




Article

HYDRUS-1D Simulation of Soil Water Dynamics for Sweet Corn under Tropical Rainfed Condition

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Abstract: Assessment of soil water balance is essential to understand water dynamics for optimal use of water and fertilizers. The study intended to simulate soil water dynamics in sweet corn production under tropical rainfed conditions. Surface runoff, subsurface leaching, and evapotranspiration are the main components of water balance, especially in tropical environments. Therefore, intensive field experiments and HYDRUS-1D numerical modeling were applied to investigate the water balance components and analyzing water dynamics. The study was carried out in a sweet corn field for two growing seasons under the rainfed conditions at the Malaysian Agricultural Research and Development Institute (MARDI), Serdang, Malaysia. The total water inputs during the first and second seasons were 75.8 cm and 79.7 cm, respectively. Simulated results of evapotranspiration (ET) accounted for 40.7% and 33.1% of total water input during the first and second seasons. Surface runoff accounted for 41% and 28.6% in the first and second season, respectively. Water leaching accounted for 10.6%–26.8% of total water input during both seasons respectively. As rainfall fulfilled the crop water requirement throughout the growing seasons no additional irrigation was required. The overall simulation results validate the HYDRUS-1D as an effective tool to simulate soil water dynamics under rainfed conditions.

Keywords: rainfed conditions; water balance; soil water; runoff and leaching losses; HYDRUS-ID simulation

1. Introduction

Around 190.6 million hectares produced 1076.18 million tons of corn at the rate of 5.65 tons/ha for the year 2017–2018 worldwide [1]. In 2017, Malaysia consumed around 4 million tons of grain corn. Most of the grain corn consumed in Malaysia is imported, while sweet corn is grown locally [2]. About 10,477.30 ha of the cultivated area produced 72,560.52 tons of sweet corn for the year 2017 in the country [3]. Sweet corn is used for both human and animal consumption, along with its use in industry as raw material [4]. In Malaysia, sweet corn grows on acidic, weathered soils with low pH and soil fertility, which results in low corn yield [5]. Imbalance in fertilizer application also results in low corn production in tropical regions [6]. The change in water balance components such as evapotranspiration, runoff, soil moisture, and rainfall might also affect this fertilizer imbalance.

Accurate estimation of water balance in agricultural fields is also key to water resources management in agriculture, which is the primary consumer of the water. Evapotranspiration and leaching have considered as leading sinks of water that affect soil water status in a soil–plant–atmosphere

environment [7]. That is why devising water management strategies depend on information relating to crop water requirement (represented as evapotranspiration). Measuring other water balance components such as deep percolation, runoff in field conditions is also a big challenge [8]. The response of the water balance components also varies with climate geographically. The significant differences between regions necessitate a need to evaluate responses of water balance components in various geoclimatic regions. Rainfall is the most investigated components of water balance. A significant regional variation in rainfall has also been recorded [9]. Climate change also has a significant effect in altering rainfall patterns in humid tropics [10]. Therefore, in a tropical region like Malaysia, the change in rainfall patterns is more crucial than in temperature due to climate change.

Simulation models are recognized as a valuable tool to assess water transport and the extent to which management practices affect crop yield and the environment. However, the validation of simulation models for local conditions is crucial [11]. Among different available models, a software package HYDRUS-1D [12] has been widely used for simulating water flow and solute transport in soils, to analyze flow and transport processes in agricultural fields. Several researchers have applied HYDRUS-1D to evaluate water balance successfully. As compared to other models, HYDRUS-1D has the flexibility of accommodating different boundary conditions and the capability to consider the root uptake of water and nutrient simultaneously. The model is capable of simulating soil water and solute dynamics under different management practices [13–22]. All these researchers validated HYDRUS-1D as a reliable tool for such investigations.

It is necessary to improve agricultural water management and to develop new strategies to increase agricultural productivity [23]. The heavy rainfall results in the solute loss to increase manifold in the tropical climate. Therefore, the study was carried out to quantify water losses (surface runoff and leaching) from the field that results in fertilizer loss in Malaysia. Quantifying the water balance components under rainfed conditions can be useful to improve irrigation management and to assess the scale of fertilizer loss for sweet corn production. The study can further be used to link rainfall intensity with fertilizer loss. Besides, HYDRUS-1D has rarely been used for sweet corn production in tropical environment. The model validation through the field experiments in quantifying water losses is worthwhile for sweet corn production. Indeed, heavy rainfall in Malaysia can potentially meet crop water requirements. However, the duration and frequency of rainfall are uncertain that can affect the water availability to plant. Therefore, the objectives of the study were (1) to simulate the soil water dynamics under rainfed conditions, and (2) to evaluate the HYDRUS-1D model for the rainfall potential to meet the water requirement of sweet corn in the tropical region.

2. Material and Methods

2.1. Field Experiments and Measurements

2.1.1. Site Description

The experiment field located 2°59' N latitude and 101°42' E longitude, 43 m above the mean sea level at the Malaysian Agricultural Research and Development Institute (MARDI) in Selangor, Malaysia. Total annual precipitation of the area has been recorded as 2632 mm for the year 2017, whereas minimum and maximum temperatures were 21.3 °C and 35.8 °C, respectively. The rainfall occurs throughout the year, with seasonal variation. Most of the rainfall occurs in months October–December. February and March are relatively dry months. Research work was carried out from February to May 2018 and September to November 2018. The soil layer classified as clay throughout the sampling depth of 0–140 cm. The physical and chemical properties of soil are presented in Tables 1 and 2. The variety of sweet corn cultivated was 'Hibridmas'.

Table 1. Physical properties of the soil in the experimental field at Malaysian Agricultural Research and Development Institute (MARDI).

Depth (cm)	Clay %	Silt %	Sand %	Textural Class	Bulk Density (g cm ⁻³)	Conductivity Ks (cm d ⁻¹)
0–20	65.36	09.79	24.84	Clay	1.36	12.86
20–40	53.28	15.24	31.45	Clay	1.39	12.43
40–60	58.66	13.12	28.23	Clay	1.31	12.78
60–80	70.20	20.22	09.58	Clay	1.22	18.11
80–140	71.74	18.03	10.23	Clay	1.24	17.56

Table 2. Chemical properties of the soil in the experimental field at MARDI.

Depth (cm)	pH (Airdry)	EC umoh/cm	CEC cmol (+)/kg	Organic Matter %N	P mg/Kg	K mg/Kg
0–20	6.87	62.80	5.88	0.14	55	74.1
20–40	5.95	64.90	5.68	0.12	26	74.1
40–60	6.20	45.75	6.49	0.12	39	19.5
60–80	5.80	41.47	7.47	0.11	30	42.9
80–140	5.98	85.78	7.13	0.09	22	19.5

2.1.2. Experimental Design and Measurements

The research work was designed based on an intensive field experiment in real field conditions. The experiment was carried out in a 770 m² (35 m × 22 m) field. Sweet corn ‘Hibridmas’ was planted during both seasons at 10 kg/ha where plant-plant (P × P) and row-row (R × R) space were maintained as 20 cm and 75 cm respectively. Harvesting dates were on 3rd May and 15th November for the first and second season 2018 respectively. The growing period for the first season (February–May 2018) was 76 days whereas for the second season (September–November 2018) it was 71 days. The total rainfall recorded during the first and second season is 75.8 cm and 79.7 cm, respectively.

In the experimental field, rain-gauge, RBC Parshall Flume, evapotranspiration (ET)-gauge, and 5TE sensors with EM 50 data logger were installed as shown in Figure 1; Figure 2. The sprinkler irrigation system was installed in the field for supplement irrigation. The amount of precipitation was measured using a data-logging rain-gauge. The amount of water drained from the field was measured by using Parshall Flume RBC with CR200X logger (SZ-CR200X/7070) whenever the runoff event occurs at the outlet point. ET gauge was used for evapotranspiration (ET) measurements. However, the evapotranspiration (ET) calculations were also made using the Penman–Monteith equation. The daily climate data required for ET calculations, i.e., temperature, humidity, radiation, and wind speed were obtained from the adjacent meteorological station. Soil moisture measuring sensors (5TE) with EM 50 data logger was installed at 20, 40, 60, 80, and 140 cm depths. TDR-300 was used for monitoring soil moisture of topsoil. For a few samples, soil moisture measurement was done through the oven dry method in the laboratory. Laboratory and TDR-300 measurements also helped in calibrating sensor measurements.

Two observation wells were installed to monitor groundwater table daily. The water fluctuated with rainfall occurring, otherwise, it remained around 150 cm. Three tensiometers were also installed at depths 20, 40, and 60 cm to observe pressure head within the root zone.

Soil samples were collected from the field at different depths of 0–20, 20–40, 40–60, 60–80, and 80–140 cm to determine the physical and chemical properties of the soil. The standard pipette method was used for soil texture analysis, which is considered as a reference method to classify soil texture. Table 1 presents the percentages of sand, silt, and clay of soil. The textural analysis was performed at Soil Physics Laboratory, Faculty of Agriculture, UPM. For the chemical properties, soil samples were tested at United Plantations Laboratory, Teluk Intan, Perak.

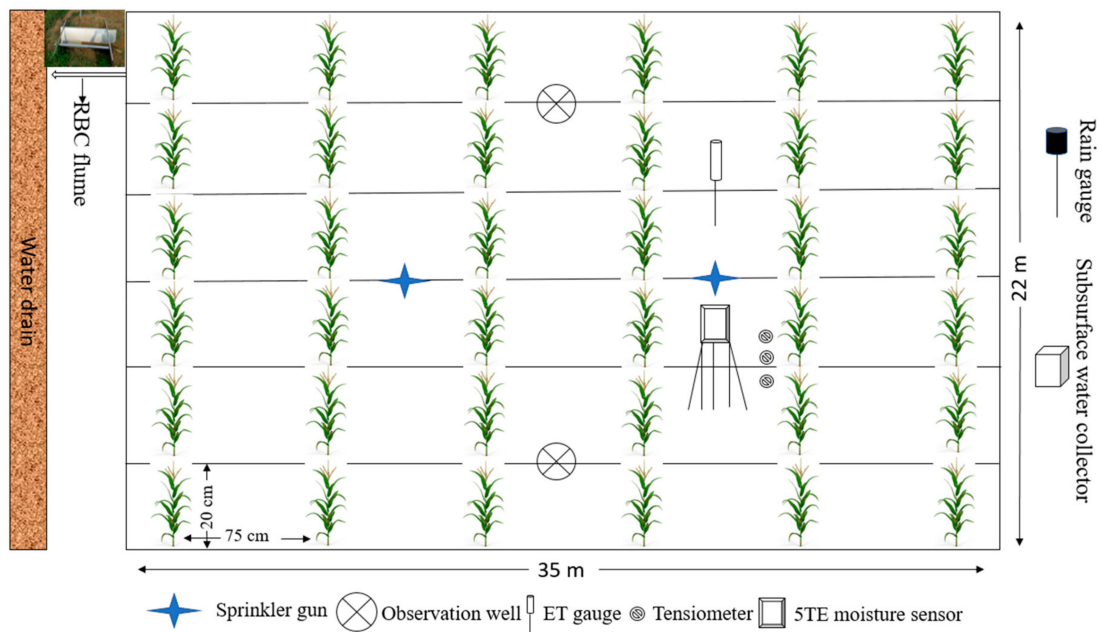


Figure 1. Field layout of equipment installed for investigation of water balance components.



Figure 2. A view of the installation of different equipment in the field.

The subsurface water collection system was designed and installed to collect water percolated below the root zone (Figure 3). The concrete block of 1 m³ was buried in soil for this purpose. Soil bulk density of a block filled with soil equal to field bulk density. The blocks drain was connected to a bucket with a 72-L capacity to collect water leached in the block. The collected water was pumped out at the end of each rainfall with the help of a small-diaphragm pump.

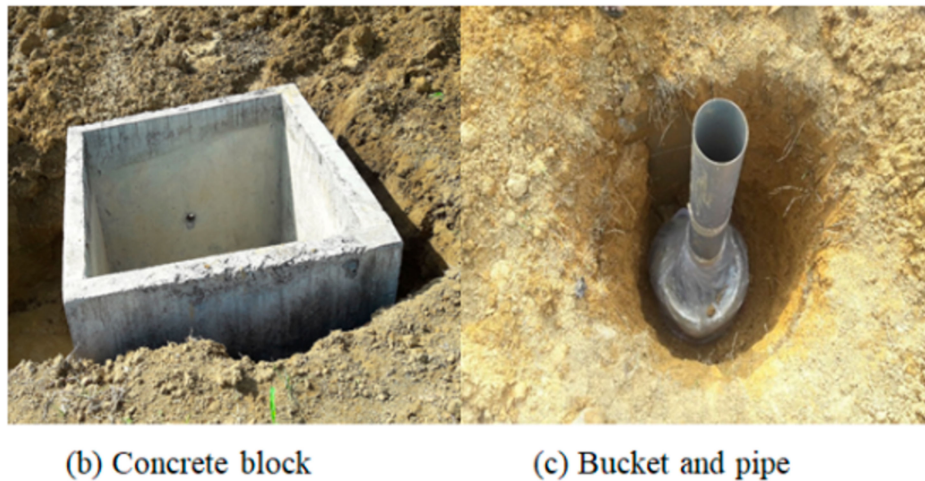
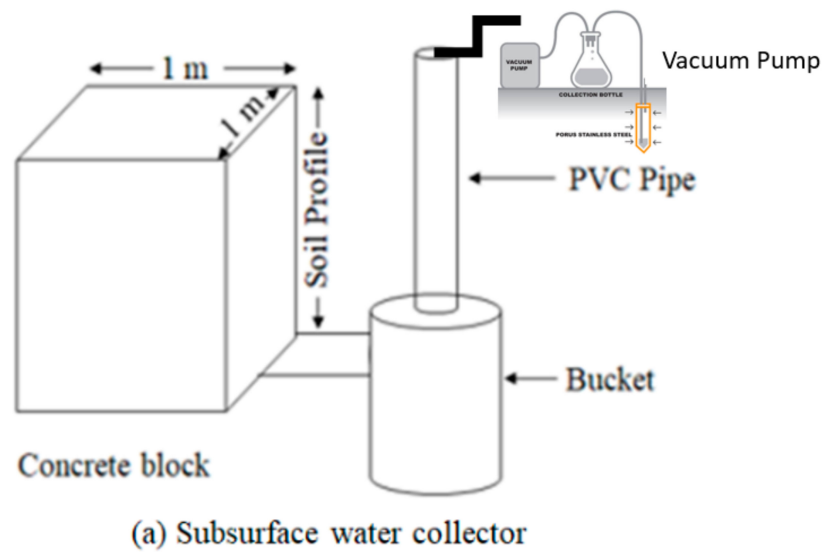


Figure 3. View of the sub-surface water collection system in the field experiment.

2.1.3. Water Balance Components

The soil water balance equation used for determining available water in a sweet corn field as follows:

$$SS = WI - RO - ET - L, \tag{1}$$

where, SS is the available soil storage (cm) determined using 5TE sensor; WI is the amount of total water input (cm) recorded using rain gauge; RO is the amount of runoff water from field (cm) measured using RBC flume; ET is the amount of evapotranspiration (cm) observed using ET gauge; L is the amount of water leaching (cm) calculated using the equation.

2.2. HYDRUS-1D Model

2.2.1. Model Description

The one-dimensional numerical model HYDRUS-1D [13] was used to simulate soil water dynamics in the sweet corn field. As the water flows from surface to groundwater is in a vertical direction under rainfall, and horizontal flow such as runoff can be covered through boundary conditions, there was no need to simulate multi-dimensional movement. The HYDRUS-1D solves the Richards equation for

saturated and unsaturated water flow. Following is the governing equation for water flow, which is the modified form of Richards equation assuming water flow due to thermal gradient is neglected.

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left[K \left(\frac{\partial h}{\partial z} + 1 \right) \right] - S, \tag{2}$$

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

The soil hydraulic properties were modeled using [24] as follows:

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

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

Here

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r}, m = 1 - \frac{1}{n}. \tag{5}$$

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

The details of simulation process and model description have been presented in the flow chart (Figure 4).

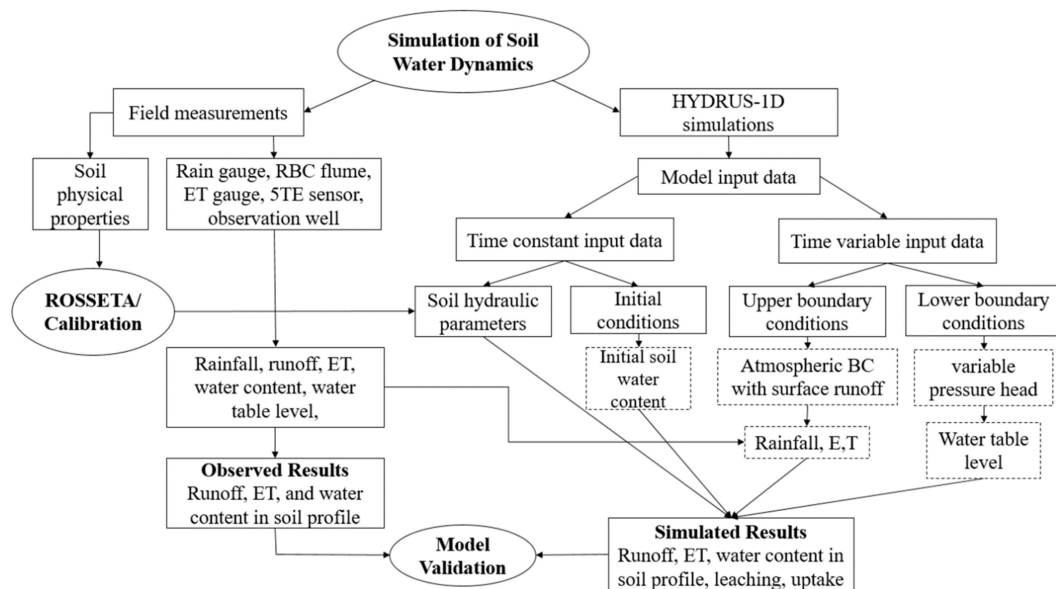


Figure 4. Flow chart presenting model simulation process and calculation of water balance components.

2.2.2. HYDRUS-1D Input Parameters

Estimation of Soil Hydraulic Parameters

The soil hydraulic parameters such as θ_s , θ_r , m , a , and n (Table 3) were estimated using the ROSSETA computer program for the HYDRUS-1D input. The value of the pore connectivity parameter (l) was assumed to be (0.5) [13].

Table 3. Optimized value of soil hydraulic properties.

Depth (cm)	Soil Type	θ_s (cm ³ cm ⁻³)	θ_r (cm ³ cm ⁻³)	a (cm ⁻¹)	n	K_s (cm Day ⁻¹)	L
0–20	Clay	0.0973	0.4750	0.0250	1.1625	12.86	0.5
20–40	Clay	0.0930	0.4561	0.0252	1.2019	12.43	0.5
40–60	Clay	0.0952	0.4661	0.0254	1.1828	12.78	0.5
60–80	Clay	0.1020	0.5084	0.0201	1.1903	18.11	0.5
80–140	Clay	0.1017	0.5066	0.0203	1.1825	17.56	0.5

Estimation of Potential ET

HYDRUS-1D requires potential evaporation and potential transpiration fluxes as input values to simulate soil water effect on transpiration. The Penman–Monteith equation [25] was used to calculate the reference evapotranspiration (ET_0) using available soil, crop, and climate data. The crop potential evapotranspiration (ET_c) was calculated from the reference evapotranspiration (ET_0) and the crop coefficient (K_c) as given in Equation (7) under normal conditions [25]. The K_c values for four stages (early, development, mid, and late seasons) of sweet corn were 0.4, 0.8, 1.15, and 1, respectively [26]. Potential evapotranspiration (ET_p) was divided into potential evaporation (E_p) and Potential transpiration (T_p) using the AquaCrop model.

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}, \quad (6)$$

where, ET_0 = reference crop evapotranspiration (mmday⁻¹), R_n = net radiation at the crop surface (MJm⁻²day), G = soil heat flux density (MJm⁻²day), T = air temperature at 2 m height (°C), u_2 = wind speed at 2 m height (ms⁻¹), $e_s - e_a$ = saturation vapour pressure deficit (kPa), Δ = slope vapor pressure curve (kPa/°C), γ = psychrometric constant (kPa/°C), and 900 = conversion factor

$$ET_c = ET_0 \times K_c. \quad (7)$$

Root Water Uptake

The root water uptake was determined from [27].

$$S = \alpha(h)S_{max}, \quad (8)$$

where S is the rate of root water uptake, S_{max} is the maximum rate of root water uptake, and $\alpha(h)$ is the coefficient of root water uptake. The values of coefficients h_0 , h_{opt} , h_{2H} , h_{2L} , and h_3 were taken as -10, -25, -500, -1000, and -16,000 respectively [13]. It is assumed that the water uptake is zero near saturation and for pressure heads less than the wilting point (h_3). The root water uptake is assumed optimal between pressure head h_{opt} and h_2 , whereas it shows a linear increase or decrease for pressure heads between h_2 and h_3 .

2.2.3. Initial and Boundary Conditions

The initial conditions were defined in water contents. The soil profile was subjected to rainfall and evaporation. Therefore, the upper boundary conditions were defined as the atmosphere boundary condition (BC) with runoff and lower boundary condition was opted as variable pressure head. The measured and recorded values of E_p , T_p , and rainfall fluxes were used to represent atmospheric boundary conditions.

2.3. Model Evaluation

To evaluate the model performance, the agreement between observed and modeled data was assessed through the statistical procedure. The coefficient of determination R^2 , modeling efficiency (EF) and root mean square error (RMSE) were used for this purpose, which are given as [28].

Coefficient of determination

$$R^2 = \left\{ \frac{\sum_{i=1}^n (O_i - \bar{O})(P_i - \bar{P})}{\left[\sum_{i=1}^n (O_i - \bar{O})^2 \right]^{0.5} \left[\sum_{i=1}^n (P_i - \bar{P})^2 \right]^{0.5}} \right\}^2 \tag{9}$$

Modeling efficiency

$$EF = 1 - \frac{\sum_{i=1}^n (O_i - P_i)^2}{\sum_{i=1}^n (O_i - \bar{O})^2} \tag{10}$$

Root Mean Square Error

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (O_i - P_i)^2}{n}} \tag{11}$$

where P_i are predicted values; \bar{P} is mean of predicted values; O are observed values; and \bar{O} is mean of observed values. The optimum value of R^2 and EF is 1 while for $RMSE$ it is 0.

2.4. Model Calibration and Validation

Data sets of the first and second seasons were used to calibrate and validate the model, respectively. HYDRUS-1D requires soil hydraulic parameters as input. The required parameters were determined through ROSETTA computer program [29] using field soil data. The determined soil hydraulic parameters θ_s , θ_r , α , n , and K_s were further calibrated using observed soil water contents of the first season. Observed and simulated soil water content were found in good agreement. The calibrated parameters were then used to simulate soil water contents of the second season, for model validation.

The model was tested by comparing observed water content values with HYDRUS-1D simulated values using statistical indicators including the determination coefficient (R^2), modelling efficiency (EF) and the root mean square error $RMSE$ for both seasons as shown in Table 4. The average values of the goodness of fit indicators: R^2 , EF , and $RMSE$ for depths of 20, 40, 60, and 80 cm were 0.72, 0.68, and 0.017, and 0.86, 0.73, and 0.014 for the first and second seasons, respectively. The goodness of fit indicators was within the range of values reported by different researchers [22,30–34]. The statistical analysis shows that HYDRUS-1D captured the change in water content at all depths except at 140 cm depth. The reason for that might be the no variation in simulated water content due to the shallow water table. Therefore, the relative change simulated water content w.r.t observed water content could not be predicted.

Table 4. Statistical analysis of the comparison between observed and simulated water contents.

Season	Depth (cm)	R^2	EF	RMSE (cm ³ cm ⁻³)
1	0–20	0.72	0.73	0.017
	20–40	0.72	0.63	0.021
	40–60	0.75	0.70	0.018
	60–80	0.67	0.65	0.012
	80–140	0.51	−8.24	0.014
2	0–20	0.84	0.70	0.013
	20–40	0.85	0.82	0.014
	40–60	0.94	0.72	0.017
	60–80	0.82	0.69	0.013
	80–140	0.36	−14.9	0.019

3. Results and Discussions

3.1. Evapotranspiration (ET)

Figure 5 presents the daily evapotranspiration data for the first and second season. The mean simulated evapotranspiration (ET_m) values for the first and second seasons were 4.1 mm and 3.7 mm,

respectively. The mean observed evapotranspiration (ET) values for the first and second seasons were 4.0 mm and 3.7 mm, respectively. The minimum and maximum evapotranspiration during the first season were recorded as 1.6 mm and 6.2 mm whereas for the second season the values were 1.3 mm and 5.9 mm, respectively. The evapotranspiration was low at early stages of crop due to less transpiration requirements by crop canopy, whereas it reached to the maximum between 40 and 60 days of crop plantation. The variation in the evapotranspiration (ET) values for peak days might be due to the difference in sunshine hours and duration of rainfall occurrence. The rainfall durations in the region are long, the cloudy sky also affects the evaporation. The evapotranspiration (ET) of total water use was recorded as 40.7% and 33.1% for first and second season, respectively, i.e., the rainfall amount was much higher than total plant water requirements for both seasons. The ratio of evaporation to evapotranspiration (E_a/ET_a) for crop during two seasons were recorded as 0.24 and 0.26 respectively. The computed values obtained are close to reported research works [16,35].

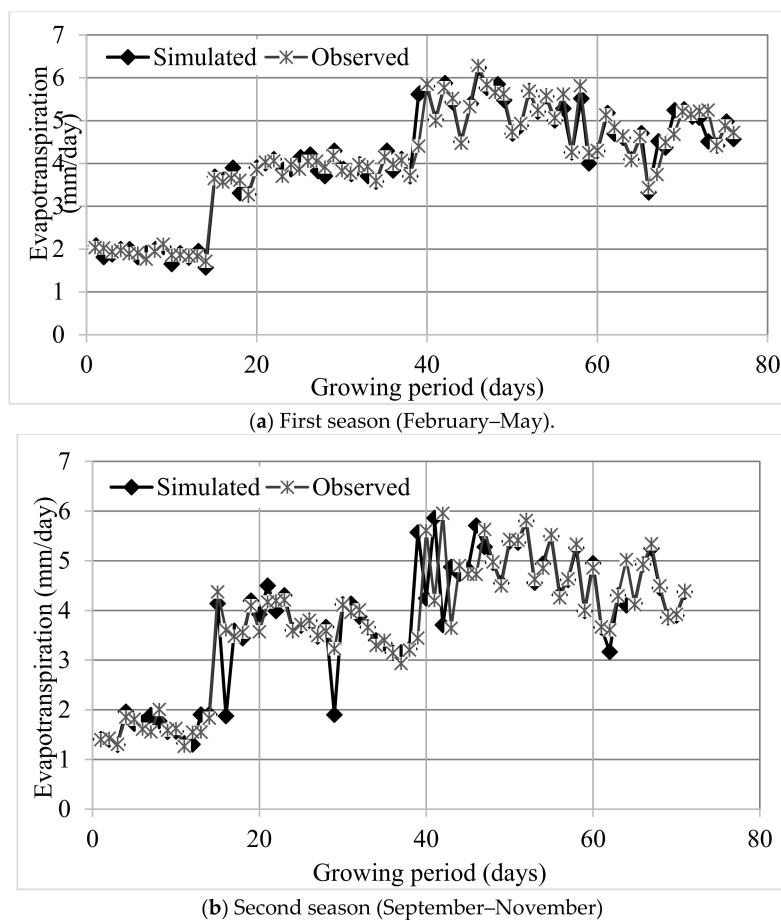


Figure 5. Simulated and observed daily crop evapotranspiration for sweet corn during two growing seasons.

3.2. Water Contents

The comparison between simulated and observed values of water contents in the soil profile within the root zone (0–60 cm) during two crop seasons shown in Figure 6. During the first and second season of field crop the simulated water content values at 60 cm depth ranged from 0.31 to 0.46 $\text{cm}^3 \text{cm}^{-3}$ and 0.31 to 0.49 $\text{cm}^3 \text{cm}^{-3}$ with average values of 0.41 and 0.43 $\text{cm}^3 \text{cm}^{-3}$ respectively. Whereas observed water content values for the first season and second season of field crop at 60 cm soil depth ranged from 0.32 to 0.45 $\text{cm}^3 \text{cm}^{-3}$ and 0.32 to 0.46 $\text{cm}^3 \text{cm}^{-3}$ with average values of 0.40 and 0.41 $\text{cm}^3 \text{cm}^{-3}$ respectively. The comparison between observed and simulated values of water contents in the soil profile below the root zone (60–140 cm) is illustrated in Figure 7. The values of water

contents at different depths increased with rainfall events and then decreased until the next event due to evapotranspiration (ET). This variation of water content was larger in shallower depths as compared to deeper [30]. Simulated water content results at 140 cm soil depth were found constant for both seasons due to shallow water table, i.e., soil remained at field capacity (FC) or near saturation for all growing season. Whereas, a small fluctuation in observed water contents was recorded for 140 cm depth. The average simulated value at 140 cm depth for both seasons was $0.42 \text{ cm}^3 \text{ cm}^{-3}$ whereas average observed values were $0.43 \text{ cm}^3 \text{ cm}^{-3}$ and $0.44 \text{ cm}^3 \text{ cm}^{-3}$ respectively. The simulated and observed water contents remained above the permanent wilting point (PWP, i.e., in the range of plant available water). The performance of HYDRUS-1D in predicting water content was found satisfactory.

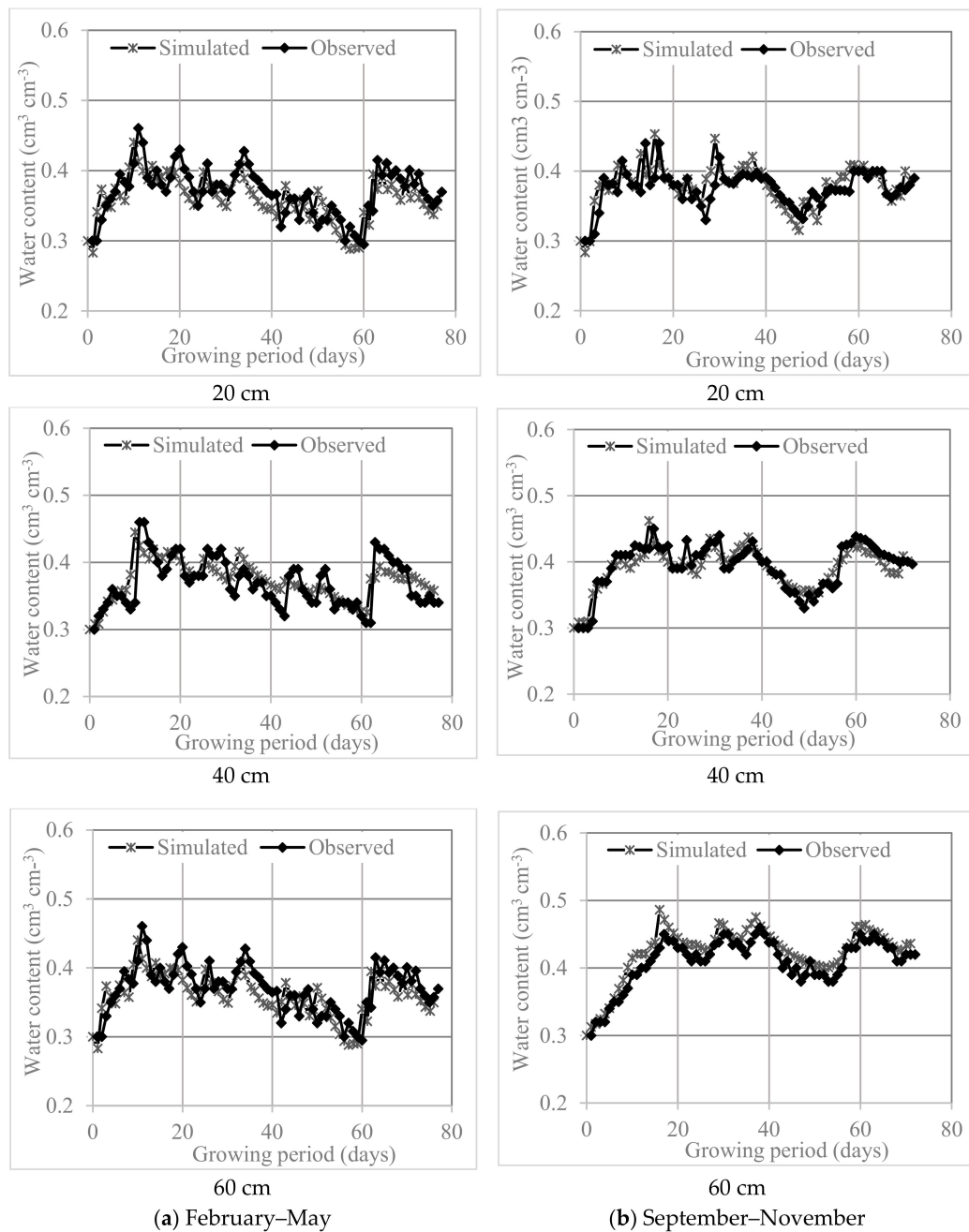


Figure 6. Simulated and observed soil water contents within the root zone (0–60 cm) during the (a) first season and (b) second season.

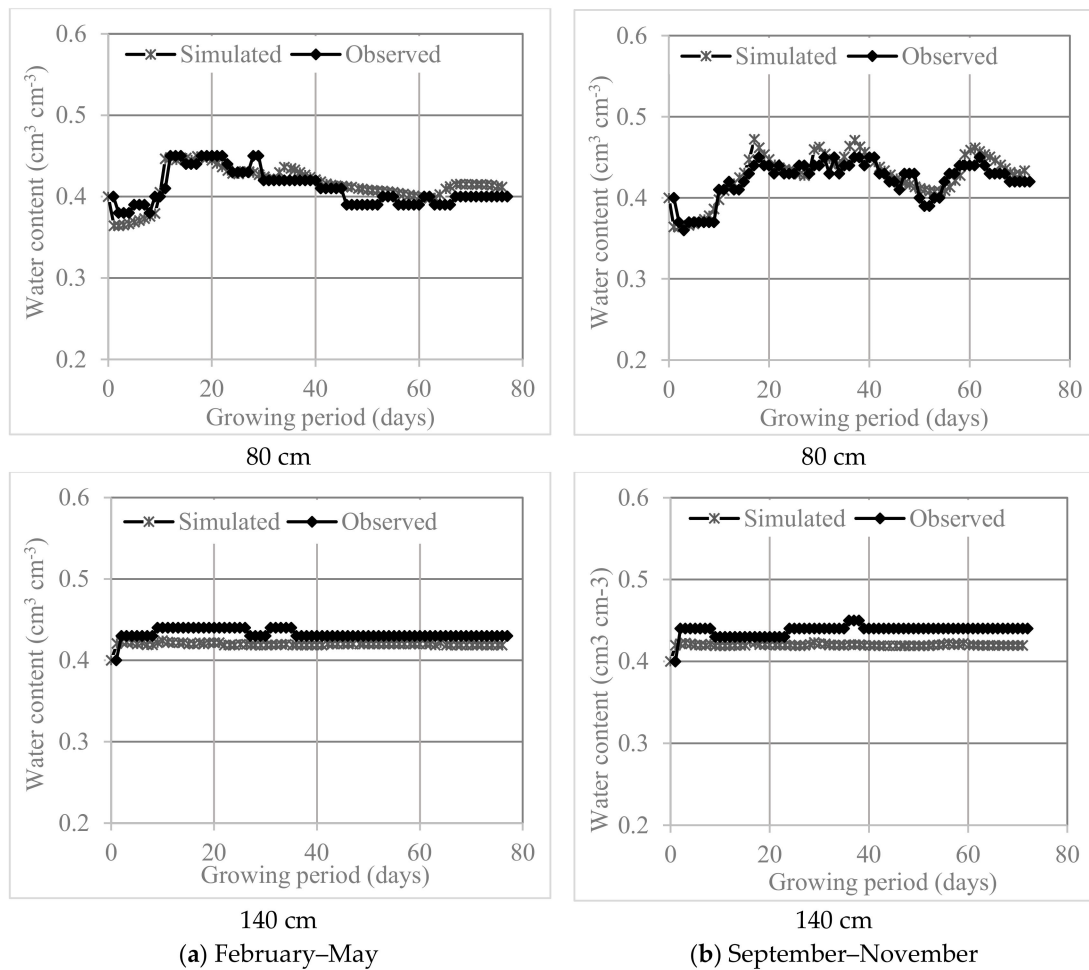


Figure 7. Simulated and observed soil water contents below the root zone (60–140 cm) during the (a) first season and (b) second season.

3.3. Surface Runoff

Figure 8 shows the comparison of simulated and observed values of surface runoff for two consecutive seasons. The results for cumulative simulated and observed values were found in good correspondence. However, the results differ for some of the individual rainfall events. The first few low-intensity rainfall events do not produce runoff in actual field conditions while HYDRUS-1D simulation shows runoff for those events for both seasons. The reason for deviation seems to be fine soil tilth at the time of crop plantations that enhance the water holding capacity of the soil. The maximum rainfall value during the first season was recorded as 11.3 cm on the 33rd day of the plantation, which produced peak simulated and observed runoff of 9.61 and 9.12 cm, respectively. Whereas the maximum rainfall value during the second season was recorded as 6.47 cm on the 29th day of the plantation, that produced peak simulated and observed runoff of 4.92 and 6.05 cm, respectively. The difference in the ratio of runoff to total rainfall varies from event to event due to soil antecedent moisture level, rainfall amount, and intensity. Surface runoff accounted for 41% and 28.6% of total water input for first and second season respectively. Effective runoff simulation also shows HYDRUS-1D ability to handle the upper boundary condition.

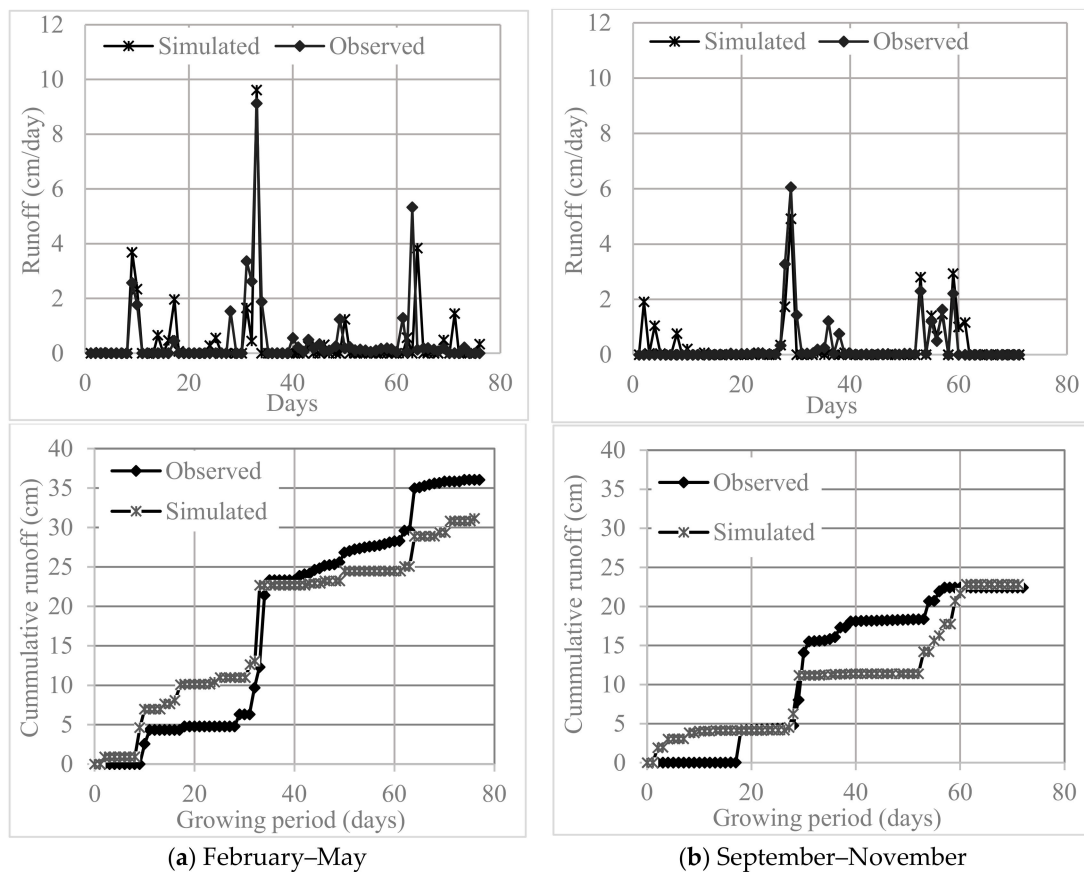
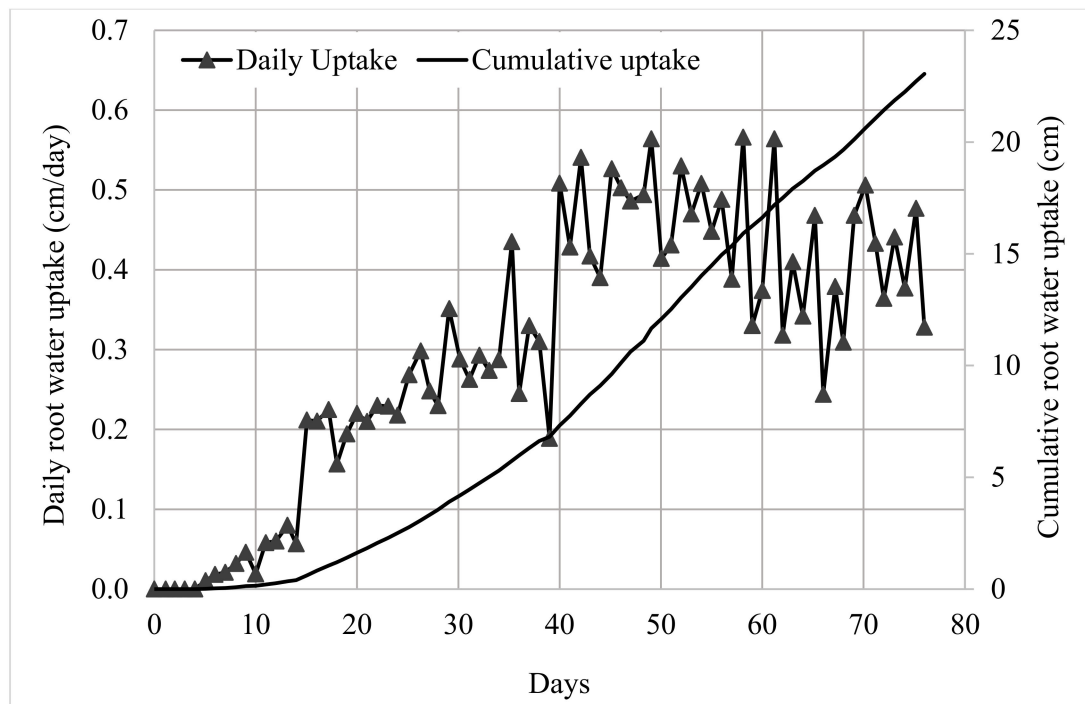


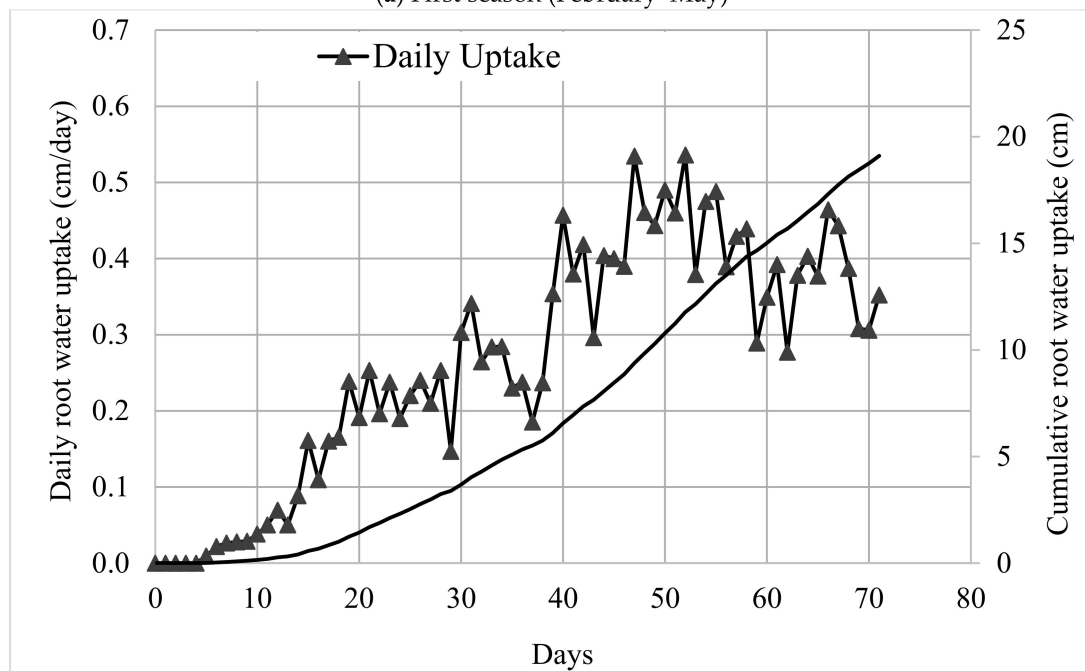
Figure 8. Simulated and observed surface runoff during two growing seasons.

3.4. Root Water Uptake

Figure 9 shows the simulated results for root water uptake (transpiration). Daily and cumulative root water uptake results for two consecutive seasons. Daily uptake mainly depends on the growth stage of the plant. It shows relatively lower values at the initial stage and maximum values at peak growth stages. For the time between sowing to emergence, the water uptake values were 0 for both seasons, while maximum values for the first and second season recorded on 58th and 52nd day after plantation were 0.56 cm/day and 0.54 cm/day, respectively. After the 60th day of the plantation, the root water uptake started to decline during crop ripening stage for both seasons. However, as the crop was harvested in fresh form and it was not left in the field (as in grain corn) the decline in uptake was less. The total amount of root water uptake recorded 30.3% of total water input during the first season and 24% in the second season. This shows the availability of water is enough to meet crop water requirements.



(a) First season (February–May)



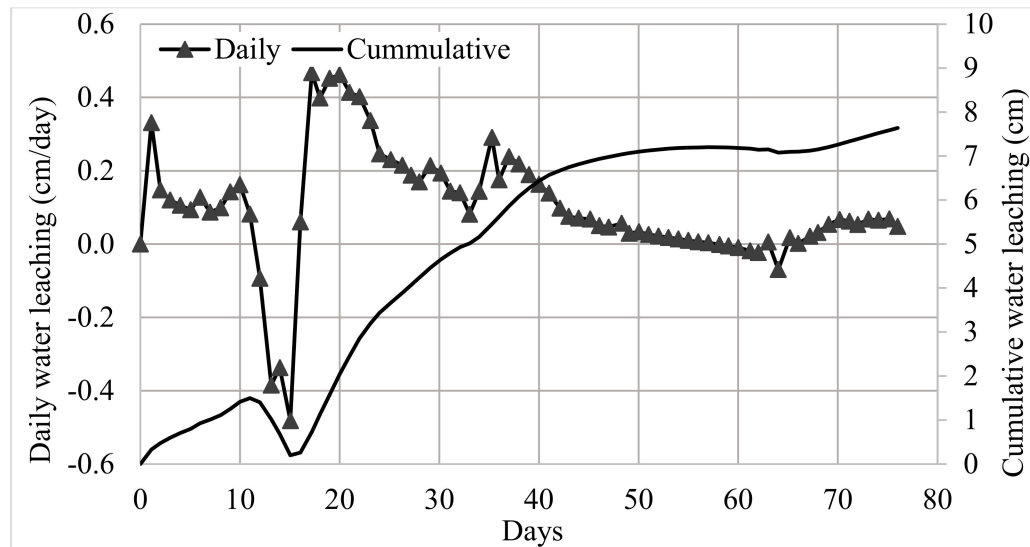
(b) Second season (September–November)

Figure 9. Simulated daily and cumulative root water uptake during two growing seasons.

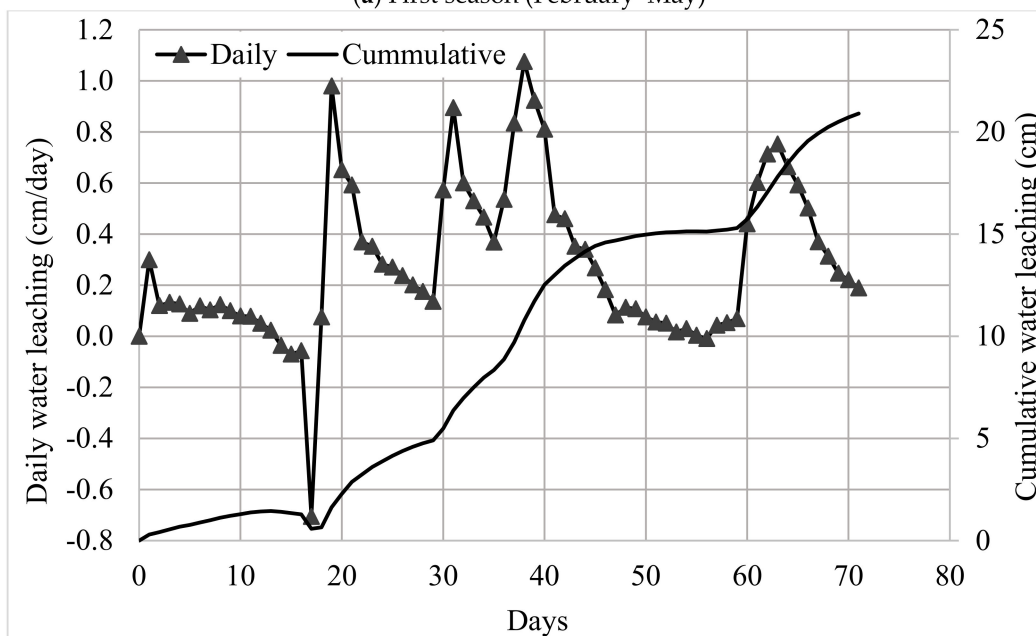
3.5. Water Leaching

Daily as well as cumulative water leaching results for both seasons presented in Figure 10. The total amount of water percolated in the first and second seasons was 7.64 cm and 20.9 cm, respectively. Water leaching accounts for 10.6%–26.8% of total water input during both seasons respectively. The daily leaching results show negative values during early days of the experiments, i.e., days 12–15 (first season) and days 14–17 (second season), which reflects groundwater contribution for the early days because of capillary rise due to the shallow water table. The difference in water leaching between the two seasons was quite significant. Relatively longer and frequent rainfall events in the second

season caused the high antecedent moisture level, and the high antecedent moisture level resulted in the increased water leaching. Some of the results of observed leaching losses through designed subsurface water collection systems were missing due to difficulty in setting up the system in the first season and leakage detection in the system in the second season. Therefore, they were not presented for comparison with simulated results. The reason that the concrete block was sealed from the bottom while the soil profile was exposed to the shallow water table in real field conditions, the difference in observed and simulated leaching was higher. The designed subsurface system can be an excellent tool to determine water leaching but needs calibration under low water table conditions to overcome the effect of capillary rise on water leaching.



(a) First season (February–May)



(b) Second season (September–November)

Figure 10. Simulated water leaching losses during two growing seasons.

3.6. Water Balance

Water balance components such as water input (WI), evapotranspiration (ET), surface runoff (RO), and leaching (L) were monitored through intensive field observations. Simulated and observed water balance components of the soil profile are presented in Table 5.

Table 5. Simulated and observed water balance components (cm) in the soil profile during two seasons of sweet corn in MARDI, Malaysia.

Season		WI	ET	RO	L	SS	Σ
First	Simulated	75.8	−30.88	−31.10	−07.64	3.70	2.48
	Observed		−30.84	−36.00			
Second	Simulated	79.7	−26.40	−22.80	−20.90	5.90	3.70
	Observed		−26.70	−22.40			

WI—total input water, ET—evapotranspiration, RO—surface runoff, L—water leaching, SS—soil storage, Σ water balance error.

The total water inputs during the two seasons were 75.8 cm and 79.7, respectively. Simulation results of evapotranspiration (ET) for the first and second season were 40.7% and 33.1% of total water input, which shows the rainfall amount was much higher than total plant water requirements for both seasons. Surface runoff accounted for 41% and 28.6% of total water input for the first and second season, respectively. Water leaching accounts for 10.6% to 26.8% of total water input during both seasons respectively. The total water balance error for both seasons was recorded as 2.48 cm and 3.70 cm, respectively, which accounted for 4.8% and 7.4% of the total water input. This shows the model's effectiveness in simulating the water balance components.

4. Conclusions

The HYDRUS-1D simulation model was used to evaluate water flow and water losses during two growing seasons of sweet corn in MARDI, Malaysia under the tropical rainfed conditions in the presence of a shallow groundwater table. HYDRUS-1D (despite considerable demand for input data) has proven to be a reliable tool to evaluate water movement in agricultural fields under various irrigation schemes and different crops [17,31,32]. Similarly, HYDRUS-1D was found useful in evaluating water fluxes and to evaluate the HYDRUS-1D model for the rainfall potential to meet the water requirement of sweet corn in the tropical region. The sprinkler system was set up to deal with water-stressed conditions. As rainfall fulfilled the crop water requirement throughout the growing seasons no additional irrigation (sprinkler) was applied. The soil water content and crop uptake did not drop below the threshold level. The results suggest avoiding scheduled irrigation, which is the general practice in Malaysia. Excess irrigation triggers the runoff and leaching losses that result in fertilizer loss. However, the study was carried out in the presence of shallow water table that also contributes to soil water through the capillary rise. Therefore, it is recommended to repeat the research with deep water table scenario to establish the findings for the tropical region.

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