

# Nitrogen Losses in Paddy Field Drainage Modified by Different Water Level Regulations

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## Abstract

Nitrogen losses from farmland, through improper drainage and rainstorm runoff, cause non-point source pollution and limit sustainable agriculture development. We determined the effects of controlled drainage (CTD) and conventional drainage (CVD) on migration responses, the transformation of nitrogen, and  $\text{NH}_4^+\text{-N}$  and  $\text{NO}_3^-\text{-N}$  losses. The results showed that four days after a rainstorm, compared with day one,  $\text{NH}_4^+\text{-N}$  and  $\text{NO}_3^-\text{-N}$  decreased by ranges of 28.7-46.7% and 7.5-47.5% in CTD, which was significantly higher than CVD. CTD also significantly reduced  $\text{NH}_4^+\text{-N}$  and  $\text{NO}_3^-\text{-N}$  losses in field drainage compared with CVD.  $\text{NH}_4^+\text{-N}$  was reduced by 66.72% and  $\text{NO}_3^-\text{-N}$  reduction was 55.56%.  $\text{NH}_4^+\text{-N}$  contributed most to nitrogen losses, while  $\text{NO}_3^-\text{-N}$  contributed less. Following rainstorm events, varying the water level using CVD and CTD had significant effects on  $\text{NH}_4^+\text{-N}$  and  $\text{NO}_3^-\text{-N}$  concentrations. The DRAINMOD-II model was used to simulate  $\text{NH}_4^+\text{-N}$  and  $\text{NO}_3^-\text{-N}$  levels. It indicated that the observed and simulated values of  $\text{NH}_4^+\text{-N}$  and  $\text{NO}_3^-\text{-N}$  concentrations in both CVD and CTD were fitted better. Lastly, the innovation of this study was that it focused on nitrogen concentrations and load changes in paddy field drainage after rainstorms, firstly using the DRAINMOD-N II model to simulate  $\text{NH}_4^+\text{-N}$  and  $\text{NO}_3^-\text{-N}$  concentration changes under field scale. It further validated the pollution-reduction effect under water level control in the paddy field. Also, it improved the irrigation-drainage system of paddy rice and provided a scientific basis for optimizing irrigation-drainage project design in rice irrigation district.

**Keywords:** water level control,  $\text{NH}_4^+\text{-N}$ ,  $\text{NO}_3^-\text{-N}$ , non-point source pollution, DRAINMOD-N II

## Introduction

Eutrophication can result from inadequate treatment of water pollutants, and it is an important environmental

issue. Agricultural non-point source pollution is a key contributor to the eutrophication process. Fertilizers, pesticides, and other chemicals used in agriculture can enter surface water through farmland drainage and surface runoff from precipitation or irrigation, resulting in pollution of rivers, lakes, and port areas [1-2]. Runoff and drainage are key sources of groundwater pollution

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and cause degradation of wetlands. Nitrogen compounds comprise the majority of agricultural fertilizers, and nitrogen is the most important nutrient used by crop plants [3]. Nitrogen loss by runoff causes economic losses, environmental pollution, and threatens human health. In conventional farmland irrigation and drainage, drainage water carries large amounts of nutrients directly into the surrounding environment, causing soil and water pollution as well as eutrophication of rivers and lakes [4]. Nitrogen loss amounts per unit area of paddy fields, through leakage and runoff, were four times greater than losses from upland rice production areas. Paddy field irrigation methods therefore pose a serious hazard to rural water environments. Therefore, controlled irrigation-drainage techniques have been implemented through regulation of the water levels in paddy fields [5-7]. Controlled irrigation-drainage increases water use efficiency through water level control while ensuring normal rice yields [8-9]. Water level control reduces levels of nitrogen and phosphorus in drainage and effectively reduces farmland losses of nitrogen and phosphorus [10-12].

The transport and transformation of agricultural non-point source pollution is associated with natural environmental factors, agricultural management, and engineering. This process involves multi-level, multi-objective, real-time, and temporality increasingly sensitive multi-factor interactions within complex systems [13]. Many laboratory and field experiments have been conducted on nitrogen and phosphorus transport mechanisms and corresponding control measures. Because these studies have typically focused on only one or a few selected factors, it is difficult to extrapolate the results to other field situations [14]. A quantitative analysis model can be an effective tool for the study of agricultural water, fertilizer management, and nitrogen pollution control. Computer simulation can be used to evaluate agricultural management alternatives related to soil nitrogen transport [15]. A field-scale model is the most widely used. This model does not consider climatic conditions, agricultural land use, soil texture, spatial variability of soil, water management, land use, or soil texture conditions. However, it can accurately describe and evaluate the effects of different agricultural management practices on soil erosion and nitrogen transport, and this provides input for large-scale, GIS-based parametric model studies [16-18].

Field-scale model development and applications are areas of active current research. These models include CREAMS (chemicals, runoff, and erosion from agricultural management systems), GLEAMS (groundwater loading effects of agricultural management systems), DRAINMOD-N, LEACHM (leaching estimation and chemistry model), RZWQM (root zone water quality model), and EPIC (erosion/productivity impact calculator) [19]. Breve developed the DRAINMOD-N model based on DRAIN-MOD [20]. DRAINMOD-N was used to study vertical migration of water and nitrogen in one-dimensional unsaturated zone farmland, and vertical and lateral migration of

water and nitrogen in a two-dimensional saturated zone. DRAINMOD-N has been extensively used worldwide. The main model input parameters include weather, soils, crops, drainage system design, and nitrogen transport parameters. DRAINMOD-NII has been expanded to enable description of the transformation and migration of organic fertilizer nitrogen. It has been tested and applied in many countries and regions, and has provided accurate prediction and high significant confidential level [21-22].

This study focuses on nitrogen concentrations and load changes in paddy drainage following storms and through the use of different water level controls. We used the DRAINMOD-N II model to simulate  $\text{NH}_4^+$ -N and  $\text{NO}_3^-$ -N concentration changes on a farmland scale. This approach is meaningful for rational irrigation and drainage schemes and non-point source pollution control, and it also provides basic data for the development of rice irrigation and drainage strategies.

## Materials and Methods

### Experimental Site and Soil Properties

The experiment was conducted from October 2011 to October 2012 in the Yunnan Irrigation District, Sucheng, Jiangsu Province, China. The experimental site is located in a warm temperate zone of monsoon climate. The mean annual rainfall is 892.3 mm, and rainfall occurs on an average of 120 d per year. Rain amounts during the main monsoon season account for nearly 70% of the annual total. The mean annual evaporation is 900 mm, mean annual temperature is 14.1°C, and the highest mean monthly temperature is 27.2°C. The mean hours of annual sunshine is 2,314 h and the annual frost-free period is 211 d. The topsoil (0-30 cm) pH is 6.95 and it contains 10.45 g  $\text{kg}^{-1}$  organic matter, 0.8945 g  $\text{kg}^{-1}$  total nitrogen, 27.95 mg  $\text{kg}^{-1}$  available nitrogen, 0.34 g  $\text{kg}^{-1}$  total phosphorus, and 12.2 mg  $\text{kg}^{-1}$  available phosphorus.

### Experimental Design

Early Japonica rice was grown according to local methods. There were two water level control programs (treatments): conventional irrigation-drainage (CVD) and controlled irrigation-drainage (CTD). Each treatment had three replications. At 50 cm below the balk, each experimental plot had plastic isolating film to prevent water exchange. Fertilizer regime was determined according to local methods. There were three fertilizer applications. These were basal fertilizer on 25 June, tillering fertilizer on 9 July, and panicle fertilizer on 10 August. Pure nitrogen amounts were, respectively, 120  $\text{kg}/\text{hm}^2$  (30%), 60  $\text{kg}/\text{hm}^2$  (17%), and 60  $\text{kg}/\text{hm}^2$  (17%), for an annual total of 240  $\text{kg}/\text{hm}^2$ . Each treatment was applied with 50  $\text{kg}/\text{hm}^2$   $\text{P}_2\text{O}_5$  and  $\text{K}_2\text{O}$ . Water management of paddy fields with CVD was based on local methods. The water level control indicator of CVD is shown in Table 1 and CTD is shown in Table 2.

Table 1. Water level control indicators at rice growth stages under CVD mode.

Growth stage	Regreening stage	Tillering stage		Jointing -booting stage	Heading -flowering stage	Milking stage
		Early stage	Later stage			
Upper water level limit (mm)	30	30	0	30	30	30
Lower water level limit (mm)	10	0	0.6θ	0	0	0
The water depth allowed (mm)	50	50	0	70	70	70

Notes: θ is the observed saturated water content of bulk soil in the root zone

Table 2. Water level control indicators at rice growth stages under CTD mode.

Growth stage	Tillering stage	Jointing-booting stage	Heading-flowering stage	Milking stage
Upper water level limit(mm)	30	30	30	30
Lower water level limit(mm)	-200	-300	-300	-300
The water depth allowed (mm)	100 (5d)	200 (5d)	250 (5d)	250 (5d)

Notes: Positive value is flooding depth while negative value is the length from field surface to underground water level. Number within parentheses indicates flooding days

### Experiment Materials and Methods

The losses of NH<sub>4</sub><sup>+</sup>-N and NO<sub>3</sub><sup>-</sup>-N are mass concentrations of NH<sub>4</sub><sup>+</sup>-N and NO<sub>3</sub><sup>-</sup>-N of each treatment discharged from surface water following rainstorms. This value was set at 0, when the water level was less than the lower control limit and the amount by which the water depth exceeded the lower control limit. Water samples were collected from surface flooding by polyethylene bottles. Surface water was collected, without soil disturbance, using a 50-mL syringe. NH<sub>4</sub><sup>+</sup>-N and NO<sub>3</sub><sup>-</sup>-N in the water samples were analyzed by the indophenol blue method and the disulfonic acid phenol method using a UV-2800 spectrophotometer [23].

The DRAINMOD-N II model was used to simulate the NH<sub>4</sub><sup>+</sup>-N and NO<sub>3</sub><sup>-</sup>-N concentrations. The DRAINMOD-N II models the nitrogen and carbon cycle on the basis of DRAINMOD. The water balance results were used as input for nitrogen transport. The multiphase one-dimensional convection dispersion equation was used for transport modeling of nitrogen. The multiphase one-dimensional advection dispersion equation was:

$$\frac{\partial}{\partial t} (\theta_a C_a + \theta_g C_g + \rho_b C_s) = \frac{\partial}{\partial z} \left( \theta_a D_a \frac{\partial C_a}{\partial z} + \theta_g d_g \frac{\partial C_g}{\partial z} \right) - \frac{\partial (v_a C_a)}{\partial z} - S \tag{1}$$

...where θ<sub>a</sub> and θ<sub>g</sub> are, respectively, volume fraction of liquid phase and gas in soil (L<sup>3</sup>/L<sup>3</sup>); C<sub>a</sub>, C<sub>g</sub>, and C<sub>s</sub> are, respectively, the form of nitrogen in liquid, gas, and solid concentrations (M/L<sup>3</sup>); ρ<sub>b</sub> is referred to as the solid phase

of soil dry bulk density (M/L·T<sup>2</sup>); D<sub>a</sub> is the hydrodynamic dispersion coefficient (L<sup>2</sup>/T); d<sub>g</sub> is the molecular diffusion coefficient (L<sup>2</sup>/T); v<sub>a</sub> is the liquid volume flux phase (L/T); and S is the source term.

The simulation evaluation index of total relative error, correlation coefficient R, and CD index were further drawn into the evaluation system:

$$R = \sqrt{\frac{\sum_{i=1}^n (O_i - \bar{O})(S_i - \bar{S})}{\sum_{i=1}^n (O_i - \bar{O})^2 \sum_{i=1}^n (S_i - \bar{S})^2}} \tag{2}$$

$$CD = \frac{\sum_{i=1}^n (O_i - \bar{O})^2}{\sum_{i=1}^n (S_i - \bar{O})^2} \tag{3}$$

...where O<sub>i</sub> was the observed value for the period of i,  $\bar{O}$  was the mean value of observation, S<sub>i</sub> was the simulated value for the period of i, and  $\bar{S}$  was the mean value of simulated values. R reflected the correlation between simulated and observed values, and CD reflects the simulation value degree of deviation from the observed mean. The optimal value of both R and CD values was 1.

### Statistical Analysis

Statistical analysis was carried out by standard procedures on a randomized plot design (SPSS 19.0). Significance was calculated based on F-tests and least significant differences (LSD) at the 0.05 probability level. The DRAINMOD-N II model was used to simulate the NH<sub>4</sub><sup>+</sup>-N and NO<sub>3</sub><sup>-</sup>-N concentrations.

**Results and Discussion**

**Changes in NH<sub>4</sub><sup>+</sup>-N Concentrations in Paddy Drainage**

NH<sub>4</sub><sup>+</sup>-N concentrations in the different treatments are shown in Fig. 1. At 1 d after a rainstorm, the NH<sub>4</sub><sup>+</sup>-N concentration in CVD was higher than that in CTD.

This is mainly because the highest water storage depth allowed in CTD treatment was greater than that in CVD treatment. In CVD, the NH<sub>4</sub><sup>+</sup>-N concentration, after each rainstorm, initially decreased then increased. This is mainly because the field water level decreased gradually in CVD, resulting in NH<sub>4</sub><sup>+</sup>-N concentration rising again at 4 d after the rainstorm. NH<sub>4</sub><sup>+</sup>-N concentration was decreased in CTD, indicating that CTD can effectively

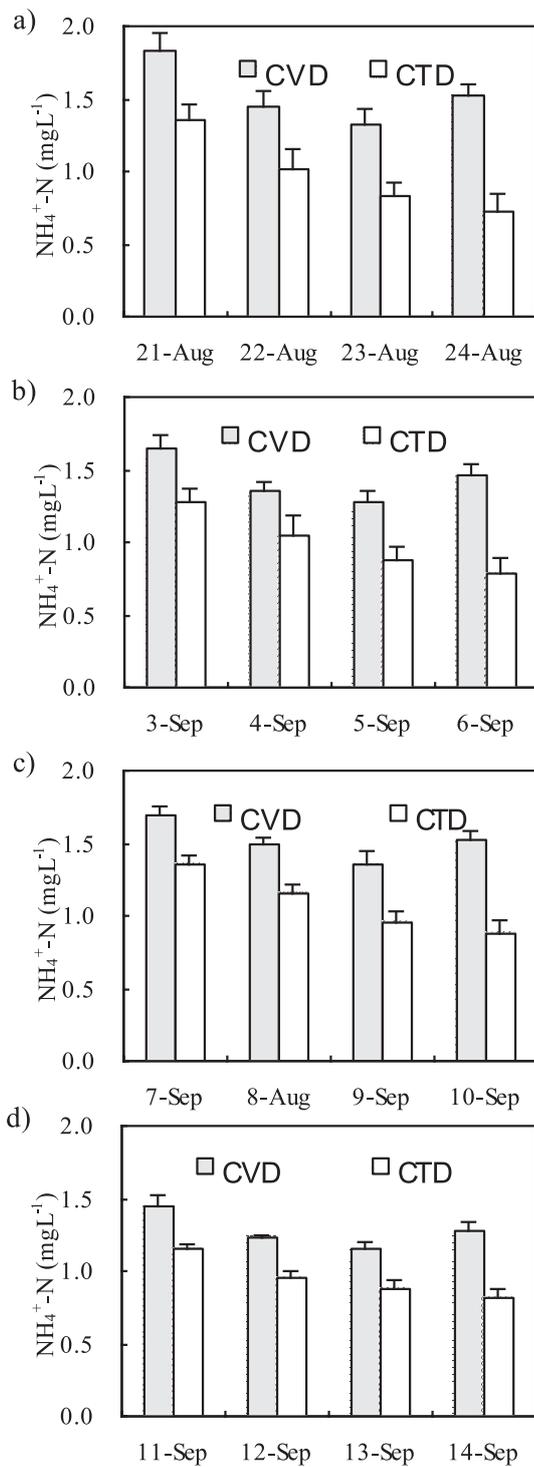


Fig. 1. Changes in NH<sub>4</sub><sup>+</sup>-N concentrations in paddy drainage after a) rainstorms-1, b) rainstorm-2, c) rainstorm-3, d) rainstorm-4.

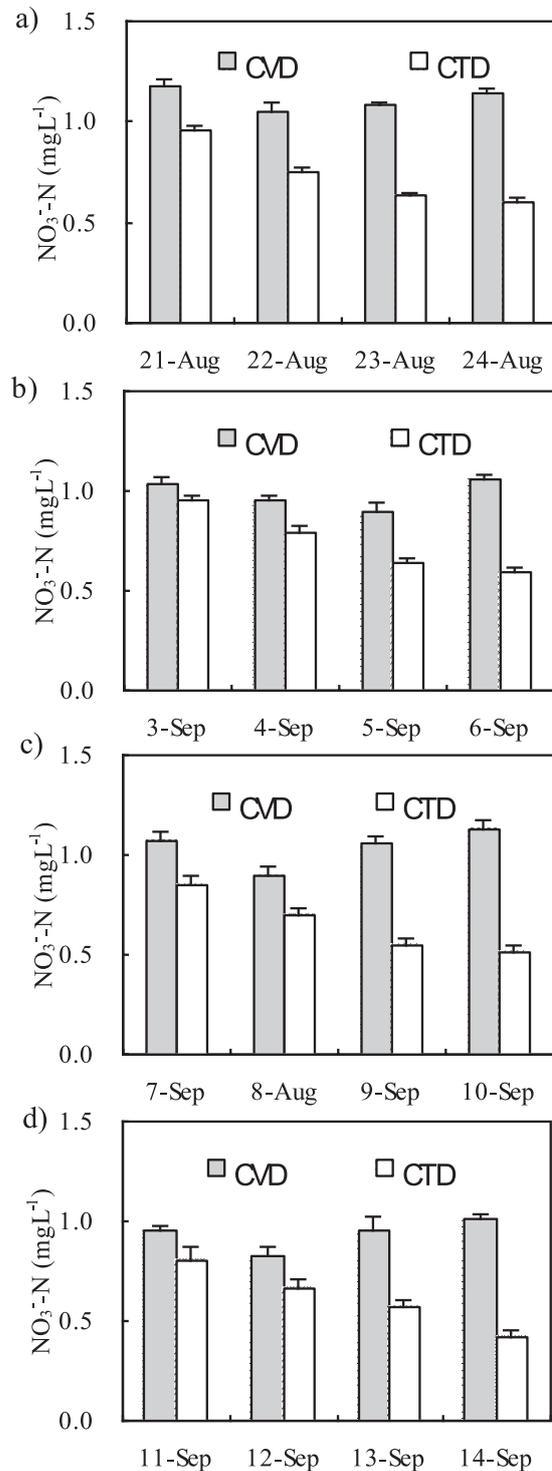


Fig. 2. Changes in NO<sub>3</sub><sup>-</sup>-N concentrations in paddy drainage after a) rainstorms-1, b) rainstorm-2, c) rainstorm-3, d) rainstorm-4.

Table 3. Influence of different water level controls on  $\text{NH}_4^+\text{-N}$  and  $\text{NO}_3^-\text{-N}$  concentrations.

Rainstorm	Water level control	$\text{NH}_4^+\text{-N}$			$\text{NO}_3^-\text{-N}$		
		Starting (mg L <sup>-1</sup> )	Ending (mg L <sup>-1</sup> )	Sig. $\alpha$	Starting (mg L <sup>-1</sup> )	Ending (mg L <sup>-1</sup> )	Sig. $\alpha$
Rainstorm-1	CVD	1.204	0.252	*( $p = 0.020$ )	0.504	0.433	** ( $p = 0.005$ )
	CTD	0.794	0.084		0.416	0.122	
Rainstorm-2	CVD	2.106	0.378	*( $p = 0.019$ )	3.933	0.508	** ( $p = 0.003$ )
	CTD	1.826	0.157		2.693	0.236	
Rainstorm-3	CVD	1.807	0.733	*( $p = 0.014$ )	3.606	0.461	** ( $p = 0.006$ )
	CTD	1.852	0.697		3.556	0.696	
Rainstorm-4	CVD	3.360	1.024	*( $p = 0.015$ )	3.644	1.547	( $p = *0.011$ )
	CTD	2.313	0.617		3.565	1.152	

Notes: \* = significant at the 0.05 level.

\*\* = significant at the 0.01 level

reduce the  $\text{NH}_4^+\text{-N}$  concentration in drainage. The mean  $\text{NH}_4^+\text{-N}$  concentration after each rainstorm in CVD was 1.53 mg L<sup>-1</sup>, 1.44 mg L<sup>-1</sup>, 1.52 mg L<sup>-1</sup>, and 1.28 mg L<sup>-1</sup>, respectively, while concentrations were 0.98 mg L<sup>-1</sup>, 1.00 mg L<sup>-1</sup>, 1.08 mg L<sup>-1</sup>, and 0.95 mg L<sup>-1</sup> in CTD. The CTD amounts were 63.9%, 69.8%, 71.1%, and 74.5% those of CVD, respectively. Compared with 1 d after rainstorms, the  $\text{NH}_4^+\text{-N}$  concentrations at 4 d decreased by 16.4%, 11.0%, 10.0%, and 12.4%, respectively, and the range of decrease was small in CVD. In CTD, decreases were 46.7%, 38.3%, 35.6%, and 28.7%, respectively, and the range of decrease was higher than that of the CVD treatment.  $\text{NH}_4^+\text{-N}$  loss typically occurs through surface drainage. Large proportions of  $\text{NH}_4^+\text{-N}$  in paddy field water comes from the slow mineralization and decomposition of organic nitrogen in the subsoil. Cui et al. have demonstrated that leaching losses of fertilizer  $\text{NH}_4^+\text{-N}$  are very low, accounting for only 5.60-6.40% of the total leaching losses of  $\text{NH}_4^+\text{-N}$  and 0.310-0.340% of the nitrogen input during rice growth stages [24].

#### Changes in $\text{NO}_3^-\text{-N}$ Concentrations in Paddy Drainage

$\text{NO}_3^-\text{-N}$  concentration in different treatments in a paddy field after a rainstorm are shown in Fig. 2.  $\text{NO}_3^-\text{-N}$  concentrations in each treatment after rainstorms

Table 4.  $\text{NH}_4^+\text{-N}$  and  $\text{NO}_3^-\text{-N}$  losses in paddy drainage related to water-level controls.

Treatment	$\text{NH}_4^+\text{-N}$ losses (kg ha <sup>-1</sup> )	The proportion accounting for N loss (%)	$\text{NO}_3^-\text{-N}$ losses (kg ha <sup>-1</sup> )	The proportion accounting for N loss (%)
CVD mode	5.80	53.70	0.63	5.83
CTD mode	1.93	53.61	0.28	7.78

were lower than  $\text{NH}_4^+\text{-N}$  concentrations. The reason might be the nitrogen fertilizer type. At 1 d after rain,  $\text{NO}_3^-\text{-N}$  concentration in CVD was higher than that in CTD. This is because the allowed water storage depth was greater in CVD.  $\text{NO}_3^-\text{-N}$  concentrations following each rainstorm initially decreased before increasing, and this was most evident at 1 d. This is because the field water level in CVD gradually decreased, resulting in  $\text{NO}_3^-\text{-N}$  concentrations increasing, while in CTD concentrations decreased. These data indicate that CVD can effectively reduce  $\text{NO}_3^-\text{-N}$  concentrations in drainage. After each rainstorm, mean  $\text{NO}_3^-\text{-N}$  concentration in CVD was 1.11 mg L<sup>-1</sup>, 0.99 mg L<sup>-1</sup>, 1.04 mg L<sup>-1</sup>, and 0.94 mg L<sup>-1</sup>, respectively, while in CTD it was 0.74 mg L<sup>-1</sup>, 0.73 mg L<sup>-1</sup>, 0.65 mg L<sup>-1</sup>, and 0.61 mg L<sup>-1</sup>, respectively. The CTD amounts were 66.1%, 75.4%, 62.7%, and 65.5% those of CVD. Compared

Table 5. Model input data of soil data of depth, water content, and hydraulic conductivity.

Soil data	Value range		
Soil depth (cm)	0-20	20-50	50-300
Soil saturated water content $\theta_s$	0.360	0.394	0.410
Soil participated water content $\theta_r$	0.07	0.10	0.16
$\alpha$	0.005	0.007	0.007
n	1.725	1.396	1.749
m	0.430	0.267	0.419
Lateral saturated hydraulic conductivity (cm/h)	1.45		
Vertical saturated hydraulic conductivity (cm/h)	4.20		
Vertical hydraulic conductivity (cm/h)	285		

Note:  $\alpha$ , m and n were as statistical parameters of the soil water characteristic curve formula  $\theta = \theta_r + (\theta_s - \theta_r) / (1 + |\alpha h|^n)$   
m,  $m = 1 - 1/n$ .

Table 6. Model input data of meteorological, irrigation-drainage, crops, and nitrogen transport parameters.

Parameter type	Parameter	Selection value		
Meteorological data	Max and min daily temperature, rainfall, amount of transpiration	Information provided by Sucheng District Water Authority		
Irrigation and drainage parameters	The irrigation depth during the growth period	CVD	According to water level control in different growth periods, controls are given in Table 1. In CVD mode, when water shortage occurs, irrigation water should be added to the appropriate upper limit, free draining and not stored.	
		CTD	According to water level control given in Table 2, in CTD mode, when water shortage occurs, irrigation water should be added to the appropriate upper limit. When the amount of water is too great, it should regulate the control gate to drain to maximum allowed water depth, and the duration of submergence tolerance was less than 5 d.	
			Date	Apr.1 <sup>st</sup> , May.11 <sup>th</sup> , June.26 <sup>th</sup> , July.28 <sup>th</sup> , Aug.23 <sup>rd</sup> , Sep.1 <sup>st</sup> , Oct.1 <sup>st</sup>
			Crest elevation (cm)	40,50, 80, 100, 120, 120, 40
Corp parameter	Rice root depth	Date	15 April, 1 May, 15 May, 12 May, 12 July, 2 August, 15 September, 7 October	
		Root depth (cm)	3, 5, 15, 25, 30, 30, 30, 30, 30	
Nitrogen transportation parameter	Nitrogen fertilizer application	The basal, tillering and panicle fertilizations were applied on 25 June, 9 July, and 10 August, respectively. Nitrogen fertilization was calculated by amounts of pure nitrogen, which were, respectively, 120 kg/hm <sup>2</sup> (30%), 60 kg/hm <sup>2</sup> (17%), and 60 kg/hm <sup>2</sup> (17%). Total nitrogen was 240 kg/hm <sup>2</sup> .		

to 1 d, NO<sub>3</sub><sup>-</sup>-N concentration in CVD was reduced by 3.4%, but increased by 1.9%, 5.6%, and 6.3% at 4 d, while in CTD it was reduced by 37.5%, 37.9%, 40.0%,

and 47.5%. The amount of reduction was significant, indicating that water level control by CTD can help purify water and reduce NO<sub>3</sub><sup>-</sup>-N concentrations, thus reducing agricultural non-point source pollution. These results have aided plot experiment research [25]. The controlled irrigation-drainage technology index system determined by the plot experiment were perfected and popularized in the field experiment. This improved water conservation, reduced emissions, and validated the emission reduction benefits of controlled drainage [26]. The results are of great significance to the design of ecologically based irrigation district construction in China.

#### Analysis of Different Water Control Levels on Losses of NH<sub>4</sub><sup>+</sup>-N and NO<sub>3</sub><sup>-</sup>-N

Changes in NH<sub>4</sub><sup>+</sup>-N and NO<sub>3</sub><sup>-</sup>-N concentrations indicate that different water level controls can modify NH<sub>4</sub><sup>+</sup>-N and NO<sub>3</sub><sup>-</sup>-N concentrations in the surface drainage of paddy fields. After each rainstorm, the concentrations of NH<sub>4</sub><sup>+</sup>-N and NO<sub>3</sub><sup>-</sup>-N in CTD were lower than in the CVD. Differences in the concentrations of NH<sub>4</sub><sup>+</sup>-N and NO<sub>3</sub><sup>-</sup>-N in the different water level control treatments were significant (Table 3). After each rainstorm, the different water level controls associated with CVD and CTD had significant effects on the NH<sub>4</sub><sup>+</sup>-N and NO<sub>3</sub><sup>-</sup>-N concentrations. These results differ from earlier (2012) research [27]. This is likely due to different water level controls resulting in different amounts of leakage. In this field experiment the water level controls of CVD and CTD

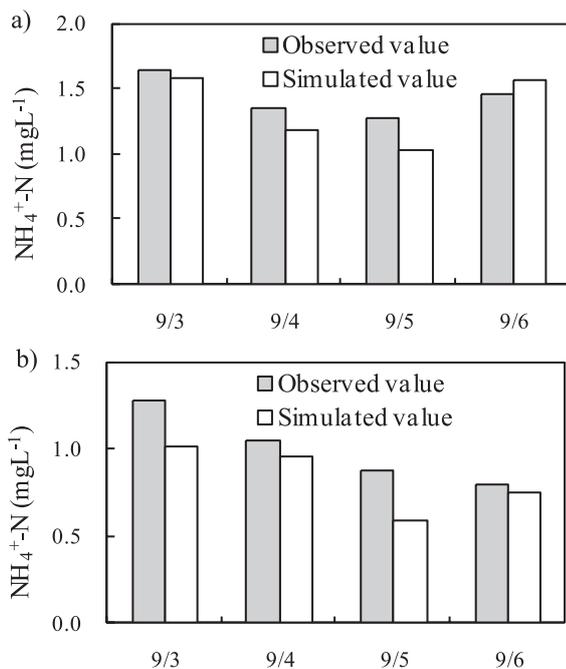


Fig. 3. Observed and simulated values of NH<sub>4</sub><sup>+</sup>-N concentrations at different water levels: a) rainstorm-2-CVD, b) rainstorm-2-CTD.

had relatively larger differences in leakage compared to leakage in the plot experiment.

### Nitrogen Loss Amounts

NH<sub>4</sub><sup>+</sup>-N was the main source of N losses in the different paddy field drainage modes, while the NO<sub>3</sub><sup>-</sup>-N contributed relatively little (Table 4). In CVD, mean NH<sub>4</sub><sup>+</sup>-N loss was 5.80 kg ha<sup>-1</sup>, accounting for 53.70% of total nitrogen (TN). In CTD mean loss was 1.93 kg ha<sup>-1</sup>, accounting for 53.61%. This was 3.87 kg ha<sup>-1</sup> less than CVD, and the reduction was 66.72%. In CVD, mean NO<sub>3</sub><sup>-</sup>-N loss was 0.63 kg ha<sup>-1</sup>, accounting for 5.83% of TN, while in CTD it was 0.28 kg ha<sup>-1</sup>, accounting for 7.78%. This was 0.35 kg ha<sup>-1</sup> less than that in CVD, and reduction was 55.56%. NH<sub>4</sub><sup>+</sup>-N loss in paddy field drainage was affected by fertilizer level and irrigation management modes. At the same fertilizer level, CTD can more effectively reduce NH<sub>4</sub><sup>+</sup>-N loss in paddy fields than CVD. NO<sub>3</sub><sup>-</sup>-N loss was relatively lower, which was mainly because the NO<sub>3</sub><sup>-</sup>-N content in paddy soil was lower. NO<sub>3</sub><sup>-</sup>-N in drainage was mainly from wheat biomass remains, rainfall, and irrigation, while during the rice season NO<sub>3</sub><sup>-</sup>-N content was lower. This was mainly because the rice field was flooded and soil was under reducing conditions. Under these conditions, there was low soil oxygen content, low nitrifying bacteria activity, and low nitrification rate, resulting in a small part of nitrogen fertilizer converting to NO<sub>3</sub><sup>-</sup>-N after converting to NH<sub>4</sub><sup>+</sup>-N.

### Simulation of NH<sub>4</sub><sup>+</sup>-N and NO<sub>3</sub><sup>-</sup>-N Concentrations Using the DRAINMOD-N II Model

The crop water demand during the heading-flowering stage of rice is relatively high. On 2 September the daily rainfall reached its highest level and it was typical rainfall weather. Thus, the second rainstorm was selected as being typical. NH<sub>4</sub><sup>+</sup>-N and NO<sub>3</sub><sup>-</sup>-N concentrations were continuously measured during the four days after rainstorms. NH<sub>4</sub><sup>+</sup>-N and NO<sub>3</sub><sup>-</sup>-N concentrations of CVD and CTD were simulated using the DRAINMOD-N II model. Model input data including soil, meteorological,

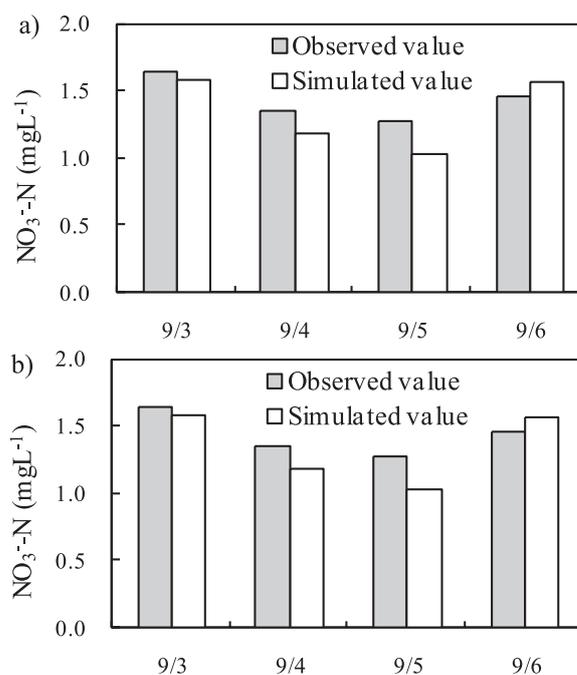


Fig. 4. Observed and simulated value of NO<sub>3</sub><sup>-</sup>-N concentrations in different water level controls: a) rainstorm-2-CVD, b) rainstorm-2-CTD.

crop, drainage system design, and nitrogen transport parameters are listed in Tables 5 and 6.

Observed and simulated values of NH<sub>4</sub><sup>+</sup>-N concentrations with different water level controls are shown in Fig. 3. On 6 September the simulated results of NH<sub>4</sub><sup>+</sup>-N concentration were decreased by 1.0% compared with those on 3 September in CVD mode, while the simulated results of NH<sub>4</sub><sup>+</sup>-N concentration were decreased by 25.7% in CTD mode. This indicated that the observed and simulated values of NH<sub>4</sub><sup>+</sup>-N concentration in CVD and CTD were similar and the simulation result was good.

Observed and simulated values of NO<sub>3</sub><sup>-</sup>-N concentration in different water level control are shown in Fig. 4. On 6 September the simulation results of

Table 7. Simulation evaluation parameter statistics with different water level controls.

Treatment	Observed value (mg/L)	Simulated value (mg/L)	Relative error (%)	Correlation coefficient R	CD
NH <sub>4</sub> <sup>+</sup> -N in rainstorm-2-CVD	2.97	3.28	10.44	0.95	0.32
NH <sub>4</sub> <sup>+</sup> -N in rainstorm-2-CTD	5.72	5.21	8.92	0.89	0.23
NO <sub>3</sub> <sup>-</sup> -N in rainstorm-2-CVD	3.99	3.31	17.04	0.79	0.56
NO <sub>3</sub> <sup>-</sup> -N in rainstorm-2-CTD	3.94	3.98	1.02	0.71	0.23
Total NH <sub>4</sub> <sup>+</sup> -N in rainstorm-CVD	23.03	22.02	4.39	0.88	1.55
Total NH <sub>4</sub> <sup>+</sup> -N in rainstorm-CTD	16.93	14.59	8.98	0.83	1.85
Total NO <sub>3</sub> <sup>-</sup> -N in rainstorm-CVD	16.29	15.80	3.01	0.59	2.12
Total NO <sub>3</sub> <sup>-</sup> -N in rainstorm-CTD	10.97	11.88	8.30	0.91	1.66

$\text{NO}_3^-$ -N concentration were decreased by 19.5% compared with those on 3 September in CVD mode. The simulation results of  $\text{NH}_4^+$ -N concentration were decreased by 44.2% in CTD mode. This indicated that the simulation results were similar to the observed values.

The simulation evaluation indicators are listed in Table 7. The relative errors of total  $\text{NH}_4^+$ -N and  $\text{NO}_3^-$ -N concentrations in CTD had relatively larger fluctuations than those in CVD. This is probably because the model is sensitive to changes of precipitation and elevation retaining weir. In simulation of the shorter sequence, the relative errors of both CVD and CTD mode increased. However, with the four precipitation series combined, the total relative error was lower. Except for the correlation coefficient and CD index of  $\text{NO}_3^-$ -N in CVD mode that had relatively greater variability, the simulation results of the other evaluation indexes were reasonable. Limitations of experimental observation accuracy and deviation resulting from the selection of some model parameters were the main reason for this phenomenon. Therefore, the experimental means used to measure the parameters of the observed data should be increased in future work. The results demonstrate that the DRAINMOD model can effectively describe the paddy field drainage and nitrogen process. It is an important method for figuring out suitable water management practices, and that is significant for improving water and fertilizer efficiency and preventing non-point source pollution.

### Conclusions

CTD can effectively reduce  $\text{NH}_4^+$ -N and  $\text{NO}_3^-$ -N concentrations in rice field drainage. Four days after a rainstorm, the mean  $\text{NH}_4^+$ -N and  $\text{NO}_3^-$ -N concentrations in CVD were, respectively, 1.28-1.53 mg L<sup>-1</sup> and 0.94-1.11 mg L<sup>-1</sup>, while in CTD they were 0.95-1.08 mg L<sup>-1</sup> and 0.61-0.74 mg L<sup>-1</sup>. Compared with 1 d after a rainstorm,  $\text{NH}_4^+$ -N and  $\text{NO}_3^-$ -N concentrations, respectively, decreased by 28.7-46.7% and 37.5-47.5% at 4 d in CTD, which was significantly greater than in CVD. Significant differences in  $\text{NH}_4^+$ -N and  $\text{NO}_3^-$ -N concentrations under different water level control conditions were found.

The mean  $\text{NH}_4^+$ -N and  $\text{NO}_3^-$ -N losses were 1.93 kg ha<sup>-1</sup> and 0.28 kg kg ha<sup>-1</sup>, reducing 3.87 kg ha<sup>-1</sup> and 0.35 kg ha<sup>-1</sup>, compared to CVD, and the reductions were, respectively, 66.72% and 55.56%.  $\text{NH}_4^+$ -N contributed the most to nitrogen loss while  $\text{NO}_3^-$ -N contribution was less.

The DRAINMOD- II model was used to simulate the  $\text{NH}_4^+$ -N and  $\text{NO}_3^-$ -N under the CVD and CTD treatments. At 4 d after a rainstorm, the simulated  $\text{NH}_4^+$ -N and  $\text{NO}_3^-$ -N concentrations were decreased by 1.0% and 19.5%, respectively, compared with 1 d in the CVD mode. In contrast, the simulated results of  $\text{NH}_4^+$ -N concentration were decreased by 25.7% and 44.2% in the CTD treatment. This indicated that the observed and simulated values of  $\text{NH}_4^+$ -N and  $\text{NO}_3^-$ -N concentrations in CVD and CTD were similar and the simulation results were good.

In summary, this study focused on nitrogen concentrations and load changes in paddy drainage under storms in different irrigation and drainage modes. The DRAINMOD-N II model was used to simulate  $\text{NH}_4^+$ -N and  $\text{NO}_3^-$ -N concentration changes under field scales. The results can be used to improve drainage systems and water level controls in farmlands. They can also help improve the irrigation-drainage system of paddy rice and provide a scientific basis for optimizing irrigation-drainage project design in rice irrigation districts.

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