Comparison of One- and Two-Dimensional Models to Simulate Alternate and Conventional Furrow Fertigation

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Abstract: Simulation models have recently been used in many studies for simulation of water flow and solute transport in soil under different irrigation systems. The objective of this study was to compare the HYDRUS-1D and HYDRUS-2D simulation models to simulate water and nitrate transfer for three furrow irrigation technologies [conventional furrow irrigation (CFI), fixed alternate furrow irrigation (FFI), and variable alternate furrow irrigation (AFI)] under fertigation practice. Filed measured data were used to calibrate and validate the one-dimensional (1D) and two-dimensional (2D) HYDRUS models. An inverse solution technique was applied to optimize soil-hydraulic and solute transport parameters to calibrate the models. The results indicated that the HYDRUS-2D model provided better performance to predict soil water contents, nitrate concentrations, and deep percolation caused by the geometry of the infiltration domain in furrow irrigation. Standard errors for HYDRUS-1D ranged from 0.107 to 0.170 for soil water content and 0.256 to 0.295 for soil nitrate concentration; whereas these values for HYDRUS-2D varied between 0.089 and 0.096 and 0.144 and 0.205 for soil water content and soil nitrate concentration, respectively. Application of HYDRUS-1D increased the risk of overestimation of nitrate leaching. CFI had higher water and nitrate deep percolation compared to AFI and FFI. Although the HYDRUS-2D model required much more computational time than HYDRUS-1D, using this model is recommended in furrow fertigation because of its more reliable and accurate simulation results.
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Introduction

In recent years, water resources for irrigated agriculture have declined because of increasing industrial and domestic water consumption. Water saving and increased irrigation water productivity are essential to cope with the water crisis in arid and semi arid regions. Several researchers reported that alternate furrow irrigation can be used for this purpose (Kang et al. 2000; Thind et al. 2010; Ebrahimian et al. 2011b; Slatni et al. 2011). Surface fertigation has resulted in increasing fertilizer-distribution uniformity and application efficiency (Playán and Faci 1997; Santos et al. 1997; Abbasi et al. 2003a; Adamsen et al. 2005; Perea et al. 2010). Moreover, low energy and labor requirements, potential for small and frequent fertilizer application, and reduction in soil compaction and crop damage resulting from machine traffic are other advantages of surface fertigation. Therefore, alternate furrow fertigation could simultaneously reduce water and fertilizer losses and also has a great potential to mitigate the environmental risks from agriculture (Ebrahimian et al. 2011a).

Simulation models are widely used to improve the design, management, and performance of irrigation systems. Flexibility, cost effectiveness, and analysis and evaluation of various scenarios are some advantages of this modeling approach. Benjamin et al. (1994) evaluated the SWMS-2D model (Šimůnek et al. 1994) for simulating fertilizer distribution in the soil under broadcast fertilization for conventional and alternate furrow irrigation. The fertilizer applied on the non irrigated (dry) furrows (alternate furrow irrigation) in a loamy sand soil may not be taken up by plants because of the low water content at the upper layer of the dry furrow. Santos et al. (1997) applied the OPUS model (Smith 1992) to simulate water and nitrate in a level basin for different fertigation strategies. Good agreement between observed and simulated soil water and nitrate profiles was reported. Abbasi et al. (2004) reported that the HYDRUS-2D model (Šimůnek et al. 1999) could successfully simulate water flow and solute transport under furrow fertigation. There was satisfactory agreement between measured and predicted soil water and solute concentration along the blocked-end furrow cross-section. Zerihun et al. (2005) developed and verified a coupled surface-subsurface solute transport model for surface fertigation. The HYDRUS-1D model (Šimůnek et al. 1998) was used to simulate water flow and solute transport through the subsurface. The model was capable to predict bromide breakthrough curves for border and basin irrigation satisfactorily. Mailhol et al. (2007) tested HYDRUS-2D to estimate nitrogen leaching with fertilizer replacement on the upper part of the ridge for 1.5-m-long blocked

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furrows. The model predicted approximately 10% of the applied nitrogen leaching behind the root zone during the irrigation season under high water application depth. Crevoisier et al. (2008) calibrated and validated HYDRUS-2D for conventional furrow irrigation and fixed alternate furrow irrigation under broadcasting fertilization. The model performance was satisfactorily accurate to simulate soil matric potential and nitrate concentration and nitrogen leaching, particularly for conventional furrow irrigation.

Wöhling et al. (2004) showed the potential of the two-dimensional (2D) analytical furrow infiltration model (FURINF-A) in predicting cumulative infiltration from furrows into a wide range of soils. They suggested that this model is a robust and rather simple alternative to HYDRUS-2D because of its low CPU time requirement and easily measurable soil parameters. Two-dimensional numerical simulation models usually requires considerable computational time and more input data compared to one-dimensional (1D) simulation models. In fact, there is a trade-off between the accuracy, cost, and time issues in using these models. Comparison of these two different models could lead to better judgment and decisions about applying them in practical application. Therefore, the goal of this paper was to compare the HYDRUS-1D and HYDRUS-2D models in terms of (1) estimation of soil water content and nitrate concentration, (2) estimation of water and nitrate deep percolation, and (3) computational time for two alternate furrow irrigations (i.e., fixed and variable) and also for conventional furrow irrigation under fertigation practice. Field data were used to calibrate and validate these simulation models.

Materials and Methods

Field Experiment

The field experiment was carried out to collect filed data at the Experimental Station of College of Agriculture and Natural Resources at the University of Tehran, Karaj, in 2010. The field study was conducted for fixed and variable alternate furrow irrigation (FFI and AFI, respectively) and conventional furrow irrigation (CFI) under fertigation practice for maize production. Pre sowing fertilizer application was limited to 10% of the nitrogen fertilizer requirements (200 $\mathrm{kg\,N\,ha^{-1}}$), and was applied the day before sowing using a mechanical broadcaster. Three nitrogen dressings (with equal amount of 30% of the fertilizer requirements) were applied at the vegetative (seven leaves, in July 7), flowering (August 9), and grain-filling (August 30) growth stages using surface fertigation. Nitrogen fertilizer was applied in the form of granulated ammonium nitrate. The same amount of water and fertilizer was applied to all irrigated furrows. Thus, the water and fertilizer application rate per unit area was twice as much for conventional irrigation as for the two alternate irrigation treatments.

Soil depth was limited to 0.60 m because of the presence of an underlying gravel layer. The physical characteristics of soil at the upstream, middle, and downstream parts of the experimental field are presented in Table 1. The furrow spacing was 0.75 m, the furrow length was 86 m, and the longitudinal slope was 0.0093. Auger soil samples were collected at wet (irrigated) furrow bed from three soil layers (0.0–0.2, 0.2–0.4, and 0.4–0.6 m). The soil samples were taken at the upstream, middle, and downstream of the experimental field to measure soil water content and nitrate concentration before and after the first and second fertigation events. Irrigation was applied on a 7-day interval throughout the irrigation season. During the first fertigation event, discharge was 0.262 L/s and cutoff time was 240 min. In this event, the fertilizer solution was injected after the time of advance (approximately 50 min, depending on the particular furrow). The injection time was 150 min in all furrows. During the second fertigation event, discharge was 0.388 L/s, and cutoff time was 360 min. In this event, the fertilizer solution was injected during the first half of irrigation time (injection time of 180 min). More details about the field experiments can be obtained from Ebrahimian et al. (2011c).

HYDRUS-2D

The HYDRUS-2D model (Šimůnek et al. 1999) uses the two-dimensional form of Richards' equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x_i}\left[K\left(K_{ij}^{A}\frac{\partial h}{\partial x_j} + K_{iz}^{A}\right)\right] - S \tag{1}$$

where θ = volumetric water content (dimensionless); h = pressure head [L]; S is a sink term [$\mathrm{T^{-1}}$]; x_i and x_j = spatial coordinates [L]; t = time [T]; K_{ij}^{A} = components of a dimensionless anisotropy tensor K^A; and K = unsaturated hydraulic conductivity function [$\mathrm{L\,T^{-1}}$].

The HYDRUS-2D model implements the soil-hydraulic functions proposed by van Genuchten (1980) and Mualem (1976) to describe the soil water retention curve, $\theta(h)$, and the unsaturated hydraulic conductivity function, $K(h)$, respectively:

$$\theta(h) = \begin{cases} \theta_r + \frac{\theta_s - \theta_r}{[1+|\alpha h|^n]^m} & h < 0 \\ \theta_s & h \geq 0 \end{cases} \tag{2}$$

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

$$m = 1 - 1/n, \quad n > 1 \tag{4}$$

Table 1. Soil Physical Properties Determined at Upstream, Middle, and Downstream Parts of Experimental Field

Location	Depth (m)	Texture classification (USDA)	Soil particles (%)			Bulk density ($\mathrm{Mg\,m^{-3}}$)
			Clay	Silt	Sand	
Upstream	0.0–0.2	Clay loam	28.5	35.0	36.5	1.50
	0.2–0.4	Clay loam	28.5	33.8	37.8	1.45
	0.4–0.6	Sandy loam	16.0	17.5	66.5	1.47
Middle	0.0–0.2	Loam	26.0	30.0	44.0	1.50
	0.2–0.4	Sandy clay loam	23.5	25.0	51.5	1.45
	0.4–0.6	Sandy clay loam	21.0	22.5	56.5	1.52
Downstream	0.0–0.2	Clay loam	31.0	31.7	37.3	1.51
	0.2–0.4	Loam	26.8	30.4	42.8	1.48
	0.4–0.6	Sandy loam	20.2	24.6	55.3	1.49

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$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad (5)$$

where θ_r and θ_s denote the residual and saturated water content, respectively (dimensionless); α = inverse of the air-entry value [L^{-1}]; K_s = saturated hydraulic conductivity [$L\,T^{-1}$]; n = pore-size distribution index (dimensionless); S_e = effective water content (dimensionless); and l = pore-connectivity parameter (dimensionless), with an estimated value of 0.5, resulting from averaging conditions in a range of soils (Mualem 1976).

HYDRUS-2D numerically solves the convection-diffusion equation with zero- and first-order reaction and sink terms. The Galerkin finite-element method is used in this model to solve the governing equation subjected to appropriate initial and boundary conditions. In this study, only the nitrate (NO_{3^-}) transfer was simulated by solving the following equation:

$$\frac{\partial \theta c}{\partial t} = \frac{\partial}{\partial x_i}\left(\theta D_{ij}\frac{\partial c}{\partial x_j}\right) - \frac{\partial q_i c}{\partial x_i} + \gamma_w \theta - S c_s \quad (6)$$

where c = nitrate concentration in the soil [$M\,L^{-3}$]; q_i = ith component of the volumetric flux [$L\,T^{-1}$]; D_{ij} = dispersion coefficient tensor [$L^2\,T^{-1}$]; γ_w = zero-order rate constant for nitrate production by ammonium degradation in the soil solution [$M\,L^{-3}\,T^{-1}$]; S = sink term of the water flow in the Richards' equation; and c_s = concentration of the sink term [$M\,L^{-3}$]. D_{ij} can be defined as follows:

$$\theta D_{ij}^w = D_T|q|\delta_{ij} + (D_L - D_T)\frac{q_j q_i}{|q|} + \theta D_w \tau_w \delta_{ij} \quad (7)$$

where D_w = molecular diffusion coefficient in free water [$L^2\,T^{-1}$]; τ_w = tortuosity factor (dimensionless); δ_{ij} = Kronecker delta function ($\delta_{ij} = 1$ if $i = j$, and $\delta_{ij} = 0$ if $i \neq j$); D_L = longitudinal dispersivity [L]; and D_T = transverse dispersivity [L]. Appropriate spatial discretization is crucial to avoid numerical oscillations and achieve acceptable mass balance error (Šimůnek et al. 1999; Valiantzas et al. 2011). At the soil surface (with sharp gradients), the discretization decreased to approximately 1 cm and in the other parts was approximately 3–4 cm. As suggested in the manual of the HYDRUS-2D model for minimizing or eliminating numerical oscillations, the criterion "$\mathsf{P}.Cr \leq 2$" was used, in which P and Cr are the Peclet and Courant (Cr) numbers, respectively.

The sink term (S) represents the volume of water removed from a unit volume of soil per unit time because of plant water uptake. This term was determined according to the Feddes et al. (1978) approach, as implemented in the HYDRUS-2D model. Measured nitrate concentrations and soil water contents before each fertigation event were used as initial conditions within the flow domain. Maximum concentrations of nitrate in the sink term c_s were estimated using the values obtained by Crevoisier et al. (2008). As a consequence, the nitrate c_s values for the first and second fertigation events were chosen as 0.15 and 0.55 $kg\,m^{-3}$, respectively, according to the evolution of plant height during the growing season. The simulation geometry and boundary conditions for alternate furrow irrigation are presented in Fig. 1. Similar conditions were applied for conventional furrow irrigation as well (i.e., for the wet furrow and ridge).

The first fertigation event was used for the calibration of the model. A number of water flow and nitrate transport parameters were estimated using an inverse solution procedure implementing the Levenberg-Marquardt optimization module built-in HYDRUS-2D (Šimůnek et al. 1999). The inverse method is based on the minimization of a suitable objective function, which expresses the discrepancy between the observed and model predicted values.

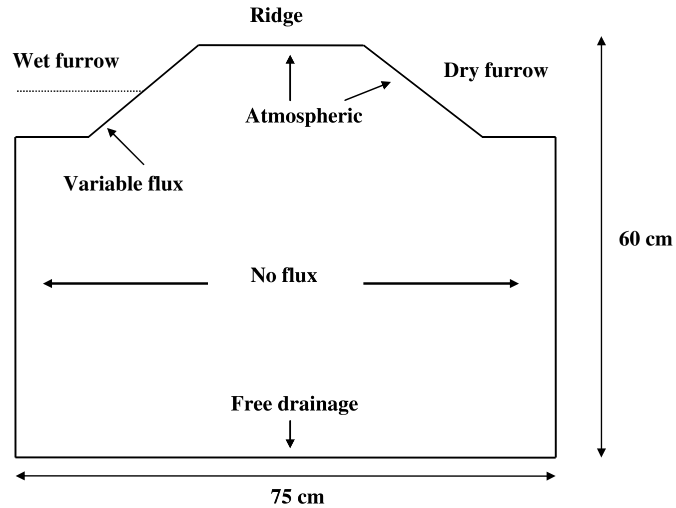

Fig. 1. Schematic representation of boundary conditions used in HYDRUS-2D for alternate furrow irrigation

The objective function was defined as the sum of squared residuals (SSQ):

$$\mathrm{SSQ} = \sum_{j=1}^{m} v_j \sum_{i=1}^{n} w_{ij}[q_j^*(x,z,t_i) - q_j(x,z,t_i,b)]^2 \quad (8)$$

where n = number of measurements for the jth measurement set (e.g., water contents, concentrations, ...); $q_i^*(x,z,t_i)$ = measurement at time t_i, location x, and depth z; $q_i(x,z,t_i,b)$ = corresponding model prediction obtained with the vector of optimized parameters $b = (\theta_s, K_s D_L, \ldots)$; and v_j and w_{ij} = weights associated with a particular measurement set or point, respectively. Weighting coefficients were assumed to be equal to 1 in all cases. Quality in parameter estimation was assessed using two dimensionless indicators: the coefficient of determination (R^2) and SSQ.

This approach has been successfully applied by several researchers (Abbasi et al. 2003b; Crevoisier et al. 2008; Verbist et al. 2009) to estimate soil-hydraulic and solute transport parameters. In this paper, inverse estimation was applied to three water flow parameters, including K_s (saturated hydraulic conductivity), θ_s (saturated soil water content), and n (corresponding to the van Genuchten water retention function), and three nitrate transport parameters, including D_L (longitudinal dispersivity), D_T (transverse dispersivity), and γ_w (zero-order production rate constant for dissolved phase). The γ_w coefficient was applied to the process of ammonium nitrification in the soil (biological conversion of NH_{4^+} to NO_{3^-}). The experimental data set only contained nitrate measurements. These measurements (and their temporal and spatial changes) were used to characterize the nitrification process. The α and θ_r parameters of the soil water retention curve were estimated using the neural network approach provided by HYDRUS-2D. The soil-hydraulic and solute transport parameters were simultaneously estimated. The inverse optimization method simultaneously uses all measured data, i.e., water contents and nitrate concentrations, and yields better estimation than sequential optimization because it considers the interactive effects between the water flow and solute transport parameters (Abbasi et al. 2003b; Šimůnek et al. 2002). The second fertigation event was used for the validation of the model. HYDRUS-2D was run for this event using the parameters calibrated for the first fertigation event.

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HYDRUS-1D

The HYDRUS-1D model (Šimůnek et al. 1998) solves the one-dimensional form of the governing equations of HYDRUS-2D for simulating water movement and solute transport in the soil. The one-dimensional forms of Eqs. 1, 6, and 7 are as follows, respectively:

$$\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial x}\left[K\left(\frac{\partial h}{\partial x}+\cos\alpha\right)\right]-S \tag{9}$$

$$\frac{\partial\theta c}{\partial t}+\frac{\partial\rho s}{\partial t}=\frac{\partial}{\partial x}\left(\theta D^{w}\frac{\partial c}{\partial x}\right)-\frac{\partial qc}{\partial x}+\mu_w\theta c+\mu_s\rho s+\gamma_w\theta+\gamma_s\rho-Sc_s \tag{10}$$

$$\theta D^{w}=D_L|q|+\theta D_w\tau_w \tag{11}$$

where α = angle between the flow direction and the vertical axis ($\alpha=0°$ for vertical flow, 90° for horizontal flow, and $0° < \alpha < 90°$ for inclined flow).

The inputs, outputs, and assumptions of this model are also similar to HYDRUS-2D. Similar methodology was applied for HYDRUS-1D, such as calibration (inverse solution) for the first fertigation and validation for the second fertigation. Inverse estimation was applied to three water flow parameters, K_s, θ_s, and n, and two nitrate transport parameters, D_L and γ_w. The data corresponding to the wet furrow were only used for the calibration and validation process. Thus, the geometry and initial and boundary conditions were only defined for the wet furrow, as described in Fig. 1.

Evaluation

To evaluate the performance of both models, the predicted values of soil water content and nitrate concentration below wet furrows were compared with the measured values for two and six days after the second fertigation event. To determine the accuracy of each model, standard error (SE) was calculated using the following equation:

$$\text{SE}=\frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}[M_i-P_i]^2}}{\bar{P}} \tag{12}$$

where n = number of measurements; M_i = ith measured value; P_i = ith predicted value, and $\bar{P}$ = average of the predicted values. The better is the fit, the closer SE is to zero.

The paired-samples t-test procedure was also used to statistically compare validation variables (Minitab 1995). The test computes the differences between values of the two variables for each case and tests whether the average differs from zero. If the p-value exceeds 0.05, no significant differences can be established between measured and predicted data.

Water and nitrate deep percolation were considered in this assessment as well. The water deep-percolation fraction (DP_w) is the percentage of the applied water (V_{tot}) percolating below the root zone, as follows:

$$DP_w=\frac{V_{dp}}{V_{\text{tot}}}\times 100 \tag{13}$$

where V_{dp} = mean of volume of percolated water at the upstream, middle, and downstream parts of the wet furrow (m^3).

The nitrate deep-percolation fraction (DP_n) is the percentage of the applied nitrate (M_{tot}) percolating below the root zone

$$DP_n=\frac{M_{dp}}{M_{\text{tot}}}\times 100 \tag{14}$$

where M_{dp} = mean of nitrate mass in deep percolation at the upstream, middle, and downstream parts of the wet furrow (g).

The value of DP_w was experimentally determined from field data (such as soil water content at different depths and runoff) and using the water balance equation, and by the simulation models. In the case of DP_n, both models provided an estimate of it for each irrigation treatment; this estimate could not be determined from the experimental data.

Table 2. Summary of Optimized Soil-Hydraulic and Nitrate Transport Parameters for Different Irrigation Treatments Using HYDRUS-1D and HYDRUS-2D

			Soil-hydraulic parameters			Nitrate transport parameters				
Model	Irrigation	Furrow location	θ_s (−)	n (−)	K_s (cm h^{-1})	D_L (cm)	D_T (cm)	γ_w (mg cm^{-3} h^{-1})	R^2 (−)	SSQ (−)
HYDRUS-1D	AFI	Upstream	0.352	1.50	0.60	1.23	—	0.00189	0.875	0.343
		Middle	0.350	1.40	0.47	1.58	—	0.00201	0.863	0.247
		Downstream	0.350	1.57	0.45	3.04	—	0.00128	0.931	0.125
	FFI	Upstream	0.395	2.92	0.30	0.17	—	0.00153	0.922	0.216
		Middle	0.350	1.69	0.46	0.01	—	0.00166	0.875	0.259
		Downstream	0.350	1.51	0.53	6.99	—	0.00130	0.939	0.197
	CFI	Upstream	0.465	1.68	0.46	7.13	—	0.00197	0.945	0.136
		Middle	0.350	1.40	0.57	0.62	—	0.00154	0.948	0.316
		Downstream	0.363	2.03	0.27	4.74	—	0.00137	0.950	0.238
HYDRUS-2D	AFI	Upstream	0.372	1.31	2.52	0.54	0.10	0.00133	0.768	0.537
		Middle	0.365	1.53	1.19	4.27	0.00	0.00126	0.690	0.730
		Downstream	0.350	1.47	1.20	2.36	0.35	0.00109	0.748	0.692
	FFI	Upstream	0.405	1.97	0.76	1.26	1.67	0.00133	0.799	0.480
		Middle	0.382	1.30	2.39	7.82	0.40	0.00112	0.912	0.104
		Downstream	0.350	1.22	3.69	5.79	1.21	0.00107	0.819	0.450
	CFI	Upstream	0.517	1.71	2.63	2.94	2.10	0.00153	0.639	0.828
		Middle	0.350	1.43	1.42	3.73	0.91	0.00127	0.764	0.667
		Downstream	0.389	2.07	0.44	1.38	0.25	0.00124	0.866	0.320

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Results and Discussions

Models Calibration

The inverse solution was performed for a homogeneous soil profile (a single 0.6-m layer). Both models could not converge for estimating the parameters of the three layers reported in Table 2 because of insufficient measured data. The optimized soil-hydraulic and nitrate transport parameters at the upstream, middle, and downstream for each irrigation treatment obtained by both models are presented in Table 2. These parameter values resulted in minimum error between the observed and simulated values. The R^2 and SSQ indicators attained satisfactory values in all cases. The R^2 and SSQ values varied between 0.863–0.950 and 0.125–0.343, respectively, for HYDRUS-1D, and 0.639–0.912 and 0.104–0.828, respectively, for HYDRUS-2D.

For HYDRUS-1D, the ranges of optimum K_s, θ_s, and n values were 0.27–0.60 $\mathrm{cm\,h^{-1}}$, 0.350–0.465 $\mathrm{cm^3\,cm^{-3}}$, and 1.40–2.92, respectively. The optimized D_L values varied between 0.01 and 7.13 cm, whereas the optimum γ_w ranged frp, 0.00128 to 0.00201 $\mathrm{mg\,cm^{-3}\,h^{-1}}$. For HYDRUS-2D, the optimized K_s, θ_s and n values ranged from 0.44 to 3.69 $\mathrm{cm\,h^{-1}}$, 0.350 to 0.517 $\mathrm{cm^3\,cm^{-3}}$, and 1.22 to 2.07, respectively. Ranges of optimum D_L, D_T, and γ_w values were 0.54–7.82 cm, 0.00–2.10 cm, and 0.00107–0.00153 $\mathrm{mg\,cm^{-3}\,h^{-1}}$, respectively. Thus, there was a difference between two models in estimating soil parameters.

Validation and Comparison

The validation processes were done by running the HYDRUS-1D and HYDRUS-2D models for the conditions of the second fertigation with the optimized values obtained by the inverse solution from the first fertigation. Both models were compared for estimating soil water content, nitrate concentration, and deep percolation, and also for computational time.

Water Content

The predicted values of soil water content were compared with the measured data for all irrigation treatments after the second fertigation (Fig. 2). The SE values for the AFI, FFI, and CFI treatments were 0.170, 0.107, and 0.134, respectively, for HYDRUS-1D and 0.095, 0.089, and 0.096, respectively, for HYDRUS-2D. The R^2 values for the AFI, FFI, and CFI treatments were 0.487, 0.693, and 0.623, respectively, for HYDRUS-1D and 0.571, 0.878, and

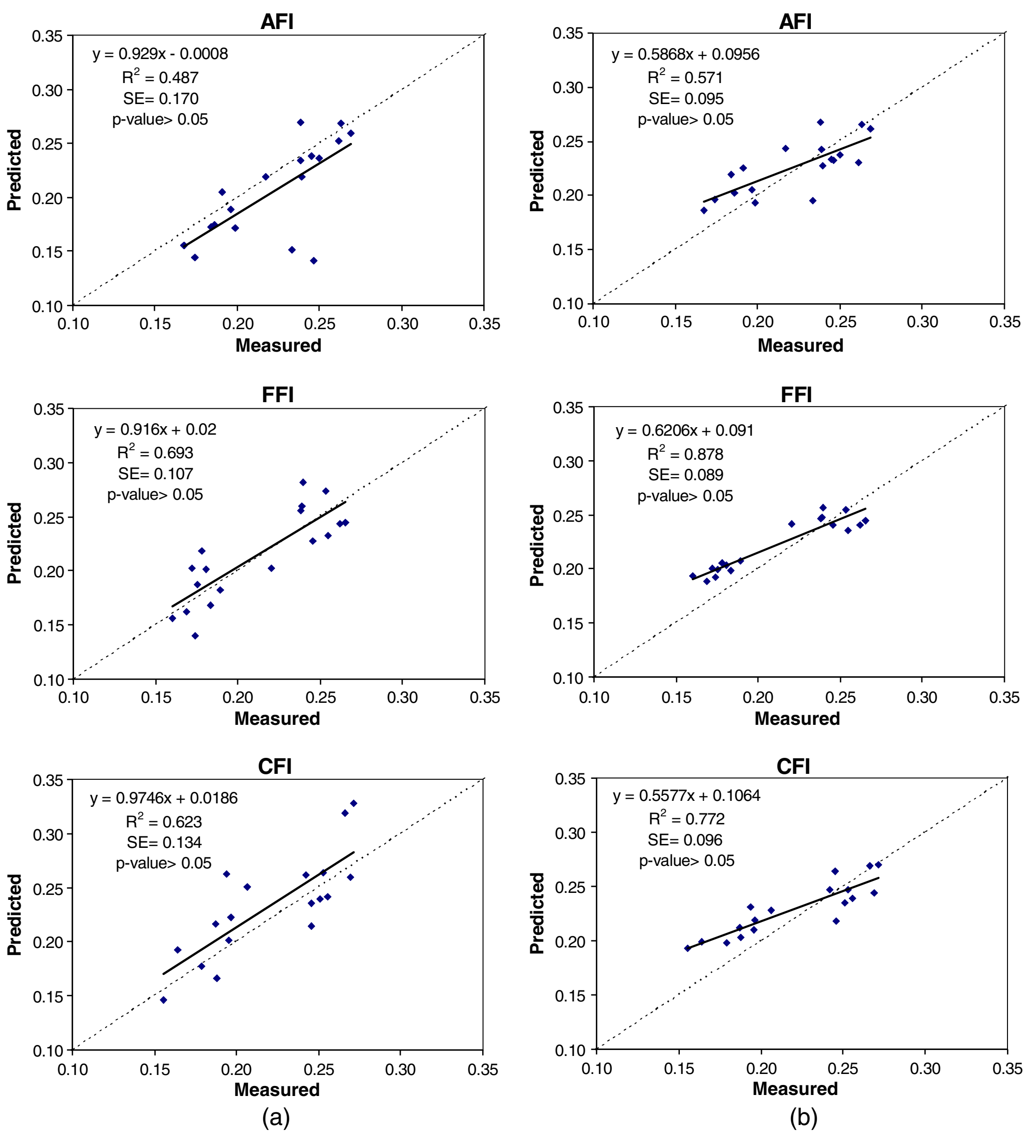

Fig. 2. Comparison between (a) HYDRUS-1D and (b) HYDRUS-2D to simulate soil water content below irrigated furrows

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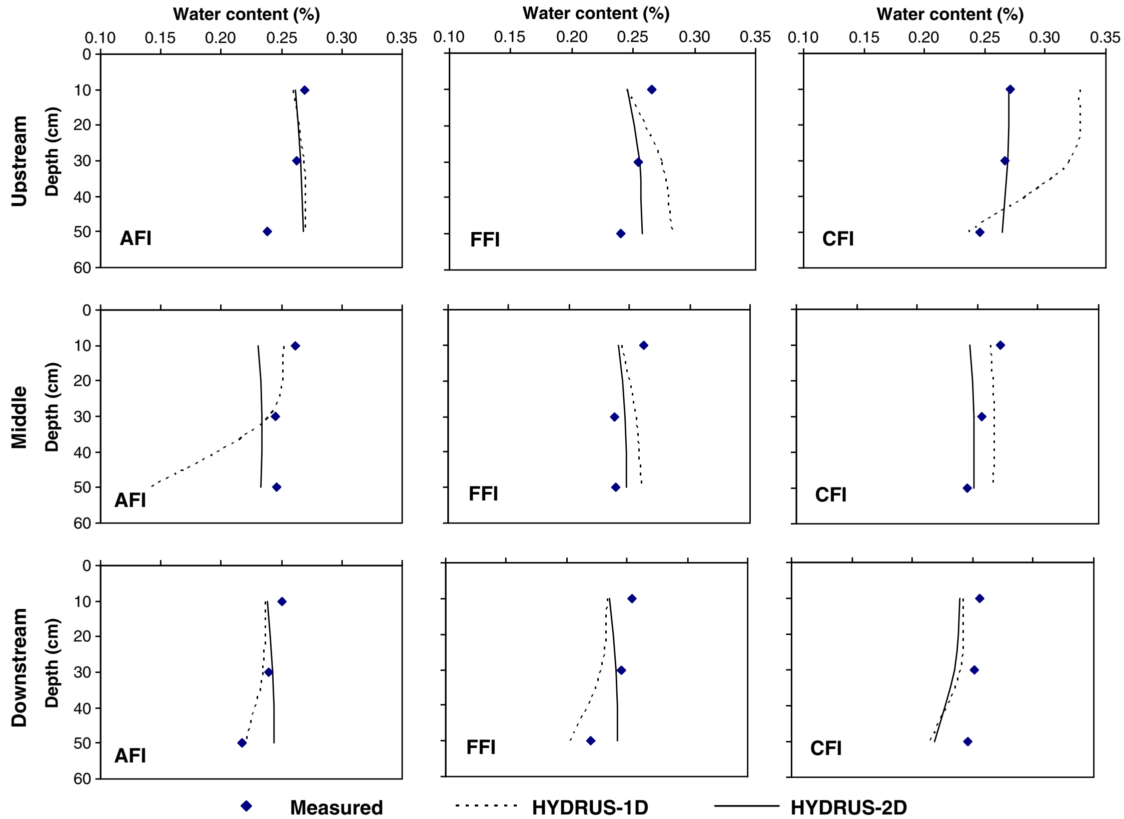

Fig. 3. Measured and predicted water content profiles below the irrigated furrow for all irrigation treatments two days after second fertigation (August 11)

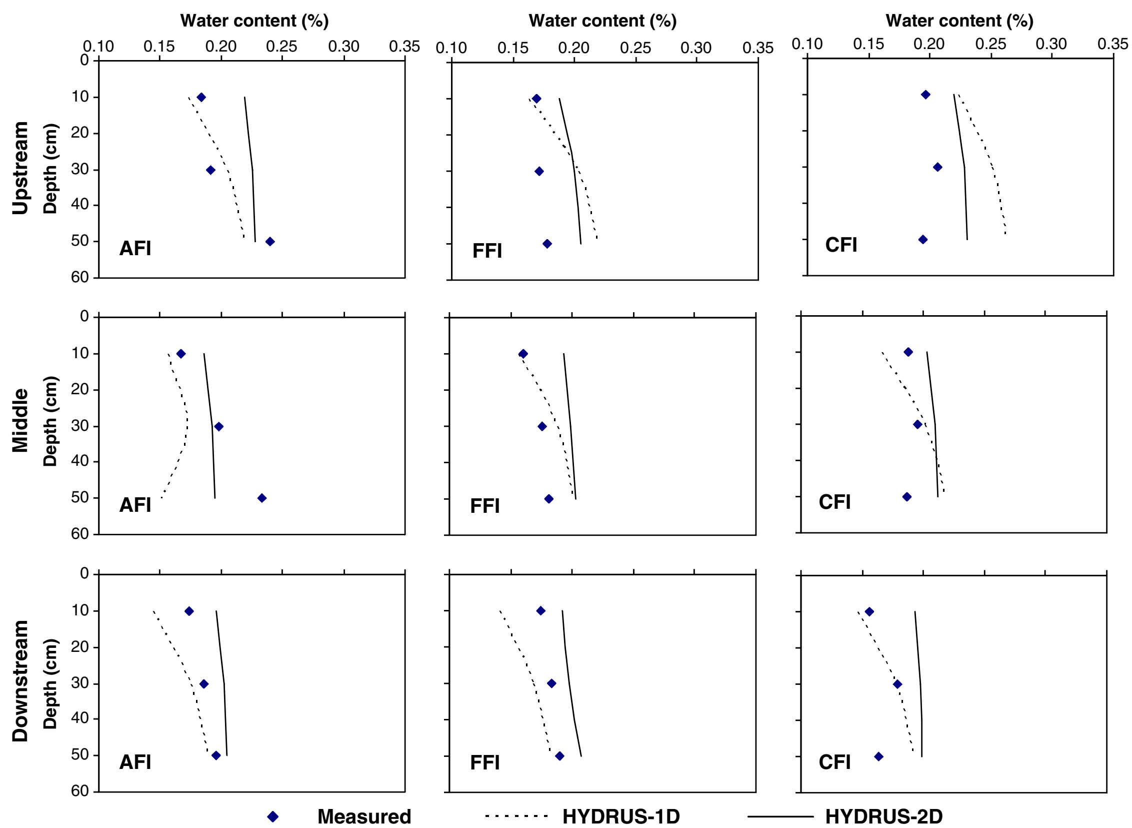

Fig. 4. Measured and predicted water content profiles below the irrigated furrow for all irrigation treatments six days after second fertigation (August 15)

J. Irrig. Drain Eng. 2012.138:929-938.

0.772, respectively, for HYDRUS-2D. Thus, HYDRUS-2D provided better performance when predicting soil water content than HYDRUS-1D. Significant differences could not be established between measured and predicted water content, considering all irrigation treatments (p-value > 0.05).

The graphical comparison between measured and simulated profiles of soil water content for each irrigation treatment and for two and six days after the second fertigation are shown in Figs. 3 and 4, respectively. Both models could successfully predict soil water content and also redistribution process of soil water below irrigated furrows. These figures also confirm that HYDRUS-2D had higher accuracy than HYDRUS-1D. Because water movements are rather two-dimensional in furrow irrigation at the scale of a cross section because of the geometry of infiltration domain, particularly for alternate furrow irrigation.

Nitrate Concentration

The predicted values of soil nitrate concentration were compared with the measured data after the second fertigation for each irrigation treatment (Fig. 5). The SE values for the AFI, FFI and CFI treatments were 0.290, 0.295, and 0.256, respectively, for HYDRUS-1D and 0.195, 0.205, and 0.144, respectively, for HYDRUS-2D. The R^2 values for the AFI, FFI, and CFI treatments were 0.421, 0.304, and 0.458, respectively, for HYDRUS-1D and 0.826, 0.791, and 0.803, respectively, for HYDRUS-2D. Therefore, HYDRUS-2D also provided higher accuracy and correlation when predicting soil nitrate concentration than HYDRUS-1D. The paired samples t-test procedure for soil nitrate concentration showed p-values exceeding the 0.05 threshold, thus excluding the existence of significant differences between measured and predicted values.

The graphical comparison between measured and simulated profiles of soil nitrate concentration for all irrigation treatments and for two and six days after the second fertigation are shown in Figs. 6 and 7, respectively. Both models could also predict the temporal and spatial distribution of nitrate below wet (irrigated) furrows well. The better performance of HYDRUS-2D can be seen in these figures compared to HYDRUS-1D can be seen in these figures. Crevoisier et al. (2008) and Mailhol et al. (2001, 2007) also reported that the bi dimensional model resulted in better

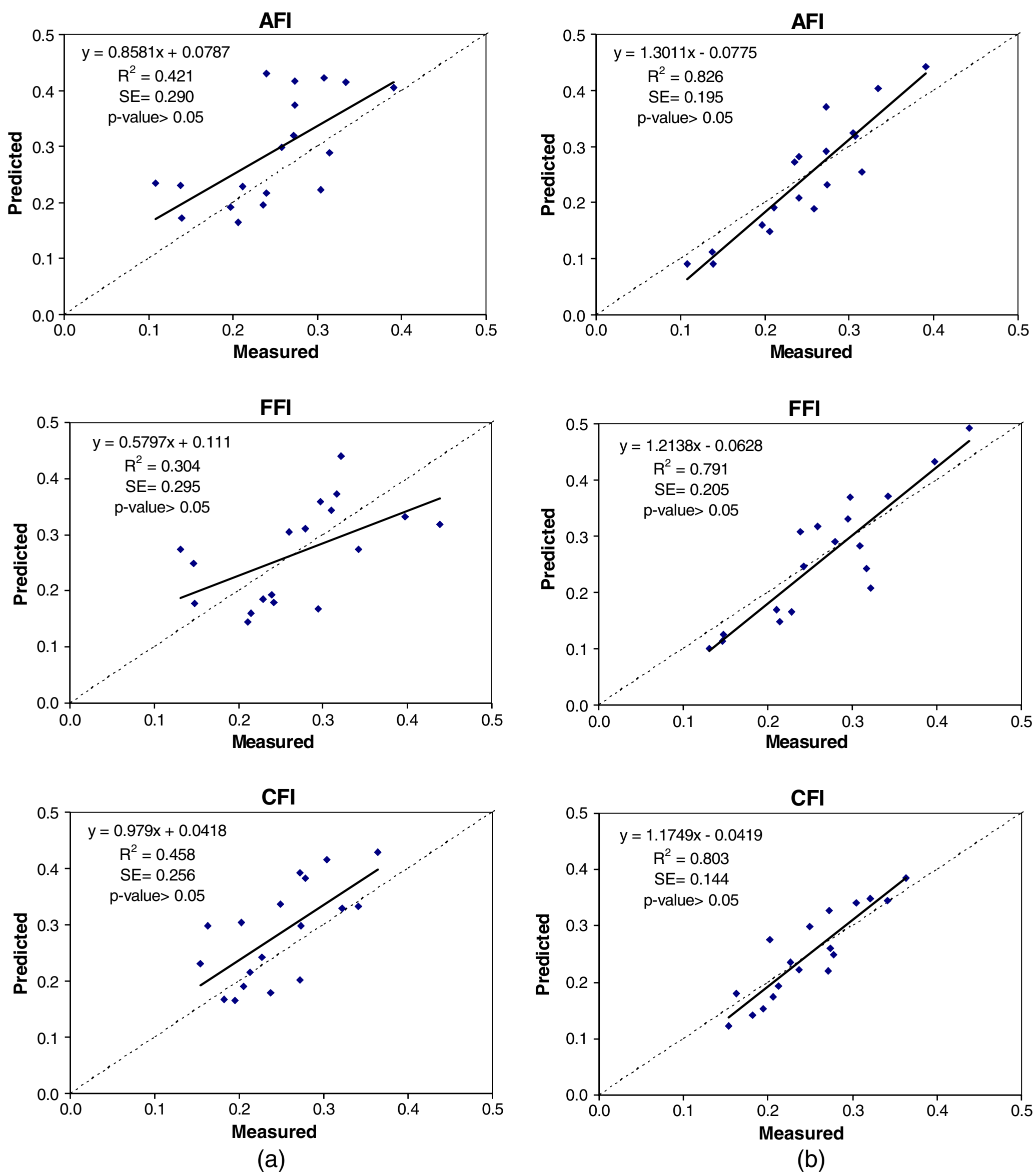

Fig. 5. Comparison between (a) HYDRUS-1D and (b) HYDRUS-2D to simulate nitrate concentration below irrigated furrows

J. Irrig. Drain Eng. 2012.138:929-938.

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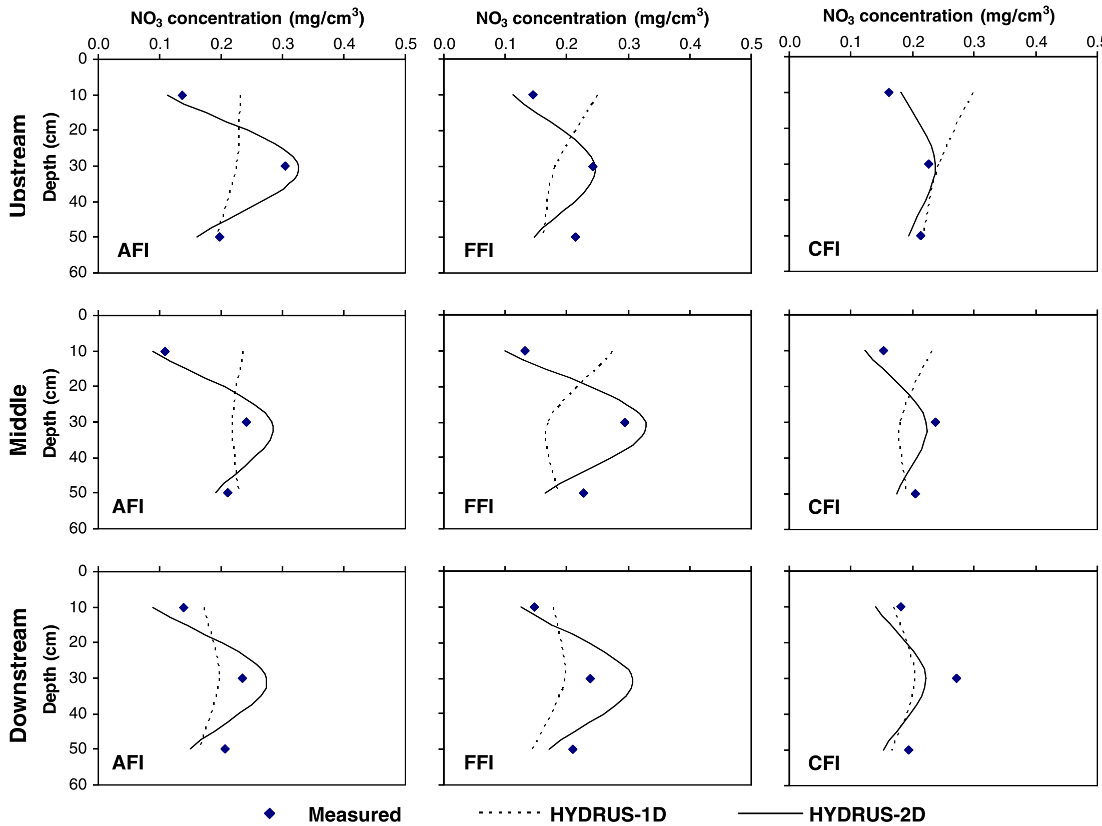

Fig. 6. Measured and predicted nitrate (NO_{3^-}) concentration profiles below the irrigated furrow for all irrigation treatments two days after second fertigation (August 11)

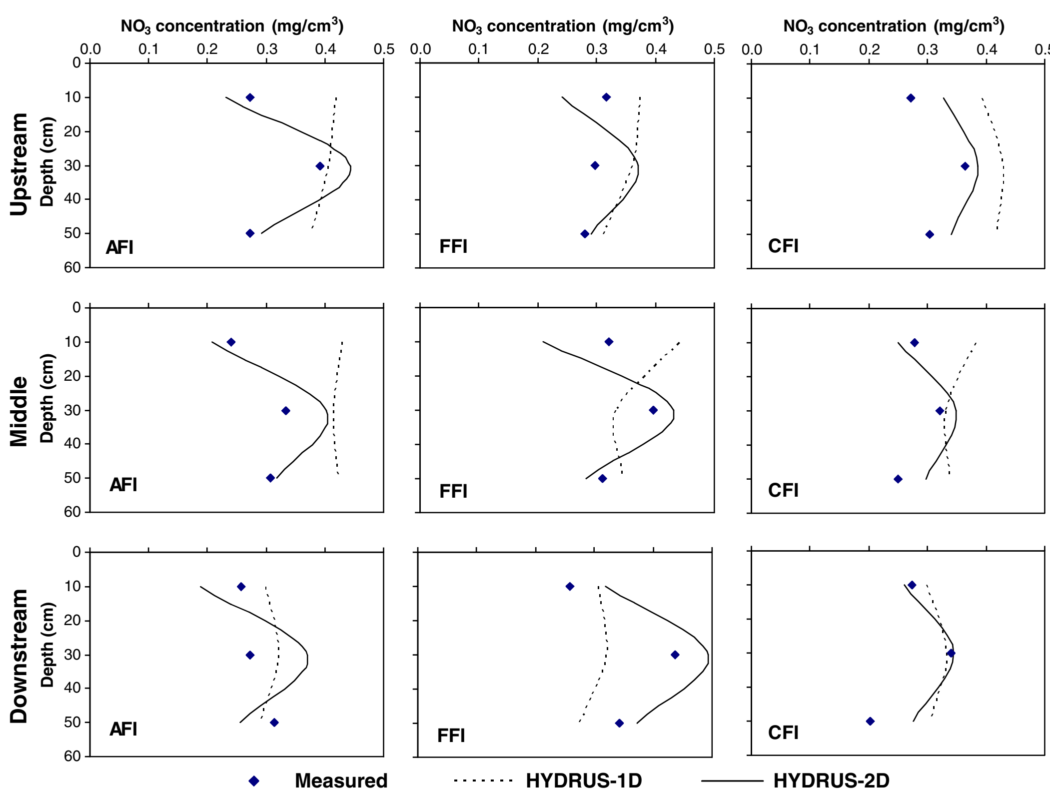

Fig. 7. Measured and predicted nitrate (NO_{3^-}) concentration profiles below the irrigated furrow for all irrigation treatments six days after second fertigation (August 15)

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Table 3. Deep Percolation of Water (Measured and Predicted) and Nitrate (Predicted) for Three Irrigation Treatments and Two Models

	Measured	HYDRUS-1D		HYDRUS-2D	
Irrigation	$DP_w(\%)$	$DP_w(\%)$	$DP_N(\%)$	$DP_w(\%)$	$DP_N(\%)$
AFI	0.0	5.5	6.6	2.6	3.4
FFI	0.0	6.4	9.1	2.9	5.1
CFI	6.3	9.3	11.7	6.6	8.9

Table 4. Computational Times (Seconds) for Running the HYDRUS Models for Calibration and Validation

		Calibration (inverse solution)		Validation	
Irrigation	Furrow location	HYDRUS-1D	HYDRUS-2D	HYDRUS-1D	HYDRUS-2D
AFI	upstream	12.5	19159.0	0.0	84.0
	middle	20.5	159840.0	0.0	12.0
	downstream	13.5	28852.0	0.5	19.0
FFI	upstream	12.0	4709.0	0.5	11.0
	middle	14.0	198720.0	0.0	94.0
	downstream	8.5	44354.0	0.0	120.0
CFI	upstream	12.5	3614.0	0.0	5.0
	middle	10.0	8974.0	0.0	159.0
	downstream	8.5	6098.0	0.5	11.0

Note: Run on a laptop computer; GIGABYTE 1.66 GHz Core 2 CPU with 1024 MB RAM.

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simulations relative to the one-dimensional model under fertilization practices for furrow irrigation.

Similar to water content, measured and predicted values of nitrate concentration at the upstream part of the furrows were higher than the ones at the middle and downstream parts because differences in opportunity time yielded different water and fertilizer infiltration along the furrows for all irrigation treatments.

Similarly to HYDRUS-1D, HYDRUS-2D predicted water flow better than nitrate transport because of the complexity of chemical reactions and the difficulty in modeling the chemical and biochemical process of nitrogen in the soil. Both models resulted in better nitrate simulations for CFI than for AFI and FFI. The simulation models provided satisfactory performance not only for conventional furrow fertigation but also for alternate furrow fertigation.

Deep Percolation

The solution of water balance equation resulted in negative values of DP_w for both alternate furrow irrigation types (assumed to be zero), whereas both simulation models predicted positive values of DP_w (Table 3). The predicted values of DP_w by HYDRUS-2D were closer to the measured values than the values of HYDRUS-1D. Having higher water and fertilizer application, CFI had larger values of DP_w and DP_n relative to AFI and FFI. Kang et al. (2000) and Slatni et al. (2011) also reported that the deep percolation in AFI and FFI was smaller than in CFI, whereas Crevoisier et al. (2008) stated that double nitrogen leaching was predicted by HYDRUS-2D in FFI compared to CFI because of intensive rainfall. Because fertilizer was spread only in dry furrows in the case of FFI, and in each furrow in the case of CFI, this was with the same fertilizer application per unit area for both irrigation treatments. HYDRUS-1D over predicted water and nitrate leaching compared to HYDRUS-2D, particularly for the AFI and FFI treatments. Indeed, lateral movements of water and nitrate happened more in the alternate furrows. If the HYDRUS-1D model was not calibrated by the measured data of the three irrigation treatments, overestimation of water and nitrate leaching would greatly increase. Therefore, the HYDRUS-2D water and solute modeling provided better performance because it considered the real condition of the infiltration process at a furrow section.

Computational Time

HYDRUS-2D required much more time to be run than HYDRUS-1D, especially for the inverse solution (Table 4). For instance, 5.3–44.5 hours were spent for a complete run of inverse solution for the AFI treatment in HYDRUS-2D, whereas HYDRUS-1D was converged just for few seconds (12.5–20.5). Interestingly, the run speed of the HYDRUS-2D model greatly increased after the calibration. Its runs took up to 3 min. HYDRUS-2D generally converged longer for the alternate furrow irrigation treatments than for the CFI treatment because of the larger flow domain defined in the model. There was a slight difference in computational time between the irrigation treatments in HYDRUS-1D.

Conclusion

Two numerical codes, HYDRUS-1D and HYDRUS-2D, were calibrated and validated to simulate water flow and nitrate transport for alternate and conventional furrow fertigation. Differences between the one- and two-dimensional modeling approaches were investigated in estimating soil water content and nitrate concentration, deep percolation and computational time. Both models could predict temporal and spatial distribution of water and nitrate below wet furrows reasonably well. HYDRUS-2D provided better performance, not only for water flow but also for nitrate transport. Both models predicted water flow better than nitrate transport for each irrigation treatment. Conventional furrow irrigation had larger deep percolation of water and nitrate than fixed and variable alternate furrow irrigation. HYDRUS-1D overpredicted water and nitrate leaching compared to HYDRUS-2D, particularly for the AFI and FFI treatments. HYDRUS-2D could predict water deep percolation well. There was a considerable difference in computational time between the two models. HYDRUS-2D's run took much longer relative to the HYDRUS-1D model, particularly for inverse solution. Although HYDRUS-1D can be used for border and basin

J. Irrig. Drain Eng. 2012.138:929-938.

irrigation and also for sprinkle irrigation, application of this model for furrow irrigation did not give satisfactory results because of two-dimensional transfers of water and solute in a furrow cross section, especially for alternate furrows. In conclusion, the application of HYDRUS-2D would be recommended as an accurate and reliable tool for various designs and management in furrow irrigation.

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