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Evaluation of water movement and water losses in a direct-seeded-rice field experiment using Hydrus-1D

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ABSTRACT

In the recent decade, increasing costs of labor, water, and fertilizers around the world led to a change in the method of crop establishment from traditional transplanted rice (TPR) to direct-seeded rice (DSR) and to a substantial rise in the DSR-managed area. Since water management in areas with DSR is quite different from those with TPR, vertical water movement and water and nutrient losses during the crop season may be different as well. Water flow and water losses in a DSR field in the Taihu Lake Basin of east China were monitored and evaluated using Hydrus-1D during two seasons with different rainfalls and irrigation managements. While during the 2008 season, irrigation accounted for 57% of the total water input (TWI), during the 2009 season, it accounted for only 32%. Due to large rainfall during the wet, 2009 rice season, surface runoff accounted for about 17.0% of TWI. During the much drier 2008 rice season with higher irrigation inputs, surface runoff (4.6% of TWI) could be controlled much better. Modeled evapotranspiration during the 2008 and 2009 seasons accounted for 54.6% and 44.6% of TWIs, respectively. Measured and simulated results indicate that water leaching (approximately 42.7% and 34.9% of TWIs in the 2008 and 2009 seasons, respectively) was the main path of water loss from the DSR fields, which implies that frequent irrigation increases water leaching. The plough sole layer played a major buffering role for water flow during both dry and wet seasons. Water productivities evaluated from TWIs during the 2008 and 2009 seasons were 0.71 and 0.59 kg/m^3, respectively; they were 1.30 and 1.33 kg/m^3 when evaluated from modeled evapotranspiration fluxes. Pressure heads and vertical fluxes simulated using Hydrus-1D matched measured data well. The Hydrus-1D can be used to simulate water flow and water balance in the DSR fields.

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1. Introduction

Rice is the most widely consumed staple food for a large part of the human population, especially in Asia, providing more than one fifth of the calories consumed by humans worldwide (Smith, 1998). In many Asian countries, rice accounts for more than 70% of human caloric intake. China is the world's largest rice producer, accounting for 30% of the total world production, followed by India (22%), Indonesia (9%), and Bangladesh (7%) (Kögel-Knabner et al., 2010). The traditional method of rice cultivation in the world used to be transplanting rice (TPR), which ensured a steady yield during the long history of mankind (Cabangon et al., 2002; Chen et al., 2009).

However, in all climatic zones, human labor represents more than 50% of the cost of TPR farming (Weerakoon et al., 2011), followed by the cost of other inputs such as water (Cabangon et al., 2002; Choudhury et al., 2007) and fertilizers (Pandey and Velasco, 1999; Farooq et al., 2011). With the development of rice cultivation science and the requirements of different climatic zones, many other methods of rice cultivation gradually emerged, such as dry or wet direct rice seeding (Chen et al., 2009). Direct-seeded rice (DSR), which is cultivated by directly broadcasting seeds onto the topsoil of paddy fields without needing to raise and transplant seedlings, provides an opportunity to save both labor and time (Chen et al., 2009). This farming method also enables earlier crop establishment, providing an opportunity to make better use of early season rainfall, while increasing crop intensification in some rice-based systems (Tuong et al., 2000). Moreover, the development of early-maturing varieties and improved nutrient

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management techniques, along with increased availability of chemical weed control methods, have encouraged many farmers in Asia to switch from transplanted to direct-seeded rice culture (Gupta and Seth, 2007; Farooq et al., 2011).

During the last two decades, the change in the method of crop establishment from manual transplanting of seedlings to direct-seeding has occurred in many Asian countries in response to rising production costs, especially those of labor and water (Rao et al., 2007; Chen et al., 2009). In the Taihu Lake Basin (TLB) of east China, many farmers have accepted the cultivation of DSR, although the average yield of DSR is not as stable and is still slightly lower than that of TPR (Zhang et al., 2009). The area with DSR cultivation has rapidly increased and has already exceeded 50% of the total farmland in many TLB regions (Zhang et al., 2009). In accordance with this development trend, the direct-seeding approach will likely continue to remain popular in the TLB.

Water flow in paddy fields with cultivated rice involves the interaction of very complex processes, and their observation and evaluation under field conditions is relatively difficult, costly, and time consuming. Therefore, a large number of scientists increasingly use computer models to study the complex processes in the soil and to provide management and planning guidance. Hydrus-1D and Hydrus (2D/3D) (Šimůnek et al., 2008) are numerical models that have often been used by many researchers to simulate water flow in agricultural fields with different crops and various irrigation schemes (Kandelous et al., 2012; Ramos et al., 2012; Siyal et al., 2012), including TPR fields (Phogat et al., 2010; Sutanto et al., 2012). However, the Hydrus-1D model has not yet been used for simulating water flow in DSR fields. Compared to traditional TPR, DSR requires different water management, which provides rice with a different growth environment, particularly during its seedling stage (Chen et al., 2009). During the first two weeks after seeding, rather than being flooded as with TPR, the top soil only needs to keep sufficient moisture to allow for seed germination (Cabangon et al., 2002). As a result, the root mass of DSR is distributed shallower than that of traditional TPR, which consequently produces different vertical profiles of the water content (Naklang et al., 1996; Yadav et al., 2007). Furthermore, compared to TPR, DSR prefers an alternative drying and wetting soil environment during the middle-late season when multiple smaller irrigations can benefit both the plant growth and deeper root growth (Chen et al., 2009). This water management produces distinctly different characteristics of the water flow regime and water losses from DSR fields compared to TPR fields. In this study, field observations in a DSR field in the TLB during two consecutive rice-growing seasons (2008–2009) are evaluated using Hydrus-1D, and the main characteristics of the water flow regime and water losses are discussed.

2. Material and methods

2.1. Field experimental data

2.1.1. Site description

The agricultural land in the Taihu Lake Basin is used for very intensive production of the rice crop. The basin area, which is located south of the Yangtze River, is approximately 36,900 km^2, with rice fields accounting for about 34.8% of this area. Rotations of rice with either wheat or rape are the most popular cultivating modes in this region. The basin 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. The study site is in the Dangyang region (31°56′N, 119°43′E), upstream of Taihu Lake (the third largest fresh water lake in China). The dominant soil type in this region is classified as a hydromorphic paddy soil, and the parent material is a lacustrine deposit. The physical and chemical properties of the soil at the site are listed in Table 1.

2.1.2. Experimental design

In our experiments, the variety of rice used for the DSR cultivation was *Wuxiangjing* 14 (lowland rice), a type of Japonica rice that is predominantly cultivated in the Dangyang region. The observations were carried out in the same field during two growth seasons. After the mechanical field preparation, the seeds were evenly broadcasted by hand on the soil surface at 75 kg/ha, without prior soaking, on June 8th in 2008 and June 11th in 2009. After seeding, the fields were irrigated until the surface soil was saturated (without flooding). The harvest dates were on November 1st in 2008 and November 5th in 2009. The total growing periods during these two years were thus 147 and 149 days, respectively.

The water management in the DSR field followed instructions from the local Agricultural Technical Guidance Station and drew from the farmers' own experience. The amount and distribution of both rainfall and irrigation during these two rice-growing seasons are shown in Fig. 1. During the 2009 season, the total rainfall of 97.4 cm was higher than the long-term average (which is about 65.0 cm) and occurred mainly during the first three months of the crop growth. During the 2008 season, the total rainfall of only about 54.3 cm was lower than the long-term average. During the 2008 and 2009 seasons, 14 and 9 irrigations (each 5–6 cm) were applied, resulting in total water depths of 72 and 46 cm, respectively. To prevent long flooding and anaerobic conditions and to control rice insects and weeds, rice fields need to be naturally dried for about 5–10 days during the season, depending on the rice and soil conditions. The soil drying stage in the 2008 season was between August 7th and 12th, while in the 2009 season it was between August 14th and 20th.

2.1.3. Measurements

The daily climate data, including temperature, wind speed, humidity, and daylight hours, were obtained from an adjacent agro-meteorological station (about 5 km south) in the Dangyang region. The amount of irrigation water was measured using flow meters at inlets, and the flooding water depth was recorded every two days at several points in the field. The total amounts of surface runoff at outlets were measured by flow meters to be 5.2 and 22.5 cm during the 2008 and 2009 seasons, respectively (Fig. 1). Before rice seeding, self-made flux lysimeters for measuring vertical water fluxes (Wang et al., 2001) were installed at a depth of 60 cm below the soil

Table 1
Physical and chemical properties of the paddy soil in the Taihu Lake Basin.

Depth (cm)	Soil particle size distribution (%)			Bulk density (g/cm^3)	Organic matter (%)	pH (H_2O)
	Sand (>0.05 mm)	Silt (0.002–0.05 mm)	Clay (<0.002 mm)			
0–20	7.01	73.70	19.29	1.42	0.51	6.65
20–40	0.02	81.01	18.97	1.56	0.54	6.85
40–60	18.53	72.83	8.64	1.51	0.37	6.85
60–80	14.44	81.64	3.91	1.43	0.35	6.80
80–100	14.25	81.59	4.16	1.43	0.33	6.80
100–120	11.32	80.30	8.38	1.43	0.33	6.85

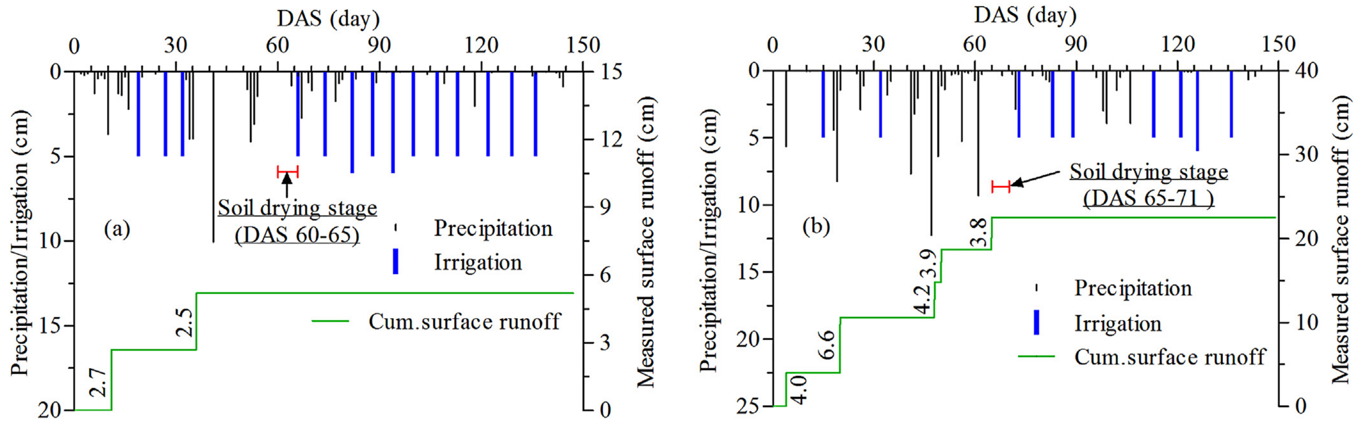

Fig. 1. Distribution of rainfall/irrigation and measured surface runoff in the direct-seeded-rice experimental field in the Taihu Lake Basin during the (a) 2008 and (b) 2009 seasons. DAS—days after seeding.

surface. Each device consisted of an open-cylinder (25 cm in diameter × 12 cm in height) that was connected to a glass bottle. The top surface of an open-cylinder was welded using stainless steel ribbons to avoid soil falling down into the cylinder. Leached water that was collected in the cylinder freely flowed into the outside glass bottle through a flexible tube. The water volume in the bottle was measured once every two weeks.

The groundwater table was observed once a week at an observation point near the experimental field. The recorded data show that the groundwater table slightly fluctuated, but remained around a depth of 120 cm (between 117.7 and 121.8 cm) below the soil surface.

Piezoelectric tube tensiometers (0–100.00 kPa) were installed at five observation points in the field to measure pressure heads one month before rice seeding. At each observation point, five tensiometers were installed at depths of 20, 40, 60, 80, and 100 cm below the soil surface (each of the five tensiometers was installed on a different vertical line to avoid mutual interference). The pressure head values were recorded every two days. The averaged data from each of the depths at the five observation points were used for model simulation.

2.2. Hydrus-1D model

2.2.1. Model description

The one-dimensional Hydrus-1D computer program (Šimůnek et al., 2008) was selected to simulate water movement in the experimental field. Since the flow in the soil profile between the soil surface (the ponding layer) and groundwater is predominantly in the vertical direction, and horizontal flow in the ponding surface layer, such as surface runoff and/or irrigation, can be accounted for using boundary conditions, there was no need to use a model such as Hydrus (2D/3D) that would consider multiple dimensions. The Hydrus-1D program numerically solves the Richards equation for saturated and unsaturated water flow and the convection-dispersion equations for heat and solute transport. The governing one-dimensional water flow equation for a partially saturated porous medium is described using the modified form of the Richards equation, under the assumptions that the air phase plays an insignificant role in the liquid flow process and that water flow due to thermal gradients can be neglected:

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

where h is the water pressure head (cm), θ is the volumetric water content (cm^3/cm^3), t is time (day), z is the spatial coordinate (cm), K is the unsaturated hydraulic conductivity function (cm/day), and S is the sink term in the flow equation (cm^3/cm^3/day) accounting for root water uptake.

The soil water retention, $\theta(h)$, and hydraulic conductivity, $K(h)$, functions according to van Genuchten (1980), are given as

$$\theta(h) = \theta_r + \frac{\theta_S - \theta_r}{[1+(\alpha h)^n]^m} \quad h < 0 \quad (2a)$$

$$\theta(h) = \theta_S \quad h \geq 0 \quad (2b)$$

$$K(h) = K_s S_e^l \left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2 \quad (3)$$

here θ_S is the saturated water content (cm^3/cm^3); θ_r is the residual water content (cm^3/cm^3); m, α and n are empirical shape factors in the water retention function, where $m = 1 - 1/n$; K_s is the saturated hydraulic conductivity (cm/day) measured using soil column experiments; l is the shape factor in the hydraulic conductivity function; and S_e is the relative saturation, which is defined as follows:

$$S_e = \frac{\theta - \theta_r}{\theta_S - \theta_r} \quad (4)$$

2.2.2. Hydrus-1D input parameters

2.2.2.1. Estimation of soil hydraulic parameters. The van Genuchten soil hydraulic parameters, θ_r, θ_S, m, α, and n (Table 2), which are required by the Hydrus-1D model, were estimated using the RETC software by fitting retention data, $\theta(h)$, measured using the pressure plate apparatus. The pore connectivity parameter (l) was assumed equal to an average value (0.5) for many soils.

2.2.2.2. Estimation of potential ET. To simulate the influence of soil water on transpiration (root water uptake), Hydrus-1D requires potential evaporation (the upper boundary condition) and potential transpiration (a sink term in the Richards equation) fluxes to be specified as separate input values at a daily time step. The Penman–Monteith equation (Allen et al., 1998) was used for calculating the reference crop evapotranspiration (ET_0) from available climatic, crop, and soil parameters. 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 (Allen et al., 1998):

$$ET_C = ET_0 \times K_C \quad (5)$$

For the crop, which only partly covers the soil surface, ET_P is divided into potential evaporation, E_P, and potential transpiration, T_P. This partitioning was achieved using the crop leaf area index

Table 2
Optimized values of the residual water content, θ_r, the saturated water content, θ_S, van Genuchten's shape parameters, α, n, and m, and the saturated hydraulic conductivity, K_s.

Depth (cm)	Soil type	θ_r (cm^3/cm^3)	θ_S (cm^3/cm^3)	α (cm)	n	m	K_s (cm/day)
0–20	Silt loam	0.132	0.505	0.0095	1.415	0.293	0.767
20–40	Silt loam	0.075	0.449	0.0125	1.113	0.102	0.523
40–60	Silt loam	0.074	0.497	0.0041	1.841	0.457	0.748
60–80	Silt	0.043	0.501	0.0052	1.349	0.259	1.196
80–100	Silt	0.083	0.530	0.0024	1.826	0.452	0.696
100–120	Silt	0.054	0.501	0.0037	1.424	0.298	0.711

Table 3
Leaf area index (LAI) of direct-seeded-rice at various growth stages during the 2008 and 2009 seasons (DAS—days after seeding).

DAS/year	30	60	90	120	147
2008	2.9	5.2	7.2	7.2	3.4
2009	2.8	5.0	6.8	6.9	3.3

as given by Belmans et al. (1983), which is a function of the crop development stage:

$$E_P = ET_C \times e^{-K_{gr} \times LAI}$$
$$T_P = ET_C - E_P \tag{6}$$

here K_{gr} is an extension coefficient for global solar radiation; its value was taken as 0.3 for the rice crop (Phogat et al., 2010). Measured values of *LAI* at various growth stages in two continuous seasons are given in Table 3. Estimated values of E_P and T_P were then used as input parameters in the Hydrus-1D simulations (Fig. 2).

2.2.2.3. Root water uptake functions. Root growth was simulated using measured rooting depths during the growing season as input. The method to consider water stress was used to determine root water uptake. Parameter values optimized by Singh et al. (2003) 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 function proposed by Feddes et al. (1978) and Homaee et al. (2002). Parameters h_1 through h_4 represent different pressure head values, which affect root water uptake in the soil. The water uptake is assumed to be zero for $h > h_1$. For $h < h_4$ (the wilting point pressure head), water uptake is also assumed to be zero. Water uptake is considered optimal between pressure heads h_2 and h_3, whereas for pressure heads between h_3 and h_4 (or h_1 and h_2), water uptake linearly decreases (or increases) with h.

2.2.3. Initial and boundary conditions

The initial conditions were defined using the measured pressure head distribution. The soil surface was subjected to the atmosphere boundary condition (BC) with specified values of precipitation, irrigation, and evaporation. Furthermore, to reflect changing water management conditions during the season, during the first two weeks and during the soil-drying stage, the upper boundary condition was set equal to an "Atmospheric BC with Surface Runoff". During the second stage (14–35 days) and during remaining growth stages, the upper boundary condition was set equal to an "Atmospheric BC with a Surface Layer" (with a maximum of 6 cm and 10 cm, respectively). The Hydrus-1D model was modified so that it could accommodate these dynamic changes in the surface boundary condition. Potential values of E_p and T_p, and irrigation and rainfall fluxes were used to represent the atmospheric boundary condition. Based on the observed data of the groundwater table, the constant pressure head BC was considered at the bottom boundary.

2.3. Statistical tests

A paired *t*-test was used to test the difference between the means ($\bar{x}$) of measured and simulated values:

$$t_{\mathrm{cal}} = \frac{d}{\sqrt{s\left[1/n_1 + 1/n_2\right]}} \tag{7a}$$

$d = \overline{x_1} - \overline{x_2}$, and

$$d = \overline{x_1} - \overline{x_2}, \quad \text{and} \quad s = \sqrt{\frac{n_1 s_1^2 + n_2 s_2^2}{n_1 + n_2 - 2}} \tag{7b}$$

where n is the number of comparable paired points, s is the standard deviation of the mean, subscripts 1 and 2 indicate measured and simulated values, and t_{cal} is the calculated t value.

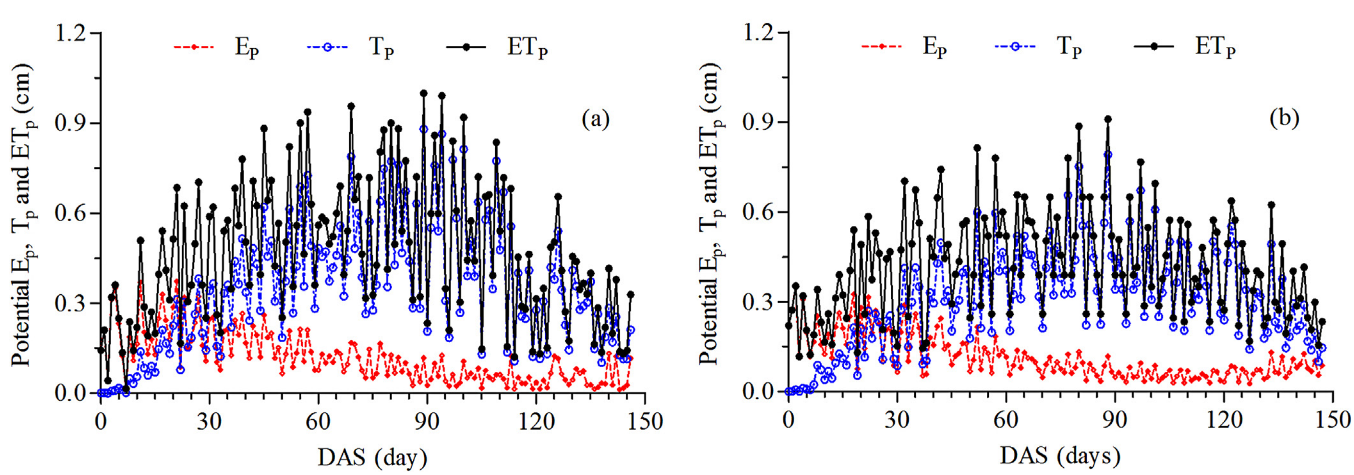

Fig. 2. Potential values of evaporation, E_p, transpiration, T_p, and evapotranspiration, ET_p, estimated using the Penman–Monteith equation during the (a) 2008 and (b) 2009 seasons.

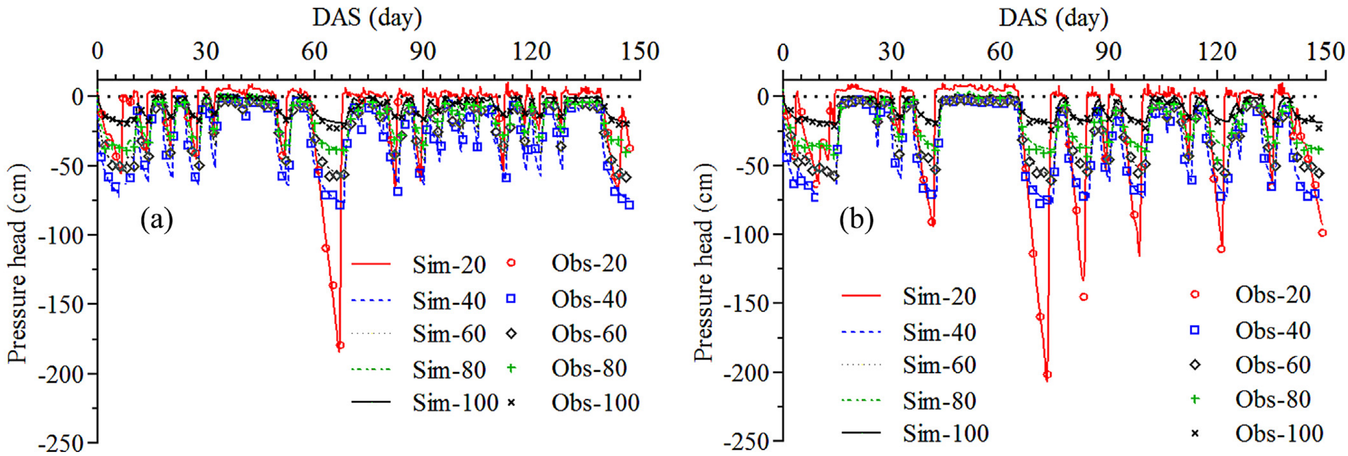

Fig. 3. Simulated and observed pressure head values during the (a) 2008 and (b) 2009 seasons. 0–65 DAS and 66–147 DAS in the 2008 season were used for Hydrus-1D calibration and validation, respectively. Positive pressure head values were not observed by tensiometers.

The root mean square error (*RMSE*) was also calculated to compare the measured and simulated values:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(M_i - S_i)^2} \tag{8}$$

where M_i and S_i are measured and simulated values for an output variable (e.g., pressure heads, water fluxes), and N is the number of observations.

3. Results and discussion

3.1. Hydrus-1D model calibration and validation

Sutanto et al. (2012) has previously validated that the Hydrus-1D model is a good and reliable tool to simulate water flow and solute transport in the TPR field. Here, we will evaluate the effectiveness of Hydrus-1D for the DSR conditions. Using the soil hydraulic parameters estimated by RETC (Table 2) as initial estimates, the observed values of the pressure heads at soil depths of 20, 40, 60, 80, and 100 cm during 0–65 DAS (Days After Seeding) in the 2008 season were used to further calibrate (fine-tune) these parameters (i.e., θ_r, θ_S, α, and n). The correspondence between observed and simulated pressure heads during this calibration period was very good, with $r = 0.97$ ($n = 135$, $t_{cal} = 4.1$, $RMSE = 2.61$ cm). The calibrated parameters were then used to simulate the remaining data from the 2008 season, i.e., during 66–147 DAS, to validate the model. The correspondence between observed and simulated pressure heads during this validation period was similarly good, with $r = 0.95$ ($n = 158$, $t_{cal} = 9.3$, $RMSE = 2.86$ cm). The results during both calibration and validation time-periods of the 2008 season are presented in Fig. 3a, indicating a good match of observed data. Fig. 3b shows the measured and simulated pressure heads during the 2009 rice season ($n = 288$, $r = 0.94$, $t_{cal} = 1.9$, $RMSE = 9.54$ cm).

Due to frequent rainfall in 2009, most pressure head values at a depth of 20 cm were positive during the first half of the season, as opposed to the 2008 season's values. During the second half of the2008 season, frequent irrigations produced more frequent changes between drying and wetting conditions in the soil. During the soil drying stage, pressure heads at a depth of 20 cm reached the minimum values of −184.1 cm and −206.9 cm during the 2008 and 2009 seasons, respectively. The pressure heads at a depth of 60 cm were mostly between 0 and −57.2 cm, and their peaks lagged about 1–2 days behind those at a depth of 20 cm.

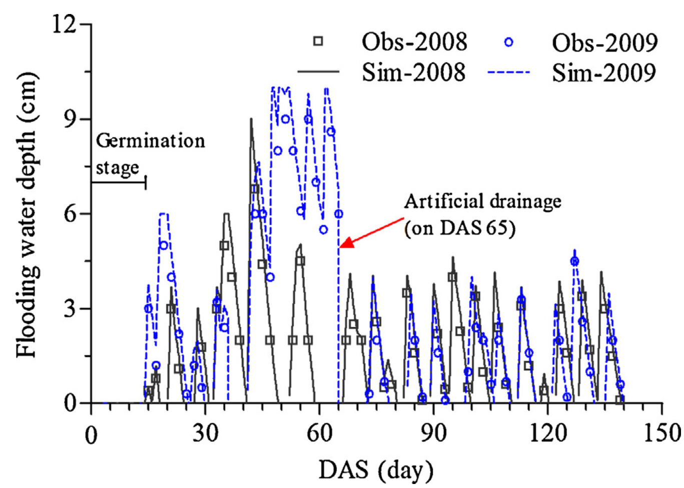

Fig. 4. Observed and simulated flooding water depths during the 2008 and 2009 seasons.

Percolation fluxes can also be used to compare model simulations with observed values. While total simulated percolation at a depth of 60 cm before 56 DAS in the 2008 season was 21.8 cm (the average flux of 0.389 cm/day), the observed value was 23.3 cm (the average flux of 0.416 cm/day). For the entire growing season of 2008, total percolation at a 60-cm depth simulated by Hydrus-1D was 53.9 cm (the average flux of 0.367 cm/day), and the observed value was 55.6 cm (the average flux of 0.378 cm/day). The correspondence between measured and simulated percolation fluxes during both early and entire growing periods is very good. The difference between simulated and observed values may be caused by macro-pores, earthworm burrows, roots, soil cracks, and lateral leakage (Akay et al., 2008; Janssen and Lennartz, 2009; Sander and Gerke, 2009; Wang et al., 2011).

3.2. Flooding water depths and surface runoff

Observed values of the flooding water depth can also be a good indicator for evaluating the effectiveness of Hydrus-1D for simulating conditions in DSR fields, especially its ability to correctly handle the upper boundary conditions. Measured and simulated flooding water depths are depicted in Fig. 4, which shows a good match between measured and simulated values ($n = 87$, $r = 0.98$, $t_{cal} = 16.4$, $RMSE = 0.56$ cm) when using the calibrated soil hydraulic parameters. Overall, the measured data were slightly lower than

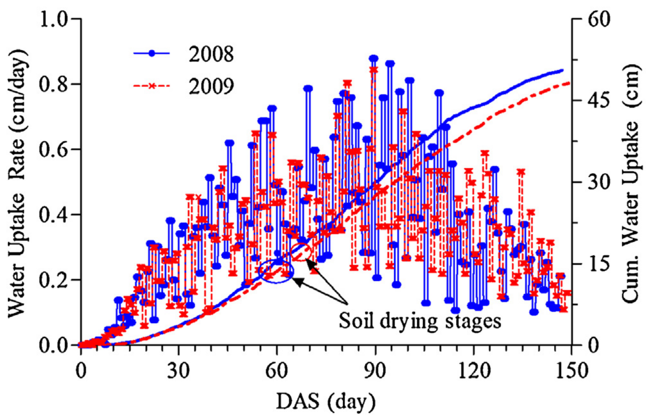

Fig. 5. Simulated actual and cumulative root water uptake during the 2008 and 2009 seasons.

simulated values. As expected, larger differences in flooding water depths between the 2008 and 2009 seasons were mainly found during the first half of the season. The frequent intensive rainfall in the early 2009 season caused the water depth to reach the maximum depth of 10 cm within several days. On the other hand, during the 2008 season, the water depth was always below the maximum controlled depth, because the water input was mainly determined by irrigation. According to simulated values, flooding water depths between 0 and 5 cm and between 5 and 10 cm during the 2008 season were 90 and 7 days, respectively, while during the 2009 season the corresponding values were 72 and 26 days, respectively. Overall, rainfall was sufficiently utilized by the rice crop during the 2009 season.

Although DSR could effectively use early rainfall, a large amount of water was still lost from fields as surface runoff. During the 2009 season, most rainfall occurred during the early part of the season, resulting in five surface runoff events. The biggest surface runoff event (6.6 cm) was observed on 20 DAS, just after continuous intensive precipitation (Fig. 1). During the 2008 season, only two surface runoff events were observed. To prevent long-flooded and anaerobic conditions in 2009, the field was artificially drained on 65 DAS. Simulated and observed total surface runoff during the 2009 season was 24.4 and 22.5 cm, respectively, which was approximately four times more than during the 2008 season, when simulated and observed runoff was 5.8 and 5.2 cm, respectively. The difference between simulated and observed surface runoff can be attributed to several small surface runoff events simulated by Hydrus-1D that were not observed in the field. This could also be due to preferential flow caused by macropores and cracks, which was not considered in the simulation, and which would increase water infiltration and reduce surface drainage to a certain extent (Tsubo et al., 2007; Garg et al., 2009; Patil et al., 2011).

3.3. Evapotranspiration

Phogat et al. (2010) showed that the Hydrus-1D model can describe root water uptake of transplanted rice very well. In their simulations of water and salt movement in rice fields, they showed that simulated root water uptake closely corresponded with crop performance in their experiment. Fig. 5 shows daily root water uptake by DSR during the 2008 and 2009 seasons, as simulated using Hydrus-1D. Root water uptake was initially almost zero during the seeds' germination stage. Root water uptake then gradually increased after about 10 DAS, reflecting the crop growth, and reached its maximum values between 90 and 120 DAS. The maximum daily root water uptake rate was approximately 0.6 cm/day around 100 DAS. During later stages of crop growth, daily root water uptake substantially declined. The cumulative root water uptake only slowly increased during the initial 30 days, then quickly increased and ultimately reached 51.4 and 48.2 cm during the entire growing seasons of 2008 and 2009, respectively. Actual evaporation rates (not shown) simulated using Hydrus-1D and estimated potential evaporation rates (Fig. 2) were 17.4 and 15.8 cm during the 2008 and 2009 seasons. Most evaporation occurred during the early part of the season when the crop cover was still relatively small. Similar results have been reported in the literature. For example, Choudhury et al. (2007) estimated the seasonal DSR evapotranspiration loss in dry-seeded rice, on a flat land with row spacing of 20-cm in New Delhi, India, to be 55.6–56.0 cm during 2001 and 2002. Sudhir-Yadav et al. (2011) reported that the estimated *ET* values in intermittently irrigated DSR fields were 49.7–70.7 cm during the 2008 and 2009 seasons in Punjab, India.

3.4. Soil water movement and changes in soil storage

Dynamic changes in water contents of the soil profile of rice fields depend on many natural (e.g., rainfall and evaporation) and artificial (e.g., irrigation) factors. Differences in soil hydraulic properties (e.g., retention or hydraulic conductivity) between different soil layers cause characteristic water content profiles. While the plough sole layer was often saturated, unsaturated conditions occurred in the subsoil below the plough sole layer (Chen and Liu, 2002; Garg et al., 2009). This is because the subsoil is often more permeable than the plough sole layer and its hydraulic conductivity is 1.5–2.3 (or more) times higher than that of the plough sole layer. Actually, the plough sole layer often plays an obstructing or buffering role on vertical water flow (Liu et al., 2005; Filipović et al., 2013). The low hydraulic conductivity of the plough sole controls the vertical water movement during both drying and wetting in rice fields.

Simulation results indicated that the soil water storage in the upper 60 cm of the soil profile throughout the 2008 season decreased 1.2 cm, while during the 2009 season, it decreased by about 2.3 cm. The change of soil water storage predominantly depended on the initial water content and water contents at harvest.

3.5. Water leaching

Downward leaching represented the largest loss of water from the rice field. Leaching predominantly depended on the soil hydraulic conductivity of individual soil layers and the overall pressure head gradient. As shown in Fig. 6, leaching closely corresponded with precipitation and irrigation events. Due to early intensive rainfalls, relatively continuous high leaching rates were mainly observed during 30–60 DAS. During the later growth stages when the water input was predominately provided by irrigation, leaching was relatively regular and reflected particular irrigation events. The maximum leaching rate (0.71 cm/day) at a depth of 60 cm occurred on 42 DAS during the 2008 rice season, immediately after an intensive rainfall (10.06 cm) on 41 DAS. During the 2009 season, the maximum leaching rate (0.76 cm/day) at a depth of 60 cm occurred on 48 DAS after a continuous intensive rainfall (12.25 cm on 46 DAS and 6.39 cm on 48 DAS). Chen and Liu (2002) reported similar results when an increase in the flooding water depth from 6 to 16 cm produced a 1.5 fold increase in the infiltration rate in a paddy field.

As shown in Fig. 6, the differences in leaching rates between two seasons were mainly caused mainly by different water managements. While the water input in the 2008 season was predominately accomplished by irrigation, in the 2009 season, it was mainly by rainfall (Fig. 1). Average simulated flux rates at a depth of 60 cm before 66 DAS in the 2008 season and before 72

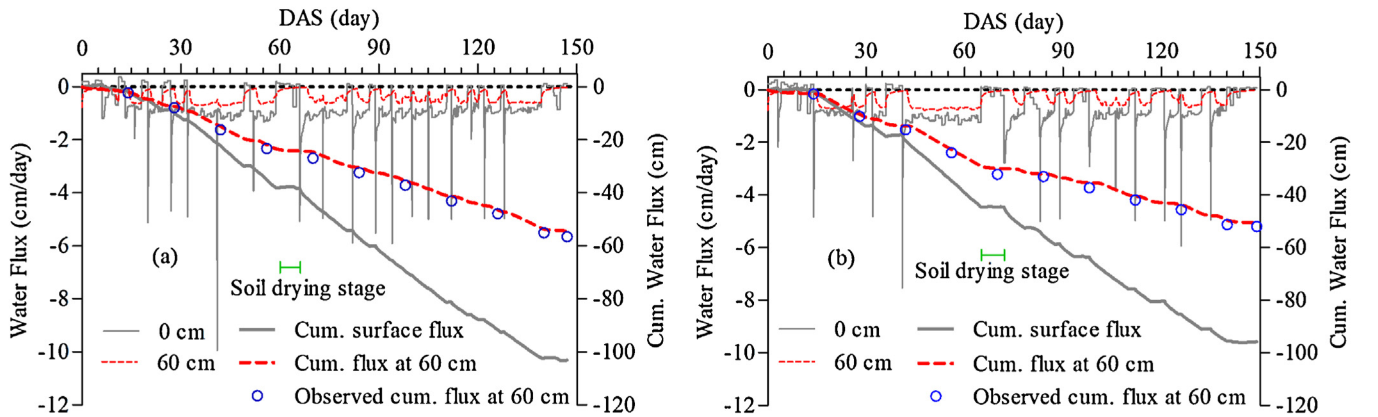

Fig. 6. Actual and cumulative water fluxes at the soil surface and at a depth of 60 cm during (a) 2008 and (b) 2009 seasons.

Table 4
Measured and simulated (using Hydrus-1D) water balance components (cm) in the 60 cm soil profile, and water productivities (*WP*) (kg/m^3) for the direct-seeded-rice crop in the Taihu Lake Basin.

Growing season		*R*	*I*	*SR*	*ET*	*SS*	*L*	$\sum$	WP_I	WP_{IR}	WP_{ET}
2008	Simulated	54.3	72.0	−5.8	−68.9	−1.2	−53.9	−3.5	1.25	0.71	1.30
	Measured			−5.2	NA	−1.5	−55.6	–			–
2009	Simulated	97.4	46.0	−24.4	−64.0	−2.3	−50.1	2.7	1.85	0.59	1.33
	Measured			−22.5	NA	−3.1	−52.9	–			–

R—rainfall, *I*—irrigation, *SR*—surface runoff, *ET*—evapotranspiration, *SS*—soil storage, *L*—leaching, $\sum$—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*.

DAS in the 2009 season were 0.36 and 0.41 cm/day, respectively, while those during the entire 2008 and 2009 seasons were 0.37 and 0.34 cm/day, respectively. More frequent irrigations in the late 2008 season resulted in more water leaching compared to the late 2009 season. Similarly, frequent and intensive rainfall during the early half season of 2009 resulted in much more water leaching. The leaching rate in paddy field soils in the area is about 0.3–0.5 cm/day, which is considered to be an optimal leaching rate for good rice growth in this region (Xu et al., 1998). Soils with a higher leaching rate are considered "water-wasting" soils, while soils with a lower leaching rate often have *Eh* too low for rice growth (Shan et al., 2005). Lian et al. (2003) also reported that the water leaching rates measured by lysimeters in adjacent paddy fields were between 0.49–0.56 cm/day.

3.6. Water balance and productivity

The measured and simulated components of the water balance of the upper 60 cm of the soil profile are presented in Table 4. The total measured water inputs during the 2008 and 2009 seasons were 126.3 and 143.4 cm, respectively. Simulated evapotranspiration during the 2008 and 2009 seasons accounted for 54.6% and 44.6% of corresponding volumes of water input, respectively, while leaching at a depth of 60 cm accounted for approximately 42.7% and 34.9%, respectively. The total water balance errors were −3.5 and 2.7 cm during the 2008 and 2009 seasons, respectively, which account for about 2.8% and 1.9% of the total water input. This indicates that the Hydrus-1D model is a good tool for simulating the water balance components in the DSR fields.

The average grain yields in the 2008 and 2009 seasons were 8980 kg/ha and 8530 kg/ha, respectively. The grain yield of DSR is greatly affected by local climate and water and fertilizer management. Water productivity (*WP*), also known as water use efficiency, is a measure that characterizes the crop production per unit of water used. Three measures of water productivity were computed: irrigation water productivity (WP_I)—the ratio of grain yield to the amount of irrigation water; input water productivity (WP_{IR})—the ratio of grain yield to the amount of irrigation water plus rainfall; and evapotranspiration water productivity (WP_{ET})—the ratio of grain yield to crop *ET* (Phogat et al., 2010; Sudhir-Yadav et al., 2011). The *ET* value for these calculations was taken as the sum of cumulated root water uptake and evaporation during the entire season, as simulated by the Hydrus-1D model. Measured seasonal values of precipitation and irrigation were used in the above calculations as the total water input (*IR*). Using this definition, the *WPs* in the 2008 and 2009 seasons are listed in Table 4.

The differences between WP_I and WP_{IR} values in the 2008 and 2009 seasons can be attributed mostly to different amounts of irrigation water. Sudhir-Yadav et al. (2011) estimated the WP_I for intermittently and daily irrigated DSR fields in India to be 0.7–1.6 kg/m^3 and 0.2–0.3 kg/m^3, respectively. The WP_{IR}s in our experiments are close to a value (0.67 kg/m^3) reported by Ginigaddara and Ranamukhaarachchi (2009) in Thailand for DSR with one week irrigation, followed by three weeks without irrigation. Ye et al. (2013) reported that the WP_{IR}s of intermittently irrigated TPR in the Taihu Lake Basin were between 0.48 and 1.06 kg/m^3 for different fertilizer managements, with average values of 0.88 and 0.77 kg/m^3 during the 2010 and 2011 seasons, respectively. The WP_{ET}s in our experiments fall in the range of globally measured values for rice (0.6–1.6 kg/m^3), and are higher than the average value (1.09 kg/m^3) (Zwart and Bastiaanssen, 2004) but slightly lower than the median value of 1.52 kg/m^3 (ranging from 0.89–2.03 kg/m^3) reported by Roost et al. (2008) for TPR of the Zhanghe Irrigation District in Central China. The evaluated water productivities indicated that DSR in the 2008 season had a better water use efficiency compared to DSR in the 2009 season, and that the DSR in the 2009 season sufficiently used rainfall. Similar water productivities in the two seasons, with respect to the simulated evapotranspiration, signified that the crop yields were closely associated with the root water uptake.

4. Conclusions

Water flow and water losses in a DSR field in the Taihu Lake Basin of east China were monitored and evaluated using Hydrus-1D during two seasons with different rainfalls and irrigation managements. Frequent and intensive rainfall during the 2009 season resulted in long periods of flooding and more surface runoff. The plough sole layer, with a relatively low hydraulic conductivity, played a buffering role during both drying and wetting processes in the DSR fields and controlled the vertical water movement. Water leaching was the main path of water loss from the DSR fields, independent of whether the water input was mainly by irrigation or precipitation.

Water productivities evaluated based on the irrigation and total water inputs explained the different water use efficiency of DSR in the 2008 and 2009 seasons. On the other hand, water productivities with respect to evapotranspiration were numerically similar in the two seasons due to similar grain yields and evapotranspiration.

The Hydrus-1D model simulations of pressure heads and percolation fluxes matched the observed data obtained from direct-seeded-rice fields in the Taihu Lake Basin, China fairly well. Differences between the observed and Hydrus-1D simulated means of pressure heads and percolation fluxes as tested by the paired t test were not found to be significant at $p = 0.05$. Low values of *RMSE* also indicated the applicability of Hydrus-1D to simulate percolation fluxes and pressure heads in the DSR fields. Hydrus-1D was able to analyze the most important processes, such as infiltration, surface runoff, root water uptake, and leaching.

Hydrus-1D, despite the considerable demand on input data, has proven to be an effective tool for evaluating various water and solute fluxes in agricultural fields with different crops and various irrigation schemes (e.g., Kandelous et al., 2012; Ramos et al., 2012; Siyal et al., 2012). In this manuscript, we have demonstrated that Hydrus-1D is a similarly effective tool for evaluating water fluxes and associated processes in direct-seeded rice fields. After proper calibration and validation, Hydrus-1D should be considered a useful tool for establishing sound irrigation policies and for management of irrigation in regions with similar climatic conditions and similar crops.

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