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Water-saving irrigation of paddy field to reduce nutrient runoff

Tadayoshi Hitomi[1,*], Yusaku Iwamoto[2], Asa Miura[1], Koji Hamada[1], Kyoji Takaki[1], Eisaku Shiratani[1]

1. National Institute for Rural Engineering, 2-1-6, Kan'nondai Tsukuba City, Ibaraki 305-8609, Japan. E-mail: thitomi@affrc.go.jp
2. Kyusyu Regional Agricultural Administration Office, 1-2, Ninomaru Kumamoto City, Kumamoto 860-8527, Japan

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Abstract

The purpose of this work is to study the effect of a type of water-saving irrigation (WSI) on nutrient runoff of paddy field. The volume of surface drainage was maintained low by WSI. In particular, WSI effectively reduced surface drainage in rain events. Model simulation indicated that net runoff load of total nitrogen (TN) from the paddy field was increased by WSI. Meanwhile, net runoff loads of total phosphorus (TP) and total organic carbon (TOC) from the paddy field was decreased by WSI. Because ponding waters of the study fields were enriched with TP and TOC, WSI reduced runoff of these nutrients by controlling the volume of surface drainage. WSI could be considered an efficient method for reducing runoff loads and could conserve water quality in an agricultural watershed.

Key words: model simulation; net runoff load; storage capacity; surface drainage; tank model; water management

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Introduction

Water management of a paddy field influences the nutrient runoff loads from the field. The runoff loads of nitrogen and phosphorus from paddy fields were reported to be influenced stronger by water management after fertilizer application than by the amount of fertilizer (Oka, 1979). Controlling nutrient matters in turbid surface drainage during the puddling period is a good practice to reduce runoff loads (Kaneki et al., 1998; Kaneko and Yamamoto, 1999). Meanwhile, in the case of that nutrient concentrations of irrigation water are significantly low, the concentration of ponding water is higher than that of irrigation water even during the irrigation period, except for the puddling and fertilizing periods (Misawa, 1987). The dissolved organic matter concentrations of ponding water were reported to be higher than that of irrigation water throughout the irrigation period (Hitomi et al., 2007). Therefore, control of surface drainage plays an important role in reducing runoff loads when the nutrient concentration of irrigation water is low or the concentration of ponding water is kept high over a long term.

Few studies have considered the relationship between water management of a paddy field and runoff loads from the field. Nutrient-reducing effect with water management of a paddy field was investigated during the fertilizing period (Oka, 1979; Hasegawa, 1992); however, no investigation has been studied on the effect of the period without fertilizing. In this study, we investigated the paddy field's nutrient runoff loads after transplanting, as for the irrigation period after transplant, basal fertilizer might not directly influence the paddy's load balance. In a field study, we carried out a peculiar water management regimen to reduce runoff loads throughout the irrigation period. The water management was characterized by using a type of water-saving irrigation (WSI) to control surface drainage. The WSI maintains the ponding water level low by conserving the irrigation water. Moreover, the WSI sets the level of the outlet weir higher than in a conventional irrigation regimen. Regulation under low ponding water level and the high outlet weir level make the storage capacity (SC) of the paddy field high under WSI to control the surface drainage (Fig. 1).

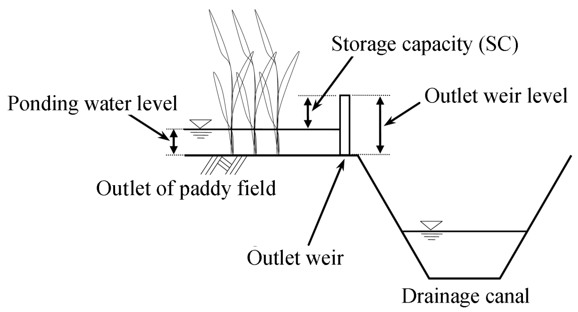

Fig. 1 Storage capacity and outlet weir level.

1 Methods

We investigated two paddy fields located in the lowland creek area facing Ariake Bay, Japan (Fig. 2). This area's

* Corresponding author. E-mail: thitomi@affrc.go.jp

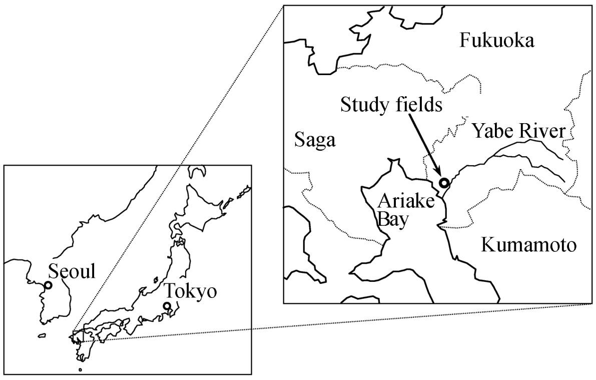

Fig. 2 Site of study fields area.

soil is alluvial soil, and soil texture is SiC. The direct distance between the two fields is around 250 m. Irrigation water for the two fields was pumped up from the creek through a pipeline. Different water management regimens were carried out by cultivators in the two fields. One field (field A) was irrigated in the conventional manner which was common practice in this area, and the other field (field B) was irrigated by the WSI. The cultivator practiced environment conservation agriculture by reducing the amount of pesticides in field B. Therefore, WSI was carried out to avoid losses of the diffused pesticides and preserve their effectiveness. The height of field A's outlet weir was about 7 cm, which is the conventional weir height in the study area. Meanwhile, the height of field B's outlet weir was about 15 cm, which is about twice field A's height. During the mid-summer drainage period, ponding water was forced to be drained off in field A by removing the outlet weir. In field B, the weir was kept in the outlet throughout the irrigation period. Table 1 shows the areas, amounts of fertilizer, and agricultural schedules of the study fields.

Figure 3 shows the points of water sampling and equipment for measuring water balance. The irrigation water and ponding water were sampled once a week, and the infiltration water was sampled once every three weeks. The sampling point of the ponding water was near the outlets and the nutrient concentrations in the surface drainage

Table 1 Agricultural condition and schedule of study fields

		Field A (3685 m^2)	Field B (1001 m^2)
Amount of fertilizer			
Basal dressing	N (kg/ha)	37	43
	P (kg/ha)	14	16
Topdressing	N (kg/ha)	21	21
	P (kg/ha)	8	8
Agricultural schedule			
Basal fertilizer application		Jun 7	Jun 4
start of irrigation		Jun 8	Jun 6
Rough puddling		Jun 8	Jun 6
Pre-transplanting puddling		Jun 10	Jun 9
Transplanting		Jun 11	Jun 10
Mid-summer drainage		Jul 16–28	Jul 13–31
Topdressing		Aug 5	Jul 24
End of irrigation		Aug 29	Aug 24
Harvesting		Sep 15	Sep 19

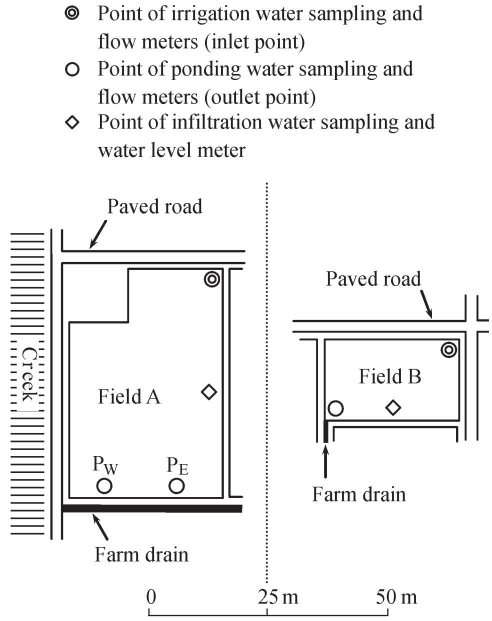

Fig. 3 Points of sampling and measuring equipment.

were considered to be almost equal to those in the ponding water. The infiltration water was taken from a point 1.0 m below the ground, approximately equal to the groundwater level. Concentrations of total nitrogen (TN) and total organic carbon (TOC) were analyzed by a TOC analyzer (TOC-V and TNM-1, Shimadzu, Japan). Concentration of total phosphorus (TP) was analyzed by molybdenum blue-spectrophotometry. The flow rates of irrigation and surface drainage were measured by parshall flume type flow meters. Field A had two outlet points (P_E and P_W), and field B had one outlet point. Changes in ponding water levels were recorded by float-type water level meters. The water level meters were set a few days after transplant. Therefore, ponding water levels were recorded from Jun. 20 at field A, and from Jun 14 at field B. The data of the flow rates and water levels were collected from record of the meters at 2-hour intervals. Amounts of rainfall were estimated from the automated meteorological data acquisition system of Japan Meteorological Agency. Evapotranspiration was calculated by the Makkink method.

2 Results and discussion

2.1 Water quality

The concentrations of TN, TP, and TOC versus time are shown in Fig. 4 during the irrigation period. For nearly the entire irrigation period, TN concentrations in both fields decreased in the order of irrigation water, ponding water, and infiltration water. Meanwhile, the concentrations of TP and TOC in both fields in ponding water were higher than those in irrigation water, for nearly the entire irrigation period. The concentrations of TP in infiltration water in both fields were lower than or equal to those of the irrigation water and ponding water during the irrigation period. In field A the concentrations of TOC in infiltration water were lower than those in irrigation water and ponding water, and

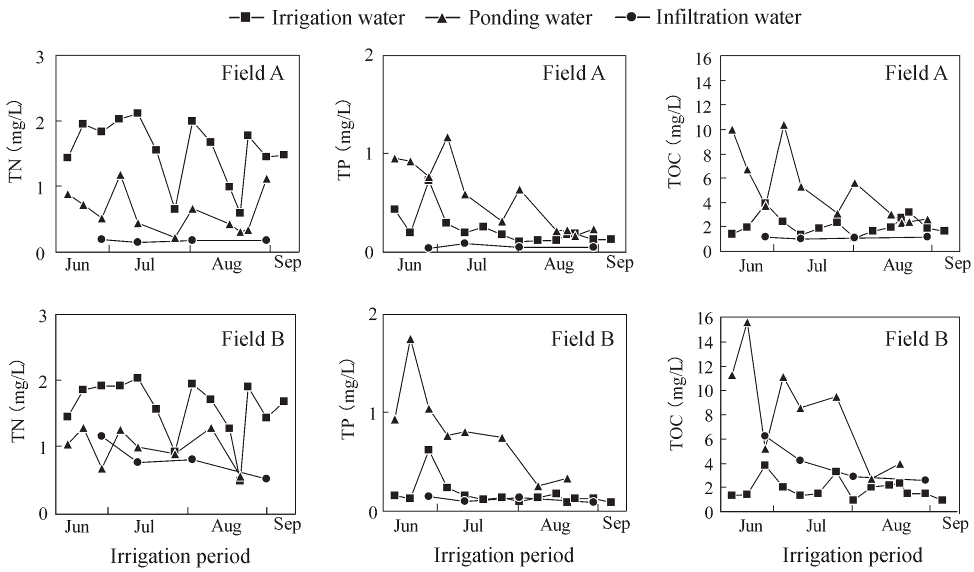

Fig. 4 Time changes of concentrations of TN, TP, and TOC.

in field B the concentrations of TOC in infiltration water were lower than those in ponding water and higher than those in irrigation water.

In paddies, the nutrients in irrigation water are generally removed in case of irrigation with nutrient-enriched water. Irrigation water in a paddy from which nitrogen had been removed was reported to have a nitrogen concentration of more than 2–3 mg/L (Miyoshi, 1978). Furthermore, the nutrient concentrations in irrigation in case where nutrient loads in inflow balanced with those in outflow in the paddy were estimated at about 2.5 mg/L of TN, and 0.25 mg/L of TP (Kunimatsu, 1983). The nutrient concentrations in irrigation of the study fields were lower than the values described above. Therefore, study fields might remove small amounts of nitrogen and phosphorus. On the other hand, TP and TOC concentrations in the ponding water of the study fields showed a tendency to be higher than those of the irrigation and infiltration water. The field studies suggest that the control of surface drainage is an effective practice to reduce runoff loads of TP and TOC.

2.2 Water balances

We can define two ponding terms during the irrigation period: Stage 1 and Stage 2 are the ponding terms before and after the mid-summer drainage. Table 2 shows the water balances in both fields for the irrigation period. Infiltration is estimated from the overall balance of water amounts in irrigation, rainfall, surface drainage, evapotranspiration, and infiltration. The total amount of irrigation in field B was 74 percent that in field A, and the total amount of surface drainage in field B was only 27 percent that in field A. The surface drainage from field B was assumed to be significantly reduced by WSI.

2.3 Surface drainage characteristics

The amount of overflow from the outlet weir is considered to be controlled by outlet weir level (Fig. 1). We estimate the outlet weir level by the following calculation method:

(1) Classify the surface drainage amounts from each outlet according to the ponding water levels when surface drainage occurred.

(2) Calculate the median of the surface drainage amounts in increments of every 5 mm of ponding water level.

(3) Define outlet weir level as the median of the 5 mm ponding water levels when the median of surface drainage amounts rises above 1 m^3/2 hr.

As a result of this calculation, outlet weir level is estimated at 82.5 mm for field A and 102.5 mm for field

Table 2 Water balances

	Period	Irrigation		Rainfall		Surface drainage		Evapotranspiration		Infiltration	
		(mm)	(mm/day)	(mm)	(mm/day)	(mm)	(mm/day)	(mm)	(mm/day)	(mm)	(mm/day)
Field A	Stage 1	332.0	9.8	465	13.7	294.4	8.7	111.3	3.3	391.3	11.5
	Mid-summer drainage	0.0	0.0	190	14.6	107.9	8.3	44.5	3.4	37.6	2.9
	Stage 2	394.1	12.3	157	4.9	117.1	3.7	164.3	5.1	269.7	8.4
	Total	726.1	9.2	812	10.3	519.4	6.6	320.1	4.1	698.6	8.8
Field B	Stage 1	241.1	7.5	465	14.5	133.0	4.2	93.6	2.9	479.5	15.0
	Mid-summer drainage	0.0	0.0	190	10.0	0.6	0.0	85.0	4.5	104.4	5.5
	Stage 2	283.5	11.8	149	6.2	10.8	0.4	121.5	5.1	300.2	12.5
	Total	524.6	7.0	804	10.7	144.4	1.9	300.1	4.0	884.1	11.8

B in Stage 1; While, outlet weir level is estimated at 57.5 mm for field A and 92.5 mm for field B in Stage 2.

Surface drainage from paddy field is regarded to occur because of several factors. We can give three factors, (1) leakage from the outlet weir, (2) rise of ponding water level above the outlet weir level in rain events, and (3) rise of ponding water level above the outlet weir level by irrigation. We define that the surface drainage can be affected by the factors including leakage water (LAW), overflow in rain events (ORE), and overflow by spill-over irrigation (OSI). These factors can affect the occurrence of surface drainage in combination; however, we can not evaluate the strength of the individual factors. Therefore, we divide the irrigation period into three phases, each principally influenced by one of the three factors. We assumed that the period with LAW as the principal factor in surface drainage is the phase when ponding water level is lower than outlet weir level. Moreover, when ORE is the principal factor in surface drainage in the phase, the ponding water level is higher than outlet weir level during and after rain events. In addition, we postulate that the periods when ORE is the principal factor of surface drainage is from the beginning of rainfall to before the start of irrigation. During the periods other than these, OSI might be the principal factor influencing the occurrence of surface drainage.

The amounts of surface drainage that the respective factors might influence principally are shown in Table 3. In field A, the amount of surface drainage of ORE was 273.9 mm, and the amount of LAW was 79.1 mm. The sum of these surface drainage amounts affected by ORE and LAW was 95 percent of the whole. It follows that controlling surface drainage in rain events and preventing leakage of water from the outlet weirs are effective practice in reducing surface drainage. As compared with field A, field B lessened surface drainage of LAW, ORE, and OSI by 41.8 mm, 175.4 mm, and 18.2 mm, respectively. Field B was assumed to control the surface drainage amount mostly by limiting the amount of ORE.

The surface drainage of ORE might be reduced by maintaining SC high (Fig. 1). SC and accumulated surface drainage amounts as function of time are shown in Fig. 5. In Stage 1, average SC was 18.1 mm in field A and 36.4 mm in field B. During 87 percent of Stage 1, the SC of field B was greater than that of field A. In Stage 2, average SC was 30.9 mm in field A and 70.1 mm in field B. During 92 percent of Stage 2, the SC of field B was greater than that of field A. The accumulated surface drainage of field B increased dramatically only at June 25 and July 5. There were heavy rainfalls at those two days. On the other hand, the accumulated surface drainage of field A increased even in days of relatively low rainfalls during the irrigation period. These facts suggest that WSI was effective in maintaining SC at high level to control the surface drainage of ORE.

2.4 Scenario analysis by model simulation

2.4.1 Construction of simulating model on water balance

To evaluate the effect of WSI objectively, we simulated the water balance in the scenarios of different amounts of irrigation water and different outlet weir levels. We applied the tank model with one step to this simulation. The input data of this model are amounts of rainfall, irrigation, and evapotranspirarion, and the output data are amounts of surface drainage, infiltration, and ponding water level. We simulated the water balance in field A for the period when actual measurement was available at 2 hr intervals. The water balance equations applied to the tank model are

Table 3 Surface drainage amounts of each factor

	LAW	ORE	OSI	Non-surface drainage
Field A				
Water amounts (mm)	79.1	273.9	18.3	–
Time of occurrence (hr)	628	162	52	276
Field B				
Water amounts (mm)	37.3	98.5	0.1	–
Time of occurrence (hr)	324	42	2	750

LAW: leakage water; ORE: overflow in rain events; OSI: overflow by spill-over irrigation.

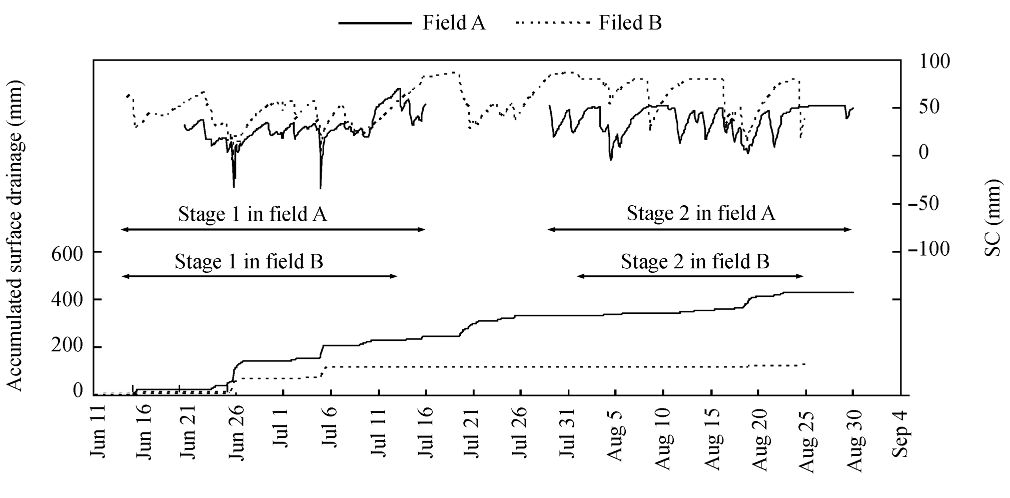

Fig. 5 Accumulated surface drainage and SC vs. time.

expressed by the following Eqs. (1)–(3):

$$\frac{dh}{dt} = r + i - q_1 - q_2 - e \tag{1}$$

$$q_1 = a(h - z) \quad h \geqslant z; \qquad = 0 \quad h < z \tag{2}$$

$$q_2 = b \times h \tag{3}$$

where, h (mm) is ponding water level; r (mm/2 hr) is amount of rainfall; i (mm/2 hr) is amount of irrigation; q_1 (mm/2 hr) is amount of surface drainage; q_2 (mm/2 hr) is amount of infiltration; e (mm/2 hr) is amount of evapotranspiration; a (1/2 hr) is coefficient of surface drainage; b (1/2 hr) is coefficient of infiltration; and z (mm) is outlet weir level. The daily evapotranspiration amounts are estimated by the Makkink method. e is calculated by dividing the daily evapotranspiration amounts into values weighted by temperatures taken every 2 hours.

The optimum coefficients of a and b are identified for each period: Stage 1, mid-summer drainage, and Stage 2. We optimized the coefficients by minimizing the valuation basis of error (J). J can be expressed by the following Eq. (4):

$$J = \frac{1}{N}\sum_{k=1}^{N}\frac{(q_{1c} - q_{1m})^2}{q_{1m}} + \frac{1}{N}\sum_{k=1}^{N}\frac{(h_c - h_m)^2}{h_m} \tag{4}$$

where, values with subscript c denote calculated values, and those with subscript m denote measured values. Also, we calculated the error rate of surface drainage amounts (j) to evaluate the ability of the model to represent surface drainage amounts. j can be expressed by the following Eq. (5):

$$j = \frac{|\sum q_{1c} - \sum q_{1m}|}{\sum q_{1m}} \times 100\% \tag{5}$$

The estimated optimum coefficients and j are shown in Table 4. Figure 6 shows a comparison between the measured and calculated values of h and q_1. As can be seen in Fig. 6, this simulation model can represent well the observed ponding water level. Meanwhile, j is high in mid-summer drainage and Stage 2. We could not definitely indicate the factor for the high error rates in calculated surface drainage amounts. However, the deviation of the peak time of calculated ponding water level from the observed time in some periods; e.g., from Aug 3 to Aug 9 as evidenced by Fig. 6, indicates that measurement error is likely to be one factor for this high error rate in calculated values.

Table 4 Optimum coefficients and j

	a	b	$\sum q_{1m}$ (mm)	$\sum q_{1c}$ (mm)	j (%)
Stage 1	0.46	0.014	249.8	223.9	10.4
Mid-summer drainage	0.28	0.056	107.9	54.8	49.1
Stage 2	0.21	0.059	117.1	12.5	89.3

2.4.2 Evaluation of WSI by scenario analysis

We employ the model constructed above to simulate the water balance on the scenarios. We define the managed water level as the ponding water level when cultivators stop irrigation in daily water management. The irrigation flow rate is calculated by the following Eq. (6):

$$i_c = \frac{h_s - h_0}{t} + e_a \quad h_s \geqslant h_0; \qquad = 0 \quad h_s < h_0 \tag{6}$$

where, i_c (mm/2 hr) is irrigation flow rate; h_s (mm) is managed water level; h_0 (mm) is ponding water level before irrigation; t (2 hr) is time for daily irrigation; and e_a (mm/2 hr) is average evapotranspiration for daily irrigating time.

Table 5 shows the standard conditions of the simulation including standard managed water level, irrigation frequency, and the start and stop time of irrigation. These standards are average values in field A to which conventional irrigation was applied. In this scenario, z is changed from plus 0 mm to plus 30 mm at 10 mm intervals on the basis of the standard managed water levels. In each z set, the amounts of irrigation water are controlled in two cases by maintaining the managed water level according

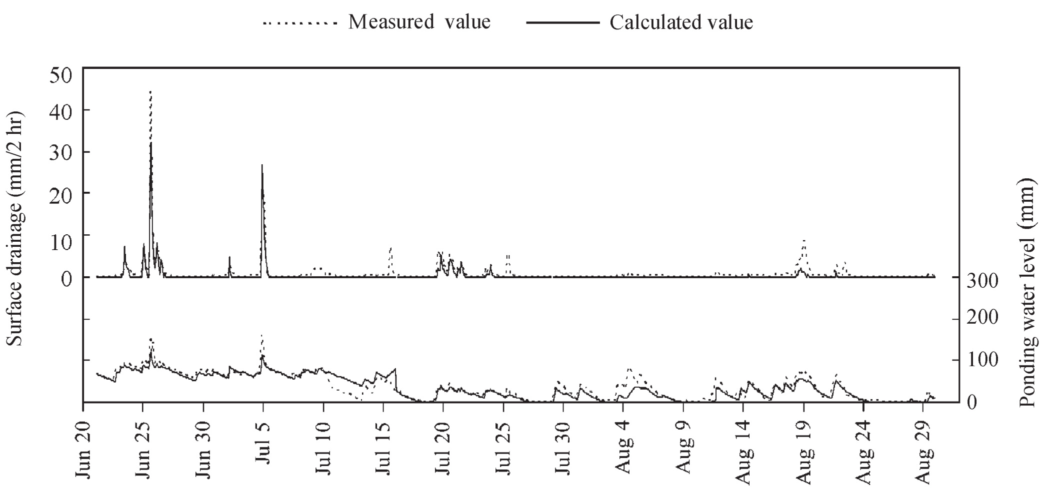

Fig. 6 Comparison between measured and calculated values.

Table 5 Standard conditions of simulation

	Period	Standard managed water level (mm)	Irrigation frequency	Start time of irrigation	Stop time of irrigation
Stage 1	Jun 12–Jul 15	64.3	Two days every three days	10:00	16:00
Mid-summer drainage	Jul 16–Jul 28	–	–	–	–
Stage 2	Jul 29–Aug 9	32.7	One day every three days	8:00	16:00
	Aug 10–Aug 21	32.7	Every other day	8:00	16:00
	Aug 22–Aug 29	32.7	One day every three days	8:00	16:00

to different rules. In one case, the managed water level is equal to standard managed water level. In the other case, managed water level is set at eight-tenths standard managed water level to achieve water-saving irrigation. We define the former case as default irrigation (DI), and the latter case as water-saving irrigation (WI).

The total water amounts for the irrigation period of each scenario are shown in Fig. 7, and the average values of ponding water level and SC for both Stage 1 and Stage 2 are shown in Fig. 8. The amounts of surface drainage in WI are 29–73 mm smaller than those in DI. The reason for the smaller amounts of surface drainage on WI may be a large SC on WI, as described in Fig. 8. The average ponding water levels in WI are 4.8–5.0 mm smaller than those in DI, to result in larger SC in WI by 4.8–5.0 mm. Similarly, the decrease in the total amounts of surface drainage with z could be explained by the increase in SC. In both irrigation regimens, when z increases by 10 mm, the average values of SC increase by 8.1– 8.7 mm. Therefore, the amounts of surface drainage could be controlled by the combined effect of WI and large z.

Figure 9 shows the simulated loads of each type of water and net runoff loads for the irrigation period in the scenarios. These loads are calculated by multiplying each water quality of field A described in Fig. 4 by the water volume, and the net runoff loads are calculated by subtracting the inflow loads (loads of irrigation and rainfall) from outflow loads (loads of surface drainage and infiltration). The surface drainage and irrigation loads of all water qualities in WI are smaller than those in DI, and these

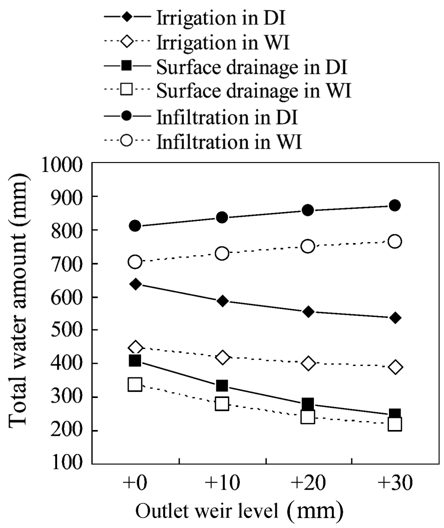

Fig. 7 Total water amounts of each scenario. DI: default irrigation; WI: water-saving irrigation.

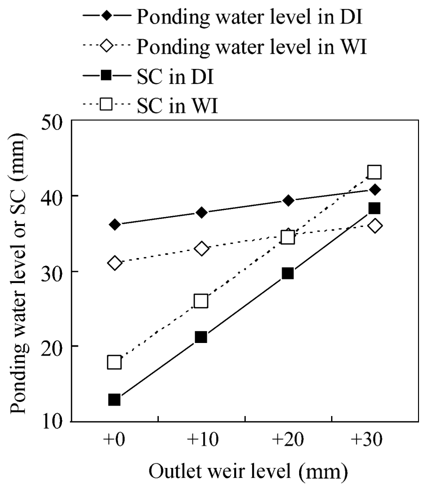

Fig. 8 Average ponding water levels and SC of each scenario.

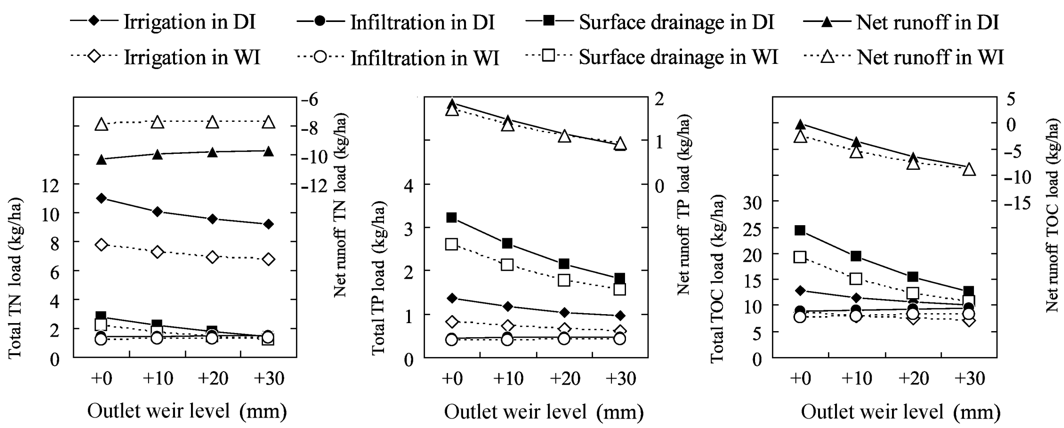

Fig. 9 Simulated loads and net runoff loads of TN, TP and TOC in scenarios.

loads decrease with z. Because loads are calculated by multiplying water quality and water volume, the tendencies of the loads could be explained in terms of change in water amount described in Fig. 7. However, infiltration water amounts are 2–4 times of surface drainage water amount, infiltration loads of all water qualities are smaller than other loads. These results from the low concentrations of infiltration water. As can be seen in Fig. 9, the effect of WSI on net runoff loads is assumed to vary with water quality. When irrigation water amount is controlled by WI and z is larger, the net runoff load of TN may increase and the net runoff loads of TP and TOC may decrease. This must be due to the difference in concentration of ponding water compared with that of irrigation and infiltration. In this scenario, controlling the irrigation under WI is estimated to reduce the net runoff loads of TP and TOC by 0.04–0.15 kg/ha and 0.3–2.4 kg/ha, respectively, and setting z by plus 10 mm is estimated to reduce the net runoff loads of TP and TOC by 0.17–0.39 kg/ha and 1.2–3.4 kg/ha, respectively.

3 Conclusions

In the study paddy fields, the concentrations of TP and TOC in ponding water were higher than those in irrigation water throughout the irrigation period. Therefore, using WSI to control the surface drainage of high concentrations of those water qualities could be expected an effective method in reducing the runoff loads from the paddy fields. We clarified the characteristics of surface drainage in WSI by analyzing the investigated data, and evaluated the effect of WSI on runoff loads by scenario analysis. The results can be summarized as follows:

(1) The amount of surface drainage in the field of WSI was only 27 percent that of the conventional irrigation regimen. WSI may reduce the surface drainage amount significantly.

(2) In the field employing conventional irrigation, the amount of surface drainage that occurred in leakage water and overflow in rain events accounted for 95 percent of the whole. WSI might control the surface drainage amount mostly by limiting the overflow in rain events.

(3) During 87 percent of the period before the mid-summer drainage, and during 92 percent of the period after the mid-summer drainage, the storage capacities of the field employing WSI were greater than those of the conventional irrigation regimen, to reduce overflow in rain events.

(4) The simulation with a tank model gave a result which suggested that the amount of surface drainage could be controlled by the combined effect of water-saving irrigation and high outlet weir level.

(5) The scenario analysis suggests that the application of WSI in the study fields could increase the net runoff load of TN. Meanwhile, under the scenario condition, water-saving irrigation was estimated to reduce the net runoff loads of TP and TOC by 0.04–0.15 kg/ha and 0.3–2.4 kg/ha, respectively, and setting outlet weir level by plus 10 mm was estimated to reduce the net runoff loads of TP and TOC by 0.17–0.39 kg/ha and 1.2–3.4 kg/ha, respectively.

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