water

MDPI

Article

Modeling of Soil Water Regime and Water Balance in a Transplanted Rice Field Experiment with Reduced Irrigation

Yong Li [1,2,*], Jirka Šimůnek [3], Shuang Wang [2], Jiahui Yuan [2] and Weiwei Zhang [2]

1. Ministry of Education Key Laboratory of Integrated Regulation and Resource Development on Shallow Lakes, Hohai University, Nanjing 210098, China
2. College of Environment, Hohai University, Nanjing 210098, China; sswwhhu@163.com (S.W.); riverbasin@163.com (J.Y.); zwwhhu@163.com (W.Z.)
3. Department of Environmental Sciences, University of California Riverside, Riverside, CA 92521, USA; jsimunek@ucr.edu

* Correspondence: liyonghh@hhu.edu.cn; Tel.: +86-25-83787145

Academic Editor: Tim Hess
Received: 26 February 2017; Accepted: 28 March 2017; Published: 1 April 2017

Abstract: Available water resources for agricultural irrigation have decreased worldwide in recent decades, prompting advances in water saving methods. In this study, soil water regime and water balance in a transplanted rice field with reduced irrigation (multiple shallow depth irrigations) in the Taihu Lake Basin of East China were observed and then evaluated using Hydrus-1D model during two consecutive growing seasons. During the 2008 season, irrigation water accounted for 48% of the total water input (TWI, 94.6 cm), but only 20% of TWI (120.4 cm) during the 2009 season. Due to heavy rainfalls during the wet 2009 season, surface runoff accounted for about 6.4% of the TWI, whereas during the much drier 2008 season with higher controlled irrigation inputs, no surface runoff occurred. Simulated evapotranspiration during the 2008 and 2009 seasons accounted for 67.4% and 54.9% of TWIs, respectively. Measured and simulated results indicate that water percolation (approximately 32.5% and 37.6% of TWIs during the 2008 and 2009 seasons, respectively) was the main path of water losses from the transplanted rice fields, suggesting that long and high standing water during the 2009 season increased water percolation. Water productivities evaluated from total irrigations and TWIs were 2.08 and 0.99 kg·m^{-3} during the 2008 season and 3.85 and 0.77 kg·m^{-3} during the 2009 season, respectively, and were 1.47 and 1.40 kg·m^{-3}, respectively, when evaluated from modeled evapotranspiration fluxes. The cultivation method with multiple shallow depth irrigation efficiently used rainfall water and reduced the losses due to water percolation and surface runoff by stabilizing rice yields.

Keywords: soil water regime; water productivity; multiple-shallow irrigation; transplanted rice; Hydrus-1D model; Taihu Lake Basin

1. Introduction

The traditional transplanting method for rice cultivation worldwide has ensured a stable rice yield during the long history of humankind [1,2]. Although several new cultivation methods (e.g., direct-seeded and seedling-thrown) have been developed in recent years to adapt to different climates or to save labor [1,3], cultivation of transplanted rice (TPR) remains popular in many regions. However, in most regions, the traditional TPR cultivation still involves continuous flood irrigation (e.g., with a water depth of 5–10 cm), which has drawn attention due to the excessive associated losses of water and nutrients [4,5]. Increasingly scarce water resources for agricultural irrigation and deteriorating water environments necessitate improvements and optimization of water and fertilizer managements for TPR [6–9].

Therefore, various water-saving irrigation strategies have been developed in different rice growing regions to maintain acceptable rice yields [10,11]. For example, a combination of a shallow water depth with wetting and drying [12,13], alternate wetting and drying [14,15], semi-drying [16], aerobic rice cropping [10,17], partial rootzone drying [18], moistening, and non-flooded mulching [19] cultivations are popular techniques that have been adopted around the world. Among these, the alternate wetting and drying (AWD, also referred to as "alternately submerged-nonsubmerged" or "intermittent irrigation") irrigation techniques have been frequently reported for different climates and different local water resource conditions in recent years [5,6,20]. Ye et al. [15] reported that AWD irrigation during the TPR paddy field experiments in the Taihu Lake Basin (China) required less frequent irrigations (reduced by five and three in 2010 and 2011, respectively) and reduced the amount of irrigation water used (saved 41.9% and 28.0% in 2010 and 2011, respectively). AWD irrigation techniques not only save water resources, but also increase rice yields compared to traditional flood irrigation [6,8,13]. However, Bouman and Tuong [20] reported that although alternately submerged-nonsubmerged conditions reduced water inputs, yields usually declined when the soil water potential in the root zone dropped below −10 to −30 kPa.

Compared to the traditional rice cultivation with flood irrigation, AWD provides a different growth environment, particularly different vertical soil water content profiles and corresponding nutrient transport and transformations [2,21]. Tan et al. [5] reported that AWD irrigation during the 2007 and 2008 growing seasons produced a decrease in percolation by 27.8% and 19.0% and in nitrogen leaching by 5.0%–11.2% and 3.0%–23.5%, respectively, compared to continuous flood irrigation. The AWD cultivation produces less water percolation due to lower vertical pressure head gradients during most of the growing season [20]. Due to complex soil water flow conditions in rice fields under water-saving irrigation conditions, many scientists increasingly use computer models to study water movement and water balance in the soil and to develop management and planning guidance [22–24]. The Hydrus-1D model [25] has been used by many researchers to simulate water flow in agricultural fields with different crops and various irrigation schemes, including in TPR fields [5,6,23]. However, the use of Hydrus-1D for simulating water flow conditions and water balance in TPR fields under water-saving irrigation has been limited.

In the Taihu Lake Basin of East China, various water-saving irrigation methods for transplanted rice have been increasingly adopted to decrease the loss of water and associated nutrients and to better protect surface and groundwater environments [7,21,26]. Multiple-shallow irrigation (MSI) is a type of the AWD irrigation method that irrigates rice fields multiple times at shallow depths (e.g., 1–3 cm), depending on soil conditions and weather predictions.

In this study, to exploit rainfall and decrease water losses, the MSI cultivation method was used in TPR field experiments in the Taihu Lake Basin during two consecutive rice-growing seasons (2008–2009). Water flow in the TPR field under MSI conditions was observed and then evaluated using Hydrus-1D to improve our understanding of the main characteristics of the soil water regime and the overall water balance. The water balance, water percolation, and crop water productivities in the MSI TPR field, during the two seasons (2008–2009) with significantly different rainfall distributions, are discussed and compared in this study. Furthermore, the soil water regimes and water balances in the MSI TPR field are compared with the direct-seeded rice management approach in the same field (in different sub-plots) during the two consecutive seasons.

2. Materials and Methods

2.1. Field Experimental Data

2.1.1. Study Site Description

The Taihu Lake Basin of East China has a very intensive production of rice crops, regularly rotating with either wheat or rape. The basin area is approximately 36,900 km^2, with rice fields accounting for about 34.8%. This region has a subtropical monsoon climate with average annual rainfall of 1181 mm, 60% of which occurs from May through September. The annual pan evaporation from the water surface is approximately 822 mm, and the average annual air temperature is 15–17 °C. Our experimental site is in the Dangyang region (31°56′ N, 119°43′ E), upstream of the Taihu Lake (the third largest fresh water lake in China). Different cultivations of rice are currently grown in this region, including transplanted rice, direct-seeded rice, and seedling-thrown rice. The dominant soil type in this region is classified as a hydromorphic paddy soil, and the parent material is a lacustrine deposit. The physical properties of the soil at the study site are listed in Table 1.

Table 1. Physical properties and calibrated van Genuchten hydraulic parameters of the tested paddy soil in the Taihu Lake Basin.

Depth (cm)	Soil Particle Size Distribution (%)			Bulk Density ($g \cdot cm^{-3}$)	θ_r ($cm^3 \cdot cm^{-3}$)	θ_S ($cm^3 \cdot cm^{-3}$)	α (cm)	n	K_s ($cm \cdot Day^{-1}$)
	Sand (>0.05 mm)	Silt (0.002–0.05 mm)	Clay (<0.002 mm)						
0–20	7.01	73.70	19.29	1.42	0.125	0.510	0.0092	1.420	0.758
20–40	0.02	81.01	18.97	1.56	0.073	0.441	0.0130	1.100	0.533
40–60	18.53	72.83	8.64	1.51	0.075	0.489	0.0040	1.853	0.724
60–80	14.44	81.64	3.91	1.43	0.046	0.500	0.0051	1.326	1.159
80–100	14.25	81.59	4.16	1.43	0.081	0.521	0.0021	1.811	0.702
100–120	11.32	80.30	8.38	1.43	0.052	0.512	0.0039	1.436	0.714

2.1.2. Experimental Design

Only the experimental design for the MSI TPR field is described here. Three 150 m^2 sub-plots were selected to plant *Wuxiangjing* 14 (lowland rice), a variety predominantly cultivated in this region. The rice seeds were soaked in a 100 $mg \cdot kg^{-1}$ uniconazole solution prior to their sowing in a seedling bed. The paddy field (with about a 5-cm water depth) was prepared by machine on 19 June 2008 and 14 June 2009, respectively, and basal fertilizer was evenly applied by hand. The mean age of the rice seedlings at transplanting was approximately 1 month. Rice seedlings were mechanically transplanted at a rate of about four seedlings per hill two days after the basal fertilizer application (i.e., 21 June 2008 and 16 June 2009, respectively). The harvest dates were 25 October 2008 and 20 October 2009, therefore the total growing periods for TPR during these two seasons were each 128 days. The direct-seeded rice (*Wuxiangjing* 14) was directly sowed on 8 June in 2008 and 11 June in 2009, respectively, and harvested on 1 November in 2008 (a growing season of 147 days) and 5 November in 2009 (a growing season of 149 days), respectively [27].

Water-saving irrigation implemented in the TPR experiment involved multiple irrigations at a shallow water depth (multiple-shallow irrigation, MSI) in order to minimize losses of water and associated nutrients. During the first 10 days after transplanting, a shallow water depth (0–5 cm) was maintained to facilitate seedling recovery and greening. When a deeper water depth (>6 cm) developed due to precipitation, it was partially drained to protect seedlings. After this stage, each regular irrigation depth was generally controlled at about 2–3 cm of water, but at about 4–5 cm of water when fertilizer and/or pesticide were applied. In addition, the rainfall forecast was considered in the water management. When rainfall supplied water for the crop, irrigation was reduced or even eliminated [11]. For example, when rain was predicted for the next day, no irrigation was applied, even if the irrigation demand was reached. When rain was predicted after two days, an irrigation depth of about 2 cm was applied. If no rainfall was predicted, an irrigation depth of 3 cm was applied. The soil drying stages in the 2008 and 2009 seasons were between 23 and 27 July and between 16 and 20 July, respectively. Additionally, all floodwater was drained from the field about 2 weeks before harvest.

Rainfall and irrigation were significantly different during the 2008 and 2009 seasons (Figure 1). During the 2008 season, total rainfall was 49.6 cm and total irrigation was 45.0 cm (15 irrigations). During the 2009 season, total rainfall and irrigation were 96.4 and 24.0 cm (only seven irrigations), respectively. The irrigation water depths under MSI conditions in the TPR fields were substantially lower than those in the direct-seeded rice (DSR) fields (72 and 46 cm during the 2008 and 2009 seasons, respectively; each irrigation was about 5–6 cm). The fertilizer management in the MSI TPR field, including the total application rate and application times, was the same (220 kg·ha^{-1}) during the two seasons. The total application rates were the same and application times were different compared with the DSR fields (for details for DSR fields refer to [27]).

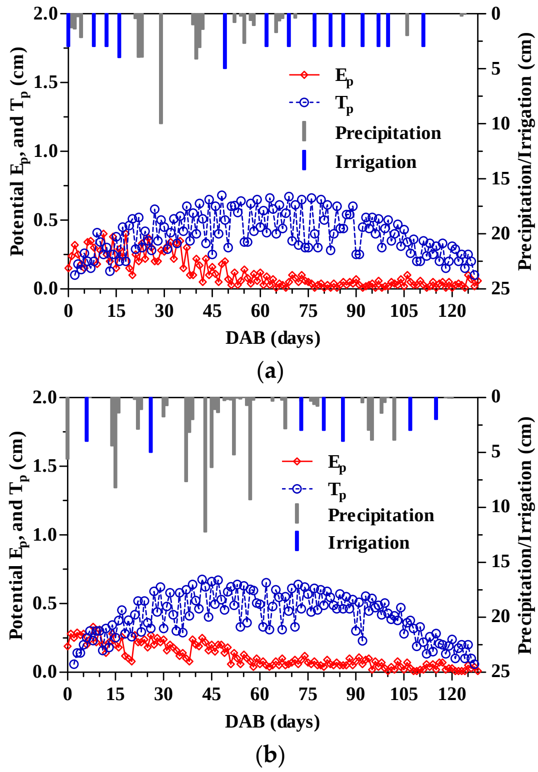


Figure 1. Potential evaporation, E_P, potential transpiration, T_P, precipitation and irrigation during the (**a**) 2008 and (**b**) 2009 seasons in the Taihu Lake Basin (DAB—days after basal fertilization).

2.1.3. Measurements and Analysis

Daily climate data were obtained from an adjacent agro-meteorological station in the Dangyang region. Irrigation water was measured by using flow meters at inlets, and the flooding water depth was recorded every two days at five random points in each sub-plot. Self-made flux lysimeters were installed at a depth of 60 cm below the soil surface to measure vertical water fluxes every two weeks. Piezoelectric tube tensiometers (0–100.00 kPa) were installed at five observation points in the field to measure pressure heads, which were installed at depths of 20, 40, and 60 cm below the soil surface, respectively. The pressure heads were recorded every two days. The groundwater table was observed once a week at an observation point near the experimental field, which slightly fluctuated but remained around a depth of 120 cm below the soil surface [27].

Three measures of water productivity (*WP*, kg of grain per m^3 of water): the irrigation water productivity (WP_I), which is the ratio of grain yield to the amount of irrigation water; the input water productivity (WP_{IR}), which is the ratio of grain yield to the amount of irrigation water plus rainfall; and the *ET* water productivity (WP_{ET}), which is the ratio of grain yield to crop *ET*, were calculated to compare the water use efficiencies [28–30].

2.2. *Hydrus-1D Model*

The one-dimensional Hydrus-1D software [25] was used to simulate water movement in the experimental field. Detailed descriptions of the model can be found in Šimůnek et al. [25] and Li et al. [27]. The van Genuchten soil hydraulic parameters (Table 1), θ_r, θ_S, α, and n, were directly adopted from Li et al. [27]. The pore connectivity parameter (l) was assumed equal to an average value of 0.5 [31].

The Penman–Monteith equation was used for calculating the reference crop evapotranspiration (ET_0) from available climatic, crop, and soil parameters [32,33]. The reference evapotranspiration, ET_0, and the crop coefficient, K_C, were used to determine the potential crop evapotranspiration ET_C under normal conditions as [32,34]:

$$ET_C = ET_0 \times K_C, \tag{1}$$

For the crop, which only partly covered the soil surface, ET_P was divided into potential evaporation, E_P, and potential transpiration, T_P. This partitioning was achieved using the crop leaf area index (LAI) as given by Belmans et al. [35], which is a function of the crop development stage:

$$E_P = ET_C \times e^{-K_{gr} \times LAI}, \tag{2}$$

$$T_P = ET_C - E_P, \tag{3}$$

here K_{gr} is an extinction coefficient for global solar radiation; its value was taken as 0.3 for the rice crop [29]. Values of LAI of the MSI transplanted rice at various growth stages during two seasons were measured (Table 2), and estimated values of potential evaporation (E_P) and potential transpiration (T_P) (Figure 1) were then used as input variables in the Hydrus-1D simulations.

Table 2. Leaf Area Index (LAI) of transplanted rice at various growth stages during the 2008 and 2009 seasons (DAB—days after the basal fertilizer application).

Season	DAB				
	2	30	60	90	128
2008	3.1 ± 0.5	4.4 ± 1.1	6.3 ± 1.3	7.3 ± 1.7	4.9 ± 1.1
2009	3.0 ± 0.6	4.6 ± 1.0	6.4 ± 1.1	7.3 ± 1.9	4.8 ± 0.9

The initial conditions were defined using the measured pressure head distributions. The soil surface was subjected to the atmosphere boundary condition (BC) with specified daily values of precipitation, irrigation, and evaporation. During the soil drying stage and the last 2 weeks before the harvest, the upper boundary condition was set equal to an "Atmospheric BC with Surface Runoff". During the rest of the season, the upper boundary condition was set equal to an "Atmospheric BC with a Surface Layer", with maximum water depths of 6 cm during the first 10 days after transplanting and 10 cm during remaining growth stages, respectively. Potential values of E_P, T_P, irrigation, and rainfall were used to represent the atmospheric boundary condition. The bottom boundary was set to a time-variable pressure head based on observed groundwater table data.

2.3. Model Evaluation

Simulated values of the pressure heads and percolation water fluxes were compared with the observed data from the experimental paddy field during the 2008 and 2009 seasons. The correspondence between simulated and observed data was evaluated using the coefficient of determination (R^2) and the root mean square error ($RMSE$), calculated as:

$$R^2 = 1 - \frac{SS_{err}}{SS_{tot}}, \tag{4}$$

$$RMSE = [\frac{1}{n}\sum_{1}^{n}(S_i - M_i)^2]^{\frac{1}{2}}, \tag{5}$$

where SS_{err} is the sum of squared differences between simulated and observed values, SS_{tot} is the sum of squared differences between observed values and the mean of observed values, S_i and M_i are simulated and measured values, respectively, and n is the number of compared values. An R^2 value of 1.0 indicates a "perfect" fit to the observed data, whereas an optimal value of $RMSE$ is 0.

3. Results

3.1. Model Assessment

Simulated pressure heads at depths of 20, 40, and 60 cm matched well with observed data during the 2008 (n = 164, R^2 = 0.97, $RMSE$ = 4.25 cm) and 2009 (n = 154, R^2 = 0.97, $RMSE$ = 3.88 cm) seasons, and responded well to the water input events (i.e., rainfall and irrigation) (Figure 2). In contrast to the 2008 season (Figure 2a), due to frequent and continuous rainfall, most pressure heads at 20 cm remained positive during the first half of the 2009 season (Figure 2b). During the late 2008 and 2009 seasons, multiple-shallow irrigations produced more variations between wetting and drying conditions in the soil. Pressure heads at 20 cm reached minimum values of −130.0 cm and −112.0 cm during the soil drying stages of the 2008 and 2009 seasons, respectively. Pressure heads at 60 cm during the two seasons were mostly between 0 and −63.0 cm, and their peaks lagged about 1–2 days behind those at 20 cm.

Simulated total percolation flux at 60 cm before the soil drying stage in the 2008 season was 14.6 cm, which agreed well with the observed value of 15.2 cm. For the entire growing season of 2008, simulated total percolation at 60 cm was 29.7 cm, and the observed value was 31.8 cm. By comparison, during the entire 2009 season, the simulated and observed cumulative water fluxes at 60 cm were 44.4 cm and 46.1 cm, respectively. The correspondence between observed and simulated percolation fluxes both early on and throughout the growing periods was good.

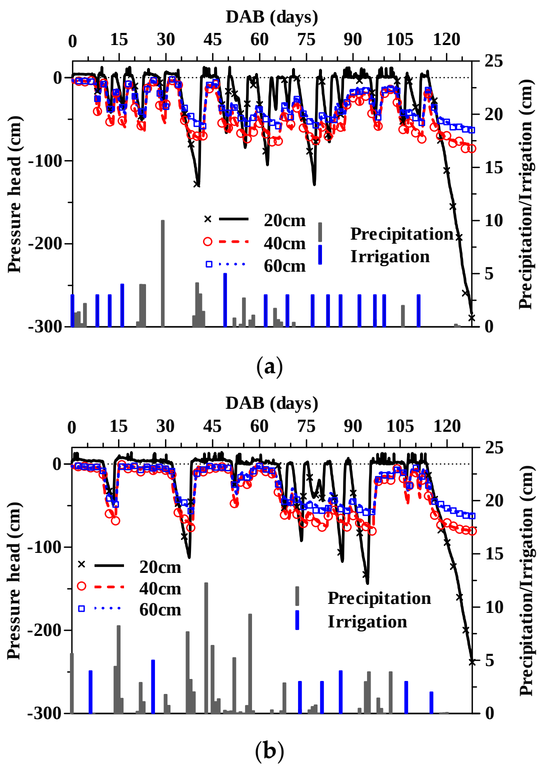


Figure 2. Simulated (lines) and observed (points) pressure heads at 20, 40, and 60 cm depths, and precipitation and irrigation water depths (vertical lines) during the (**a**) 2008 and (**b**) 2009 seasons. Positive pressure heads were not observed by tensiometers.

3.2. Flooding Water Depths and Surface Runoff

Rainfall, irrigation, and runoff caused the surface water to suddenly rise and fall in paddy fields. Daily field water levels showed more frequent fluctuations in the 2008 season than in the 2009 season (Figure 3). Changes in the surface water depth between observed and simulated values were closely matched during the 2008 (n = 34, R^2 = 0.96, $RMSE$ = 0.9 cm) and 2009 (n = 38, R^2 = 0.95, $RMSE$ = 1.1 cm) seasons. The maximum standing water depth (8.1 cm) during the 2008 season appeared on 30 DAB (days after the basal fertilizer application), when a heavy rainfall (10.1 cm) occurred. During the 2008 season, surface water depth was always below the maximum controlled depth because the water input was mainly determined by shallow irrigations (Figure 3a). During the 2009 season, several heavy rainfall events resulted in the water depths exceeding or approaching 10 cm (Figure 3b), which was specified as a maximum water depth in the simulation.

During the 2008 season, no surface runoff was observed in the field. Due to a few heavy rainfall events during the 2009 season, some water was lost from the fields as surface runoff during two main surface runoff events on 43 and 45 DAB. Simulated and observed total surface runoffs during the 2009 season were 7.7 and 6.5 cm, respectively.

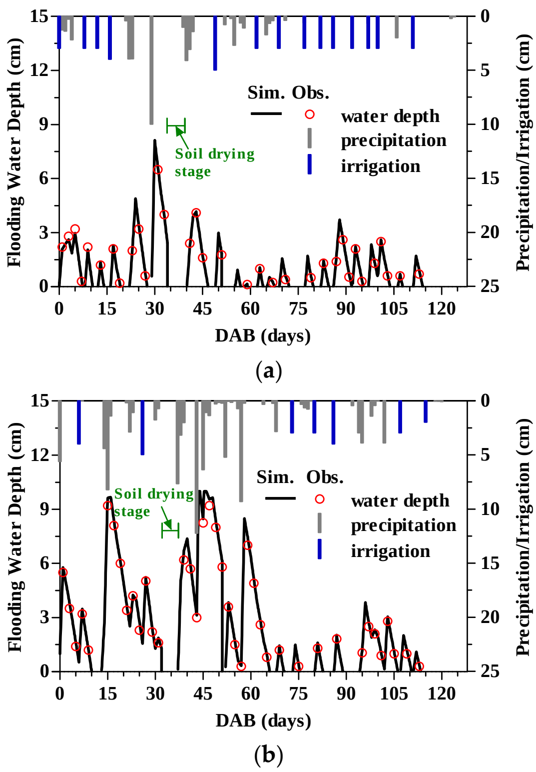


Figure 3. Observed (points) and simulated (lines) flooding water depths during the 2008 (**a**) and 2009 (**b**) seasons.

3.3. EvapoTranspiration

Reflecting general crop growth, simulated root water uptake during the 2008 and 2009 seasons gradually increased after transplanting and reached maximum values between 30 and 60 DAB (Figure 4). The maximum daily rate of root water uptake was approximately 0.7 cm·day^{-1} on around 45 DAB. During the later stages of crop growth, daily root water uptake gradually declined. Cumulative root water uptake slowly increased during the initial 30 days, then quickly increased and ultimately reached 49.8 and 51.6 cm over the entire growing seasons of 2008 and 2009, respectively. Simulated cumulative evaporations in the MSI TPR field were 14.0 and 14.5 cm during the 2008 and 2009 seasons, respectively. The total *ET* amounts in MSI TPR field throughout the 2008 and 2009 seasons were 63.8 cm (an average of 0.50 cm·day^{-1}) and 66.1 cm (an average of 0.52 cm·day^{-1}), respectively.

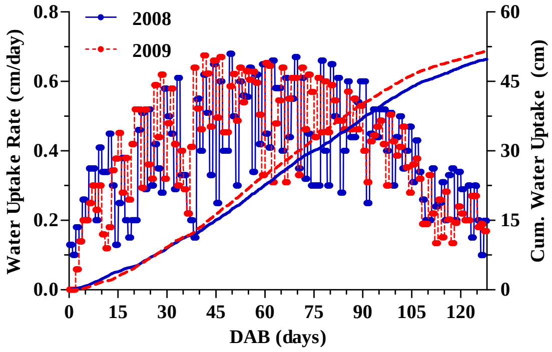
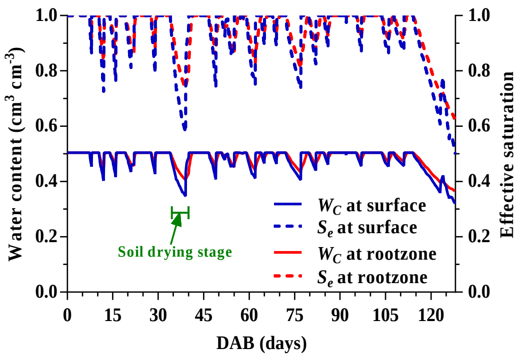


Figure 4. Simulated actual daily water uptake rate and cumulative root water uptake during the 2008 and 2009 seasons.

3.4. Soil Water Content Changes

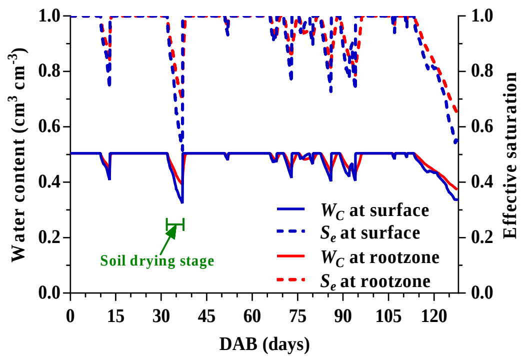
Simulated soil water contents and water saturations (Figure 5) at the soil surface and in the root zone had similar distributions as the pressure heads and responded well to rainfall and irrigation events. Surface soil water contents varied quickly between 0.318–0.505 cm^3·cm^{-3} (average 0.479 cm^3·cm^{-3}) and 0.325–0.505 cm^3·cm^{-3} (average 0.484 cm^3·cm^{-3}) during the 2008 and 2009 seasons, respectively, compared to smaller and more gradual changes at deeper depths. As the depth increased, variations in soil water contents gradually decreased, but were still apparently influenced by the rainfall and irrigation events (Figure 1). Contrary to the 2008 season, during most days of the 2009 season, the soil water content at the soil surface and in the root zone remained mostly close to saturation due to frequent precipitation events. Several small rainfalls (e.g., <1 cm) had only a slight effect on water contents in the root zone, but a more substantial effect on the soil surface water content. Simulation results indicated that the soil water storage in the upper 60 cm of the soil profile throughout the 2008 season decreased by 3.9 cm, whereas during the 2009 season, it decreased by about 4.2 cm; their observed differences were 4.1 and 4.5 cm, respectively.

During the 2008 and 2009 seasons, the effective saturation (S_e) [25] values at the surface ranged between 0.500 and 1.00 (an average of 0.929) and between 0.517 and 1.00 (an average of 0.943), respectively (Figure 5). In the root zone, these values ranged during the 2008 and 2009 seasons between 0.621 and 1.00 (an average of 0.943) and between 0.642 and 1.00 (an average of 0.953), respectively. However, the soil at both 40 and 60 cm depths remained unsaturated throughout both growing seasons (Figure 2), even when the surface soil and the soil at 20 cm were saturated.



(**a**)

Figure 5. *Cont.*

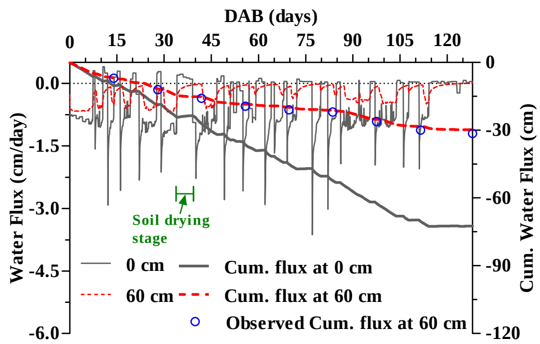


(**b**)

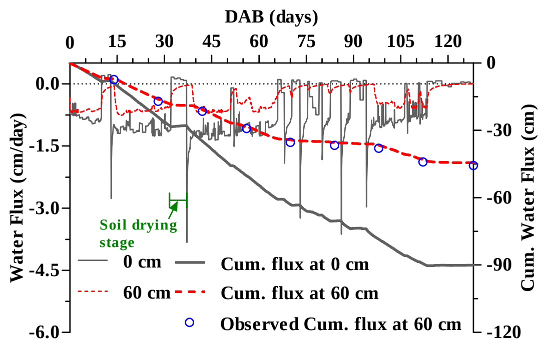
Figure 5. Simulated water contents (W_C) and effective saturation (S_e) at the soil surface and in the root zone during the 2008 (**a**) and 2009 (**b**) seasons.

3.5. Water Percolation

Downward water percolation (Figure 6) closely corresponded with precipitation and irrigation events (Figure 1). Intensive rainfalls during the early 2009 season (before 65 DAB) resulted in relatively continuous high percolation rates (average 0.51 cm·day^{-1}) at a depth of 60 cm. During the entire 2009 season, the average percolation rate was about 0.34 cm·day^{-1} (varying between 0.01 and 0.76 cm·day^{-1}), which was substantially higher than the corresponding value of 0.24 cm·day^{-1} (0.01–0.69 cm·day^{-1}) during the 2008 season. The cumulative water percolation fluxes at 60 cm in the MSI TPR field were 29.7 and 44.4 cm during the 2008 and 2009 seasons, respectively, which matched well with the observed values of 31.5 and 46.1 cm.



(**a**)



(**b**)

Figure 6. Observed (points) and simulated (lines) water fluxes at the soil surface and at a depth of 60 cm during the 2008 (**a**) and 2009 (**b**) seasons.

4. Discussion

Generally, rice is a typical water consuming crop. Water contents in the soil root zone are critical for the growth and yield of rice. In this study, the average grain yields of TPR under the MSI conditions in the 2008 and 2009 seasons were 9380 and 9250 kg·ha^{-1}, respectively, approaching the average value of about 9500 kg·ha^{-1} for TPR in this region [36,37]. They were markedly higher than those for DSR in the same field (8980 and 8530 kg·ha^{-1}) [27]. The DSR yield during the 2009 season was influenced by two typhoons, which resulted in significant DSR lodging. Contrary to DSR, TPR could better persist during the bad weather due to relatively deeper root systems and stronger straw [37,38]. Maqsood et al. [39] reported for Faisalabad (Pakistan) that transplanted rice had 19.18% higher yield than DSR. In the MSI TPR field, pressure heads in the root zone were higher than −100 cm during most days of the two seasons, which also agrees well with the water stress thresholds for a high and stable rice yield [20].

The total water inputs (TWIs) in the MSI TPR field during the 2008 and 2009 seasons were 94.6 and 120.4 cm, respectively (Table 3). Irrigation water in the MSI TPR field was substantially lower compared to those in the DSR fields (72.0 and 46.0 cm during the 2008 and 2009 seasons, respectively) [27]. Liang et al. [12] reported that a similar irrigation method ("thin-shallow-wet-dry") used in South China, at the middle nitrogen level, led to a decrease in the total water consumption by 21.7%–23.5% and an increase in the rice water use efficiency by 17.8%–27.2%.

Surface runoffs (Table 3) from the MSI TPR field are substantially lower than those (5.8 and 24.4 cm during the 2008 and 2009 seasons, respectively) from the DSR field [27], where most surface runoff was lost during the germination period (the first 2 weeks). This indicates that different water managements between multiple-shallow irrigated TPR and regular irrigated DSR fields led to different surface runoff volumes. Ye et al. [15] reported for this region that in 2010, surface runoff was 4.2 cm for continuous flood irrigation (CF) and 1.8 cm for AWD irrigation; surface runoff in 2011 was 8.0 cm for CF and 6.4 cm for AWD irrigation. In another TPR field experiment in this region, Zhao et al. [40] reported that by controlling most flooding water depths below 3–5 cm, surface runoff reached 47.0, 15.4, and 88.2 cm during the 2007, 2008, and 2009 seasons, respectively.

Table 3. Simulated (using Hydrus-1D) components of water balance (cm) in the upper 60 cm of the soil profile, and water productivities (*WP*) (kg·m^{-3}) for the transplanted rice crop in the Taihu Lake Basin.

Season	Input		Output				δ	Water Productivity		
	R	*I*	*SR*	*ET*	*SS*	*P*		WP_I	WP_{IR}	WP_{ET}
2008-TPR	49.6	45.0	0	−63.8	−3.9	−29.7	−2.8	2.08	0.99	1.47
2009-TPR	96.4	24.0	−7.7	−66.1	−4.2	−44.4	−2.0	3.85	0.77	1.40
2008-DSR	54.3	72.0	−5.8	−68.9	−1.2	−53.9	−3.5	1.25	0.71	1.30
2009-DSR	97.4	46.0	−24.4	−64.0	−2.3	−50.1	2.7	1.85	0.59	1.33

Note: *R*—rainfall, *I*—irrigation, *SR*—surface runoff, *ET*—evapotranspiration, *SS*—soil storage, *P*—percolation, δ—total water balance error, WP_I—the ratio of grain yield to the amount of irrigation water, WP_{IR}—the ratio of grain yield to the amount of irrigation water plus rainfall, WP_{ET}—the ratio of grain yield to crop *ET*.

Estimated evapotranspiration volumes in the MSI TPR field (Figure 4 and Table 3) are slightly lower than those (17.4 and 15.8 cm during the 2008 and 2009 seasons, respectively) in the DSR fields [27] due to relatively shorter growing periods. Studies have demonstrated that excessive irrigation with large depths of standing water in paddy fields would lead to high water losses by evaporation [13,41]. In this study, simulated *ET*s during the 2008 and 2009 seasons accounted for 67.4% and 54.9% of corresponding volumes of TWIs, respectively. Compared to the 2008 season, a slight increase in *ET* during the 2009 season did not produce a corresponding increase in the rice yield. Jia et al. [7] reported that average *ET* in the Taihu Lake Basin during the 2010 and 2011 TPR seasons was 44.1 cm (an average of 0.40 cm·day^{-1}) under controlled flooding water depth conditions, and it declined by about 22.6% compared to traditional continuous flooding irrigation (average 0.54 cm·day^{-1}). Jiang et al. [8] reported that, in an experimental field in Shanghai (China) during the 2012 season, *ET* from TPR fields with intermittent and moistening irrigation was 70.8 cm (an average of 0.52 cm·day^{-1}) and 73.9 cm (an average of 0.54 cm·day^{-1}), respectively, lower by 5.9% and 1.8%, respectively, than from traditionally flooded TPR fields.

Excessive water inputs with large depths of surface water lead to excessively high percolation [10,14]. Lian et al. [42] reported that water percolation rates in this region were between 0.49 and 0.56 cm·day^{-1} under the traditional flooding irrigation method. In this study, water percolation at a depth of 60 cm accounted for approximately 31.4% and 36.9% of TWIs, respectively; and the average water percolation rates from the MSI TPR field were 0.24 cm·day^{-1} during the 2008 season and 0.34 cm·day^{-1} during the 2009 season. In the DSR fields, the average water percolation rates were 0.37 cm·day^{-1} and 0.34 cm·day^{-1} during the 2008 and 2009 seasons, respectively [27]. These differences from the same paddy field indicated that the water management significantly affected water percolation by altering the duration of surface flooding and corresponding pressure head gradients and consequent water fluxes. Jiang et al. [8] reported that, compared to traditional flood irrigation, the intermittent and moistening irrigation techniques in the Shanghai (China) experimental TPR fields during the 2012 season resulted in a significant reduction of water percolation by 2.0% and 17.3%, respectively. Similar to the DSR field [27], downward percolation (Table 3) was the main component of water losses in the MSI TPR field. However, downward percolation and surface runoff in the MSI TPR field were significantly reduced as compared to the DSR field [27].

Usually, the water productivity can be used to evaluate the water use efficiency in a paddy field and compared with other conditions. The irrigation water productivity (WP_I) and water input water productivity (WP_{IR}) for TPR under MSI conditions were 2.08 and 0.99 kg·m^{-3} during the 2008 season and 3.85 and 0.77 kg·m^{-3} during the 2009 season, respectively (Table 3). These were higher than the corresponding values for the DSR [27]. Both rice yields and water use efficiencies were thus higher in the MSI TPR field than in the DSR field. In the same region, Ye et al. [15] reported the WP_I values for AWD and continuously flood irrigated TPR fields during the 2010 and 2011 seasons to be 1.56–3.45 kg·m^{-3} and 1.05–2.02 kg·m^{-3} under different fertilizer treatments, respectively, and the WP_{IR} values to be 0.48–1.06 kg·m^{-3} and 0.41–0.82 kg·m^{-3}, respectively. Bouman et al. [10] reported that the average WP_{IR} for TPR under water-saving irrigation conditions was 0.8 kg·m^{-3} (0.6–0.97 kg·m^{-3}) in northern China during the 2002 season. However, Cabangon et al. [1] reported for Malaysia that TPR had similar TWI with DSR (dry-seeded), but had significantly more irrigation water and lower WP_I values than DSR (dry-seeded). This was attributed to the ability of DSR to capture more early rainfall after crop establishment.

Using ET as the water use term enables a better comparison between sites, cultivars, seasons, and management options [43]. The WP_{ET} values in our simulations (Table 3) fall in the range of globally measured values for rice (0.6–1.6 kg·m^{-3}) [6] and are higher than the average value (1.09 kg·m^{-3}) [44]. Singh et al. [43] reported an average WP_{ET} of 0.94 kg·m^{-3} for TPR in the Sirsa district (India). Belder et al. [6] reported that the WP_{ET} in a TPR field experiment (Hubei, China) under submerged-nonsubmerged conditions was 4%–20% higher than that under continuous submerged conditions with the same fertilizer management. Due to relatively higher yields and similar ETs, the W_{ET} values in the MSI TPR field were slightly higher than those (1.30 kg·m^{-3} in 2008 and 1.33 kg·m^{-3} in 2009) in the DSR field [27]. Cabangon et al. [1] also reported for Malaysia that, due to relative higher yield and lower ET, the TPR had higher W_{ET} values compared to DSR.

In general, in dry or semi-dry areas where water is the most limiting factor, maximizing WP may be economically more profitable for the farmer than maximizing yields [11,45]. While in the Taihu Lake basin, water is not a limiting factor for the agricultural production, a worsening quality of surface waters and groundwater, due to increasing nitrogen and phosphorus surface runoff and leaching from agricultural lands [21,26], has become a serious problem. Increasing the WP by adopting the MSI method can reduce water and nutrient losses from TPR fields, compared to DSR fields. However, the effects of the MSI method in the TPR fields on reducing nutrient losses needs to be studied and compared with the DSR cultivation method.

5. Conclusions

Soil water regimes and water balance were monitored in an MSI (multiple-shallow irrigation) TPR field in the Taihu Lake Basin of East China, and then evaluated using the Hydrus-1D model. The Hydrus-1D can simulate well soil water flow in the TPR field under MSI conditions. Evapotranspiration under the MSI conditions was not affected by water management, and percolation substantially increased with increasing water inputs and flooding days. Percolation was the main path of water losses, independent of whether the water input was mainly by irrigation or precipitation. The MSI cultivation of TPR substantially reduced water losses by percolation and surface runoff, and correspondingly increased water use productivities, while sustaining relatively high rice yields compared to the regular cultivation of DSR in the same field. Water productivities showed that the MSI TPR cultivation, which considers both soil conditions and rainfall forecast when scheduling irrigation, efficiently used rainfall water and reduced water losses from paddy fields. Water savings can be realized by adopting MSI without reducing rice yield. Additionally, it needs to be emphasized that because most water savings resulted from reduced percolation rates, adoption of this approach will reduce groundwater recharge and associated nutrient percolation.

Acknowledgments: The work described in this publication was supported by the National Natural Science Foundation of China (Nos: 51579074 and 51079048), the National Science and Technology Ministry of China (No. 2015BAB07B02), the Fundamental Research Funds for the Central Universities (No. 2009B16914), the Priority Academic Program Development of Jiangsu Higher Education Institutions (PAPD), and the China Scholarship Council. The authors would like to thank two anonymous reviewers for providing thoughtful comments that helped us to improve the manuscript significantly and the editors for their careful and responsible work.

Author Contributions: Yong Li conceived and designed the experiments; Shuang Wang, Jiahui Yuan, and Weiwei Zhang performed the experiments; Shuang Wang, Jiahui Yuan, and Weiwei Zhang analyzed the data; Yong Li and Jirka Šimůnek contributed reagents/materials/analysis tools; Yong Li and Jirka Šimůnek wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

Summary of Abbreviations

TPR	Transplanted rice
DSR	Direct-seeded rice
MSI	Multiple-shallow irrigation
AWD	Alternate wetting and drying
CF	Continuous flood
TWI	Total water input
WP	Water productivity
WP_I	Irrigation water productivity
WP_{IR}	Input water productivity
WP_{ET}	Evapotranspiration water productivity
ET	Evapotranspiration
E_P	Potential evaporation
T_P	Potential transpiration
ET_P	Potential evapotranspiration
W_C	Water content
S_e	Effective saturation
DAB	Days after basal fertilization
LAI	Leaf area index

References

1. Cabangon, R.J.; Tuong, T.P.; Abdullah, N.B. Comparing water input and water productivity of transplanted and direct-seeded rice production systems. *Agric. Water Manag.* **2002**, *57*, 11–31. [CrossRef]
2. Chen, S.; Cai, S.G.; Chen, X.; Zhang, G.P. Genotypic differences in growth and physiological responses to transplanting and direct seeding cultivation in rice. *Rice Sci.* **2009**, *16*, 143–150. [CrossRef]

3. Farooq, M.; Siddique, K.H.M.; Rehman, H.; Aziz, T.; Lee, D.; Wahid, A. Rice direct seeding: Experiences, challenges and opportunities. *Soil Till. Res.* **2011**, *111*, 87–98. [CrossRef]
4. Liu, Y.; Yu, X.; He, Y. The research progress of water-saving irrigation in China since 2000. *Adv. Mater. Res.* **2014**, *955–959*, 3206–3210. [CrossRef]
5. Tan, X.; Shao, D.; Gu, W.; Liu, H. Field analysis of water and nitrogen fate in lowland paddy fields under different water managements using HYDRUS-1D. *Agric. Water Manag.* **2015**, *150*, 67–80. [CrossRef]
6. Belder, P.; Spiertz, J.H.J.; Bouman, B.A.M.; Lu, G.; Tuong, T.P. Nitrogen economy and water productivity of lowland rice under water-saving irrigation. *Field Crops Res.* **2005**, *93*, 169–185. [CrossRef]
7. Jia, G.; Yan, Z.; Wang, Y.; Zhu, F. Field test and research on agricultural water-saving irrigation and pollution reduction in Taihu Lake Basin. *Yangtze River* **2013**, *44*, 81–84.
8. Jiang, P.; Yuan, Y.; Zhu, R.; Dai, Y.; Shen, Y.; Zhao, Z.; Yue, Y.; Zhao, Q.; Cao, L. Study on the nitrogen loss from paddy fields on different water management. *Chin. J. Agro-Environ. Sci.* **2013**, *32*, 1592–1596.
9. Waraich, E.A.; Ahmad, R.; Ashraf, M.Y.; Saifullah; Ahmad, M. Improving agricultural water use efficiency by nutrient management in crop plants. *Acta Agric. Scand. Sect. B Soil Plant Sci.* **2011**, *61*, 291–304. [CrossRef]
10. Bouman, B.A.M.; Feng, L.; Tuong, T.P.; Lu, G.; Wang, H.; Feng, Y. Exploring options to grow rice using less water in northern China using a modelling approach II. Quantifying yield, water balance components, and water productivity. *Agric. Water Manag.* **2007**, *88*, 23–33. [CrossRef]
11. Geerts, S.; Raes, D. Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas. *Agric. Water Manag.* **2009**, *96*, 1275–1284. [CrossRef]
12. Liang, Y.; Li, F.; Nong, M.; Luo, H.; Zhang, J. Microbial activity in paddy soil and water use efficiency of rice as affected by irrigation method and nitrogen level. *Commun. Soil Sci. Plant Anal.* **2015**, *47*, 19–31. [CrossRef]
13. Mao, Z. Water Efficient Irrigation and environmentally Sustainable Irrigated Rice Production in China. International Commission on Irrigation and Drainage, 2001. Available online: http://www.icid.org/wat_mao.pdf (accessed on 23 December 2013).
14. Tan, X.; Shao, D.; Liu, H.; Yang, F.; Xiao, C.; Yang, H. Effects of alternate wetting and drying irrigation on percolation and nitrogen leaching in paddy fields. *Paddy Water Environ.* **2013**, *11*, 381–395. [CrossRef]
15. Ye, Y.; Liang, X.; Chen, Y.; Liu, J.; Gu, J.; Guo, R.; Li, L. Alternate wetting and drying irrigation and controlled-release nitrogen fertilizer in late-season rice. Effects on dry matter accumulation, yield, water and nitrogen use. *Field Crops Res.* **2013**, *144*, 212–224. [CrossRef]
16. Prathapar, S.A.; Qureshi, A.S. Modelling the effects of deficit irrigation on soil salinity, depth to water table and transpiration in semi-arid zones with monsoonal rains. *Water Resour. Dev.* **1999**, *15*, 141–159. [CrossRef]
17. Kato, Y.; Okami, M. Root morphology, hydraulic conductivity and plant water relations of high-yielding rice grown under aerobic conditions. *Ann. Bot.* **2011**, *108*, 575–583. [CrossRef] [PubMed]
18. El-Sadek, A. Water use optimisation based on the concept of partial rootzone drying. *Ain Shams Eng. J.* **2014**, *5*, 55–62. [CrossRef]
19. Zhang, Z.; Zhang, S.; Yang, J.; Zhang, J. Yield, grain quality and water use efficiency of rice under non-flooded mulching cultivation. *Field Crops Res.* **2008**, *108*, 71–81. [CrossRef]
20. Bouman, B.A.M.; Tuong, T.P. Field water management to save water and increase its productivity in irrigated lowland rice. *Agric. Water Manag.* **2001**, *49*, 11–30. [CrossRef]
21. Peng, S.; Yang, S.; Xu, J.; Luo, Y.; Hou, H. Nitrogen and phosphorus leaching losses from paddy fields with different water and nitrogen managements. *Paddy Water Environ.* **2011**, *9*, 333–342. [CrossRef]
22. Garg, K.K.; Das, B.S.; Safeeq, M.; Bhadoria, P.B.S. Measurement and modeling of soil water regime in a lowland paddy field showing preferential transport. *Agric. Water Manag.* **2009**, *96*, 1705–1714. [CrossRef]
23. Tan, X.; Shao, D.; Liu, H. Simulating soil water regime in lowland paddy fields under different water managements using HYDRUS-1D. *Agric. Water Manag.* **2014**, *132*, 69–78. [CrossRef]
24. Tsubo, M.; Fukai, S.; Tuong, T.P.; Ouk, M. A water balance model for rainfed lowland rice fields emphasising lateral water movement within a toposequence. *Ecol. Model.* **2007**, *204*, 503–515. [CrossRef]
25. Šimůnek, J.; van Genuchten, M.T.; Šejna, M. Development and applications of the HYDRUS and STANMOD software packages, and related codes. *Vadose Zone J.* **2008**, *7*, 587–600. [CrossRef]
26. Yang, S.; Peng, S.; Xu, J.; Hou, H.; Gao, X. Nitrogen Loss from paddy field with different water and nitrogen managements in Taihu lake region of China. *Commun. Soil Sci. Plant Anal.* **2013**, *44*, 2393–2407. [CrossRef]
27. Li, Y.; Šimůnek, J.; Jing, L.; Zhang, Z.; Ni, L. Evaluation of water movement and water losses in a direct-seeded-rice field experiment using Hydrus-1D. *Agric. Water Manag.* **2014**, *142*, 38–46. [CrossRef]

28. Molden, D. A water-productivity framework for understanding and action. In *Water Productivity in Agriculture: Limits and Opportunities for Improvement*; Kijne, J.W., Barker, R., Molden, D., Eds.; International Water Management Institute: Colombo, Sri Lanka, 2003; pp. 1–18.
29. Phogat, V.; Yadav, A.K.; Malik, R.S.; Kumar, S.; Cox, J. Simulation of salt and water movement and estimation of water productivity of rice crop irrigated with saline water. *Paddy Water Environ.* **2010**, *8*, 333–346. [CrossRef]
30. Humphreys, E.; Kukal, S.S.; Gill, G.; Rangarajan, R. Effect of water management on dry seeded and puddled transplanted rice Part 2: Water balance and water productivity. *Field Crops Res.* **2011**, *120*, 123–132.
31. Van Genuchten, M.T. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Sci. Soc. Am. J.* **1980**, *44*, 892–898. [CrossRef]
32. Allen, R.G.; Pereira, L.S.; Raes, D.; Smith, M. *Crop Evapotranspiration-Guidelines for Computing Crop Water Requirements. Irrigation and Drain*; Paper No. 56; FAO: Rome, Italy, 1998.
33. Feddes, R.A.; Kowalik, P.J.; Zaradny, H. (Eds.) *Simulation of Field Water Use and Crop Yield*; John Wiley & Sons: New York, NY, USA, 1978.
34. Arif, C.; Setiawan, B.I.; Sofiyuddin, H.A.; Martief, L.M.; Mizoguchi, M.; Doi, R. Estimating Crop Coefficient in Intermittent Irrigation Paddy Fields Using Excel Solver. *Rice Sci.* **2012**, *19*, 143–152. [CrossRef]
35. Belmans, C.; Wesseling, J.G.; Feddes, R.A. Simulation model of the water balance of a cropped soil: SWATRE. *J. Hydrol.* **1983**, *63*, 271–286. [CrossRef]
36. Xu, Q.; Yang, L.; Dong, Y. *Rice Field Ecosystem in China*; Chinese Agricultural Press: Beijing, China, 1998. (In Chinese)
37. Zhang, H.C.; Li, J.; Yao, Y.; Huo, Z.Y.; Dai, Q.G.; Xu, K.; Yang, B.; Zhao, P.H.; Wei, H.Y. *Scientific Issues of Direct Seeding Rice Cultivation*; Chinese Agricultural Science Press: Beijing, China, 2009. (In Chinese)
38. Ünan, R.; Sezer, İ.; ŞAhin, M.; Mur, L.A.J. Control of lodging and reduction in plant length in rice (Oryza sativa, L.) with the treatment of trinexapac-ethyl and sowing density. *Turk. J. Agric. For.* **2013**, *37*, 257–264. [CrossRef]
39. Maqsood, M.; Shehzad, M.A.; Ali, S.N.A.; Iqbal, M. Rice cultures and nitrogen rate effects on yield and quality of rice (*Oryza sativa*, L.). *Turk. J. Agric. For.* **2013**, *37*, 665–673. [CrossRef]
40. Zhao, X.; Zhou, Y.; Min, J.; Wang, S.; Shi, W.; Xing, G. Nitrogen runoff dominates water nitrogen pollution from rice-wheat rotation in the Taihu Lake region of China. *Agric. Ecosyst. Environ.* **2012**, *156*, 1–11. [CrossRef]
41. Tuong, T.P.; Bouman, B.A.M. Rice production in water-scarce environments. In *Water Productivity in Agriculture: Limits and Opportunities for Improvement*; Kijne, J.W., Barker, R., Molden, D., Eds.; CABI Publishing: Wallingford, UK, 2003; pp. 53–67.
42. Lian, G.; Wang, D.; Lin, J.; Yan, D. Characteristics of nutrient leaching from paddy field in Taihu Lake area. *Chin. J. Appl. Ecol.* **2003**, *14*, 1879–1883.
43. Singh, R.; van Dam, J.C.; Feddes, R.A. Water productivity analysis of irrigated crops in Sirsa district, India. *Agric. Water Manag.* **2006**, *82*, 253–278. [CrossRef]
44. Zwart, S.J.; Bastiaanssen, W.G.M. Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize. *Agric. Water Manag.* **2004**, *69*, 115–133. [CrossRef]
45. English, M. Deficit irrigation. I. Analytical framework. *J. Irrig. Drain. Eng. ASCE* **1990**, *116*, 399–412. [CrossRef]