Effects of different irrigation-fertilization combinations on rice yield, water use and Non-point pollution discharge in typical hilly land of Southern China

Cheng Lu¹, Menghua Xiao and Xinkai Qiu
Zhejiang Institute of Hydraulics and Estuary, Hangzhou 310020, China.

¹ Email: lc1001cn@163.com

Abstract. The effects of different irrigation-fertilization combinations on single cropping rice yield, water use and non-point pollution discharge were investigated in field experiment. The result demonstrated that, the average water demand, leakage, irrigation quota and water productivity of intermittent irrigation (II) and rainfall-collect intermittent irrigation (RCII) were 10.9%, 45.2%, 49.0% and 97.7% lower than those of basin irrigation (BI) (\(P < 0.01\)), while II and RCII did not show a significant difference on those parameters (\(P > 0.05\)). The yield and water productivity of three-time fertilization (3TF) were 4.1% and 4.8% higher than two-time fertilization (2TF) (\(P < 0.05\)). The interaction of water and fertilizer on yield achieved 40%, which showed positive influence. The average NO\(_3\)-N and NH\(_4\)+-N discharges of II and RCII were reduced 1.0% and 55.7% respectively compared with BI, while the NO\(_3\)-N and NH\(_4\)+-N discharges of RCII were reduced 1.0% and 67.6% than II; the NO\(_3\)-N and NH\(_4\)+-N discharges of 3TF were reduced 1.0% and 10.2% than 2TF. The optimal method of irrigation-fertilization combination was revealed by using the multi-objective decision model of entropy TOPSIS, the results indicated that, RCII combined with 3TF could optimize the effects of yield-increasing, water-saving, pollution-decreasing and fertilizer-conservation.

1. Introduction
Rice is the basic food to support the needs for above half population of the world. According to the statistics of FAO, in 2014, there were about 163,250,000 ha of paddy field with a production of 740,960,000 t. Paddy field is an important carrier of ecological environment, which is related to regional economic development, social harmony and eco-environment improvement [1, 2]. However, the sustainable development of paddy field is still restricted by the inefficient usage of water and fertilizer, the waste of water, and the discharge of non-point pollution. Therefore, the study of water-saving and pollution-decreasing on paddy field has practical meanings [3, 4, 5].

High water demand for rice restricts the planting area of rice in China. Different irrigation methods have been studied to ease the contradiction between water supply and water demand, and the methods were transit from basin irrigation to thin-water-layer irrigation to no-water-layer irrigation [6, 7, 8]. Rice belongs to swamp crops, its tolerance to flood makes it possible to store certain amount of water in paddy field after rain, meanwhile, the utilization of rain-fall is increased, the irrigation water is saved, and the regional drainage pressure is reduced. Paddy field is one kind of artificial wetland, which can purify the water after fertilization and insecticide, if it is stored in the field for several days [9, 10]. Some research proved that, by controlling the water conditions of paddy field, irrigation methods could ensure the yield, reduce the discharge of CH\(_4\), N\(_2\)O and NH\(_4\)+-N[11, 12]; By controlling
the amount of irrigation water, it could also increase the water use efficiency[13, 14], reduce the total nitrogen discharged with surface runoff[15, 16]. XU (2012) proved the discharge of NH₄⁺-N was reduced 23.2% when the paddy field is alternated between dry and wet, compared with flooding irrigation [17]. XIAO (2015) proved the concentration of NH₄⁺-N and NO₃⁻-N in the paddy field were decreased 55.56% and 42.81% respectively, when the water was stored in the paddy field for 5 days [18]. XU (2007) observed the concentration of total nitrogen and total phosphorus in field drainage were decreased significantly through the drainage ditch [19].

The water-saving irrigation methods combined with rational fertilization techniques could reduce the irrigation water amount, drainage water amount and non-point pollution discharge, and increase the nitrogen use efficiency. However, current researches focus more on the adjustment of top and bottom limitations of irrigation water level; on the opposite, the research on controlling the water depth of paddy field after rain to optimize the effects of rainfall-storage, water-saving, pollution-decreasing is needed. Meanwhile, the interaction of irrigation and fertilization, and their effect on non-point pollution discharge are also the focus of recent research [20, 21, 22].

In this research, field experiments were conducted to reveal the effects of different irrigation-fertilization combinations on single cropping rice yield, water demand and non-point pollution discharge. Three irrigation methods (BI, II and RCII) and two fertilization techniques (2TF and 3TF) were tested, among them, the rainfall-collect intermittent irrigation method (RCII) was proposed based on years of field experiments in irrigation experiment station of Zhejiang province, China. It concerned more on the controlling of paddy field water depth after rain, and the top and bottom limitations of irrigation have been adjusted accordingly to enhance the effects of rainfall utilization, water saving, pollution decreasing. Quantitative research on water-fertilizer interaction of rice yields has also been done, multi-objective decision model of entropy TOPSIS was used to reveal the optimal method of irrigation-fertilization combination.

2. Methodology

2.1. Experimental site and the soil properties

The experiment was conducted in Yongkang irrigation experiment station (120°12′ E, 28°24′ N, 85.4m ASL) of Zhejiang province, China from June 30th to October 18th, 2015. The station area belongs to subtropical monsoon climate, the rainfall in rice growing season was 493 mm, and it was high flow year relatively in 2015. The experiment was carried out in 24 standard experiment districts (6 × 22-m), each district was brick settled and covered by two layers of fabric and one layer of membrane to prevent lateral leakage. The soil texture was clay loam, the soil bulk density was 1.45 gꞏcm⁻³, the soil porosity was 0.43, the pH value was 5.41, the soil organic matter content was 27.17 gꞏkg⁻¹, and the groundwater level was 0.8 m.

2.2. Treatments and design

Three irrigation methods were tested: W₀ Basin irrigation (BI), W₁ intermittent irrigation (II) and W₂ rainfall-collect intermittent irrigation (RCII). RCII utilized the flood-enduring capacity of paddy rice, and was adapted to the traits of rainfall in south china. It could save the irrigation water supplied by reservoirs, cut the frequency of irrigation and improve the utilization rate of rainfall in hilly regions by increasing the amount of water stored in rice field after rain. The field water level control index of all the irrigation methods is showed in Table 1.

Two fertilization techniques were tested: F₁ two-time fertilization (2TF) (50% basic fertilizer and 50% in tiller stage), F₂ three-time fertilization (3TF) (50% basic fertilizer, 30% in tiller stage and 20% in jointing stage). The quantity of fertilizer was based on the recommended indexes from soil testing (N--225 kgꞏhm⁻², P₂O₅--100 kgꞏhm⁻², K₂O--120 kgꞏhm⁻²).

The design of treatment was a completely random design. Treatment combinations (showed in Table 2) had three replications. The crop was transplanted at 20 × 20-cm spacing with 3-5 seedling per hill. Seeding age was 30days. The variety used was Zhongzheyou1.
Table 1. The control indexes of field water level

| Growth stage                  | Basin Irrigation (BI)       | Intermittent irrigation (II) | Rainfall-collect intermittent irrigation (RCII) |
|-------------------------------|----------------------------|------------------------------|-----------------------------------------------|
| Greenup                       | 20 mm--30 mm--50 mm         | 10 mm--30 mm--40 mm          | 10 mm--30 mm--50 mm                           |
| Early tillering               | 20 mm--50 mm--70 mm         | *1~2 d--30 mm--50 mm         | *1~2 d--30 mm--70 mm                          |
| Late tillering                | 30 mm--60 mm--90 mm         | *7~12 d--0 mm--0 mm          | *7~12 d--0 mm--90 mm                          |
| Jointing-booting              | 30 mm--60 mm--100 mm        | *2~4 d--30 mm--60 mm         | *2~4 d--30 mm--120 mm                         |
| Head-flowering                | 10 mm--50 mm--100 mm        | *2~4 d--30 mm--60 mm         | *2~4 d--30 mm--100 mm                         |
| Milk-ripe                     | 10 mm--50 mm--60 mm         | *2~4 d--30 mm--50 mm         | *2~4 d--30 mm--60 mm                          |
| Yellow maturity               | 0 mm--0 mm--20 mm           | Set drying                  | Set drying                                   |

* Take early tillering stage as example. 20mm--30mm--50 mm means min irrigation level--max irrigation level--max of rainfall storage level, 1~2 d--30 mm--50 mm means revealing the field surface for 1-2 days--refill water to 30mm--max rainfall storage to 40mm.

b The indexes with mark “*” means letting the field surface reveal.

Table 2. Experiment settings.

| Combination | Irrigation methods | Fertilization Methods |
|-------------|--------------------|----------------------|
| W0 F1       | W0                 | F1                   |
| W0 F2       | W0                 | F2                   |
| W1 F1       | W1                 | F1                   |
| W1 F2       | W1                 | F2                   |
| W2 F1       | W2                 | F1                   |
| W2 F2       | W2                 | F2                   |

2.3. Parameter measurements and analytical method

The irrigation quota was determined by reading flow meters installed in the irrigation pipes of the districts. The water consumption was determined by reading the point paddy field water level gauge. The leakage was determined by reading the lysimeter. The water demand was calculated by subtracting the leakage from water consumption. The yield was measured from the each district. The water productivity was calculated by dividing yield by corresponding irrigation quota. The water discharge was determined by reading the point gauge to obtain the difference of water level before and after the drainage. The discharged water samples were collected to analysis the concentration of NO3--N, NH4+-N. Multiplies the concentration and discharge quantity could engender the nitrogen containing pollution discharge amount.

Statistical analyses consisted of analysis of variance. When irrigation or fertilization effects were significant, Duncan’s test was performed to analyze the effects of irrigation or fertilization on water demand, yield and water productivity. The multi-objective decision model of entropy TOPSIS was used to evaluate the six combinations of treatments. The ideal solution and negative ideal solution were calculated by weighting decision matrix of the parameters. The combinations were ranked by their distance to the real outputs and ideal result, which had the closest Euclidean distance to the ideal solution meant to be the optimal choice.

3. Results and analysis

3.1. Effects of irrigation-fertilization combinations on water use

The effects of different irrigation-fertilization combinations on water demand (Table 3 and Table 4), leakage (Table 3 and Table 5) and irrigation quota (Table 3 and Table 6) were large. The result
indicates that differences between irrigation treatments in water demand \((P<0.01)\), leakage \((P<0.05)\) and irrigation quota \((P<0.01)\) of single cropping rice were significant; while differences between fertilization treatments in water demand, leakage and irrigation quota were not significant \((P>0.05)\).

**Table 3.** Effects of irrigation-fertilization combinations on water demand and irrigation quota

| Combinations | Water demand/(mm) | Leakage/(mm) | Irrigation quota/(m³·hm⁻²) |
|--------------|------------------|--------------|-----------------------------|
| W₀ F₁        | 480.8 a A        | 23.0 a A     | 3412 a A                    |
| W₀ F₂        | 467.8 a AB       | 24.3 a A     | 3329 a A                    |
| W₁ F₁        | 416.5 b B        | 13.3 b B     | 1718 b B                    |
| W₁ F₂        | 429.4 b AB       | 13.3 b B     | 1710 b B                    |
| W₂ F₁        | 422.5 b B        | 12.2 b B     | 1718 b B                    |
| W₂ F₂        | 422.9 b B        | 13.1 b B     | 1736 b B                    |

**Table 4.** ANOVA of irrigation-fertilization combinations affecting water demand

| Variation sources | SS   | df  | MS    | F         | P-value | F crit  |
|-------------------|------|-----|-------|-----------|---------|---------|
| Irrigation        | 10596.09 | 2   | 5298.045 | 13.03827 | 0.00098 | 3.8852938 |
| Fertilization     | 0.027222 | 1   | 0.027222 | 6.7E-05  | 0.993604 | 4.7472253 |
| Interaction       | 505.9344 | 2   | 252.9672 | 0.622542 | 0.553043 | 3.8852938 |
| Internal          | 4876.148 | 12  | 406.3457 |           |         |         |
| Total             | 15978.2 | 17  |       |           |         |         |

**Table 5.** ANOVA of irrigation-fertilization combinations affecting leakage

| Variation sources | SS   | df  | MS    | F         | P-value | F crit  |
|-------------------|------|-----|-------|-----------|---------|---------|
| Irrigation        | 457.09 | 2   | 228.545 | 305.793546 | 5.07814E-11 | 3.885293835 |
| Fertilization     | 2.42  | 1   | 2.42   | 3.237963562 | 0.097126219 | 4.476225347 |
| Interaction       | 1.33  | 2   | 0.665  | 0.889770979 | 0.436193096 | 3.885293835 |
| Internal          | 8.9686 | 12  | 0.747383333 |          |         |         |
| Total             | 469.8086 | 17  |       |           |         |         |

**Table 6.** ANOVA of irrigation-fertilization combinations affecting irrigation quota

| Variation sources | SS   | df  | MS    | F         | P-value | F crit  |
|-------------------|------|-----|-------|-----------|---------|---------|
| Irrigation        | 10896726 | 2   | 5448363 | 540.4725 | 1.75E-12 | 3.8852938 |
| Fertilization     | 2679.852 | 1   | 2679.852 | 0.265839 | 0.615503 | 4.7472253 |
| Interaction       | 8214.11 | 2   | 4107.055 | 0.407416 | 0.674233 | 3.8852938 |
| Internal          | 120968.9 | 12  | 10080.74 |          |         |         |
| Total             | 11028589 | 17  |       |           |         |         |

Duncan’s test showed that the water demand, leakage and irrigation quota of were 10.8%, 43.8% and 49.1% higher in BI than in II \((P<0.01)\), respectively, and were 10.9%, 46.5% and 48.8% higher in BI than in RCII \((P<0.01)\), respectively. RCII had 0.05% lower water demand, 4.9% lower leakage and 0.8% higher irrigation quota than II, but all the comparison did not result in significant differences \((P>0.05)\).

### 3.2. Effects of irrigation-fertilization combinations on yield and water productivity

The effects of different irrigation-fertilization combinations on yield and water productivity were shown in Figure 1.
Figure 1. Effects of irrigation-fertilization combinations on yield and water productivity.

Figure 2. The discharging amount of non-point pollution (with nitrogen) under different irrigation-fertilization combinations.

The result indicates that difference between fertilization treatments in yield (Table 7) of single cropping rice was significant ($P<0.05$), but differences between irrigation treatments in yield was not ($P>0.05$). Duncan’s test showed that, the yield was 4.1% higher in 3TF than in 2TF, while the increasing of yield achieved 7.7% under RCII ($P<0.05$).

Table 7. ANOVA of irrigation-fertilization combinations affecting yield

| Variation sources | SS    | df  | MS     | F      | P-value | F crit   |
|-------------------|-------|-----|--------|--------|---------|----------|
| Irrigation        | 33381 | 2   | 16690.5| 0.346317 | 0.714129 | 3.885294 |
| Fertilization     | 617716.1 | 1 | 617716.1 | 12.81722 | 0.003781 | 4.747225 |
| Interaction       | 230931 | 2   | 115465.5 | 2.395836 | 0.133206 | 3.885294 |
| Internal          | 578331 | 12  | 48194.25 |        |         |          |
| Total             | 1460359 | 17 |        |        |         |          |

Quantitative calculation was done to determine the water-fertilizer interaction, take RCII as example, the effect of interaction was calculated by subtract irrigation effect (yield of treatment W2F1 minus treatment W0F1) and fertilization effect (yield of treatment W0F2 minus treatment W0F1) from total yield increasing (yield of treatment W2F2 minus treatment W0F1). The result indicated (Table 8) that water-fertilizer positive interaction was existed in paddy field in this research, and it had a contribution rate of 40% on yield increasing.

Table 8. Contribution of irrigation and fertilization to yield increasing

| Irrigation Methods | Water-fertilizer Combination | Irrigation Method | Fertilization Method | Interaction |
|--------------------|------------------------------|-------------------|----------------------|-------------|
|                    | Yield increasing/ (kg·hm$^{-2}$) | Contribution rate/% | Yield increasing/ (kg·hm$^{-2}$) | Contribution rate/% | Yield increasing/ (kg·hm$^{-2}$) | Contribution rate/% |
| RCII               | 315                          | 100               | 37.5                 | 11.9        | 151.5              | 48.1                  | 126                  | 40.0                  |

Difference between irrigation treatments in water productivity (Table 9) was significant ($P<0.01$), difference between fertilization treatments in water productivity was also significant ($P<0.05$). Duncan’s test showed that, the water productivities of II and RCII were 98.2% and 97.1% higher than that of BI, respectively, but it did not result in significant difference between II and RCII ($P<0.05$); the water productivity was 4.8% higher in 3TF than in 2TF ($P<0.05$).
Table 9. ANOVA of irrigation-fertilization combinations affecting water productivity

| Variation sources | SS     | df | MS      | F       | P-value | F crit |
|-------------------|--------|----|---------|---------|---------|--------|
| Irrigation        | 28.0787| 2  | 14.03935| 3.44E-14| 3.885294|
| Fertilization     | 0.204963| 1  | 0.204963| 0.002079| 4.747225|
| Interaction       | 0.099019| 2  | 0.04951 | 0.056384| 3.885294|
| Internal          | 0.161038| 12 | 0.01342 |
| Total             | 28.54372| 17 |         |

3.3. Effects of irrigation-fertilization combinations on the discharge of non-point pollution
The effects of different irrigation-fertilization combinations on nitrogen containing pollution discharge were shown in Figure 2.

The NH$_4^+$-N discharge amounts of II and RCII were 33.0% and 78.3% lower than that of BI, respectively, while the difference between irrigation treatments in NO$_3^-$-N discharge amount was not significant ($P>0.05$). The discharge amounts of NO$_3^-$-N and NH$_4^+$-N were 1.0% and 67.5% lower in RCII than in II, respectively.

Five times of drainages were recorded through the whole growth stage, displacements of BI, II and RCII were 207 mm, 199mm and 191 mm, respectively, and it was 3.9% and 7.7% lower in II and RCII than in BI. The reduction ratios of pollution discharge amount and displacement were compared accordingly, the result indicates that the reduction of the concentration played a major role in non-point pollution discharge reduction in this research.

The discharge amounts of NO$_3^-$-N and NH$_4^+$-N were 1.0% and 10.2% lower in 3TF that in 2TF, fertilize separately could help reducing the non-point pollution discharge.

3.4. Evaluation models for the effects of water-saving and pollutant-reducing
In order to evaluate and rank these 6 kinds of irrigation-fertilization combinations, the data of yield, water productivity and pollutant discharge amount (NO$_3^-$-N and NH$_4^+$-N) were collected to build the matrix (as Y). It was anticipated that higher grain yield and water productivity resulted in a better combination of grain granules, while lower nitrogen pollutants discharge amount led to more environmental profits. With this principle, the standard decision matrix was made (as R). The entropy was defined as: E= (e1, e2, e3, e4) = (0.6027, 0.6028, 0.4472, 0.2069), and entropy objective was defined as: W= (w1, w2, w3, w4, w5, w6) = (0.1856, 0.1856, 0.2583, 0.3705), to measure the weight of all the parameters. The standard decision matrix was $Z = (z_{ij})_{6 \times m}$, which could engender the ideal solution $x^+ = (0.1856, 0.1856, 0.0000, 0.0000)$, and the negative ideal solution $x^- = (0.0000, 0.0000, 0.2583, 0.3705)$. The matrixes was calculated by entropy TOPSIS model, and showed in Figure 3.

Figure 3. The calculation of original matrix and decision matrix by TOPSIS model.
The Euclidean distance between the six combinations and the ideal solution, the Euclidean distance between the six combinations and negative ideal solution, and their proximity ($S_i$) to ideal solution were shown in Table 10. By ranking the proximity from large to small, the “RCII and 3TF” method was chosen to be the best combination (Table 11), which could optimize the effects of yield-increasing, water-saving, pollution-decreasing and fertilizer-conservation.

Table 10. The Euclidean distance of six combinations to ideal solutions and negative ideal solutions and their proximity

| Combination | $d_i^+$ | $d_i^-$ | $S_i$ |
|-------------|---------|---------|-------|
| W₀ F₁       | 0.35608 | 0.59672 | 0.6263 |
| W₀ F₂       | 0.33663 | 0.58020 | 0.6328 |
| W₁ F₁       | 0.40111 | 0.63333 | 0.6122 |
| W₁ F₂       | 0.20564 | 0.45348 | 0.6880 |
| W₂ F₁       | 0.37481 | 0.61222 | 0.6203 |
| W₂ F₂       | 0.13997 | 0.37413 | 0.7277 |

Table 11. Ranking of six combinations by proximity to ideal solution

| Ranking number ($S_i$ from large to small) | Combinations | $S_i$ |
|-------------------------------------------|--------------|-------|
| 1                                         | W₂ F₂        | 0.7277 |
| 2                                         | W₁ F₂        | 0.6880 |
| 3                                         | W₀ F₂        | 0.6328 |
| 4                                         | W₀ F₁        | 0.6263 |
| 5                                         | W₂ F₁        | 0.6203 |
| 6                                         | W₁ F₁        | 0.6122 |

4. Discussion

The water-fertilizer controlling method with effects of water-saving, emission-reduction, yield-increasing and fertilizer-conservation is an important way to ease the regional water shortage, decrease the non-point pollution discharge and achieve the sustainable agricultural development. It could ensure the food security, water security and ecological security. This research explored the effects of pollution decreasing under different irrigation methods (BI, II, and RCII), fertilization methods (2TF and 3TF) by field experiments, theoretical analysis and numerical calculation. The result showed the combination of RCII and 3TF could reduce 10% of water demand, increase 3.35% of productivity and reduce 55.7% of NH₄⁺-N discharge compared with traditional way. The water demand was affected by irrigation, and it was due to the decreasing of irrigation frequency. For instance, water-saving irrigation needs to irrigate twice while BI needs 6 to 7 times. The NH₄⁺-N discharge was affected by irrigation, water-saving irrigation reduced the pollutant concentration of paddy field drainage. The NH₄⁺-N discharge was also affected by fertilization method, the discharge reduced with more frequencies of fertilizer application. Earlier study on water discharging control method in Yinnan irrigation area in Ningxia province showed that NO₃⁻-N discharging was reduced by 13.88 kg, and its concentration was hold below 10 mg/L in gutter waters [23]. The research of irrigation-discharging-wetland management system showed that by increasing the gutter water retention time, the concentration of TN, NH₄⁺-N, NO₃⁻-N in discharging water could decrease 12.08%, 20.33% and 13.5% compared with traditional methods [24]. Besides, the leaching-pit experiments were also done by Menghua XIAO to explore the concentration variations under the control of discharging water, the result revealed that the NO₃⁻-N concentration was reduced by 32.6%-83.7%, and NH₄⁺-N
concentration was reduced by 56.6%-77.5%, whose result was more significant since the leaching-pit experiment had more side-effects than the field experiment in this study [25]. XIAO also found that water-saving irrigation with controlled drainage could help to increase the rainfall utilization efficiency and reduce the drain of Nitrogen, but it will reduce the productivity slightly [26]. In the meanwhile, the RCII with 3TF in this study showed positive effect on paddy rice yield, and showed optimizes effects on water-saving, pollution-decreasing and fertilizer-conservation.

5. Conclusions
In this research, water use of single cropping rice was affected by irrigation, the average amounts of water demand, leakage and irrigation quota of II and RCII were 10.9%, 45.2% and 49.0% lower than that of BI, respectively. But it did not show significant difference on these parameters between II and RCII (P>0.05). Yield was affected by fertilization, the yield of 3TF was 4.1% higher than that of 2TF. The water-fertilizer interactions also had positive effects on yield, which had 40% contribution rate. The NH$_4^+$-N discharge was affected by irrigation and fertilization, the average NH$_4^+$-N discharge of water-saving methods was 55.7% lower than BI, and that of 3TF was 10.2% lower than 2TF. Furthermore, the NH$_4^+$-N discharge of RCII was 67.5% lower than II, it drew the conclusion that RCII was better than II in reducing non-point pollution discharge. The six water-fertilizer combinations were ranked by TOPSIS model, the “RCII and 3TF” showed the optimize effects on water-saving, pollution-decreasing and fertilizer-conservation. Based on this research, this optimized combination was generalized more than 300 hectares in Zhejiang province in 2016 and 2017, it could gain the multipurpose of water-saving, pollution-decreasing and fertilizer-conservation, and it was suitable for rainy rice-growing areas in southern China.

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