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Simulation of nitrate leaching under varying drip system uniformities and precipitation patterns during the growing season of maize in the North China Plain

Zhen Wang[a,b], Jiusheng Li[a,b,*], Yanfeng Li[a,b]

[a] State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, Beijing 100038, China
[b] National Center of Efficient Irrigation Engineering and Technology Research-Beijing, Beijing 100048, China

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ABSTRACT

Drip irrigation has been recognized as an efficient irrigation method to improve water and nitrogen use efficiency. However, less-than-optimum management of drip system may cause deep percolation and nitrate leaching. The effects of drip system uniformity and precipitation on deep percolation and nitrate leaching under maize in a subhumid region were evaluated using a water and solute transport model HYDRUS-2D. Field experiment data on the spatial and temporal distribution of water and nitrate content during the growing seasons (2011 and 2012) of maize were collected to calibrate and validate the model. The validation indicated that the model performed well with an *RMSE* (root mean square error) value of 0.03–0.05 $cm^3 cm^{-3}$ for soil water content and 2.6–8.9 $mg kg^{-1}$ for nitrate content during the growing season. Then, deep percolation and nitrate leaching were simulated under varying drip system uniformities and precipitation patterns. In the simulations, three Christiansen uniformity coefficients (*CU*) of 60%, 80%, and 95% were tested under typical precipitation patterns of dry, normal, and wet growing seasons that were determined from 32 years (1980–2011) of meteorological data. The result demonstrated that deep percolation and nitrate leaching most likely occurred following a heavy precipitation event, whereas slight deep percolation was observed following an irrigation event. The averaged seasonal nitrate leaching over the three drip system uniformities was 34.1 $kg ha^{-1}$ for dry growing seasons (precipitation less than 287 mm), 60.3 $kg ha^{-1}$ for normal seasons (precipitation from 287 to 480 mm), and 109.3 $kg ha^{-1}$ for the wet seasons (precipitation greater than 480 mm). Drip system uniformity had a more significant effect on nitrate leaching during dry seasons than during normal and wet seasons. A correlation analysis between seasonal nitrate leaching and precipitation, irrigation, and drip system uniformity revealed that it was most significantly affected by seasonal rainfall, followed by system uniformity. Both the amount of precipitation and the temporal distribution of precipitation during the growing season of crop should therefore be considered when the target drip irrigation uniformity is determined.

1. Introduction

The North China Plain is one of the main grain production areas in China, producing approximately 22% of China's grain yield (Sun et al., 2010). During the last three decades, excessive quantities of nitrogen (N) fertilizers were applied to guarantee the high crop yields in the region (Wang et al., 2010). It has been found that excessive application of N and unreasonable management of water and N led to nitrate pollution of groundwater and surface water (Zhu and Chen, 2002). Both N and water management need to be considered where the goal is high crop yield with minimal water quality deterioration. Drip irrigation is becoming a widely accepted irrigation/fertigation method to improve water and N use efficiency and minimize nitrate leaching due to its advantages of precise application in amount and at location throughout the field (Bar-Yosef, 1999). Nevertheless, a potential problem associated with drip irrigation is deep percolation and nutrient leaching beyond the root zone (Cote et al., 2003; Gärdenäs et al., 2005; Rajput and Patel, 2006; Ajdary et al., 2007; Doltra and Muñoz, 2010).

Drip system uniformity is one of the main factors that impact deep percolation and nutrient leaching in the field (Barragán et al., 2010). Provided that the drip irrigation system is properly

* Corresponding author at: National Center of Efficient Irrigation Engineering and Technology Research-Beijing, Beijing 100048, China. Tel.: +86 10 68786545; fax: +86 10 68451169.
E-mail addresses: lijs@iwhr.com, jiushengli@126.com (J. Li).

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managed, a higher level of uniformity potentially leads to a more uniform distribution of water and nutrients in the soil, resulting in less nitrate leaching. However, the initial installation costs of system usually increase with uniformity values (Wilde et al., 2009). Several design and evaluation standards of drip system uniformity have been developed in different countries (e.g., ASAE Standards, 1988; Chinese Standard, 1995; ASAE Standards, 2003). Chinese National Standard SL 103-1995 (1995) suggests a design Christiansen uniformity coefficient (*CU*) of greater than 80%. ASAE Standard EP405.1 (2003) recommends a design emission uniformity (*EU*) of 70%–95% depending on the source (point or line source), crop, emitter spacing, and field slope. Several researchers reported that the uniformity of water content in soil produced by a non-uniform water application could be improved over time due to redistribution of water in soil, accumulated irrigation received, uniform natural precipitation, and the development of the crop root system (Perrens, 1984; Li and Kawano, 1996; Li et al., 2005a). Other researchers reported that the effect of system uniformity on crop yield was not as important as expected (Stern and Bresler, 1983; Mateos et al., 1997; Bordovsky and Porter, 2008). These results suggest that a uniformity that is lower than the values recommended by current standards may be used. However, few studies were conducted on the effect of system uniformity on nitrate leaching for microirrigation systems. It remains unclear whether the drip system uniformity lower than the recommended values by the current standards produces significant nitrate leaching.

Precipitation might be an additional factor that affects nitrate leaching in the North China Plain, where the typical monsoonal climate results in 70–80% of annual precipitation concentrating in the growing season of maize (June to September). The residual nitrate in soil is readily leached to deeper soil layers when heavy precipitation occurred (Liu et al., 2003). There has been considerable interest in studying the effect of temporally varied precipitation on nitrate leaching. Using the CERES-Maize model, Pang et al. (1998) studied nitrate leaching from soils under different nitrogen and irrigation management practices and different weather conditions and found that the factors affecting the risk of nitrate leaching were in the order of irrigation schedule > climatic variability > nitrogen application rate. Through simulating nitrate transport under heavy rainfall and high-intensity irrigation rates in the North China Plain with the HYDRUS-1D model, Wang et al. (2010) reported that nitrate leaching in wet years was significantly greater than that in a dry or a normal year. The aforementioned studies confirmed the important effect of precipitation on nitrate leaching. Moreover, when nitrogen fertilizers were applied through a drip system, the interaction between precipitation and a low level of system uniformity might enhance nitrate leaching. Evaluating nitrate leaching under varying precipitation patterns and drip system uniformities will therefore be helpful for developing water and nitrogen management practices to reduce the risk of nitrate leaching in the North China Plain.

Direct measurements of simultaneous migration of water and nitrogen under drip irrigation in the field scale are labor intensive, time consuming, and expensive (Bar-Yosef and Sheikholslami, 1976). Simulation models have proved to be valuable tools for assessing the effects of design and management parameters on nitrate leaching (Pang and Letey, 1998), especially when the conditions are economically or technically impossible to carry out in field experiments (Li and Liu, 2011). In the present study, a simulation model was particularly necessary because the nitrate leaching characteristics under various precipitation conditions can hardly be evaluated by conducting experiments over many years. HYDRUS-2D (Šimůnek et al., 2008, 2011) has been extensively and successfully used for evaluating the effects of soil hydraulic properties and drip irrigation management parameters (Cote et al., 2003; Gärdenäs et al., 2005; Hanson et al., 2006; Ajdary et al., 2007; Doltra and Muñoz, 2010). This model was therefore selected for

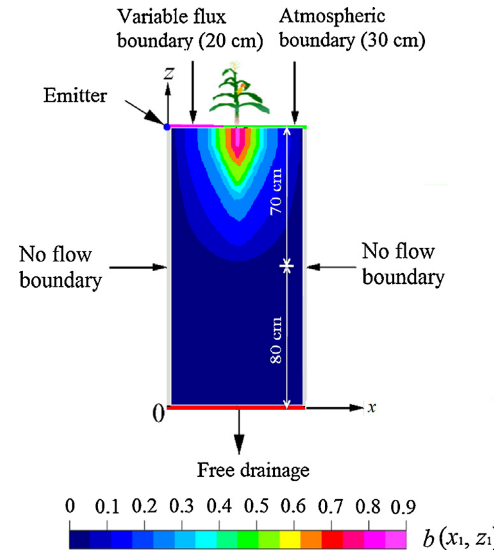

Fig. 1. The conceptual geometry, boundary conditions, and normalized root water uptake distribution ($b(x_1, z_1)$) used for HYDRUS-2D simulations.

the present study to simulate nitrate leaching under varying drip system uniformities and precipitation conditions.

The objectives of the present study were to investigate the effects of drip system uniformities and precipitation patterns on nitrate leaching in the subhumid region and to assess the relative importance of the two factors mentioned above to nitrate leaching for managing microirrigation systems using a water and solute transport model HYDRUS-2D.

2. Model description

HYDRUS-2D software (Šimůnek et al., 2011) can simulate two- or three-dimensional axially symmetric water flow, solute transport, and root water and nutrient uptake based on finite-element numerical solutions of the flow equations. A conceptual geometry (Fig. 1) was used to represent a typical maize field in which two rows of maize (with a row spacing of 50 cm) were irrigated with one dripline. The domain geometry was defined as 50 cm wide and 150 cm deep with a dripline on the upper left corner and a plant of maize in the middle of the domain surface (Fig. 1). The dripline was able to be considered as a line source when emitter spacing along the dripline was relatively small (e.g., 40 cm in our field experiments) and the movement of water and solute were simulated in a two-dimensional vertical plane as performed by Skaggs et al. (2004).

Two-dimensional movement of water in soil is described by the Richards' equation (Šimůnek et al., 2011):

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

where x is the horizontal coordinate (<L); z is the vertical coordinate taken positive upward (L); t is the simulating time (T); θ is the volumetric water content ($L^3\,L^{-3}$); h is the soil water pressure head (L); $K(h)$ is the unsaturated hydraulic conductivity ($L\,T^{-1}$); and $S(x, z, h)$ is the root water uptake (T^{-1}).

The root water uptake sink term $S(x, z, h)$ was determined by Feddes et al. (1978) equation:

$$\begin{cases} S(x, z, h) = \alpha(x, z, h) b(x_1, z_1) W T_p \\ x_1 = |x - 25|\,; z_1 = 150 - z \end{cases} \quad (2)$$

where $\alpha(x, z, h)$ is the soil water stress function (dimensionless); $b(x_1, z_1)$ is the normalized root water uptake distribution (L^{-2}); W is the width of the soil surface associated with the atmospheric boundary (L). The $\alpha(x, z, h)$ was obtained from the HYDRUS-2D database for maize (Šimůnek et al., 2011). As many researches (e.g., Asadi et al., 2002; Zhou et al., 2008; Gheysari et al., 2009) have indicated that most of the maize root was concentrated in 0–60 cm layer of the soil, we set the depth of the root zone as 70 cm in this study. The $b(x_1, z_1)$ was defined as (Vrugt et al., 2001):

$$b(x_1, z_1) = \begin{cases} \left[1 - \dfrac{x_1}{x_{1m}}\right]\left[1 - \dfrac{z_1}{z_{1m}}\right] e^{-\left(p_x/x_{1m}\left|x_1^* - x_1\right| + p_z/z_{1m}\left|z_1^* - z_1\right|\right)} & 0 \le x_1 \le 25, 0 \le z_1 \le 70 \\ 0 & 70 < z_1 \le 150 \end{cases} \quad (3)$$

where z_{1m} is the maximum rooting depth in vertical direction, being equal to the depth of the root zone (70 cm); x_{1m} is the maximum rooting length in horizontal direction, set to 25 cm with an assumption that the roots distributed in the width of the domain; x_1^* and z_1^* are parameters that describe the location of maximum water uptake occurred in horizontal and vertical directions, set to 0 and 10 cm according to the root distribution (Zhou et al., 2008), respectively. The p_x and p_z are the empirical parameters that describe nonsymmetrical root geometrics in horizontal and vertical directions, both set to 1.0 (Vrugt et al., 2001). The variation of $b(x_1, z_1)$ in the simulation domain is illustrated in Fig. 1.

Similar to the study of Wang et al. (2010), soil organic N was assumed to be mineralized directly into NO_3-N. NH_4-N volatilization was ignored as the volatilization was negligible in relation to the N applied as fertilizer (Doltra and Muñoz, 2010). Field experiment results have reported that the NO_3-N content was much greater than the NH_4-N content in the North China Plain (Li et al., 2005a). The NH_4-N movement was therefore ignored in the present study. In the North China Plain, urea is the most widely used nitrogen fertilizer for maize. When urea was applied into the soil, a series of complex process was undergoing hydrolysis and nitrification. As only the behavior of nitrate (nitrate leaching) was concerned in the simulation, we assumed that the urea was transformed to NO_3-N instantaneously when the urea was applied into the soil. This assumption may be justified by the fact that the process of hydrolysis and nitrification generally takes only a few days (Havlin et al., 2005) that are considerably shorter compared to the simulation period of the whole growing season of maize.

Two-dimensional transport of NO_3-N is described by the modified advection-dispersion form (Šimůnek et al., 2011):

$$\frac{\partial \theta c}{\partial t} = \frac{\partial}{\partial x}\left(\theta D_{xx}\frac{\partial c}{\partial x} + \theta D_{xz}\frac{\partial c}{\partial z}\right) + \frac{\partial}{\partial z}\left(\theta D_{zz}\frac{\partial c}{\partial z} + \theta D_{zx}\frac{\partial c}{\partial x}\right) - \left(\frac{\partial q_x c}{\partial x} + \frac{\partial q_z c}{\partial z}\right) - S_c \quad (4)$$

where c is the NO_3-N concentration of the solute in the liquid phase ($M L^{-3}$); q_x and q_z are the components of the volumetric flux density ($L T^{-1}$); D_{xx}, D_{zz}, and D_{xz} are the components of the dispersion tensor ($L^2 T^{-1}$); S_c is sink term, which generally includes the local passive NO_3-N uptake, mineralization, microbial immobilization, and denitrification ($M L^{-3} T^{-1}$). In the present study, the S_c was calculated by:

$$S_c = c_s \times S(x, z, h) - k_{\min} \times \rho + k_{\text{im}} \times \theta \times c + k_{\text{den}} \times \theta \times c \quad (5)$$

where c_s is the NO_3-N concentration taken up by plant roots ($M L^{-3}$); $S(x, z, h)$ is the root water uptake (T^{-1}); $k_{\min}$ is the mineralization rate constant (T^{-1}); ρ is the soil bulk density ($M L^{-3}$); k_{im} is the microbial immobilization rate constant (T^{-1}); k_{den} is the denitrification rate constant (T^{-1}).

3. Materials and methods

3.1. Experimental data

Field experiment data obtained during the 2011 and 2012 growing seasons of drip-irrigated maize were used to calibrate and validate the model, respectively. The experiment was conducted at the Experimental Station of the National Center of Efficient Irrigation Engineering and Technology Research in Beijing (39°39′ N, 116°15′ E, and 40.1 m above the sea level) of the North China Plain, which is in a subhumid region. The physical properties of soil at the experimental field are summarized in Table 1. Weather parameters for the calculation of the reference evapotranspiration (ET_0) were observed from an automated wireless weather station that was installed 50 m from the experimental field.

In the 2011 and 2012 experiments, maize (*Zea mays* L.) was seeded on May 3 and May 1, respectively, with a row spacing of 50 cm. For both years, thinning operations were performed on the 25th day after planting at a planting spacing of 40 cm, resulting in a population density of 50,000 plants per hectare. Maize was harvested on August 30 in 2011 and August 27 in 2012. The experimental plot was 30 m by 3 m, with 6 rows of maize. The driplines with emitter spacing of 40 cm and individual emitter nominal discharge rate of 1.65 L h^{-1} (Netafim Ltd., Tel Aviv, Israel) were installed in the middle of two adjacent maize rows (Fig. 2). Prior to dripline installation, the emitter flow rates along the dripline were measured by cans spaced at an interval of 80 cm and the Christiansen uniformity coefficient (CU) (Christiansen, 1941) was used to quantify the uniformity of the emitter discharge rate:

$$CU = 100 \times \left(1 - \frac{\sum_{i=1}^{N}\left|x_i - \bar{x}\right|}{N\bar{x}}\right) \quad (6)$$

where x_i is emitter discharge rate (L h^{-1}); $\bar{x}$ is the mean of x_i (L h^{-1}); and N is the number of emitters. A quite high CU value of 97% was observed and the uniform distribution of emitter discharge rates along the dripline was confirmed.

Soil water content from 0 to 100 cm depth was measured by a TRIME-T3 (IMKO GmbH, Germany) time domain reflectometry (TDR) handheld instrument combined with a T3 access tube probe. The accuracy of the probe reported by the manufacturer was ±2–3% when volumetric soil water was varied from 0 to 0.40 cm^3 cm^{-3} (IMKO GmbH, 2009). Six 1.5 m long T3 access tubes were installed at 5 m intervals along the dripline (Fig. 2). All the T3 access tubes were installed in the middle of the dripline and the maize row (Fig. 2). The initial soil water content was measured one day prior to the seeding and the temporal variation of soil water content was obtained by

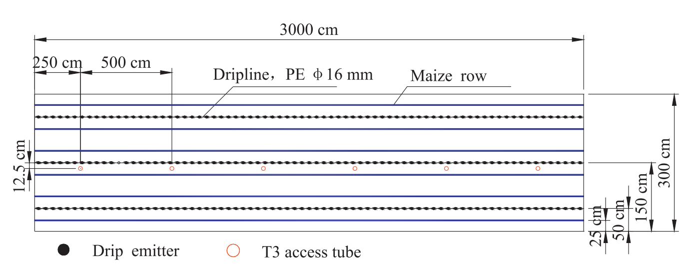

Fig. 2. Schematic of dripline placement and locations of T3 access tubes within an experimental plot.

Table 1
Physical properties of soil at the experimental field.

Depth (cm)	Particle size distribution (%)			Texture	Soil bulk density ($g\,cm^{-3}$)	Field capacity ($cm^3\,cm^{-3}$)	Soil water content at 33 kPa ($cm^3\,cm^{-3}$)	Soil water content at 1500 kPa ($cm^3\,cm^{-3}$)
	Clay	Silt	Sand					
0–20	13.7	52.4	33.9	Silt loam	1.37	0.33	0.246	0.096
20–60	13.5	54.1	32.4	Silt loam	1.41	0.33	0.238	0.091
60–100	16.5	52.8	30.7	Silt loam	1.46	0.33	0.239	0.095

measuring the soil water content weekly during the growing seasons. Irrigation was applied when average soil water content within the target wetted soil layer depleted to 60–70% of the field capacity that was determined by in situ test (Veihmeyer and Hendrickson, 1949). The amount of irrigation was determined to replenish the soil water in the target wetted layer to 90% of the field capacity. A target wetted depth of 40, 50, 70, and 60 cm was used for the seedling, jointing, heading, and filling stages, respectively. During the 2011 season, a total of 385 mm precipitation was received and 90 mm of irrigation was applied over four irrigation events. In the 2012 season, a total of 419 mm of precipitation was received and 88 mm of water were applied over four irrigation events. In both seasons, nitrogen was applied at a rate of 210 kg N ha^{-1} that approximated the conventional N usage (Zhao et al., 2009). A readily soluble fertilizer of urea was used as the N source. All of the N fertilizer was applied at four different splits through a drip irrigation system in the growing seasons. The detail information on irrigation and fertilization was presented in a previous article (Wang et al., 2014a).

Soil samples at depths of 0–20, 20–40, 40–60, 60–80, and 80–100 cm were collected using a 4-cm diameter auger at the locations in the proximity of T3 access tubes in each plot prior to seeding to determine the initial nitrogen content for both seasons. To obtain the seasonal variation of nitrate distribution, soil cores were collected at a distance of approximately 100 cm from the T3 access tubes two days after a fertigation event or several intermittent precipitation events. Generally, soil cores were collected in the center of the dripline and the maize row to represent a location similar to that of the T3 access tube. For each sample, 20 g of air-dried soil passing through a 2 mm sieve were extracted with 50 mL of 1 mol L^{-1} KCl, and the NO_3-N content was determined using an Autoanalyzer III (Bran+Luebbe, Norderstedt, Germany) (Soil Science Society of China, 1999). The remaining soil samples were used to determine the soil water content gravimetrically.

3.2. Initial and boundary conditions

The initial water and NO_3-N content in different soil layers within the flow domain were obtained from the measurements conducted prior to seeding. A uniform distribution of water and NO_3-N in the soil profile from 100 to 150 cm depth was assumed because the water and nitrate content were measured to a depth of 100 cm in the experiments.

As illustrated in Fig. 1, a no flux boundary of water and nitrate was applied to the sides of the soil profile. The bottom boundary was considered as the free drainage boundary. During an irrigation event, water and solute entered the simulation domain through a saturation zone that was a time-dependent function of emitter discharge rate (Li et al., 2005b). For simplicity, a constant width of saturation zone of 20 cm was assumed in this study according to the field observation of the saturation zone during irrigation. The constant flux ($\sigma(t)$, cm h^{-1}) in the saturation zone during an irrigation event was defined as:

$$\sigma(t) = \frac{Q(t)}{2WL_e} \tag{7}$$

where $Q(t)$ is the discharge rate of an individual emitter ($L^3\,T^{-1}$); L_e is the emitter spacing along the dripline (L). During the no irrigation period, the saturation surface zone would transform to atmospheric boundary condition.

The actual evaporation rate of the atmospheric boundary was mainly determined by the E_p ($L\,T^{-1}$) that can be calculated as (Nakamura et al., 2004):

$$\begin{cases} E_p = ET_p - T_p = ET_P \times \exp(-\eta \times LAI) \\ ET_P = k_c \times ET_0 \end{cases} \tag{8}$$

where ET_p is the potential evapotranspiration rate ($L\,T^{-1}$); T_p is the potential transpiration rate ($L\,T^{-1}$); η is the fixed light extinction coefficient that was equal to 0.65 for maize according to Allen et al. (1964); LAI is the leaf area index ($L^2\,L^{-2}$) that was observed in the experiments and presented in a previous article (Wang et al., 2014b); k_c is the crop coefficient modified from the values proposed by Allen et al. (1998); ET_0 is the reference evapotranspiration that was computed by the Penman–Monteith equation ($L\,T^{-1}$) (Allen et al., 1998).

3.3. Model parameters

The van Genuchten–Mualem model of soil hydraulic properties (Mualem, 1976; van Genuchten, 1980) was selected in the numerical simulations:

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + (\alpha h)^n\right]^m} \quad h < 0 \tag{9}$$

$$\theta(h) = \theta_s \quad h \ge 0 \tag{10}$$

$$K(h) = K_s S_e^l [1 - (1 - S_e^{1/m})^m]^2 \tag{11}$$

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \tag{12}$$

where θ_r and θ_s are the residual and saturated water contents ($L^3\,L^{-3}$), respectively; $K(h)$ is the unsaturated hydraulic conductivity ($L\,T^{-1}$); K_s is the saturated hydraulic conductivity ($L\,T^{-1}$); α (L^{-1}), n, and m (both dimensionless) are empirical shape parameters where $m = 1 - (1/n)$; l is the pore connectivity parameter (dimensionless); S_e is the effective saturation (dimensionless). The l parameter was estimated by Mualem (1976) to be about 0.5 for many soils and this value was adopted in the present study. The hydraulic parameters including θ_r, θ_s, K_s, α, and n were estimated using Rosetta software (Schaap et al., 2001) from the soil particle fractions, bulk density and soil water content at 33 and 1500 kPa (Table 1). The HYDRUS-2D simulations were carried out on hourly basis for the whole growing season from 3 May to 29 August 2011. Values of θ_s for different layers were further fine-tuned using an inverse modeling technique from 125 values of water content observed during the 2011 growing season of maize.

The solute transport parameters including longitudinal dispersivity (D_L, L), transversal dispersivity (D_T, L), molecular diffusion (D_W, $L^2\,T^{-1}$), k_{min}, k_{im}, and k_{den} involved in the simulation were determined according to the values reported in the literature (Gärdenäs et al., 2005; Hu et al., 2008; Doltra and Muñoz, 2010).

Table 2
Calibrated soil hydraulic parameters and soil solute transport parameters in soil profile.

Depth (cm)	θ_r ($cm^3\,cm^{-3}$)	θ_s ($cm^3\,cm^{-3}$)	α (cm^{-1})	n	K_s ($cm\,h^{-1}$)	l	D_L (cm)	D_T (cm)	D_W ($cm^2\,h^{-1}$)	k_{min} ($mg\,g^{-1}\,h^{-1}$)	k_{im} (h^{-1})	k_{den} (h^{-1})
0–20	0.034	0.390	0.0116	1.409	1.448	0.5	20	2	0.06	1.2×10^{-5}	0.00028	0.00007
20–60	0.033	0.421	0.0119	1.407	1.303	0.5	20	2	0.06	3.0×10^{-7}	0.00026	0.00006
60–100	0.035	0.420	0.0117	1.402	0.883	0.5	20	2	0.06	0	0.00025	0.00005

θ_r is the soil residual water content, θ_s is the soil saturation water content, α, n and l are the parameters of soil hydraulic function, and K_s is the soil saturated hydraulic conductivity, D_L is the longitudinal dispersivity, D_T is the transverse dispersivity, D_W is molecular coefficient in free water, k_{min} is the mineralization rate constant, k_{im} is the microbial immobilization rate constant, k_{den} is the denitrification rate constant.

During the calibration of the model, the value of D_T was simply set as one tenth of D_L (Ramos et al., 2012). All the other parameters (D_L, D_W, k_{min}, k_{im}, and k_{den}) were adjusted by comparing the simulated and observed values of NO_3-N content in 2011. The calibrated soil hydraulic parameters and soil solute transport parameters of the soil profile are summarized in Table 2.

3.4. Model performance criteria

To evaluate the model performance for predicting soil water content and soil NO_3-N content, the root mean square error (*RMSE*) and the index of agreement (d) (Willmott, 1982) were computed:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(O_i - P)^2}{n}} \tag{13}$$

$$d = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(\left|O_i - O\right| + \left|P_i - O\right|)^2} \tag{14}$$

where O_i and P_i are the observed and simulated values; n is the number of measurements; and O is the mean of the observed values. The *RMSE* has a minimum value of 0, with a better agreement close to 0. The value of d ranges from 0 to 1.0, with 1.0 representing a perfect fit of the data.

3.5. Consideration of drip irrigation uniformity and precipitation

The validated model was used to evaluate the effect of the drip system uniformity and precipitation on deep percolation and NO_3-N leaching. Three designed *CU* levels of 60% (referred to as low uniformity, C1), 80% (referred to as medium uniformity, C2), and 95% (referred to as high uniformity, C3) were considered. For each uniformity value, the length of dripline, average emitter discharge rate, and emitter spacing were similar to those used in the field experiments. For simplicity, each dripline was divided into 25 segments, each having three emitters with a similar discharge rate. For each treatment, 25 different discharge rates for the 25 segments were generated by the Monte Carlo method (Pei and Wang, 1998) with the assumption that the distribution of emitter discharge rates within a unit could be represented by a normal distribution function (Nakayama et al., 1979). Fig. 3 illustrates the variation of segment emitter discharge rates along a dripline used in the simulations for the three uniformities evaluated. The exchange of water and solute between the adjacent segments was assumed to be negligible because the emitter discharge rates usually decreased gradually from the inlet to the end of the dripline as affected by hydraulic loss (Lamm et al., 2007). Then, the deep percolation and nitrate leaching was simulated for each of the 25 segments with different emitter discharge rates varying along the dripline. For each simulation, the daily deep percolation and nitrate leaching below the root zone depth of 70 cm were calculated on the basis of the water and N balance results. The daily deep percolation and nitrate leaching for a given system uniformity was defined as the average value over all the 25 simulations.

To address the interaction of drip irrigation system uniformity and precipitation on nitrate leaching, simulations for the three uniformities were conducted under different precipitation patterns of 32 years (1980–2011) at the site where the field experiments were conducted. A similar initial water and NO_3-N content to that observed at the beginning of the 2011 season was used in these simulations. The daily evapotranspiration rates during the growing seasons of maize (3 May to 29 August) were determined from the meteorological data. Irrigation was determined to replenish the soil water in the target wetted layer to 90% of the field capacity when average soil water content within the target wetted soil layer was depleted to 65% of the field capacity. For all the growing seasons, 210 kg N ha^{-1} was applied at four different splits through fertigation on 31 May (52.5 kg N ha^{-1}), 21 June (52.5 kg N ha^{-1}), 12 July (73.5 kg N ha^{-1}) and 2 August (31.5 kg N ha^{-1}). Ten millimeters of water were applied for fertilizer injection when no irrigation was required on the designated fertigation dates.

For the simulations of 32 years (1980–2011), the amounts of precipitation during the growing season of maize ranged from 173 to 750 mm, with a mean of 397 mm. Precipitation values with exceedance probability of 75%, 50%, and 25% during the growing season of maize were 287, 367, and 480 mm, respectively. The growing season was therefore defined as a dry season if precipitation was less than 287 mm, a normal season if precipitation was between 287 and 480 mm, and a wet season if precipitation was greater than 480 mm. Of the 32 years, there were 8 dry seasons, 16 normal seasons, and 8 wet seasons. The mean values of monthly precipitation and irrigation applied throughout the growing seasons for dry, normal, and wet seasons are illustrated in Fig. 4. The seasonal irrigation amount ranged from 160 to 299 mm for a dry season, 109 to 271 mm for a normal season, and 84 to 165 mm for a wet season.

4. Results and discussion

4.1. Calibration and validation of the model

The model performance statistics *RMSE* and d for water and NO_3-N content at different depths for the calibration (2011) and

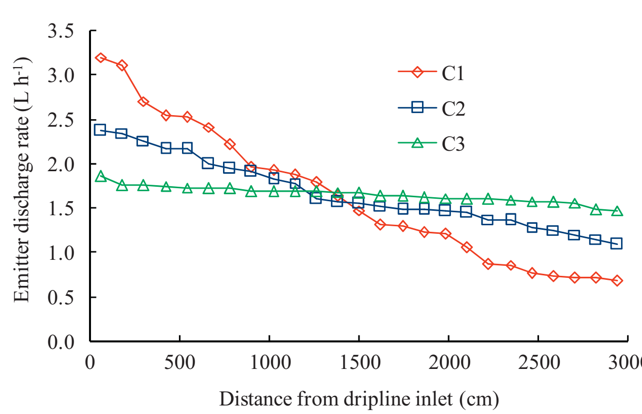

Fig. 3. The variations of drip emitter discharge rates along a dripline for uniformity coefficients of 60% (C1), 80% (C2), and 95% (C3).

Table 3
The root mean square error (*RMSE*) and the index of agreement (*d*) of the soil water and soil NO_3-N content.

Soil depth (cm)	2011 (calibration)				2012 (validation)			
	Water content θ		NO_3-N		Water content θ		NO_3-N	
	RMSE ($cm^3\ cm^{-3}$)	*d*	*RMSE* ($mg\ kg^{-1}$)	*d*	*RMSE* ($cm^3\ cm^{-3}$)	*d*	*RMSE* ($mg\ kg^{-1}$)	*d*
0–20	0.023	0.940	6.713	0.851	0.054	0.671	8.856	0.894
20–40	0.022	0.940	5.880	0.740	0.038	0.795	4.336	0.905
40–60	0.028	0.878	2.374	0.847	0.035	0.787	3.508	0.699
60–80	0.025	0.851	3.127	0.537	0.026	0.817	3.226	0.500
80–100	0.022	0.870	1.924	0.651	0.025	0.820	2.563	0.560

validation dataset (2012) are summarized in Table 3. For the calibration dataset, *RMSE* values for water content ranged from 0.02 to 0.03 $cm^3\ cm^{-3}$, indicating a good agreement between the simulated and the measured water content. Kandelous and Šimůnek (2010) reported comparable *RMSE* values of 0.01–0.05 $cm^3\ cm^{-3}$. The simulation accuracy for NO_3-N was also found acceptable with the *RMSE* values of 1.9–6.7 $mg\ kg^{-1}$ (Doltra and Muñoz, 2010). Similarly, the relatively larger values of *d* (0.85–0.94 and 0.54–0.85 for the water content and NO_3-N content, respectively) also indicated a good performance of the model.

Fig. 5 compares the simulated and the observed soil water and NO_3-N at various depths during the 2012 season (validation data) to illustrate the capability of the model in capturing the temporal and spatial trends of water and NO_3-N. Simulated and observed soil water content increased greatly following an irrigation or precipitation event and then decreased gradually due to drainage and evapotranspiration. For NO_3-N content, simulated and observed values demonstrated a great increase following a fertigation event, especially in the top layers (0–40 cm). Generally, the simulated water and nitrate content agreed well with the observed values as the *RMSE* values ranged from 0.03 to 0.05 $cm^3\ cm^{-3}$ for water content and 2.6–8.9 $mg\ kg^{-1}$ for NO_3-N content (Table 3). The *RMSE* of water and NO_3-N content in the surface layer were generally larger than that in the lower layer. This could probably be attributed to the less obvious change in water and NO_3-N content in deeper depths during the growing season of maize. Similar results were reported by Ramos et al. (2012). The close match between the simulated and observed water and NO_3-N contents in the growing season indicates that the HYDRUS 2D software can be successfully used to predict the transport of water and NO_3-N in this region. Other studies have also reported good performance of the software for various soils and crops under pressurized irrigation conditions (Ajdary et al., 2007; Ramos et al., 2012; Phogat et al., 2013).

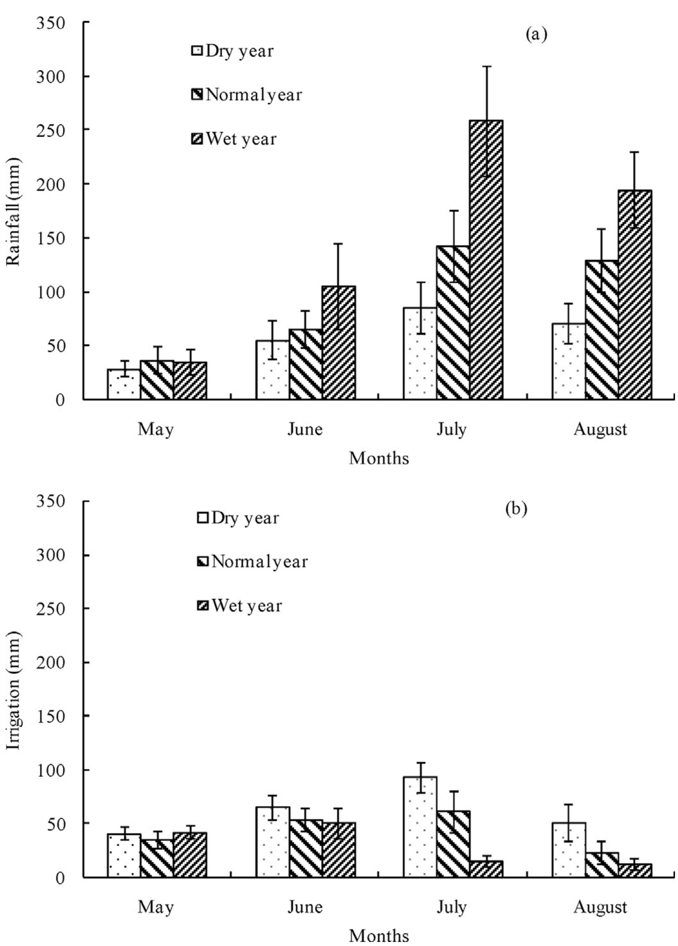

Fig. 4. The averaged monthly precipitation (a) and simulated irrigation amount (b) throughout the growing seasons of maize over 32 years from 1980 to 2011.

4.2. Dynamic of the deep percolation and nitrate leaching

The daily deep percolation and NO_3-N leaching under three drip system uniformities during the typical dry season (2003), normal season (1992) and wet season (1988) selected are illustrated in Fig. 6 to address the influence of temporal variation of precipitation on deep percolation and nitrate leaching. A positive value represents deep percolation and NO_3-N leaching below 70 cm, while a negative value represents replenishment from the deep soil layer. Deep percolation and NO_3-N leaching were always observed immediately after an irrigation event or a heavy precipitation event for the three uniformities simulated. For the dry season of 2003, 280 mm of irrigation was applied through nine irrigation events. A slight deep percolation was observed following an irrigation event, whereas the deep percolation following a precipitation was negligible because of the considerably less rainfall during the dry season. The maximum daily percolation rate was 2.3, 1.2, and 1.0 mm for the low (C1), medium (C2), and high (C3) system uniformity treatment, respectively, indicating that a greater uniformity in the drip system produced a lower deep percolation. NO_3-N leaching most likely occurred following a fertigation event. Greater drip system uniformity also produced a lower rate of nitrate leaching. For example, the daily NO_3-N leaching rate following the irrigation event on 19 July decreased from 2.2 to 0.7 $kg\ ha^{-1}$ as *CU* increased from 60% (C1) to 95% (C3).

For the normal (1992) and wet seasons (1988), intensive precipitation during the latter growing seasons resulted in considerable deep percolation and NO_3-N leaching. For example, the amount of NO_3-N leaching caused by the intensive precipitation events after 10 July accounted for 74% and 79% of seasonal NO_3-N leaching for the normal and wet season, respectively. The influence of drip irrigation uniformity became minor as intermittent precipitation occurred in the later growing season. For example, the daily percolation rates peaked at 18.3, 18.4, and 18.3 $mm\ d^{-1}$ on 3 August 1988 for the C1, C2, and C3 treatments, respectively. The NO_3-N leaching rates were also approximately the same for all three uniformity levels on 3 August 1988. These results demonstrated

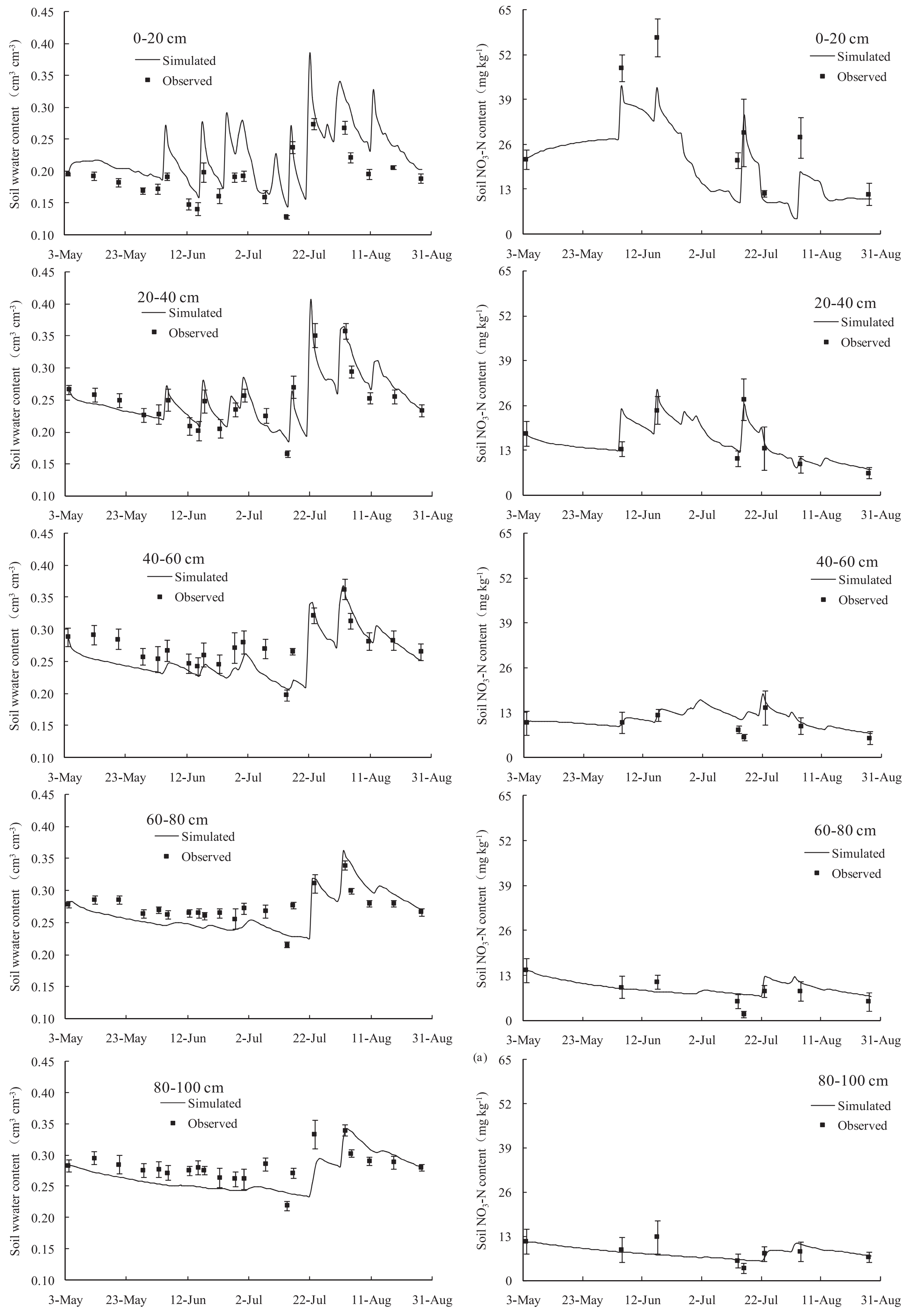

Fig. 5. Observed and simulated soil water and nitrate contents at different soil depths during 2012 growing season of maize. The vertical bar represents standard deviation of the six measurement points.

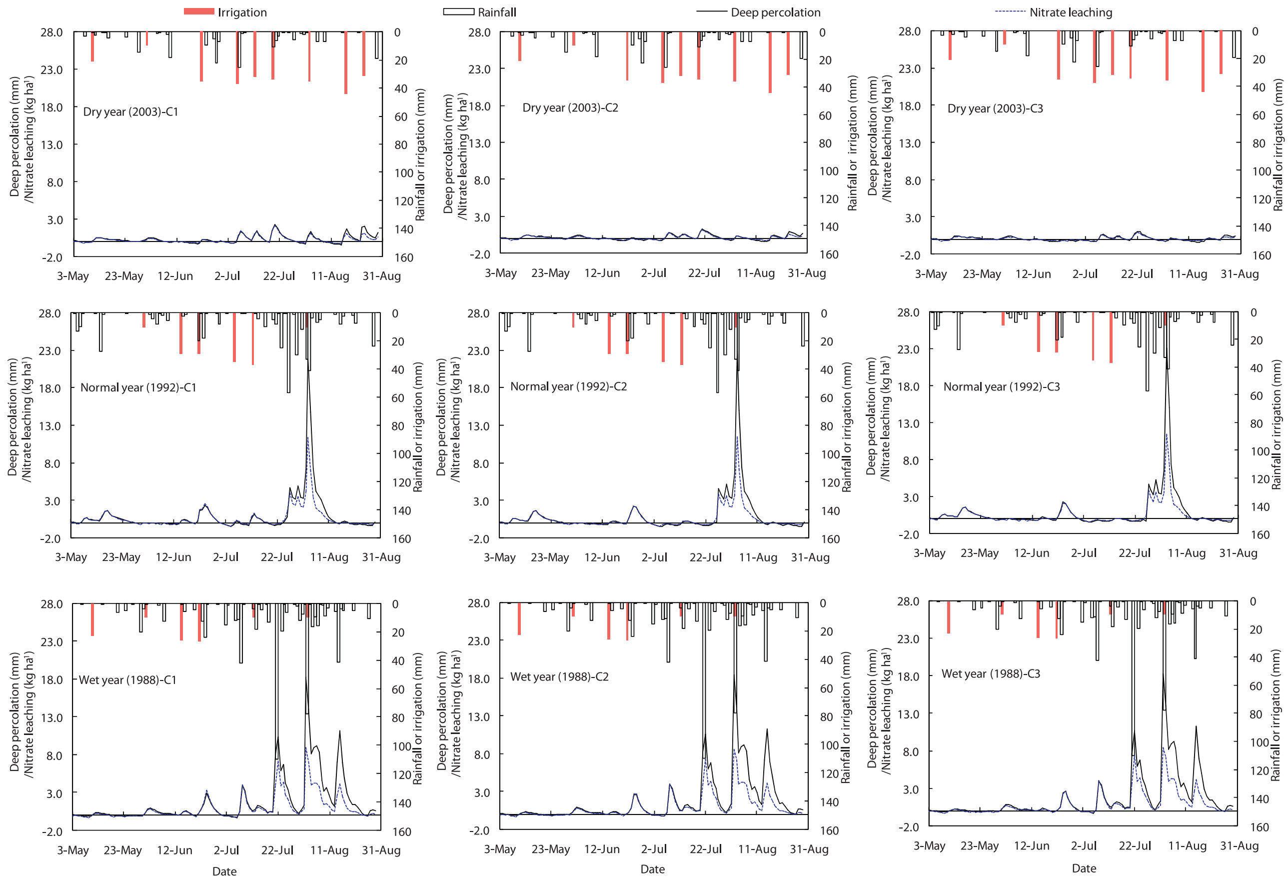

Fig. 6. Dynamics of simulated deep percolation and nitrate leaching for uniformity coefficients of 60% (C1), 80% (C2), and 95% (C3) during the typical dry (2003), normal (1992), and wet (1988) seasons.

the importance of temporal distribution of precipitation on deep percolation and NO_3-N leaching. A great precipitation at the end of the season produced more drainage than an even distribution of precipitation during the growing season. This fact was confirmed by a previous observation of deep percolation during the growing season of maize in the same field (Wang et al., 2014a). Similar results were presented by Arbat et al. (2013) who indicated that NO_3-N leaching during the irrigation season mainly occurred in the fall when heavy precipitation events occurred and the water consumption of maize was relatively small. Daudén and Quílez (2004) also reported that the risk of nitrate leaching on corn fertilized with mineral N was weather-dependent and the risk of nitrate leaching would increase considerably when water and N uptake by crops were minor and precipitations were high.

4.3. Seasonal deep percolation and nitrate leaching

Variations of the simulated seasonal deep percolation and NO_3-N leaching along a dripline under three system uniformities for the typical dry season selected (2003) are illustrated in Fig. 7. Similar results were observed for the normal and wet seasons. Both deep percolation and nitrate leaching decreased as the distance from the dripline inlet increased, being highly dependent on the variation pattern in emitter discharge rate that was indicated in Fig. 3. A great emitter discharge resulted in a large amount of deep percolation and nitrate leaching rate. The variation in seasonal deep percolation and NO_3-N leaching rates along a dripline decreased greatly as the uniformity increased from 60% to 95%. The seasonal NO_3-N leaching rate, for instance, decreased from 168.7 kg ha^{-1} at the beginning of the dripline to −18.4 kg ha^{-1} at the end of the dripline with a range of 187.1 kg ha^{-1} for the low uniformity of 60% in a dry season (2003). While a considerably small range of 22.5 kg ha^{-1} (from −2.4 to 20.1 kg ha^{-1}) was observed for the high uniformity of 95%. These results suggested a substantial influence of system uniformity on the variation of deep percolation and NO_3-N leaching along a dripline.

The seasonal deep percolation and NO_3-N leaching rates for the dry, normal, and wet growing seasons under different drip system uniformities are summarized in Table 4. Seasonal averaged deep percolation rates over the three drip system uniformities were 45.1, 94.7 and 210.1 mm for the dry, normal, and wet seasons, respectively. Similarly, seasonal NO_3-N leaching for the wet seasons was 109.3 kg ha^{-1}, being 81% and 220% greater than those for the normal (60.3 kg ha^{-1}) and dry (34.1 kg ha^{-1}) seasons. Equivalently, 16%, 29%, and 52% of N applied (210 kg ha^{-1}) leached out of the root zone during the dry, normal, and wet seasons.

The data in Table 4 demonstrates that the effects of drip system uniformity on deep percolation and nitrate leaching rates were greatly dependent on precipitation. Increased drip system uniformity produced a more considerable reduction of deep percolation and NO_3-N leaching during a dry growing season than that of a normal or a wet season. For example, the mean NO_3-N leaching rate in dry seasons reduced by 36% as drip irrigation uniformity increased from 60% (C1, 43.1 kg ha^{-1}) to 95% (C3, 27.6 kg ha^{-1}). As there exists an obvious decreasing trend of precipitation in July and August when maize is growing in North China Plain (Tan et al., 2010), the influence of uniformity might be strengthened if climate change is considered. For a wet growing season, however, the mean nitrate leaching rate was only reduced by 4% as the system uniformity increased from 60% (C1, 112.2 kg ha^{-1}) to 95% (C3, 107.2 kg ha^{-1}). The seasonal nitrate leaching rates ($NL_{seasonal}$, kg ha^{-1}) were correlated with drip system uniformity (CU, %), precipitation (P, mm),

Table 4
The seasonal deep percolation and NO_3-N leaching rates in maize growing seasons for dry, normal, and wet seasons.

Precipitation years	Drip system uniformity *CU* (%)	Precipitation (mm)		Irrigation (mm)		Deep percolation (mm)		Nitrate leaching (kg ha^{-1})	
		Mean	Stand deviation	Mean	Stand deviation	Mean	Stand deviation	Mean	Stand deviation
Dry years	60	241.9	42.1	252.7	46.4	55.6	15.4	43.1	10.7
	80					42.2	15.8	31.6	11.8
	95					37.5	16.2	27.6	12.5
Normal years	60	375.2	57.0	175.8	53.8	100.2	34.4	66.1	20.0
	80					93.2	35.6	58.7	21.9
	95					90.6	36.4	56.0	22.8
Wet years	60	595.8	79.2	123.7	25.6	212.3	77.5	112.2	24.7
	80					209.5	77.0	108.4	24.9
	95					208.5	76.7	107.2	24.9

and irrigation (*I*, mm) to quantify the relative importance of these factors to nitrate leaching, yielding:

$$NL_{seasonal} = -2.06 - 0.27CU + 0.23P \quad (r^2 = 0.94,\ SE = 12.0) \quad (15)$$

where r^2 is the determination coefficient and *SE* (kg ha^{-1}) is the standard error. Eq. (15) was statistically significant (*F* value = 331.90, p = 4.59E − 43). The variable of irrigation (*I*) was excluded from the equation because the coefficient of *I* did not show significant difference at p = 0.05, implying an insignificant influence of irrigation amount on nitrate leaching. The equation indicated that the seasonal NO_3-N leaching decreased with the improving system uniformity, whereas it increased with precipitation. The significance levels of the coefficients for *CU* and *P* showed that the precipitation amount (p = 4.57E − 44) had a more important influence on nitrate leaching than the system uniformity (p = 8.95E − 04).

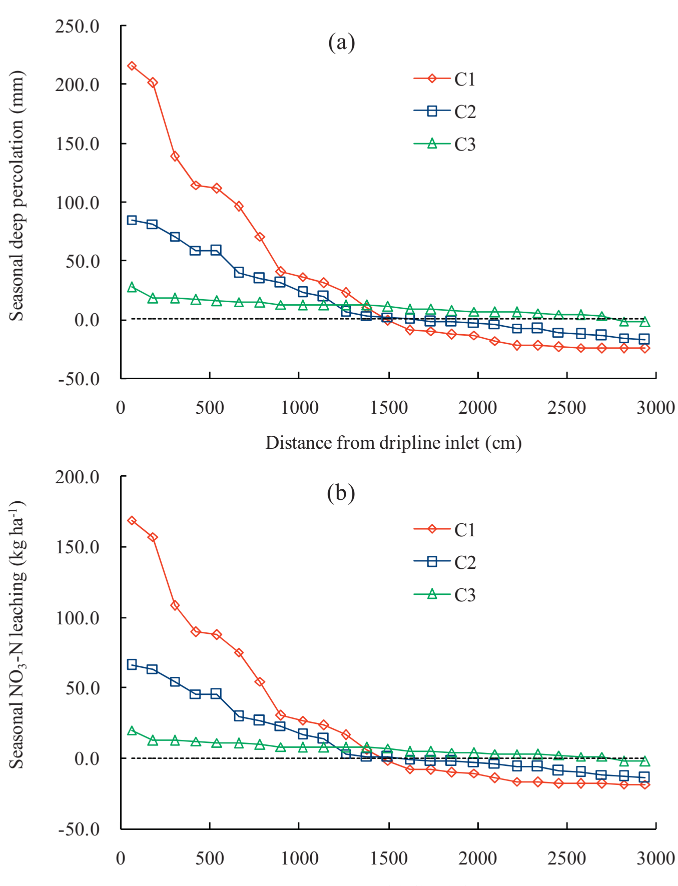

Fig. 7. The variations of the seasonal deep percolation (a) and NO_3-N leaching (b) rates along a dripline under uniformity coefficients of 60% (C1), 80% (C2), and 95% (C3) for a typical dry season of 2003.

A high drip irrigation uniformity usually represents a high initial installation cost of the systems. Moreover, the maintenance of a drip system for a very high uniformity is labor intensive, time consuming and expensive (Lamm et al., 2007). The design and evaluation standards of drip system uniformity are mostly set arbitrarily with a uniformity value as high as possible (Barragán et al., 2006). However, the necessity of high system uniformity is becoming questionable because various studies conducted under different environments from a greenhouse of Chinese cabbage in the absence of rainfall (Zhao et al., 2012) to a field of cotton in the Texas High Plains (Bordovsky and Porter, 2008) and maize in the North China Plain (Zhang and Li, 2011; Wang et al., 2014b) have reported that system uniformity imposed an insignificant influence on crop yield. The present study indicated that the effects of drip system uniformity on nitrate leaching were greatly dependent on precipitation patterns. It is suggested that both the amount of precipitation and the temporal distribution of precipitation during the growing season of crop should also be considered when the target drip irrigation uniformity is determined.

5. Conclusions

The effects of drip system uniformity and precipitation pattern on deep percolation and nitrate leaching in the subhumid region were evaluated during the growing season of maize using a water and solute transport model (HYDRUS-2D). The following conclusions were drawn from the present study:

(1) The HYDRUS-2D model performed reasonably well in predicting soil water content and nitrate distribution during the growing season of drip-irrigated maize under varying weather conditions at a field scale.
(2) The effects of drip system uniformity on deep percolation and nitrate leaching rates were greatly dependent on precipitation. Increased drip irrigation uniformity produced a more considerable reduction of deep percolation and NO_3-N leaching during a dry growing season than that of a normal or a wet season. For a normal or wet growing season, however, the difference in the seasonal NO_3-N leaching rate between the high system uniformity (*CU* = 0.95) and the low system uniformity (*CU* = 60%) was minor. Both the amount of precipitation and the temporal distribution of precipitation during the growing season of crop should therefore be considered when the target drip irrigation uniformity is determined.

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