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Effectiveness of cyclic irrigation in reducing suspended solids load from a paddy-field district

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Abstract

The reduction of suspended solids, nutrients, and organic matter loads in drainage water from paddy fields is an important issue for water quality management in closed water areas in Japan. We evaluated the ability of cyclic irrigation to reduce the suspended solids load from paddy fields. In 2006 and 2007, we investigated water and mass balances during the irrigation period in a low-lying paddy-field district neighboring Lake Biwa, which is the largest lake in Japan. We confirmed that cyclic irrigation reduced effluent loads during the puddling season. With cyclic irrigation, 118 kg ha^{-1} of suspended solids was returned to the paddy fields in 2006 and 199 kg ha^{-1} in 2007. The effect of cyclic irrigation on the net suspended solids load can be represented by three ratios: the concentration ratio, which represents the ratio of the suspended solids concentration 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 irrigation water in cyclic irrigation; and the surplus irrigation water ratio, which represents the ratio of the volume of surplus irrigation water to that of irrigation water. The cyclic irrigation ratio and the surplus irrigation water ratio interact to determine the effect of cyclic irrigation on the net suspended solids load. Simultaneously increasing the cyclic irrigation ratio and decreasing the surplus irrigation water ratio will maximize the purification effect on drainage water from paddy fields.

Keywords

Cyclic irrigation, water reuse, suspended solids, paddy fields.

1. Introduction

The reduction of pollutants such as suspended solids, nutrients, and organic matter from non-point sources is an important issue for water quality management in closed water areas. In particular, pollutant loads from paddy-field districts, which use large amounts of water, must be reduced.

Cyclic irrigation is considered an effective water management practice for reducing pollutant loads from paddy-field districts. 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 cyclic irrigation systems, drainage water is partially reused as irrigation water, so that the downstream effluent volume is decreased by the amount of reused water. This approach is expected to decrease pollutant loads, both because less water leaves the fields and because at least some of the pollutants in the water will be returned to the fields.

Several researchers have studied the reduction effect of cyclic irrigation. 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 may increase the hydraulic retention time of nutrients and thereby enhance water purification in a paddy-field district (Feng et al., 2004, 2005; Takeda and 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). There is, however, a low upper limit to the potential recycling ratio in many paddy-field districts that capture industrial or domestic wastewater from upstream areas, because 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 and Brazier, 2008).

We have been investigating a paddy-field district neighboring Lake Biwa, the largest lake in Japan, since 2004. We previously reported characteristics of the mass balances of nitrogen and phosphorus in the district, and evaluated the ability of cyclic irrigation to reduce nutrient loads in effluent (Hama et al, 2007, 2008). In the present paper, we present the results for 2006 and 2007 and discuss the ability of cyclic irrigation to reduce suspended solids load.

2. Materials and methods

2.1. Study site

The study site is located in Konohama District (35°05′N, 135°56′E), on the southeastern side of Lake Biwa in Shiga Prefecture. Lake Biwa is the largest lake in Japan and the most important water resource for the Kinki region, which includes Osaka and Kyoto (Fig. 1). Konohama District covers 1.48 km^2, of which more than 90% is used as paddy fields. About one-third of the paddy fields are cultivated under a system of crop rotation of wheat and soybeans.

There is no inflow of industrial or domestic wastewater from outside the study area into the drainage and irrigation canals, because the paddy-field district does not have upstream watersheds. The amount and flow pattern of drainage and irrigation water in the district is strongly influenced by water management practices in the paddy fields. The drainage and irrigation canals are separated (Fig. 1b). In the study area, the drainage system is mainly composed of 14 lateral drainage canals that supply a main drainage canal, which passes through the district from north to south. The length, width, and depth of the main drainage canal are about 1.5 km, 2 - 4 m, and 0.5 - 2 m, respectively. 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. There is a floodgate at each end of the main drainage canal. Outflow of drainage water from the paddy-field district is controlled by operation of the floodgates.

Pumps at the northern and southern ends of the main drainage canal have capacities of 0.7 and 0.1 $m^3 s^{-1}$, 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 - I7 in Fig. 1b) 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.

Two types of irrigation have been practiced in the district: lake water irrigation and cyclic irrigation. In lake water irrigation, irrigation water is pumped from Lake Biwa into the irrigation canals by the northern pump. The lake water irrigation is a conventional irrigation system that is widely used in low-lying paddy-field districts along the lake shore. Under cyclic irrigation, most irrigation water is pumped from the main drainage canal, which functions as a retention pond. The infrastructure for cyclic irrigation (pump stations, main drainage canal, and floodgates) in the district was developed between 1998 and 2005, and cyclic irrigation has been practiced since 2004. The increased cost of practicing of cyclic irrigation in the district is met by direct agri-environmental payments from the government of Shiga Prefecture.

The irrigation period is about 130 days, including a mid-summer drainage season of about 10 days (Table 1). Cyclic irrigation is conducted from the beginning of the irrigation period to the mid-summer drainage season (the cyclic irrigation period), then lake water irrigation is conducted to the end of the irrigation period (the lake water irrigation period). The cyclic irrigation and lake water irrigation periods are both about 60 days long. Soil puddling is accompanied by tillage of the paddy field to soften the soil before rice seedlings are transplanted at the beginning of the irrigation period. The suspended solids concentration in the drainage canals water is especially high during the soil puddling season (Kaneki, 2003; Somura et al., 2009).

2.2. Water quality and hydrological data

Since 2004, we have undertaken weekly water quality measurement within the district during the irrigation period. In addition, we have investigated two paddy plots in the district. We sampled water at the outlet for pumped irrigation water (I1), at both ends of the main drainage canal (St.1 and St.2), and at the inner lake (St.3) (Fig. 1b).

In the laboratory, we analyzed suspended solids according to the method in Japanese Industrial Standard (JIS) K0102. For this paper, we defined suspended solids as suspended matter with particle sizes ranging from 1 μm to 2 mm. We placed turbidimeters (Compact-CLW, JFE Alec Co., Ltd.) at both ends of the main drainage canal, set to a measurement interval of 20 min. 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 turbidmeter readings.

Fig. 2 is a conceptual diagram for water flow in the district. Rainfall, air temperature, wind velocity, relative humidity, and solar radiation were measured at the southern pump station. The flow rate of drainage water was measured using 2150 Area Velocity Flow Module flow meters (Teledyne Isco Inc.) installed at both ends of the main drainage canal. Evapotranspiration was estimated by the Penman method (Penman, 1948; Miura and Okuno, 1993) using data collected at the southern pump station. 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, but assumed it to be negligible because the district is low-lying and close to the lake, and the groundwater level is high. We measured the irrigation and runoff water flow rates delivered to and drained from each paddy plot using a Parshall flume set at the inlet and a triangular weir set at the outlet. We estimated the volumes of irrigation and runoff water to and from the paddy field by averaging the measured values for the paddy plots.

3. Results

3.1. Water balances

Table 2 shows the water balances in the paddy field during the irrigation periods. The large amount of runoff water during the 2007 mid-summer drainage season was due to rainfall and the temporary removal of shuttering boards at the outlets of the paddy plots during the irrigation season. The difference between total inflow and total outflow (which equals the sum of stored water, leakage from paddy levees, and percolation) was 771 mm over 130 days in 2006 and 577 mm over 127 days in 2007. From these results, we calculated that water loss from the paddy fields by leakage and percolation was less than 6 mm d^{-1} during the irrigation period.

The amount of surplus irrigation water can be estimated as the volume of pumped water minus the volume of irrigation water used in the paddy fields (evapotranspiration plus percolation plus leakage). Total amounts of pumped water in the irrigation periods were 1737 mm in 2006 and 1681 mm in 2007, and the amounts of surplus irrigation water were therefore 1226 mm in 2006 and 1112 mm in 2007. We defined the surplus irrigation water ratio (α_{SW}) as the ratio of surplus irrigation water to irrigation water. The overall surplus irrigation water ratio in the district in the irrigation periods was 70% in 2006 and 66% in 2007.

We measured daily variations in rainfall and drainage water from the district through the floodgates (Fig. 3). 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.

Table 3 shows the water balances in the district during the irrigation periods. 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.

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 in the rest of this paper.

The mean cyclic irrigation ratio of the weekly measurements during the cyclic irrigation periods was 88% in 2006 and 82% in 2007.

3.2. Mass balances of suspended solids

We measured temporal variations in the drainage water suspended solids concentration at the southern end of the main drainage canal during the irrigation periods (Fig. 4). The variation trends were similar in 2006 and 2007. The suspended solids concentration was high during the puddling season (from late April to mid-May) and during heavy rainfall events; the suspended solids concentration was more than 100 mg L^{-1} at its peak during the puddling season. The suspended solids 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 suspended solids concentration in irrigation water during the suspended solids periods nearly equaled suspended solids concentration 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.

Table 4 shows mass balances for suspended solids load in the district during the irrigation periods. We calculated the suspended solids loads by multiplying the suspended solids concentrations by the flow volumes. The outflow of suspended solids loads 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 the suspended solids load in runoff water from the paddy plots was very high. Clearly, the amount of suspended solids load discharged from the district was reduced during the cyclic irrigation periods.

Another effect of cyclic irrigation is to return suspended solids to the paddy fields along with the reused water. The return of suspended solids to the paddy field during cyclic irrigation, estimated from the product of the suspended solids concentration and the amount of irrigation water, was 118 kg ha^{-1} in 2006 and 199 kg ha^{-1} in 2007.

4. Discussion

In this section, we discuss the effect of cyclic irrigation on the net suspended solids load during the normal irrigation period, which represents the irrigation period after the puddling season. The net suspended solids load associated with irrigation is defined as the outflow of suspended solids load minus the inflow of suspended solids load (e.g., Takeda et al., 1997).

The net load indicates whether there is an increase or decrease in suspended solids load discharged from the district compared to that in the irrigation water entering the district. A positive value of the net suspended solids load during cyclic irrigation indicates that cyclic irrigation is increasing suspended solids load.

The suspended solids load is the product of the suspended solids concentration and the water flow volume, as described above. Thus, the net suspended solids load, L_{net} (kg ha^{-1} d^{-1}), is given by the following equation:

$$L_{net} = C_{out}\,Q_{out} - C_{in}\,Q_{in} \qquad (1)$$

where C is the suspended solids 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 suspended solids concentration in the drainage water, Q_{out} is the amount of drainage water discharged from the district per day, C_{in} is the suspended solids 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 and each variable, as described in the following sections.

4.1. Relationship between the cyclic irrigation ratio and the suspended solids concentration

We plotted the relationship between the cyclic irrigation ratio (α_{CI}) and C_{out} during the normal irrigation periods (Fig. 5). C_{out} may be proportional to α_{CI} because more pumping of drainage water leads to higher water flow and more erosion of bottom sediments in the main drainage canal. 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 suspended solids 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} in 2007 than in 2006.

On the other hand, it is clear that C_{in} is essentially independent of α_{CI} because the impact of drainage water discharged from the district on suspended solids concentration in the lake water would be negligible. C_{in} ranged from 0 to 10 mg L^{-1} during the irrigation period. The mean value of C_{in} was 4.5 mg L^{-1}.

4.2. Relationship between the cyclic irrigation ratio and the flow volume

Consider the water flow during the cyclic irrigation period on a sunny day (Fig. 6). 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 district. We have assumed that water in the paddy field on a sunny day is mainly lost by evapotranspiration and that the amount of leakage water is negligible. In addition, runoff water occurs mainly during rainfall events. Thus, runoff and leakage (water flows from the paddy field into the main drainage canal via the lateral drainage canals) are not depicted in Fig. 6.

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:

$$Q_{out} = (\alpha_{SW} - \alpha_{CI})\, Q_p \quad (2)$$

The model of water flow illustrated in Fig. 6 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. Eq. (2) means that the upper limit of α_{CI} is α_{SW} when water flows out (Q_{out} >

0). If $\alpha_{SW} < \alpha_{CI}$ in Eq. (2), another inflow of water from the lake must occur (negative Q_{out} in Fig. 6). 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:

$$Q_{in} = (1 - \alpha_{CI})\, Q_p \quad (3)$$

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

4.3. 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 suspended solids load) or net purification (cyclic irrigation decreases the suspended solids load). The neutral effect, $L_{net} = 0$, can be converted into the following equation by substituting the relationships between α_{CI} and Q_{out} (Eq. (2)) and Q_{in} (Eq. (3)) into Eq. (1):

$$C_{out} / C_{in} = (1 - \alpha_{CI}) / (\alpha_{SW} - \alpha_{CI}) \quad (4)$$

The effect of cyclic irrigation on L_{net} for a given α_{SW} value is illustrated in Fig. 7. If we replace the right side of Eq. (4) 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. 8 shows the measured concentration ratios during the normal 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. 8 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. 5.

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. 8 suggests that improving both parameters simultaneously will reduce net suspended solids load more effectively than improving either parameter alone.

5. Conclusions

We 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 return of suspended solids to the paddy fields in the irrigation district by means of cyclic irrigation totaled 118 kg ha^{-1} in 2006 and 199 kg ha^{-1} in 2007.

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 effect of cyclic irrigation on the net suspended solids load can be represented by three ratios: the concentration ratio, which represents the ratio of the suspended solids concentration 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 irrigation water in cyclic irrigation; and the surplus irrigation water ratio, which represents the ratio of the volume of surplus irrigation water to that of irrigation 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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Tables

Table 1 Water management and farming activities in the paddy field.

Date 2006	Date 2007	Water managemant and farming activities	Remarks
Late April	Late April	Fertilizer application	Input*: N = 28 kg ha^{-1}, P = 26 kg ha^{-1}
24 April	25 April	Start of irrigation (pumps begin operation)	The start of the irrigation period
Late April - mid May		Soil puddling and transplanting of rice seedling	Puddling season
Late June	Late June	Fertilizer application	Input*: N = 14 kg ha^{-1}, P = 0 kg ha^{-1}
26 June to 7 July	24 June to 5 July	Drying of the paddy soil (temporary cessation of pumping)	Mid-summer drainage season
Mid-July	Mid-July	Fertilizer application	Input*: N = 48 kg ha^{-1}, P = 0 kg ha^{-1}
31 August	28 August	Cessation of irrigtation (pumps cease operation)	The end of the irrigation period
September	September	Hervesting of rice	

* Input of N and P were estimated from records of fertilizer application in the paddy plots.

Table 2 Water balances in the paddy field during the irrigation periods. CI, cyclic irrigation; LWI, lake water irrigation.

Year	Period	Inflow (mm)		Outflow (mm)	
		Rainfall	Irrigation water	Evapotranspiration	Runoff
2006	CI period (24 April to 25 June)	277	275	212	72
	Mid-summer drainage season	102	0	37	8
	LWI period (8 July to 31 August)	400	500	241	213
	Total	779	775	490	293
2007	CI period (25 April to 23 June)	281	356	273	138
	Mid-summer drainage season	175	0	38	157
	LWI period (6 July to 28 August)	319	506	261	193
	Total	775	862	572	488

Table 3 Water balances in the district during the irrigation periods.

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

Table 4 Mass balances for the suspended solids load in the district during the irrigation periods. "Inflow" refers to the suspended solids load in the lake water intake, whereas "outflow" refers to the suspended solids load in the drainage water discharged from the district into the lake.

Year	Period	Inflow (kg ha^{-1})	Outflow (kg ha^{-1})
2006	CI period (24 April to 25 June)	7	90
	Mid-summer drainage season	0	35
	LWI period (8 July to 31 August)	26	152
	Total	33	277
2007	CI period (25 April to 23 June)	28	80
	Mid-summer drainage season	0	39
	LWI period (6 July to 28 August)	30	183
	Total	58	302

Figure captions

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.

Fig. 2. Conceptual diagram of water flow in the district. Upper-case “P” represents a pump and arrows indicate flow direction.

Fig. 3. Daily drainage water from the district, and rainfall during the irrigation periods in (a) 2006 and in (b) 2007. CI, cyclic irrigation; LWI, lake water irrigation.

Fig. 4. Temporal variation in the suspended solids concentration (SSC) in the drainage water at the southern end of the main drainage canal during the irrigation periods in (a) 2006 and in (b) 2007.

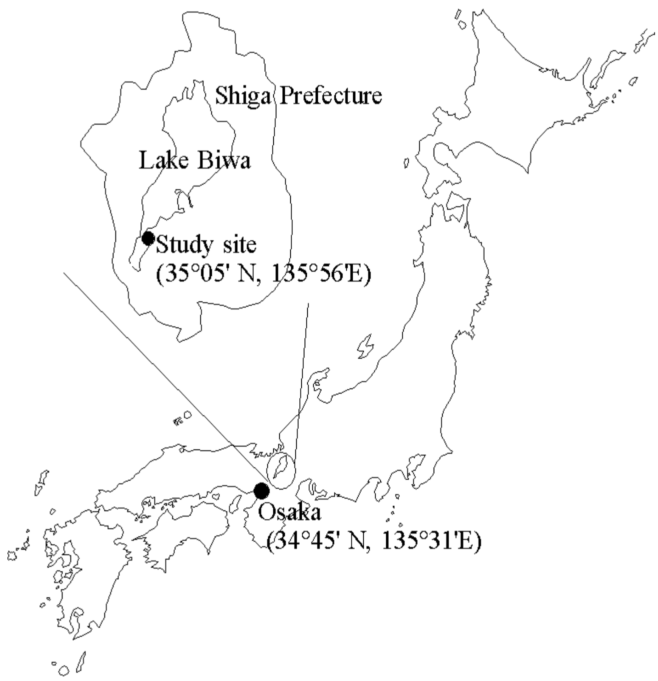
Fig. 5. Relationship between the cyclic irrigation ratio (α_{CI}) and the suspended solids concentration in the drainage water. CI, cyclic irrigation; LWI, lake water irrigation.

Fig. 6. Conceptual diagram of water flows under cyclic irrigation: upper-case “P” represents a pump and arrows indicate the flow direction.

Fig. 7. The effect of cyclic irrigation on the net suspended solids load (L_{net}) as a function of the cyclic irrigation ratio.

Fig. 8. Measured concentration ratios in the district in 2006 and 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.

a) Location



b) Map

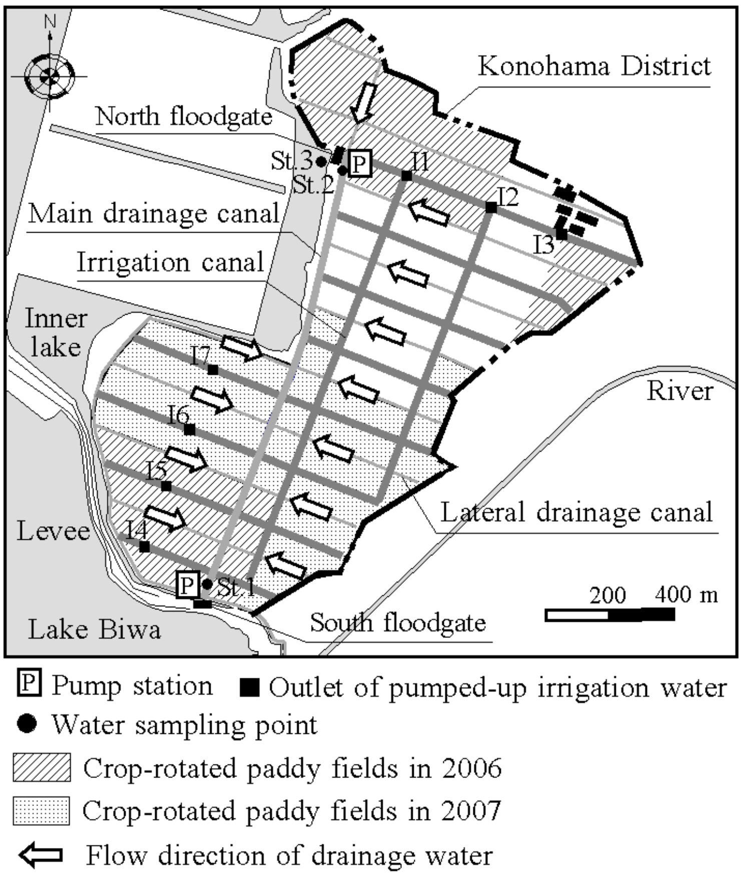


Figure 1 Hama et al.

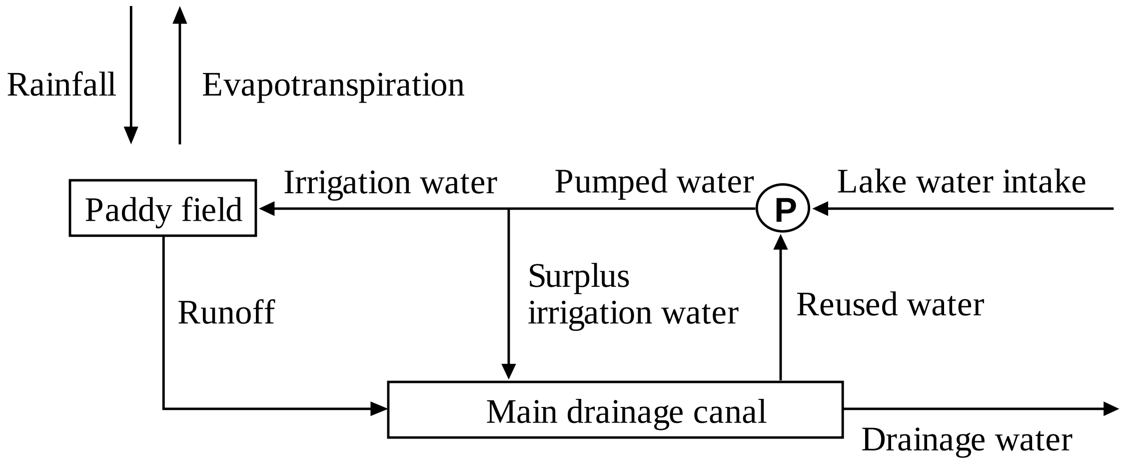


Figure 2

Hama et al.

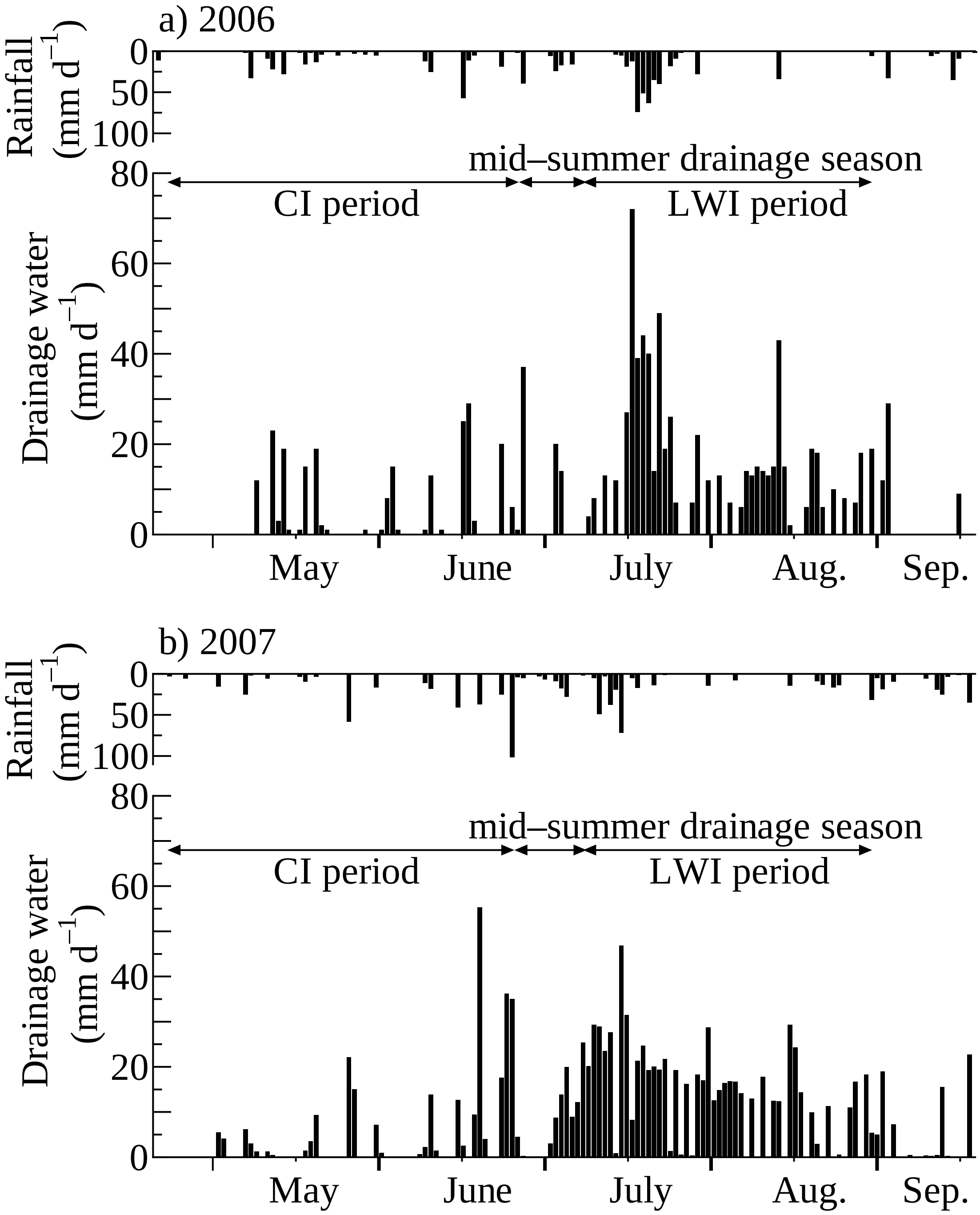


Figure 3 Hama et al.

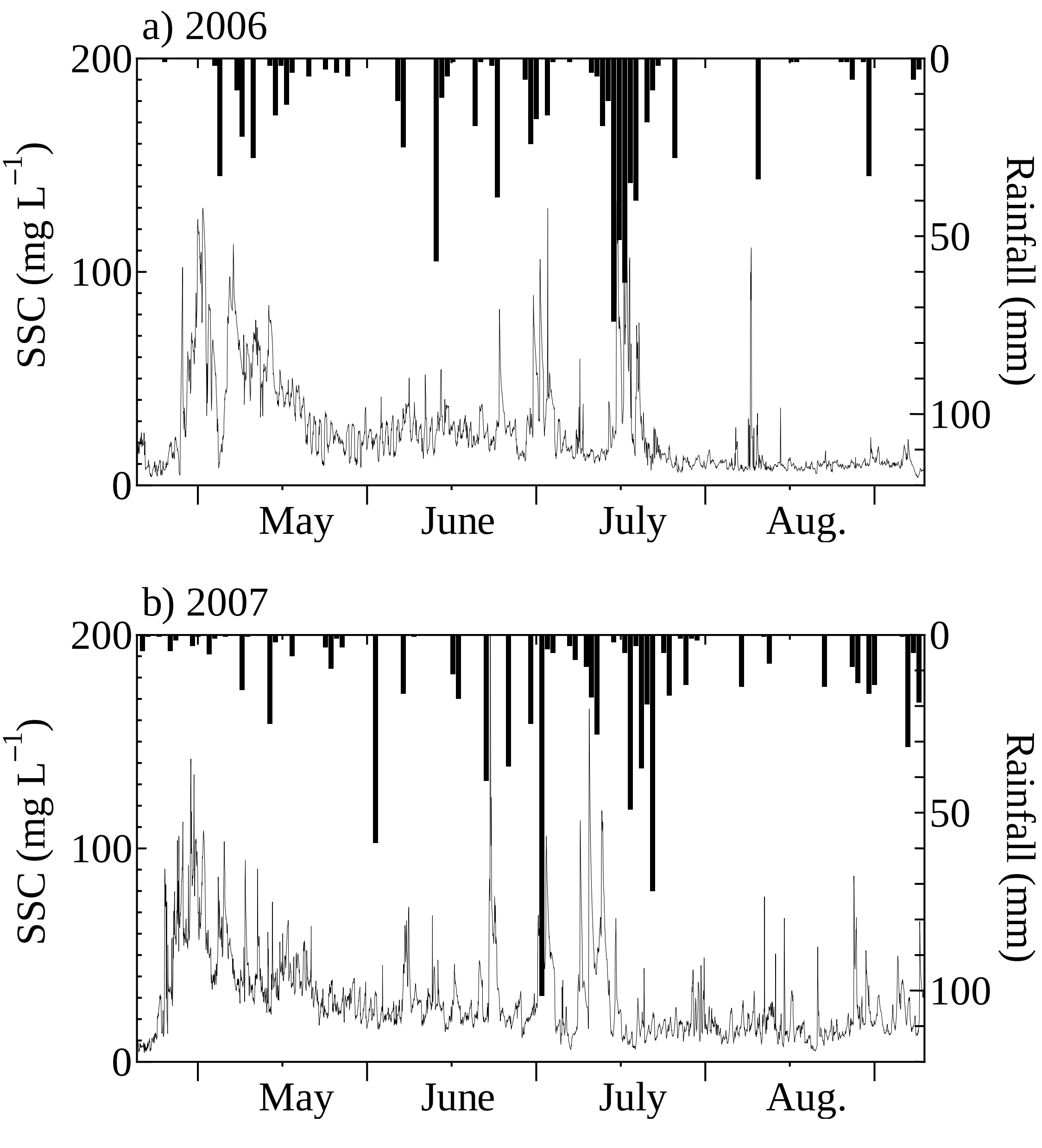


Figure 4 Hama et al.

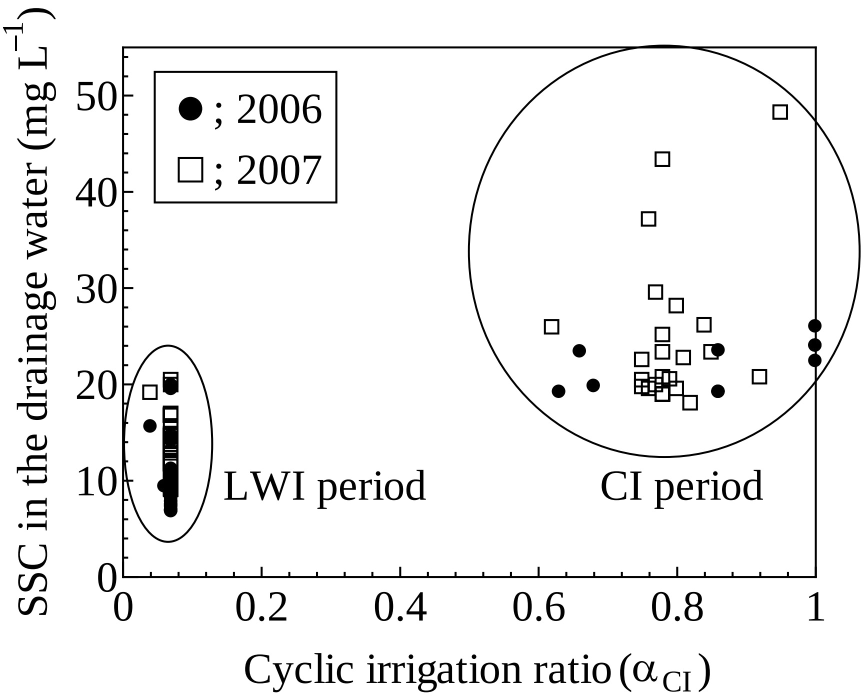


Figure 5 Hama et al.

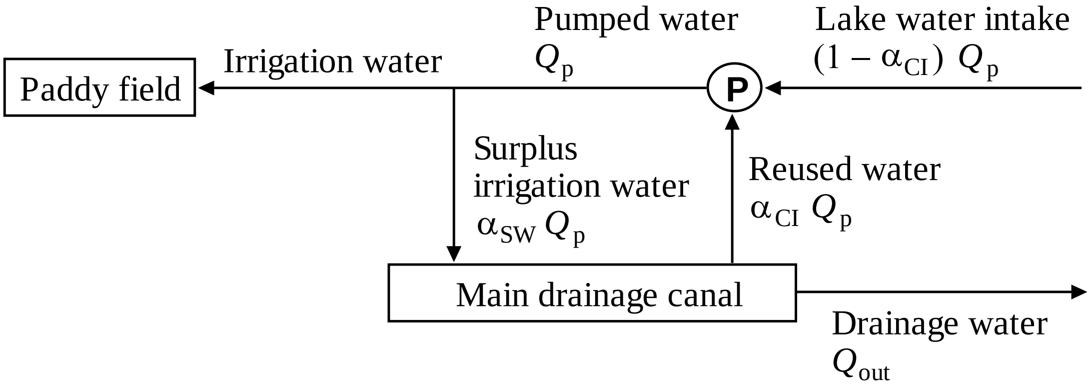


Figure 6 Hama et al.

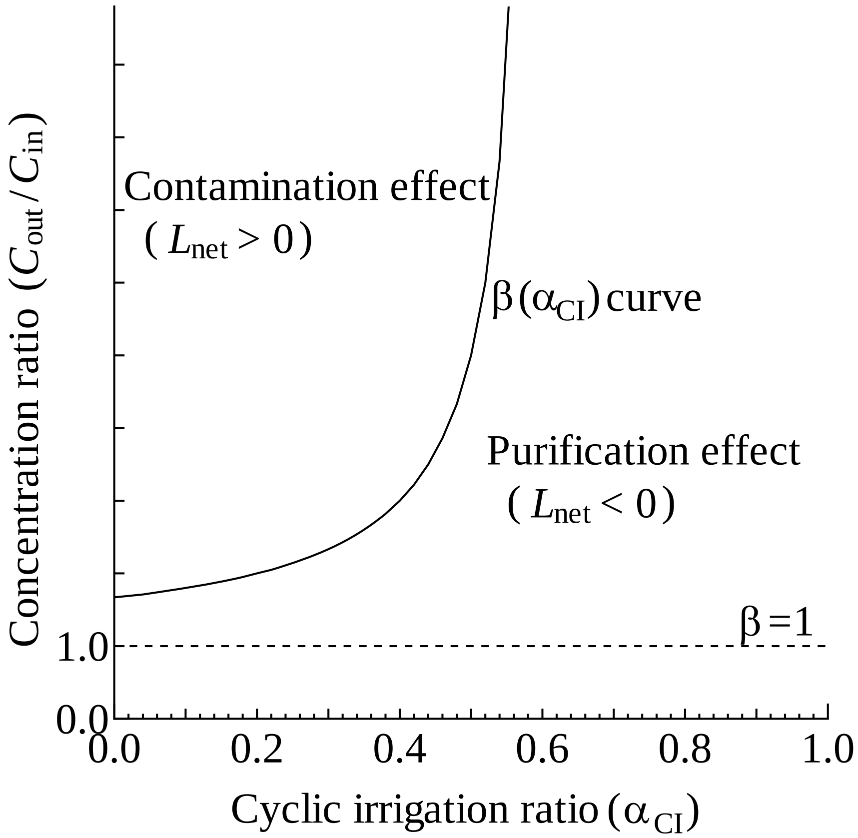


Figure 7 Hama et al.

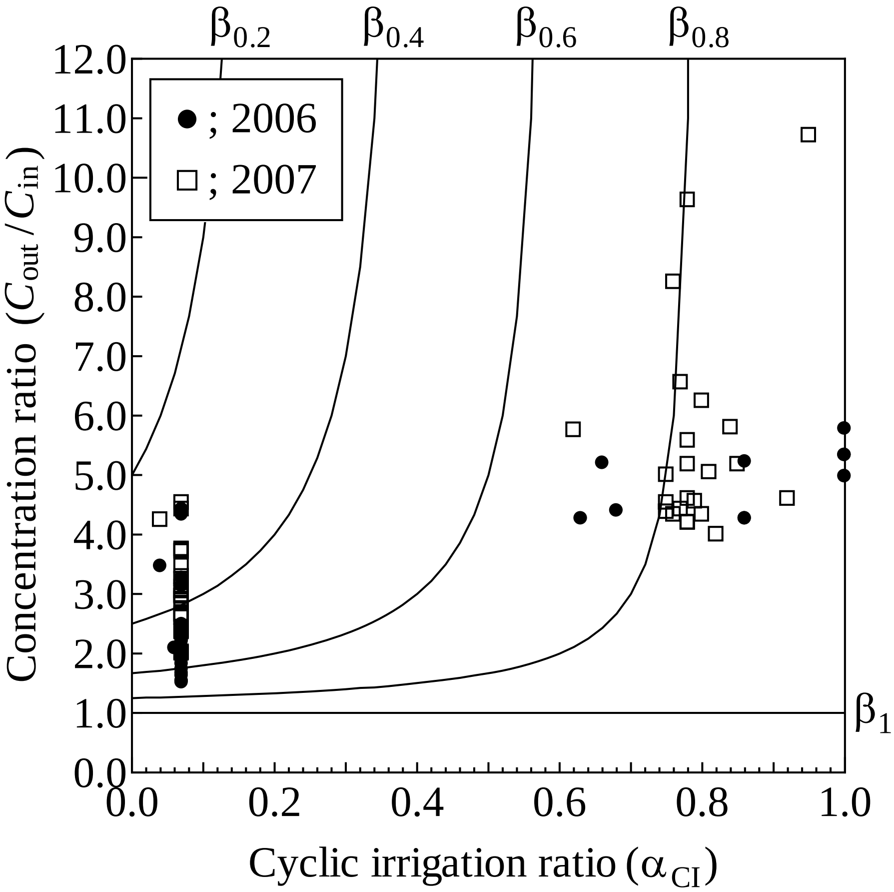


Figure 8 Hama et al.