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Cyclic Irrigation for Reducing Nutrients and Suspended Solids Loadings from Paddy Fields in Japan

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1. Introduction

The reduction of pollutants such as nitrogen, phosphorus, organic matter, and suspended solids discharged from non-point sources is an important aspect of improving water quality of downstream water areas (Reinelt et al., 1992; Gunes, 2008; Collins et al., 2010). Paddy fields, which produce rice as staple food in many countries, especially in the Asian monsoon region, and use large amounts of water during the rice growing season, are a major non-point source of pollution. Various environmental measures to reduce effluent load such as the reduction of chemical fertilizer (field-scale practices) (e.g., Choi & Nelson, 1996; Fan & Li, 2010) and reuse of drainage water (district-scale practices), are applied in paddy-field districts.

Cyclic irrigation (reuse of drainage water as irrigation water) is considered an effective water management practice for saving irrigation water resources and reducing effluent load from a paddy-field district. Cyclic irrigation was originally developed as a method for saving water in low-lying paddy fields (Kudo et al., 1995; Takeda et al., 1997) or terraced paddy fields (Tabuchi, 1986; Nakamura et al., 1998), where a stable and sufficient water source was not available. In a cyclic irrigation system, drainage water discharged from the paddy field is partially reused as irrigation water, so that the actual downstream effluent volume is decreased. Cyclic irrigation is also expected to decrease pollutant loads both because less water leaves the district and because some of the pollutants in the drainage water will be returned to the paddy field. Kubota et al. (1979) reported that cyclic irrigation with a recycling ratio (the ratio of reused water to drainage water) of 34% reduced nitrogen loads by 29% and phosphorus loads by 37%. In addition, cyclic irrigation system may increase the hydraulic retention time of nutrients in the paddy field and thereby enhance the purity of water leaving the field (Takeda et al., 1997; Feng et al., 2004, 2005; Takeda & Fukushima, 2006).

It has been also reported that the ability of cyclic irrigation to reduce loads of nutrients is directly proportional to the amount of reused water (Kaneki et al., 2003) and the recycling ratio (Hasegawa et al., 1982; Shiratani et al., 2004; Hitomi et al., 2006). However, the cyclic irrigation ratio, that is defined as the ratio of reused water to irrigation water, in paddy-field districts that have upstream areas is limited to low values due to large amount of uncontrollable inflow of water to the districts. Especially in paddy-field districts that capture industrial or domestic wastewater from upstream areas, irrigation water must have

a large fresh water component to reduce the risks posed by pollutants including pathogens and heavy metals (Kaneki, 1989; Zulu et al., 1996).
Little is known about the ability of cyclic irrigation conducted with high recycling ratios to reduce loads from paddy-field districts. Furthermore, there have been few studies of this reduction effect as a function of the suspended solids load, even though suspended solids can cause various deleterious impacts (Bilotta & Brazier, 2008). In this chapter, we aimed to clarify the effects of cyclic irrigation with high cyclic irrigation ratio on water balance and nutrient and suspended solids loads in a paddy field and in the paddy-field district. We discussed the ability of cyclic irrigation to reduce the net exports of nutrient and suspended solids.

2. Description of study site

The study site was a low-lying paddy-field district located in Konohama district, on the southeastern edge of Lake Biwa (35°05′ N, 135°56′ E; Fig. 1). Lake Biwa is the largest lake in Japan and the most important water resource for the Kinki region, which includes Osaka and Kyoto. The mean annual temperature and rainfall are about 15 °C and 1550 mm (Japan Meteorological Agency, 2010). The district covers an area of about 1.5 km^2, of which more than 90% is used as paddy fields. Rotation crops are grown in about one-third of the paddy area each year on a 3-year cycle (Fig. 1). In rotation years, two rotation crops are grown, wheat and soybeans. The sequence of farming activities in paddy cultivation and rotation crop cultivation are summarized in Table 1. The rotation cropping cycle extends for one year, beginning in November with the sowing of wheat, which follows the harvesting of rice in September. The wheat is harvested in the middle of the next June. A crop of soybeans is sown soon after the harvesting of wheat and harvested in late November. The area is then left fallow and re-planted to paddy rice the following April. Chemical fertilizer (e.g., ammonium sulfate and calcium superphosphate) was not applied to soybeans. Base fertilizer was not applied to paddy fields after crop rotation.
The drainage and irrigation canals in the district are separated. There is no inflow of industrial or domestic wastewater from outside the study area into the drainage and irrigation canals. The drainage system contains lateral drainage canals, a main drainage canal, which passes through the district from north to south, and floodgates at both ends of the main drainage canal (Fig. 1). Rainfall runoff from the paddy fields and surplus irrigation water from the irrigation canals flow into the main drainage canal via the lateral drainage canals. All outflow of drainage water from the district is controlled by operation of the floodgates.
Two types of irrigation are practiced in the district: lake water irrigation and cyclic irrigation. In lake water irrigation, water is pumped from Lake Biwa into the irrigation canals. Under cyclic irrigation, drainage water in the main drainage canal is pumped into the irrigation canals and reused as irrigation water and water flowed from the lake to the drainage canal through the floodgate when the water level of drainage water decreased by evapotranspiration. There are two pump stations, one at the northern end and one at the southern end of the main drainage canal. The fields are not irrigated during the growing of rotation crops (i.e., crops other than paddy rice). The irrigation period is about 4 months, including a mid-summer drainage season of about 10 days. Cyclic irrigation is used from the beginning of the irrigation period to the mid-summer drainage season (referred to as the cyclic irrigation period), then lake water irrigation is used until the end of the irrigation period (the lake water irrigation period). The period from the end of the irrigation period to the beginning of the next irrigation period is referred to as the non-irrigation period.

(a) Location

(b) Map

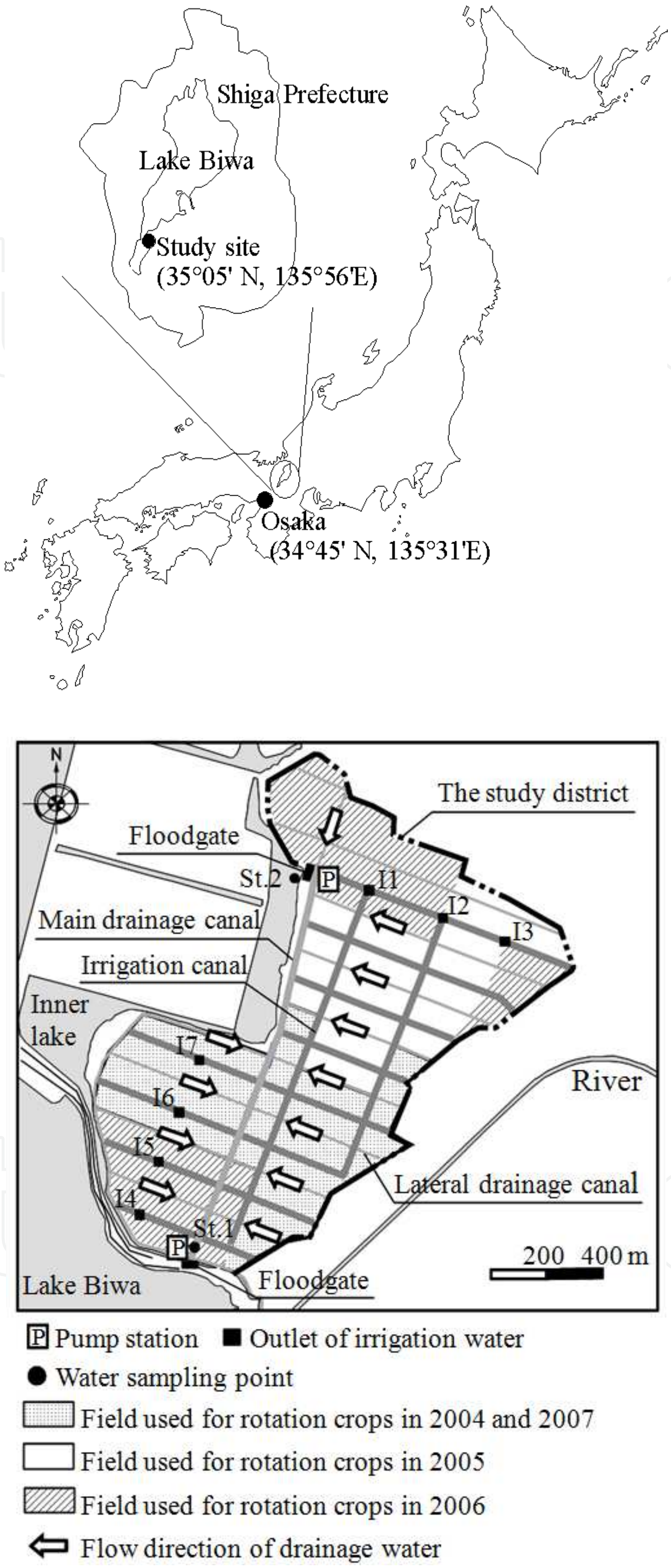

Fig. 1. (a) Location of the study site. (b) Map of land use, irrigation and drainage canals and of the water sampling points at the study site.

Pumps at the northern and southern ends of the main drainage canal have capacities of about 40 and 6 m^3 min^{-1}, respectively. The northern pump station has two water inlets that connect to the lake and the main drainage canal, respectively, whereas the southern pump station has a single water inlet that only connects to the main drainage canal. Pumped water is delivered to outlets (points I1 to I7 in Fig. 1) through underground pipelines, and is supplied to the paddy fields through the several irrigation canals. The maximum amount of irrigation water depends solely on the capacity of the pumps, because there is no other source of water to the irrigation canals. Rainfall is not included in the irrigation water. The pumps operate for about 12 h per day, from 6:00 am to 6:00 pm.

Paddy rice		Rotation crops (wheat and soybeans)	
Farming activity	Timing	Farming activity	Timing
Base fertilization (N = 30, P = 30)	late April	Base fertilization (N = 60, P = 80)	November
Start of irrigation	late April	Sowing of wheat	November
Puddling, Sowing	late April – May	Additional fertilization (N = 30, P = 30)	late December
Additional fertilizaion (N = 10, P = 0)	late June	Additional fertilization (N = 30, P = 30)	late February
Mid-summer drainage	late June – July	Additional fertilization (N = 20, P = 0)	late April
Additional fertilizaion (N = 50, P = 0)	mid July	Harvesting	June
End of irrigation	late August	Sowing of soybeans	June
Harvesting	September	Harvesting	November

[a] N, the amouts of ferilizer of nitrogen (kgN ha^{-1}); P, the amouts of ferilizer of phosphorus (kgP ha^{-1}).

Table 1. The sequence of farming activities in the paddy-field district during the cultivation of paddy rice and cultivation of rotation crops.

3. Methodology

3.1 Field investigation of the paddy field

From 2004 to 2007, we performed weekly hydrological and water-quality measurement at two paddy fields in the district during the irrigation period each April to September. A location in the southwestern part of the district was used. The area of each paddy field is about 30 m × 100 m. The study fields were cultivated in normal farming methods for paddy rice, as other paddy fields in Japan or other countries (e.g., Liu et al., 2001; Kim et al., 2006). The paddy fields in the district were surrounded by earthen levees and ponded during the irrigation period except the mid-summer drainage season. Soil puddling is accompanied by tillage of the paddy fields to soften the soil before rice seedlings are transplanted at the beginning of the irrigation period. Nutrient and suspended solids concentration in a paddy field is especially high during the soil puddling season (Kaneki, 2003; Somura et al., 2009).

Figure 2 illustrates the components of water balance in the paddy field. Hydrological measurement instruments for rainfall (RT-5E, Ikeda-Keiki, Tokyo, Japan), air temperature (CS215L, Campbell Scientific, Inc., Logan, UT USA), wind velocity (014A-L, Campbell Scientific, Inc.), relative humidity (CS215L, Campbell Scientific, Inc.), and solar radiation (LP02-L, Campbell Scientific, Inc.) were installed in an open area at the southern pump station. Evapotranspiration was estimated by the Penman method (Penman, 1948) using data measured at the southern pump station and crop coefficient value for rice (Sakuratani & Horie, 1985). We measured the irrigation and runoff water (outflow through the outlet) flow rates delivered to and drained from the paddy fields using a Parshall flume set at the inlet and a triangular weir set at the outlet. A water-level meter (WT-HR, Intech Instruments Ltd., Christchurch, New Zealand) was set in each paddy field to calculate the change in water storage. The sum of percolation water volumes, which includes leakage water (lateral seepage to the drainage canal through the levee), was estimated from water balance calculations. Water balance in the paddy field is given by the following equation:

$$\Delta S = (R + I) - (ET + D + P) \quad (1)$$

where ΔS is the change in water storage, R is rainfall, I is irrigation water, ET is evapotranspiration, D is runoff water drained through the outlet, and P is percolation (all expressed in mm). However, percolation from the paddy field to the groundwater seems to be negligible because the district is low-lying and close to the lake and the groundwater level is high. Horizontal flow from or to the adjacent paddy fields is not considered since the district is located in the low-lying area.

The sum of rainfall and irrigation water minus runoff water ($R + I - D$) was used to estimate the potential water demand of the paddy field in the district.

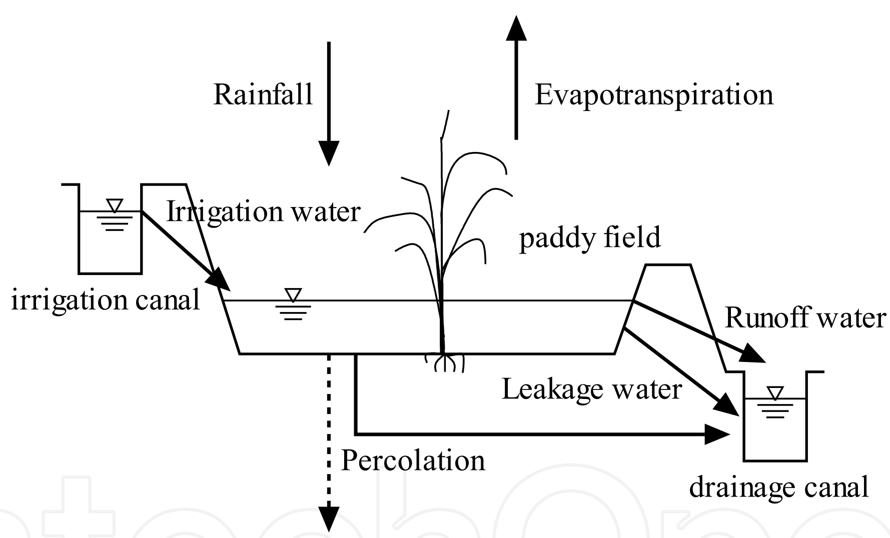

Fig. 2. Schematic diagram of water balance in the paddy field. Arrows indicate flow direction.

Each week, ponded water was sampled at the outlet of each paddy field and irrigation water was sampled at the outlet of the irrigation pipeline from the northern pump station (I1; Fig. 1). A small plastic tank was set near the northern pump station to collect rainfall water, which was sampled during the weekly field investigation. The manually sampled water was analyzed for total nitrogen (TN), dissolved total nitrogen (DTN), total phosphorous (TP), ammonium nitrogen (NH_4-N), nitrate nitrogen (NO_3-N), nitrite nitrogen (NO_2-N), and phosphate phosphorus (PO_4-P). Rainfall water sampled by the rain tank was analyzed for TN and TP.

Daily inputs and exports of nutrients in water were estimated by multiplying water nutrient concentrations by flow volumes. Percolation (including leakage) loss of nitrogen was estimated by using the TN in the ponded water as an estimate of nitrogen concentration in percolation or leakage water. Percolation loss of phosphorus was not estimated because it was thought phosphorus in the ponded water was strongly adsorbed to the paddy soil. Averaged data of the fields measurements in the fields were used for the estimation.

3.2 Field investigation of the study district

From 2006 to 2007, we performed weekly hydrological and water-quality measurement for the district during the irrigation period each April to September. Figure 3 is a conceptual diagram for water flow in the district. The flow rates of discharged drainage water during lake water irrigation or on rainy days and inflowing lake water during cyclic irrigation were measured using flow meters (2150 Area Velocity Flow Module, Teledyne Isco Inc., Lincoln, NE USA) installed at both ends of the main drainage canal. We estimated the volume of pumped water by multiplying the operating duration of the pumps by their capacity. We did not measure subsurface percolation from the district and assumed it to be negligible because the district is adjacent to the lake and the groundwater level is high, as mentioned above.

The characteristics of cyclic irrigation can be described by two different parameters (Kudo et al., 1995). One parameter is the ratio of reused water to pumped water (reused water plus lake water intake). Here, we refer to this parameter (α_{CI}) as the cyclic irrigation ratio. The other is the ratio of reused water to potential drainage water (reused water plus district drainage water discharged from the district), which is referred to as the recycling ratio and has often been used in previous studies (e.g., Kubota et al., 1979; Hasegawa et al., 1982; Hitomi et al., 2006). The recycling ratio depends more on drainage water than on reused water; in other words, the recycling ratio is affected more by water management in the paddy field and by weather conditions than is the cyclic irrigation ratio. For example, an increase in irrigation water into the paddy fields leads to a decrease in drainage water discharged from the district and results in a larger recycling ratio. Alternatively, in the case of cyclic irrigation after a rainfall event, increases in drainage water discharged from the district decrease the recycling ratio. Because of these problems with the recycling ratio, we have only analyzed and discussed the cyclic irrigation ratio. The mean cyclic irrigation ratio of the weekly measurements during the cyclic irrigation periods was 88% in 2006 and 82% in 2007, as described later.

The amount of surplus irrigation water can be approximately estimated as the volume of pumped water minus the volume of irrigation water used in the rice paddy fields (the percentage of the rice paddy fields in the district was set 66% in each investigation year). We defined the surplus irrigation water ratio (α_{SW}) as the ratio of surplus irrigation water to pumped water.

Water quality was measured within the district at weekly intervals from 2006 to 2007 by taking samples of drainage water at the southern end of the main drainage canal (St. 1; Fig. 1), irrigation water at the outlet of the pump (I1), and inner lake water (St. 2). In addition, an automatic water sampler (3700 Full-Size Portable Sampler, Teledyne Isco Inc.) was installed at St. 1 and used to sample drainage water daily at noon. Turbidimeters (Compact-CLW, JFE Alec Co., Ltd., Kobe, Japan) were set at both ends of the main drainage canal, set to a measurement interval of 20 min. The manually sampled water was analyzed for suspended solids (SS), TN, DTN, NH_4-N, NO_3-N, NO_2-N, TP and PO_4-P. Drainage water samples from the automatic sampler was analyzed for TN and TP.

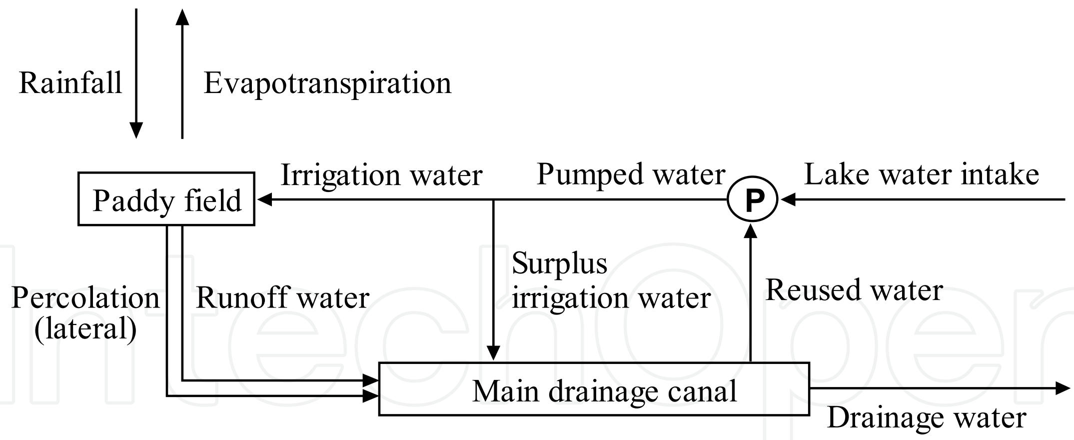

Fig. 3. Conceptual diagram of water flow in the study district. Upper-case "P" represents a pump and arrows indicate flow direction.

3.3 Water quality measurement

Nutrient concentration measurements were made using the following methods: TN and DTN were measured using an ultraviolet spectrophotometer (UV-1200, Shimadzu Corp., Kyoto, Japan) after alkaline potassium-peroxydisulfate digestion; TP by the molybdenum blue method after potassium-peroxydisulfate digestion; NH_4-N by the indo-phenol blue method; nitrate nitrogen by ion chromatography (LC-10A, Shimadzu Corp.); NO_2-N by the N-(1-naphthyl) ethylenediamine method; and PO_4-P by the molybdenum blue method. For this study, we defined SS as suspended matter with particle sizes ranging from 1 μm to 2 mm. Particulate-state and dissolved-state nutrients were also distinguished by filtering the sample with a 1-μm filter prior to analysis.

We calculated total inorganic nitrogen as the sum of NH_4-N, NO_3-N, and NO_2-N, and used PO_4-P as an estimate of total inorganic phosphorus. We calculated the total concentration of organic nitrogen or organic phosphorus as the difference between the total concentration and the total inorganic concentration. We calculated the concentration of particulate organic nitrogen as the difference between total nitrogen and dissolved total nitrogen, and the concentration of dissolved organic nitrogen as the difference between total dissolved nitrogen and total inorganic nitrogen.

Turbidimeter measurements were calibrated to convert turbidity readings to suspended solids content: calibration was performed by developing a relationship between field-measured turbidity and laboratory-measured suspended solids concentration of drainage water samples taken concurrently with turbidimeter readings.

3.4. Effects of cyclic irrigation on net exports of nutrients and suspended solids

The nutrient or SS loads are the product of the concentration and the water flow volume. Thus, the net export of nutrients or SS, L_{net} (kg ha^{-1} d^{-1}), is given by the following equation:

$$L_{net} = C_{out}\, Q_{out} - C_{in}\, Q_{in} \quad (2)$$

where C is the concentration (mg L^{-1}), Q is the water flow volume (mm d^{-1}), and the subscripts *out* and *in* refer to outflow from and inflow into the district, respectively. In this case, C_{out} is the nutrient or SS concentration in the drainage water, Q_{out} is the amount of drainage water discharged from the district per day, C_{in} is the nutrient or SS concentration in the lake water, and Q_{in} is the amount of lake water intake per day. We estimated the relationship between the cyclic irrigation ratio (α_{CI}) and each variable.

3.4.1 Relationship between the cyclic irrigation ratio and the flow volume and the concentrations

The nutrient and SS concentration in the drainage water (C_{out}) during the normal irrigation periods may be proportional to the cyclic irrigation ratio because more pumping of drainage water leads to higher water flow and more erosion of bottom sediments in the main drainage canal. On the other hand, it is clear that C_{in} is essentially independent of the cyclic irrigation ratio because the impact of drainage water discharged from the district on the nutrients and SS concentration in the lake water would be negligible.

Consider the water flow during the cyclic irrigation period on a sunny day. Q_p represents the volume of pumped water and is about 20 mm d^{-1}. On sunny days, Q_p is the only driving force for water flow in the study district, which has a closed irrigation canal. We have assumed that water in the paddy field on a sunny day is mainly lost by evapotranspiration and that the amount of percolation or leakage water is negligible. In addition, runoff water occurs mainly during rainfall events. Thus, runoff and percolation (water flows from the paddy field into the main drainage canal via the lateral drainage canals) are not depicted in Fig. 4.

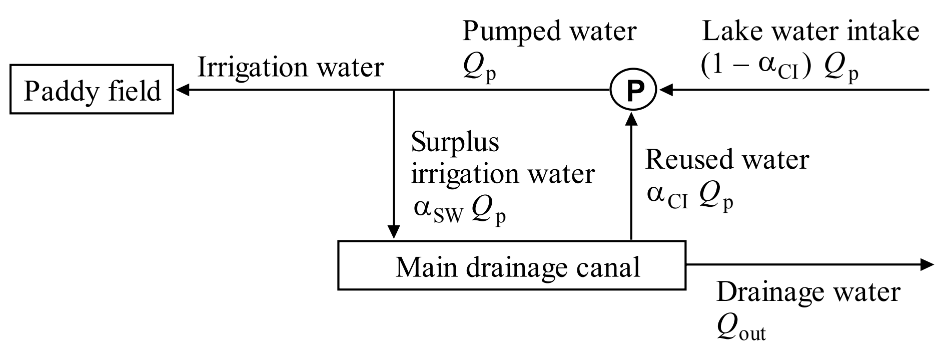

Fig. 4. Conceptual diagram of water flows under cyclic irrigation. Upper-case "P" represents a pump and arrows indicate flow direction.

Drainage water discharged from the district may potentially equal to the surplus irrigation water, $\alpha_{SW}\ Q_p$. Cyclic irrigation reduces the outflow of this potential drainage water due to reuse, $\alpha_{CI}\ Q_p$. Therefore, Q_{out} (actual drainage water) is written:

$$Q_{out} = (\alpha_{SW} - \alpha_{CI})\ Q_p \qquad (3)$$

The model of water flow illustrated in Fig. 4 does not consider temporary deficits of inflow water, which in practice are compensated for by decreases in drainage water flow in the main drainage canal. Equation (3) means that the upper limit of α_{CI} is α_{SW} when water flows out ($Q_{out} > 0$). If $\alpha_{SW} < \alpha_{CI}$ in Equation (3), another inflow of water from the lake must occur (negative Q_{out} in Fig. 4). In that case, $L_{net} = -(1 - \alpha_{SW})\ C_{in}\ Q_{in}$; that is, under these conditions, L_{net} varies with α_{SW} and is negative for any α_{CI}.

Cyclic irrigation also reduces the inflow of water (lake water intake), Q_{in}, due to reuse. Thus, Q_{in} is written as follows:

$$Q_{in} = (1 - \alpha_{CI})\ Q_p \qquad (4)$$

These two parameters, α_{CI} and α_{SW}, can be taken as a supply- (source-) and demand- (user-) side water use parameter, respectively.

3.4.2 The effect of cyclic irrigation as a function of the cyclic irrigation ratio

Whether L_{net} is greater or less than zero indicates whether the effect of cyclic irrigation as a function of α_{CI} represents net contamination (cyclic irrigation increases the loadings from the district) or net purification (cyclic irrigation decreases the loadings). The neutral effect, $L_{net} = 0$, can be converted into the following equation by substituting the relationships between α_{CI} and Q_{out} (Equation (3)) and Q_{in} (Equation (4)) into Equation (2):

$$\frac{C_{out}}{C_{in}} = \frac{1-\alpha_{CI}}{\alpha_{SW}-\alpha_{CI}} \tag{5}$$

The effect of cyclic irrigation on L_{net} for a given α_{SW} value is illustrated in Fig. 5. If we replace the right side of Equation (5) with β, then β varies as a function of both α_{CI} and α_{SW}. Whether the effect of cyclic irrigation represents net contamination or net purification depends on whether the actual concentration ratio (C_{out}/C_{in}) for a given α_{CI} is above or below the β curve. In addition, the effect of cyclic irrigation at any α_{CI} is net purification if the concentration ratio is less than 1, because the value of β for any combination of α_{CI} and α_{SW} is greater than or equal to 1.

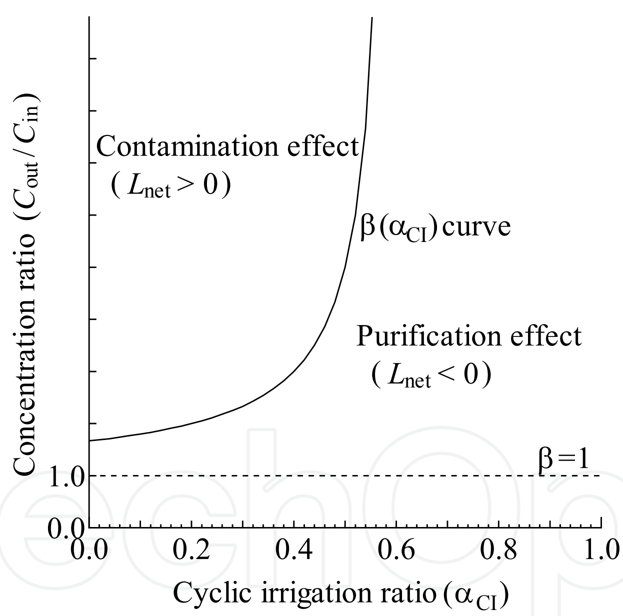

Fig. 5. The effect of cyclic irrigation on the net exports of nutrients and suspended solids (L_{net}) as a function of the cyclic irrigation ratio (α_{CI}).

4. Results and discussion

4.1 Characteristics of water balance and nutrient loads in a paddy field

4.1.1 Water balance in the paddy field

Figure 6 shows daily variations in inflow water (rainfall and irrigation water) and outflow water (evapotranspiration and runoff water) in the paddy field during each irrigation period from 2004 through 2007.

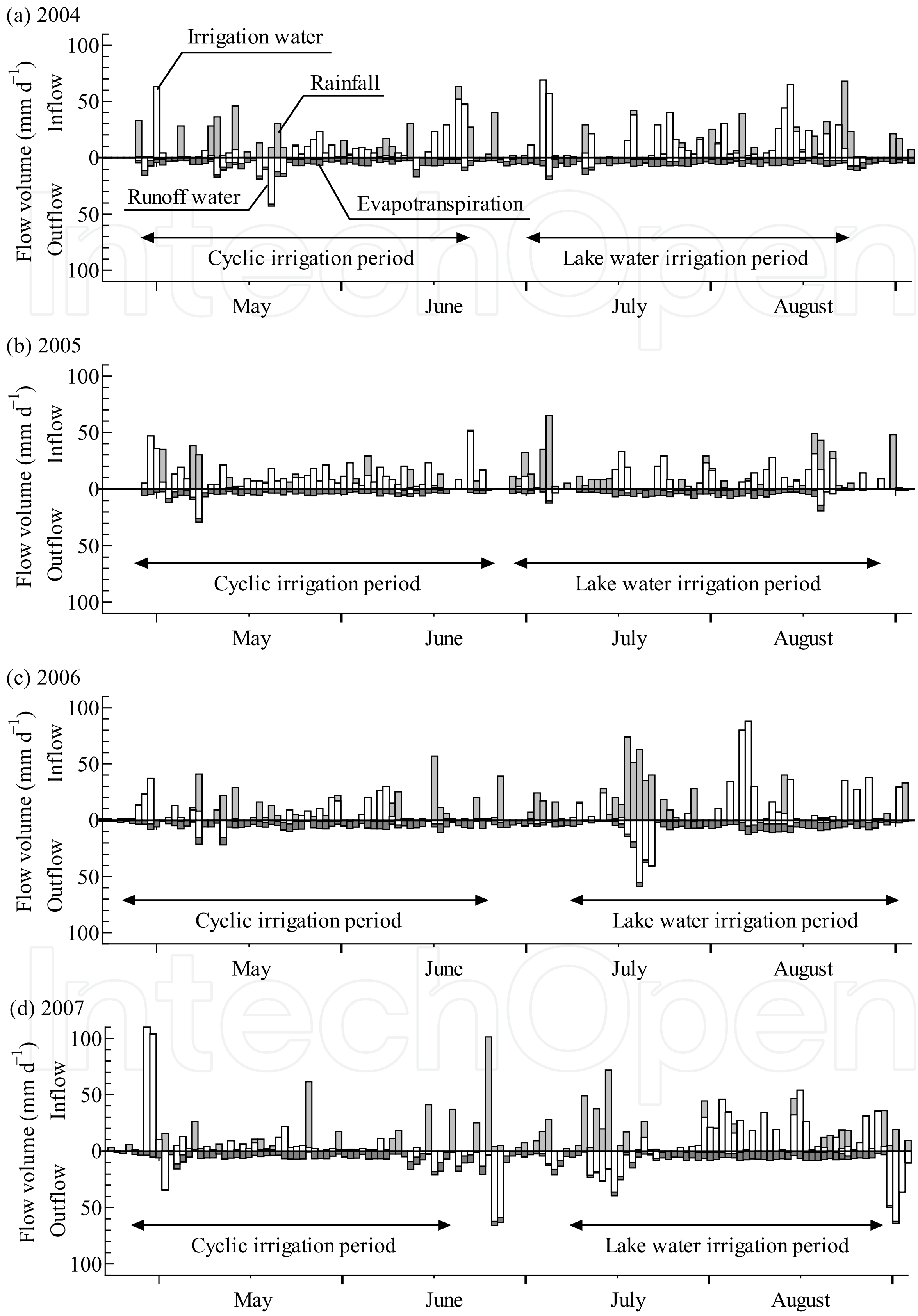

Fig. 6. Daily irrigation water, rainfall, runoff water, and evapotranspiration in the paddy fields during the irrigation period in (a) 2004, in (b) 2005, in (c) 2006 and in (d) 2007.

A complementary relationship was seen between irrigation water and rainfall because the pumps were not operated on rainy days. Runoff mainly occurred during and after rainfall. Runoff of 34 mm d^{-1} in early May in 2007 occurred because of artificial drainage by the farmer, who intended to dry the paddy fields and then transplant rice earlier. In addition, the large amount of runoff water during the 2007 mid-summer drainage season was due both to rainfall and to the temporary removal of shuttering boards at the outlets of the paddy fields during the irrigation season.

Table 2 shows the water balances for the paddy field during the irrigation periods in 2004–2007. The water level of the field at the begging and the end of each period was 0 (i.e., $\Delta S = 0$). Total amounts of rainfall during the irrigation periods ranged from 469 mm in 2005 to 779 mm in 2006. Weather conditions in the investigation years except 2005 were considered normal because the amounts of rainfall during the irrigation period were within the range of the mean ± standard deviation (766 ± 205 mm) from three decades of data (1980–2009) in Otsu City, which is near the study district (Japan Meteorological Agency, 2010).

Year	Period[a]	Inflow (mm)		Outflow (mm)	
		Rainfall	Irrigation water	Evapotranspiration	Runoff water
2004	CI period (28 April – 20 June)	313	377	213	178
	Mid-summer drainage season[b]	73	0	37	8
	LWI period (1 July – 21 August)	139	624	252	65
	Total	525	1001	502	251
2005	CI period (25 April – 30 June)	210	563	210	71
	Mid-summer drainage season	115	0	7	14
	LWI period (6 July – 28 August)	139	379	179	46
	Total	464	942	396	131
2006	CI period (24 April – 25 June)	277	275	212	72
	Mid-summer drainage season	102	0	37	8
	LWI period (8 July – 31 August)	400	500	241	213
	Total	779	775	490	293
2007	CI period (25 April – 23 June)	281	356	273	138
	Mid-summer drainage season	175	0	38	157
	LWI period (6 July – 28 August)	319	506	261	193
	Total	775	862	572	488

[a] CI, cyclic irrigation; LWI, lake water irrigation.

[b] From the end of CI period to the beginning of LWI period.

Table 2. Mean water balances for the paddy fields during the irrigation period.

The total amount of irrigation water each year was inversely proportional to rainfall, and the sum of rainfall and irrigation water during each irrigation period was fairly constant (about

1400–1600 mm each year). About 1100–1200 mm was estimated as the potential water demand during the irrigation period (without the mid-summer drainage season). The difference between total inflow and total outflow during the irrigation period, which equals the sum of stored water and percolation, ranged from 577 mm (in 2007) to 879 mm (in 2005). From these results, it was estimated that water loss from the paddy fields by percolation was about 7 mm d^{-1} (at most) during the irrigation period. The amount of water lost through percolation was likely more than that lost through evapotranspiration, which ranged from 396 mm (in 2005) to 572 mm (in 2007).

The reason that the difference in water management practices in 2004–2007 was not reflected in the water balances of each irrigation period is because irrigation water was supplied only from the pumps, and the irrigation schedule for each field depended on the pump operation. In other words, supply-side water management practices seemed to have a greater influence on water balance in the paddy fields than did individual farmers' management practices. An irrigation system with a closed irrigation canal (receiving no inflow of water from outside the area) that enables the paddy-field district to conduct cyclic irrigation with a high cyclic irrigation ratio, combined with supply-side water management (e.g., stopping the pumps during rainfall events), can provide efficient use of rainfall for crop irrigation, though such an irrigation system is less flexible for meeting the water use demands of individual farmers.

Total amounts of pumped water in the irrigation periods were 1528 mm in 2004, 1720 mm in 2005, 1737 mm in 2006 and 1681 mm in 2007, and the amounts of surplus irrigation water (= the volume of pumped water minus the volume of irrigation water used in the rice paddy fields) were therefore 867 mm (= 1528 mm – 0.66 × 1001 mm) in 2004, 1098 mm in 2005, 1226 mm in 2006 and 1112 mm in 2007. The overall surplus irrigation water ratio in the district in the irrigation periods was 57% (= 867 mm / 1528 mm × 100) in 2004, 64% in2005, 71% in 2006 and 66% in 2007.

4.1.2 Nutrient loads in the paddy field

Figure 7 shows the temporal variations in TN and TP of irrigation water and ponded water during the 2007 irrigation period. Nutrient concentrations in the ponded water were higher than in irrigation water during the puddling season. In contrast, nutrient concentrations in the ponded water were similar to those in irrigation water during the irrigation period following the puddling season (i.e., the normal irrigation period referred to in this paper). These results indicate that the quality of irrigation water has a large influence on ponded water during the normal irrigation period.

Nutrient concentrations in irrigation water in 2004–2007 are shown in Table 3. The trends for each nutrient component in irrigation water were similar over the study years, except for lower nutrient concentrations of TN and TP during the puddling season in 2004, which may have been caused by dilution in successive rainfall events during that season. Nutrient concentrations in irrigation water in the study years were highest during the puddling season (TN = 3.26–4.07 mg L^{-1}, TP = 0.04–0.29 mg L^{-1}), and higher during the cyclic irrigation period (TN = 1.76–2.27 mg L^{-1}, TP = 0.09–0.24 mg L^{-1}) than during the lake water irrigation period (TN = 0.53–0.73 mg L^{-1}, TP = 0.04–0.06 mg L^{-1}). The high nutrient concentrations in irrigation water during the puddling season are likely due to dissolution and leaching of nutrients from paddy soil.

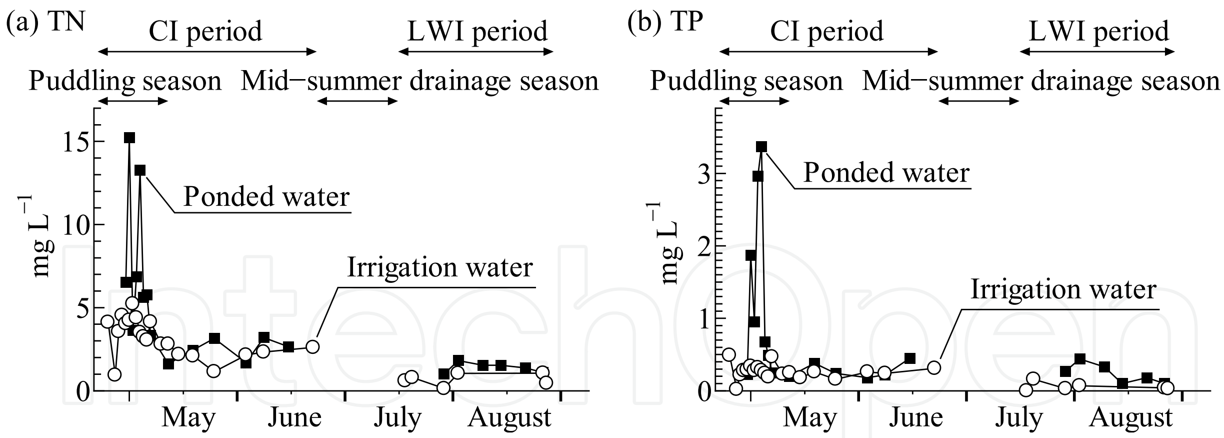

Fig. 7. Temporal variations of (a) total nitrogen and (b) total phosphorus in irrigation water and ponded water during the irrigation period in 2007. CI, cyclic irrigation; LWI, lake water irrigation.

Year	Period[a]	Water quality ($mg\ L^{-1}$)[d]							
		TN	DTN	NH_4-N	NO_3-N	NO_2-N	TP	PO_4-P	n[f]
2004	Puddling season[b]	3.26	—[e]	0.35	1.98	0.05	0.04	0.03	4
	CI period[c]	1.76	—	0.26	0.44	0.02	0.09	0.05	5
	LWI period	0.54	—	0.06	0.05	0.00	0.04	0.01	5
2005	Puddling season	4.07	2.35	0.43	1.03	0.00	0.24	0.04	4
	CI period	2.04	1.13	0.26	0.21	0.00	0.18	0.02	6
	LWI period	0.73	0.52	0.04	0.04	0.00	0.03	0.01	3
2006	Puddling season	3.91	1.92	0.15	0.72	0.00	0.26	0.04	5
	CI period	1.83	0.85	0.17	0.41	0.00	0.16	0.03	4
	LWI period	0.53	0.40	0.05	0.05	0.00	0.06	0.02	5
2007	Puddling season	4.00	2.81	0.46	1.77	0.00	0.29	0.03	10
	CI period	2.27	1.41	0.40	0.36	0.00	0.24	0.02	8
	LWI period	0.72	0.53	0.05	0.04	0.00	0.05	0.01	7

[a] CI, cyclic irrigation; LWI, lake water irrigation.

[b] From the beginning of the irrigation period to early May.

[c] Cyclic irrigation period after the puddling season.

[d] TN; total nitrogen; DTN, dissolved total nitrogen; TP, total phosphorus.

[e] No data.

[f] The number of sapmles.

Table 3. Mean nutrient concentrations in irrigation water in 2004–2007.

The mean concentration of inorganic nitrogen (= NH_4-N + NO_3-N + NO_2-N) in cyclic irrigation water (irrigation water during the cyclic irrigation period) in 2004–2007 was 0.47–0.76 mg L^{-1}, whereas the level was constantly about 0.1 mg L^{-1} in lake water (irrigation water during the lake water irrigation period). Organic nitrogen (= total nitrogen – inorganic nitrogen) in cyclic irrigation water was 1.04–1.57 mg L^{-1}, of which 60–80% was particulate organic nitrogen. In contrast, organic nitrogen in lake water was 0.43–0.65 mg L^{-1}, of which about 70% was dissolved organic nitrogen.

The inputs and exports of nitrogen and phosphorus are shown in Table 4 and Table 5 respectively.

In each of the four years of this study, the inputs of nitrogen from irrigation water were greater during the cyclic irrigation period than during the lake water irrigation period (Table 4). Exports of nitrogen during the cyclic irrigation period were also larger than that during the lake water irrigation period. Percolation (including leakage) loss of nitrogen was estimated as from 7.2 kg ha^{-1} (in 2006) to 12.3 kg ha^{-1} (in 2005). However, it seems that the actual percolation loss of nitrogen was less than the estimated values, which might be because nutrients in the ponded water were mainly in an organic state and easily adsorbed by the paddy soil as water flowed through.

Year	Period[a]	Inputs (kg ha^{-1})		Exports (kg ha^{-1})		
		Rainfall	Irrigation water	Runoff water	Percolation	Net[c]
2004	CI period (28 April – 20 June)	1.8	7.2	6.7	5.3	3.0
	Mid-summer drainage season[b]	0.7	0.0	0.1	0.0	-0.6
	LWI period (1 July – 21 August)	1.4	2.8	0.9	2.4	-0.9
2005	CI period (25 April – 30 June)	1.6	10.0	2.3	10.1	-0.8
	Mid-summer drainage season	0.9	0.0	0.1	0.0	-0.8
	LWI period (6 July – 28 August)	1.0	3.4	0.8	2.2	-1.4
2006	CI period (24 April – 25 June)	1.4	7.1	2.2	4.9	-1.4
	Mid-summer drainage season	0.8	0.0	0.3	0.0	-0.5
	LWI period (8 July – 31 August)	3.9	3.5	2.0	2.3	-3.1
2007	CI period (25 April – 23 June)	2.2	12.5	5.0	5.1	-4.6
	Mid-summer drainage season	1.4	0.0	3.4	0.0	2.0
	LWI period (6 July – 28 August)	2.5	4.6	2.9	2.7	-1.5

[a] CI, cyclic irrigation; LWI, lake water irrigation.

[b] From the end of CI period to the beginning of LWI period.

[c] Runoff water + Percolation —(Rainfall + Irrigation water).

Table 4. Nitrogen loads in the paddy fields during the irrigation period.

Net exports of nitrogen from a paddy field, which is estimated as exports (= runoff water and percolation water) minus inputs (= rainfall and irrigation water), indicates whether the water management practices associated with that field may increase or decrease the nitrogen load. A negative value of net exports means that the paddy field decreased nitrogen load during the calculation period. In this study, net exports of nitrogen were negative during all lake water irrigation periods. A similar situation was observed for a paddy field adjacent to Kasumigaura Lake (the second largest lake in Japan), a region that is aiming to remove nitrogen from river water (Zhou & Hosomi, 2008). Our data indicate that lake water irrigation may remove nitrogen from the outside water area (i.e., Lake Biwa), whereas cyclic irrigation using a high cyclic irrigation ratio probably does not because almost all the nitrogen in cyclic irrigation water was originally input as fertilizer. In this case, the major benefit of cyclic irrigation is considered to be the return of nitrogen to the paddy field, which possibly leads to a reduction in fertilizer usage. From other viewpoints, it may be said that cyclic irrigation system realizes the smallest nitrogen cycle, with the paddy field acting as a means of self-purification in the district.

Year	Period[a]	Inputs (kg ha^{-1})		Exports (kg ha^{-1})	
		Rainfall	Irrigation water	Runoff water	Net[c]
2004	CI period (28 April – 20 June)	0.04	0.50	1.18	0.64
	Mid-summer drainage season[b]	0.02	0.00	0.02	0.00
	LWI period (1 July – 21 August)	0.03	0.20	0.10	-0.13
2005	CI period (25 April – 30 June)	0.04	0.70	0.46	-0.28
	Mid-summer drainage season	0.02	0.00	0.01	-0.01
	LWI period (6 July – 28 August)	0.02	0.30	0.10	-0.22
2006	CI period (24 April – 25 June)	0.05	0.46	0.24	-0.27
	Mid-summer drainage season	0.01	0.00	0.04	0.03
	LWI period (8 July – 31 August)	0.07	0.32	0.33	-0.06
2007	CI period (25 April – 23 June)	0.05	0.95	1.06	0.06
	Mid-summer drainage season	0.03	0.00	0.62	0.59
	LWI period (6 July – 28 August)	0.06	0.30	0.61	0.25

[a] CI, cyclic irrigation; LWI, lake water irrigation.

[b] From the end of CI period to the beginning of LWI period.

[c] Runoff water —(Rainfall + Irrigation water).

Table 5. Phosphorus loads in the paddy fields during the irrigation period.

Similar to inputs of nitrogen, inputs of phosphorus from irrigation water was larger during the cyclic irrigation period than during the lake water irrigation period (Table 5). The export of phosphorus, however, was relatively large, and the net exports were positive during the irrigation periods in both 2004 and 2007. The large exports of phosphorus during the cyclic irrigation periods in 2004 and 2007 were most likely due to rainfall and artificial drainage, respectively. The influence of weather conditions and water management appear to have a greater influence on exports of phosphorus than on exports of nitrogen. Therefore, water management practices at the paddy-field level (e.g., drying paddy fields without artificial drainage) are important for reducing the export of phosphorus, even though practices at the district level (e.g., conduction of cyclic irrigation throughout the entire irrigation period) can further reduce net export, as described next.

4.2 Characteristics of water balance and nutrient and suspended solids loads in the paddy-field district

4.2.1 Water balance in the study district

Daily variations in rainfall and drainage water from the district through the floodgates in 2006 and 2007 are shown in Fig. 8. Drainage water was not released during the cyclic irrigation periods, except during rainfall events, whereas during the lake water irrigation periods drainage water of more than 10 mm d^{-1} was released even on sunny days. The amount of drainage water discharged from the district on sunny days during the lake water irrigation periods nearly equaled the amount of surplus irrigation water, suggesting that cyclic irrigation reduced the outflow of surplus irrigation water from the district.

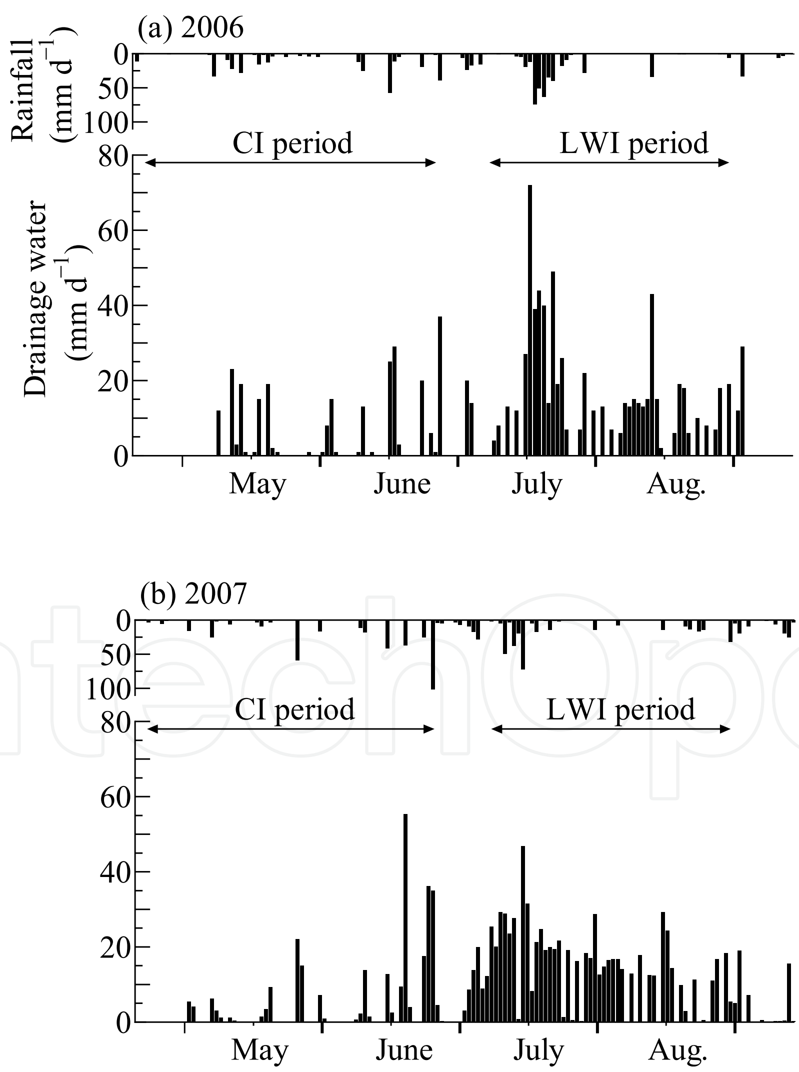

Fig. 8. Daily variations in the drainage water from the study district and rainfall during the irrigation in (a) 2006 and in (b) 2007: CI, cyclic irrigation; LWI, lake water irrigation.

Table 6 shows the water balances in the district during the irrigation periods.

Year	Period[a]	Inflow (mm)		Outflow (mm)	
		Rainfall	Lake water intake	Evapotranspiration	Drainage water
2006	CI period (24 April – 25 June)	277	134	186	221
	Mid-summer drainage season[b]	102	0	29	71
	LWI period (8 July – 31 August)	400	582	237	707
	Total	779	716	452	999
2007	CI period (25 April – 23 June)	281	174	248	237
	Mid-summer drainage season	175	0	31	94
	LWI period (6 July – 28 August)	319	669	258	768
	Total	775	843	537	1099

[a] CI, cyclic irrigation; LWI, lake water irrigation.

[b] From the end of CI period to the beginning of LWI period.

Table 6. Water balance in the study district during the irrigation periods in 2006 and 2007.

Although the amounts of pumped water during the cyclic irrigation periods (1111 mm in 2006 and 962 mm in 2007) were larger than those during the lake water irrigation periods (626 mm in 2006 and 719 mm in 2007), the amounts of lake water intake during the cyclic irrigation periods were less than those during the lake water irrigation periods, because pumped water was mainly supplied by the reuse of drainage water during cyclic irrigation. The smaller amounts of drainage water discharged from the district during the cyclic irrigation periods were also due to the reuse of drainage water. The amounts of reused water (pumped water minus lake water intake) during the cyclic irrigation periods were 977 mm in 2006 and 788 mm in 2007.

4.2.2 Nutrient and suspended solids concentrations in the drainage water

Temporal variations in nutrient and suspended solids concentrations during the irrigation periods in 2006 and in 2007 are shown in Fig. 9. The variation trends were similar in 2006 and 2007. The nutrient concentrations were higher during the puddling season and on days on which rain fell. Nutrient concentrations on fine days during the irrigation period ranged from 1.0 to 2.0 mg L^{-1} for TN and from 0.10 to 0.20 mg L^{-1} for TP. The nutrient concentrations in the drainage water were higher during the cyclic irrigation period than during the lake water irrigation period. The SS concentration was also high during the puddling season (from late April to mid-May) and during heavy rainfall events; the SS concentration was more than 100 mg L^{-1} at its peak during the puddling season. The SS concentration on sunny days during the cyclic irrigation periods after the puddling season was about 20 mg L^{-1} and was higher than about 10 mg L^{-1} on sunny days during the lake water irrigation periods. The nutrient and SS concentrations in irrigation water during the cyclic irrigation periods nearly equaled the nutrient and SS concentrations in the drainage water because the cyclic irrigation ratios during the cyclic irrigation periods were high and the dilution volumes from the lake water were small.

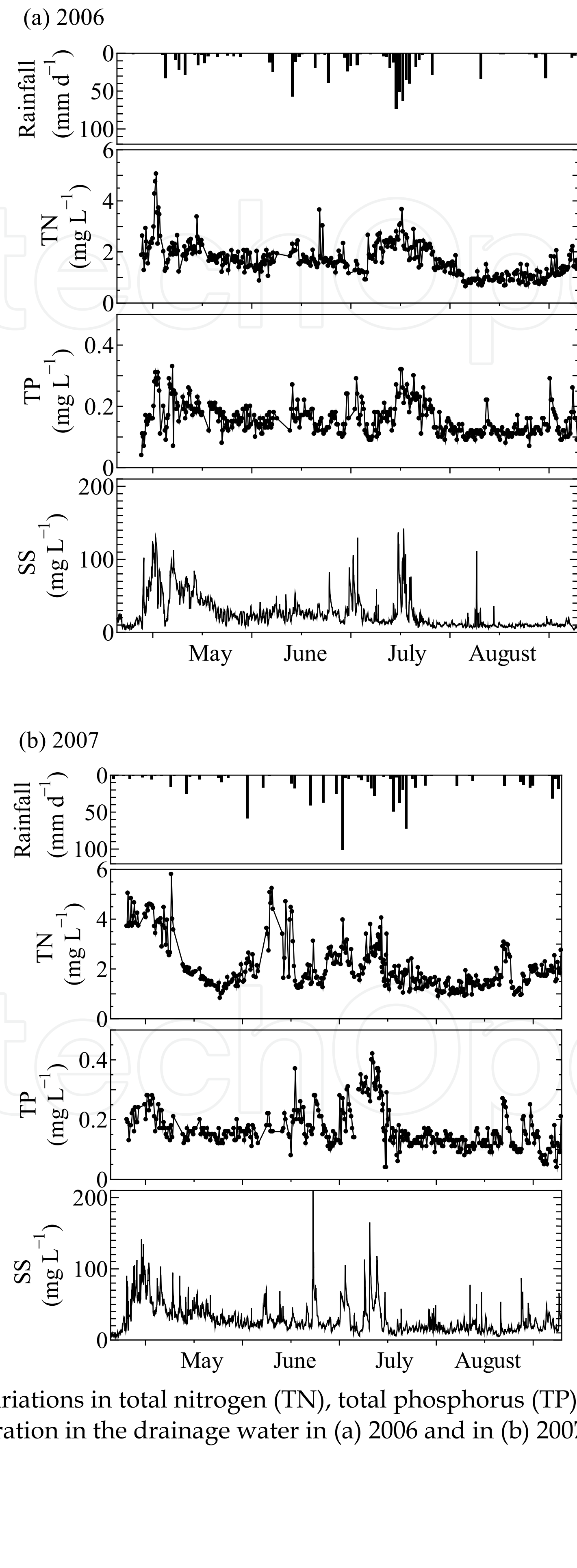

Fig. 9. Temporal variations in total nitrogen (TN), total phosphorus (TP) and suspended solids (SS) concentration in the drainage water in (a) 2006 and in (b) 2007.

4.2.3 Nutrient and suspended solids loads in the study district

The inputs of TN and TP in rainfall and lake water and exports of TN and TP in discharged drainage water during the irrigation periods are shown in Table 7 and Table 8. The total exports of nitrogen and phosphorus were about 20 kg ha^{-1} and 2.0 kg ha^{-1}, respectively. Net exports of nitrogen and phosphorus from the paddy field (= runoff water – rainfall – lake water intake) were positive during all irrigation periods. Therefore, it is suggested that the study district acts as source of nutrients. The export of nutrients during the cyclic irrigation periods was less than that during the lake water irrigation period, in line with the small amounts of water discharged (Table 6). Some of the nutrient exports during the lake water irrigation periods were caused by the discharge of surplus irrigation water on fine days (Fig. 8), although nutrient concentrations in the drainage water were lower than during cyclic irrigation.

Year	Period[a]	Inputs (kg ha^{-1})		Exports (kg ha^{-1})	
		Rainfall	Lake water intake	Drainage water	Net[c]
2006	CI period (24 April – 25 June)	1.4	1.1	4.4	1.9
	Mid-summer drainage season[b]	0.8	0.0	1.1	0.3
	LWI period (8 July – 31 August)	3.9	4.5	12.9	4.5
2007	CI period (25 April – 23 June)	2.2	2.8	5.2	0.2
	Mid-summer drainage season	1.4	0.0	2.3	0.9
	LWI period (6 July – 28 August)	2.5	4.6	13.7	6.6

[a] CI, cyclic irrigation; LWI, lake water irrigation.

[b] From the end of CI period to the beginning of LWI period.

[c] Drainage water —(Rainfall + Lake water intake).

Table 7. Nitrogen loads in the study district.

Year	Period[a]	Inputs (kg ha^{-1})		Exports (kg ha^{-1})	
		Rainfall	Lake water intake	Drainage water	Net[c]
2006	CI period (24 April – 25 June)	0.00	0.10	0.40	0.30
	Mid-summer drainage season[b]	0.00	0.00	0.20	0.20
	LWI period (8 July – 31 August)	0.10	0.30	1.40	1.00
2007	CI period (25 April – 23 June)	0.10	0.20	0.40	0.10
	Mid-summer drainage season	0.00	0.00	0.20	0.20
	LWI period (6 July – 28 August)	0.10	0.40	1.40	0.90

[a] CI, cyclic irrigation; LWI, lake water irrigation.

[b] From the end of CI period to the beginning of LWI period.

[c] Drainage water —(Rainfall + Lake water intake).

Table 8. Phosphorus loads in the study district.

Table 9 shows the SS loads in the district during the irrigation periods. The exports of SS during the cyclic irrigation periods were less than those during the lake water irrigation periods, even though the cyclic irrigation periods included the puddling seasons, when SS concentration in runoff water from the paddy fields was very high. Clearly, the exports of SS from the district were reduced during the cyclic irrigation periods. Another effect of cyclic irrigation is to return SS to the paddy fields along with the reused water. The return of SS to the paddy field during cyclic irrigation, estimated from the product of the SS concentration and the amount of irrigation water, was 118 kg ha^{-1} in 2006 and 199 kg ha^{-1} in 2007.

Year	Period[a]	Inputs (kg ha^{-1})		Exports (kg ha^{-1})	
		Rainfall	Lake water intake	Drainage water	Net[c]
2006	CI period (24 April – 25 June)	0	7	90	83
	Mid-summer drainage season[b]	0	0	35	35
	LWI period (8 July – 31 August)	0	26	152	126
2007	CI period (25 April – 23 June)	0	28	80	52
	Mid-summer drainage season	0	0	39	39
	LWI period (6 July – 28 August)	0	30	183	153

[a] CI, cyclic irrigation; LWI, lake water irrigation.

[b] From the end of CI period to the beginning of LWI period.

[c] Drainage water —(Rainfall + Lake water intake).

Table 9. Suspended solids loads in the study district.

4.3 Effects of cyclic irrigation on net exports of nutrients and suspended solids

In this section, we discuss the effect of cyclic irrigation on reducing the net exports of nutrients and SS (Equation (2)) from the district on a sunny day during the normal irrigation period, which represents the irrigation period after the puddling season.

We plotted the relationship between the cyclic irrigation ratio (α_{CI}) and the nutrient and SS concentration in the drainage water (C_{out}) during the normal irrigation periods (Fig. 10). C_{out} may be proportional to α_{CI}. The distribution of the fields under rotation crops (i.e., crops other than paddy rice) may also influence C_{out}. The fields were distributed around the northern and southern of the district in 2006 and around the center of the district in 2007. We hypothesize that more of the SS in rainfall runoff from the field under crop rotation settled out in the main drainage canal in 2007 than in 2006 because the distance from the rotation crop areas to the floodgates was shorter in 2006. Accordingly, the cyclic irrigation may have led to higher C_{out} on a sunny day in 2007 than in 2006. The mean TN concentrations (C_{in} for nitrogen) were 0.78 mg L^{-1} in 2006 and 0.68 mg L^{-1} in 2007. The mean TP concentrations (C_{in} for phosphorus) were 0.06 mg L^{-1} in 2006 and 2007. The mean SS concentrations (C_{in} for SS) were 4.5 mg L^{-1} in 2006 and 2007.

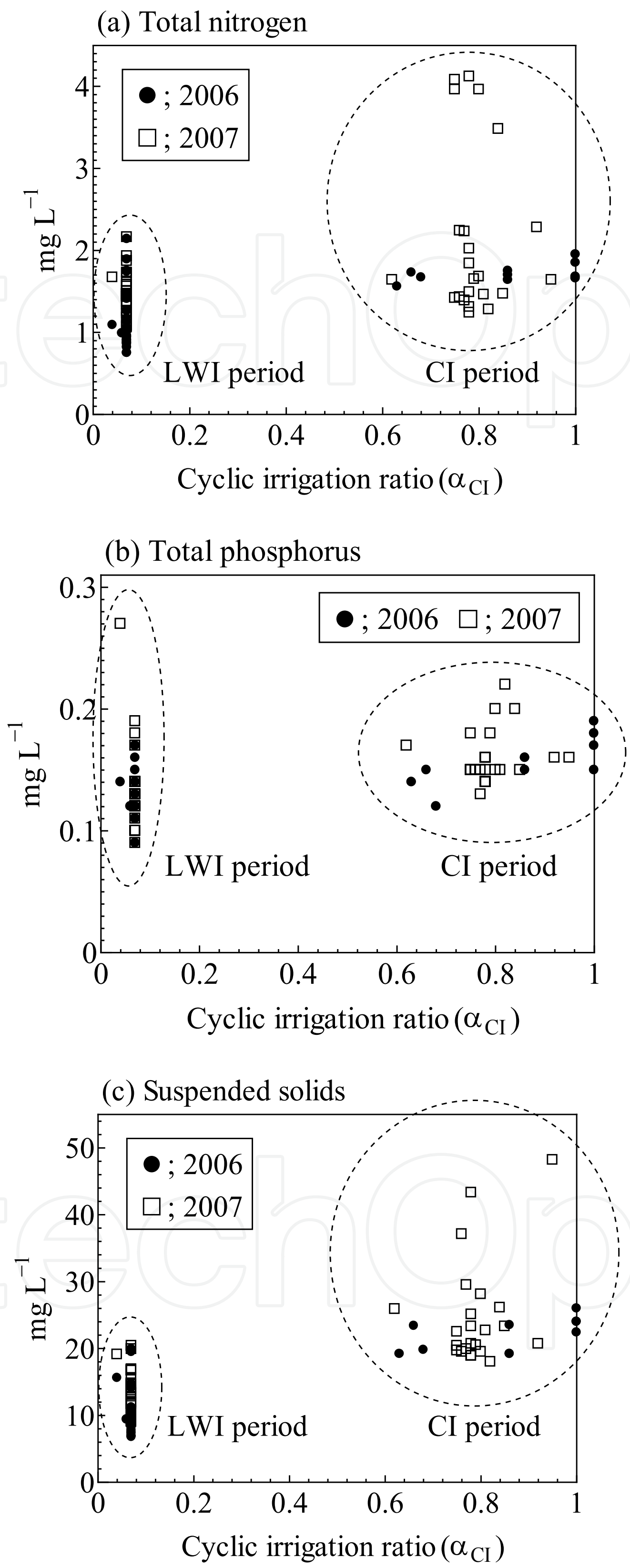

Fig. 10. Relationship between the cyclic irrigation ratio (α_{CI}) and (a) total nitrogen, (b) total phosphorus and (c) suspended solid concentration in the drainage water: CI, cyclic irrigation; LWI, lake water irrigation.

Whether the effect of cyclic irrigation represents net contamination or net purification depends on whether the actual concentration ratio (C_{out}/C_{in}) for a given α_{CI} and α_{SW} (the surplus irrigation water ratio) is above or below the β curve (Fig. 5). The β is calculated from Equation (5). Figure 11 shows the measured concentration ratios during the normal

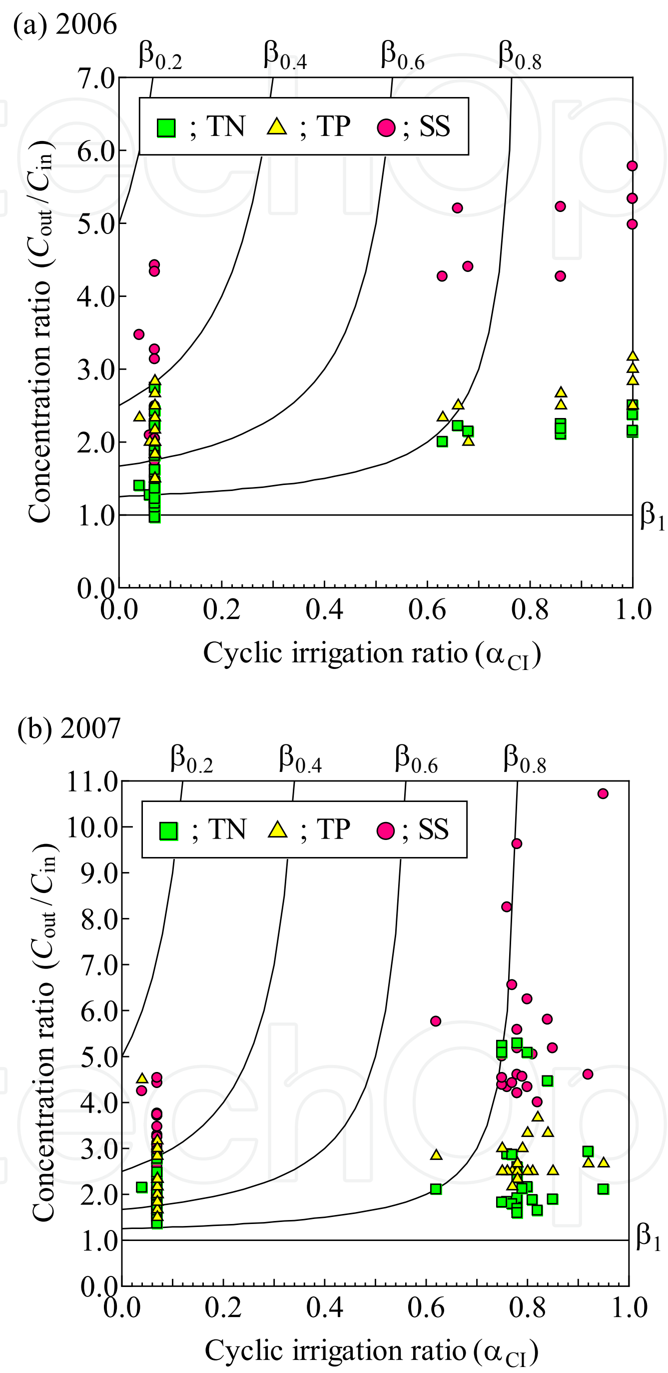

Fig. 11. Measured concentration ratios of total nitrogen (TN), total phosphorus (TP) and suspended solids (SS) in (a) 2006 and in (b) 2007. The subscript for each β value ($= [1 - \alpha_{CI}] / [\alpha_{SW} - \alpha_{CI}]$) represents the value of the surplus irrigation ratio (α_{SW}) used to calculate the β curve.

irrigation periods, as well as five β curves for various values of α_{SW} (=0.2, 0.4, 0.6, 0.8, and 1.0). It is clearly that the effect of cyclic irrigation at high α_{CI} will be net purification even if α_{SW} is high, whereas at low α_{CI} the effect of cyclic irrigation may be net contamination when α_{SW} is greater than 0.6. Though intermediate values of the cyclic irrigation ratio were not used in the district, Fig. 11 indicates that conducting cyclic irrigation with a moderate value of α_{CI} will not necessarily cause net purification if increasing α_{CI} increases the concentration ratio. The possibility that increasing α_{CI} increases C_{out} is shown in Fig. 10.

α_{SW} is another important parameter to consider when predicting the effect of cyclic irrigation. When the value of α_{SW} is high, the effect of cyclic irrigation is net contamination for almost all values of α_{CI}. In contrast, the effect of cyclic irrigation is net purification for almost all value of α_{CI} when α_{SW} has a low value. α_{SW} is strongly influenced by weather conditions, especially evapotranspirational demand and rainfall, and by water management practices in the paddy fields. In fact, daily α_{SW} ranged from 0.3 to 0.9 and was high in the spring and low in the summer in the study district.

Based on these results, two approaches can be used to produce net purification through cyclic irrigation; increasing α_{CI} and decreasing α_{SW}. Both parameters interact to determine the net effect of cyclic irrigation. Fig. 11 suggests that improving both parameters simultaneously will reduce net exports of nutrients and SS more effectively than improving either parameter alone.

Reduction of effluent loads in the drainage canals is also important, because the canals connect the fields with the downstream water bodies and function as a sink or source of nutrients and SS. However, there is little research on the dynamics of nutrients and SS in agricultural drainage canals: It is essential for the appropriate management of drainage canals to understand the deposition and resuspension of SS and the adsorption and dissolution of nutrients on sediment.

5. Conclusions

It is suggested that a cyclic irrigation system that enables the paddy-field district to use a high cyclic irrigation ratio may lead to more efficient use of rainfall for crop irrigation because there was a clear inverse relationship between amount of irrigation water applied and amount of rainfall each year. Drainage water discharged from the district may potentially equal to the surplus irrigation water on a sunny day during the normal irrigation period. Cyclic irrigation reduces the outflow of this potential drainage water due to reuse.

The export of nutrients from the district during the cyclic irrigation periods was less than that during the lake water irrigation period. It is also confirmed that cyclic irrigation can effectively reduce the suspended solids load during the puddling season when the suspended solids concentration in drainage water is high. The influence of weather conditions and water management appear to have a greater influence on exports of phosphorus than on that of nitrogen.

The effect of cyclic irrigation on the net nutrient and suspended solids exports can be represented by three ratios: the concentration ratio, which represents the ratio of the nutrient and suspended solids concentrations in drainage water to that in lake water; the cyclic irrigation ratio, which represents the ratio of the volume of reused water to that of pumped water in cyclic irrigation; and the surplus irrigation water ratio, which represents the ratio of the volume of surplus irrigation water to that of pumped water. Both the latter parameters interact to determine the net effect of cyclic irrigation. Simultaneously increasing the cyclic irrigation ratio and decreasing the surplus irrigation water ratio is important to maximize purification effect.

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