Nitrogen and phosphorus changes and optimal drainage time of flooded paddy field based on environmental factors

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Abstract: While many controlled irrigation and drainage techniques have been adopted in China, the environmental effects of these techniques require further investigation. This study was conducted to examine the changes of nitrogen and phosphorus of a flooded paddy water system after fertilizer application and at each growth stage so as to obtain the optimal drainage time at each growth stage. Four treatments with different water level management methods at each growth stage were conducted under the condition of ten-day continuous flooding. Results show that the ammonia nitrogen (4NH$_4^+$-N) concentration reached the peak value once the fertilizer was applied, and then decreased to a relatively low level seven to ten days later, and that the nitrate nitrogen (3NO$_3^-$-N) concentration gradually rose to its peak value, which appeared later in subsurface water than in surface water. Continuous flooding could effectively reduce the concentrations of 4NH$_4^+$-N, NO$_3^-$-N, and total phosphorus (TP) in surface water. However, the paddy water disturbance, in the process of soil surface adsorption and nitrification, caused NH$_4^+$-N to be released and increased the concentrations of NH$_4^+$-N and NO$_3^-$-N in surface water. A multi-objective controlled drainage model based on environmental factors was established in order to obtain the optimal drainage time at each growth stage and better guide the drainage practices of farmers. The optimal times for surface drainage are the fourth, sixth, fifth, and sixth days after flooding at the tillering, jointing-booting, heading-flowering, and milking stages, respectively.

Key words: ammonia nitrogen; nitrate nitrogen; phosphorus; optimal drainage time; flooded paddy field

1 Introduction

China is one of the largest producers and consumers of synthetic fertilizers in the world. Its partial factor productivity from applied nitrogen fertilizer decreased from 55.0 kg/hm$^2$ in 1997 to 20.0 kg/hm$^2$ in 2005 (Ju et al. 2009). The excessive use of nitrogen and phosphorus fertilizers has resulted in a large amount of nitrogen and phosphorus entering ambient water...
bodies and the atmosphere through various means (Xie et al. 2007; Li et al. 2008; Chirinda et al. 2010). Drainage is a main cause of nitrogen and phosphorus release to agricultural fields. Controlled drainage is based on the capacity of crops controlled by the construction of structures such as overflow weirs to raise the export of water drainage and to reduce emissions of water to downstream water bodies, with the aim of reducing environmental pollution and protecting the environment (Wang et al. 2003). Controlled drainage research began in the late 1970s and especially in Europe and America, focusing on research on underground pipes. Controlled drainage can play the following roles. First, it can allow soil moisture to be fully utilized by raising the water level, thereby reducing the frequency of irrigation and the pressures on water resources. Second, it can reduce the drainage discharge through manipulation of the height of the drainage exit gates and implementation of groundwater management, and can reduce the concentrations of nitrogen and phosphorus in the drainage channel that mainly relies on crop uptake (Ng et al. 2002), nitrification-denitrification (Zhang et al. 2003), and sediment deposition (Yin et al. 2006). Lastly, it can also control the drainage of rainfall and drainage time during and after raining (Elmi et al. 2000). Thereby, it is an effective measure for improving the utilization of rainwater resources and avoiding water-logging and salinization by controlling the retention time of stormwater in the fields and drains (Boumans et al. 2005; Yang et al. 2009). A field experiment conducted by Huang et al. (2001) showed that the agricultural nitrogen loss and cumulative runoff were positively related. The paddy fields in China mainly use surface drainage systems, where the traditional drainage, namely drainage immediately through the rain, is the immediate drainage, and the losses of nitrogen and phosphorus to surface runoff are the main means of agricultural nonpoint source pollution.

Most of the existing reports on changes of nitrogen and phosphorus under the condition of controlled drainage are limited to the dry crop areas with underground pipes. The controlled drainage in dry crop-growing areas involves less rice (Evans et al. 1995; Skaggs et al. 1994). Few studies have focused on changes of nitrogen and phosphorus in a continuous flooding process at each stage of rice growth. The regions south of the Huaihe River are the major rice production areas in China, accounting for 90% of the total rice cultivation in China. These areas usually experience heavy rains or rainstorms continuously during the period of rice growth. Many areas even have serious floods. Therefore, research on the nitrogen and phosphorus dynamics in a continuous flooding process and determination of the optimal drainage time are important not only for controlling and improving the water quality, but also for decreasing the drainage water volume.

2 Materials and methods

2.1 Experimental area and soil

This experiment was conducted at the Saving-Water and Agro-Ecological experimental
plot in the Jiangning Campus of Hohai University, in Jiangsu Province, China, from 2009 to 2010. The region is a humid subtropical monsoon climate zone, with an average annual evaporation of 900 mm, a mean annual temperature of 15.4°C, and maximum and minimum air temperatures of 43.0°C and −14.0°C, respectively. The mean annual rainfall is 1041 mm, of which more than 60% occurs in the rainy season from May to September. There are 220 frost-free days per year. The soil in the area is typical permeable paddy soil, formed on the loess deposits, with loamy clay. A five-year rice-wheat rotation system is adopted in this area. There are 32 fixed lysimeter plots (28 with a closed bottom and four without a bottom) with the specifications of 2.5 m in length, 2 m in width, and 2 m in depth. The layout of the lysimeters was divided into two groups, each group containing 16 plots. Underground corridors and underground equipment rooms were built between the two groups and a mobile canopy was equipped on the ground. The irrigation system is an automatic irrigation system controlled by a host electromagnetic valve. The topsoil (0 to 30 cm) had a pH value of 6.97 in a lysimeter containing 2.40% of soil organic matter, 0.9048 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.

2.2 Experimental design

According to the characteristics of rice growth stages, the tillering, jointing-booting, heading-flowering, and milking stages were chosen for experimentation under flooding conditions with different leakage rates. Four treatments were set up in the lysimeter plots with closed bottoms, and each treatment was repeated four times during the flooding experiment. The water level was controlled to satisfy the leakage requirement via irrigation and drainage during ten days of each stage, while during the other days of each stage, the water management complied with the requirements of shallow and wetting irrigation. Water control programs in the years 2009 and 2010 are shown in Table 1. Three different inorganic fertilizers were applied at the time of seeding and during the cultivation. Only the basal fertilizers were incorporated into the surface soil and the other fertilizers were applied on the surface. The basal fertilizer was a compound fertilizer (the mass percents of nitrogen, P₂O₅, and K₂O are all 15%), and 1200 kg/hm² of the fertilizer was applied on June 13, 2009 and June 30, 2010. The tillering fertilizer was urea (with a nitrogen content of 46.4%), and 647 kg/hm² was applied on

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Water level at different stages (mm)</th>
<th>Flooding time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tillering stage</td>
<td>Jointing-booting stage</td>
</tr>
<tr>
<td>LT</td>
<td>120</td>
<td>−300-30</td>
</tr>
<tr>
<td>LH</td>
<td>−200-20</td>
<td>−300-30</td>
</tr>
<tr>
<td>LM</td>
<td>−200-20</td>
<td>−300-30</td>
</tr>
</tbody>
</table>

Note: The leakage rate was 2 mm/d during the water level control period at each growth stage.
June 28, 2009 and July 6, 2010. The panicle fertilizer was also urea (with a nitrogen content of 46.4%), with 647 kg/hm$^2$ applied on August 10, 2009 and August 7, 2010. The weed was controlled manually and pesticides were applied occasionally.

**2.3 Water sample collection and analysis**

Water samples were collected in polyethylene bottles four times during the flooding period of ten days. The surface water was collected with a 50 mL syringe randomly without disturbing the soil. All bottles were rinsed first, and then the appropriate amount of water was sampled. The subsurface water was collected with an underground drainage pipe. The ammonia nitrogen ($\text{NH}_4^+$-N), nitrate nitrogen ($\text{NO}_3^-$-N), and total phosphorus (TP) concentrations of the water samples were analyzed using a Shimadzu UV-2800 spectrophotometer. The $\text{NH}_4^+$-N concentration was determined with Nessler’s reagent colorimetric method, the $\text{NO}_3^-$-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**

The $t$-tests were used to evaluate the difference of measured variables from different plots. In addition, SPSS 16.0.0 was used for curve-fitting, and Matlab 7.0 was used for numerical analysis to establish the multi-objective controlled drainage model.

**3 Results and discussion**

**3.1 Changes of nitrogen after fertilizer application**

The $\text{NH}_4^+$-N concentration after the fertilizer application is shown in Fig. 1, where bars indicate standard errors. The $\text{NH}_4^+$-N concentrations in surface water after the tillering and panicle fertilizer applications varied in the same pattern. The maximum values were 56.3 mg/L (on June 28, 2009) and 56.0 mg/L (on July 6, 2010) after the tillering fertilizer application, and 40.2 mg/L (on August 10, 2009) and 35.5 mg/L (on August 7, 2010) after the panicle fertilizer application, which were a little bit lower than those after the tillering fertilizer application. The $\text{NH}_4^+$-N concentration in surface water decreased sharply to 4.5 mg/L (on July 5, 2009) and 1.02 mg/L (on July 13, 2010), indicating that the $\text{NH}_4^+$-N concentration decreased to a relatively lower level in a period of seven to ten days. After the application of the tillering fertilizer, the $\text{NH}_4^+$-N concentration in groundwater increased to 14.3 mg/L (on June 28, 2009) and 13.5 mg/L (on July 6, 2010). Moreover, the $\text{NH}_4^+$-N concentration maintained a relatively high level for a long period. However, after application of the panicle fertilizer, the $\text{NH}_4^+$-N concentration in groundwater remained at a relatively low level.

The $\text{NO}_3^-$-N concentration after the fertilizer application is shown in Fig. 2. As shown
Fig. 1 Changes of \( \text{NH}_4^+ \)-N concentration after fertilizer application in 2009 and 2010

Fig. 2 Changes of \( \text{NO}_3^- \)-N concentration after fertilizer application in 2009 and 2010

in the figure, the \( \text{NO}_3^- \)-N concentration ranged from 0.231 mg/L to 0.602 mg/L in 2009 and from 0.287 mg/L to 0.587 mg/L in 2010 in surface water, and from 0.109 mg/L to 0.923 mg/L.
in 2009 and from 0.075 mg/L to 0.817 mg/L in 2010 in groundwater. The $\text{NO}_3^-$-N concentration varied in the same pattern after the tillering and panicle fertilizer applications. After the tillering fertilizer application, the $\text{NO}_3^-$-N concentration increased to 0.602 mg/L on July 1, 2009 and 0.512 mg/L on July 9, 2010 in surface water, which were the peak values in surface water after the fertilizer was applied, and increased to 0.617 mg/L (on July 4, 2009) and 0.325 mg/L (on July 12, 2010) in groundwater. After the panicle fertilizer application, for the surface water, the $\text{NO}_3^-$-N concentration increased to 0.543 mg/L (on August 19) and 0.506 mg/L (on August 13), respectively, in the years 2009 and 2010. For the groundwater, the $\text{NO}_3^-$-N concentration increased to 0.923 mg/L (on August 13) and 0.817 mg/L (on August 9), respectively, in the years 2009 and 2010.

### 3.2 Changes of NH$_4^+$-N concentration in continuous flooding

Figs. 3 and 4 show the NH$_4^+$-N concentration in the years 2009 and 2010, respectively. For the surface water, the NH$_4^+$-N concentration of each treatment at different stages during the period of rice growth had a similar decreasing tendency. For the tillering stage, the NH$_4^+$-N concentration of treatment LT in surface water on the tenth day decreased by 69.3% in 2009 and 62.6% in 2010, compared with that of the first day of flooding. For the jointing-booting stage, the NH$_4^+$-N concentration of treatment LJ in surface water decreased by 49.4% and 34.1%, respectively, in 2009 and 2010. For the heading-flowering stage, the NH$_4^+$-N concentration decreased by 64.7% and 57.8%, respectively, in 2009 and 2010.
concentration of treatment LH in surface water decreased by 27.9% in 2009 and 11.5% in 2010. For the milking stage, the $\text{NH}_4^+$ concentration of treatment LM in surface water decreased by 53.1% in 2009 and 64.7% in 2010. The $\text{NH}_4^+$ concentration maintained a relatively higher level in the milking stage than in the jointing-booting and heading-flowering stages. The reason for this phenomenon was that the higher temperature had a more significant effect on the microbial activity level, promoting the decomposition of organic nitrogen and the release of nitrogen into water. Furthermore, reduction of the depth of the oxide layer due to rapid consumption of the oxygen in the water slowed down the nitrification, and accelerated the release rate of $\text{NH}_4^+$ in the sediment. The $\text{NH}_4^+$ concentration of LT in groundwater decreased by 67.2% and 67.8%, respectively, in 2009 and 2010. The $\text{NH}_4^+$ concentration of LJ and LH in groundwater changed less: it decreased by 12.6% in 2009 and 6.9% in 2010 for LJ, and decreased by 7.1% in 2009, but increased slightly by 1.7% in 2010 for LH. The $\text{NH}_4^+$ concentration of LM in groundwater decreased by 53.8% and 58.9%, respectively, in 2009 and 2010. Peng et al. (2009) studied the management system of irrigation-drainage wetlands and found that the concentrations of $\text{NH}_4^+$ decreased by 20.33% in the outlet of the drainage ditch, compared with the conventional irrigation. This result was similar to the conclusion of this study because the paddy field had similar wetland characteristics.
### 3.3 Changes of NO$_3^-$-N concentration in continuous flooding

Figs. 5 and 6 show the changes of NO$_3^-$-N concentration in 2009 and 2010, respectively. For the surface water, the NO$_3^-$-N concentration decreased gradually, except at the tillering stage in 2009 and the heading-flowering stage in 2010, when the NO$_3^-$-N concentration of treatment LT on the tenth day increased by 72.6% and 42.7%, respectively, compared with that of the first day in the years 2009 and 2010. This may have been caused by the disturbance of surface irrigation on the field surface soil. The NH$_4^+$-N adsorbed by the surface soil was re-dissolved in water, and then converted into NO$_3^-$-N by nitrification in the aerobic environment. The NO$_3^-$-N concentration decreased by 58.7% and 72.6% for treatment LJ at the jointing-booting stage, 69.9% and 60.6% for treatment LH at the heading-flowering stage, and 32.4% and 73.2% for treatment LM at the milking stage in 2009 and 2010, respectively. The reduction was caused by crop uptake, leaching of NO$_3^-$-N to the groundwater without adsorption to negatively-charged soil particles, and denitrification by denitrifying bacteria under anoxic conditions. For the groundwater, the relatively low NO$_3^-$-N concentration at the milking stage did not change significantly. The reason for this phenomenon was that the paddy field surface formed a relatively stable layer of protection, which hindered the NO$_3^-$-N from entering the groundwater. Data showed that flooding can reduce the NO$_3^-$-N concentration in surface water, but maintain the NO$_3^-$-N concentration at a higher level at the early jointing-booting, heading-flowering, and milking stages. Therefore, the preferred control measures should be taken to control the surface water drainage at these stages. The
\textbf{Fig. 6} Changes of $\text{NO}_3^-$-N concentration in continuous flooding in 2010

$\text{NO}_3^-$-N concentration was relatively lower in groundwater than in surface water, and did not vary significantly, except at the tillering stage. The $\text{NO}_3^-$-N concentration of LT increased by 35.6\% in 2009, but decreased by 12.0\% in 2010. The $\text{NO}_3^-$-N concentrations of LJ, LH, and LM decreased by 46.6\% and 26.3\%, 48.3\% and 41.7\%, and 22.0\% and 40.7\%, in 2009 and 2010, respectively. The low concentration at the last two stages was attributed to high rice production and the ability of nitrogen uptake via the root system. Data demonstrated that a relatively high concentration appeared at the late tillering stage, so sub-drainage should be avoided during this period. This is consistent with the research of Liu et al. (2009) in the Ningxia irrigation area, where the $\text{NO}_3^-$-N decreased by 13.88 kg/hm$^2$ over the whole growth stage, and the $\text{NO}_3^-$-N concentration was less than 10 mg/L in the drainage water.

\section*{3.4 Changes of TP concentration in continuous flooding}

Figs. 7 and 8 show the TP concentration in the years 2009 and 2010, respectively. The TP concentration had a significant downward trend for the surface water, and fluctuated at a small scale for the subsurface water. For the surface water, the TP concentration of treatment LT after ten days' flooding decreased by 53.9\% and 41.7\% compared with that at the beginning of flooding in 2009 and 2010, respectively, at the tillering stage; the TP concentrations of treatments LJ, LH, and LM gradually decreased at the early flooding, then increased slightly at the end of flooding due to the surface water consumption, and finally decreased by 28.3\%, 11.7\%, and 11.2\% in 2009, and 13.8\%, 10.2\%, and 15.8\% in 2010, respectively, at the
Fig. 7 Changes of TP concentration in continuous flooding in 2009

Fig. 8 Changes of TP concentration in continuous flooding in 2010
jointing-booting, heading-flowering, and milking stages. For the groundwater, at the end of flooding, the TP concentration of LT increased slightly by 1.70% and 1.24% at the tillering stages in 2009 and 2010, respectively; the TP concentration of LJ slightly increased by 1.54% in 2009 and 5.78% in 2010; the TP concentration of LH decreased by 25.8% in 2009, but increased by 16.7% in 2010; and the TP concentration of LM increased by 21.9% and 18.6%, respectively, in 2009 and 2010. Data demonstrated that relatively high TP concentrations appeared at the early tillering stage and in the early and late periods of other stages, so surface drainage should be avoided during these periods. This is consistent with the research of Evans (1995), in which the TP concentration in surface water decreased by 35% under the condition of controlled drainage compared with that of conventional drainage.

3.5 Multi-objective controlled drainage model for reducing nitrogen and phosphorus losses

In the paddy water system, NH$_3$-N, composed of NH$_3$ and NH$_4^+$-N, is the most stable component of nitrogen. Although NO$_3^-$-N is also a form of nitrogen, it is very unstable in water. Furthermore, the surface drainage discharge is much higher than the infiltration in clay soil when a continuous heavy rainfall or flooding occurs. In this case, the main drainage method is surface drainage and it is particularly important in controlling the contents of NH$_4^+$-N and TP in surface water in the paddy field. Based on the surface water features and water environment protection targets, the surface water is divided into five grades in Environmental Quality Standards for Surface Water (GB3838-2002) of China. The results in sections 3.2 and 3.4, demonstrated above, mean that the NH$_4^+$-N and TP concentrations in surface water were maintained at a relatively high level, corresponding to grades III to V for NH$_4^+$-N, and grades II to IV for TP. The amounts of the NH$_4^+$-N and TP taken away by the large amount of drainage displacement are tremendous.

By fitting the concentration curves of NH$_4^+$-N and TP, a new evaluation index, i.e., a fixed function ($X_{\text{fix}}$), can then be obtained. $X_{\text{fix}}$ takes the two factors NH$_4^+$-N and TP into account and assumes the weights of NH$_4^+$-N and TP to be 1/6 and 5/6, respectively. The theoretical polynomial fitting functions and optimal solutions are listed in Table 2.

The submergence-tolerant depth and duration of the rice are limited. When the rice flooding depth and duration exceed this limit, the rice is harmed, leading to production cuts. The submergence-tolerant depth and duration at each stage of the rice growth season are shown in Table 3.

Considering the low concentrations of NH$_4^+$-N and TP, as well as the submergence-tolerant depth and duration of rice, the drainage time should be regulated within a certain scope without significantly reducing the yield according to the fitting functions at different stages. For the tillering stage, the optimal time was the fourth day, when $X_{\text{fix}}$ decreased by 24.0% in 2009 and by 47.7% in 2010 compared with that at the beginning of flooding. For the jointing-booting stage, the optimal time was the sixth day, when $X_{\text{fix}}$ decreased by 37.4%
and 32.3%, respectively, in 2009 and 2010. For the heading-flowering stage, the optimal time was the fifth day, when $X_{\text{FIX}}$ decreased by 45.9% and 40.3%, respectively. For the milking stage, the optimal time was the sixth day, with decreases of 27.6% and 27.4%, respectively. Furthermore, after the tillering fertilizer application, the concentration of $\text{NH}_4^+\text{-N}$ was much higher than the concentration of $\text{NO}_3^-\text{-N}$, but dropped to a relatively low level in seven to ten days, while after panicle fertilizer application, the concentration of $\text{NH}_4^+\text{-N}$ decreased to a much lower level in three to six days. Surface drainage should be avoided during these periods.

Table 2 Curve fittings and optimal solutions for different stages in years 2009 and 2010

<table>
<thead>
<tr>
<th>Year</th>
<th>Growth stage</th>
<th>Constraint condition</th>
<th>Fitting function</th>
<th>Optimal solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>Tillering</td>
<td>$X_{X_0} &lt; X_{X_1}$</td>
<td>$X_{\text{fix}} = 0.000 6t^2 - 0.008 t^2 - 0.018 5t + 0.588 1$</td>
<td>$\min X_{\text{fix}} = 0.193 1$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$t = 10$</td>
</tr>
<tr>
<td></td>
<td>Jointing-booting</td>
<td>$X_{X_0} &lt; X_{X_1}$</td>
<td>$X_{\text{fix}} = 0.000 3t^2 - 0.002 4t^2 - 0.017 4t + 0.304 3$</td>
<td>$\min X_{\text{fix}} = 0.174 9$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$t = 7.809 1$</td>
</tr>
<tr>
<td></td>
<td>Heading-flowering</td>
<td>$X_{X_0} &lt; X_{X_1}$</td>
<td>$X_{\text{fix}} = 0.000 2t^2 + 0.001 2t^2 - 0.039 2t + 0.262 5$</td>
<td>$\min X_{\text{fix}} = 0.113 2$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$t = 6.326 7$</td>
</tr>
<tr>
<td></td>
<td>Milking</td>
<td>$X_{X_0} &lt; X_{X_1}$</td>
<td>$X_{\text{fix}} = 0.001 5t - 0.026 3t^2 + 0.107 9t + 0.245 4$</td>
<td>$\min X_{\text{fix}} = 0.179 7$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$t = 9.035 0$</td>
</tr>
<tr>
<td>2010</td>
<td>Tillering</td>
<td>$X_{X_0} &lt; X_{X_1}$</td>
<td>$X_{\text{fix}} = -0.000 6t^2 + 0.017t^2 - 0.531t + 0.551 2$</td>
<td>$\min X_{\text{fix}} = 0.191 8$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$t = 6.089 9$</td>
</tr>
<tr>
<td></td>
<td>Jointing-booting</td>
<td>$X_{X_0} &lt; X_{X_1}$</td>
<td>$X_{\text{fix}} = 0.000 4t^2 - 0.004 6t^2 + 0.003 5t + 0.178 6$</td>
<td>$\min X_{\text{fix}} = 0.114 6$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$t = 7.265 2$</td>
</tr>
<tr>
<td></td>
<td>Heading-flowering</td>
<td>$X_{X_0} &lt; X_{X_1}$</td>
<td>$X_{\text{fix}} = -0.000 7t^2 + 0.015t^2 - 0.088 8t + 0.277 9$</td>
<td>$\min X_{\text{fix}} = 0.117 7$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$t = 4.187 4$</td>
</tr>
<tr>
<td></td>
<td>Milking</td>
<td>$X_{X_0} &lt; X_{X_1}$</td>
<td>$X_{\text{fix}} = 0.001 8 t - 0.032 2 t^2 + 0.141 2t + 0.205 7$</td>
<td>$\min X_{\text{fix}} = 0.178 7$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$t = 9.036 4$</td>
</tr>
</tbody>
</table>

Note: $X_0$ and $X_1$ are the maximum emission concentrations of $\text{NH}_4^+\text{-N}$ and TP for agricultural drainage, respectively. $X_{X_0}$ and $X_{X_1}$ are the concentrations of $\text{NH}_4^+\text{-N}$ and $\text{NO}_3^-\text{-N}$, $t$ is the flooding days, and $\min X_{\text{fix}}$ is the minimum value of $X_{\text{fix}}$.

Table 3 Submergence-tolerant depth and duration of paddy rice in each stage

<table>
<thead>
<tr>
<th>Growth stage</th>
<th>Submergence-tolerant depth (mm)</th>
<th>Submergence-tolerant duration (d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tillering</td>
<td>60-100</td>
<td>2-3</td>
</tr>
<tr>
<td>Jointing-booting</td>
<td>150-250</td>
<td>4-6</td>
</tr>
<tr>
<td>Heading-flowering</td>
<td>200-250</td>
<td>4-6</td>
</tr>
<tr>
<td>Milking</td>
<td>300-350</td>
<td>4-6</td>
</tr>
</tbody>
</table>

4 Conclusions

(1) Under the present experimental conditions, after fertilizer application, the ranges of concentrations of $\text{NH}_4^+\text{-N}$ and $\text{NO}_3^-\text{-N}$ were 0.785 mg/L to 56.3 mg/L and 0.231 mg/L to 0.602 mg/L, respectively, in surface water, and 0.33 mg/L to 14.3 mg/L and 0.075 mg/L to 0.923 mg/L, respectively, in groundwater. The peak value of the $\text{NH}_4^+\text{-N}$ concentration appeared immediately after the fertilizer application and decreased to relatively low levels in seven to ten days.

(2) During the period of flooding, the concentrations of $\text{NH}_4^+\text{-N}$ and $\text{NO}_3^-\text{-N}$
decreased significantly in both surface water and groundwater, the TP concentration decreased significantly in surface water, but increased slightly in groundwater except at the heading-flowering stage in 2009. Compared with the first day of flooding, at the end of flooding, the NH$_4^+$-N concentration decreased by 11.5% to 69.3% and 7.1% to 67.8%, respectively, in surface water and groundwater; the NO$_3^-$-N concentration decreased by 32.4% to 73.2% and 12.0% to 48.3%, respectively, in surface water and groundwater; and the TP concentration decreased by 10.2% to 53.9% in surface water.

(3) In groundwater, the contents of the nitrogen and phosphorus were lower than those in surface water, except for the NH$_4^+$-N concentration at the jointing-booting and heading-flowering stages. The main form of the nitrogen fertilizer loss was NH$_4^+$-N, so drainage should be avoided during these stages. Therefore, it is essential for the flooded paddy field to control surface drainage so as to increase the utilization of nitrogen by decreasing the losses of nitrogen and phosphorus.

(4) The optimal surface drainage time was determined by establishing the multi-objective controlled drainage model. It is suitable for surface drainage on the fourth, sixth, fifth, and sixth day, respectively, at the tillering, jointing-booting, heading-flowering, and milking stages after flooding. It is efficient in reducing the concentrations of NH$_4^+$-N and TP. Compared with the beginning of flooding, the fixed function decreased by 24.0% and 47.7%, 37.4% and 32.3%, 45.9% and 40.3%, and 27.6% and 27.4% in the years 2009 and 2010, respectively, in the four growth stages.

(5) The results of this study also show that the main form of nitrogen loss was NH$_4^+$-N during rice growth seasons. The maximum concentration of NH$_4^+$-N at a leakage rate of 2 mm/d reached 1.90 mg/L, exceeding the standards of the World Health Organization and the Ministry of Health of People’s Republic of China for the NH$_4^+$-N concentration in drinking water, 1.5 mg/L and 0.5 mg/L, respectively. Thus, effective measures should be taken to restrain the high NH$_4^+$-N concentration in the drainage water during rice growth seasons.

References


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