Experimental study on water-saving and emission-reduction effects of controlled drainage technology

Meng-hua Xiao*, Xiu-jun Hu, Lin-lin Chu

Research Center of Fluid Machinery Engineering and Technology, Jiangsu University, Zhenjiang 212013, PR China

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Abstract

Field experiments and laboratory analysis were carried out to determine the effects of controlled drainage (CTD) and conventional drainage (CVD) technologies on drainage volume, concentrations of NH$_4^+$-N, NO$_3^-$-N, and total phosphorus (TP), nitrogen and phosphorus losses, rice yield, and water utilization efficiency. Results show that CTD technology can effectively reduce drainage times and volume; NH$_4^+$-N, NO$_3^-$-N, and TP concentrations, from the first to the fourth day after four rainstorms decreased by 28.7%–46.7%, 37.5%–47.5%, and 22.7%–31.2%, respectively, with CTD. These are significantly higher rates of decrease than those observed with CVD. CTD can significantly reduce nitrogen and phosphorus losses in field drainage, compared with CVD; the reduction rates observed in this study were, respectively, 66.72%, 55.56%, and 42.81% for NH$_4^+$-N, NO$_3^-$-N, and TP. Furthermore, in the CTD mode, the rice yield was cut slightly. In the CVD mode, the water production efficiencies in unit irrigation water quantity, unit field water consumption, and unit evapotranspiration were, respectively, 0.85, 0.48, and 1.22 kg/m$^3$, while in the CTD mode they were 2.91, 0.84, and 1.61 kg/m$^3$—in other words, 3.42, 1.75, and 1.32 times those of CVD. Furthermore, the results of analysis of variance (ANOVA) show that the indicators in both the CVD and CTD modes, including the concentrations of NH$_4^+$-N, NO$_3^-$-N, and TP, the losses of NH$_4^+$-N, NO$_3^-$-N, and TP, irrigation water quantity, and water consumption, showed extremely significant differences between the modes, but the rice yield showed no significant difference.

Keywords: Controlled drainage; Nitrogen; Phosphorus; Rice yield; Drainage volume; Water utilization efficiency

1. Introduction

To ease the tension between supply and demand of water resources, water-saving irrigation techniques for paddy fields were widely investigated (Tabbal et al., 2002; Belder et al., 2004). As China is the largest producer and consumer of synthetic fertilizers in the world, large amounts of nitrogen have entered its water bodies through various means, resulting in water eutrophication in China (Li et al., 2008; Chirinda et al., 2010). However, paddy fields can achieve the effect of water purification through maintenance of a proper water level for a certain number of days after fertilization, pollutant control, and heavy rain. Therefore, controlled drainage (CTD) technology for paddy fields has attracted attention of researchers (Wesström et al., 2001), and been a focus of study for agricultural water environment protection. This technology can effectively improve the utilization efficiency of irrigation water and water productivity (Zhang et al., 2003), ease the tension between supply and demand of water resources, reduce nitrogen and phosphorus losses from paddy fields, improve the water environment, maintain the nutrient cycle of paddy fields, improve the utilization efficiency of rainfall,

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* Corresponding author.
E-mail address: menghuaxiao@aliyun.com (Meng-hua Xiao).
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effectively reduce the concentrations of nitrogen and phosphorus in drainage, and maintain the yield (Peng et al., 2009; Li et al., 2008).

With the development of the theory and practice of modern irrigation and drainage technology, people have fully realized that it would be more conducive to improving the efficiency of rice production by combining water-saving irrigation with CTD (Peng et al., 2011; Xiao et al., 2013). Through the combination of existing water-saving irrigation and CTD theories for paddy rice, an irrigation-drainage technology that saves water, reduces emissions, and generates a high yield can be developed. Based on its characteristics as a semi-aquatic plant, we can make full use of the stress of drought and, especially, water-logging on rice to coordinate the stress degree (Xiao et al., 2012). While the lower irrigation limit is maintained, appropriately increasing the upper rain water storage limit can make full use of rainfall, thus reducing the irrigation quota as well as nitrogen and phosphorus loads (Yu et al., 2002). While meeting the requirements of no significant reduction of crop yield and quality, CTD technology can also achieve the goals of saving water and reducing emissions (Ng et al., 2002; Ju et al., 2009). According to the research on the key supporting technologies of large-scale agricultural water-saving improvement projects in China, research on water-saving irrigation and CTD systems was carried out, and the results show that the water level in the paddy field can be used as an efficient irrigation and drainage indicator (Xie et al., 2007; Yang et al., 2009).

In this study, an experiment was conducted in Suqian City, in Jiangsu Province, China to further confirm the environmental effect of CTD. The aims of this study were to investigate the application of CTD technology and water level control rules in farmland experiments, to improve rice irrigation-drainage systems, to verify the water-saving and emission-reduction effects of CTD, and to provide a scientific basis for optimal design of irrigation-drainage projects in rice irrigation districts.

2. Materials and methods

2.1. Experimental site

An experiment was conducted from October 2011 to October 2012, in the Sankeshu experimental field in the Yunnan irrigation district, which is located in the Sucheng District of Suqian City, in China (Fig. 1). The experimental site has a warm temperate zone monsoon climate, with four distinct seasons and mild average temperatures. The average annual rainfall is 892.3 mm, and the average annual amount of rainfall days is 120 d, with rainfall in the main flooding season accounting for nearly 70% of the total. The average annual evaporation amount is 900 mm, the annual average temperature is 14.1°C, the highest monthly average temperature is 27.2°C, the average annual amount of sunshine hours is 2 314 h, and the annual non-frost period is 211 d. The topsoil (from 0 to 30 cm), with a pH value of 6.95, contains 2.35% of soil organic matter, 0.894 g/kg of total nitrogen (TN), 27.95 mg/kg of available nitrogen, 0.34 g/kg of total phosphorus (TP), and 12.2 mg/kg of available phosphorus.

2.2. Experimental design

The variety of rice used in the experiment was Japonica rice, according to the local custom. There were two irrigation-drainage modes, conventional drainage (CVD) and CTD. Each mode included three replications. Plastic isolating film was used at each experimental plot at 50 cm below the balk, in order to avoid water exchange. The fertilizer regime was determined according to the local custom. There were three fertilizer applications: a base fertilizer on June 25, a tillering fertilizer on July 9, and an earing fertilizer on August 10, with pure nitrogen amounts of 120, 60, and 60 kg/hm², respectively, for a total of 240 kg/hm². In addition, a total of 50 kg/hm² P₂O₅ and K₂O were applied to each mode.

Water management of a paddy field in CVD was based on local custom. The water level control indicators in CVD are shown in Table 1, while those in CTD are shown in Table 2.

2.3. Experimental mechanism and methods

In this study, the evapotranspiration for a paddy field was calculated based on the water balance principle as follows:

\[ ET_t = P_t + I_t + W_{t-1} + W_t - D_t \]  

(1)

<table>
<thead>
<tr>
<th>Growth stage</th>
<th>Upper water level limit (mm)</th>
<th>Lower water level limit (mm)</th>
<th>Allowed water depth (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regreening stage</td>
<td>30</td>
<td>10</td>
<td>50</td>
</tr>
<tr>
<td>Early tillering stage</td>
<td>30</td>
<td>0</td>
<td>50</td>
</tr>
<tr>
<td>Late tillering stage</td>
<td>0</td>
<td>0.6θ</td>
<td>0</td>
</tr>
<tr>
<td>Jointing-booting stage</td>
<td>30</td>
<td>0</td>
<td>70</td>
</tr>
<tr>
<td>Heading-flowering stage</td>
<td>30</td>
<td>0</td>
<td>70</td>
</tr>
<tr>
<td>Milking stage</td>
<td>30</td>
<td>0</td>
<td>70</td>
</tr>
</tbody>
</table>

Note: θ is the observed saturated water content of soil bulk in the root zone.
where $ET$ is the evapotranspiration (mm); $P$ is the precipitation (mm), which was recorded daily by an automatic weather station in the experiment; $I$ is the irrigation water quantity (mm), which was recorded with water meters installed on the pipes in each plot; $W$ is the flooding depth or the soil water content in the root zone (mm), with the soil water content measured with a time domain reflectometer (TDR) in this study, and the flooding depth measured with a vertical ruler; $t$ represents the day of measurement; and $D$ represents the drainage volume or the underlying root leakage (mm). Since the bottom of each lysimeter was closed with concrete, surrounded by an impervious isolation board, the underlying root leakage was not considered in this study.

The losses of NH$_4^+$-N, NO$_3^-$-N, and TP were mass concentrations of NH$_4^+$-N, NO$_3^-$-N, and TP of each mode discharged from surface water at the end of flooding. The values were set to 0 if the water level was below the lower water level limit; the value was set to the exceeded amount if the water level was higher than the lower water level limit. Water samples were collected in polyethylene bottles. The surface water was collected randomly with a 50 mL syringe, without disturbing the soil. All bottles were rinsed first, and then the appropriate amount of water was sampled. The NH$_4^+$-N, NO$_3^-$-N, and TP concentrations of the water samples were analyzed using a Shimadzu UV-2800 spectrophotometer. The NH$_4^+$-N concentration was determined with the Nessler’s reagent colorimetric method, the NO$_3^-$-N concentration was determined with the UV spectrophotometry method, and the TP concentration was measured in the unfiltered samples with the indophenol blue method.

2.4. Statistical analysis

A $t$-test was used to evaluate the differences in measured variables from different plots. The software package SPSS 16.0.0 was used for analysis of variance (ANOVA).

3. Results and discussion

3.1. Field drainage volume in different irrigation-drainage modes

Water was drained through the drainage exit when the rainfall exceeded the allowed water depth, according to the highest water depth in field surface. The drainage dates and volumes in different irrigation-drainage modes are shown in Table 3. There was only one controlled drainage in CTD, but five in CVD in 2012, owing to heavy rainfall and rainfall concentration. In 2012, the total rainfall was 720.6 mm, and there were four rainstorms (larger than 50 mm in 24 h), which resulted in field drainage. Table 3 also shows that the total drainage volume in the CTD mode was 6.60 mm, which was far below that in CVD (59 mm) and accounted for 11.19%. This shows that the CTD mode can improve the rainfall utilization efficiency.

3.2. Changes of NH$_4^+$-N concentration in field drainage

NH$_4^+$-N concentrations in different drainage modes after four rainstorms are shown in Fig. 2. On the first day after rainstorms, the NH$_4^+$-N concentration in CVD was higher than that in CTD. This was mainly because the allowed water depth in the CTD mode was higher than that in CVD. The NH$_4^+$-N concentration in CVD after each rainstorm showed a trend of first decreasing and then increasing, which was mainly because the field water level decreased gradually in CVD, resulting in the NH$_4^+$-N concentration rising again on the fourth day after rainstorms, while in CTD the NH$_4^+$-N concentration decreased day by day, which showed that the CTD mode could effectively reduce the NH$_4^+$-N concentration in drainage. The average NH$_4^+$-N concentrations of the four rainstorms in CVD were 1.53, 1.44, 1.52, and 1.28 mg/L, respectively, while in CTD they were 0.98, 1.00, 1.08, and 0.95 mg/L, accounting for 64.1%, 69.4%, 71.1%, and 74.2%, respectively, of the concentrations in CVD. Compared with the first day after the rainstorm, the NH$_4^+$-N concentration on the fourth day decreased by 16.4%, 11.0%, 10.0%, and 12.4%, respectively, in CVD. Meanwhile, in CTD the NH$_4^+$-N concentration decreased by 46.7%, 38.3%, 35.6%, and 28.7%, respectively, higher rates of decrease than those in CVD mode. This result is consistent with the study of Pierobon et al. (2013).

3.3. Changes of NO$_3^-$-N concentration in field drainage

NO$_3^-$-N concentrations in different drainage modes after four rainstorms are shown in Fig. 3. The NO$_3^-$-N concentration in each mode after a rainstorm was lower than the NH$_4^+$-N concentration after the rainstorm. On the first day after a rainstorm, the NO$_3^-$-N concentration in CVD was higher than that in CTD, because the allowed water depth in CTD is higher.
Fig. 2. Changes of NH$_4^+$-N concentration in different drainage modes after four rainstorms.

Fig. 3. Changes of NO$_2^-$-N concentration in different drainage modes after four rainstorms.
than that in CVD. The NO$_3^-$-N concentration after each rainstorm showed a trend of first decreasing and then increasing, to a level even higher than that on the first day. This is because the field water level in CVD decreased gradually, resulting in the rising of the NO$_3^-$-N concentration. Meanwhile, in CTD the NO$_3^-$-N concentration decreased continuously, indicating that CTD can effectively reduce the NO$_3^-$-N concentration in drainage. In the four rainstorms, the average NO$_3^-$-N concentrations in CVD were 1.11, 1.09, 1.04, and 0.94 mg/L, respectively, while in CTD they were 0.74, 0.73, 0.65, and 0.61 mg/L, respectively, only 66.7%, 73.7%, 62.5%, and 64.9% of the concentrations in CVD, respectively. Compared with the first day, the NO$_3^-$-N concentration in CVD decreased by 3.4% and increased by 1.9%, 5.6%, and 6.3%, respectively, on the fourth day, for the four rainstorms. Meanwhile, in CTD the NO$_3^-$-N concentration decreased by 37.5%, 37.9%, 40.0%, and 47.5%, respectively; the reduction was significant, which means that CTD technology can purify water and reduce the NO$_3^-$-N concentration significantly, thus reducing agricultural non-point source pollution. This result is consistent with the study of Kröger et al. (2012), which showed that extending the residence time of the surface water in the gutter can significantly reduce the NO$_3^-$-N load to the downstream drainage system, and the reduction rate may reach 79%.

3.4. Changes of TP concentration in field drainage

TP concentrations in different drainage modes after four rainstorms are shown in Fig. 4. On the first day after a rainstorm, the TP concentration in CVD was higher than that in CTD. This was mainly because the allowed water depth in CTD was higher. In CVD, after a rainstorm, the TP concentration showed a trend of first decreasing and then increasing, to a level even higher on the fourth day than on the first day after a rainstorm. This is due to the fact that the water level in CVD gradually decreased, resulting in the rising of the TP concentration. Meanwhile, in CTD, the TP concentration decreased day by day, showing that CTD can reduce the TP concentration in drainage. For the four rainstorms, the average TP concentrations in CVD were 1.51, 1.63, 1.69, and 1.88 mg/L, respectively, while in CTD they were 1.23, 1.20, 1.22, and 1.24 mg/L, respectively, only 81.5%, 73.6%, 72.1%, and 66.0% of the respective concentrations in CVD. Compared with the first day after rainstorm, the TP concentration on the fourth day in CVD decreased by 8.3% and 3.4%, respectively, for the first and second rainstorms, but increased by 8.8% and 7.2% for the third and fourth rainstorms, while in CTD the TP concentration decreased by 22.7%, 28.4%, 24.3%, and 31.2%, respectively, across the four rainstorms, showing a significant decrease.

3.5. Nitrogen and phosphorus losses

Nitrogen and phosphorus losses in different drainage modes were investigated in this experiment. The results show that NH$_4^+$-N was the main form of nitrogen losses in both drainage modes, while NO$_3^-$-N contributed a little. In CVD, the average NH$_4^+$-N loss was 5.80 kg/hm$^2$, accounting for 53.70% of nitrogen losses, while in CTD it was 1.93 kg/hm$^2$, accounting for 53.61%. This was 3.87 kg/hm$^2$ lower than the loss in CVD, a reduction rate of 66.72%. In CVD, the average NO$_3^-$-N loss was 0.63 kg/hm$^2$, accounting for 5.83% of TN, while in CTD it was 0.28 kg/hm$^2$, accounting for 7.78%. This was 0.35 kg/hm$^2$ lower than the loss in CVD, a reduction rate of 55.56%. The NH$_4^+$-N loss in paddy field drainage was affected by the fertilizer level and irrigation management mode; at a given fertilizer level, CTD can effectively reduce the NH$_4^+$-N loss in a paddy field. The NO$_3^-$-N loss was rather low, which was mainly due to the low NO$_3^-$-N content in the paddy field soil. The NO$_3^-$-N concentration in drainage was mainly from what remained from the wheat-growing season, rainfall, and irrigation. In the rice-growing season, the NO$_3^-$-N content was lower, and this was mainly because the paddy field was flooding and soil had a low oxygen content, low levels of nitrifying bacteria activity, and a low nitrification rate, resulting in a small portion of nitrogen fertilizer converting to NO$_3^-$-N after converting to NH$_4^+$-N. Phosphorus runoff loss was one of the main losses in the paddy field, another important reason for eutrophication. In this experiment, the average TP loss in CVD was 2.85 kg/hm$^2$, accounting for 5.70% of the phosphorus fertilizer input, while in CTD it was 1.63 kg/hm$^2$, accounting for 3.26%. This was 1.22 kg/hm$^2$ lower than the loss in CVD, a reduction rate of 42.81%. Thus, CTD can significantly reduce TP losses in field drainage. Phosphorus fertilizer was always applied as base fertilizer. At that time, rice had not yet become green, and the root had low phosphorus absorption ability. If a rainstorm or drainage occurred, the phosphorus loss was huge. Thus during the first week after base fertilizer application, field drainage should be avoided in order to reduce the phosphorus loss. Fractionated fertilization may be used to reduce the TP concentration in field drainage to reduce phosphorus runoff loss.

3.6. Rice yield and water utilization efficiency changes

Rice production is the ultimate goal of rice cultivation; water-saving and reduction of nitrogen and phosphorus losses cannot occur at the expense of the rice yield. Reasonable irrigation-drainage modes and fertilizer management practices will play an important role in maximizing the water and fertilizer utilization efficiencies. Therefore, analysis of indicator systems of different irrigation techniques on rice yield is important. The rice yield and water utilization efficiency in different drainage modes are shown in Table 4. In CVD, the rice yield was 7.143.6 kg/hm$^2$, while in CTD it was 6.856.4 kg/hm$^2$. The rice yield decreased slightly in CTD (4.0%). This was mainly because of different years, regions, or varieties.

According to final rice yield, the water utilization efficiency in a paddy field was calculated using irrigation amount, water consumption, and evapotranspiration throughout the growth stage (Table 4). It is found that the unit irrigation water quantity, unit water consumption, and unit evapotranspiration in CTD were significantly lower than in CVD. In CVD
2012, the water utilization efficiencies for unit irrigation water quantity, unit water consumption, and unit evapotranspiration \( (E_{IR}, E_{WU}, \text{and } E_{ET}) \) respectively, were 0.85, 0.48, and 1.22 kg/m\(^3\), while in CTD they were 2.91, 0.84, and 1.61 kg/m\(^3\), respectively, about 3.42, 1.75, and 1.32 times those in CVD. This shows that CTD technology can reduce water consumption, improve water utilization efficiency, ensure rice yield, and realize efficient use of water resources.

Reasonable soil water control using CTD technology can not only reduce irrigation times and irrigation amount, but also promote the growth of rice roots, significantly reduce surface evaporation and field leakage, effectively reduce transpiration of the rice plant, and realize water saving.

### 3.7. ANOVA in CVD and CTD modes

The ANOVA results for each indicator of the CVD and CTD modes are shown in Table 5. The indicators in the CVD and CTD modes of the concentrations of \( NH_4^+ -N, NO_3^- -N, \) and TP, the losses of \( NH_4^+ -N, NO_3^- -N, \) and TP, irrigation water quantity, and water consumption showed extremely significant differences, but the rice yields in the CVD and CTD modes showed no significant difference from one another. This indicates that, although the rice yield decreased slightly in the CTD mode, the concentrations of \( NH_4^+ -N, NO_3^- -N, \) and TP, the losses of \( NH_4^+ -N, NO_3^- -N, \) and TP, irrigation water quantity, and water consumption were effectively reduced.

### Table 4

Rice yield and water utilization efficiency in different drainage modes.

<table>
<thead>
<tr>
<th>Drainage mode</th>
<th>Rice yield (kg/hm(^2))</th>
<th>Unit irrigation water quantity (mm)</th>
<th>Unit water consumption (mm)</th>
<th>Unit evapotranspiration (mm)</th>
<th>( E_{IR} ) (kg/m(^3))</th>
<th>( E_{WU} ) (kg/m(^3))</th>
<th>( E_{ET} ) (kg/m(^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>CVD</td>
<td>7 143.6</td>
<td>840.3</td>
<td>1 473.4</td>
<td>584.3</td>
<td>0.85</td>
<td>0.48</td>
<td>1.22</td>
</tr>
<tr>
<td>CTD</td>
<td>6 856.4</td>
<td>235.6</td>
<td>814.5</td>
<td>425.7</td>
<td>2.91</td>
<td>0.84</td>
<td>1.61</td>
</tr>
</tbody>
</table>

### Table 5

ANOVA results for each indicator in CVD and CTD modes.

<table>
<thead>
<tr>
<th>Influencing factor</th>
<th>( F )</th>
<th>( P )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( NH_4^+ -N ) concentration</td>
<td>41.62</td>
<td>3.97 ( \times 10^{-7} )</td>
</tr>
<tr>
<td>( NO_3^- -N ) concentration</td>
<td>52.98</td>
<td>4.19 ( \times 10^{-7} )</td>
</tr>
<tr>
<td>TP concentration</td>
<td>40.31</td>
<td>5.28 ( \times 10^{-7} )</td>
</tr>
<tr>
<td>( NH_4^+ -N ) loss</td>
<td>14.22</td>
<td>2.02 ( \times 10^{-3} )</td>
</tr>
<tr>
<td>( NO_3^- -N ) loss</td>
<td>6.90</td>
<td>1.15 ( \times 10^{-3} )</td>
</tr>
<tr>
<td>TP loss</td>
<td>6.58</td>
<td>1.19 ( \times 10^{-3} )</td>
</tr>
<tr>
<td>Irrigation water quantity</td>
<td>697.34</td>
<td>1.23 ( \times 10^{-7} )</td>
</tr>
<tr>
<td>Water consumption</td>
<td>102.51</td>
<td>5.67 ( \times 10^{-6} )</td>
</tr>
<tr>
<td>Rice yield</td>
<td>0.78</td>
<td>0.45</td>
</tr>
</tbody>
</table>

Note: \( P \) is the test level (\( P < 0.05 \) means significant), and \( F \) is the significant difference level.
4. Conclusions

(1) Under the experimental conditions, the CTD mode can effectively reduce drainage times and increase the rainfall utilization efficiency. In 2012, the CTD mode included only one drainage but the CVD mode included five times of drainage. The total drainage volume in CTD was 6.60 mm, which was far less than that in CVD.

(2) The CTD mode can effectively reduce nitrogen and phosphorus concentrations in drainage. Compared with the first day, NH$_4^+$-N, NO$_3^-$-N, and TP concentrations on the fourth day decreased by 28.7%–46.7%, 37.5%–47.5%, and 22.7%–31.2%, respectively, in CTD, significantly higher rates of decrease than those in CVD.

(3) CTD can significantly reduce nitrogen and phosphorus losses in field drainage: the average NH$_4^+$-N, NO$_3^-$-N, and TP losses decreased by 3.87, 0.35, and 1.22 kg/hm$^2$, respectively, compared with CVD, and the reduction rates were, respectively, 66.72%, 55.56%, and 42.81%. NH$_4^+$-N contributed most to the nitrogen loss, while NO$_3^-$-N contributed least.

(4) In the CTD mode, the rice yield was cut slightly. The CTD mode can not only reduce water consumption, but also improve the water utilization efficiency, ensuring economic yield of rice and realizing efficient utilization of farmland water resources.

(5) The ANOVA results showed that the indicators in both CVD and CTD modes of the concentrations of NH$_4^+$-N, NO$_3^-$-N, and TP, the losses of NH$_4^+$-N, NO$_3^-$-N, and TP, irrigation water quantity, and water consumption showed extremely significant differences between the modes, but the rice yield showed no significant difference.

(6) The results of the present study should help promote the application of the CTD technology and water level control rules in farmlands; contribute to water savings, emission reduction, high yield, and fertility conservation of paddy rice irrigation-drainage systems; verify water-saving and pollutant-reduction effects of CTD; and provide a scientific basis for optimization of irrigation-drainage project design in rice irrigation districts.

References


