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Original Research

Impact of Alternate Drought and Flooding Stress on Water Use, and Nitrogen and Phosphorus Losses in a Paddy Field

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Abstract

Alternate drought and flooding stress has become more prevalent during paddy growth stages as a result of climate change, especially in southern China. This study aims to assess the effect of alternate drought and flooding stress on water use, and nitrogen (N) and phosphorus (P) losses in paddy fields. Two controlled irrigation and drainage (CID) managements (namely drought at the beginning of growth stages followed by flooding (CID-1), and flooding at the beginning of growth stages followed by drought (CID-2) and one alternated wetting and drying (AWD) management were designed in specially designed experimental tanks with three replications in 2015 and 2016. Results showed that CID increased effective irrigation quantities and rainwater storage ability with a significant decrease in water use efficiency compared with AWD. For surface water, CID-1 significantly improved possible losses of nitrogen and phosphorus during the fertilizer application period over CID-2. For subsurface water, CID can significantly reduce the leaching losses of nitrate N and P compared with AWD. Meanwhile, CID-1 significantly increased the leaching losses of nitrate N at the former two growth stages compared to CID-2, yet no significant difference was found for ammonia N and P. Therefore, the application of controlled irrigation and drainage – especially for CID-1 – was an efficient method for obtaining high water quality and reducing eutrophication.

Keywords: controlled irrigation and drainage, alternate wetting and drying, control drainage, paddy

Introduction

Paddy is the most important grain crop in China. In addition, water is one of the most important components for sustainable paddy production, and the quantity of irrigation for paddy fields accounts for approximately 70% of its total agricultural water resource consumption [1]. However, water supply is limited because of serious regional and seasonal water shortages, and paddy production is impaired by increasing water shortage [2]. Meanwhile, China is the largest producer and consumer of synthetic fertilizers in the world. Fertilizer and pesticide overuse in order to achieve high paddy yields might result not only in poor grain yield but also low N use

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efficiency, massive N losses, and environmental pollution [3-4]. Nitrogen and phosphorus losses are determined by the concentration and the runoff volume, yet when the amounts of N and P in topsoil are small, their losses mostly depend on the volume of runoff [5]. Moreover, irrational surface and subsurface drainage by farmers can enhance the loss of water, which leads to serious N and P losses [6]. Therefore, several water-saving irrigation technologies and control drainage practices have been developed to solve water shortage and water environment deterioration.

The most typical water-saving irrigation technology is alternate wetting and drying (AWD), in which paddy soil is treated with alternating periods of wet or dry and standing water [7-8]. AWD irrigation can reduce unproductive losses of water due to lower percolation and evaporation. Previous studies have shown that AWD can reduce the N and P leaching by significantly cutting the volume of percolating water compared with conventional flooding irrigation [9-10]. Controlled drainage can control the groundwater table effectively via the installation of a subsurface drain. This method is widely employed in northeastern Italy, southwestern Japan, and southern Sweden [11-13]. Controlled drainage not only can improve water use by regulating the water table reasonably, but it promotes the absorption and utilization of N and P by controlling the retention times of stormwater in fields and drains [14, 15]. N and P concentrations were not significantly different between controlled drainage and conventional drainage, whereas N and P losses tend to be lower due to lower runoff volumes in control drainage [14, 15].

Recently, researchers implemented controlled irrigation and drainage (CID), which takes advantage of both AWD and control drainage. It has been a focus of agricultural water conservation and environmental study [16-17]. Peng et al. demonstrated that control of groundwater depth not only can significantly promote the efficient use of water and change the water demand regulation, but also can control and reduce N and P losses in surface and underground drain discharge from paddy fields [18]. Xiao et al. found that prolonging flood times under CID can significantly reduce ammonia N (NH_4^+-N) and total P (TP) concentrations [19]. A field experiment conducted by Gheysari et al. showed that N uptake decreased and final soil N leaching increased for deficit irrigation management as compared to adequate irrigation management [20]. Most of the existing studies on water management in paddy fields are focused on the effect of single flooding or deficit water stress on N and P losses. Nevertheless, few studies have focused on the effect of alternate drought and flooding conditions on N and P losses and water systems. Under CID, paddy fields can store a higher water volume after a storm or irrigation and endure moisture deficit periods, which may form an alternate drought and flood conditions for plant growth. Alternate drought and flooding may become more prevalent at any paddy growth stage as a result of climate change, especially in southern China [21]. Paddy is a semi-aquatic plant, thus we can take full advantage of the stress of drought and waterlogging on paddy to control stress. We previously reported the potential of CID at the single growth stage for the changes of N and P concentrations from rice paddies in Southern China [22]. In that study, the effect of CID at continuous growth stages of paddy was not deeply investigated. Therefore, the present study was designed to further explore the effect of alternate drought and flooding stress on water use, and N and P losses under CID in paddy fields at continuous growth stages. This can provide a series of research technical indicators on CID in paddy fields not only for improving water quality and maintaining high yield, but also for achieving comprehensive benefits from environmental and economic resources. Our study hypothesizes that tanks have the same seepage and percolation rates when a water table exists at the soil surface, and water table recession occurs evenly when floodwater recedes.

Materials and Methods

Experimental Site and the Soil Properties

Experiments were implemented in experimental tanks at the Key Laboratory of Efficient Irrigation-Drainage and Agricultural Soil-Water Environment in Southern China, Ministry of Education (31°57′N, 118°50′E, and 144 m above sea level), during the paddy growing season of 2015, and repeated in 2016. The study area has a subtropical humid monsoon climate with an average annual temperature of 15.4ºC, annual precipitation of 1,051 mm, annual evaporation of 900 mm, and a frost-free period of 220 days per year. The soil type of the experimental field is a typical permeable paddy soil formed on losses deposits with loamy clay. The soil (0-30 cm) in tanks with pH of 6.97 includes 2.19% of soil organic matter, 0.91 g/kg of total nitrogen, 27.65 mg/kg of available nitrogen, 0.32 g/kg of total phosphorus, and 12.5 mg/kg of available phosphorus. Nine fixed tanks 2 m wide, 2.5 m long, and 2 m high were needed, and the container was constructed from concrete block and sealed with waterproof paint. An integrated irrigation-drainage system was installed in the experimental field (Fig. 1). A mobile canopy is equipped on the ground, and remains closed during the rain period.

Plant Material and Agricultural Activities

Nangeng 9108 was used in the experimental tanks. For two years in a row, seedlings were raised in a seedbed on 13 May 2015 (15 May 2016) and then transplanted on 16 June 2015 (24 June 2016) at a hill spacing of 0.2 m×0.14 m, with three seedlings per hill. The soil was soaked the day before transplanting and then flooded for about a week with a 20-30 mm water layer to promote good crop establishment. Weeds were controlled manually and pesticides were applied

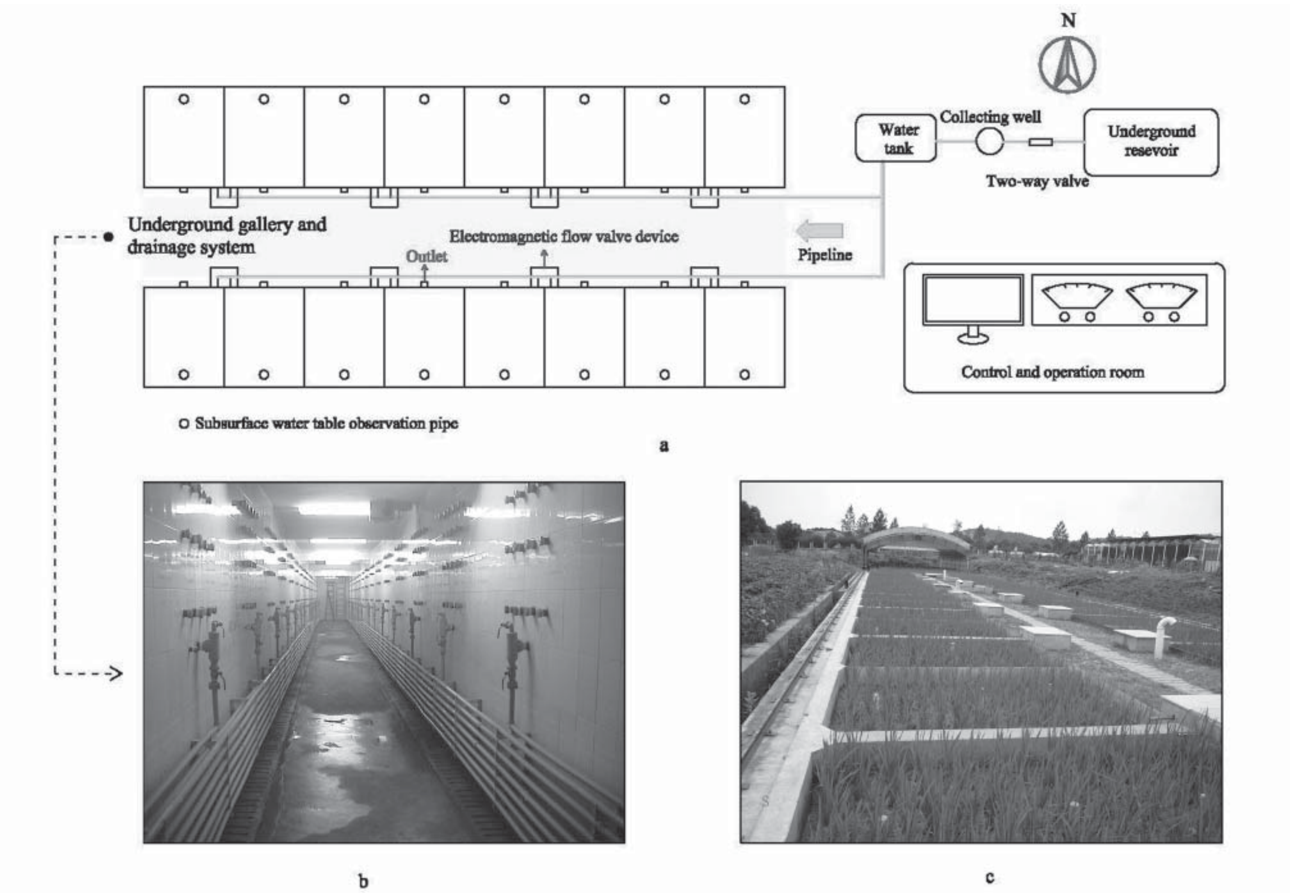

Fig. 1. a) Layout of the study area and experimental management. Water was supplied from an underground reservoir to every fixed tank plot through pipelines. b) Picture of underground gallery and drainage system. (c) Picture of fixed tank plot.

occasionally. The fertilizer activities used in this experiment were described in Table 1.

Experimental Designs

We designed two controlled irrigation and drainage management systems: drought at the beginning of growth followed by flooding (CID-1), and flooding at the beginning of growth followed by drought (CID-2). Conventional AWD management was designed f or comparison. All treatments were set up in the experimental tanks with closed bottoms and kept to three replications. For the first 10 days after transplanting, shallow water (10-40 mm) was kept in both water regimes to facilitate seedling recovery and turning green. Hereafter the CID and AWD were managed differently, as shown in Table 2.

Sample Collection and Measurement

In this study we calculated the seasonal water use of paddy by the water balance principle as follows:

$$ET_{\mathrm{t}} = P_t + I_t - W_{t-1} + W_t - D_t$$

…where *ET* is evapotranspiration (mm); *P* is precipitation (mm), recorded daily by an automatic weather station (ICT, Australia); *I* is irrigation water (mm), recorded by the integrated irrigation systems; *W* is water depth (measured by vertical rulers every morning at 09:00)

Table 1. Date of fertilizer activities during the rice growing season.

Activities	Remarks	Date	
		2015	2016
Base fertilizer	Compound fertilizer (N:P_2O_5:K_2O, 15:15:15, 900 kg/ha)	13 June	22 June
Tillering fertilizer	Urea (nitrogen content of 46.4%, 100 kg/ha)	28 June	5 July
Panicle fertilizer	Urea (nitrogen content of 46.4%, 50 kg/ha)	26 July	3 August

Table 2. Design of controlled irrigation and drainage scheduling.

Stages	Water depth design (mm)			Period of water control (month/day)			
	CID-1	CID-2	AWD	CID-1		CID-2	
				2015	2016	2015	2016
Tillering	-500~150	250~-500	-200~30 ~60	July 3-July 8-July 13	July 14-July 21-July 30	July 3-July 7-July 14	July 7-July 11-July 22
Jointing-booting	-500~250	250~-500	-300~50 ~100	July 29-Aug. 3-Aug. 8	Aug. 7-Aug. 10-Aug. 17	July 29-Aug. 3-Aug. 9	Aug. 7-Aug. 11-Aug. 16
Heading-flowering	-500~250	250~-500	-200~50 ~150	Aug. 23-Aug. 28-Sept. 1	Aug. 19-Aug. 23-Sept. 2	Aug. 23-Aug. 28-Sept. 4	Aug. 19-Aug. 23-Aug. 28
Milky	-500~250	250~-500	-200~50 ~150	Sept. 13-Sept. 18-Sept. 23	Sept. 10-Sept. 15-Sept. 23	Sept. 12-Sept. 17-Sept. 23	Sept. 10-Sept. 14-Sept. 23

Note: -I ~ J~ K denotes that water depth was kept between -I mm and J mm at four stages of paddy fields at normal time; the maximum storage water depth after rain was kept at K mm; -H ~ L indicates that at the beginning of growth period water was consumed naturally to the lower limit value of H, then irrigated water to the upper limit value of L and kept at natural consumption; L ~ -H indicates that at the beginning of growth period the upper limit vale L was obtained, then drained to no water lever and naturally consumed to the lower limit value H; the rest of growth days for CID were performed according to the requirement of AWD; the middle value of growth period indicates the day of drought turned to flooding or flooding drain to no water level.

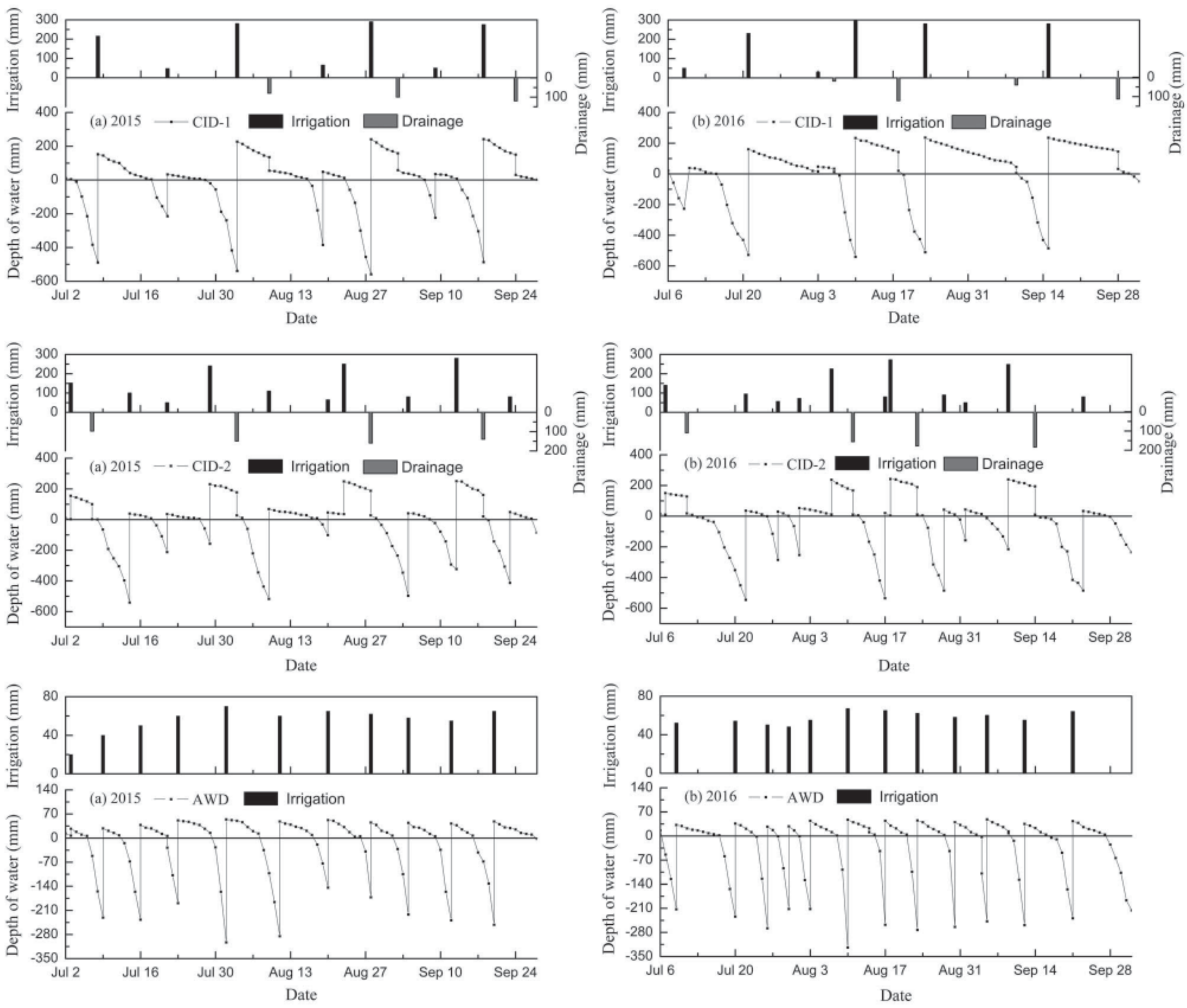

Fig. 2. Typical irrigation, drainage, and water table depth of CID and AWD in 2015 a) and 2016 b).

or the soil water content in the root zone (mm); *D* is the volume of drainage and underlying root leakage (mm); and *t* is the day of determination. A 2 mm water leak per day was allowed when the paddy soil existed at water level.

Water samples were collected in polyethylene bottles three times during the water control period. The surface water was collected using 50 mL syringes (without disturbing the soil and selecting the top surface water randomly); the subsurface water was collected from an underground drainage pipe; all bottoms were rinsed before an appropriate amount of water sample was obtained. Water collection times are shown in Figs 3-4. Ammonia nitrogen (NH_4^+-N), nitrate nitrogen (NO_3^--N), and total phosphorus (TP) in the water were analyzed by the indophenol blue, disulfonic acid phenol, and

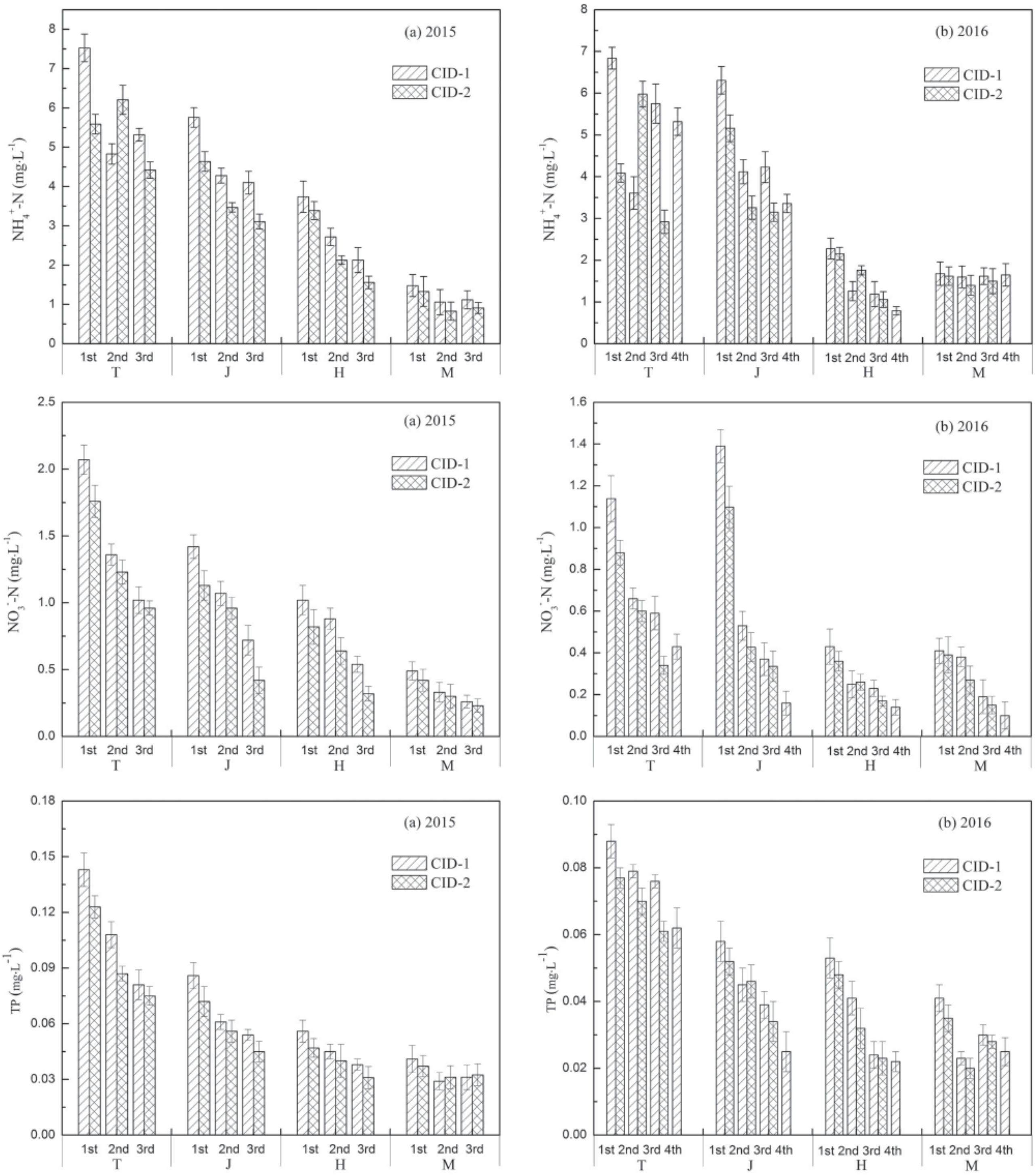

Fig. 3. Changes of NH_4^+-N, NO_3^--N, and TP concentrations in surface water under CID in 2015 a) and 2016 b). 1st, 2nd, and 3rd means the concentration on the first, third, and fifth day of flooding. 4th means the concentration in the end of flooding control for CID-1 treatment. T, J, H, and M represent tillering stage, jointing-booting stage, heading-flowering stage, and milky stage, respectively.

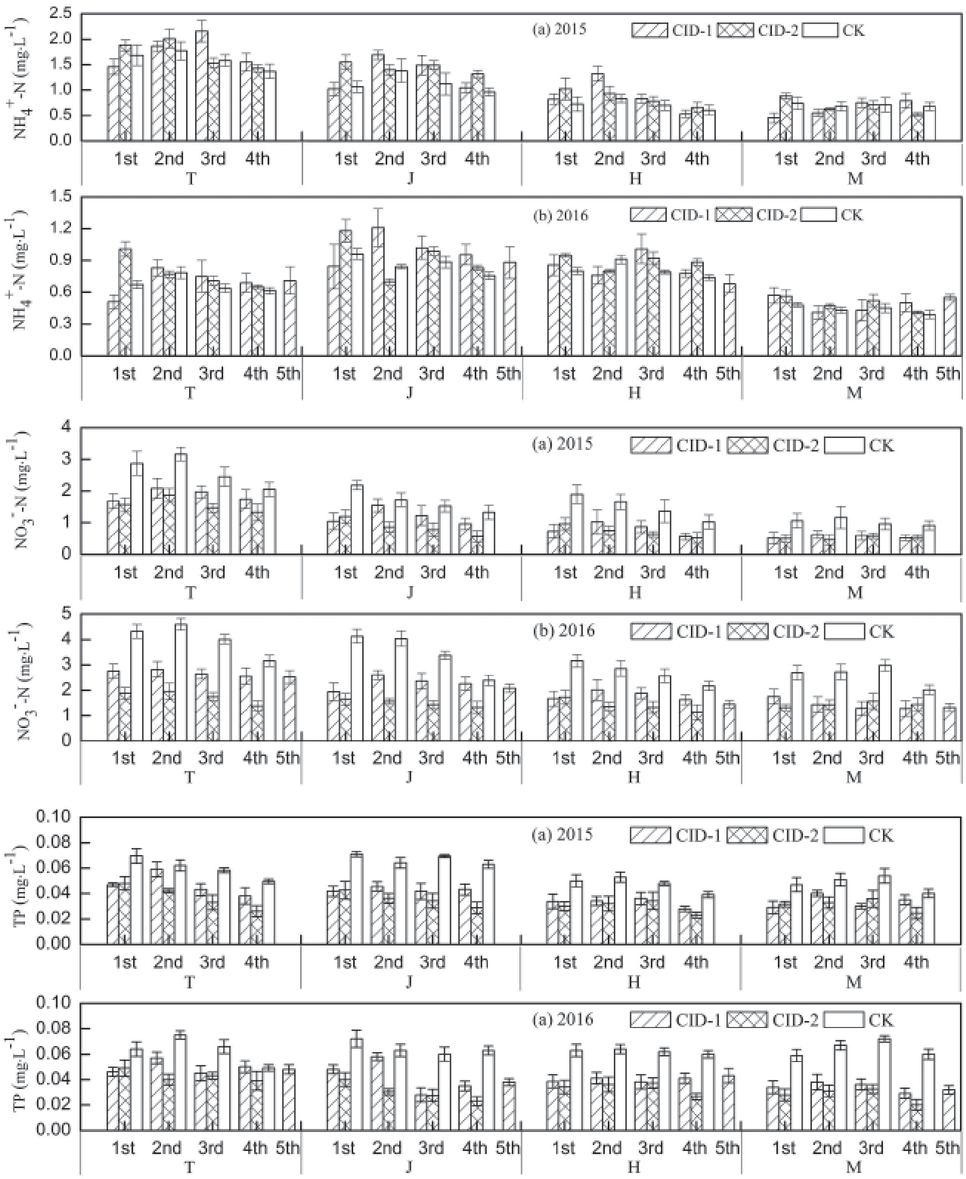

Fig. 4. Changes of NH_4^+-N, NO_3^--N, and TP concentrations in subsurface water under CID and AWD in 2015 a) and 2016 b). For CID-1, 1st and 5th means concentration in the end of drought and flooding day, and 2nd, 3rd, and 4th means concentration on the first, third, and fifth day of flooding. For CID-2, 1st, 2nd, and 3rd means concentration on the first, third, and fifth day of flooding, and 4th means concentration in the end of drought. For AWD, 1st, 2nd, 3rd, and 4th means concentration at once every other day during one wetting and drying cycle. T, J, H, and M represent tillering stage, jointing-booting stage, heading-flowering stage, and milky stage, respectively.

ammonium molybdate spectrophotometric methods using a Shimadzu UV-2800 spectrophotometer. The possible losses from surface water were calculated by multiplying the concentration and the excessive allowable water depth. The losses via subsurface water were calculated by multiplying the water leakage volume between the two dates and the concentration in the sample taken on a later day.

Statistical Analysis

Statistical analysis was carried out using the standard procedures on a randomized plot design (SPSS 19.0). The method of t-text was used to evaluate the difference of measured variables at the 0.05 probability level. Significance was calculated based on least significance (LSD) test at the 0.05 probability level. The chart in this study was drawn using the software of origin 8.0.

Results

Water Table Depth and Paddy Yields

Water table depth fluctuations, typical irrigation volumes, and drainage volumes of treatments in 2015 and 2016 are shown in Fig. 2. Irrigation and drainage events caused the tank water depth to rise or drop. Duration

Table 3. Evapotranspiration (ET), paddy fields, and water use efficiency (WUE) for CID-1, CID-2, and AWD.

Treatment	2015			2016		
	ET (mm)	Yields (kg ha^{-1})	WUE (kg m^{-3})	ET (mm)	Yields (kg ha^{-1})	WUE (kg m^{-3})
CID-1	631^a	6954^c	1.12^c	644^a	6678^c	1.04^b
CID-2	539^a	7680^b	1.42^b	584^a	7246^b	1.24^b
AWD	493^a	8310^a	1.68^a	540^a	8126^a	1.50^a

Note: Means followed by the same letter (a, b, c) do not differ significantly at the 5% level by LSD.

without water level conditions for CID-1, CID-2, and AWD treatments was 26, 38, and 35 days in 2015 and 27, 45, and 40 days in 2016, respectively. Effective irrigation quantities (calculated by subtracting total drainage volumes from total irrigation volumes) for CID-1 and CID-2 were 1.54 and 1.40 times higher in 2015, and 1.30 and 1.13 times higher in 2016 than AWD, respectively. For CID-1 and CID-2, evapotranspiration (ET) was increased by 28.0% and 9.4% in 2015, and 19.3% and 8.2% in 2016 compared to AWD, respectively. However, compared with AWD, the grain yields under CID-1 and CID-2 were decreased by 13.8% and 6.8% across two years, and water use efficiency (WUE) was significantly reduced by 36.4% and 13.9%, respectively (Table 3).

Nitrogen and Phosphorus Concentrations and Losses in Surface Water

The changes of NH_4^+-N, NO_3^--N, and TP concentrations in the surface water of paddy fields under CID in 2015 (a) and 2016 (b) are shown in Fig. 3. During the four growth stages of water control, NH_4^+-N, NO_3^--N, and TP concentrations under CID reached the peak in the first day of flooding and then dropped to stable values as flooding times went on, except that NH_4^+-N concentration under CID-2 at the tillering stage obtained peak value in the third flooding day. NH_4^+-N, NO_3^--N, and TP concentrations of CID-1 treatment in the first flooding day at four growth stages for CID-1 treatment were higher than of CID-2 treatment (34.0%, 24.1%, 10.1%, and 11.2% higher in 2015, and 67.2%, 22.3% , 5.5%, and 3.7% higher in 2016 for NH_4^+-N; 17.6%, 25.6%, 19.5%, and 11.3% higher in 2015, and 29.4%, 26.6%, 19.4%, and 5.1% higher in 2016 for NO_3^--N; and 16.3%, 19.4%, 19.1%, and 10.2% higher in 2015, and 14.2%, 11.5%, 10.4%, and 11.4% higher in 2016 for TP). Possible losses of NH_4^+-N, NO_3^--N, and TP on the fifth day of flooding for CID-1 treatment were higher than for CID-2 treatment at each growth stage in two years. However, for NH_4^+-N and TP significant differences ($P<0.05$) only existed at the tillering and jointing-booting stages, yet for NO_3^--N significant differences were observed at the former three growth stages (Table 4).

Nitrogen and Phosphorus Concentrations and Losses in Subsurface Water

The changes of NH_4^+-N, NO_3^--N, and TP concentrations in subsurface water under CID and AWD in 2015 (a) and 2016 (b) are shown in Fig. 4. For CID-1 treatment at each growth stage, NH_4^+-N, NO_3^--N, and TP concentrations in the first flooding day showed higher values than at the end of drought control. Changes in NH_4^+-N, NO_3^--N, and TP concentrations for CID-1 during the flooding period showed a decreased trend except for NH_4^+-N concentrations at the milky stage, which presented an upward trend. The changes of NH_4^+-N, NO_3^--N, and TP concentrations for CID-2 and AWD varied in similar patterns. During four growth stages of water control, NH_4^+-N, NO_3^--N, and TP concentrations

Table 4. Nitrogen and phosphorus possible losses by surface drainage at the fifth flooding day during the four growth stages in 2015 and 2016.

Form of N and P	Treatments	2015				2016			
		T	J	H	M	T	J	H	M
NH_4^+-N (g ha^{-1})	CID-1	335^a	492^a	256^a	135^a	327^a	575^a	163^a	249^a
	CID-2	230^b	435^b	239^a	128^a	228^b	369^b	147^a	216^a
NO_3^--N (g ha^{-1})	CID-1	64^a	80^a	55^a	31^a	34^a	51^a	30^a	29^a
	CID-2	50^b	59^b	43^b	32^a	27^b	39^b	21^b	27^a
TP (g ha^{-1})	CID-1	51^a	72^a	48^a	41^a	56^a	60^a	33^a	44^a
	CID-2	39^b	61^b	46^a	46^a	41^b	45^b	32^a	40^a

Note: T, J, H, and M refer to the tillering, jointing-booting, heading-flowering, and milky stages, respectively. Means followed by the same letter (a,b) do not differ significantly at the 5% level by t test.

Table 5. Nitrogen and phosphorus losses through subsurface water leakage after five days flooding during the four growth stages in 2015 and 2016.

Form of N and P	Treatments	2015				2016			
		T	J	H	M	T	J	H	M
NH_4^+-N ($g\ ha^{-1}$)	CID-1	185.6[a]	80.8[a]	135.0[a]	72.6[a]	74.2[a]	103.2[a]	86.7a	45.4a
	CID-2	179.2[a]	88.8[a]	146.6[a]	71.2[a]	83.4[a]	92.6[a]	87.8a	50.8a
	CK	167.6[a]	75.7[a]	121.2[a]	70.4[a]	70.4[a]	88.2[a]	84.0[a]	46.8[a]
NO_3^--N ($g\ ha^{-1}$)	CID-1	208.8[b]	118.1[b]	77.6[b]	56.8[b]	264.0[b]	236.4[b]	180.5[b]	131.2[b]
	CID-2	164.5[c]	89.4[c]	74.4[b]	51.6[b]	185.2[c]	152.6[c]	141.9[b]	146.3[b]
	CK	301.6[a]	151.6[a]	158.6[a]	104.0[a]	563.9[a]	488.3[a]	310.1[a]	281.8[a]
TP ($g\ ha^{-1}$)	CID-1	4.42[b]	4.30[b]	3.23[b]	3.40[b]	4.94[b]	3.88[b]	3.99[b]	3.18[b]
	CID-2	3.96[b]	3.65[b]	3.25[b]	3.37[b]	4.32[b]	3.12[b]	3.62[b]	3.09[b]
	CK	6.20[a]	6.76[a]	5.04[a]	5.14[a]	6.92[a]	6.36[a]	6.31[a]	6.74[a]

Note: T, J, H, and M refer to the tillering, jointing-booting, heading-flowering, and milky stages, respectively. Means followed by the same letter (a,b) do not differ significantly at the 5% level by t test.

for CID-2 and AWD reached peak at the first or third flooding day before dropping to a stable value, whereas that of NO_3^--N at the tillering stage and TP at the heading-flowering and milky stages showed a slightly increased trend.

Table 5 shows N and P losses through subsurface water leakage after five days of flooding at four growth stages in two years. The losses of NH_4^+-N from CID-1 and CID-2 treatments at four growth stages were increased on average by 8.0% and 9.8%, 11.9% and 10.3%, 7.3% and 12.7%, and 2.3% and 7.3% for two years, respectively, whereas no significant differences were observed among them compared with the AWD treatments. The losses of NO_3^--N for CID-1 and CID-2 treatments during the four growth stages were significantly reduced on average by 35.6% and 49.3%, 44.3% and 56.3%, 33.7% and 48.9%, and 49.9% and 49.7% for two years, respectively. However, significant differences in NO_3^--N losses were only observed at the tillering and jointing-booting stages. The losses of TP from CID-1 and CID-2 treatments at four growth stages on average for two years were significantly reduced by 28.7% and 37.0%, 37.6% and 48.4%, 36.3% and 39.0%, and 43.4% and 44.2%, respectively, compared to the AWD. No significant difference for the losses of TP was discovered between CID-1 and CID-2 treatments at four growth stages in two years.

Discussion

In South China, paddy-growing season coincides with the rainy season. For AWD management, rainfall use efficiency is not very favorable due to the low storage ability of rainfall. Meanwhile, high nutrient losses may be found in drainage water through the root zone, as a result of intense rainfall, regardless of organic or mineral [23]. Controlled irrigation and drainage (CID) can retain higher water depths after concentrated rainfall or extreme rainstorms and keep lower drainage, which leads to periods of alternating drought and flooding during rice growth. Researches on water use and N and P losses under CID are important for improving the ability of water savings and reducing non-point source pollution.

Effect on Water Use

Research on AWD confirmed that high water-saving potential does exist [24-25]. However, rainwater harvesting, storage, and use for AWD were significantly lower than CID due to the lower-field water depth [26]. Similar observations were made in the present study, and CID treatment improved the effective irrigation volumes and reduced irrigation frequencies over AWD, which means that efficient use of rainwater is improved and drainage pressure of paddy fields is reduced. Water use efficiency for paddy fields is mainly determined by the ratio of evapotranspiration-to-grain yield. Research has demonstrated that long depths of standing water in paddy fields would lead to high water evaporation [27], which was similar with our conclusion that ET under CID treatments was higher than AWD – especially for the CID-1 treatment. Meanwhile, CID treatment with severe soil drying and long periods of flooding led to heavier yield losses than AWD treatment, which might be explained by various anatomical changes in plants [28]. Therefore, WUE under CID was lower than AWD, which is not economic for farmers even if with improved available irrigation, rainwater harvesting, and reduced irrigation frequencies.

Effect on the N and P Losses in Surface Water

Many studies have suggested that N and P losses in drainage water are closely related to water management.

Yoshinaga et al. showed that less irrigation water with a low percolation flux in paddy fields can keep runoff N low [29]. Lu et al. reported that N concentrations in surface water and N runoff losses decline with the persistence of a flooding condition, which was overall consistent with the founding of CID in our study [15]. However, as we have found, NH_4^+-N concentrations under CID at tillering and milky stages slightly increased at the end of flooding, which might be caused by the lower absorbing ability of plants at that period and the limited nitrification process. When paddy soil remained a drought environment for a period of time, the aboveground biomass and N accumulation were significantly higher than that experienced in a period of flooding time [30]. As a consequence, N and P concentrations at the flooding day for CID-1 were higher than CID-2. This phenomenon also explains that the possible losses of NH_4^+-N and NO_3^--N for CID-1 at the fifth flooding day were higher than CID-2 treatment. Similarly, Gao et al. had reported that the mean concentrations of NH_4^+-N, NO_3^--N, and TP in FDTF (first drought then flooding) for the single growth stage of paddy were significantly higher than in FFTD (first flooding then drought) [22]. Therefore, the drought period followed by irrigation or rainfall increased the risk of N and P losses. Optimum drainage time should be selected according to the changes in N and P concentrations. However, previous studies found that NH_4^+-N and TP concentrations mainly corresponded with fertilizer application, whereas that of NO_3^--N was mostly attributed to water depth change [31-32]. The alternate drought and flooding process can form a protective film on the soil surface, which causes the disturbance by irrigation or rainfall at the next growth stage to be lower than the previous stages [8]. Thus, in our experiments CID-2 can significantly reduce the possible losses of NH_4^+-N and TP at the fertilizer application period and significantly cut down possible losses of NO_3^--N at the former three growth stages compared with CID-1. Meanwhile, the discrepancy of N and P concentrations at the first flooding day between CID-1 and CID-2 gradually decreased at four growth stages.

Effects on N and P Losses in Subsurface Water

Soil cracks formed in paddy fields under drought stress may be the main routes of preferential flow, which can improve the velocity and volume of N and P transport to the subsoil and the groundwater [33-34]. As a result, CID-1 treatment enhanced N and P concentrations at the first re-flooding day and improved the risk of leaching losses. Alternating wetting and drying changes the anaerobic environment caused by continuous flooding and accelerates the nitrification process, which improved the consumption of NH_4^+-N and expedite NO_3^--N loading to the groundwater [10]. On the other hand, the retardation factor and dynamic adsorption capacity for NO_3^- are lower than those for NH_4^+ ions, and the migration velocity of NH_4^+ in the subsoil is very small [35]. Thus the average NH_4^+-N concentrations from CID and AWD treatments at four growth stages for two years are kept on lower and stable values than NO_3^--N concentrations, and the leaching losses of NH_4^+-N were not significantly different in AWD and CID. Furthermore, in the present study CID can significantly reduce the leaching losses of NO_3^--N compared with AWD, which was also confirmed by Katsura et al. that the losses of NO_3^--N in percolation water under AWD were significantly higher than a period of flooding treatment [30]. Moreover, CID-2 treatment significantly reduced the leaching losses of NO_3^--N compared to CID-1 at the former two stages, whereas no significant difference was found at other stages. This is because the drought period before irrigation can accumulate NO_3^--N and easily transport NO_3^--N to the subsoil after irrigation, especially for the former growth stages that corresponded to the possible losses of NO_3^--N in surface water. Flooding conditions created anaerobic conditions with the reduction of Fe^{3+} to Fe^{2+}, which increased the release of P into the soil solution. Tang et al. mentioned that the threshold value of eutrophication induced by P in paddy fields of water was 0.05 mg/L [36]. Xiao et al. had demonstrated that P leaching can take place and may give rise to eutrophication, particularly in the latter day of flooding [19], which was consistence with our research. However, fluctuations in TP concentration under CID and AWD treatments were not obvious, which may due to the stronger adsorption ability of soil, which limited the migration of P [37]. In addition, compared to AWD, CID treatment can significantly reduce the leaching losses of TP, whereas no significant difference was found between CID-1 and CID-2. Higher irrigation for CID played a dilution effect in the subsurface water compared to AWD, and no distinction for subsurface water leakage among them was observed.

Conclusions

Although the effective irrigation quantities for CID-1 and CID-2 were 1.54 and 1.40 times higher in 2015 and 1.30 and 1.13 times higher in 2016, respectively, water use efficiency significantly decrease compared with AWD. During four growth stages of water control, N and P concentrations in surface water at the first flooding day for CID-1 were higher than CID-2, while the discrepancy gradually decreased. Moreover, the possible losses of NH_4^+-N and TP for CID-1 on the fifth day of flooding were significantly higher than for CID-2 during the fertilizer application period, whereas significant differences for NO_3^--N losses were observed at the former three growth stages. Fluctuation ranges of NH_4^+-N, NO_3^--N, and TP concentrations were lower in subsurface water. Compared to AWD, CID treatments can significantly reduce the leaching losses of NO_3^--N and TP, whereas no significant difference for the leaching losses of NH_4^+-N were observed. CID-1 significantly increased the leaching losses of NO_3^--N at the former two stages over CID-2, but no significant difference was found at the leaching losses of NH_4^+-N and TP. Under CID, the main losses of N in surface water were derived from NH_4^+-N, whereas in subsurface water, NO_3^--N was the main loss form of N. Therefore, the present study has provided a platform for farmers to choose optimum drainage time and reasonable drainage method.

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