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Integrating Ecological Restoration of Agricultural Non-Point Source Pollution in Poyang Lake Basin in China

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Abstract: This study addresses the excessive consumption of river basin water from the Poyang Lake area in China. Consumption of water for irrigation, together with the discharge of agricultural non-point source pollution, is seriously affecting the water quality of Poyang Lake. This study assesses the application of integrated ecological restoration technology for agricultural non-point source pollution in the Ganfu Plain Area, which is an important agricultural production base in the Poyang Lake basin. The results indicated that the water-fertilizer comprehensive regulation mode for double-cropping rice provided water savings of 10.4% and increased rice yield by 6.5% per hectare. Furthermore, it reduced drainage water pollution by 20.4%, and emissions of ammonium nitrogen (NH_4^+-N), nitrate nitrogen (NO_3^--N), total phosphorus (TP), and total nitrogen (TN) from rice paddy surfaces by 18.6%, 11.1%, 15.4%, and 16.0%, respectively. The eco-channel–pond wetland system effectively reduced TN and TP pollutant levels in rice paddy drainage water; the eco-channel reduced TN and TP by 9.3% and 14.0%, respectively; and the pond wetland system showed reductions of 8.6% and 22.9%, respectively. The “three lines of defense” purification technology, including rice field source control, eco-channel interception, and pond wetland purification, removed 29.9% of TN and 44.3% of TP.

Keywords: pollution; integrated technology; water conservation; drainage; nitrogen; phosphorous; Poyang Lake Basin; wetland ponds

1. Introduction

Poyang Lake (28°22′ to 29°45′ N and 115°47′ to 116°45′ E), located downstream of the Yangtze River in the northern region of Jiangxi Province, is the largest freshwater lake in China, regulating a yearly average of 145 billion m^3 of water and constituting approximately 15.6% of the runoff channeled into the Yangtze River [1,2]. The lake plays an important role in protecting the health of the aquatic ecosystems midstream and downstream of the Yangtze River. The Poyang Lake drainage basin includes the Poyang Lake region and five rivers—Gan, Fu, Xin, Rao, and Xiu—which flow into the lake. The drainage basin covers an area of 162,200 km^2, accounting for approximately 97% of the basin area in Jiangxi Province and 9% of the basin area of the Yangtze River [3]. The Poyang Lake drainage basin is located within the subtropical monsoon climate zone, covering 1.9 million km^2 of arable land with an effective irrigation area of 1.6 million km^2 and total grain output of 17.9 million tons. Hence, it is one of the most important agricultural, economic, and grain-producing zones in China [4].

In recent years, with the rapid increase in the basin population and socio-economic development, the overall water quality of Poyang Lake has declined. Jiangxi water quality monitoring results showed that pollution from nitrogen and phosphorus in Poyang Lake is increasing, thereby exacerbating eutrophication. In 2011, the average total nitrogen (TN) and total phosphorus (TP) contents of the Poyang Lake water body during the wet season were 1.389 and 0.067 mg/L, respectively, which far exceeds the eutrophication thresholds of nitrogen and phosphorus [5]. Multiple factors have exacerbated eutrophication and non-point source pollution, such as a predominantly rice-paddy-based agricultural system, excessive consumption of drainage basin water from inefficient water use, large amounts of fertilizer discharge, and direct drainage of farmlands into rivers. Guo et al. reported that excessive application of nitrogen and phosphorous fertilizers have led to serious unsustainability of local agriculture in the Yongding River Basin, and the estimated overall nitrogen and phosphorus losses are 96 kg/ha and 9 kg/ha, respectively [6]. Surveys conducted by Rao et al. show that peasants rely heavily on fertilizers and chemicals, suggesting that the government should take long-term economic measures to encourage peasants to actively adopt eco-friendly farming techniques [7]. Jiang et al. analyzed the variations in landscape patterns based on high-resolution remote sensing images of the Jiulongjiang estuary region, and their results indicate that the area under nitrogen non-point source pollution in this region has increased by 32.75 km^2 in 5 years [8]. To eliminate the limitations of conventional field-scale observation methods used for detecting non-point source pollution, Huang et al. proposed a direct method to observe non-point source pollution in paddy fields [9]. Effective measures of water conservation for rice paddy irrigation and control of agricultural nonpoint source pollution are required to avoid severe limitations to sustainable economic development in the Poyang Lake basin. Systematic studies on preventive measures for amelioration and targeted control of agricultural non-point source pollution, and ecological restoration of the Poyang Lake drainage basin, have important theoretical and practical implications for improving the quality of water of the Poyang Lake, as well as the ecological environment of the drainage basin.

Control methods for agricultural non-point source pollution can be divided into two categories: source control techniques and runoff process restoration techniques. Wu et al. proposed a novel strategy for nonpoint source pollution control based on three phases (liquid, solid, and bio-phase), and highlighted the ability to regulate an agricultural ecosystem by optimizing land use and cover types [10]. Rissman and Carpenter suggested that policy-makers should gain a better understanding of existing scientific knowledge and act to protect public values in order to overcome the barriers to non-point source pollution prevention [11]. Reducing fertilizer application rates and filtering nutrients coming off croplands with restored wetlands are two alternative strategies for reducing nutrient loads in the Mississippi Basin [12].

Source control techniques reduce and control the discharge of nitrogen and phosphorus from non-point sources through eco-agriculture technology. Sun et al. pointed out several measures to reduce non-point source pollution from croplands, including correcting distortion in fertilizer prices and improving incentives for the recycling of organic manure [13]. Wu et al. proposed a "reduce–retain–restore" theory to control agricultural non-point source pollution in China in tune with the economic model of Chinese agriculture [14]. Xia et al. studied different planting treatments to explore the effects of protective methods on soil and nutrient losses from sloping arable lands in the Three Gorges area of China, and found that contour hedgerows and ridge furrow cultivation are effective in reducing phosphorous loss via surface runoff [15]. Yang et al. reviewed studies on the control technologies of agricultural non-point source pollution, suggesting the use of a combination of systematic control and regional treatment [16].

Runoff process restoration techniques involve the construction of ecological devices that intercept and recycle pollutants downstream from the runoff, where pollutants accumulate. This mainly includes the ecological filter belt technique and a variety of wetland techniques [17,18]. Grismer et al. reported that using vegetative filter strips, intercepting surface water runoff, trapping sediment, capturing nutrients in runoff, promoting degradation, and removing pathogens from runoff are some of the measures used to control agricultural non-point source pollution [19]. Wu et al. reviewed ecological engineering solutions to control rural non-point source water pollution, and recommend the adoption of best management practices, including the use of vegetated filter strips, ecological ditches, constructed wetlands, and biogas plants [20]. A paddy eco-ditch and wetland system can dramatically reduce TN and TP losses by 87.8% and 70.4%, respectively [21]. It has been reported that planted floating treatment beds can maintain the concentrations of TN and TP at low levels [22]. Shan et al. have estimated the optimal width of buffer strips using geographic information systems to control non-point source pollution in the Three Gorges Reservoir area [23]. In this study, we combined the characteristics of both main and non-point sources of agricultural pollutants of the Poyang Lake drainage basin, and used water and fertilizer regulation techniques in the fields to reduce non-point source pollutant discharges from their sources. Simultaneously, we used an eco-channel and an eco-pond to effectively intercept runoff, and organically combined source control, eco-channel interception, and eco-pond purification into "three lines of defense", thereby forming an integrated technique for addressing non-point source pollution for the purpose of ecological restoration in Poyang Lake basin.

2. Materials and Methods

2.1. Study area Overview

We performed experiments from April to October of 2013 in the Lifang Natural Village of Gaotian Village, in the town of Xiangtang, within the Ganfu Plain Irrigation Area of Jiangxi Province shown in Figure 1 (28°43′ N, 116°01′ E). The study area covers approximately 62,000 m^2. The main crop activity in the area is double-cropping of varieties of rice. Surrounding the rice paddies are typical farm drainage channels and pond wetlands, with rice paddies covering a total area of 60,187.5 m^2 and pond wetlands covering a total area of 1875 m^2. The area ratio of pond wetlands to rice paddies receiving drainage is 32.1:1. The climate zone is subtropical, humid monsoon, with a mild climate, and abundant sunshine and rainfall, and is thus suitable for growing a variety of crops. According to the 1980–2014 meteorological data from the weather station at the irrigation center of Jiangxi province (116°00′ E, 28°26′ N), the study area has an average annual temperature of 24.6 °C, average annual sunshine of 1079.6 h, average evaporation of 992.5 mm, and average annual rainfall of 1063.8 mm during the testing period from April to October. The rainfall of 1404.8 mm in 2013 was typical the frequency of this rainfall over the last 30 years is 57.89%, and thus considered to be representative for this experimental study.

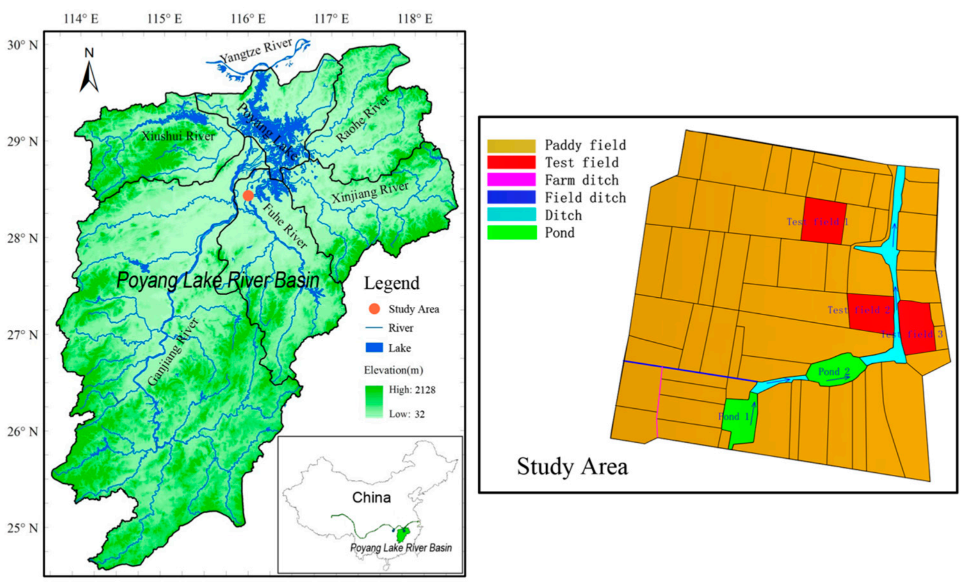


Figure 1. Generalized map of the study area.

2.2. Construction of Purification Technology

The "three lines of defense" purification technology utilized the comprehensive regulation technique of paddy rice water-fertilizer and the ecological restoration technologies of eco-ditches and eco-ponds to control the agricultural non-point source pollution of Poyang Lake Basin. First, in the paddy fields, intermittent irrigation was provided depending on which paddy was dry in order to decrease the drainage, and the fertilizer frequency was increased to improve the fertilizer efficiency, thus reducing the discharge of nitrogen and phosphorus from surface runoff. Second, drainage from paddy fields was collected into an eco-channel system. In this system, eco-bag treatment technology was used. Eco-bag treatment technology refers to the use of double-sided needle-punched, non-woven bags made from polypropylene (PP) or polyester (PET) as raw materials that were filled with grass seeds and soil, and wetland plants were planted in the eco-channel to absorb nitrogen and phosphorus as nutrients [24,25]. Control structures at the inlet and outlet of the ditches were installed to reduce water flow velocity and lengthen agrochemical retention time, further promoting nutrient assimilation by plants and sedimentation [26]. Last, the drainage from paddy fields was stored in the eco-channel and then routed to the pond wetland, where control structures were similarly installed; this lengthened the agrochemical retention time and thus provided a further opportunity for nutrients and sediment to degrade and be absorbed [19].

2.3. Experimental Design

2.3.1. Water-Fertilizer Comprehensive Regulation Technique in Rice Paddies

To address the serious loss of phosphorus and nitrogen at the source due to water and fertilizer management in the paddy fields, three 1000 m^2 paddy fields with flat terrain and convenient irrigation and drainage, balanced soil fertility, and consistent planting systems were chosen to study the effects of source control (first line of defense) techniques on reduced drainage of nitrogen and phosphorus pollutants. Temporary ridges were used to further divide each plot into six cells that were used to compare the customary methods of local farmers (W_0F_1) with the rice paddy water-fertilizer comprehensive regulation technique (W_1F_2) with two treatments and three replicated plots. The customary method used by local farmers was flood irrigation (W_0), which utilized 180 kg/ha of nitrogenous fertilizer, applied at a base-to-tiller fertilizer ratio of 5:5 (F_1). In comparison, the rice paddy water-fertilizer comprehensive regulation technique used the intermittent irrigation method (W_1), which utilized 180 kg/ha of nitrogenous fertilizer, applied at a base-to-tiller-to-panicle fertilizer ratio of 5:3:2 (F_2). The ridges of the paddy cells were wrapped with plastic film to block lateral leaching and streaming from individual cells. Paddy management measures were consistent throughout, except for the difference in water management and nitrogenous fertilizer application in the model cells. The water layer control standards under different irrigation methods for early and late rice are shown in Table 1.

Table 1. Water layer control standards in different irrigation methods for early and late rice (Unit: mm).

Irrigation Method	Rice Season	Re-Greening Stage	Early Tillering Stage	Late Tillering Stage	Jointing–Booting Stage	Heading and Flowering Stage	Milky Stage	Yellow Ripening Stage
Flooding irrigation	Early rice	0-20-40	0-20-50	0-20-50 Late paddy sunning	0-20-50	0-20-50	0-20-50	0-30 Late drying
	Late rice	0-20-40	0-20-50	0-20-50 Late paddy sunning	0-20-50	0-20-50	0-20-50	0-30 Late drying
Intermittent irrigation	Early rice	0-20-30 Drying for 4 days	0-20-50 Drying for 4 days	0-20-50 Late paddy sunning	0-20-50 Drying for 4 days	0-20-50 Drying for 4 days	0-20-50 Drying for 4 days	0-20-30 Late drying
	Late rice	0-20-40 Drying for 3 days	0-20-50 Drying for 3 days	0-20-50 Late paddy sunning	0-20-50 Drying for 3 days	0-20-50 Drying for 3 days	0-20-50 Drying for 3 days	0-20-30 Late drying

Note: Values in the table indicate the depth of the water layer, where the first and middle values indicate the lower and upper limits of irrigation, respectively, and the last value indicates the upper limit of water storage during rainfall.

2.3.2. Ecological Restoration by Eco-Channel–Pond–Wetland System

Eco-channels and eco-ponds are the second and third lines of defense, respectively, in the "three-line defense." Through dredging, slope remediation, and other ecological transformations of the typical channels and ponds that receive rice paddy drainage in the demonstration area, the interception and purification functions of natural channels and ponds towards nitrogen and phosphorous pollutants in rice paddy drainage were strengthened, thereby decreasing the effects of agricultural non-point source pollution on the hydrological environment of Poyang Lake.

The existing trunk drainage ditch was reconstructed to an eco-ditch of 170 m length, 3.60–8.50 m width at the upper opening, 2–3 m width at the lower opening, and 0.20 m depth, with a slope coefficient of 2:1. The plants in the channels were mainly arrowheads (*Sagittaria sagittifolia*), wild rice (*Zizania latifolia*), sedge (*Fimbristylis miliacea*), and lotus (*Nelumbo nucifera*). Slopes were covered with eco-bags (eco-bag slope protection refers to the use of double-sided needle-punched, non-woven bags made from polypropylene (PP) or polyester (PET) as raw materials that are filled with grass seeds and soil) and planted with wild rice and vetiver (*Chrysopogon zizanioides*). Water control devices, such as triangular weirs, were installed at the ends of the rill ditch, farm ditch, and principal drainage channels to maintain a suitable water level (10–30 cm). This practice extended the retention time of agricultural drainage in the eco-channel and increased the interception of nitrogen and phosphorus pollutants in the drainage channels.

Pond wetlands in the study area were named Pond 1 and Pond 2 in order of the direction of water flow. Pond 1 and Pond 2 were also modified by installing water control devices and multi-stage baffles at the inlet and outlet of each pond. Pond 1 was generally square in shape, approximately 40 cm deep, with a surface area of 965 m^2, and planted with lotus. Water flowed in from the middle of one side and out of the middle of the opposite side. Pond 2 was a 910 m^2 oblong wetland, approximately 50 cm deep, and planted with water caltrop (*Trapa natans*). Water flowed along the long side, with almost no still water areas. Water drainage from the paddies was discharged after flowing through Pond 1, Pond 2, and the principal drainage channel.

2.4. Measured Variables and Methods

2.4.1. Measured Variables

Measured variables for the paddy plots included rainfall, irrigation volume, drainage volume, crop yields, and composition of yield. Rainfall was measured by the experimental research base weather station of the Jiangxi Province Irrigation Experiment Station Center, located within 1 km of the study area (28°26′ N, 116°00′ E). Irrigation volume was calculated using the triangular weirs installed in the paddies. Drainage volume was determined by observing the difference in water level in the paddies before and after drainage. Crop yield and factors affecting crop yield were determined in accordance with "Specifications for Irrigation Experiments" [27].

Water levels at the inlets and outlets of the channels and pond wetlands were observed daily. Water samples were collected from the inlets and outlets of the channels and pond wetlands at least once during each growth stage of rice. Water samples were collected simultaneously from the paddy drainage and from inlets and outlets of the channels and ponds after rainfall. During the early rice planting period, 90, 26, and 32 water samples were collected from the paddy fields, eco-channels, and eco-ponds, respectively. During the late rice planting period, 72, 20, and 28 water samples were collected from the paddy fields, eco-channels, and eco-ponds respectively, for a total of 268 water samples. Collected water samples were tested for total nitrogen (TN), nitrate nitrogen (NO_3^--N), ammonia nitrogen (NH_4^+-N), and total phosphorus (TP). TN content was determined using alkaline potassium persulfate digestion—UV spectrophotometry [28], and the detection limit was 0.05 mg/L. TP content was determined using ammonium molybdate spectrophotometry [29], and the detection limit was 0.01 mg/L. Ammonia nitrogen content was determined using Nessler's reagent colorimetry [30], and the detection limit was 0.02 mg/L. Nitrate nitrogen content was determined using UV spectrophotometry [31], and the detection limit was 0.08 mg/L.

2.4.2. Formulas

$$\text{Irrigation water use efficiency (kg/m}^3\text{) = yield/irrigation volume used} \quad (1)$$

$$\text{Rainfall utilization rate (\%) = (rainfall volume} - \text{drainage volume)/rainfall volume} \times 100 \quad (2)$$

Nitrogen and phosphorus concentration and load reduction rate in channel and pond wetlands:

$$R = \frac{C_{in} \times V_{in} - C_{out} \times V_{out}}{C_{in} \times V_{in}}, \quad (3)$$

where R represents the removal rate (%) of each index; C_{in} represents the nitrogen and phosphorus concentration (mg·L^{-1}) in the water at the inlets of channels and ponds; V_{in} and V_{out} represent the volume of water (L) flowing in and out of the channels and ponds, respectively; and C_{out} represents the concentration of nitrogen and phosphorus pollutants (mg·L^{-1}) in the water at the outlets of channels and ponds.

Total removal rate:

$$R_{Total} = 1 - \left(1 - R_f\right) \times (1 - R_c) \times \left(1 - R_p\right), \quad (4)$$

where R_{Total} represents the total removal rate of nitrogen and phosphorus pollutants (%) after purification through the "three lines of defense" technique; R_f represents the removal rate of nitrogen and phosphorus (%) through the regulation of water and fertilizers in the paddies; R_C represents the removal rate of nitrogen and phosphorus (%) through eco-channels; and R_p represents the removal rate of nitrogen and phosphorus (%) through ponds.

2.5. Data Processing and Statistical Analyses

Data processing and map construction were conducted using Excel software (Microsoft 2003). DPS7.05 software was used for statistical testing and variance analysis (ANOVA).

3. Results

3.1. Effect on Water Conservation

Table 2 shows that, compared with the customary method used by local farmers (W_0F_1), the water-fertilizer comprehensive regulation technique (W_1F_2) reduced irrigation and surface drainage volumes for double-cropping early and late rice, which improved the effective utilization of rainfall and irrigation water. The early rice model showed that the irrigation and drainage volumes were reduced by 248.18 m^3/ha and 462.02 m^3/ha, respectively, corresponding to a reduction of 11.1% and 15.3%, respectively. Rainfall and irrigation water use efficiency were improved by 10.83 kg/m^3 and 0.61 kg/m^3, corresponding to an increase of 37.0% and 18.6%, respectively. The late rice model showed that irrigation and drainage volumes were reduced by 436.09 m^3/ha and 29.01 m^3/ha, corresponding to a reduction of 10.1% and 25.4%, respectively. Effective and efficient utilization of rainfall and irrigation water were improved by 2.42 kg/m^3 and 0.34 kg/m^3, which represented increases of 2.7% and 18.6%, respectively.

Comprehensive analysis of the effect of the optimized water-fertilizer regulation technique on water conservation showed a total of 684.27 m^3/ha, at a rate of 10.4%, for conserved irrigation water for the entire year. Effective and efficient utilization of rainfall and irrigation water were increased by 21.1% and 18.8%, respectively.

Table 2. Effect of water-fertilizer comprehensive regulation technique on water conservation in rice paddies.

Rice Season	Treatment	Rainfall/ $m^3 \cdot ha^{-1}$	Displacement/ $m^3 \cdot ha^{-1}$	Rainfall Utilization Rate/%	Irrigation Amount/ $m^3 \cdot ha^{-1}$	Yield/ $kg \cdot ha^{-1}$	Irrigation Water Use Efficiency/ $kg \cdot m^{-3}$
Early rice	W_1F_2	4266.21	2560.13	40.0	1994.88	7756.01	4.03
	W_0F_1	4266.21	3022.15	29.2	2243.06	7354.39	3.37
Late rice	W_1F_2	1196.06	85.00	92.9	3891.40	8442.78	2.15
	W_0F_1	1196.06	114.01	90.5	4327.49	7938.40	1.81
Total	W_1F_2	5462.27	2645.13	51.6	5886.28	16,390.38	2.78
	W_0F_1	5462.27	3136.16	42.6	6570.55	15,386.22	2.34

Note: W_0F_1 means the customary method of water irrigation and fertilization used by local farmers; W_1F_2 means the water-fertilizer comprehensive regulation technique in this study.

3.2. Effect on Yield

Table 3 shows that the use of the water-fertilizer comprehensive regulation technique in early and late rice paddies increased the panicle length, grain number per panicle, and 1000-grain weight. In addition, it improved the effective panicle number and seeding rate per unit area, thereby significantly improving rice yield per unit area. Early rice treated with the W_1F_2 method showed increased panicle length, effective panicle number, total grain number, seeding rate, 1000-grain weight, and rice yield by 0.58 cm (2.9%), 77,700/ha (3.4%), 5.18 (3.6%), 2.27 (2.7%), 0.48 g (1.7%), and 474.51 kg/ha (6.3%), respectively. For late rice, the W_1F_2 method increased panicle length, effective panicle number, total grain number, seeding rate, 1000-grain weight, and rice yield by 0.29 cm (1.4%), 51,100/ha (1.5%), 5.31 (4.3%), 3.00 (3.4%), 0.67 g (3.0%), and 529.65 kg/ha (6.8%), respectively. The optimized water-fertilizer comprehensive regulation technique increased the total crop yield of double-cropping early and late rice by 1004.16 kg/ha, which represented an average increase of 6.5%.

Variance analysis for crop yield and factors affecting crop yield showed that different water-fertilizer regulation techniques resulted in significantly different effective panicle numbers and highly significant differences in total grain number, seeding rate, 1000-grain weight, and rice yield. This indicated that the water-fertilizer comprehensive regulation technique increased the rice yield mainly by increasing the effective panicle number, seeding rate, and 1000-grain weight.

Table 3. Effect of rice paddy water-fertilizer comprehensive regulation technique on yield.

Rice Season	Treatment	Ear Length/cm	Effective Panicle/ $10^4 \cdot ha^{-1}$	Total Grains	Seed Setting Rate/%	1000-Grain Weight/g	Yield/ $kg \cdot ha^{-1}$
Early rice	W1F2	20.65aA	234.59aA	150.84aA	86.97aA	28.73aA	8042.13aA
	W0F1	20.07aA	226.82bA	145.66bB	84.70bB	28.25bB	7567.62bB
Late rice	W1F2	20.44aA	345.23aA	127.73aA	92.43aA	23.34aA	8348.25aA
	W0F1	20.15bA	340.12bA	122.42bB	89.43bB	22.67bB	7818.60bB
Average	W1F2	20.55aA	289.91aA	139.29aA	89.70aA	26.04aA	8195.19aA
	W0F1	20.11bA	283.47bA	134.04bB	87.07bB	25.46bB	7693.11bB

Note: Duncan's multiple range test (MRT) was used in univariate statistical analysis. Lowercase letters represent a significance level of 5%; uppercase letters represent a significance level of 1%. 20.65aA and 20.07aA means that there is no significant difference between the two treatments in ear length; 234.59aA and 226.82bA means that there is a significant difference in 5% level between the two treatments in effective panicle; 150.84aA and 145.66bB means that there is a significant difference in 1% level between the two treatments in total grains.

3.3. Effect on Pollutant Reduction

3.3.1. Effect of Efficient Use of Water and Fertilizers on Pollutant Reduction

Table 4 shows that, compared with the customary method used by local farmers (W_0F_1), the optimized water-fertilizer regulation technique (W_1F_2) effectively reduced pollutants by decreasing the discharge of ammonia nitrogen, nitrate nitrogen, total nitrogen, and total phosphorus in the surface runoff from paddies. The W_1F_2 method reduced ammonia nitrogen, nitrate nitrogen, total nitrogen, and total phosphorus levels in early rice paddies by 0.96 (17.1%), 0.04 (13.8%), 1.04 (16.5%), and 0.03 kg/ha (12.0%), respectively. For late rice paddies, pollutants were reduced by 0.01 (20.0%), 0.001 (8.3%), 0.01 (14.3%), and 0.001 kg/ha (20.0%), respectively. For double-cropping early and late rice, the total accumulation of ammonia nitrogen, nitrate nitrogen, total nitrogen, and total phosphorus for the entire year was reduced by 0.97 (18.16%), 0.04 (11.1%), 1.05 (15.4%), and 0.03 kg/ha (16.0%), respectively.

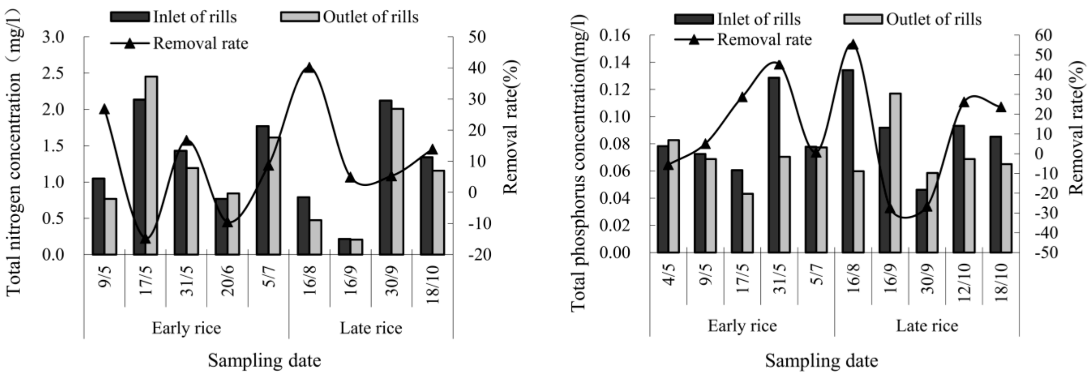
Variance analysis was performed on nitrogen and phosphorus nutrient run-off volume during both early and late rice seasons. Results showed that the total phosphorus, ammonia nitrogen, and nitrate nitrogen runoff under different water and fertilizer management measures in the early and late seasons were significantly or very significantly different. It can be seen that, compared with the patterns and habits of local farmers, the use of integrated water and fertilizer regulation technology can significantly decrease the emission of agricultural non-source pollutants at the source.

Table 4. Effect of efficient water-fertilizer utilization technique on the discharges of nitrogen and phosphorus in paddy runoff.

Rice Season	Treatment	Nitrogen/kg·ha^{-1}			Phosphorus/kg·ha^{-1}
		Ammonia Nitrogen (NH_4^+-N)	**Nitrate Nitrogen (NO_3^--N)**	**Total Nitrogen (TN)**	**Total Phosphorus (TP)**
Early rice	W_1F_2	4.66bB	0.25bB	5.27bB	0.22bA
	W_0F_1	5.62aA	0.29aA	6.31aA	0.25aA
Late rice	W_1F_2	0.04bB	0.011bA	0.06bB	0.004bA
	W_0F_1	0.05aA	0.012aA	0.07aA	0.005aA

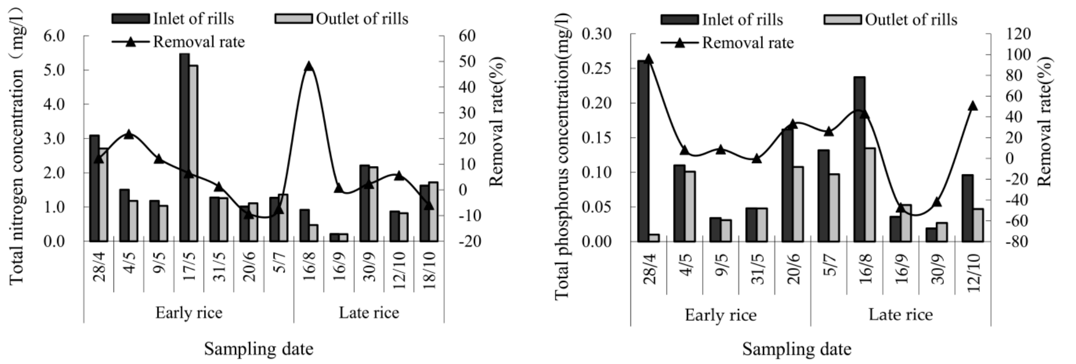
3.3.2. Effect of Eco-Channels on Pollutant Reduction

The rill ditch and farm ditch are the primary filters for drainage from paddies and have relatively good purification effects on nitrogen and phosphorus pollutants. A rill ditch is a ditch situated between areas of paddy field that directly receives drainage water from each small field section. An agricultural ditch then receives water from the rill ditch. The control area of a farm ditch is several times larger than that of a rill ditch. Figures 2 and 3 show that the average removal rates for TN and TP by rill ditch during the early rice cultivation period were 5.4% and 14.8%, respectively, while average removal rates during the late rice cultivation period were 17.5% and 10.3%, respectively. Over the entire year, the average removal rates of TN and TP by rill ditch were 11.5% and 12.6%, respectively. The average removal rates for TN and TP by farm ditch during the early rice cultivation period were 4.8% and 29.2%, respectively; during the late rice cultivation period, they were 9.5% and 1.8%, respectively. The average removal rates of TN and TP by farm ditch over the entire year were 7.2% and 15.5%, respectively. For both rill ditch and farm ditch together, the average removal rates of TN and TP in the study area were 9.3% and 14.0%, respectively. Therefore, the eco-channel system showed good degradation and removal effects on nutrients in the drainage from paddies, effectively controlling nitrogen and phosphorus in the agricultural runoff discharged directly into the nearby river bodies.



(**a**) (**b**)

Figure 2. Effect of rill ditch on total nitrogen and total phosphorus removal: (**a**) Reduction of total nitrogen concentration; (**b**) Reduction of total phosphorus concentration.



(**a**) (**b**)

Figure 3. Effect of farm ditch on total nitrogen and total phosphorus removal: (**a**) Reduction of total nitrogen concentration; (**b**) Reduction of total phosphorus concentration.

3.3.3. Effect of Pond Wetlands on Pollutant Reduction

Pond wetland conditions during the early and late rice growth periods of 2013 are shown in Tables 5 and 6. Removal rates for TN and TP during the early rice growth period were 11.3% and 21.3% in Pond 1, and 11.3% and 29.4% in Pond 2, respectively. For the late rice growth period, the respective removal rates of TN and TP were 5.6% and 18.8% in Pond 1, and 6.1% and 22.3% in Pond 2. Comprehensive analysis of the purifying effects of the pond wetlands on early and late rice paddies showed that the average removal rates of TN by Pond 1 and Pond 2 were 8.5% and 8.7%, respectively. Average removal rates of TP were 20.0% and 25.8%, respectively. From a timing perspective, the overall purification effect of pond wetlands on TN and TP was better during the early rice growth period than the late rice growth period, which might have been due to frequent rainfalls during the early rice growth period that led to greater loads of nitrogen and phosphorus discharge. Additionally, the majority of plants in the pond wetlands during the early rice growth period were in the vegetative phase of growth, with a strong ability to absorb nutrients.

Table 5. Purification of total nitrogen and total phosphorus in pond wetlands during the early rice growth period.

Nutrient Elements	Location	Collection Date of Water Sample								Average Removal Rate/%
		28 April	4 May	9 May	17 May	31 May	20 June	3 July	5 July	
$TN/mg{\cdot}L^{-1}$	Inlet of Wetland 1	3.07	1.50	1.14	5.14	1.36	1.02	1.05	1.19	11.3
	Outlet of Wetland 1	2.71	1.17	1.09	4.48	1.29	0.76	1.07	1.06	
	Inlet of Wetland 2	2.14	1.46	1.69	5.12	1.28	1.12	2.37	1.37	11.3
	Outlet of Wetland 2	2.14	1.00	1.35	3.51	1.20	1.02	2.44	1.44	
$TP/mg{\cdot}L^{-1}$	Inlet of Wetland 1	0.27	0.12	0.08	0.17	0.05	0.23	0.19	0.13	21.3
	Outlet of Wetland 1	0.22	0.11	0.08	0.04	0.05	0.17	0.14	0.11	
	Inlet of Wetland 2	0.01	0.14	0.14	0.05	0.05	0.19	0.15	0.37	29.4
	Outlet of Wetland 2	0.01	0.09	0.10	0.03	0.04	0.11	0.10	0.24	

Table 6. Purification of total nitrogen and total phosphorus in pond wetlands during the late rice growth period.

Nutrient Elements	Location	Collection Date of Water Sample							Average Removal Rate/%
		16 July	25 July	16 August	26 September	30 September	12 October	18 October	
$TN/mg{\cdot}L^{-1}$	Inlet of Wetland 1	4.14	/	0.96	0.22	2.18	0.89	1.89	5.6
	Outlet of Wetland 1	4.00	/	0.81	0.22	2.21	0.87	1.63	
	Inlet of Wetland 2	4.34	4.86	0.69	0.22	2.18	0.83	1.73	6.1
	Outlet of Wetland 2	4.21	4.25	0.67	0.22	2.08	0.77	1.52	
$TP/mg{\cdot}L^{-1}$	Inlet of Wetland 1	0.26	/	0.47	0.05	0.02	0.16	0.13	18.8
	Outlet of Wetland 1	0.21	/	0.25	0.04	0.02	0.12	0.13	
	Inlet of Wetland 2	0.27	0.08	0.14	0.06	0.03	0.12	0.14	22.3
	Outlet of Wetland 2	0.11	0.24	0.11	0.06	0.03	0.09	0.10	

3.4. Comprehensive Effects of the Poyang Lake Basin Agricultural Non-Point Source Pollution Ecological Restoration Integrated Technique

Comprehensive effects of the Poyang Lake basin agricultural non-point source pollution ecological restoration integrated technique (Figure 4) included 10.4% water conservation in the paddies, 6.5% increase in yield, 21.1% increase in effective rainfall utilization, 18.8% increase in irrigation water use efficiency, and 16.5% and 14.3% reductions in TN in early and late rice paddies, respectively. In addition, there were reductions of 12.0% and 20.0% in TP in early and late rice paddies, respectively. Purification by drainage channels showed removal rates of TN and TP from paddy drainage of 9.3% and 14.0%, respectively. Purification by pond wetlands showed removal rates of TN and TP from paddy drainage of 8.6% and 22.9%, respectively. Overall, the effect of the "three lines of defense" integrated technique, using source control of pollutants, eco-channel interception, and pond wetland purification, on nitrogen and phosphorus reduction was 29.9% (TN) and 44.3% (TP), respectively.

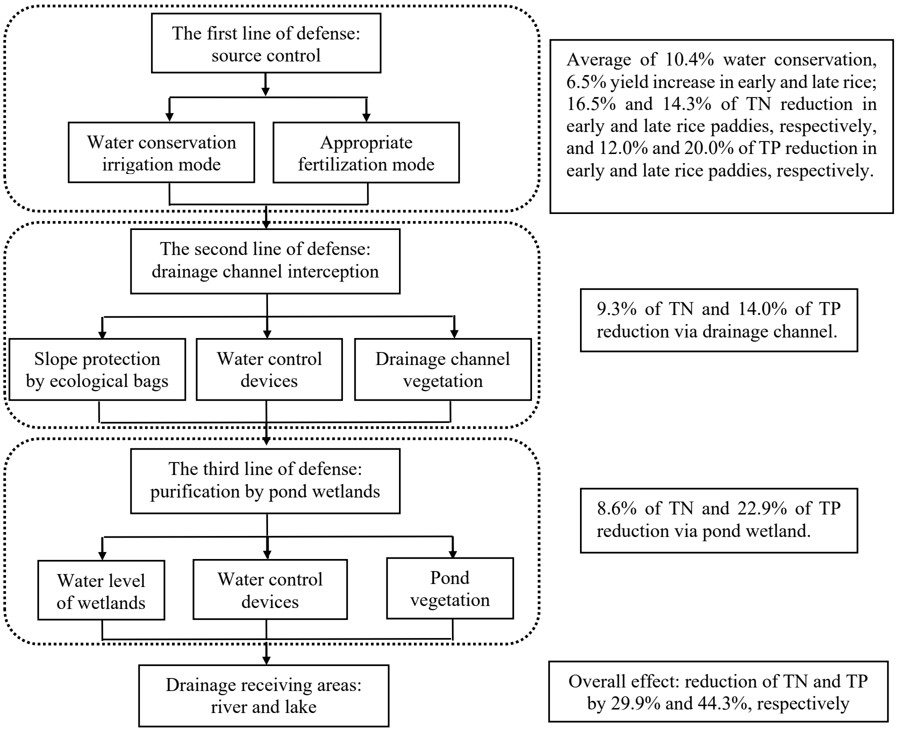


Figure 4. Overall reduction of pollutants by the Poyang Lake agricultural non-point source pollution integrated ecological restoration technique.

4. Discussion

Water and fertilizers are the main factors affecting the growth and development of rice. Appropriate management of water and fertilizers in rice paddies cannot only conserve irrigation water and increase rice yield; it can also effectively reduce discharges of nitrogen and phosphorus from the paddies, and improve the efficiency of water and fertilizer use [32–34]. This study of rice paddy water-fertilizer comprehensive regulation is part of a series of related studies on intermittent irrigation and nitrogenous fertilizer application [35,36]. The water-fertilizer management technique is based on the hydro-climatic conditions of the Poyang Lake drainage basin, and suits rice paddies well. Practical application results showed that, compared with the traditional method of water-fertilizer regulation technique (the customary methods of local farmers), the rice paddy water-fertilizer comprehensive regulation technique conserved a total of 684.27 m^3/ha irrigation water over the entire year in double-cropping rice paddies (water conservation rate of 10.4%); increased the rice yield by 1004.16 kg/ha (yield increase of 6.5%); increased the effective utilization and efficient use of rainfall and irrigation water by 21.1% and 18.8%, respectively; and reduced the surface runoff discharges of ammonia nitrogen, nitrate nitrogen, TP, and TN by 18.6%, 11.1%, 15.4%, and 16.0%, respectively. This is consistent with the results observed by Massey et al., who reported that intermittent flooding could reduce water use by 32% compared with traditional irrigation during a nearly 80 day wetting and drying cycle [35]. The use of intermittent flooding also reduces water runoff by 47% due to increased storage of rainwater compared with continuous flooding irrigation [36].

Drainage channels have the dual purposes of drainage and acting as ecological wetlands, and can reduce nitrogen and phosphorus discharge entering downstream water bodies through soil adsorption, plant uptake, and biodegradation [37,38]. In this study, we prolonged the retention time of water within the drainage channels and increased the contact time between drainage nitrogen and muddy sediments and aquatic plants in the drainage channels. We also improved the purification effect of drainage channels by adopting integrated methods, such as using eco-bags for slope protection, controlling the retention time of paddy drainage, and planting wetland plants. Our study suggests that the appropriate water level for drainage channels is 10–30 cm; the appropriate hydraulic retention time in the drainage channels for paddy drainage is 3–5 days; and suitable wetland plants for the Poyang Lake drainage basin are lotus, wild rice, and vetiver. In this study, the removal rates of paddy drainage TN and TP by drainage channels were 9.3% and 14.0%, respectively. However, this removal rate was obviously lower than that reported by Chen et al., who reported that the mean concentration removal efficiencies in the eco-ditch for TN, NO_3^--N, and $NH4^+$-N were 75.8%, 63.7%, and 77.9%, respectively [38]; this difference may have been caused by higher initial concentrations of these substances than those reported by Chen et al.

Pond wetlands are ecological purification systems composed of muddy sediments, plants, and microbes. Multiple factors affect purification effects, such as wetland surface area, physical and chemical properties of sediments, wetland plants, microbial growth, physiological and biochemical activities, hydraulic retention time, and water depth [39–41]. This study showed that the respective removal rates for TN and TP can reach above 8.6% and 22.9% through dredging of sediments, selection of appropriate wetland plants, and control of hydraulic retention time and paddy to wetland area ratio. These removal rates are almost the same as those reported by Guo et al., viz., 5.3% for TN and 6.1% for TP [38]. We recommend introducing appropriate modifications to existing ecological ponds to effectively reduce agricultural non-point source pollutants (nitrogen and phosphorus) in the Poyang Lake drainage basin, and fully develop the purification effect of pond wetlands. We also recommended selecting wetland plants with superior purification effects and economic benefits, such as wild rice and lotus. Some studies show that the capacity of the pond wetland system to control agricultural non-point source pollution is related to the drainage area of paddy fields. When the area ratio of paddy fields to wetland is approximately 19:1, the removal rate of TN in wetland reaches 90% [42]. An experiment performed for four consecutive years in Northeastern Spain in artificial wetlands to control the drainage from paddy fields showed that four different wetlands, with a surface area of 50 m^2, 200 m^2, 800 m^2, and 5000 m^2, respectively, removed 111–291 gN/m^2, 37–507 gN/m^2, 15–217 gN/m^2, and 143–75 gN/m^2 TN under a retention time of 0.7–3.5 days, 2.1–4.4 days, 2.3–10.6 days, and 8.7–31.2 days, respectively, and the suitable wetland area was suggested to be 1.5–4% of the farmland catchment area [43]. The efficiency of wetlands in nitrogen and phosphorus removal from drainage from paddy fields increased with the area of the wetlands [44], the appropriate area ratio of paddy fields to wetlands was 10:1–50:1, and the optimum hydraulic retention time was 3–4 days [45]. From 2011 to 2012, the authors performed a study on the purification effects of pond wetlands with different depths of source pollutants (nitrogen and phosphorus), farmland drainage, and suitable ratio of paddy field to wetlands. The results showed that when the wetland vegetation of ponds was lotus, a water depth of 20 cm provided the greatest fluctuation in the removal of nitrogen and phosphorus (removal rate of 30–60%), whereas a water depth of 40 cm had a better removal rate (50–90%), and a water depth of 60 cm had the slowest removal rate (50–60%). After the agricultural drainage had entered the ponds, the total nitrogen and phosphorus removal rate at day 3 was 60–80% and the total nitrogen and phosphorus removal rate at day 4 was 70–90%; furthermore, a retention time of 3–4 days was the most appropriate. Through sorting of drainage frequencies according to the drainage volume produced by paddy fields in the 1980–2012 double rice season, paddy fields with drainage frequencies of 50%, 75%, and 90% had corresponding paddy-to-wetland areas of 46.1:1, 22.3:1, and 12.6:1, respectively. According to the current status of ditch and pond wetlands and agricultural fields at the Poyang Lake basin, and based on the integrated perspective of purification effects and economics, the suitable ratio of paddy fields to wetlands is 22.3:1–46.1:1 in the Poyang Lake basin. This ratio is almost the same as that observed by Wan et al. [45].

5. Conclusions

Through optimization of water and fertilizer management in fields, and ecological transformation of channels and ponds, we constructed a "three-line defense" of source control, eco-channel interception, and pond purification to establish an integrated technology for ecological restoration for agricultural non-point source pollution at the Poyang Lake basin. Our results showed that the burden of nitrogen and phosphorus pollutants gradually decreased. After passing through the "three-line defense", the total nitrogen and phosphorous removal rates were 29.9% and 44.3%, respectively, and purification effects were evident.

The integrated water and fertilizer regulation technology in paddy fields uses the agronomic measure of combined intermittent irrigation and triple fertilizer application to achieve effects of water conservation, drainage reduction, and increased production in the double rice season. This increases water and fertilizer utilization rates (not by increasing the amount of fertilizers used, but by increasing the frequency of fertilizer application at the later period); decreases the production and emission of source control agricultural non-point source pollution; requires no additional labor and capital investment; and is the most simple, economic, and effective technology measure for reducing agricultural non-point source pollution at the Poyang Lake basin. Currently, this technique has been promoted and applied to a 90,000 ha area in the Poyang Lake basin, and is welcomed and recognized by local farmers.

Management of agricultural non-point source pollution at the Poyang Lake basin requires the organic combination of agronomic measures and engineering measures, rational water control installations, cross-sectional patterns of eco-ditches, ratio of paddy fields to wetlands, appropriate wetland vegetation and its density, and other design parameters as the key to the ecological transformation of ditch and pond wetlands. The ecological restoration technologies of eco-ditches and eco-ponds are important engineering measures to prevent agricultural non-point source pollution at the Poyang Lake basin. Eco-ditches and eco-ponds should be transformed according to local conditions of existing drainage ditches and ponds, and this requires guidance from the government and special capital investment. This will have important significance in guiding farmland water conservancy, land leveling, high-standard farmland construction, and other ecological engineering construction.

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