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EFFECTS OF DIFFERENT IRRIGATION STRATEGIES ON SOIL WATER, SALT, AND NITRATE NITROGEN TRANSPORT

WPŁYW RÓŻNYCH STRATEGII NAWADNIANIA NA TRANSPORT WODY GLEBOWEJ, SOLI I AZOTU AZOTANOWEGO W GLEBIE

Abstract: Intermittent irrigation has attracted much attention as a water-saving technology in arid and semi-arid regions. For understanding the effect of intermittent irrigation on water and solute storage varied from irrigation amount per time (*IRA*), irrigation application frequency (*IRAF*), irrigation intervals (*IRI*) and even soil texture (*ST*), intermittent irrigation experiment was carried out in 33 micro-plots in Inner Mongolia, China. The experiment results were used for the calibration and validation of HYDRUS-1D software. Then 3 *ST* (silty clay loam, silty loam, and silty clay), 5 *IRA* (2, 4, 6, 8, and 10 cm), 4 *IRAF* (2, 3, 4, and 5 times) and 4 *IRI* (1, 2, 3, and 4 days) were combined and total 240 scenarios were simulated by HYDRUS-1D. Analysis of variance (ANVOA) of simulated results indicated that *ST, IRA,* and *IRAF* had significant effect on salt and nitrate nitrogen (NO_3^--N) storage of 0-40 cm depth soil in intermittent irrigation while only *ST* affected soil water storage obviously. Furthermore, salt leaching percentage (*SLP*) and water use efficiency (*WUE*) of 0-40 cm depth were calculated and statistical prediction models for *SLP* were established based on the ANOVA using multiple regression analysis in each soil texture. Then constraint conditions of soil water storage (around field capacity), salt storage (smaller than 168 $mg\cdot cm^{-2}$), *WUE* (as large as possible) in 0-40 cm depth and total irrigation water amount (less than 25 cm) were proposed to find out the optimal intermittent irrigation strategies. Before sowing, the optimal irrigation strategy for silty clay loam soil was 6 cm *IRA*, 3 times *IRAF,* and 2 days *IRI* respectively. For silty loam and silty clay soils, *IRA, IRAF*, and *IRI* were 8 cm, 3 times, and 2 days respectively.

Keywords: intermittent irrigation, HYDRUS-1D, simulation, salt leaching percentage, water use efficiency

Introduction

The broader emergence of high levels of nitrate in surface and groundwater is attracting more and more concern throughout the world [1]. This has resulted in pressure to improve the present traditional agricultural practices, especially in irrigation strategies to reduce the amount of nitrogen entering our water systems [2]. The quality of soils, surface and ground water resources is always at risk in areas where agricultural production is dominated by irrigation such as North China and many other arid and semiarid regions [3, 4]. According to the data from IFA, the annual global nitrogen (N) fertilizer consumption was

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102.3 million tons while China accounted for more than 32% by the end of 2009 [5]. Excessive and improper application of nitrogenous fertilizers could lead to an increase in nitrate concentration in waters and one of the most common contaminants found in groundwater worldwide is nitrate (NO_3^--N), an oxidized form of dissolved nitrogen which may cause methemoglobinemia, or blue baby syndrome [6, 7].

Irrigation is essential for crop cultivation in arid and semiarid regions for increasing water storage in the soil and to leach a fraction of accumulated salts [8, 9]. However, NO_3^--N leaching in irrigation process is assumed to be an inevitable result because the N uptake efficiency of annual crops is usually smaller than 50%. Therefore, it is important to find some ways to alleviate NO_3^--N leaching in irrigation process. Siyal et al [4] studied this issue by changing fertilizer placement in furrow irrigation and found placing N fertilizer on the sides of the furrow near the ridge top or on top of the furrow at the center of the ridge could maximize the retention of N fertilizer within the root zone. Meanwhile, studies also showed that even when following good management practices, about 30% of applied N fertilizer is also leached into groundwater. Therefore, irrigation strategies are still the main factor that affect NO_3^--N leaching.

In He-Tao Irrigation District, the largest irrigation district located in North China, a flood - irrigation strategy has been developed since the 1980s to create suitable environment for crops before sowing. The flood - irrigation strategy is definitely wasting water and increasing the risk of groundwater contamination [10]. However, it is almost impossible to change the flood - irrigation into others such as spray or drip irrigation which are widely recognized as water saving because of the economic and other local factors. Differently, intermittent irrigation strategy, which is also regarded as water saving and has better effects on salt leaching is more easy to adopt and expand in above traditional irrigation regions [11].

Irrigation amount per time, irrigation application frequency, and irrigation interval are main factors of an intermittent irrigation strategy. Previous researches indicated that intermittent high frequency irrigation with less water could increase salt leaching from the root zone [12, 13]. Borojeni and Salehi [14] even found that intermittent irrigation could obtain more paddy yield than continuous irrigation. However, Tan et al [15] considered that intermittent irrigation potentially decreased the water saving effectiveness and increased the NO_3^--N loading to the groundwater. Therefore, an appropriate intermittent irrigation strategy should consider water storage, salt leaching with the NO_3^--N leaching from the root zone together. Because of the time and economic consumption, it is difficult to achieve this only by experiment and computer models have become increasingly important tools for analyzing irrigation and crop production problems [16, 17]. HYDRUS-1D was developed by the USDA Salinity Laboratory and has been used to study the leaching of accumulated salt and nitrogen in soil under rainfall or irrigation conditions in many regions and achieve comparable simulation results [18]. Our previous research used HYDRUS-1D to evaluate soil salt leaching under different irrigation regimes, but NO_3^--N leaching was not considered [10]. Furthermore, the mechanism and operation of HYDRUS software are relatively hard for local farmers and policymakers. Therefore, it is necessary to develop simple and dependable models to determine irrigation strategies considering water storage, salt and NO_3^--N leaching of root zone.

The objectives of this study were to (1) calibrate and validate the HYDRUS-1D for water, salt, and NO_3^--N storage in the root zone (0-40 cm) by field experiment data in different soil texture; (2) apply HYDRUS-1D to simulate water, salt, and NO_3^--N transport in different intermittent irrigation scenarios; (3) develop prediction models for salt leaching percentage of root zone by HYDRUS-1D simulation results and statistical analysis, then determine the optimal irrigation strategies in different soil texture.

Materials and methods

Study site

Hetao Irrigation District (40°19′-41°18′N, 106°20′-109°19′E), which is located in the arid western areas of Inner Mongolia autonomous region, is the largest Irrigation District in China (Fig. 1). It has the monsoon climate and the average annual potential evaporation is about 139-122 mm, approximately 60% of which falls in July and August, while the annual potential evaporation is about 2,200-2,400 mm. Due to the strong evaporation, the groundwater and soil water constantly migrate upward and eventually resulting in salt accumulation in the topsoil after the soil water evaporates. Therefore, Hetao Irrigation District has struggled with soil salinization issues for several years.

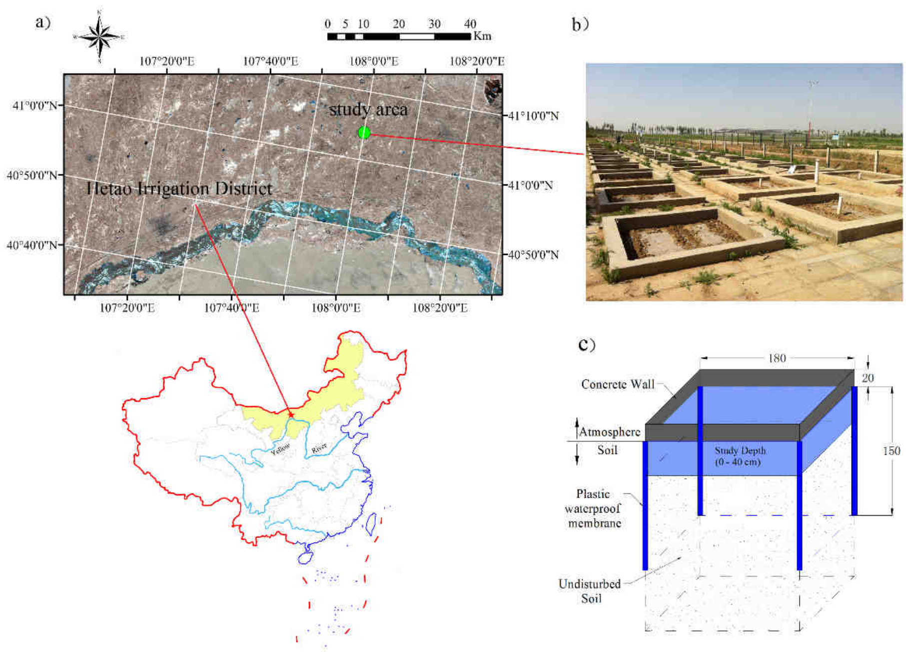

Fig. 1. Location of study site (a) and schematic diagram of Micro-plot (b and c) [cm]

Experimental design

Experimental scheme

Field experiments were conducted in micro-plots with undisturbed soil at the YiChang experimental station in the Hetao Irrigation District. More exactly, randomly combined design were used and study factors included total irrigation amount (*TIRA*), irrigation application frequency (*IRAF*), and irrigation intervals (*IRT*). Each factor had 2 levels (*TIRA* = 20 and 30 cm; *IRAF* = 2 and 3; *IRT* = 1 and 2 days, respectively) and there were 3 replicates. Furthermore, one time irrigation with 10, 20, and 30 cm were also applied with 3 replicates as reference in our experiment. All these treatments were randomly arranged in 33 micro-plots. The cross section of each micro-plot was 1.8 m×1.8 m and wrapped with impermeable plastic (0-1.5 m below the soil surface) to prevent leakage (Fig. 1c). Therefore, the water and solute transport in each micro-plot could be regarded as one dimension.

Before irrigation (May 3rd, 2013), we took soil samples from 33 micro-plots to determine the texture, water content, salt and nitrogen concentration at depths of 0-10, 10-20, 20-30, and 30-40 cm. Then we began to irrigate according to experimental scheme on the same day. The irrigation water came from a well and its total solute content was about 800.75 $mg \cdot dm^{-3}$. After irrigation (May 11th, 2013), soil samples from 33 micro-plots were also collected for water, salt and nitrogen analysis at the same depth as before irrigation sampling. Climate data were recorded by an automated weather station beside the micro-plots, provided daily precipitation data and additional weather parameters for the calculation of soil evaporation (Fig. 2).

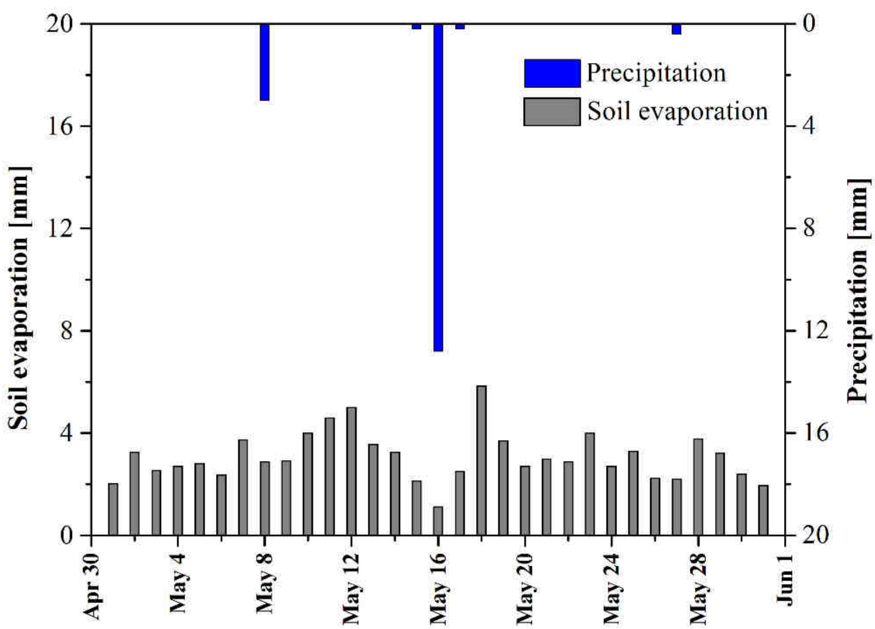

Fig. 2. Precipitation and evaporation in May 2013 of YiChang Experimental Station

Soil analysis

Soil particle size percentage was analyzed using pipette method. Soil water content was measured using conventional oven drying. The electrical conductivity ($EC_{1:5}$ [$dS \cdot m^{-1}$]) of soil was determined with an EC meter (DDSJ-318, LEICI, China) in an extract (1:5) after shaking for 3 mins. Soil NO_3^--N concentration was measured by Automatic Nitrogen Analyzer (Cleverchem-200, Dechem-Tech, Germany). In our study, we assumed the bulk density of 0-40 cm depth was same and use the average bulk density (1.4 $g\cdot cm^{-3}$) to convert measured water content into volumetric water content and then calculated the mass of total salt and NO_3^--N content.

Modeling process

Description of HYDRUS-1D

Soil water movement for the experimental situation was described as follows [18]:

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

where θ is the soil volumetric water content [$cm^3\cdot cm^{-3}$]; h is the water pressure head [cm]; K is the unsaturated hydraulic conductivity [$cm\cdot d^{-1}$]; z is the vertical axis (upward positive) depending on the origin of the surface flux.

The soil water retention ($\theta(h)$) and the hydraulic conductivity ($K(h)$) variables in Eq. (3) were described by van Genuchten as follows [19]:

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

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

$$m = 1 - \frac{1}{n} \tag{4}$$

$$S_e \frac{\theta - \theta_r}{\theta_s - \theta_r} \tag{5}$$

where θ_s and θ_r are the saturated and residual water contents [$cm^3\cdot cm^{-3}$]; K_s is the saturated hydraulic conductivity [$cm\cdot d^{-1}$], α [cm^{-1}] and n represent the empirical shape parameters, and l is a pore connectivity parameter. To reduce the number of free parameters, we took l = 0.5, a common assumption which was based on the work of Mualem [20]. S_e is the effective saturation.

The one-dimensional solute transport under transient water flow conditions in a partially saturated porous medium is expressed by the following equations:

$$\frac{\partial \theta c}{\partial t} = \frac{\partial \theta}{\partial z}\left(\theta D \frac{\partial c}{\partial z}\right) - \frac{\partial q c}{\partial z} \tag{6}$$

$$D = \alpha_L q \tag{7}$$

where c is the solute concentration [$mg\cdot cm^{-3}$]; D is the effective dispersion coefficient [$cm^2\cdot d^{-1}$]; q is the volumetric flux density given by Darcy's Law [$cm^3\cdot cm^{-2}\cdot d^{-1}$]; and α_L represents the longitudinal dispersivity [cm].

Calibration and validation

According to the soil particle size analysis and refer to the soil texture triangle (*USDA*), the texture of 0-40 cm depth of each micro-plot was uniform but varied from different micro-plots. More exactly, the 33 micro-plots could be divided into 3 types by soil texture: silty clay loam, silty loam, and silty clay (Fig. 3). Therefore, we calibrated and validated HYDRUS-1D in 3 different soil texture respectively.

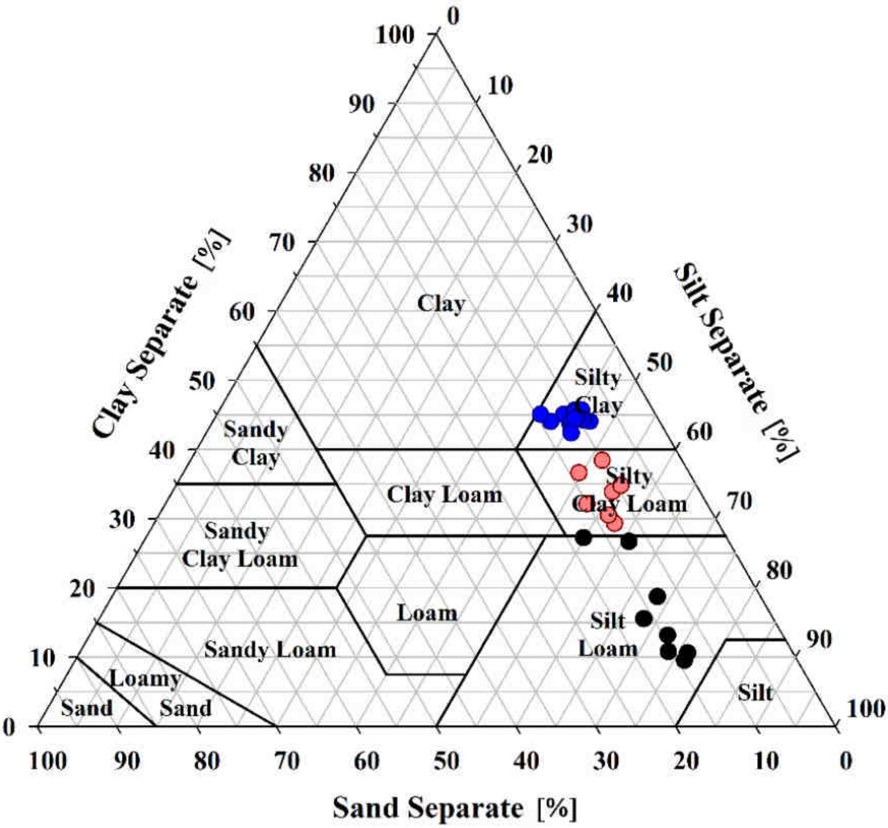

Fig. 3. Soil texture classification of 0-40 cm depth of each micro-plot (7 red points meant silty clay loam, 8 black points meant silty loam, and 18 blue points meant silty clay)

Because soil hydrodynamic and solute transport parameters vary from soil physical properties (*eg* clay percentage, specific surface area), we divided the experimental data of each soil texture into 2 sub-sets based on the clay percentage. In practical terms, the mean values for each sub-dataset should be similar with the mean value of the total data. Meanwhile, the variance of each sub-dataset should be as far as possible. In addition, the sample size in each sub-dataset should be comparable. This work was completed by a procedure based on an enumeration algorithm and one sub-dataset was used for HYDRUS-1D calibration and the other was used for validation (Fig. 4).

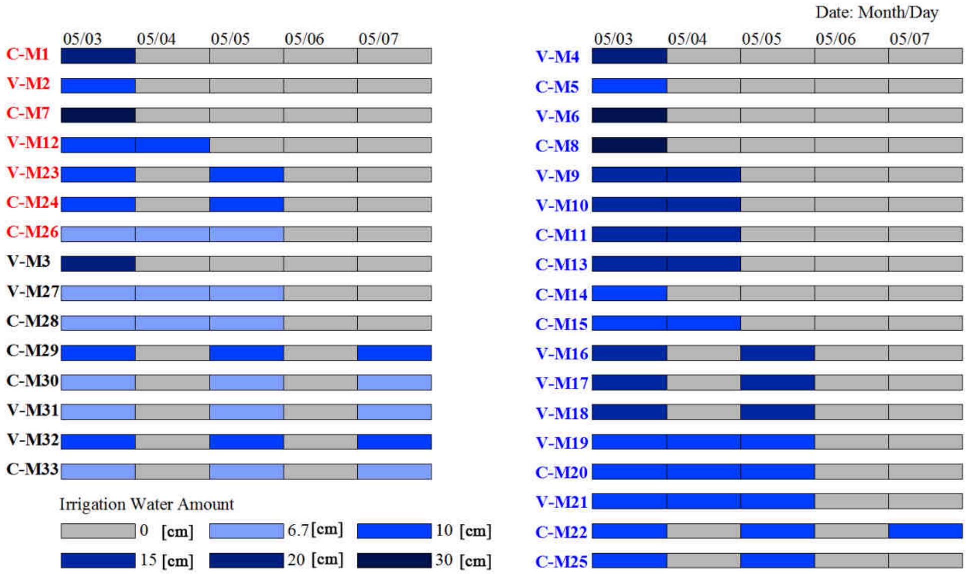

Fig. 4. Irrigation strategies of each experimental treatment (M means micro-plot; C means these treatments were used for calibration and V means these treatments were used for model validation; red colour indicates silty clay loam soil, black colour indicates silty loam soil, and blue colour indicates silty clay soil)

In the calibration process, the soil hydraulic parameters saturated and residual water content θ_s and θ_r, α, n and the saturated hydraulic conductivity (K_{sat}) were initially estimated based on the experimental soil particle percentage and bulk density using the neutral network pedotransfer functions of Rosetta module [21]. After that, we calculated the mean value of each Rosetta realization and use them as the initial parameter values and then a trial-and-error procedure was used to find out the final parameter values for each soil texture based on least-square-fitting method [22]. Firstly, we fitted the soil hydraulic parameters θ_s and θ_r, then α, n and K_{sat} were fitted simultaneously, finally, solute parameters such as longitudinal dispersivity (D_L), molecular diffusion coefficient in free water (D_w) and adsorption coefficient (K_d) of salt and nitrate nitrogen (NO_3^--N) were estimated respectively (Table 1). The convection dispersion equation for non-reactive solutes was used during simulation because the solutes were assumed non-reactive. The simulation in calibration and validation processes were conducted for 9 days (from May 3rd to May 11th) and the irrigation strategies for each treatment were shown in Figure 4.

In the modeling process, we regarded irrigation as precipitation and converted the total irrigation amount (*TIRA*) into irrigation amount per time (*IRA*). The upper conditions of the soil profile correspond to atmosphere boundary condition. Because we wanted to find out the irrigation strategies before sowing, and the main crop of study area was sunflower whose roots were mainly in 0-40 cm depth while the groundwater depth was approximately 200 cm, the lower boundary condition was free drainage. For solute transport, the upper and lower boundary conditions were concentration flux and zero concentration gradient, respectively.

Table 1

Input values of the soil hydrodynamic parameters

Texture	θ_r	θ_s	α	n	K_s	D_L	D_{wsalt}	D_{wn}	K_{dsalt}	K_{dn}
—	[$cm^3 \cdot cm^{-3}$]	[$cm^3 \cdot cm^{-3}$]	[cm^{-1}]	—	[$cm \cdot d^{-1}$]	[cm]	[$cm^2 \cdot d^{-1}$]	[$cm^2 \cdot d^{-1}$]	[$cm^3 \cdot g^{-1}$]	[$cm^3 \cdot g^{-1}$]
Silty clay loam	0.093	0.462	0.009	1.452	10.02	6.8	3.8	6.5	0.25	0.15
Silty loam	0.071	0.420	0.005	1.614	23.20	7.7				
Silty clay	0.102	0.498	0.015	1.316	8.98	5.8				

D_{wsalt} and D_{wn} meant molecular diffusion coefficient in free water of salt and NO_3^--N respectively; K_{dsalt} and K_{dn} meant adsorption coefficient of salt and NO_3^--N respectively

Table 2

Statistical evaluation indexes of calibration and validation of HYDRUS 1D

Texture	**Soil samples**	**Water content [$cm^3 \cdot cm^{-3}$]**				$EC_{1:5}$ **[$dS \cdot m^{-1}$]**				**NO_3^--N concentration [$mg \cdot kg^{-1}$]**			
		R^2	*NSE*	*Bias*	*Pbias*	R^2	*NSE*	*Bias*	*Pbias*	R^2	*NSE*	*Bias*	*Pbias*
Silty clay loam	Calibration	0.902	0.873	–0.001	–0.288%	0.942	0.901	0.063	11.287%	0.862	0.798	–0.421	–8.308%
	Validation	0.839	0.823	0.001	0.255%	0.883	0.866	0.021	4.854%	0.827	0.534	1.067	22.962%
Silty loam	Calibration	0.814	0.798	–0.001	–0.040%	0.894	0.823	0.024	6.536%	0.785	0.752	0.341	8.642%
	Validation	0.787	0.698	–0.005	–1.943%	0.799	0.653	0.050	10.272%	0.780	0.068	1.034	32.127%
Silty clay	Calibration	0.790	0.689	0.007	1.772%	0.839	0.819	0.086	11.553%	0.718	0.642	0.573	9.308%
	Validation	0.715	0.348	0.013	3.428%	0.750	0.708	0.088	10.442%	0.710	–0.666	1.181	31.785%

R^2 means the determination coefficient and *NSE* meant Nash-Sutcliffe modelling efficiency

Model evaluation

Both graphical and statistical methods were used to evaluate the model performance. In the graphical approach, the measured and predicted values were plotted in the same graph.

Different statistical techniques such as coefficient of determination (R^2), Nash-Sutcliffe efficiency (*NSE*), model bias (*Bias*), and percentage bias (*Pbias*) were used in this study.

$$NSE = 1 - \frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}{\sum_{i=1}^{n}\left(Y_i^{obs} - Y^{mean}\right)^2} \tag{8}$$

where Y_i^{obs} is the *i*th observed value, Y_i^{sim} is the *i*th simulated value and Y^{mean} is the mean of observed values. *NSE* can range from $-\infty$ to 1. *NSE* = 1 means a perfect match between the modeled value and the measured data. *NSE* = 0 means the model predictions are as accurate as the mean of the measured data. Whereas an *NSE* of less than 0 occurs when the measured mean is a better predictor than the model. Therefore, the closer *NSE* is to 1, the more accurate the model is [23].

Because *NSE* values depend on sample size, bias of magnitude and outliers. *Bias* values were also calculated along with *NSE* by:

$$Bias = \frac{1}{n}\sum_{i=1}^{n}\left(Y_i^{sim} - Y_i^{obs}\right) \tag{9}$$

In addition, the percentage bias (*Pbias*) is easier to interpret and is determined by the ratio of the Bias to the mean of the observed values multiplied by 100.

Simulation scenarios

After calibration and validation, HYDRUS-1D was used to simulate different intermittent irrigation strategies. The 5 levels of irrigation amount per time (*IRA* = 2, 4, 6, 8, and 10 cm), 4 levels of irrigation application frequency (*IRAF* = 2, 3, 4, and 5 times), and 4 levels of irrigation intervals (*IRI* = 1, 2, 3, and 4 days) were complete combination and simulated in 3 different soil texture (silty clay loam, silty loam, and silty clay) respectively. Therefore, total 240 scenarios were simulated. The initial condition of soil profile was obtained by average the water content, salt and nitrogen (NO_3^--N) concentration of all 33 micro-plots. The end time was set on the 10th day after the last irrigation in each simulation, respectively.

Data analysis

Before running HYDRUS-1D model, soil salt and NO_3^--N content should be converted into the ratio of solute mass and volume water using Eqs. (10)-(11) as follows:

$$S^{input} = \frac{EC_{1:5} \cdot 0.308 \cdot \rho \cdot 1000}{100 \cdot \theta} \tag{10}$$

$$N^{input} = \frac{N^{obs} \cdot \rho}{1000 \cdot \theta} \tag{11}$$

where S^{input} *and* N^{input} were soil salt and NO_3^--N content in solute mass/volume water [$mg \cdot cm^{-3}$] respectively; N^{obs} was the measured NO_3^--N content in initial units [$mg \cdot kg^{-1}$]; 0.308 is the coefficient obtained by experiments to convert $EC_{1:5}$ [$dS \cdot m^{-1}$] into percentage salt content [%] ρ is the bulk density [1.4 $g \cdot cm^{-3}$]; θ is the volumetric water content [$cm^3 \cdot cm^{-3}$].

All simulated results were firstly used to calculate the total storage of water, salt and NO_3^--N content in 0-40 cm depth by Eqs. (12)-(14):

$$TWS^{output} = D \cdot \frac{1}{n} \sum_{i=1}^{n} \theta_i^{output} \tag{12}$$

$$TSS^{output} = D \cdot \frac{1}{n} \sum_{i=1}^{n} \theta_i^{output} \cdot S_i^{output} \tag{13}$$

$$TNS^{output} = D \cdot \frac{1}{n} \sum_{i=1}^{n} \theta_i^{output} \cdot N_i^{output} \tag{14}$$

where θ_i^{output} [$cm^3 \cdot cm^{-3}$], S_i^{output} [$mg \cdot cm^{-3}$], and N_i^{output} [$mg \cdot cm^{-3}$] are the HYDRUS-1D results of soil water, salt, and NO_3^--N content in each calculation node; *n* is the number of nodes; *D* is the soil depth; TWS^{output} [cm], TSS^{output} [$mg \cdot cm^{-2}$], and TNS^{output} [$mg \cdot cm^{-2}$] are soil water, salt and NO_3^--N of 0-40 cm depth 10 days after irrigation.

For better evaluate the irrigation effect, we defined salt leaching percentage (*SLP* [%]) and water use efficiency (*WUE*) by Eqs. (15)-(16):

$$SLP = \frac{-\Delta TSS}{TSS^{input}} \cdot 100 \tag{15}$$

$$WUE = \frac{\Delta NTWS - \alpha \cdot \Delta NTSS + (1-\alpha)\Delta NTSS}{IRA \cdot IRAF} \quad (16)$$

where ΔTSS [mg·cm^{-2}] was obtained using the salt storage of 0-40 cm depth after irrigation (TSS^{output} [mg·cm^{-2}]) minus the salt storage before irrigation (TSS^{input} [mg·cm^{-2}]); $\Delta NTWS$, $\Delta NTSS$, and $\Delta NTNS$ are the normalized value of water, salt, and NO_3^--N storage after irrigation minus their corresponding values before irrigation respectively; and α is the weighing factor (0.7 in our study).

Then all the data were subjected to analysis of variance (ANOVA). Averages of the main effects were compared using the revised least significant difference test at the 0.05 level of probability [24]. Computations and statistical analyses were carried out using the *SPSS* software (Version 18.0).

Results

Calibration and validation of HYDRUS-1D

The experimental data were used to determine the soil parameters in HYDRUS-1D. Figure 5 plotted the experimental data and simulative data of the water, salt, and nitrogen contents of 0-40 cm depth for silty clay loam, silty loam, and silty clay soils respectively.

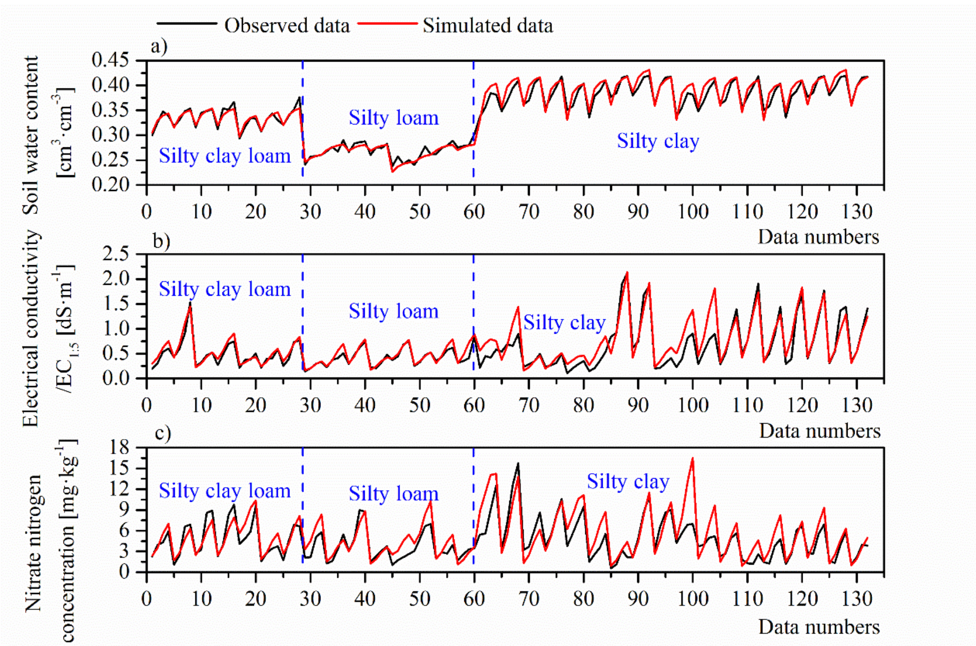

Fig. 5. Calibration and validation of HYDRUS-1D (black lines mean observed data and red lines mean simulated data)

We could find that the simulative and experimental data of water, salt and nitrogen contents in all 3 soils aggregated along the 1:1 line, which indicated the correlation between them. Furthermore, statistical evaluation indexes such as R^2, *NSE*, *Bias*, and *Pbias* for both calibration and validation process were shown in Table 2. We could find that the R^2 of water content, salt content and NO_3^--N concentration were all larger than 0.7. But if we refer to other evaluation index, the HYDRUS-1D model's performance was not that remarkable. More exactly, the *NSE* value for NO_3^--N concentration in the validation process of silty clay soil were negative (–0.666). In addition, the *Pbias* value of silty loam and silty clay soil for NO_3^--N concentration in the validation process were larger than 30% (32.13 and 31.79% respectively). However, although this model could not perform perfectly in all situations, when considering both Figure 5 and Table 2, we could also deem the HYDRUS-1D can obtain the acceptable simulative results in our study conditions.

Analysis of different simulation scenarios

Analysis of variance (ANOVA) indicated that only soil texture had significant effects on water, salt, and NO_3^--N storage of 0-40 cm soil depth (P = 0.001). Irrigation amount per time (*IRA*) and irrigation application frequency (*IRAF*) affected salt and NO_3^--N storage obviously (P = 0.001), but had no significant effect on water storage. Furthermore, irrigation intervals (*IRI*) had no obvious effects on water, salt, and NO_3^--N storage (Table 3).

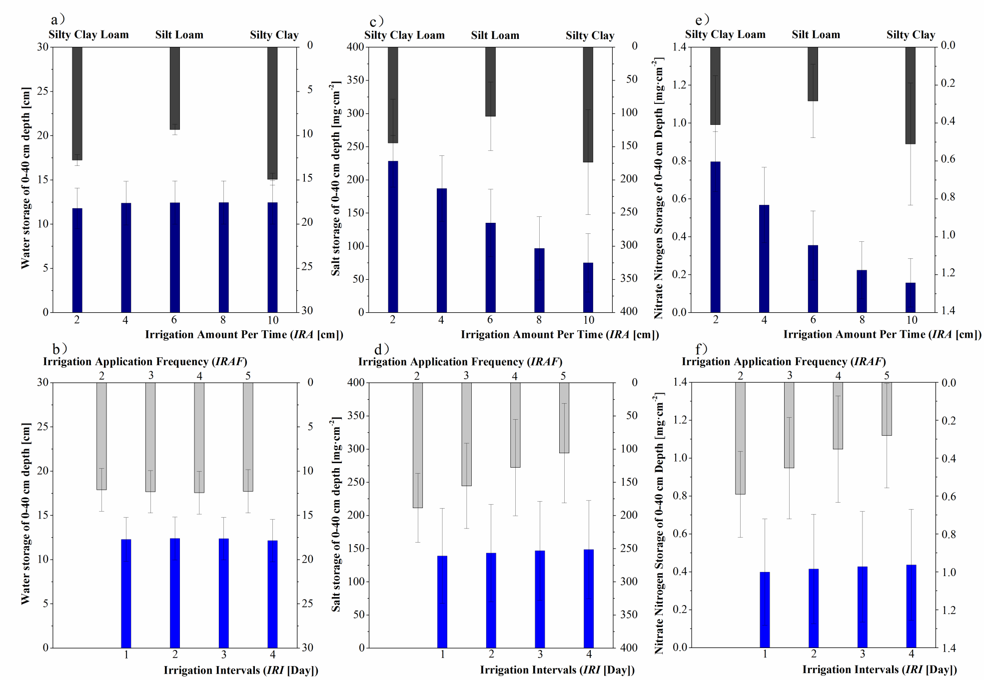

Fig. 6. Water, salt and nitrate nitrogen storage of 0-40 cm depth under different soil texture, irrigation amount per time (*IRA*), irrigation application frequency (*IRAF*), and irrigation intervals *(IRI*)

Soil texture of silty clay had the maximum water, salt, and NO_3^--N storage while silty loam had the least of them in depth of 0-40 cm depth 10 days after irrigation (Fig. 6). The 0-40 cm water storage increased with *IRA* (Fig. 6a). But when considering *IRAF*, the largest water storage was obtained in 4 times irrigation (12.450 cm) not 5 times (Fig. 6b). Moreover, 2 days other than 1 day irrigation interval achieved the largest water storage (12.380 cm). Soil salt and NO_3^--N storages all increased with *IRI* but decreased with *IRA* and *IRAF*. More exactly, 10 cm *IRA* could decrease 67.16% salt storage and 80.28% NO_3^--N storage relate to 2 cm *IRA*; 5 times *IRAF* could decrease 43.77% salt storage and 52.45% NO_3^--N storage relate to 2 times *IRAF*; but 4 days *IRI* increased 6.81% salt storage and 9.52% NO_3^--N storage of 0-40 cm soil depth relate to 1 day *IRI* (Fig. 6c-f).

Table 4 demonstrated that soil texture could affect soil water, salt, and NO_3^--N storage of 0-40 cm depth significantly. Therefore, it is necessary to analysis the effect of irrigation strategies on soil water and solute distributions in different soil textures respectively. The ANOVA results for 3 different soil textures were shown in Table 4, which illustrated *IRA* and *IRAF* affected soil salt and NO_3^--N storage of 0-40 cm depth 10 days after irrigation obviously (P = 0.001). However, *IRI* only had significant effects on salt storage in silty clay loam and on NO_3^--N storage in silty loam (P = 0.001 and 0.036, respectively). Furthermore, only *IRA* in silty clay loam and silty clay soils had significant effects on water storage of 0-40 cm depth (P = 0.015 and 0.001, respectively).

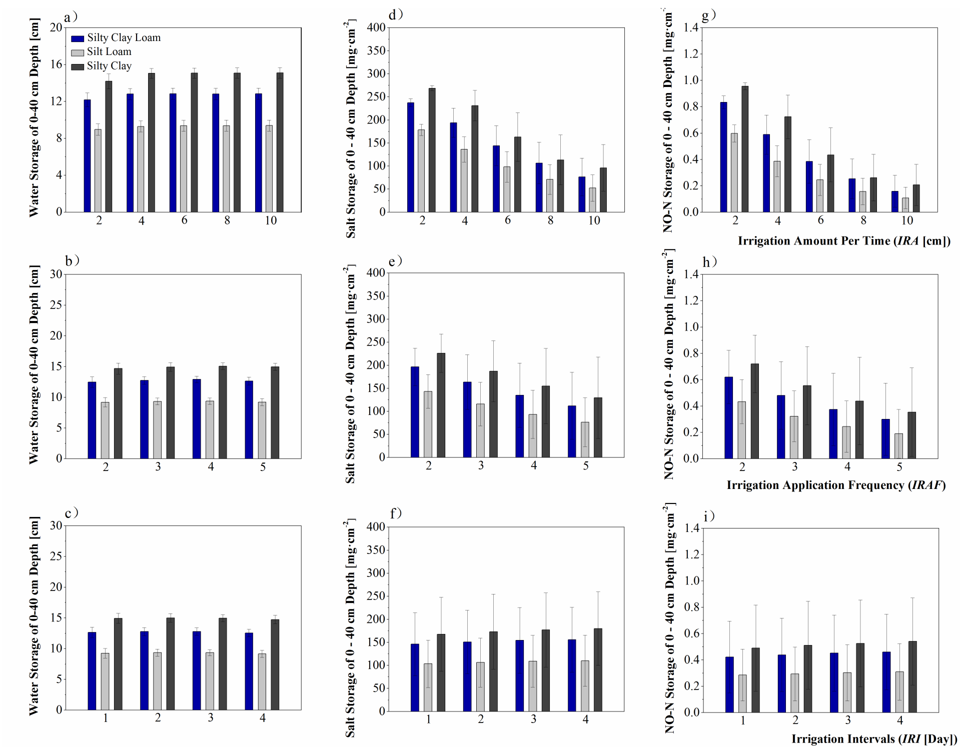

Fig. 7. Water, salt and nitrate nitrogen storage of 0-40 cm depth under different irrigation amount per time (*IRA*), irrigation application frequency (*IRFA*), and irrigation intervals (*IRI*) in specific soil texture

More exactly, 10 cm *IRA* and 4 times *IRAF* could obtain maximum water storage of 0-40 cm depth in all 3 soils. But when considering *IRI*, 3 days *IRI* obtain maximum water storage in silty clay loam while in silty loam and silty clay soils, the *IRI* for maximum water storage was 2 days (Fig. 7a-c). Salt and NO_3^--N storage of 0-40 cm depth were both decreased with *IRA* and *IRAF*, and increased with *IRI* (Fig. 7d-i). In addition, silty clay soil also had the maximum while silty loam soil had the minimum water, salt, and NO_3^--N storage in all different *IRA*, *IRAF*, and *IRI* treatments respectively (Fig. 7).

Table 3

The ANOVA of the effects of *ST*, *IRA*, *IRAF* and *IRI*

Source of variation	**Water storage**	**Salt storage**	**Nitrate nitrogen storage**	**Salt leaching percentage**	**Water use efficiency**
	of 0-40 cm depth	**of 0-40 cm depth**	**of 0-40 cm depth**	**of 0-40 cm depth**	**of 0-40 cm depth**
	(*P* > *F*)	**(*P* > *F*)**	**(*P* > *F*)**	**(*P* > *F*)**	**(*P* > *F*)**
Soil texture (*ST*)	0.001**	0.001**	0.001**	0.001**	0.001**
Irrigation amount per time (*IRA*)	0.064	0.001**	0.001**	0.001**	0.005**
Irrigation application frequency (*IRAF*)	0.745	0.001**	0.001**	0.001**	0.477
Irrigation intervals (*IRI*)	0.941	0.740	0.684	0.046*	0.651

* means significant level, $P < 0.05$; ** means significant level, $P < 0.01$

Table 4

The ANOVA of the effects of *IRA*, *IRAF* and *IRI* in specific soil texture

Soil texture	**Source of variation**	**Water storage**	**Salt storage**	**Nitrate nitrogen storage**	**Salt leaching percentage**	**Water use efficiency**
		of 0-40 cm depth	**of 0-40 cm depth**	**of 0-40 cm depth**	**of 0-40 cm depth**	**of 0-40 cm depth**
		(*P* > *F*)	**(*P* > *F*)**	**(*P* > *F*)**	**(*P* > *F*)**	**(*P* > *F*)**
Silty clay loam	Irrigation amount per time (*IRA*)	0.015*	0.001**	0.001**	0.001**	0.302
	Irrigation application frequency (*IRAF*)	0.212	0.001**	0.001**	0.001**	0.491
	Irrigation intervals (*IRI*)	0.602	0.001**	0.081	0.281	0.592
Silty loam	Irrigation amount per time (*IRA*)	0.242	0.001**	0.001**	0.001**	0.001**
	Irrigation application frequency (*IRAF*)	0.750	0.001**	0.001**	0.001**	0.001**
	Irrigation intervals (*IRI*)	0.714	0.175	0.036*	0.175	0.757
Silty clay	Irrigation amount per time (*IRA*)	0.001**	0.001**	0.001**	0.001**	0.001**
	Irrigation application frequency (*IRAF*)	0.244	0.001**	0.001**	0.001**	0.001**
	Irrigation intervals (*IRI*)	0.519	0.357	0.145	0.356	0.657

* means significant level $P < 0.05$;** means significant level $P < 0.01$

Salt leaching percentage (*SLP*)

Salt leaching percentage (*SLP*) of each scenarios were calculated according to Eq. (15). ANOVA indicated that although *IRA*, *IRAF*, and *IRI* had significant effects on *SLP* when considering all scenarios together (Table 3), only *IRA* and *IRAF* affected *SLP* significantly when considering silty clay loam, silty loam, and silty clay soils respectively (Table 4). Therefore, *IRA* and *IRAF* were selected to establish statistical prediction models for *SLP* in 3 different soils by multiple regression analysis respectively (Eqs. (17)-(19)):

$$SLP_{scl} = -55.087 + 8.513IRA + 11.700IRAF \;\; (2 \le IRA \le 10,\; 2 \le IRAF \le 5) \tag{17}$$

$$SLP_{sl} = -16.579 + 6.602IRA + 9.259IRAF \;\; (2 \le IRA \le 10,\; 2 \le IRAF \le 5) \tag{18}$$

$$SLP_{sc} = -76.915 + 9.619IRA + 13.352IRAF \;\; (2 \le IRA \le 10,\; 2 \le IRAF \le 5) \tag{19}$$

where SLP_{scl}, SLP_{sl}, and SLP_{sc} means salt storage of 0-40 cm depth 10 days after irrigation in silty clay loam, silty loam, and silty clay soils respectively.

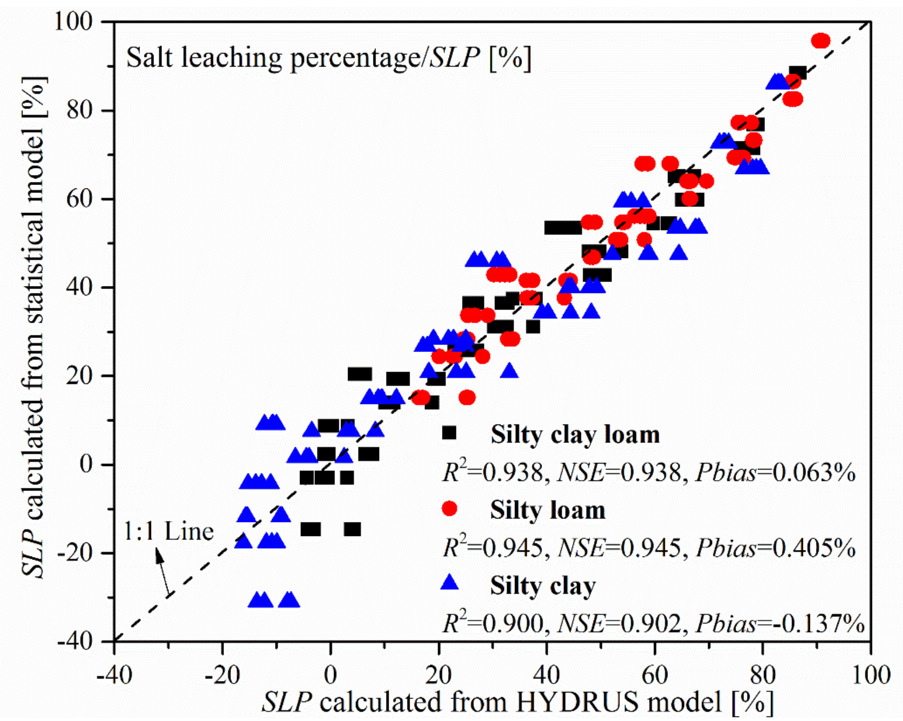

Fig. 8. Model performance evaluation of salt leaching percentage (*SLP*) between statistical model (Eqs. (17)-(19)) and HYDRUS results in 3 different soils respectively

Graphical and statistical indexes (*eg* R^2, *NSE*, and *Pbias*) were also used to evaluate the accuracy of statistical prediction models compared to HYDRUS-1D results. We found that the scatters of statistical prediction models and HYDRUS-1D results distributed along the 1:1 line in all 3 soils. In addition, both the determination coefficient (R^2) and

Nash-Sutcliffe efficiency (*NSE*) were larger than 0.9 while *Pbias* values were all smaller than 0.5% (Fig 8). Therefore, we could regard the statistical prediction models as an appropriate substitution of the HYDRUS-1D for *SLP* evaluation in silty clay loam, silty loam, and silty clay soils. Based on Eqs. (17)-(19), for 2 times *IRAF*, the minimum *IRA* in silty clay loam, silty loam, and silty clay soils to ensure *SLP* larger than 0 were 3.72, 2 and 5.22 cm respectively.

Water use efficiency (*WUE*)

Water use efficiency (*WUE*) for each scenario was calculated on the basis of our definition (Eq. (16)). If we consider all scenarios together (Table 3), only *ST* and *IRA* affect *WUE* significantly (P = 0.001 and P = 0.005, respectively). But when we did ANOVA of *WUE* in each soil texture respectively (Table 4), *IRA* and *IRAF* both had significant effect on *WUE* in silty loam and silty clay soils (P = 0.001). However, *IRI* could not affect *WUE* obviously in all 3 soils and in silty clay loam soil, both *IRA* and *IRAF* also had no significant effect on *WUE*.

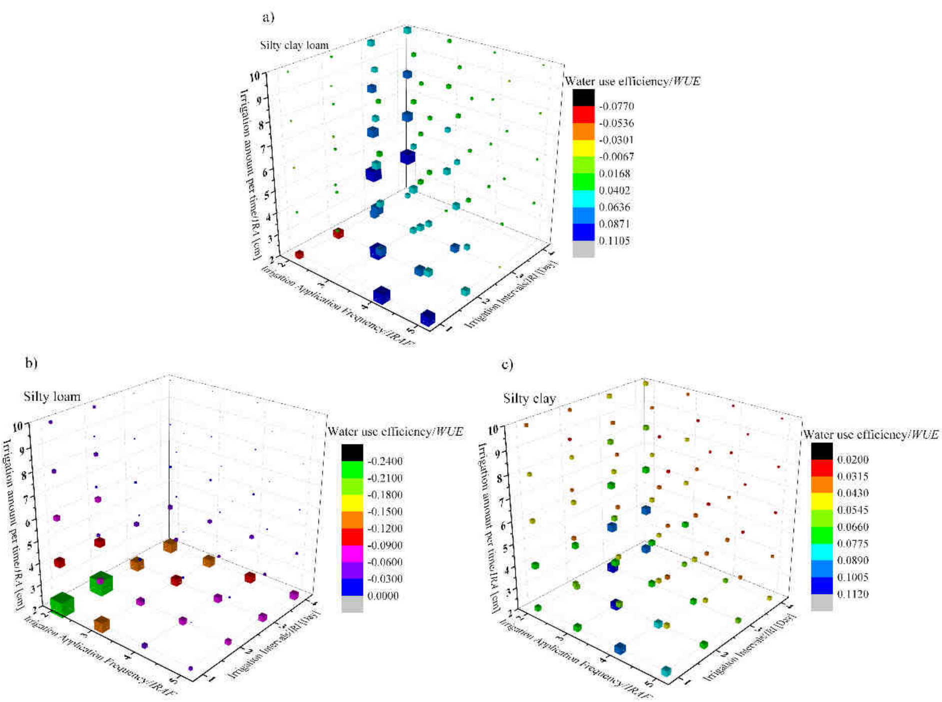

Fig. 9. Effect of irrigation application frequency (*IRAF*) and irrigation intervals (*IRI*) on water use efficiency (*WUE*) for each simulation scenario vary from different irrigation amount per time (*IRA*): a) indicates silty clay loam soil; b) indicates silty loam soil; c) indicates silty clay soil. Cube size indicates the absolute value of water use efficiency for each treatment)

More exactly, silty clay had the maximum *WUE* in these 3 soils. Furthermore, when IRA was 2 cm and *IRI* was smaller than 3 days, silty clay loam could obtain negative *WUE* and all *WUE* in silty loam were negative (Fig. 9). In silty clay loam soil, the maximum *WUE* was obtained in condition of 4 cm *IRA*, 2 times *IRAF*, and 3 days *IRI* (*WUE* = 0.110); in silty loam soil, 10 cm *IRA*, 5 times *IRAF*, and 1 days *IRI* could obtain the maximum *WUE* (*WUE* = –0.001); and in silty clay soil, the corresponding *IRA*, *IRAF*, and *IRI* were 2 cm, 2 times, and 3 days respectively (*WUE* = 0.112).

Optimal irrigation strategy

The most widespread crop in our study site is sunflower, which is defined as moderate salt tolerance sensitive crop [25]. Based on the researches for sunflower growth characteristic in our study site [26], the threshold value of soil salt content for sunflower's root zone (0-40 cm depth) was around 0.3% (168 $mg \cdot cm^{-2}$). Therefore, first important constraint condition for optimal irrigation strategy is the root zone's salt content should be less than 168 $mg \cdot cm^{-2}$. Furthermore, irrigation also plays a role of increasing soil water content, so another constraint condition is the root zone's water storage before sowing (10 days after irrigation in our study) should be around field water capacity. Here we use the "rule of thumb" that regard half of saturated water content of each soil texture as field water capacity respectively. Moreover, an appropriate irrigation strategy should cause less NO_3^--N leaching out of root zone. Therefore, the third constraint condition was *WUE* should be as large as possible. In addition, we hope to develop a water saving irrigation strategy, so the total irrigation water amount should be less than local traditional flood irrigation water amount (about 25-35 cm). In that respect, we determined the optimal irrigation strategy for silty clay loam, silty loam, and silty clay soils respectively (Table 5).

Table 5

Optimal irrigation strategies of 3 different soil texture

Items	**Silty clay loam**	**Silty loam**	**Silty clay**
Irrigation amount per time (*IRA* [cm])	6	8	8
Irrigation application frequency (*IRAF*)	3	3	3
Irrigation intervals (*IRI* [day])	2	2	2
Water storage [cm]	13.506	10.080	15.704
Salt storage [$mg \cdot cm^{-2}$]	162.130	81.288	125.486
Nitrate nitrogen (NO_3^--N) storage [$mg \cdot cm^{-2}$]	0.433	0.176	0.281
Water use efficiency (*WUE*)	0.060	–0.008	0.048

Discussion

Water, salt, and nitrate nitrogen (NO_3^--N) storage

Water storage has constrained both economic and agricultural development in many arid and semi-arid regions. Instead of flood irrigation, which is regarded as wasting water resources, many water-saving irrigation technologies have been developed and promoted to enhance water productivity and to reduce water use [27]. Our results indicated that intermittent irrigation could also keep suitable water amount before sowing. The similar results were also found by Tan et al [15], who indicated that intermittent irrigation reduced irrigation water without a significant impact on rice yields and increased the mean water productivity by 16.9% compared with continuously flood irrigation. Irrigation amount per time (*IRA*), irrigation application frequency (*IRAF*), and irrigation intervals (*IRI*) are 3 important factors of intermittent. However, because of the time and economic costing, only a few treatments of the 3 factors could be considered in experiments, Borojeni and Salehi [14] set 4 treatments to consider the effect of 3 irrigation intervals (2, 4, and 6 days) and 1 irrigation amount per time on rice yield. In the experiment of Gun Won et al [11], only 3 irrigation amount per time (2, 4, and 10 cm) were considered. In our study, due to the use of HYDRUS software, we could consider the combination effect of 5 *IRA*, 4 *IRAF* and 4 *IRI* and even 3 soil texture at the same time. Furthermore, our results demonstrated 6 cm, 8 cm, and 8 cm *IRA* and 3 times *IRAF* for silty clay loam, silty loam, and silty clay soils could create suitable water, salt, and NO_3^--N storage of root zone before sowing (Table 5), which could save about 4-48.6% water amount compared to traditional flood irrigation (nearly 25-35 cm irrigation amount per time) [3]. In addition, our study found water storage of root zone was not always increased with *IRAF* in the same level of *IRA*, and the effect of *IRI* on water storage changed with soil texture such as 3 days *IRI* obtained maximum water storage in silty clay loam soil while the maximum water storage in silty loam and silty clay soils were achieved in 2 days *IRI*. This phenomenon might because of the water hold capacity varies from different soil texture and silty clay soil could achieve largest water storage in our study.

Because our study focused on intermittent irrigation before sowing, the salt and nitrate nitrogen storage of root zone should also be considered. In previous researches, irrigation times were regarded as important factors affecting the solute leaching efficiency [6, 28]. However, issues about solute transport in intermittent irrigation conditions were controversial. Behera and Panda [29] also pointed out increasing irrigation frequency could enhance solute leaching. But Mermoud et al [30] indicated intermittent irrigation with small irrigation amount per time would retain water in upper soil layer and only large amount irrigation once a time might increase solute leaching in evaporation condition. Our results demonstrated that both salt and nitrate nitrogen storage decreased with *IRA* and *IRT* (Fig. 7), similar results were also found in some other researches [14, 31]. In our study, nitrate nitrogen storage was even smaller than salt storage in the same intermittent irrigation condition. However, we cannot define that the mobilization of nitrate nitrogen is better than salt because we did not consider the transformation of nitrogen. Although in intermittent irrigation, the normal process of gaseous exchange between the soil and atmosphere is interrupted, especially in larger irrigation amount per time. The nitrate nitrogen may be diffused into the underlying reduced layer where it may be denitrified into N_2O or N_2 which readily escapes to the atmosphere [32]. Buresh et al [33] also indicated the nitrification-denitrification processes induced by drying and wetting cycles in intermittent irrigation would increase nitrogen losing. Therefore, the mechanism of nitrogen transformation in intermittent irrigation process is complicate and deserves further deep researches.

Irrigation strategies determination

In our study, HYDRUS simulation was used to expand the experiment data, and we think this method is necessary and effective, especially in researches about agriculture. However, the calibration and validation of HYDRUS revealed that in some situation, HYDRUS could not achieve very accuracy results in our study (*eg* the validation process of NO_3^--N concentration in silty loam and silty clay soils respectively, Table 2). The possible reasons might be as follows. For one thing, due to the cracks formed in drying phase of intermittent irrigation, water could be lost by preferential flow in the rewetting phase after drying. Behera and Panda [29] indicated that the intermittent drying can lead to shrinkage and cracking, thereby increasing the risk of soil water loss. Although HYDRUS can assume an advective exchange mechanism that depends on water exchange dynamics which is relevant for describing solute transport during intermittent irrigation affecting both the solute concentrations and the water matric potentials to consider the preferential flow [34], we did not consider it because it need more real-time soil profile monitoring results to calibrate the parameters and we will do this work in future. For another, the response of water and solute transport to irrigation interruption during intermittent irrigation is indicative of non-equilibrium transport caused by physical and/or chemical processes, however, for reactive compounds, the two processes are difficult to distinguish as they occur simultaneously [35]. In addition, the soil texture of 0-40 cm depth in 33 micro-plots were divided into 3 groups according to soil particle analysis and USDA standard, but although in the same soil texture (*eg* silty loam), the percentage of each component (*eg* sand, silt, and clay) was different, which would also affect the soil hydrodynamic parameters but we assumed the parameters for water and solute were constant in the same soil texture. However, HYDRUS also achieved acceptable simulation results in our study and statistical analysis was used to establish *SLP* prediction models using the expanded data. We maintained this method was practical and convenient especially in agriculture management. Because local farmers can use these models to basically estimate *SLP* and then combined it with the initial soil salt content and the salt stress of their crops to determine the total irrigation water amount and even evaluate the economic efficiency briefly before irrigation. Many agriculture management studies used the similar method to establish empirical functions such as water production functions and water - fertilizer production functions [36, 37]. Moreover, because our statistical analysis was based on the combination of experiment and HYDRUS simulation, the prediction models should have the properties of both experience and mechanism. However, the use of these prediction models (Eqs. (17)-(19)) was also restrictive, because the models for *SLP* were established based on specific regions and climate conditions.

In addition, when searching the optimal irrigation strategy, both water, salt, and NO_3^--N distributions after irrigation should be considered. Therefore, we defined *WUE* and combined it with salt tolerance of a specific crop (sunflower), field water capacity and total irrigation water amount to determine the optimal irrigation strategy (Table 5). Coefficient used to evaluate water effectiveness was usually defined as the crop yield divided by total water applied if there were crop growth [27] or the ratio of the quantity of water draining past the root zone to that infiltrated into the soil's surface in salt leaching condition [38]. Our study defined *WUE* coefficient to reflect the coupling effects of per irrigation amount on soil water, salt, and NO_3^--N storage (Eq. (16)), the normalization processing can eliminate the effect of index dimension and quantity of data. In addition, the weighting factor for *ΔNTSS* was larger than *ΔNTNS* in our study, this was because salt leaching is the most focused issue in our study site and nitrogen fertilizer would be applied again before sowing and/or during the growth stages of crops. In our study, the *WUE* of each scenario in silty loam was negative due to the water storage of 0-40 cm depth 10 days after irrigation was even smaller than the initial water storage (before irrigation). The reason of this phenomenon was mainly for the amount of evaporation and drainage below root zone in silty loam soil were larger than silty clay loam and silty clay soils, which indicated more irrigation water and less interval between irrigation and sowing were necessary in field with silty loam soil. However, constraint conditions for determining optimal irrigation strategy would be more complicate if we focus on the whole crop growth period for some other factors such as root water uptake and water and salt stress should be taken into consideration [39, 40]. Although in conditions of before sowing like our study, factors such as field slope, farming practices (*eg* tillage, no tillage, and plastic mulched) will also affect the soil water, salt, and NO_3^--N distributions after irrigation [41] and these might be 2D/3D issues and will be studied in our future work.

Conclusions

Taking all together, *ST* had significant effects on water, salt, and NO_3^--N storage of 0-40 cm depth 10 days after irrigation, *SLP* and *WUE*. *IRA* also affected these variables except soil water storage. Furthermore, *IRAF* had significant effects on salt, NO_3^--N storage and *SLP* but could not affect water storage and *WUE* significantly while only *SLP* varied from *IRI* obviously in our study. HYDRUS-1D could achieve acceptable results of soil water and solute transport in intermittent irrigation and prediction models for *SLP* established by combining experiment, HYDRUS, and statistical analysis were effective tools for agriculture management. Based on the *WUE*, crop water demand, salt tolerance, and total irrigation water amount, the optimal *IRA* were 6, 8, 8 cm in silty clay loam, silty loam, and silty clay soils respectively before sowing, and the optimal *IRAF* and *IRI* for these 3 soils were all 3 times and 2 days respectively.

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WPŁYW RÓŻNYCH STRATEGII NAWADNIANIA NA TRANSPORT WODY GLEBOWEJ, SOLI I AZOTU AZOTANOWEGO W GLEBIE

Abstrakt: Nawadnianie przerywane zwraca uwagę jako technologia oszczędnego użycia wody w regionach suchych i półpustynnych. Dla zrozumienia wpływu parametrów nawadniania przerywanego, takich jak czas (*IRA*), częstotliwości stosowania nawadniania (*IRAF*), odstępy czasu nawadniania (*IRI*), a także struktury gleby (*ST*) na magazynowanie wody i substancji rozpuszczonych, przeprowadzono eksperyment przerywanego nawadniania na 33 mikropoletkach w Mongolii Wewnętrznej, w Chinach. Wyniki doświadczeń użyto do kalibracji i walidacji oprogramowania HYDRUS-1D. Następnie 3 *ST* (mulisty piasek gliniasty, muliste iły i gliny pylaste), 5 *IRA* (2, 4, 6, 8 i 10 cm), 4 *IRAF* (2, 3, 4 i 5 razy) i 4 *IRI* (1, 2, 3 i 4 dni) połączono ogółem w 240 scenariuszy symulowanych przez HYDRUS-1D. Analiza wariancji (ANVOA) symulowanych wyników wykazała, że *ST*, *IRA* i *IRAF* miały znaczący wpływ na sól i azot azotanowy (NO^{3-}-N), składowane na głębokości 0-40 cm gleby w nawadnianiu przerywanym, podczas gdy *ST* wpływał tylko na magazynowanie wody w glebie. Ponadto, procentowe ługowanie soli (*SLP*) i efektywność wykorzystania wody (*WUE*) zostały obliczone dla głębokości 0-40 cm i statystyczne modele predykcyjne dla *SLP* zostały ustalone na podstawie analizy wariancji i za pomocą analizy regresji wielokrotnej w każdej strukturze gleby. Aby określić optymalną strategię sporadycznego nawadniania, zaproponowano ograniczenie warunków magazynowania wody w glebie (około pojemności polowej), magazynowania soli (mniejsze niż 168 mg · cm^{-2}), *WUE* (jak największa) w 0-40 cm głębokości i całkowitej ilości wody do nawadniania (mniej niż 25 cm). Przed siewem optymalna strategia nawadniania gleb mulistych gliniastych zakładała odpowiednio 6 cm *IRA*, 3 razy *IRAF* i 2 dni *IRI*. Dla gliny pylastej i ilastych gleb gliniastych założono *IRA*, *IRAF* i *IRI* odpowiednio 8 cm, 3 razy i 2 dni.

Słowa kluczowe: nawadnianie przerywane, HYDRUS-1D, symulacja, procent wypłukiwania soli, efektywność wykorzystania wody