

Effect of controlled irrigation and drainage on nitrogen leaching losses from paddy fields

Shizhang Peng · Yupu He · Shihong Yang ·
Junzeng Xu

Received: 21 August 2013/Revised: 30 April 2014/Accepted: 14 May 2014/Published online: 3 June 2014
© The International Society of Paddy and Water Environment Engineering and Springer Japan 2014

Abstract The effect of controlled irrigation and drainage on N leaching losses from paddy fields was investigated by controlling root zone soil water content and water table depth using a lysimeter equipped with an automatic water table control system. Three treatments that combined irrigation and drainage managements were implemented: controlled irrigation (CI) + controlled water table depth 1 (CWT1), CI + controlled water table depth 2 (CWT2), and flooding irrigation (FI) + actual field water table depth (FWT). Controlled irrigation and drainage had significant environmental effects on the reduction of $\text{NH}_4^+\text{-N}$ and $\text{NO}_3^-\text{-N}$ leaching losses from paddy fields by decreasing water leakage. The $\text{NH}_4^+\text{-N}$ leaching losses from CI + CWT1 and CI + CWT2 were 3.68 and 4.45 kg ha^{-1} , respectively, which significantly reduced by 59.2 and 50.7 % compared with FI + FWT (9.02 kg ha^{-1}). The $\text{NO}_3^-\text{-N}$ leaching losses from CI + CWT1 and CI + CWT2 were 0.88 and 0.43 kg ha^{-1} with a significant reduction of 45.2 and 73.2 %, respectively, compared with FI + FWT (1.61 kg ha^{-1}). The application of CI + CWT1 can be a pollution-controlled water management method of reducing N leaching losses from paddy fields.

Keywords Paddy field · Water-saving irrigation · Drainage · Nitrogen leaching

Introduction

Conventional irrigation and drainage management approaches, along with excessive nitrogen (N) fertilizer

input have increased N leaching losses from farmlands in China, which led to serious pollution to both groundwater and surface water (Ju et al. 2009; Li et al. 2011; Liu and Diamond 2005; Min et al. 2011; Xue and Hao 2011; Zhang et al. 2013). Groundwater is one of the major drinking water sources in China. Therefore, groundwater pollution can significantly affect human health. Drinking groundwater with high N concentrations can induce methemoglobinemia and cancer in the digestive system (McElroy et al. 2008; Zeman et al. 2011). Rice is the most important cereal crop in China. In 2011, more than 27 % of the arable lands in China were devoted to rice cultivation (National Bureau of Statistics of China 2012). Water consumption by rice cultivation accounts for more than 65 % of the water used in agriculture (Cheng 2007). The Taihu Lake region is one of the most densely populated and intensively cropped areas in China. Approximately 75 % of the arable land in this region is exploited for rice cultivation. Excessive N fertilizer is usually applied to the paddy soils in this region (Lin et al. 2007). Conventional water management and extensive N fertilizer use have increased N leaching losses from paddy fields and thus have caused environmental problems. Studies show that the trophic level in the Taihu Lake is in the transition state from eutrophication to heavy eutrophication (Qin et al. 2007). The total N from agricultural non-point source pollution accounts for 37.5 % of the total N discharged into the lake (Wu et al. 2011). Therefore, developing methods to reduce N leaching losses from the paddy fields in the Taihu Lake region are necessary to address the environmental impacts of agricultural water management.

Several studies showed that water-saving irrigation (WSI) reduced N leaching losses from paddy fields (Peng et al. 2011; Cui et al. 2004; Li et al. 2001; Wang et al. 2002; Tan et al. 2013). N leaching was lower in WSI than

S. Peng · Y. He · S. Yang (✉) · J. Xu
State Key Laboratory of Hydrology-Water Resources and
Hydraulic Engineering, Hohai University, 1st Xikang Road,
Nanjing 210098, China
e-mail: ysh7731@hhu.edu.cn

in conventional flooding irrigation (Li et al. 2001). An experiment conducted in Central China showed that WSI might increase $\text{NH}_4^+\text{-N}$ and $\text{NO}_3^-\text{-N}$ concentrations in percolation water and reduce total percolation water compared with continuous flooding irrigation. N leaching loss from paddy fields under WSI was also lower than that under continuous flooding irrigation (Cui et al. 2004). Peng et al. (2011) reported that a significant reduction in N leaching losses from paddy fields under CI can be achieved by significantly decreasing both total percolation water volumes and N concentrations in percolation water.

Controlled drainage (also called drainage water management) can reduce N losses from subsurface drain fields and improve farmland environments (Bonaiti and Borin 2010; Lalonde et al. 1996; Ng et al. 2002; Wesström and Messing 2007; Woli et al. 2010; Qu et al. 2009; Wesström et al. 2001; Skaggs et al. 2012; Drury et al. 2001). This method is typically applied by installing a structure in the subsurface drain to manage the groundwater table (Skaggs et al. 2012). A previous study found that controlled drainage increased drainage volume by 8 % and reduced mean nitrate concentration of drainage water by 41 % compared with free tile drainage; thus, controlled drainage can reduce the total nitrate loss by 36 % compared with free tile drainage (Ng et al. 2002). Other studies revealed that a decrease in tile drainage water rather than in N concentrations caused significant reductions in N loads (Wesström and Messing 2007; Lalonde et al. 1996). Chinese researchers implemented controlled surface drainage in paddy fields by controlling the water levels in field ditches. Reducing the depth of field ditches from 1 to 0.4 m reduced 50–60 % of the drainage volume, but slightly increased the water salinity. However, the salinity was still below the salt tolerance level of rice (Luo et al. 2006, 2008).

WSI and controlled drainage have been separately practised in many countries to reduce N loss and non-point source pollution. Several studies attempted to reduce N loss in the runoff from paddy fields under comprehensive irrigation and drainage regulations (Peng et al. 2012; Shao et al. 2010). But, the existing studies were focused on the joint application of irrigation in paddy fields and controlled drainage in ditches. The effects of different water table levels in fields on N leaching losses from paddy fields under WSI remain unclear. With the development of WSI in China, controlled drainage applied by adjusting water table could be used in paddy fields. However, whether the combination of WSI and controlled drainage can reduce N leaching losses from paddy fields has yet to be determined. In this study, the effect of controlled irrigation and drainage on N leaching losses from paddy fields was investigated by controlling root zone soil water content and water table depth using a lysimeter.

Materials and methods

Experimental site

Experiments were conducted in lysimeters at the Kunshan Experiment Station in Suzhou, Jiangsu Province ($31^\circ 15' 50''\text{N}$; $120^\circ 57' 43''\text{E}$), which is located in the lower part of the Taihu Lake Basin. The study area has a subtropical monsoon climate with an average annual temperature of 15.5°C , annual precipitation of 1,097.1 mm, and annual evaporation of 1,365.9 mm. The soil type of experimental field is dark-yellow hydromorphic paddy soil. The soil texture in the plowed layer is clay with organic matter of 21.88 g kg^{-1} , total N of 1.03 g kg^{-1} , total P of 1.35 g kg^{-1} , total K of 20.86 g kg^{-1} , and pH 7.4 (soil/water, 1:2.5). The bulk density of soil in the plowed layer is 1.24 g cm^{-3} . The saturated soil water contents (vol vol^{-1}) for the layers of 0–20 cm, 0–30 cm, and 0–40 cm are 54.4, 49.7, and 47.8 %, respectively.

Experimental design

The experiment had two irrigation treatments, controlled irrigation (CI) and flooding irrigation (FI), and three drainage treatments, controlled water table depth 1 (CWT1), controlled water table depth 2 (CWT2), and actual field water table depth (FWT). CI is a new and widely adopted WSI technology of rice cultivation in the Taihu Lake region. FI is a traditional irrigation technology used in this region. Three treatments that combined irrigation and drainage managements were implemented: CI + CWT1, CI + CWT2, and FI + FWT. Three replicates were set up for each treatment.

For CI, a 5–25-mm standing water depth was maintained during the re-greening stage; then, irrigation was applied only to keep the soil moist. In addition, standing water depth was avoided in all the stages except during the application periods of fertilizers, herbicides, and pesticides (Ding 2007). Table 1 presents the soil moisture thresholds in different rice growth stages for CI. For FI, a 30–50-mm standing water depth was constantly maintained after transplanting, except in the late tillering and ripening stages. Water table depth controls were used to set drain limits for the different drainage treatments. Accordingly, drainage was allowed only when the water table depths exceeded the drain limits. For CWT1, the water table depth controls in different stages were selected based on previous studies in the paddy fields of Southeast China for increasing rice yields (Sheng et al. 1998). The water table depth controls in CWT2 were controlled based on the rice root zone depths in different stages of rice growth according to the water table management had been tested in the humid regions of Eastern Canada and Midwestern

Table 1 Soil moisture thresholds in different stages for controlled irrigation

Limit	G ^a	T			J/B	H/F	M	R
		Initial	Middle	Late				
Upper	25 mm ^b	100 % θ_{s1}^c	100 % θ_{s1}	100 % θ_{s1}	100 % θ_{s2}	100 % θ_{s3}	100 % θ_{s3}	Naturally drying
Lower	5 mm	70 % θ_{s1}	65 % θ_{s1}	60 % θ_{s1}	70 % θ_{s2}	80 % θ_{s3}	70 % θ_{s3}	

^a G, T, J/B, H/F, M, and R represent re-greening stage, tillering stage, jointing and booting stages, heading and flowering stages, milk stage, and ripening stage, respectively

^b The standing water depth during the regreening stage

^c θ_{s1} , θ_{s2} , and θ_{s3} represent saturated soil moistures for the layers of 0–20 cm, 0–30 cm, and 0–40 cm, respectively

Table 2 Water table depth controls for different treatments cm

Treatment	G ^a	T			J/B	H/F	M	R
		Initial	Middle	Late				
CWT1		–25 ^b	–25	–50	–35	–35	–45	–45
CWT2		–20	–20	–50	–30	–30	–30	–45
FWT		AWTF ^c	AWTF	AWTF	AWTF	AWTF	AWTF	AWTF

^a G, T, J/B, H/F, M, and R represent re-greening stage, tillering stage, jointing and booting stages, heading and flowering stages, milk stage, and ripening stage, respectively

^b Water table depth is negative value when water table below the soil surface, if not, it is positive value

^c AWTF is abbreviation of actual field water table depth

Table 3 Time and amount of fertilization

	Time (month-date)	N (kg ha ⁻¹)	P ₂ O ₅ (kg ha ⁻¹)	K ₂ O (kg ha ⁻¹)
Base fertilizer I	6–27	45.0	45.0	45.0
Base fertilizer II	7–2	64.5		
Tillering fertilizer	7–20	121.8		
Panicle fertilizer	8–10	87.0		
Total		318.3	45.0	45.0

United States (Madramootoo et al. 1998). The water table depth controls in the later tillering and latter stages were also adjusted depending upon the characteristics of rice growth and the need for cultivation. For FWT, the water table depth controls were adjusted daily based on the actual water table depths that were measured by a water table observation well, which was installed in the open paddy fields outside the lysimeter. Table 2 presents the water table depth controls in the different stages for CWT1, CWT2, and FWT.

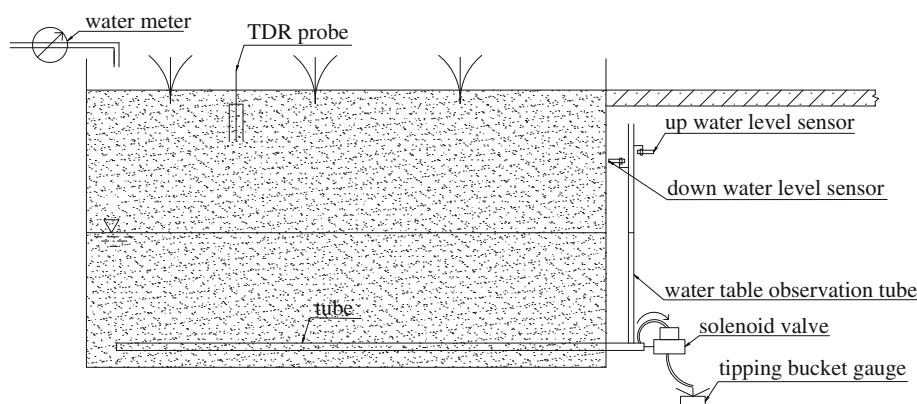
The variety of rice (*Oryza sativa* L.) planted in this area is Japonica Rice Jia 04-33. The rice seedlings were transplanted on June 28, 2012. Three to four plants were transplanted in every hill and were harvested on 24 October 2012. The fertilization process conducted in this experiment followed local rice cultivation practices (Table 3).

Experimental layout

Experiments were conducted in nine drainage-type lysimeters with a mobile shelter and gallery. Each lysimeter had an area of 2.5 m × 2 m and a depth of 1.3 m. The influence of rainfall was avoided using the mobile shelter to strictly regulate the soil moisture in CI. Each lysimeter was individually irrigated and drained using a pipe installed with a water meter and a tube (40 mm in inner diameter) installed at 1.2 m below the soil surface, respectively. Water leakage was drained through the tube into the gallery.

Irrigation was applied only when the observed pond water depth or soil moisture approached the threshold for irrigation (Table 1). Drainage was conducted based on the water table depth controls (Table 2) through an automatic water table control system. The automatic water table control system was installed on each drain tube in the gallery (Fig. 1). A transparent organic glass tube connected to the drain tube was used to observe the water table in the plot. The signal of the water table was sensed by two moveable water level sensors (FKC1810-N, JIAZHUN, China) connected to the water table observation tube. The system controlled the drainage by switching a solenoid valve (SLP-15, WANKONG, China) based on the signal. The solenoid valve opened for drainage when the up water level sensor sensed the water table signal. The water table decreased during the drainage. The solenoid valve closed to

Fig. 1 Automatic water table control system



stop drainage when the down water level sensor lost the water table signal. Water leakage volumes were measured by a tipping bucket gage placed at the end of the system. Two water level sensors were placed 2 cm above and below the water table depth control. The different drainage treatments were administered by properly changing the positions of the water level sensors began from the initial tillering stage.

Field measurement

The soil moistures were measured daily by a Trease system (6050X3, SEC, USA) when no pond water remained in the paddy fields. The pond water depths in the paddy fields were measured daily using a vertical ruler. A water table observation well was installed in the field outside the lysimeter. The actual field water table depths were measured daily after the re-greening stage. One water table observation tube was mounted on the drain tube in each plot. The water table depths of each plot were measured daily after the re-greening stage using a vertical ruler. A water meter installed on the pipe of each plot recorded the irrigation volumes. The water leakage volumes were measured using a tipping bucket gage (0.05 mm resolution) and then transferred to a computer.

Chemical and statistical analysis

Water leakage samples were collected from the sampling devices placed on both sides of the tipping bucket gages. Water samples were collected twice at 2 days intervals after each fertilizer application followed by 4 days intervals. A 7 days sampling interval was used during the rest time. $\text{NH}_4^+\text{-N}$ and $\text{NO}_3^-\text{-N}$ concentrations in the water samples were analyzed by the indophenol blue method and disulfonic acid phenol method, respectively (State Environmental Protection Administration of China 2002), using an ultraviolet-visible spectrophotometer (UV-2800, UNICO, USA). $\text{NH}_4^+\text{-N}$ or $\text{NO}_3^-\text{-N}$ leaching losses were calculated by

multiplying the water leakage volume between the two dates by the $\text{NH}_4^+\text{-N}$ or $\text{NO}_3^-\text{-N}$ concentration in the sample taken at the latter date.

Statistical analysis was carried out following standard procedures on a randomized plot design (SPSS 17.0). Significance was calculated based on F-tests and least significant differences at the 0.05 probability level.

Results and discussions

Irrigation volumes and water table depths

Controlled irrigation and drainage reduced the irrigation volumes compared with FI + FWT. The irrigation volumes of CI + CWT1 and CI + CWT2 were 648.3 and 548.4 mm with a significant reduction of 29.2 and 40.1 %, respectively, compared with FI + FWT (915.9 mm) (Table 4). No significant differences in the rice yields among the treatments were found. The rice yields of CI + CWT1 and CI + CWT2 were 4.0 and 3.8 % lower than that of FI + FWT, respectively. Irrigation water use efficiencies under CI + CWT1 and CI + CWT2 were significantly higher than that under FI + FWT due to a large decrement in water consumption. In FI + FWT, 26 irrigation times were performed from the initial tillering stage to harvest to maintain the pond water after transplanting. As a result, the irrigation volume of FI + FWT was higher than that of CI + CWT1 and CI + CWT2. The irrigation volume of CI + CWT2 was 15.4 % lower than that of CI + CWT1. The water table controls in CI + CWT2 were 5–15 cm higher than that in CI + CWT1 during the rice growth season, more soil was submerged after irrigation in CI + CWT2. The storage of water in CI + CWT2 increased, which potentially increased the water supply from the groundwater to the root zone soil and lengthened the progress of soil moisture down to the lower threshold for irrigation. Therefore, the irrigation times of CI + CWT2 were less than that of

Table 4 Irrigation volume, water leakage, rice yield, and irrigation water use efficiency for CI + CWT1, CI + CWT2, and FI + FWT

Treatment	Irrigation volume (mm)	Water leakage (mm)	Rice yield (kg ha ⁻¹)	Irrigation water use efficiency (kg m ⁻³)
FI + FWT	915.9 (16.5) a	447.6 (11.2) a	7,803.4 (120.7) a	0.852 (0.028) b
CI + CWT1	648.3 (29.5) b	226.3 (8.4) b	7,493.6 (471.6) a	1.156 (0.119) a
CI + CWT2	548.4 (25.4) b	157.5 (6.5) b	7,506.3 (148.1) a	1.369 (0.070) a

Means in the same column followed by the same letter are not significantly different ($P < 0.05$)

Numbers in parenthesis are standard deviation

Fig. 2 Typical irrigation and water table depth in CI + CWT1, CI + CWT2, and FI + FWT

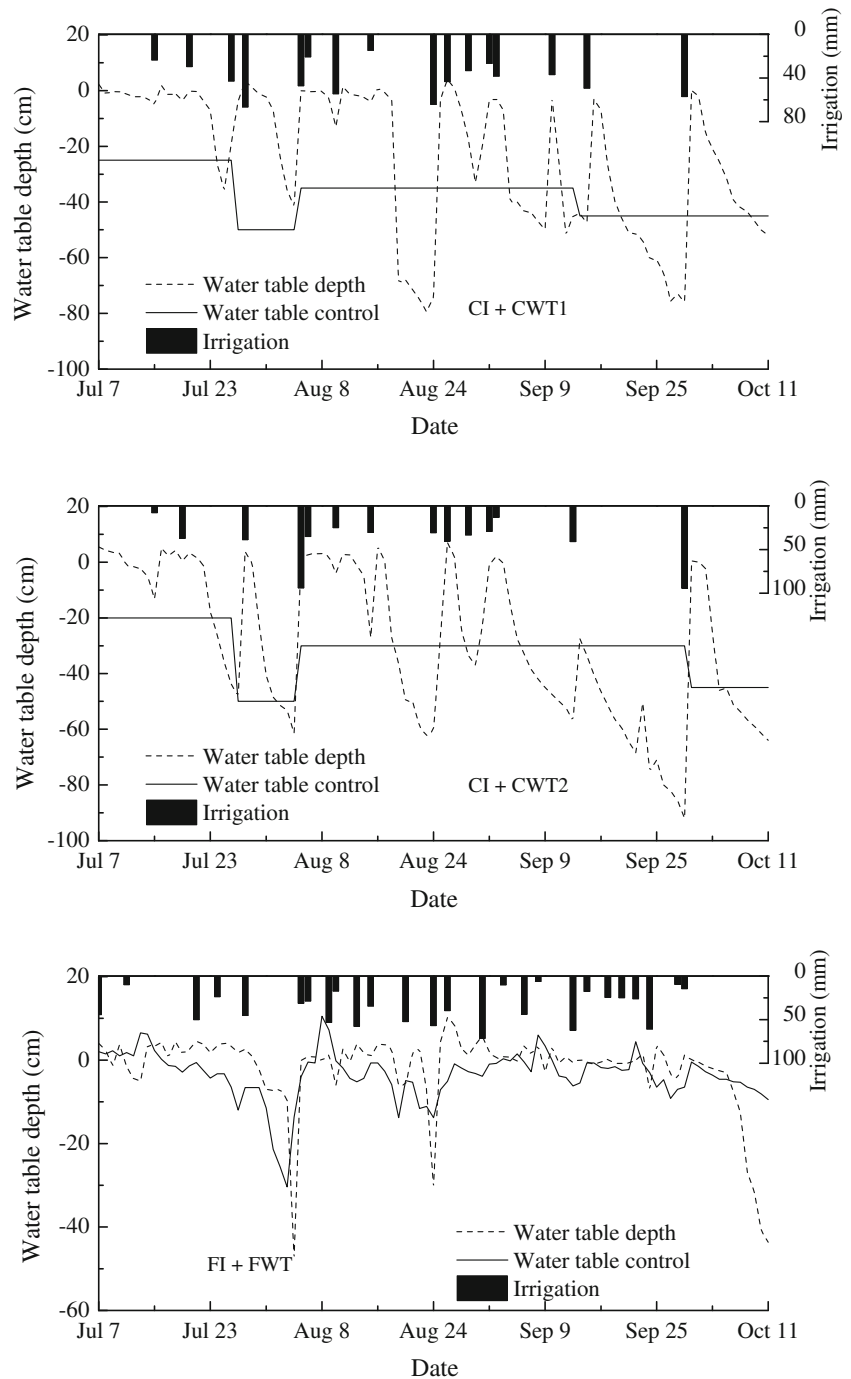
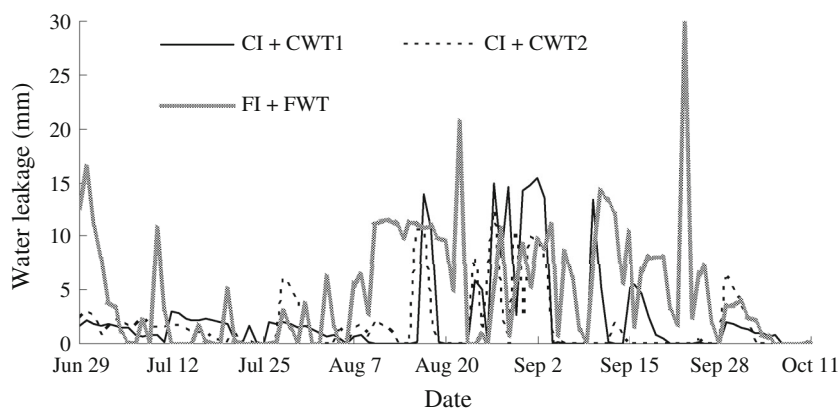


Fig. 3 Typical daily water leakage in CI + CWT1, CI + CWT2, and FI + FWT



CI + CWT1. From the initial tillering stage to harvest, 16 and 14 irrigation times were performed, along with pesticide and fertilizer applications in CI + CWT1 and CI + CWT2, respectively, showing a reduction of 12.5 %.

The water table depths fluctuated more in CI + CWT1 and CI + CWT2 than in FI + FWT, and the water table depth fluctuation in CI + CWT1 was similar to that in CI + CWT2 (Fig. 2). The water table depths in CI + CWT1 and CI + CWT2 fluctuated following the regulation of soil moisture and increased rapidly after irrigation. The water table in FI + FWT usually ranged near the soil surface and only decreased during the late tillering and ripening stages.

Water leakage

The change pattern of water leakage was significantly influenced by controlled irrigation and drainage (Fig. 3). From 7 July to 11 October, significant differences in the water leakage were confirmed among the treatments, with the higher values for FI + FWT (Table 4). The water leakage from CI + CWT1 and CI + CWT2 was 226.3 and 157.5 mm, respectively, which was 49.4 and 64.8 % lower than the water leakage from FI + FWT (447.6 mm). The water leakage from CI + CWT1 was 43.7 % greater than that from CI + CWT2. The discrepancies were caused by the greater irrigation and lower water table depth controls in CI + CWT1 compared with CI + CWT2.

Approximately 48.2 and 43.8 % of the water leakage from CI + CWT1 and CI + CWT2 occurred from late August to early September, respectively, because of the continuous irrigation for pesticide and fertilizer applications during this period. The water leakage from CI + CWT1 and CI + CWT2 maintained low levels at other times. Considerable water leakage from FI + FWT was observed in each stage because the pond water continuously existed on the soil surface during the rice growth season.

Ammonium nitrogen and nitrate nitrogen concentrations in water leakage

For CI + CWT1 and CI + CWT2, $\text{NH}_4^+\text{-N}$ concentrations in water leakage varied in the different patterns as that of FI + FWT (Fig. 4). The $\text{NH}_4^+\text{-N}$ concentrations in the water leakage from CI + CWT1 and CI + CWT2 peaked a week after fertilization and then rapidly decreased. Low values of $\text{NH}_4^+\text{-N}$ concentrations were observed after the heading and flowering stages in CI + CWT1 and CI + CWT2. Low concentrations of $\text{NH}_4^+\text{-N}$ in the water leakage from FI + FWT were maintained in the other stages after peaking in the regreening stage.

The average $\text{NH}_4^+\text{-N}$ concentrations in the water leakage from CI + CWT1 and CI + CWT2 were 1.952 and 2.273 mg L^{-1} , respectively, which were 5.8 and 23.3 % higher than that in the water leakage from FI + FWT (1.844 mg L^{-1}) (Table 5). The irrigation volumes of CI + CWT1 and CI + CWT2 were significantly lower than that of FI + FWT (Table 4). The dilution effect due to higher irrigation water for FI + FWT thereby reduced the $\text{NH}_4^+\text{-N}$ concentrations in the water leakage compared with CI + CWT1 and CI + CWT2. Tan et al. (2013) suggested that alternate wetting and drying (AWD) irrigation increased the $\text{NH}_4^+\text{-N}$ concentrations in illuvial horizon compared with FI. $\text{NH}_4^+\text{-N}$ concentrations were clearly affected by the different drainage treatments under CI, whereas the average $\text{NH}_4^+\text{-N}$ concentrations in CI + CWT1 reduced by 14.1 % compared with that in CI + CWT2. The soil aeration conditions in CI + CWT1 improved because of the increased water leakage compared with CI + CWT2. Nitrification was promoted under aerobic conditions, which reduced the concentrations of $\text{NH}_4^+\text{-N}$ in the water leakage from CI + CWT1. In addition, the dilution effect caused by the increase in irrigation water of CI + CWT1 can also reduce the concentrations of $\text{NH}_4^+\text{-N}$ compared with CI + CWT2. These phenomena

Fig. 4 Average $\text{NH}_4^+\text{-N}$ concentrations in water leakage from CI + CWT1, CI + CWT2, and FI + FWT (the arrows indicate fertilization, G, T, J/B, H/F, and M represent re-greening stage, tillering stage, jointing and booting stages, heading and flowering stages, milk stage, respectively)

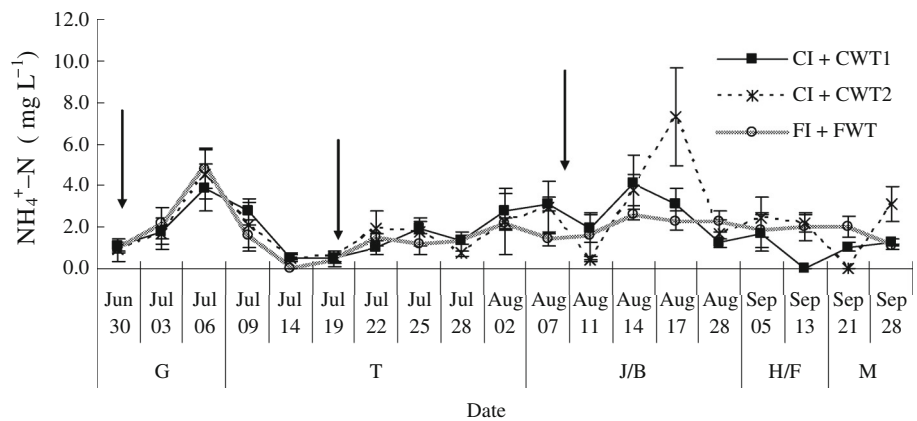
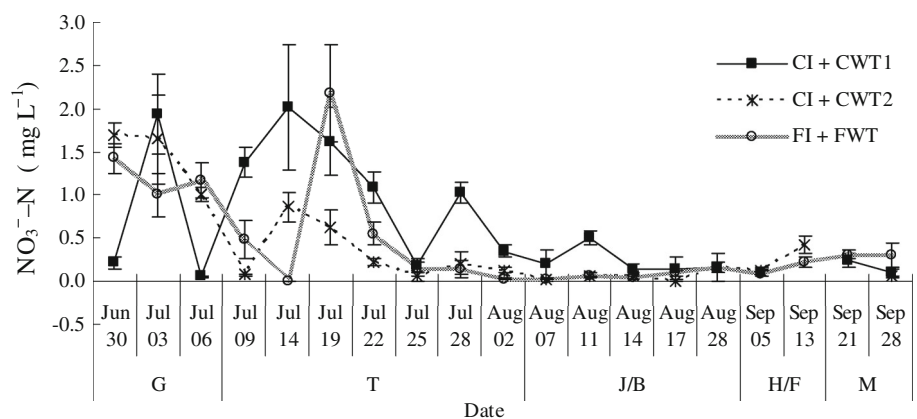


Table 5 $\text{NH}_4^+\text{-N}$ and $\text{NO}_3^-\text{-N}$ concentrations and leaching losses in water leakage from CI + CWT1, CI + CWT2, and FI + FWT

Treatment	N leaching losses (kg ha^{-1})		Average N concentrations (mg L^{-1})	
	$\text{NH}_4^+\text{-N}$	$\text{NO}_3^-\text{-N}$	$\text{NH}_4^+\text{-N}$	$\text{NO}_3^-\text{-N}$
FI + FWT	9.02 (1.18) a	1.61 (0.19) a	1.844 (0.195) a	0.468 (0.037) b
CI + CWT1	3.68 (1.00) b	0.88 (0.11) b	1.952 (0.212) a	0.637 (0.064) a
CI + CWT2	4.45 (0.43) b	0.43 (0.10) c	2.273 (0.350) a	0.414 (0.027) b

Means in the same column followed by the same letter are not significantly different ($P < 0.05$)
 Numbers in parenthesis are standard deviation

Fig. 5 Average $\text{NO}_3^-\text{-N}$ concentrations in water leakage from CI + CWT1, CI + CWT2, and FI + FWT (G, T, J/B, H/F and M represent re-greening stage, tillering stage, jointing and booting stages, heading and flowering stages, milk stage, respectively)



can reduce the $\text{NH}_4^+\text{-N}$ concentrations in the water leakage from CI + CWT1 compared with CI + CWT2.

$\text{NO}_3^-\text{-N}$ concentrations in the water leakage varied in the same pattern among different treatments (Fig. 5). The $\text{NO}_3^-\text{-N}$ concentrations in the water leakage maintained high values in the re-greening stage and then significantly decreased after the tillering stage. Low $\text{NO}_3^-\text{-N}$ concentrations were observed after the jointing and booting stages. The average $\text{NO}_3^-\text{-N}$ concentrations in the water leakage from CI + CWT1, CI + CWT2, and FI + FWT were 0.987, 0.655, and 0.792 mg L^{-1} , respectively, from the re-greening stage to the late tillering stage. By contrast, these

values were decreased to 0.199, 0.114, and 0.144 mg L^{-1} in the other stages, respectively.

Significant differences in the average $\text{NO}_3^-\text{-N}$ concentrations were confirmed among the treatments, with higher values for CI + CWT1 (Table 5). The average $\text{NO}_3^-\text{-N}$ concentration in the water leakage from CI + CWT1 was 0.637 mg L^{-1} , which was 36.0 and 53.7 % higher than that in the water leakage from CI + CWT2 (0.414 mg L^{-1}) and FI + FWT (0.468 mg L^{-1}), respectively. No significant difference in the average $\text{NO}_3^-\text{-N}$ concentration was observed between CI + CWT2 and FI + FWT. The aerobic conditions created by the dewatering progresses in

CI + CWT1 began from the tillering stage, promoted nitrification and weakened denitrification. Therefore, the average NO_3^- -N concentrations in CI + CWT1 increased compared with that in FI + FWT. The topsoil aeration conditions in CI + CWT2 were lower than that in CI + CWT1 because of the decreased water leakage. Denitrification was promoted in CI + CWT2, which reduced NO_3^- -N concentrations in water leakage compared with CI + CWT1.

Ammonium nitrogen and nitrate nitrogen leaching losses

Controlled irrigation and drainage significantly reduced NH_4^+ -N and NO_3^- -N leaching losses from paddy fields. The NH_4^+ -N leaching losses from CI + CWT1 and CI + CWT2 were 3.68 and 4.45 kg ha^{-1} , which were significantly reduced by 59.2 and 50.7 %, respectively, compared with FI + FWT (9.02 kg ha^{-1}) (Table 5). The NO_3^- -N leaching losses from CI + CWT1 and CI + CWT2 were 0.88 and 0.43 kg ha^{-1} with a significant reduction of 45.2 and 73.2 %, respectively, compared with FI + FWT (1.61 kg ha^{-1}). No significant differences in the means of NH_4^+ -N and NO_3^- -N concentrations among the treatments were found, except for the higher average NO_3^- -N concentrations in CI + CWT1. Therefore, the increases of NH_4^+ -N and NO_3^- -N concentrations in the water leakage from CI + CWT1 and CI + CWT2 had minimal effects on the N leaching losses from paddy fields. The large reductions in the water leakage from CI + CWT1 and CI + CWT2 were the main causes of the significant reductions in the NH_4^+ -N and NO_3^- -N leaching losses compared with FI + FWT. A similar result was noted by Wesström and Messing (2007) who observed that the decrease in drainage water amounts caused nitrogen loads to be significantly reduced in controlled drainage fields.

In addition, compared with FI, the reductions in NH_4^+ -N and NO_3^- -N leaching losses from paddy fields under controlled irrigation and drainage were larger than those under single WSI. Cui et al. (2004) showed the reductions in NH_4^+ -N leaching losses ranged from 9.1 to 11.6 % under AWD irrigation compared with FI. A similar relationship was also noted by Tan et al. (2013) who observed little reductions in TN and NH_4^+ -N leaching losses under AWD. CI was also reported that reduced TN losses through leaching by 41.4 % compared with FI (Peng et al. 2011). The larger reductions in NH_4^+ -N and NO_3^- -N leaching losses in this study may be because that relative less water leakage due to the reduction in irrigation volumes and usage of water table control.

Due to long-term flooding and high groundwater table of paddy fields in the Taihu Lake region, the paddy soil was maintained in reduced state. In this state,

nitrification was limited, while denitrification was intensive. Thus, the proportion of NO_3^- -N concentrations in water leakage was very low in this reductive soil. NH_4^+ -N was major component of the inorganic N losses by leaching in different treatments, which was in agreement with previous studies (Wang et al. 2011; Ji et al. 2008; Wu et al. 2001).

The NH_4^+ -N leaching losses from CI + CWT1 were reduced by 16.6 % compared with those from CI + CWT2. The reduction of NH_4^+ -N concentrations in the water leakage from CI + CWT1 may be the cause of the reduction in NH_4^+ -N leaching losses. Significant differences in NO_3^- -N leaching losses between CI + CWT1 and CI + CWT2 were confirmed, with higher values for CI + CWT1. The NO_3^- -N leaching losses from CI + CWT1 exceeded that from CI + CWT2 by 1.05 times. The greater NO_3^- -N leaching losses from CI + CWT1 than from CI + CWT2 can be attributed to the greater water leakage and higher NO_3^- -N concentrations in the former.

Conclusions

Controlled irrigation and drainage effectively reduced irrigation and water leakage by regulating water table depths and controls. The irrigation volumes for CI + CWT1 and CI + CWT2 were 648.3 and 548.4 mm with a reduction of 29.2 and 40.1 %, respectively, compared with FI + FWT (915.9 mm). This result can be attributed to the reduction in irrigation times. The water leakage from CI + CWT1 and CI + CWT2 was 226.3 and 157.5 mm, respectively, which was 49.4 and 64.8 % lower than those from FI + FWT (447.6 mm).

Controlled irrigation and drainage significantly reduced NH_4^+ -N and NO_3^- -N leaching losses from paddy fields by decreasing water leakage. The NH_4^+ -N leaching losses from CI + CWT1 and CI + CWT2 were 3.68 and 4.45 kg ha^{-1} with a significant reduction of 59.2 and 50.7 %, respectively, compared with FI + FWT (9.02 kg ha^{-1}). The NO_3^- -N leaching losses from CI + CWT1 and CI + CWT2 were 0.88 and 0.43 kg ha^{-1} with a significant reduction of 45.2 and 73.2 %, respectively, compared with FI + FWT (1.61 kg ha^{-1}).

The lowest NH_4^+ -N and NO_3^- -N leaching losses were found in CI + CWT1. The comprehensive regulation of CI and CWT1 can be an effective pollution-controlled water management plan to reduce NH_4^+ -N and NO_3^- -N leaching losses from paddy fields.

Acknowledgments The research was financially supported by the National Natural Science Foundation of China (Grant No. 51179049), the Research Fund for the Doctoral Program of Higher Education

(Grant No. 20110094110015), and the Fund for Creative Research of Postgraduate in Jiangsu Province (Grant No. CXZZ12-0250).

References

- Bonaiti G, Borin M (2010) Efficiency of controlled drainage and subirrigation in reducing nitrogen losses from agricultural fields. *Agric Water Manag* 98(2):343–352
- Cheng JP (2007) Study on foundation of physi-ecology and technique of water-saving irrigation for rice. Doctor, Huazhong Agricultural University Wuhan (in Chinese)
- Cui YL, Li YH, Lv GA, Sha ZX (2004) Nitrogen movement and transformation with different water supply for paddy rice. *Adv Water Sci* 15(03):280–285 (in Chinese)
- Ding JL (2007) Experiment and model of water use and evapotranspiration of paddy rice on controlled irrigation. Doctor, Hohai University, Nanjing (in Chinese)
- Drury CF, Tan CS, Gaynor JD, Reynolds WD, Welacky TW, Oloya TO (2001) Water table management reduces tile nitrate loss in continuous corn and in a soybean-corn rotation. *Sci World J* 1(Suppl 2):163–169
- Ji XH, Zheng SX, Shi LH, Liao YL (2008) Effect of fertilization on nutrient leaching loss from different paddy soils in dongting lake area. *Acta Pedol Sin* 45(04):663–671 (in Chinese)
- Ju XT, Xing GX, Chen XP, Zhang SL, Zhang LJ, Liu XJ, Cui ZL, Yin B, Christie P, Zhu ZL, Zhang FS (2009) Reducing environmental risk by improving N management in intensive Chinese agricultural systems. *Proc Natl Acad Sci* 106(9):3041–3046
- Lalonde V, Madramootoo CA, Trenholm L, Broughton RS (1996) Effects of controlled drainage on nitrate concentrations in subsurface drain discharge. *Agric Water Manag* 29(2):187–199
- Li RG, Xia YL, Wu AZ, Qian YS (2001) Water saving irrigation and control of nitrogen leaching in Taihu Lake Region. *Journal of Hohai University (Natural Sciences)* 29(02):21–25 (in Chinese)
- Li P, Qi XB, Hu YL, Gao Q, Hu C, An JW, Lv M (2011) Influence of different nutrient management practices on quality of ground drinking water of eastern semi-mountainous regions of Northeast China. *Trans CSAE* 27(07):89–95 (in Chinese)
- Lin DX, Fan XH, Hu F, Zhao HT, Luo JF (2007) Ammonia volatilization and nitrogen utilization efficiency in response to urea application in rice fields of the Taihu Lake region, China. *Pedosphere* 17(5):639–645
- Liu J, Diamond J (2005) China's environment in a globalizing world. *Nature* 435(7046):1179–1186
- Luo W, Jia ZH, Fang SX, Wang L (2006) Effect of drainage control on salt and water balance in rice field. *J Hydraul Eng* 37(05):608–612 + 618 (in Chinese)
- Luo W, Jia ZH, Fang S, Wang N, Liu J, Wang L, Tian S, Zhang Y (2008) Outflow reduction and salt and nitrogen dynamics at controlled drainage in the YinNan Irrigation District, China. *Agric Water Manag* 95(7):809–816
- Madramootoo CA, Johnston WR, Wilardson LS (1998) Management of agricultural drainage water quality. International Commission on Irrigation and Drainage, New Delhi, India and Food and Agriculture Organisation, Italy
- McElroy JA, Trentham-Dietz A, Gangnon RE, Hampton JM, Bersch AJ, Kanarek MS, Newcomb PA (2008) Nitrogen-nitrate exposure from drinking water and colorectal cancer risk for rural women in Wisconsin, USA. *J Water Health* 6(3):399–409
- Min J, Zhao X, Shi WM, Xing GX, Zhu ZL (2011) Nitrogen balance and loss in a greenhouse vegetable system in southeastern China. *Pedosphere* 21(4):464–472
- National Bureau of Statistics of China (2012) China statistical yearbook. China Statistics Press, Beijing (in Chinese)
- Ng HYF, Tan CS, Drury CF, Gaynor JD (2002) Controlled drainage and subirrigation influences tile nitrate loss and corn yields in a sandy loam soil in Southwestern Ontario. *Agric Ecosyst Environ* 90(1):81–88
- Peng SZ, Yang SH, Xu JZ, Luo YF, Hou HJ (2011) Nitrogen and phosphorus leaching losses from paddy fields with different water and nitrogen managements. *Paddy Water Environ* 9(3):333–342
- Peng SZ, Luo YF, Xu JZ, Khan S, Jiao XY, Wang WG (2012) Integrated irrigation and drainage practices to enhance water productivity and reduce pollution in a rice production system. *Irrig Drainage* 61(3):285–293
- Qin BQ, Wang XD, Tang XM, Feng S, Zhang YL (2007) Drinking water crisis caused by eutrophication and cyanobacterial bloom in Lake Taihu: Cause and measurement. *Adv Earth Sci* 22(09):896–906 (in Chinese)
- Qu SY, Huang JS, Yang L, Li DW, Wang XG, (2009) Experimental research on nitrogen transport and transformation of controlled drainage on dry lands. *China Rural Water Hydropower* 01:48–51 (in Chinese)
- Shao DG, Qiao X, Liu HH, Cai ZM, Wang JZ (2010) Study of moving and transforming law of water and fertilizer under different treatments of irrigation and drainage. *Eng J Wuhan University* 43 (04):409–413 + 418 (in Chinese)
- Sheng P, Xu K, Wu Q, Wu F (1998) Experimental study on suitable water table depth of main crops in Shanghai suburbs. *Shanghai Agric Sci Technol* 05:2–5 (in Chinese)
- Skaggs RW, Fausey NR, Evans RO (2012) Drainage water management. *J Soil Water Conserv* 67(6):167A–172A
- State Environmental Protection Administration of China (2002) Standard methods for water and wastewater monitoring and analysis, 4th edn. China Environmental Science Press, Beijing (in Chinese)
- Tan XZ, Shao DG, Liu HH, Yang FS, Xiao C, Yang HD (2013) Effects of alternate wetting and drying irrigation on percolation and nitrogen leaching in paddy fields. *Paddy Water Environ* 11(1–4):381–395
- Wang SP, Yu LZ, Xu SY, Cheng ST (2002) Nitrogen leaching in the purple clay and analysis on its influence on water environmental quality in Shanghai. *Resour Environ Yangtze Basin* 11(06):554–558 (in Chinese)
- Wang XT, Suo YY, Feng Y, Shohag MJI, Gao J, Zhang QC, Xie S, Lin XY (2011) Recovery of 15 N-labeled urea and soil nitrogen dynamics as affected by irrigation management and nitrogen application rate in a double rice cropping system. *Plant Soil* 343(1–2):195–208
- Wesström I, Messing I (2007) Effects of controlled drainage on N and P losses and N dynamics in a loamy sand with spring crops. *Agric Water Manag* 87(3):229–240
- Wesström I, Messing I, Linner H, Lindstrom J (2001) Controlled drainage—effects on drain outflow and water quality. *Agric Water Manag* 47(2):85–100
- Woli KP, David MB, Cooke RA, McIsaac GF, Mitchell CA (2010) Nitrogen balance in and export from agricultural fields associated with controlled drainage systems and denitrifying bioreactors. *Ecol Eng* 36(11):1558–1566
- Wu JF, Zhang ML, Liu JR, Wang HH (2001) Effect of different structure of fertilizer on the migration of nitrogen in red rice soil. *Plant Nutrizer Sci* 7(04):368–373 (in Chinese)
- Wu Y, Hu Z, Yang L (2011) Strategies for controlling agricultural non-point source pollution: reduce-retain-restoration (3R) theory and its practice. *Trans CSAE* 27(5):1–6 (in Chinese)
- Xue X, Hao M (2011) Nitrate leaching on loess soils in north-west China: appropriate fertilizer rates for winter wheat. *Acta Agric Scand Sect B* 61(3):253–263
- Zeman C, Beltz L, Linda M, Maddux J, Depken D, Orr J, Theran P (2011) New questions and insights into nitrate/nitrite and

human health effects: a retrospective cohort study of private well users' immunological and wellness status. *J Environ Health* 74(4):8–18

Zhang JH, Liu JL, Zhang JB, Cheng YN, Wang WP (2013) Nitrate-nitrogen dynamics and nitrogen budgets in rice-wheat rotations in Taihu Lake Region, China. *Pedosphere* 23(1):59–69