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Numerical modeling of soil water dynamics in subsurface drained paddies with midseason drainage or alternate wetting and drying management

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ABSTRACT

As a supplemental practice to land consolidation projects, subsurface drainage systems have been installed in paddy fields to allow for crop diversification and to improve the overall productivity of paddy soils. The HYDRUS (2D/3D) model was applied to investigate the combined effects of different subsurface drainage systems and water management strategies on water balance, groundwater table, transpiration efficiency, and water use efficiency in paddy fields. Field experiments were conducted during four rice growing seasons (2011, 2012, 2014, and 2015) at the subsurface-drained paddies of the Sari Agricultural Sciences and Natural Resources University in northern Iran. Midseason drainage (MSD) management was applied in 2011 and 2012, while alternate wetting and drying (AWD) management was adopted in 2014 and 2015. The model performance was evaluated using the model efficiency (EF), root mean square error (RMSE), normalized root mean square error (NRMSE), and mean bias error (MBE) measures. The model had strong predictive capabilities for simulating the mid-drain water table depth for both water managements. Under MSD and AWD, daily evapotranspiration rates varied from 4.9 to 6.2 mm d^{-1} and 4.9 to 5.9 mm d^{-1}, respectively. Drainage losses were higher under AWD than MSD, while the reverse order occurred for percolation losses. Compared with MSD, AWD improved the transpiration and water use efficiency of rice in the presence of subsurface drainage. Being capable of describing complex effects of AWD and MSD strategies in subsurface-drained paddy fields, the HYDRUS (2D/3D) model can serve as a practical tool for optimizing water productivity in these fields.

1. Introduction

The positive effects of drying paddy fields during non-stress periods of the rice growing season were demonstrated in multiple studies (Goto et al., 2000; Liu et al., 2013; Darzi-Naftchali and Shahnazari, 2014). Midseason drainage (MSD) is a water management practice that is traditionally carried out during the maximum tillering stage of rice to control non-productive tillers and to consequently increase rice production. Removing toxic elements (Bouman et al., 2007) and providing better conditions for nutrient uptake are additional benefits of such management, resulting in increased grain yield and increased nitrogen use efficiency (Darzi-Naftchali and Shahnazari, 2014). Alternate wetting and drying (AWD) is another water management practice in rice cultivation systems that has been reported to improve rice yield while decreasing water consumption (Chu et al., 2014; Ye et al., 2013).

Paddy soils represent a complex hydrological system. Heavy texture and the presence of a much less permeable soil layer (hardpan) below a plow pan are special characteristics of paddy soils that reduce the drying rate of soil during non-irrigation periods. Evapotranspiration (*ET*) and percolation represent two main mechanisms that result in the loss of moisture in the upper soil zone. Percolation losses are generally low in puddled, poorly drained paddy soils. Under the AWD practice, the soil water regime of paddy fields is transformed from being fully saturated to being alternately saturated and unsaturated (Tan et al., 2014). Subsurface drainage can accelerate water table drawdown and provide better aeration during drying periods. Under such conditions, experimentally quantifying all water balance components is difficult, expensive, and time consuming. On the other hand, computer-aided analytical

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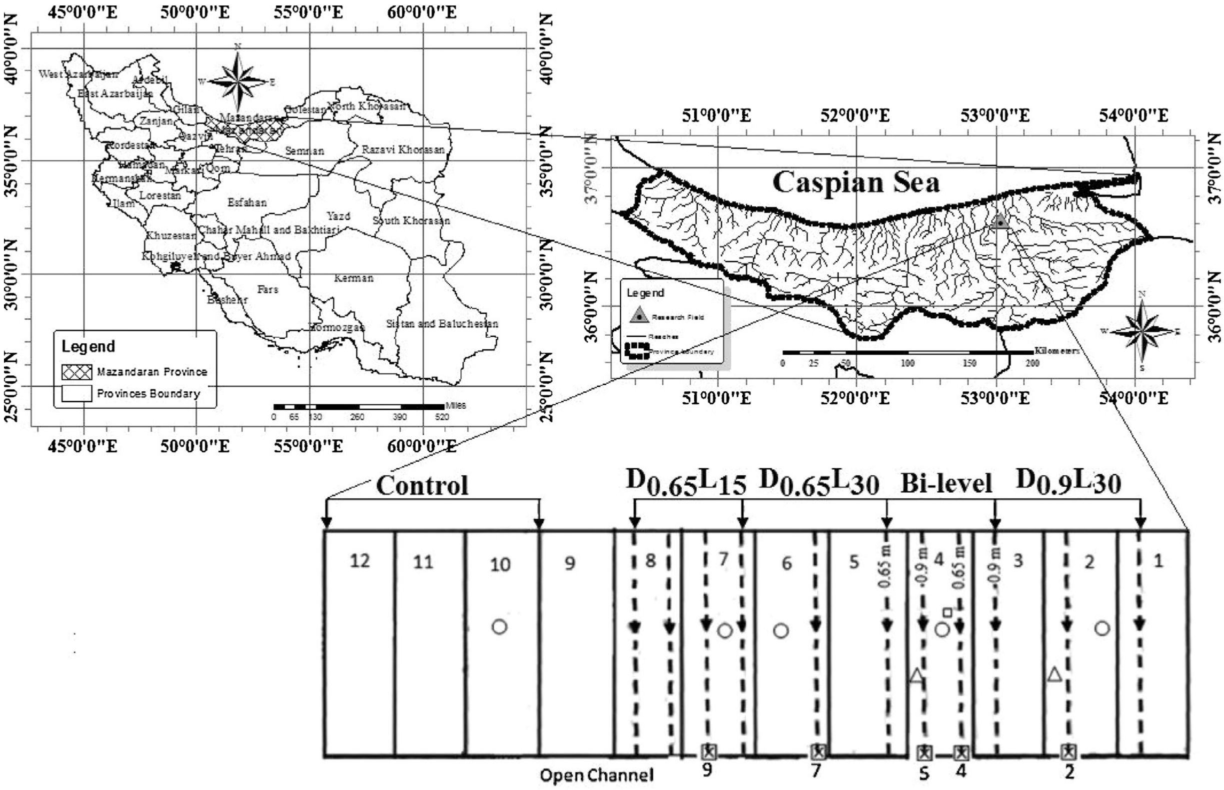
tools and models may prove helpful in assessing the consequences of different water management strategies in a quick and efficient manner (Yao et al., 2014). Numerical computer models can incorporate descriptions of many key processes and transformations in paddy soils to predict their overall systemic behavior. LEACHM (Wagenet and Hutson, 1989), DRAINMOD (Skaggs, 1978), SWAP (Van Dam et al., 1997), DSSAT (Hoogenboom et al., 2014), AquaCrop (Steduto et al., 2009), and HYDRUS (Šimůnek et al., 2008) are among the different simulation models developed for evaluating various soil-water-atmosphere-plant interactions.

Having both the flexibility to accommodate different types of boundary conditions for water flow and solute transport calculations and the capability to simultaneously consider root uptake of water and nutrients, the HYDRUS model can simulate soil water dynamics in paddy fields under different water management practices (Li et al., 2015; Hammecker et al., 2012). HYDRUS use is also greatly facilitated by its sophisticated, graphical, user-friendly interface. For example, Janssen and Lennartz (2009) applied HYDRUS-2D to quantify water fluxes through bunds in a terraced paddy landscape. Garg et al. (2009) determined a soil water regime involving preferential flow in a multi-layer paddy soil using HYDRUS-1D. Using HYDRUS-1D, Tan et al. (2014) simulated the soil water regime and nitrogen fate in paddy fields under different water managements and concluded that the model can properly simulate water flow in a multi-layered paddy soil when the saturated hydraulic conductivity of a plow pan is inversely estimated. The results of a companion study on water and nitrogen fate in paddy fields demonstrated that HYDRUS-1D can be used to assess and improve the water and nitrogen management for sustainable rice production (Tan et al., 2015). Li et al. (2014, 2015) reported that HYDRUS-1D can be used to simulate water flow, nitrogen transport and transformations, and water and nitrogen balances in direct-seeded-rice fields. In a simulation study, Ebrahimian and Noory (2015) evaluated water flow under various drain depths and spacings in a hypothetical paddy field using HYDRUS-2D and concluded that the model is a robust tool for designing subsurface drainage for paddy fields.

Integrating AWD and MSD strategies with subsurface drainage alters the water and nutrient regimes of the paddy fields and significantly increases the complexity of the system. Under such circumstances, precise knowledge of all the components of water balance is essential for increasing water productivity in paddy fields, especially because irrigated rice is the leading consumer of water in the agricultural sector (Satyanarayana et al., 2007). In view of the above-mentioned- earlier studies, no research has been yet conducted on the analysis of soil water dynamics under the AWD and MSD strategies in subsurface drained paddy fields using the HYDRUS (2D/3D) model. Therefore, the first main objective of this study was to use collected experimental data involving water table drawdown and water balance components in subsurface drained paddy fields under different water management strategies for the assessment of the capability of the HYDRUS model for describing these processes. The second main objective was to use the calibrated HYDRUS model to evaluate the combined effects of different subsurface drainage systems and water management strategies on



(1 to 12 plot no, ○ :location of observation wells and open end Lysimeters for measuring evaporation+deep percolation (E-DP), △ :location of closed end Lysimeters for measuring evaporation (E), □ :location of open end Lysimeter for measuring evapotranspiration (ET), - -▸- -: subsurface drain lines and ⊠ :points of drain flow measurements).

Fig. 1. Location of the study area in the Mazandaran province (top right) of Iran (top left) and the layout of the drainage systems (bottom).

water balance, the groundwater table, transpiration efficiency, and water use efficiency in paddy fields.

2. Materials and methods

2.1. Study site

A field study was conducted during four rice growing seasons (2011, 2012, 2014, and 2015) at the 4.5 ha consolidated paddy field at the Sari Agricultural Sciences and Natural Resources University in the Mazandaran province of northern Iran (Fig. 1). The area is located in the coastal zone of the eastern part of the Caspian Sea. The climate of the region is alternatively influenced by cold Arctic air, humid temperate air from the Atlantic Ocean, dry and cold air associated with Siberian high pressure zones, and Mediterranean warm air. Minimum and maximum daily air temperatures recorded at the study site during 4 growing seasons were 10 and 37.4 °C. Average air temperatures during the 2011, 2012, 2014, and 2015 growing seasons were 25.3, 25.1, 26.2, and 27.3 °C, respectively. Total rainfalls during these growing seasons were 136.6, 73.7, 86.4, and 88.6 mm, respectively. Fig. 2 displays daily values of minimum and maximum temperatures along with daily rainfall during the growing seasons. The soil on the site is silty clay and clay to a depth of 300 cm. The saturated hydraulic conductivities in different layers of the soil profile are very low.

Eleven PVC corrugated drain pipes (100 m long, with an outside diameter of 100 mm) were installed at the study site in June–July of 2011 at depths of 0.65 and 0.9 m and spacings of 15 and 30 m. Four different subsurface drainage systems were analyzed by installing drains at different depths (D_x, where subscript x indicates a drain depth) and spacings (L_y, where subscript y indicates a drain spacing): $\mathrm{D_{0.9}L_{30}}$, $\mathrm{D_{0.65}L_{30}}$, and $\mathrm{D_{0.65}L_{15}}$. The last drainage system, denoted as Bilevel, has a drain spacing of 15 m and alternate drain depths of 0.65 and 0.9 m. A solid plastic pipe was used to connect the lateral lines with an open channel as a collector drain at a depth of 1.2 m. Further details about the experimental design can be found in Darzi-Naftchali et al. (2013). Fig. 1 shows the location of the research field in the country and the layout of the drainage systems in the research field.

2.2. Field management

All agricultural operations except for water management followed the conventional practices of local growers in the study area. To decrease percolation losses of water and nutrients during rice growing periods, the flooded paddy plots were puddled during land preparation. Basal fertilizers were applied before rice transplanting as follows: 140 kg ha^{-1} triple superphosphate in 2011; 100 kg ha^{-1} triple superphosphate, 100 kg ha^{-1} potassium sulfate, and 80 kg ha^{-1} urea in 2014; and 50 kg ha^{-1} triple superphosphate, 50 kg ha^{-1} potassium sulfate, and 100 kg ha^{-1} urea in 2015. No basal fertilizers were applied in 2012. Rice cultivation was carried out during four cropping seasons: from July 21 to October 10 in 2011, from May 28 to August 11 in 2012, from May 10 to August 5 in 2014, and from June 4 to August 28 in 2015. During rice growing periods, urea was broadcasted as follows: 90 kg ha^{-1} at 8 days after transplanting (DAT) in 2011, 90 kg ha^{-1} at 9 DAT in 2012, 80 and 30 kg ha^{-1} at 13 and 31 DAT in 2014, respectively, and 50 kg ha^{-1} at 12 DAT in 2015. The growers in the region adjust fertilization based on their other activities in the crop rotation, which may result in minor differences in the amount of applied fertilizer between different growing seasons (Darzi-Naftchali et al., 2017).

While the usual water management practice for local rice fields is continuous flooding as it helps control weeds and pests

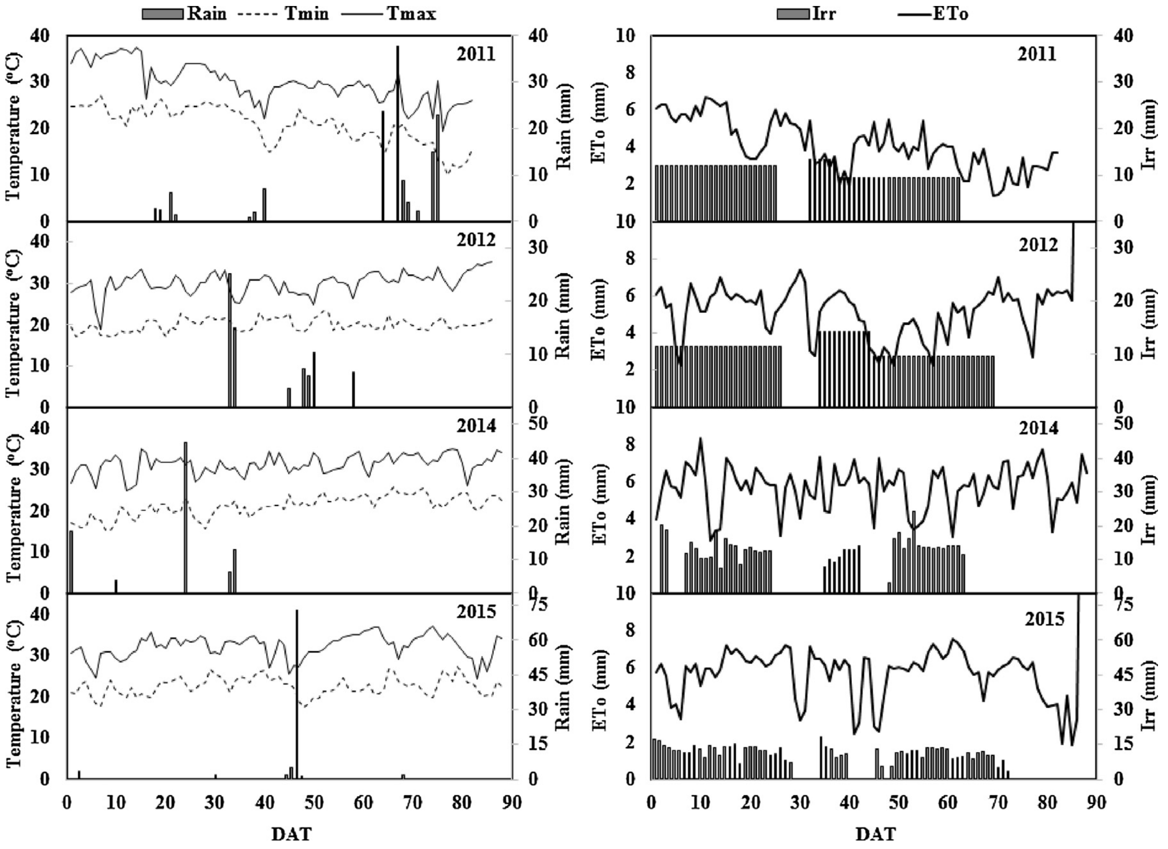


Fig. 2. Daily values of rainfall, minimum and maximum temperatures (left), irrigation depth (Irr), and potential evapotranspiration (ET_0) (right) during the four growing seasons (DAT – days after transplanting).

Table 1
Physical properties and hydraulic parameters of different soil layers in the study area.

Soil depth (cm)	Clay (%)	Silt (%)	Sand (%)	Soil texture	ρ_b (g cm^{-3})	θ_r	θ_s	α (cm^{-1})	n	l	K_s (cm d^{-1})
0–30	48.5	44.4	7	Silty Clay	1.34	0.001	0.40	0.004	1.193	0.5	25.6
30–60	55.5	42	2.5	Silty Clay	1.40	0.001	0.40	0.008	1.119	0.5	8.1
60–90	46.5	45.5	8	Silty Clay	1.37	0.192	0.40	0.008	1.355	0.5	20.7
90–120	42.5	51.5	6	Silty Clay	1.36	0.098	0.40	0.006	1.423	0.5	16.3
120–150	52	42	6	Silty Clay	1.37	0.001	0.57	0.004	1.274	0.5	10.9
150–200	58.5	35.5	6	Clay	1.38	0.229	0.59	0.004	1.467	0.5	8.3

θ_r and θ_s are the residual and saturated water contents, respectively, K_s is the saturated hydraulic conductivity, ρ_b is bulk density and α, n, and l are the shape factors in the van Genuchten-Mualem model (van Genuchten, 1980).

(Darzi-Naftchali et al., 2013), two types of water managements were followed during this experiment: midseason drainage (MSD) and alternative wetting and drying (AWD). Under both managements, the plots were continuously flooded (with about 5 cm of standing water) during 3–4 weeks after transplanting, and suitable conditions for harvesting were created by end-season drainage several days before the harvest. The plots were flooded except during the drainage periods.

The MSD water management was followed in 2011 and 2012 with the following sequence of operations: flooding, MSD (on 25 DAT for a 7 day period), re-flooding, and end-season drainage management. AWD water management was adopted in 2014 and 2015. Two periods of drainage were conducted during the vegetative growth stage (as a midseason drainage). The plots were drained during the time periods of 25–34 and 43–47 DAT in 2014 and 28–32 and 39–43 DAT in 2015. Each drainage period was ended when the formation of small cracks on the soil surface was visually observed. Temporal variations of irrigation are presented in Fig. 2 for all growing seasons.

2.3. Measurements

Before crop cultivation, soil samples were taken from each treatment plot every 30 cm to a depth of 200 cm. Soil properties were determined on these soil samples. Soil water contents at 14 different pressure heads (from 0 to 16 bar) were measured in the laboratory using a pressure plate apparatus. The van Genuchten-Mualem model (van Genuchten, 1980) was then fitted to the observed retention curves using the RETC model. Table 1 provides hydraulic parameters and soil physical properties for different soil layers in the study area.

Measurements of water table depths were manually made in the observation wells that were dug midway between drains each day during drainage periods. The water table profile between shallow and deep drains in the Bilevel drainage system was determined in 2014. To do this, additional observation wells were dug at drain trenches and 1, 2.5, and 5 m apart from deep and shallow drains. Subsurface drainage discharge was daily measured during drainage periods, and the drains were plugged the rest of the time. During flooding periods in 2014, standing water levels were daily recorded at three locations in different plots.

In 2014 and 2015, the total dry matter (*TDM*) production and leaf area index (*LAI*) were determined at 16, 28, 39, 50, 60, and 67 DAT. In addition, grain and biological yields of rice were determined at harvest each year. The HYDRUS (2D/3D) model was used to determine the water balance components under different water management strategies and drainage systems. Due to the lack of direct measurements of transpiration (*T*), this term was estimated by the model from the weather data and crop *LAI*. For all samplings and drainage systems, transpiration efficiency (*TE*) expressed in grams of biomass per liter (kg) of transpired water was calculated as a mean of three replicated measurements of *TDM* and the corresponding cumulative transpiration. The water use efficiency (*WUE*) was determined as a ratio of grain yield per total evapotranspiration.

2.4. Numerical modeling approach

HYDRUS (2D/3D) (Šimůnek et al., 2008, 2016) is powerful software for simulating transient, two- or three-dimensional movement of water and nutrients in soils for a wide range of boundary conditions, irregular boundaries, and soil heterogeneities. Water flow in soils is described using the Richards equation as follows:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right) - \frac{\partial k}{\partial z} - WU(h, x, z) \qquad (1)$$

where θ is the volumetric soil water content (SWC) [L^3L^{-3}], K is the unsaturated hydraulic conductivity [LT^{-1}], h is the soil water pressure head [L], x is the lateral coordinate [L], z is the vertical coordinate (positive downwards), t is time [T], and $WU(h, r, z)$ denotes root water uptake [T^{-1}]. WU is computed as follows:

$$WU(h, x, z) = \gamma(h) RDF(x, z) WT_{pot} \qquad (2)$$

where $\gamma(h)$ is the soil water stress function (dimensionless) of Feddes et al. (1978), RDF is the normalized root water uptake distribution [L^{-2}], T_{pot} is the potential transpiration rate [LT^{-1}], and W is the width of the soil surface [L] associated with the transpiration process. In the present study, the root distribution was assumed to be uniform in time (which is a restriction of HYDRUS-2D). The soil hydraulic properties were modeled using the van Genuchten-Mualem constitutive relationships (van Genuchten, 1980).

The two-dimensional transport domain was a rectangle 200 cm deep (the upper depth of the impermeable layer) and either 30 m wide for the $D_{0.9}L_{30}$ and $D_{0.65}L_{30}$ drainage systems, or 15 m wide for the $D_{0.65}L_{15}$ and Bilevel drainage systems. The transport domain was discretized using unstructured, triangular, finite element mesh (FEM). A non-uniform FEM was generated by HYDRUS-2D with finite element sizes gradually increasing with distance from the drains. Six soil horizons with different soil hydraulic properties were defined for the 0–30 cm, 30–60 cm, 60–90 cm, 90–120 cm, 120–150 cm, and 150–200 cm soil depths (Table 1). The soil layer below the 200 cm depth was considered to be impermeable (Darzi-Naftchali et al., 2013).

The measured pressure head distribution was applied to define the initial conditions for flow simulations. For the drainage periods, the time-variable pressure head boundary condition was applied at the top of the transport domain to represent different water managements at the field. For the rest of the simulation periods, the atmospheric boundary condition was defined at the top of the transport domain. A seepage face boundary condition was used to represent the drains during the drainage periods. All other remaining boundaries were assigned a no-flow boundary condition.

The interactions between soil and atmosphere were described using the atmospheric time-variable boundary condition and measured meteorological data. Potential evapotranspiration (ET_p) was calculated using the FAO56 Penman–Monteith method (Allen et al.,

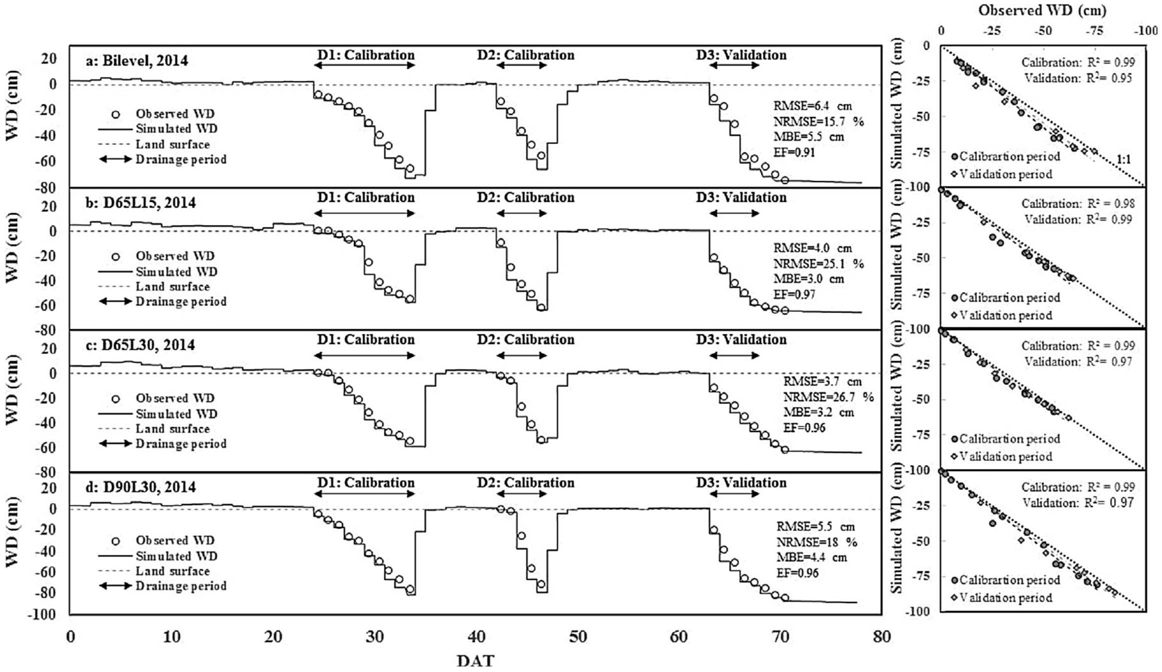


Fig. 3. Temporal variations of water depths (*WD*) midway between drains during the 2014 growing season for the four drainage systems (a: Bilevel, b: $D_{65}L_{15}$, c: $D_{65}L_{30}$, d: $D_{90}L_{30}$) and the AWD water management. D1, D2, and D3 denote the first (25–34 DAT), second (43–47 DAT), and third (64–71 DAT) drainage periods, respectively. Statistical measures evaluating the model performance are also provided.

1998), while crop evapotranspiration (ET_c) was calculated by multiplying ET_p by the crop coefficients. Using the measured leaf area index (*LAI*) for each treatment, ET_c was divided into evaporation and transpiration by using Eq. (5) (Belmans et al., 1983):

$$E_p = ET_c \times e^{-K_{gr} \times LAI}$$
$$T_p = ET_c - E_p \tag{3}$$

where E_p is potential evaporation [LT^{-1}], T_p is potential transpiration [LT^{-1}], ET_c is crop evapotranspiration [LT^{-1}], and K_{gr} is an extension coefficient for global solar radiation [–]. K_{gr} for rice was set to 0.3 based on Phogat et al. (2010). Estimated values of E_p and T_p were used as input parameters in HYDRUS-2D.

An additional calibration process was carried out for all treatments using measured temporal variations of water depths (*WD*) during the first and second drainage periods in 2014. During the calibration process, the saturated hydraulic conductivity (K_s), the residual soil water content (θ_r), and the saturated soil water content (θ_s) were optimized using the inverse analysis of HYDRUS-2D

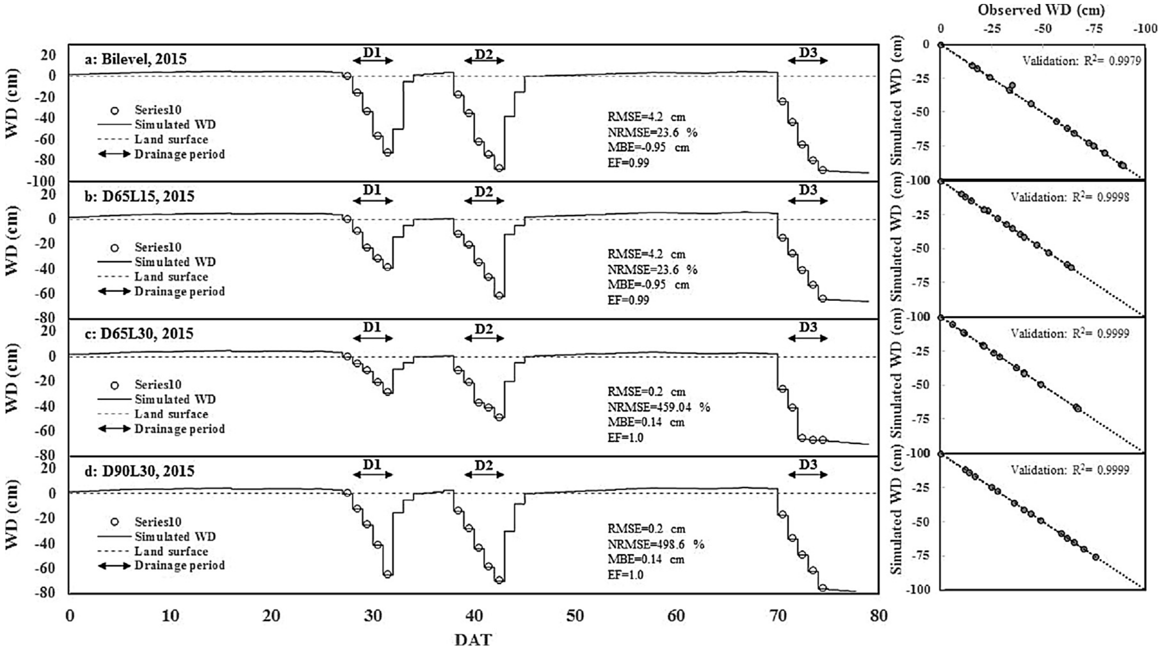


Fig. 4. Temporal variations of water depths (*WD*) midway between drains during the 2015 growing season for the four drainage systems (a: Bilevel, b: $D_{65}L_{15}$, c: $D_{65}L_{30}$, d: $D_{90}L_{30}$) and the AWD water management. D1, D2, and D3 denote the first (25–34 DAT), second (43–47 DAT), and third (64–71 DAT) drainage periods, respectively. Statistical measures evaluating the model performance are also provided.

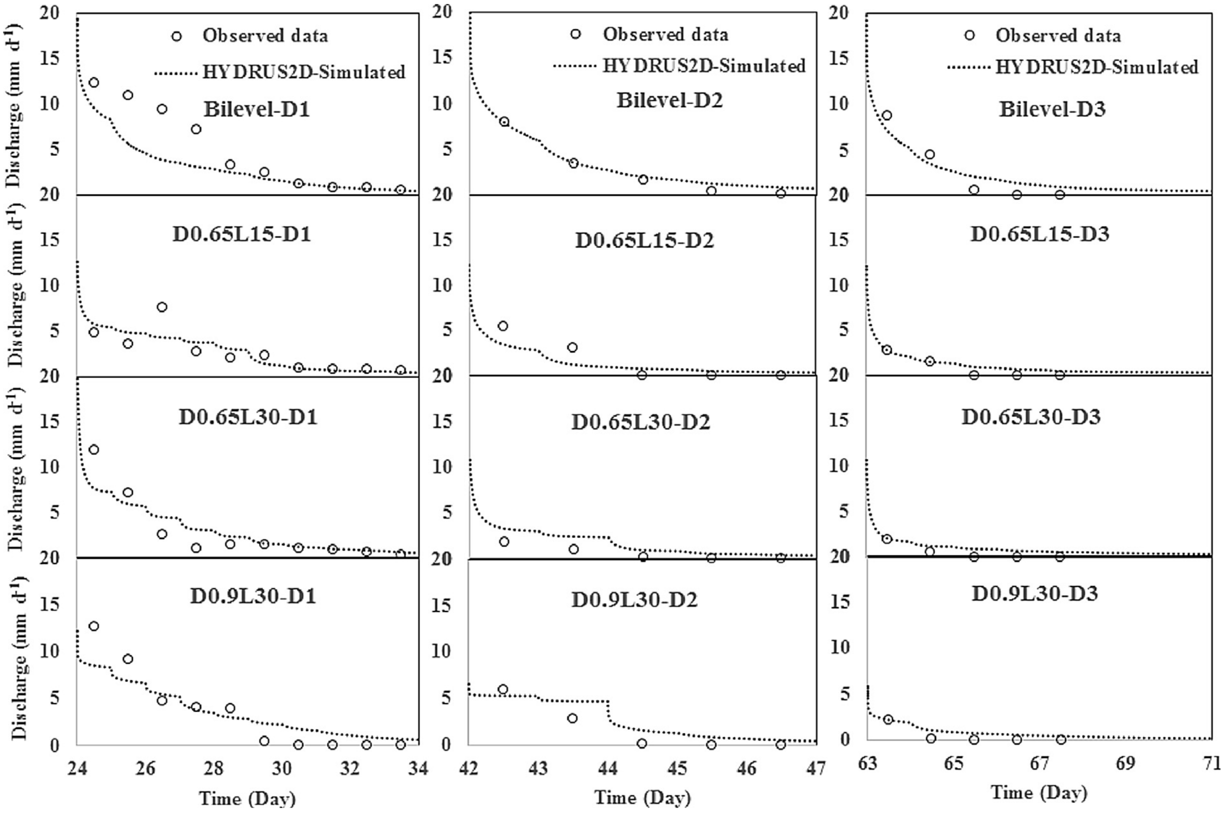


Fig. 5. Temporal variations of drain discharge during the 2014 growing season for the four drainage systems. D1 (left), D2 (middle), and D3 (bottom) denote the first (25–34 DAT), second (43–47 DAT), and third (64–71 DAT) drainage periods, respectively.

and measured *WD*s, while the shape parameters α, *l*, and *n* in the van Genuchten-Mualem model (van Genuchten, 1980) were kept equal to values obtained by RETC. Using the calibrated values of K_s, θ_r, and θ_s, HYDRUS-2D was then validated using temporal variations of *WD*s during the third drainage period in 2014 and the other drainage periods in 2011, 2012, and 2015.

2.5. Criteria indices

The root mean square error (RMSE), the normalized root mean square error (NRMSE), the mean bias error (MBE) and the model efficiency (EF) were calculated to compare the predicted and observed data (Parchami-Araghi et al., 2013).

3. Results and discussion

3.1. Calibration and validation

Figs. 3 and 4 show the simulated and observed daily water depths (*WD*s) along with the model performance criteria for different drainage systems, the AWD water management, and the drainage periods of the 2014 and 2015 growing seasons, respectively. The HYDRUS (2D/3D) model slightly over-predicted *WD*s during the calibration and validation drainage periods in 2014 (Fig. 3), while it closely matched the observed data during drainage periods in 2015 (Fig. 4). The correlation coefficients for the 2015 validation period were even higher than for the 2014 calibration period. The average observed *WD*s for the Bilevel, $D_{0.65}L_{15}$, $D_{0.65}L_{30}$, and $D_{0.9}L_{30}$ drainage systems in 2015 were −50.5, −31.1, −32.9, and −39.9 cm, respectively, while the corresponding simulated values were −50.4, −32.3, −33.1, and −40.1 cm, respectively. The model performance criteria indicate the strong predictive capability of the model. EF, RMSE, NRSME, and MBE ranged from 0.91–1, 0.2–6.4 cm, 15.7–498.6%, and 0.14–5.5 cm, respectively, across different drainage systems and the 2014 and 2015 growing seasons.

The efficiency of the HYDRUS-1D model for simulating soil water contents under the continuous flooding and AWD water management systems in traditional paddy fields was also demonstrated by Tan et al. (2015). During the irrigation periods, *WD*s were generally between 1 and 5 cm on the soil surface. *WD* fluctuations during these periods were mainly due to variations in irrigation amounts, evapotranspiration and crop water demand, as well as percolation. Regardless of soil characteristics, percolation losses are dependent on the depth of ponded water (Khepar et al., 2000), the water table depth (Kampen, 1970), and puddling (Garg et al., 2009). Tan et al. (2014) reported lower deep percolation under AWD than under continuous flooding in an undrained paddy field. However, conducting AWD in subsurface drained paddy fields may enhance crack formation and reduce the positive effects of puddling due to rapid lowering of the water table during drainage periods, which may result in increased percolation losses.

The calibrated model was then applied to simulate *WD*s for the MSD water management strategy (flooding – MSD – re-flooding – end-season drainage) during the 2011 and 2012 growing seasons (data not shown). The correspondence between observed and simulated *WD*s during the MSD periods of these two growing seasons was good, indicating that the calibrated model is well suited for the experimental field.

Fig. 5 shows temporal variations of simulated and observed drain discharges (*q*) for different drainage systems for the drainage periods of the 2014 growing season. The HYDRUS (2D/3D) model slightly under-predicted *q* during the first drainage period (D1) and overestimated it during the last days of the third drainage period (D3) for the Bilevel system. The simulated discharge generally closely matched the observed data for the other drainage systems in 2014. In addition, a visual inspection of scatter plots

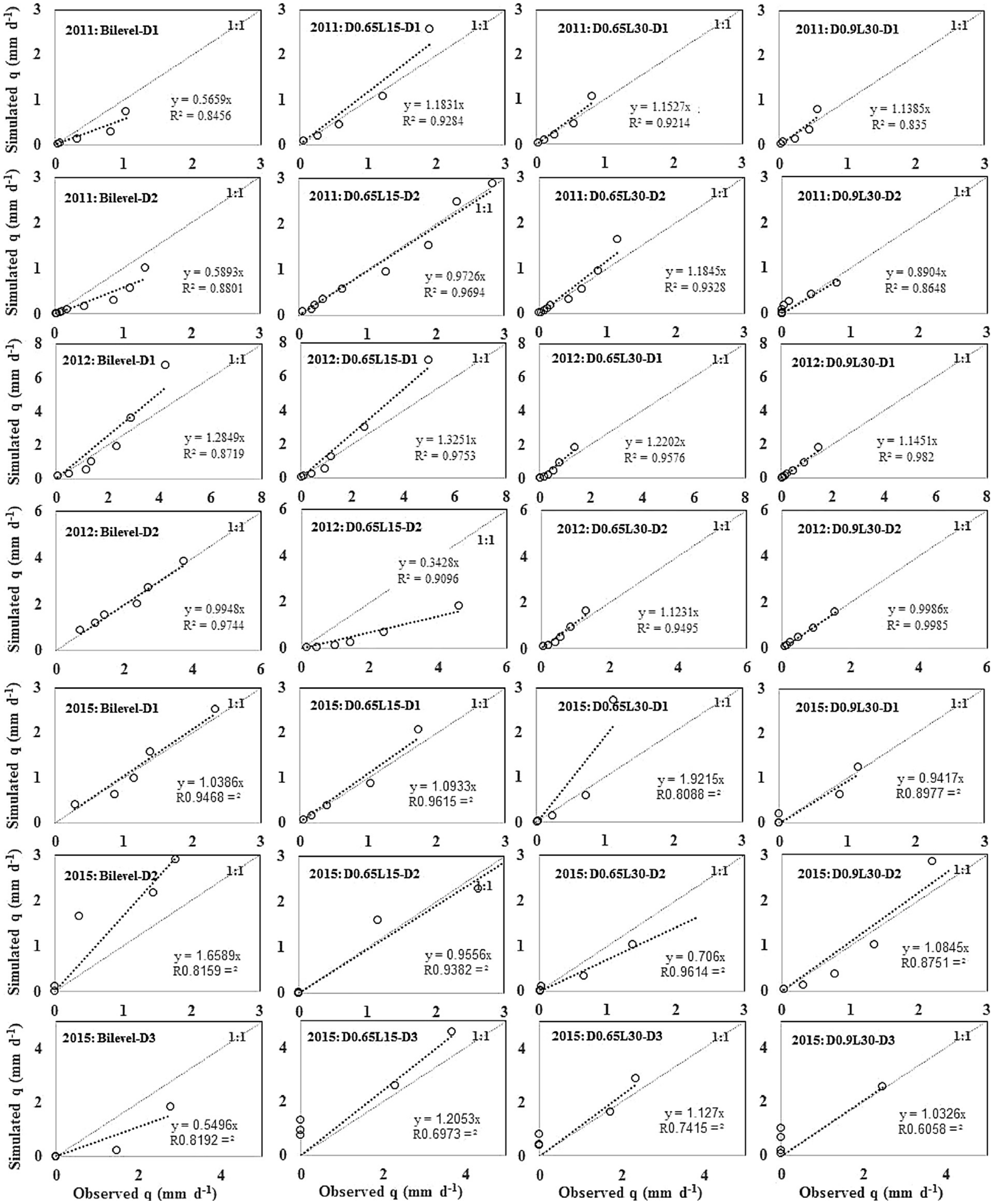


Fig. 6. Scatter plots between observed and HYDRUS-2D-simulated drain discharge (q) during the 2011 (top 2 rows), 2012 (middle 2 rows), and 2015 (bottom 2 rows) growing seasons for the four drainage systems (left to right) and the AWD water management. D1, D2 and D3 denote first, second, and third drainage periods, respectively.

in Fig. 6, which compares observed and HYDRUS-2D-estimated q during the other growing seasons (2011, 2012, and 2015), clearly indicates the high potential of the HYDRUS-2D modeling. Correlation coefficients varied in the range of 0.60-0.99 across different drainage systems, which indicates the strong predictive capability of the model.

3.2. Water table analysis

The ability of HYDRUS (2D/3D) to simulate the spatial water table profile was evaluated by comparing simulated and observed water table depths between the shallow and deep drains in the Bilevel drainage system. Temporal and spatial variations of *WDs* in the Bilevel treatment during three drainage periods in 2014 are

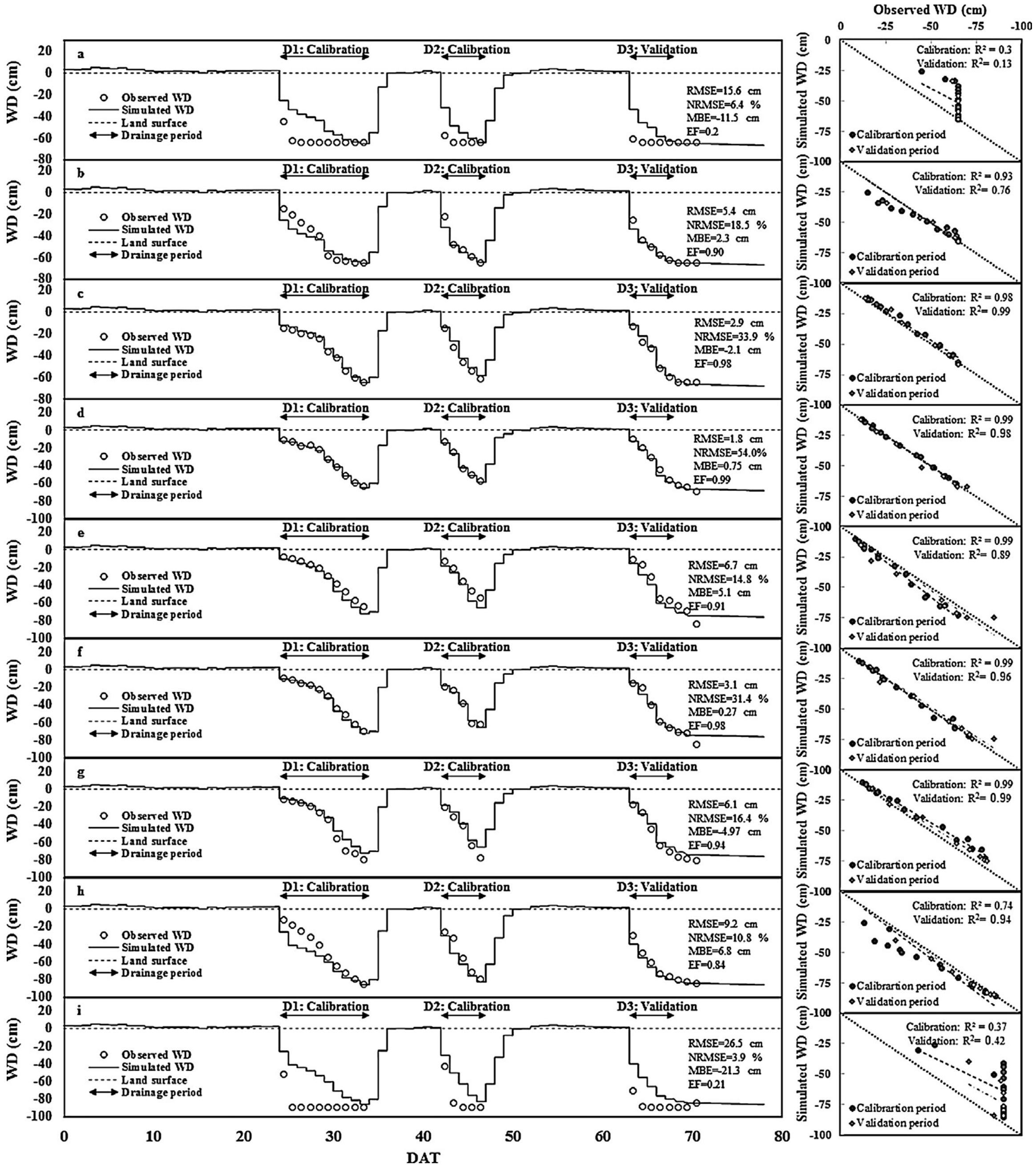


Fig. 7. Temporal variations of water depths (*WD*) at different points between shallow and deep drains in the Bilevel drainage system. "a" denotes the shallow drain, "b", "c", "d", "e", "f", "g", and "h" are 1, 2.5, 5, 7.5, 10, 12.5, and 14 m away from the shallow drain, respectively, and "i" denotes the deep drain. D1, D2, and D3 denote the first (25–34 DAT), second (43–47 DAT), and third (64–71 DAT) drainage periods, respectively.

presented in Figs. 7 and 8, respectively. The accuracy of the predictions was low at the trenches and in the vicinity of the drains. Soil properties in the vicinity of the drains are influenced by drain installations and faster draining of this area than the remaining area between drains. Due to faster soil drying during drainage periods, the surface soil layer above drains tends to develop cracks and other preferential flow paths. The cracks may originate in the backfilled trench and expand further with time. Less accurate predictions in the vicinity of the drains indicate crack development and consequently, different flow patterns and abrupt water table drops in this region.

The simulated water table depths corresponded well to the measured water table depths at distances larger than 1 m from the shallow and deep drains, where the water table falls more gradually. Different responses of the water table profile to drainage are related to specific flow patterns in paddy fields. Puddling, a traditional practice in paddy fields for controlling percolation losses, causes the formation of a less conductive soil layer (a hardpan) below a plow pan (Darzi-Naftchali et al., 2013). This layer causes water to horizontally flow from between the drains to the backfilled trench in a surface soil layer and then vertically into the drains (Ogino and Ota, 2007). Simulated water table profiles clearly indicate that HYDRUS (2D/3D) is a suitable tool for predicting water table fluctuations after irrigation or rainfall even in the presence of crop. This capability makes the model applicable to the assessment of different water table management strategies during the rice growing season.

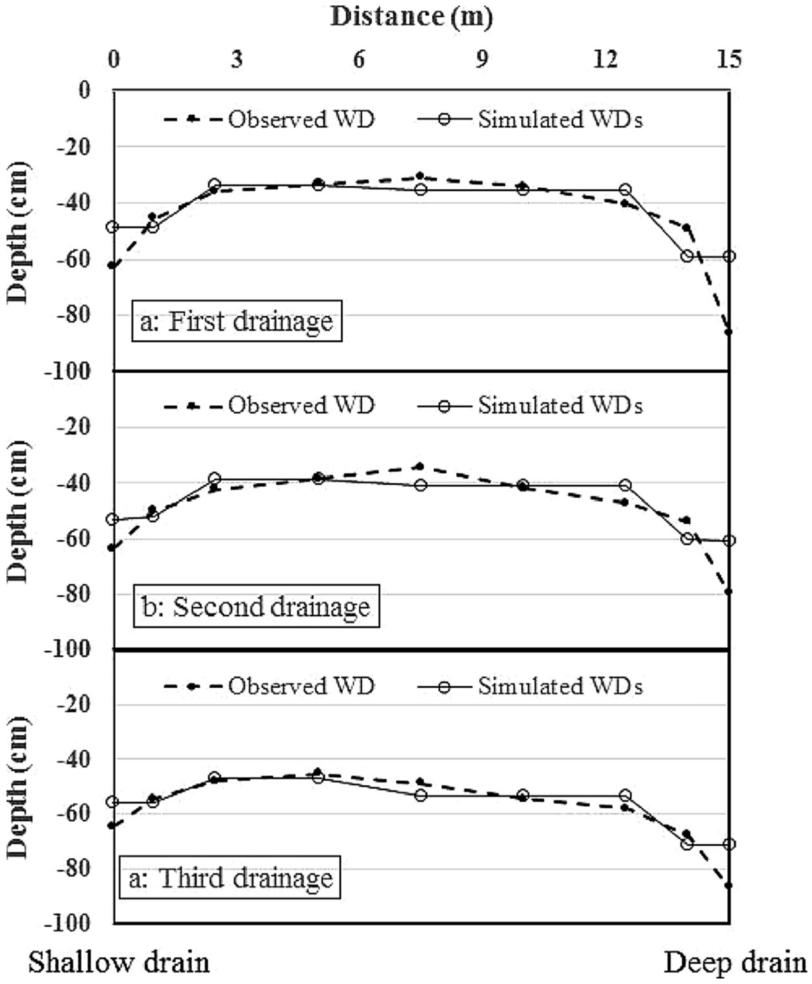


Fig. 8. Spatial variations of average *WDs* during three drainage periods in the Bilevel drainage system in 2014.

3.3. *Water balance analysis*

Since the model performed as well during the validation period as during the calibration period, the calibrated model was further used to analyze various water balance components under the AWD and MSD water management strategies (Table 2). The total measured input of water during the four growing seasons ranged from 677.3 to 786.7 mm. Water requirements of rice were reported to be 700–1500 mm (Guerra et al., 1998) and 935–1211 mm (Thakur et al., 2014) for a medium-duration rice variety (130–135 days). In our study, since an early-maturing rice variety was planted, the crop growth duration from transplanting to harvest in different growing seasons was less than 90 days, and the water consumption was correspondingly lower. The total irrigation volumes in 2011, 2012, 2014, and 2015 were 618, 669, 591, and 698 mm, respectively. Differences in water consumption between different growing seasons were related more to variations in growth conditions than to water management strategies. About 18.1, 9.5, 12.8, and 11.3% of the input water was supplied by rainfall in 2011, 2012, 2014, and 2015, respectively. Due to delayed transplanting in 2015, temperatures and sunshine durations in 2014 were lower than those in 2015, resulting in less evaporation demand in 2014. The main part of the water input was used by *ET*, which varied between 423 and 512 mm. Average daily *ET* under MSD and AWD varied from 4.9 to 6.2 mm d^{-1} and from 4.9 to 5.9 mm d^{-1}, respectively, indicating that there were no considerable differences between the two water management strategies. The differences between *ET* values in different growing seasons and drainage systems could be attributed to the differences in temperature and moisture conditions (Xie and Cui, 2011). Simulated daily *ET* values are comparable with published values of 4–7 mm d^{-1} (e.g., De Datta, 1981) or seasonal ET of 458–483 mm under aerobic rice culture reported by Xue et al. (2008).

Under both management strategies, *ET* increased for drainage systems with higher intensity (i.e., deeper depths and smaller distances between drains), and thus the minimum and maximum *ET* were obtained for $D_{0.65}L_{30}$ and Bilevel, the least and most intensive drainage systems, respectively. Increased *ET* was probably due to enhanced root activity and root development as a result of a faster decrease in the water table depth during drainage periods under more intense drainage systems. A deeper water table causes roots to grow vertically into deeper soil horizons, whereas in wetter systems, roots grow more horizontally (Mishra et al., 1997). Deeper roots increase water extraction from the soil profile during drying periods. Moreover, the crop water demand increased after the first drainage period due to the increased canopy cover. Due to the heavy textured soils at the study site and a short duration of draining periods, soil drying did not reach the threshold limit to negatively affect the crop. On the other hand, it seems that the moderate water stress increased the root activity to capture any available soil moisture. Rijal et al. (2012) reported 16 and 7% higher *ET* for corn and soybean grown in subsurface drained fields than in un-drained fields in 2009 and 2010, respectively.

Table 2
Components of the water balance (WBC) (in mm) during the 2011, 2012, 2014, and 2015 growing seasons for different drainage systems.

Year	WBC	Drainage systems			
		$D_{0.65}L_{15}$	$D_{0.65}L_{30}$	$D_{0.90}L_{30}$	Bilevel
2015	*P+I*	786.7	786.7	786.7	786.7
	ET	498	449	545	509
	E	233	213	187	236
	T	265	237	267	273
	Drainage	15.4	9.7	10.8	16.2
	ΔS	101.3	96.0	9.9	106.5
	DP	172	232	221	155
2014	*P+I*	677.3	677.3	677.3	677.3
	ET	481	434	438	492
	E	243	223	224	263
	T	238	211	215	229
	Drainage	43.2	10.0	57.0	91.1
	ΔS	72.2	77.3	68.3	59.7
	DP	80.9	156	114	34.5
2012	*P+I*	773	773	773	773
	ET	469	423	427	479
	E	237	218	218	256
	T	232	206	209	223
	Drainage	23.3	7.7	7.8	28.4
	ΔS	73.7	73.3	73.2	66.6
	DP	207	269	265	199
2011	*P+I*	755	755	755	755
	ET	502	452	457	512
	E	253	233	233	273
	T	248	220	224	239
	Drainage	15.1	6.1	3.1	7.4
	ΔS	90.9	91.9	89.9	83.6
	DP	147	205	205	152

P – precipitation, *I* – irrigation, *ET* – evapotranspiration, *E* – evaporation, *T* – transpiration, ΔS – change in storage, *DP* – deep percolation.

Table 3
Total biomass, yield, transpiration (*T*), evapotranspiration (*ET*), transpiration efficiency (*TE*), and water use efficiency (*WUE*) for different drainage systems and for the 2011, 2012, 2014, and 2015 growing seasons.

Year	Parameter	DAT	$D_{0.65}L_{15}$	$D_{0.65}L_{30}$	$D_{0.90}L_{30}$	Bilevel
2015	*T* growing season (mm)	–	265	237	267	273
	ET growing season (mm)	–	498	449	454	509
	Yield (Mg ha^{-1})	–	4.9	5.0	4.0	5.0
	TE (g kg^{-1})	16	4.6	4.6	5.3	4.6
		28	4.3	3.3	5.3	3.4
		39	5.1	3.8	4.6	3.8
		50	5.3	4.6	4.5	4.5
		60	3.9	4.4	3.8	4.4
		67	2.8	4.1	3.3	4.2
	TE harvest (g kg^{-1})	–	1.8	2.1	1.5	1.8
	WUE (kg m^{-3})	–	0.98	1.11	0.89	0.99
2014	*T* growing season (mm)	–	238	211	215	229
	ET growing season (mm)	–	481	434	438	492
	Yield (Mg ha^{-1})	–	5.0	4.6	4.3	5.3
	TE (g kg^{-1})	16	4.0	3.5	4.4	4.7
		28	4.8	4.3	5.6	5.1
		39	6.2	5.9	7.2	6.3
		50	6.8	7.2	7.6	6.8
		60	6.3	7.5	6.6	6.4
		67	5.2	6.2	5	5.3
	TE harvest (g kg^{-1})	–	2.1	2.2	2.0	2.3
	WUE (kg m^{-3})	–	1.04	1.07	0.97	1.07
2012	T growing season (mm)	–	232	206	209	223
	ET growing season (mm)	–	469	423	427	479
	Yield (Mg ha^{-1})	–	3.3	3.7	3.9	4.2
	TE harvest (g kg^{-1})	–	1.41	1.81	1.88	1.87
	WUE (kg m^{-3})	–	0.70	0.88	0.92	0.87
2011	*T* growing season (mm)	–	248	220	224	239
	ET growing season (mm)	–	502	452	457	512
	Yield (Mg ha^{-1})	–	3.0	3.5	3.9	4.2
	TE harvest (g kg^{-1})	–	1.21	1.60	1.74	1.78
	WUE (kg m^{-3})	–	0.60	0.78	0.85	0.83

Seasonally, only 0.04–13.6% of the supplied water in different drainage systems was lost to drainage. Simulated drainage losses were higher under the AWD (9.7–91.1 mm) than the MSD (3.1–28.4 mm) strategy. Higher drainage in 2014, compared to 2015, was due to the occurrence of 64.3 mm rainfall during the first drying period and a longer duration of the drainage period. Such non-beneficial losses should be reduced through suitable measures during drying periods. In different growing seasons, minimum and maximum drainage losses occurred in the $D_{0.65}L_{30}$ and Bilevel drainage systems, except in 2011.

A large part of input water was lost through deep percolation, defined here as flow below the root zone, accounting for 12–35% across the growing seasons and drainage systems. Simulated percolation losses were higher under MSD than AWD. On average, percolation losses ranged from 1.8 to 3.1 mm d^{-1} under MSD and from 0.4 to 2.7 mm d^{-1} under AWD. These values are in the range of the 1–5 mm d^{-1} percolation losses reported by Bouman and Tuong (2001). Generally, as expected, the minimum and maximum percolation losses occurred in the $D_{0.65}L_{30}$ amd Bilevel drainage systems, respectively. Total non-productive outflows through drainage and percolation varied from 159 to 277 mm for MSD and from 124 to 232 mm for AWD. Simulated total losses under both management strategies (1.4–3.2 mm d^{-1}) are lower than percolation losses reported for conventional paddies, 4.3–5.0 mm d^{-1} (Aimrun et al., 2010), 3.6 mm d^{-1} (Chen and Liu, 2002), and 5.21 mm d^{-1} (Pathak et al., 2004). The simulation results indicate that a suitable subsurface drainage system can be selected based on the optimum balance between percolation and drainage losses and a desired water management strategy. As nitrogen and phosphorus fertilizers are lost from paddy fields mainly through these routes of water losses, the reduction of percolation and drainage could be an effective measure to increase the nutrient use efficiency.

3.4. Transpiration and water use efficiency

Transpiration, *ET*, grain yield, transpiration efficiency (*TE*), and water use efficiency (*WUE*) for different drainage systems under the MSD and AWD strategies are presented in Table 3. There were no obvious trends for *T* under the different drainage systems. The *T* to *ET* ratio is a useful index to understand the crop behavior in response to the deficit water stress. Transpiration constituted 47–59% and 45–49% of *ET* under the AWD and MSD strategies, respectively, across the growing seasons and drainage systems, indicating a more plant stress to drying under MSD than AWD. It was reported that *T* accounts for 50–90% of total *ET* during a growing season in wetlands (Bachand et al., 2013). However, Bouman et al. (2005) reported lower *T* under AWD than under full flooding. The predicted range of *T* was low (0.2–0.6 mm d^{-1}) at the early stage of growth and reached its maximum (5.1–6.2 mm d^{-1}) at 50 and 60 DAT (data not shown). The maximum simulated *T* values are in agreement with the corresponding values of 5–7 mm d^{-1} reported by Tomar and O'Toole (1980) for heading time under flooded conditions.

The transpiration efficiency gradually increased in 2014 until 50 and 60 DAT and then decreased until harvest. Except for *TE* at 16 DAT, a similar trend occurred in 2015 under all drainage systems, except for $D_{0.9}L_{30}$. High *TE* at 16 DAT in 2015 was mainly attributed to the higher production of dry matter than during the same period in 2014. Additionally, climatic conditions have a considerable effect on CO_2 and water vapor diffusion processes at the leaf surface (Haefele et al., 2009), which may influence the *T* rate. The seasonal average of *TE* ranged from 3.8–5.5 g kg^{-1}, with higher *TE*s in 2014. Higher *TE* in 2014 was a possible reason for higher grain yield in all drainage systems except in $D_{0.65}L_{30}$ where a higher yield was produced in 2015. Under different drainage systems, *TE* at harvest was higher under AWD than MSD, except for $D_{0.9}L_{30}$. However, *TE* at harvest is not a helpful index to address differences in grain yield, as higher grain yield was observed under AWD in various drainage systems. Plants under a water stress likely transpire in the early hours of the morning and close their stomata later in the day (Vadez et al., 2014).

Yield is reported as a function of the quantity of water extracted from the soil to support *T*, *TE*, and the conversion of biomass into grains via the harvest index (Vadez and Ratnakumar, 2016). No study has looked at the *TE* dynamics in rice under both the MSD and AWD strategies in relation to a drying stress. However, predicted *TE*s are in agreement with some published values: 2.3–5.9 g kg^{-1} (Yoshida, 1975) and 2.5–5.4 g kg^{-1} (Impa et al., 2005). Since *T* is the only productive water consumption, assessing the *TE* dynamics should help in finding the optimum duration and timing of drying periods under the AWD and MSD strategies. In addition, the *WUE* could be enhanced by increasing *T*. The *WUE* responded differently to different water managements in different drainage systems. The $D_{0.65}L_{30}$ and $D_{0.9}L_{30}$ drainage systems produced the highest *WUE* under the AWD and MSD strategies, respectively. Moreover, a higher *WUE* was obtained under AWD (0.89–1.11 kg m^{-3}) than under MSD (0.65–0.92 kg m^{-3}).

4. Conclusions

This experimental and numerical study was carried out to analyze complex consequences of the AWD and MSD water management strategies in subsurface drained paddy fields. The HYDRUS (2D/3D) model performed well during both the calibration and validation phases for both water management strategies, as its results closely matched the observed drainage discharges and water table depths. The model predicted well the water table profile between two semi and bilevel subsurface drains except in the immediate vicinity of the drains. A higher intensity of the subsurface drainage systems increased both *ET* and drainage losses while decreasing deep percolation losses. 20.2–27.8% and 25.7–41% of supplied water were lost through drainage and percolation under the AWD and MSD strategies, respectively, indicating a better response of subsurface drained paddy fields to AWD from the water conservation viewpoint. During the study period, the maximum losses of water occurred in to $D_{0.90}L_{30}$, followed by $D_{0.65}L_{30}$, $D_{0.65}L_{15}$, and Bilevel. Simulation results indicated that there were no considerable differences between *ET* values under MSD and AWD while the *WUE* was slightly higher under the AWD strategy. Both transpiration, as the only productive water use in paddy fields, and *TE* were higher under AWD than under MSD. Under the MSD and AWD practices, the maximum *TE*s and *WUE*s were found in $D_{0.90}L_{30}$ and $D_{0.65}L_{30}$, respectively. The results of this study indicated that the HYDRUS (2D/3D) model is well suited for analyzing soil water dynamics in paddy fields equipped with different subsurface drainage systems.

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