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Supplying demands of aquatic ecosystems using bivariate optimization of water depletion strategies under uncertainty

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ABSTRACT

Water monitoring policies are recommended to ensure ecosystem preservation in industrial and agricultural development. Due to the reduction of water resources and the importance of sustainable rice production, it is necessary to develop relevant policies to promote the optimization of water and fertilizer distribution in rice paddy water environments. This article aims to plan the two objectives of water supply and reducing the environmental effects of nitrates in rice cultivation and analyzing the maximum and minimum benefits. By modifying the methods of fertilization and water distribution, the amount of production can be gradually increased by taking into account the harmful effects on the environment. Water and nitrate have a synergistic effect on the growth of paddy rice. However, the amount of runoff that is affected by nitrates is directly related to the pollution of aquatic environments. The results confirmed the correlation between nitrate concentration and production and reported the reduction of its negative effects depending on the management of inflow and outflow to rice fields. Changing the outflow according to the fertilization time and the inflow rate is an effective solution in the fertilizer nitrogen uptake and reducing the nitrate concentration in surface water sources in the long term.

Key words: ecosystem, production, rice cultivation, water environment

HIGHLIGHTS

- Achieving sustainability in the ecosystem and food security requires the development of research on the correlation between these factors and water resources.
- The multi-objective model increased the sustainability of the ecosystem against pollutants by increasing benefits.

1. INTRODUCTION

Water and nutrients interact with each other to control the amount of production due to the coupling effect created (Sang *et al.* 2023). Studies have shown that there is a significant interaction between nitrogen consumption and water management on nitrogen uptake and utilization and grain yield in rice (Ashouri 2019). The aquatic environment of paddy fields is different from rivers and marine structures. The water in the paddy fields is shallow with little salt. If the water layer is shallow, the energy input by the Sun on the water at the surface of the field and at the bottom is almost the same (Park *et al.* 2013; Zhang *et al.* 2021; Zheng *et al.* 2023). At the same time, water convection and turbulence are weakened and nitrate conversion through diffusion and dispersion is reduced. But the unit's water level has a relatively high contact with the atmosphere and soil and is more sensitive to atmospheric and geographical conditions (Yang *et al.* 2018; Liu *et al.* 2023). In addition, the water surface is relatively small and easily contaminated. The lower the bleaching ability, the weaker the buffering capacity of the water zone, and the more difficult it is to regulate pH and dissolved oxygen. In addition, rice easily casts shadows, reduces light areas, and is affected by water temperature and other factors. Therefore, as a water ecosystem, the paddy field environment is more exposed to pollution than other water streams. On the other hand, the water returned from the paddy field is considered as healthy water and is reused in aquaculture or agriculture industries (Li *et al.* 2023). Therefore, it is necessary to pay attention to the water quality in the paddy fields (Mohammadi *et al.* 2017).

Nitrogen is very important for crop yield, and the use of nitrogen fertilizer in crop production systems is one of the critical aspects of modern crop management practices (Yu *et al.* 2024) and one of the determining factors for increasing crop yield and thus keeping pace with human population growth. However, most of the nitrogen fertilizers added to rice fields are not absorbed by the rice plants, but are lost to the environment as ammonia, nitrates, and nitrogen oxides. This pollutant causes serious environmental problems and harmful effects on human health (Gu & Yang 2022; Hu *et al.* 2022). One of the factors of increasing food production in the world in the past decades has been the use of synthetic nitrogen (N) fertilizer (Tilman 1999). However, the excessive use of nitrogen fertilizer and the reduction of its use efficiency have led to the problems of environmental pollution and nitrogen oxide emissions (Chen *et al.* 2022). Nitrate nitrogen (NO_3-N) leaching has had harmful effects on groundwater and thus has been a major concern for human health in China (Zhang 2016). Therefore, the effective control mechanism of NO_3-N leaching in irrigation water has become an important issue for the development of sustainable agriculture. Field experiments on cereals have shown the effectiveness of nitrogen use in China to be about 27% (Zhang *et al.* 2007).

The effect of nitrate (NO_3) on rice growth as well as N absorption and assimilation during different growth stages was examined using three typical rice cultivars (Duan *et al.* 2006). Dry weight and N uptake were measured with solution culture experiments. Results showed that some replacement of NH_4 with NO_3 could greatly increase the growth of rice plants, mainly on account of the improved uptake of NH_4 promoted by NO_3. Nitrogen deficiency usually occurs in almost all agricultural land, unless nitrogen is applied as fertilizer or manure in the water supply process. In the past decades, the amount of synthetic nitrogen fertilizers used in rice has increased dramatically. However, only less than half of applied fertilizer N can be taken up by crop plants, with most of the unused fertilizer N being uptake into water, which can have severe environmental consequences (Gao *et al.* 2023). Water is the component of nitrogen transfer, which plays an essential role in the control of pollution in the water cycle of rice cultivation (Yang *et al.* 2017; Fang *et al.* 2023).

Yang *et al.* (2018) conducted field experiments in rice-wheat rotation under conventional management to determine the effects of straw return on crop yield, nitrogen uptake, soil properties and soil NO_3-N. The results showed that the return of straw significantly increases crop yield and nitrogen absorption. To improve the current practice of rice irrigation in the future, long-term observations of crop yield and leaching of nitrogen nitrate are necessary to identify environmentally friendly practices. Rezayati *et al.* (2020) simulated water level fluctuations and nitrate transport during two crop years based on three irrigation regimes. The simulation results showed that the HYDRUS-2D model has a good ability to simulate water movement and nitrate transfer from chemical or compost sources. Therefore, it can be used to manage irrigation and fertilizer in the case of paddy fields to analyze different scenarios.

This paper uses experiments to study the overall benefits of water allocation for the aquatic rice ecosystem to evaluate the effects of NO_3 fertilizer on environmental factors and yield production. Previous studies have confirmed that the water environment indirectly affects rice yield, but the simultaneous optimization of fertilizer application and water allocation has not been researched. The application of these two goals in the rice field provides the possibility of increasing water productivity and protecting the environment. On the one hand, the increase in water absorption reduces the nitrate concentration, and on the other hand, the increase in nitrate helps to improve production and increase economic profit. The optimization model with two objective functions has been developed using the extremal algorithm under uncertainty conditions.

2. METHODOLOGY

2.1. Methods

Conducting field experiments to determine the optimal strategy for managing water consumption in paddy fields is very time-consuming and expensive (Rezayati *et al.* 2020). The use of decision-making models based on artificial intelligence in combination with experimental information is a solution for accurate and validated conclusions (Bortolan & Degani 1985). Therefore, a two-objective optimization model was developed for the paddy water ecosystem.

2.1.1. Objective functions

As two different sides have been raised in the problem, the use of an optimization model with two objectives and two decision criteria was considered. The dependence of rice production on water and nitrate fertilizer has been measured in this research. Increasing the inflow and decreasing the outflow will reduce the concentration of nitrates and increase plant consumption and prevent environmental degradation. This objective, which is shown mathematically by Equation (1), was considered as the first objective function (WF). Increasing nitrate improves production efficiency, but has negative environmental consequences. Therefore, the minimization of nitrate reduction was formulated as the second objective function (NF) in Equation (2). The two decision criteria of water demand and rice production were also used in objective functions to control and improve the optimization process. Therefore, two objective functions have been defined for the problem as:

$$\text{Maximize WF} = \frac{(W_{\text{in}} - W_{\text{out}})}{W_D} \tag{1}$$

$$\text{Minimize NF} = \frac{(N_p - N_R)}{\text{RP}} \tag{2}$$

where $W_{\text{in}} = \text{inflow (L.s}^{-1})$, $W_{\text{out}} = \text{outflow (L.s}^{-1})$, and $W_D =$ paddy water demand, RP = the expected production of rice cultivation, $N_P =$ nitrate concentration of fertilizer (mg·L^{-1}), and $N_R =$ nitrate concentration of river (mg·L^{-1}).

2.1.2. Multi-objective optimization

In solving multi-objective optimization problems, the objective functions are usually in conflict with each other. This means that with the improvement of one function, another function will decrease (Lalehzari *et al.* 2016). Therefore, the objective functions will be relatively improved at the same time. The concept of Pareto is defined for responses that have reached a level of progress corresponding to the objective function. The best solution in the multi-objective optimization system is that the response (1) should not be worse than the others in any of the goals and (2) should be optimal than others in at least one goal.

The extremal optimization algorithm is a heuristic algorithm developed by Boettcher & Percus (2003). The most obvious difference between the extreme optimization algorithm and other heuristic algorithms such as the genetic algorithm is that the competence of the cells (local competence) needs to be determined in addition to the overall competence of the solution. In fact, this feature is the core of the extremal optimization algorithm. Solving the problem has two steps: first, it needs to find an executable schedule, so that all the constraints are set. Second, this schedule must be optimal, in which case it is necessary that the objectives of the problem achieve the best value.

2.1.3. Correlation coefficient

Pearson's correlation coefficient was used to determine the correlation between factors effective in decision making. To calculate the Pearson correlation, the standard deviation of each variable was determined and then the covariance between them was calculated. Standard deviation is defined as a measure of the dispersion of data from its average. Covariance indicates whether the variables tend to move in the same direction, while the correlation coefficient measures the strength of that relationship on a normalized scale, from −1 to 1. Therefore, the Pearson correlation coefficient, as shown in the equation below, was obtained by dividing the covariance by the product of the standard deviation of two variables.

$$\rho_{xy} = \frac{\text{Cov}(x, y)}{\sigma_x \sigma_y} \tag{3}$$

where ρ_{xy} = Pearson product–moment correlation coefficient, $\text{Cov}(x,y)$ = covariance of variables x and y, σ_x = standard deviation of x; σ_y = standard deviation of y.

Equation (3) was elaborated as follows:

$$\text{CC} = \frac{n \times \left(\sum_{i=1}^{n} (x, y) - \left(\sum_{i=1}^{n} (x) \times \sum_{i=1}^{n} (y) \right) \right)}{\sqrt{\left(n \times \sum_{i=1}^{n} (x^2) - \sum_{i=1}^{n} (x)^2 \right) \times \left(n \times \sum_{i=1}^{n} (y^2) - \sum_{i=1}^{n} (y)^2 \right)}} \tag{4}$$

where *CC* refers to correlation coefficient; *n* refers to the number of observations.

Table 1 | Data series of water flow and nitrate concentration

				NO_3 concentration ($mg{\cdot}L^{-1}$)					NO_3 concentration ($mg{\cdot}L^{-1}$)	
Farm	**Data series**	**Inflow rate $L.s^{-1}$**	**Outflow rate $L.s^{-1}$**	**River**	**Fertilizer**	**Data series**	**Inflow rate $L.s^{-1}$**	**Outflow rate $L.s^{-1}$**	**River**	**Fertilizer**
F1	S1	7.3	4.1	11.2	68.4	S4	7.4	4.2	11.3	66.9
	S2	8.2	4.4	11.1	71.2	S5	7.2	4.1	11.2	65.7
	S3	6.9	3.9	11.2	65.4	S6	7.9	4.9	11.1	70.6
F2	S1	8.7	4.1	10.6	86.4	S4	7.7	4.2	10.7	76.8
	S2	9.1	4.2	10.5	87.3	S5	8.1	4.5	10.6	79.1
	S3	9.6	4.3	10.7	76.4	S6	8.6	4.7	10.6	77.8
F3	S1	6.2	3.2	11.1	65.4	S4	6.1	3.1	11.2	82.6
	S2	5.4	2.8	11.3	63.2	S5	6.4	3.4	11.2	89.1
	S3	6.1	3.1	11.2	71.8	S6	6.3	3.3	11.4	92.1
F4	S1	4.2	2.3	12.3	56.7	S4	4.3	2.1	11.8	62.4
	S2	3.7	1.6	12.0	55.4	S5	4.7	2.6	11.7	47.9
	S3	3.1	1.2	11.9	62.2	S6	4.1	2.0	12.1	56.4

2.1.4. Experimental design

In this experiment, 24 quality samples of river water were measured for four rice fields (F1, F2, F3, and F4). The application rate of nitrogen fertilizer and the volume of water inflow and outflow to the plots were collected. The obtained information is summarized in Table 1. The concentration of fertilizer nitrate was measured from the combination with irrigation water. In other words, the concentration of irrigation nitrate before and after fertilization is recorded as river and fertilizer information.

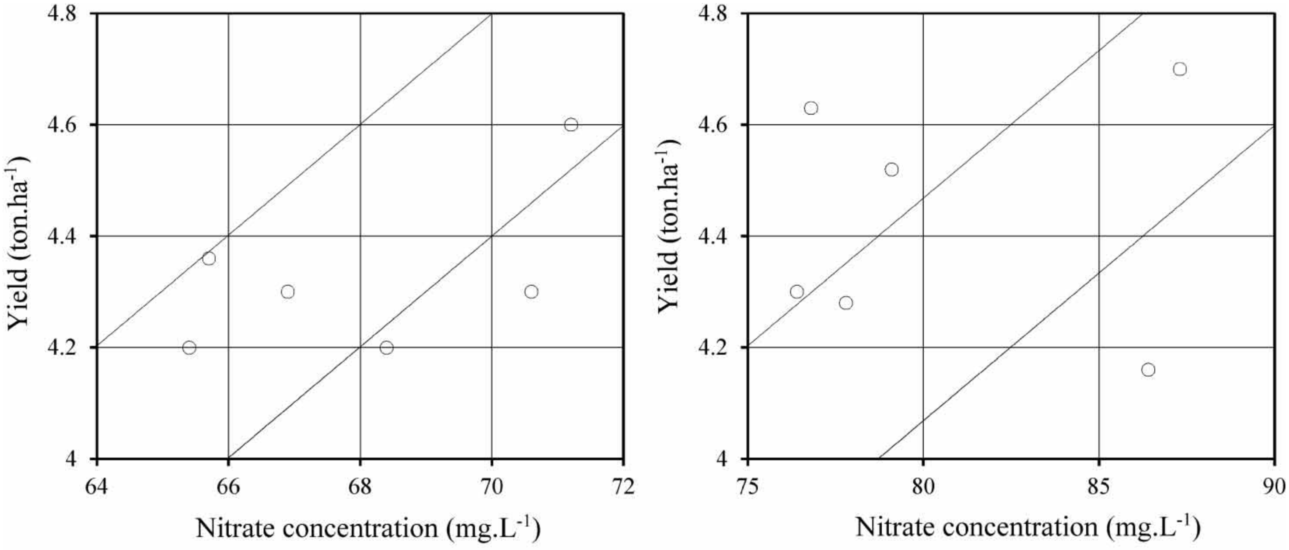
3. RESULTS AND DISCUSSION

3.1. Nitrate concentration and rice production

Figure 1 shows the correlation between production and nitrate concentration of irrigation mixed with fertilizer. The results showed that the total correlation coefficient for all samples was 0.61, which indicates the effective trend of nitrate fertilization on production. It is necessary to explain that the results were calculated based on one fertilization stage in the rice growing season. Depending on the local irrigation schedule, between one and four fertilization stages may be applied during the growing season. In the F1 test, the correlation coefficient of 0.63 reported that in two plots S3 and S4, the increase in nitrate concentration did not improve the production. In experiment F2, the correlation coefficient was the lowest, and in two plots S1 and S4, there is a direct relationship between nitrate concentration and production. The decrease in the correlation coefficient in this farm was due to the higher than average potential production, which did not show a significant effect of nitrate increase. The highest correlation coefficient equal to 0.67 was obtained for the F3 farm. In the F4 farm, according to the distribution indicated in Figure 1, the results showed a significant relationship between fertilization and production.

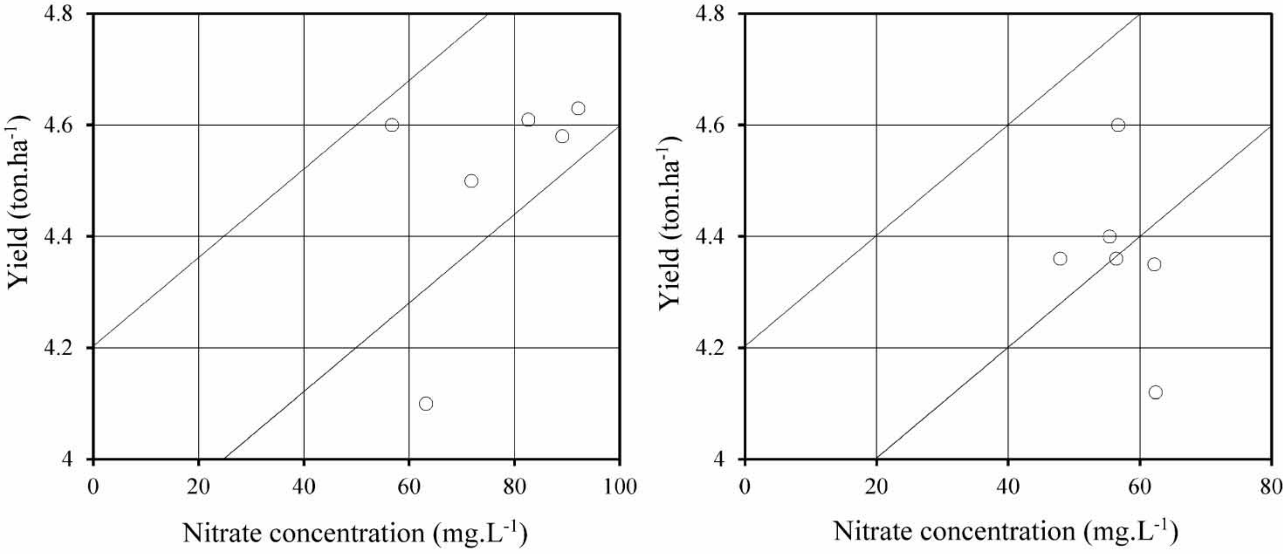
3.2. Inflow rate and rice production

The relationship between allocated water volume and rice production is a challenge in water management and food security (Chou *et al.* 2022). The average correlation coefficient in 24 tests was estimated at 0.74. A summary of the results obtained for each farm is presented in Figure 2. The highest correlation of 0.81, 0.75, and 0.61 was calculated for F3, F1, and F2, respectively. Creating a balance between inflow and outflow is also one of the factors that can affect the results. In F3 blocks, the outflow rate was adjusted by overflows with a height corresponding to the growth stage, while in F4, the height of the outflow was fixed. These policies have been implemented by farmers in current conditions and require economic analysis. Farmers in the F4 experiment have reported that changing the height of the overflow requires additional costs to control the flow. Increasing the amount of flow received by the plots reduces the concentration of nitrate in the plot and increases the outflow of nitrate as an advection process. Therefore, finding the optimal values of water flow and nitrate concentration can reduce the production and environmental damage in the aquatic ecosystem of rice cultivation.



F1: Correlation coefficient = 0.63

F2: Correlation coefficient = 0.41



F3: Correlation coefficient = 0.67

F4: Correlation coefficient = 0.52

Figure 1 | Evaluation of correlation between nitrate concentration and rice production.

3.3. Optimal flow and nitrate concentration

The application of two-objective optimization causes the solutions to move toward the Pareto front. In a decision space as shown in Figure 3, the optimal solution is obtained by approaching the solutions to the horizontal and vertical axes. The range of motion in the possible range is indicated by the directions. Entering the solutions into the green squares indicates that the values are optimized, and the bold green cell shows the best solutions. According to the results obtained in the F1 farm, three blocks S1, S3, and S4 have reached the highest level of optimality. The reason why some blocks such as S2 did not enter the optimal range is that the correlation between production and objective functions was low. In these blocks, there have been other production controlling factors that must be addressed separately. The best solution for each farm is indicated in the figure. Achieving optimal values also depends on monitoring and controlling constraints. In this research, to increase the practical aspect of the problem, the constraints were summarized only in rice production, and the primary production limit was considered as a decision criterion and definition of the error function.

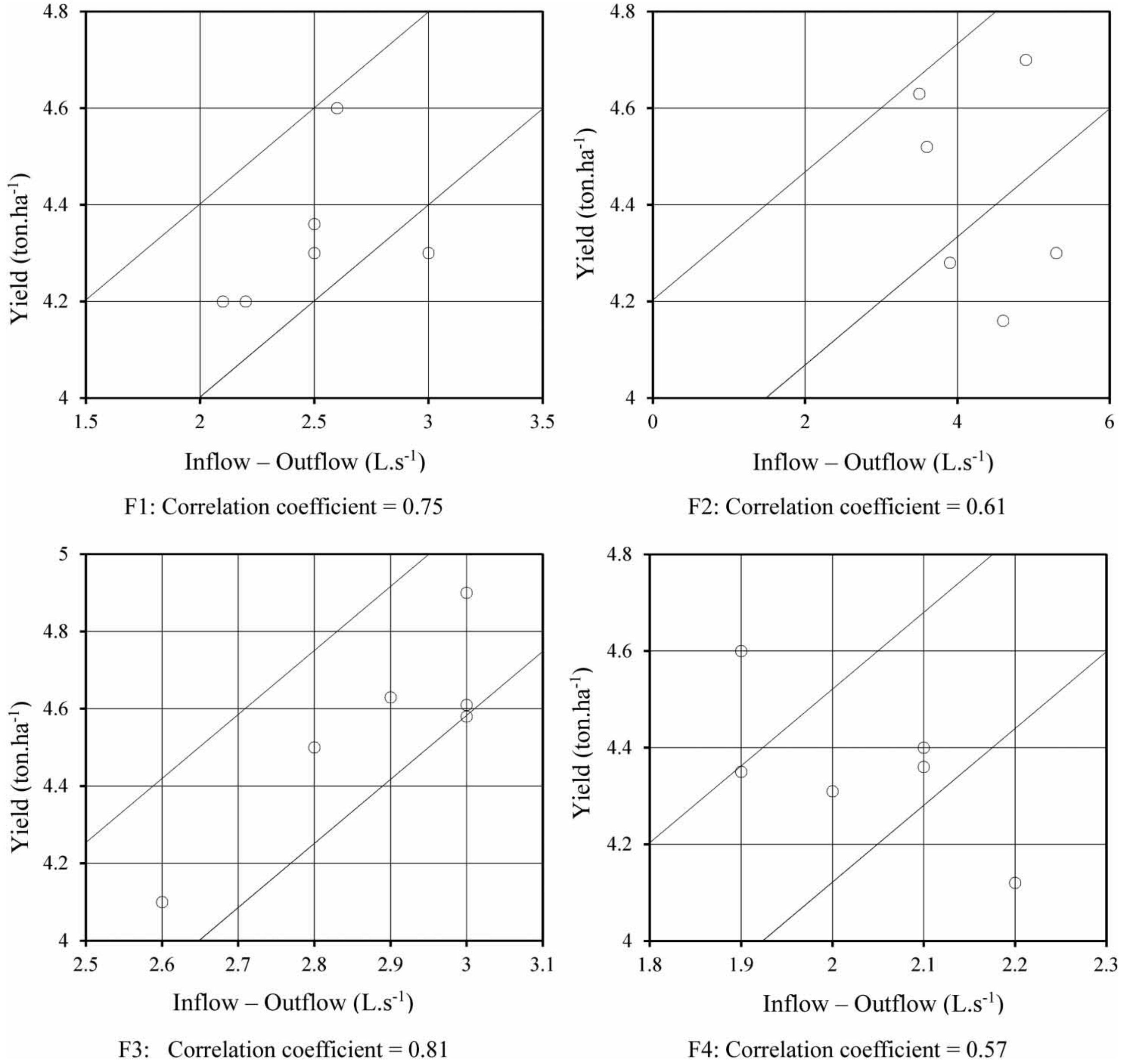
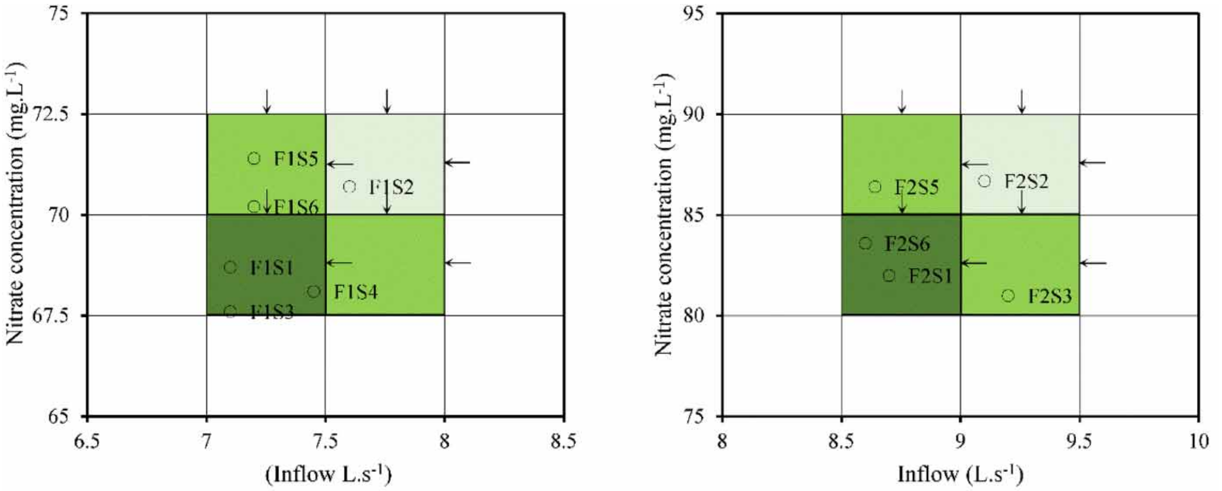


Figure 2 | Evaluation of correlation between the water flow and yield.

3.4. Uncertain values of nitrate in the river ecosystem

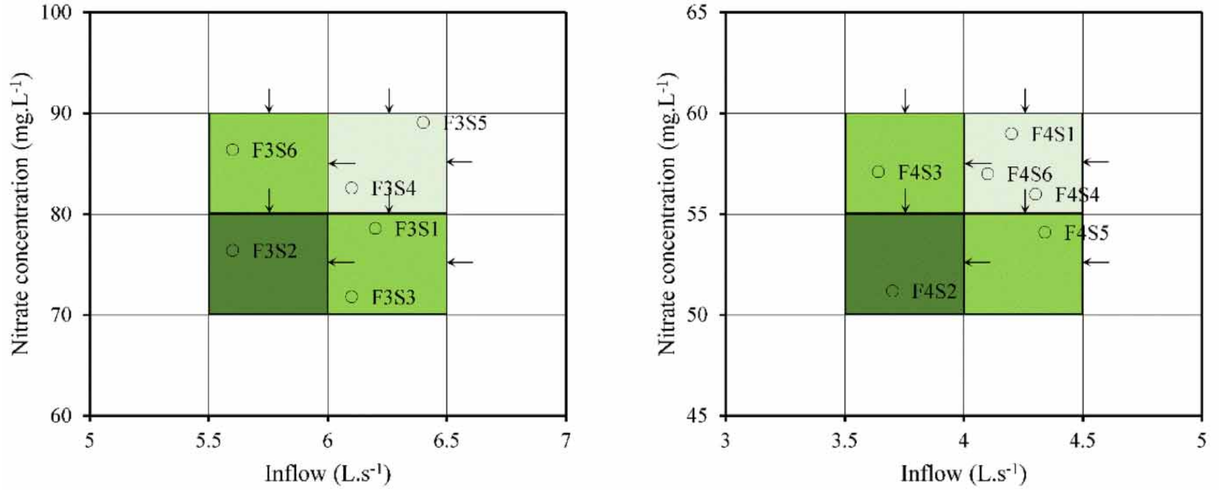
The final achievement of this research was the evaluation of the effect of optimal responses on the nitrate concentration outflow of the paddy field and the improvement of the final quality of the river. Changes in river water quality for each of the plots in different fields are shown in Figures 4–7. Nitrate concentration before optimization, the crisp optimal value obtained from the extremal optimization model and the maximum and minimum limits that may occur due to the uncertainty analysis are drawn. In F1, the average decrease in nitrate concentration was estimated to be 2.3 mg·L^{-1}, which was the largest decrease in plot S4. Plot S1 has minimal changes in river water quality due to fluctuations in outflow (Figure 4).

The average decrease in nitrate concentration in F2 was 1.86 mg·L^{-1}, which is almost the same in all plots (Figure 5). The range of maximum and minimum estimated changes ranged from 1.2 mg·L^{-1} (S2) to 1.67 mg·L^{-1} (S6). In the best situation, using the optimal plan will reduce the nitrate concentration to 7 mg·L^{-1}.



F1: Best solution = F1S3 (Inflow=7.1 L.s^{-1}, NO_3 = 67.5 mg.L^{-1})

F2: Best solution = F2S3 (Inflow=8.7L.s^{-1}, NO_3 = 82.2 mg.L^{-1})



F3: Best solution = F3S2 (Inflow=5.6 L.s^{-1}, NO_3 = 78.6 mg.L^{-1})

F4: Best solution = F4S2 (Inflow=3.7 L.s^{-1}, NO_3 = 51.5 mg.L^{-1})

Figure 3 | Spatial distribution of solutions in optimal domain.

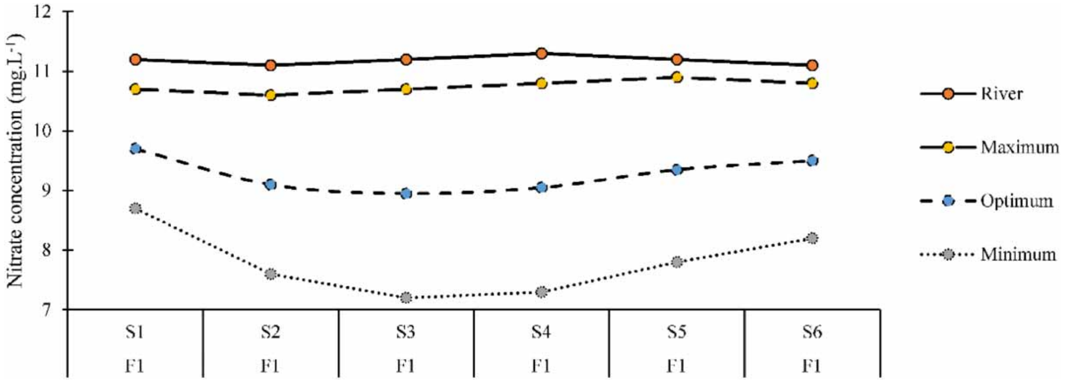


Figure 4 | Responses of the uncertain model to decrease the nitrate concentration in F1.

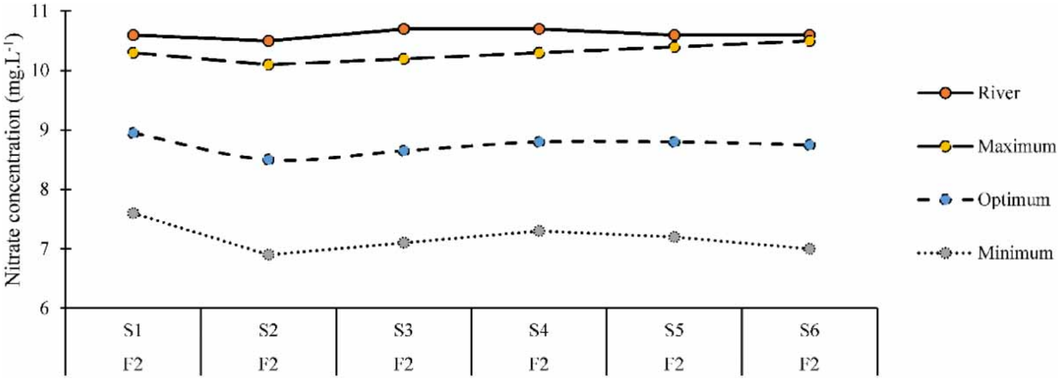


Figure 5 | Responses of the uncertain model to decrease the nitrate concentration in F2.

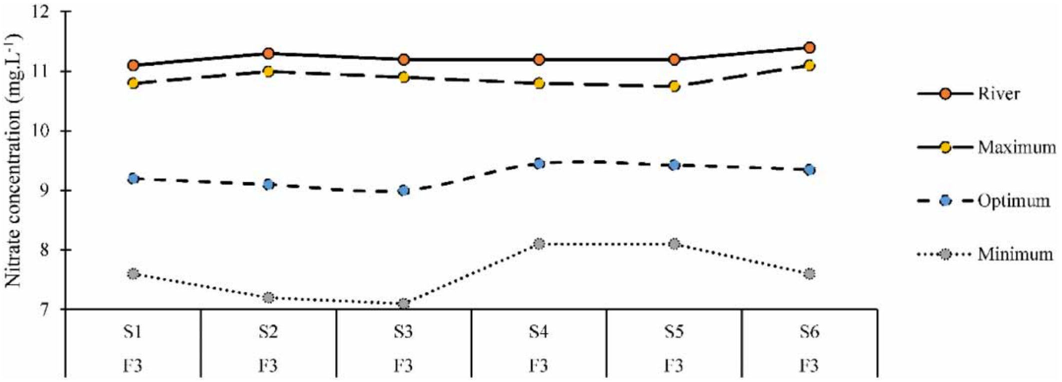


Figure 6 | Responses of the uncertain model to decrease the nitrate concentration in F3.

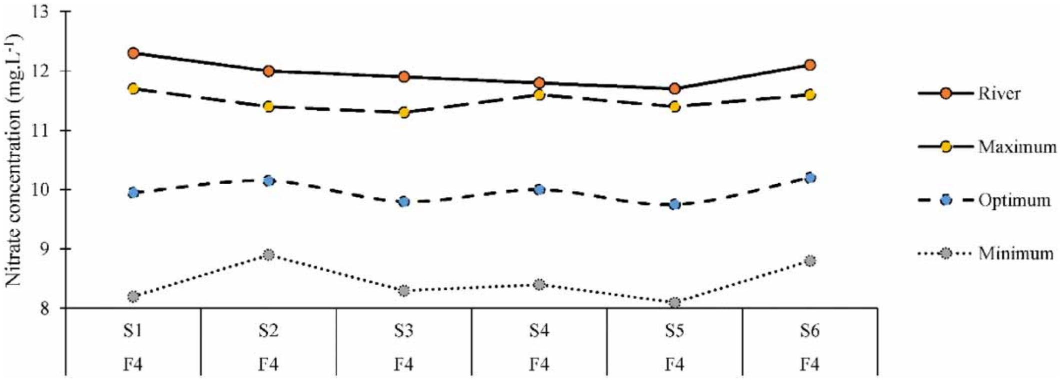


Figure 7 | Responses of the uncertain model to decrease the nitrate concentration in F4.

Changes in F3 and F4 farms have been associated with more fluctuations. Plot F3S3 has the highest range of uncertainty and F4S2 has the lowest sensitivity (Figures 6 and 7). The reduction of nitrate concentration in river water is not limited to the calculations made in this research and other factors are also involved. The processes of convection, dispersion and diffusion are among the components that affect the quality of river water in different locations. The results of this research can be investigated from the aspect of nitrates coming out of the paddy field, and the role of other factors should be investigated separately.

4. CONCLUSION

With increasing population and demand for food, cultivation of rice and providing the needs of water ecosystems have become an effective model for increasing agricultural production and efficiency and increasing the efficiency of water allocation in one season. However, water recycling technology is not developed in every region, and farmers usually cannot manage the water allocation of the river ecosystem and thus cannot achieve maximum economic benefits. Therefore, it is necessary to experiment with the water allocation needs of the ecosystem in rice paddies to find the density range that can achieve the most benefit. This article has two research objectives: increasing the efficiency of water consumption and decreasing the nitrate concentration of the ecosystem downstream of rice fields. Compared to other research models, the data accuracy of the bi-objective optimization method proposed in this article has increased, and the practicability and accuracy are higher. In this way, it can provide a reference for increasing income and rational use of water resources for farmers. One of the main limitations of the research was the control of the quality of the output stream from paddy farming for the ecosystem, which can be considered in future studies.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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