproductive stages. The measured deep percolation values were within range of 0.1–0.4 cm day⁻¹ during two rice growing seasons. Based on stagnant and deep percolation analysis, we also revealed that percolation rate increases as standing water depth in paddy plot increases. During both rice growing seasons, the average of the total water requirement of 0.75 and 0.7 cm/day, about 59.6 and 76.2%, respectively, was supplied by irrigation. From this, about 37.3 and 43.7% was transferred by drainage, 41.7 and 61% was used as evapotranspiration, and 17.1 and 19.2% was lost as deep percolation. Based on utilization of effective rainfall in the paddy

field, it clearly indicates that the irrigation water could be minimized during the off-season due to the high rainfall occurrence during that period. The highest irrigation supply occurred during mid-season during the vegetative growths and before flowering stages of paddy plants due to high crop water demand. During a heavy rainfall event (e.g., January and September), the paddy plot was unable to capture a significant amount of the rainfall for utilization in the next periods, which resulted in a considerable loss of water through surface drainage. Also, we revealed that drainage is largely dependent on rainfall and irrigation, as well as the existing water depth in the paddy field. The maximum water depth of 100 mm is maintained by controlling the drainage outlet. When the water depth in paddy field exceeds 100 mm, the remaining water is drained out automatically.

As shown in Table 6, the water productivities analysed from total water input and irrigation water were 0.43 and 0.72 kg m⁻³ during the off-season and 0.60 and 0.78 kg m⁻³ during main season, respectively. Water productivity index evaluated from observed and modeled evapotranspiration was 1.03 and 1.13 kg m⁻³ during the off-season and 0.98 and 0.94 kg m⁻³ during main season, respectively.

Table 6. Summary of water productivity index, irrigation water requirement, and crop water requirement during both seasons.

Parameters	Off-Season	Main Season
Pre-saturation	163.0	155.0
Yield (kg)	2500.00	2700.00
Irrigation requirement (cm)	49.564	71.890
Crop water requirement (cm)	68.504	72.520
Total water requirement (cm)	84.804	88.020
WPI (kg/m ³)	0.72	0.78
WPIR (kg/m ³)	0.43	0.60
WPET (kg/m ³)	1.03	0.98

4. Discussion

The total amount of water use (irrigation + rainfall) was 116.5 cm for off-season and 90.4 cm for main season. Of this, 60% to 77% was applied by irrigation during two rice growing seasons, respectively. The mean values of ET were 0.52 and 0.56 cm day⁻¹ for both seasons, respectively. During both seasons, we revealed that ET was low at early stages and then started to increase gradually as rice plant growing into reproductive stage. Globally, estimates of rice evapotranspiration range from 45 to 70 cm season⁻¹, depending on the climate and growing season [35]. In South and Southeast Asia, ET ranges from 0.4 to < 1 cm day⁻¹ [36]. Thus, in the current study, the total amount of measured ET was 48.5 cm for the off-season and 55.2 cm for main season, respectively. However, the observed values of ET in the present study were within 0.28–0.71 cm day⁻¹, which are usually quoted values for major rice producing areas in Asia [5]. Abdullhah et al. [21] estimated crop evapotranspiration using micro-paddy lysimeter under same plot and reported ET value of 0.3 to 0.7 cm day⁻¹. Rowshon et al. [22] estimated crop evapotranspiration using Marriott tube lysimeter and observed ET value of 0.4–0.9 cm day⁻¹. Lage et al [37] conducted lysimeter experiment and reported daily average rice evapotranspiration rate of 0.67 cm day⁻¹. According to [38], typical evapotranspiration values of rice fields are 0.4 to 0.5 cm day⁻¹ for wet season and 0.6 to 0.7 cm day⁻¹ but can be as high as 1 to 1.1 cm day⁻¹ in subtropical regions. Several researchers reported 0.4 to 0.9 cm day⁻¹ [5,22,39,40].

During both seasons, the total amount of effective rainfall was 35.2 and 16.1 cm respectively. Based on effective rainfall results, it clearly indicates that the irrigation water can be minimized during the off-season due to the high rainfall occurrence during that period. Lee et al. [41] suggested constructing a storage facility to store the excessive flows caused by heavy rainfall events in order to augment rainfall whenever required. Rowshon et al. [22] stated that use of rainfall is also essential in overcoming water shortages and improving the dependability of irrigation deliveries. Maina et al. [23] conducted paddy rice water requirement experiment at sawah sempadan and reported total effective rainfall of 29.9 cm during the

off-season, which is close to the value reported by the current study. Although they did not consider whole month of January, the heavy rain may occur during first two weeks of that month. However, almost same amount of effective rainfall was obtained during the month of February: 9.1 cm for the current study and 9.5 cm reported by [23]. In Tanjung Karang Rice Irrigation Scheme (TAKRIS), the farmers practice conventional irrigation system, and field water level is maintained at a level of 3–10 cm until two weeks before harvesting and when water is about to drain. Thus, a continuous irrigation system was adopted, except during rainfall and when water level exceeded 10 cm. The highest irrigation supply occurred during mid-season when paddy plants grew and water crop water demand was high. During both seasons when there was heavy rainfall, there were no irrigation events. The total amount of irrigation water was 69.5 and 68.9 cm during off and main seasons, respectively. In the present study, drainage occurred only whenever the water level exceeded the outlet height of 10 cm and also during drainage periods. Thus, the total amount of drainage was higher during the off-season due to heavy rainfall events as compared to main season. During the off-season, drainage events occurred at end of January, February, and March when there were huge rainfall events (more than 3.5 cm) and also during field draining period. Our current finding suggests that drainage is largely dependent on both rainfall and irrigation. Thus, it is necessary to adapt water saving strategies in order to minimize excessive water losses from paddy fields [42]. On the other hand, a large volume of water drained out from the study plot, especially during rainy days.

The mean rate of percolation water was 0.21 cm for the off-season and 0.18 cm for main season, respectively. It ranges from 0.17–0.28 cm day⁻¹ for the off-season and 0.12–0.25 cm day⁻¹ for main season, respectively. The deep percolation rate during the off-season was higher than that obtained during the main season. The mean rate of percolation water was 0.21 cm for the off-season and 0.18 cm for main season, respectively. It ranges from 0.17–0.28 cm day⁻¹ for the off-season and 0.15–0.25 cm day⁻¹ for main season, respectively. The deep percolation rate during the off-season was higher than that obtained during the main season. The percolation loss findings in the present study are almost close to those reported by other authors. Lee et al. [41] found mean percolation rate of 0.27 cm day⁻¹ for the off-season and 0.22 cm day⁻¹ for main season, respectively. Ayob et al. [43] reported daily average percolation value of 0.17 cm day⁻¹ at KADA Paddy Irrigation Scheme, Malaysia. However, it is much lower than those observed by other authors in Southeast Asian regions [44,45]. This is mainly due to the changes in the conditions of rice fields including soil texture and structure, top and subsoil thickness, standing water depth, water and soil temperature and salinity, depth to the groundwater table, and other topographical conditions [40]. It is well understood that percolation rate increases as standing water depth in paddy plot increases.

Currently, there is a challenge to use less water with more production. To do so, water productivity index is the best indicator with which to express the value derived from the use of water. This concept comes from “more crops per drop”. Based on experimental results, the water productivity for irrigation (WPI) during the off-season and main season was 0.72 kg/m³ and 0.78 kg/m³ respectively. The water productivity for irrigation plus rainfall (WPIR) was 0.43 kg/m³ for the off-season and 0.60 kg/m³ for main season. However, the water productivity for evapotranspiration (WPE) was 1.03 kg/m³ for the off-season and 0.98 kg/m³ for main season, respectively. Usually, low water productivity indicates that the crop water requirement is high and opposite for high water productivity. Rashid et al. [46] estimated water productivity during Boro and T.Aman seasons in Bangladesh by considering the total water input (irrigation and rainfall) and reported WP value of 0.58 and 0.49 kg/m³, respectively. Li et al. [32] conducted a field experiment under transplanted rice in China and investigated water productivity during two consecutive seasons. They reported WPI and WPIR values of 2.08 and 0.99 kg/m³ during the first season and 3.85 and 0.77 kg/m³ for the following season, respectively.

In Tanjung Karang paddy fields, farmers always use conventional irrigation system in which high water level was maintained during rice growing seasons, especially during reproductive stages. 8.5 cm to 10 cm standing water depth was recorded from mid-August to the end of September due to the frequent rainfall and irrigation supply events. Keeping water level above 7 cm may result in excess

water loss from the paddy field. Therefore, in the present, we suggest that keeping the stagnant water depth around 4–6 cm will minimize the water losses both by deep percolation and surface drainage.

5. Conclusions

The HYDRUS-1D simulation model was conceptualized and we carried out a numerical analysis to predict water movement under different soil depths (20, 40, 60, 80, and 100 cm) successfully. For the water flow analysis, the results indicated that the model performed well during the calibration and (validation) periods with the coefficient of determination (R^2) of 0.79 and (0.82) and root mean square error (RMSE) 0.06 and (0.055) respectively, which also indicates that the Hydrus-1D model can provide reliable simulation of water movement in paddy fields. Previously, [14,20] confirmed that Hydrus-1D could be a successful tool for predicting water movement under both Transplanted Paddy Rice (TPR) and Direct, Seeded Rice Field (DSR). In the present study, the overall results revealed that Hydrus-1D simulations were reasonable and effective tools for simulating the vertical water flow in both broadcasted and transplanted rice experimental fields.

Author Contributions: Abdikani Abdullahi Mo'allim and Md Rowshon Kamal designed the experiment and wrote the paper, Hadi Hamaaziz Muhammed analyzed the data, Mohamed Azwan b. Mohamed Zawawi, Hasalina bt. Che Man, Aminrun Wayayok and Nasehir Khan E.M Yahya contributed writing, material and numerical analysis.

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