Nitrogen removal function of recycling irrigation system

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Abstract The purpose of this study was to clarify the nitrogen (N) purification capacity of a paddy field in a recycling irrigation system. Irrigation water was sampled at 12-h intervals during the irrigation period from April to September 2003. In addition, ponded water in a paddy field was collected at three points (inlet, centre and outlet). Total amounts of N were 30.7 kg ha^{-1} in inflow and 27.8 kg ha^{-1} in outflow. Thus, the net outflow load was -2.9 kg ha^{-1}. The N removal rate constant when N removal is expressed as a 1st-order kinetic was 0.017–0.024 m d^{-1}. This value is close to values of wetlands and paddy fields in the literature. We found a good correlation between recycling ratio and N removal effect. These results indicate that the recycling irrigation system accumulates N in the irrigation/drainage system, and thus the paddy field does a good job of water purification by removing N.

Keywords N removal rate constant; paddy field; recycling irrigation system; recycling ratio

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Introduction

Recycling irrigation systems are used where there is a shortage of water. In catchments with poor water supply, especially in paddy fields, which require large amounts of irrigation water (1,000–1,500 mm), drainage water is reused in irrigation. In Japan, recycling irrigation systems are used in several agricultural areas.

Recycling irrigation systems reduce the effluent load from agricultural areas. They also reduce nutrient loss relative to non-recycling irrigation systems (Kaneki, 1991). In a catchment with a high recycling irrigation rate, the accumulation and consumption of nutrients were high (Kudo *et al.*, 1995). Shiratani *et al.* (2004) analysed scenarios in a recycling irrigation model and found that the effluent N load decreases as the recycling ratio increases.

The purification function of paddy fields varies with water management and soil type (Tabuchi and Takamura, 1985). The retention time and the N concentration of irrigation water affect the amount of N removal in paddy fields (Kunimatsu, 1993; Takeda *et al.*, 1997). A recycling irrigation system has a strong influence on the amount of N removed, because it increases the retention time and keeps the N concentration of the water high.

In Japan, paddy fields cover 55% of the agricultural area, and require large amounts of irrigation water. Thus, it is important to understand the purification function of paddy fields equipped with recycling irrigation systems for nutrient load management in catchments. To our knowledge few studies examined the N removal function of recycling irrigation systems.

We calculated the balance of water and N load in a paddy field with a recycling irrigation system, and reveal the characteristics of N removal in the paddy field. Then we

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analysed the relationship between N removal and recycling ratio, and elucidated the effect of the recycling irrigation system on N removal.

Methods

Study catchment

The Yoshinuma area lies to the north of Tsukuba city, Japan. Most of the land there is used for paddy fields; the rest is forest, upland fields and homes (Figure 1, Table 1). The Kokai River supplies irrigation water to the fields.

Yoshinuma has a recycling irrigation system (Figure 2). Water from the river is used to irrigate paddy fields and upland fields, and then the drainage flows into the main drainage canal. At the pump station, the water level of the main drainage canal is elevated by a movable barrage during the irrigation period. Some of the water from the canal is pumped up to other paddy fields (8.9 ha), from where the drainage flows back into the canal again. The remaining water flows back into the Kokai River. The recycling irrigation system thus reduces the amount of drainage flowing back into the river.

Study paddy field

We investigated a paddy field in the recycling irrigation area from April to September 2003. It had an area of 4,800 m^2 (76 m × 64 m), and had two inlets and one outlet. Irrigation water was supplied via a pipeline. Surface drainage flowed out through a drain, the level of which was controlled by the farmer. The farming schedule of the study field is shown in Table 2. The irrigation period went from the middle of April to the end of August. Transplanting occurred at the end of April; harvesting occurred in the middle of September.

Hydrological measurement

The flow rates at the two inlet points were measured with a cumulative flow meter. Changes of ponding water depth in the paddy field were recorded with an automatic water level register. Precipitation was estimated from the automated meteorological data acquisition system of the Japan Meteorological Agency (AMeDAS) collected at Shimotsuma observatory located 5 km northwest of the study field. Evapotranspiration was calculated by the Makkink method (Nagai, 1993).

The outflow rate was calculated from the water levels recorded by the automatic register. The flow rate of reused water through the recycling irrigation system was estimated from the working time of the pump station.

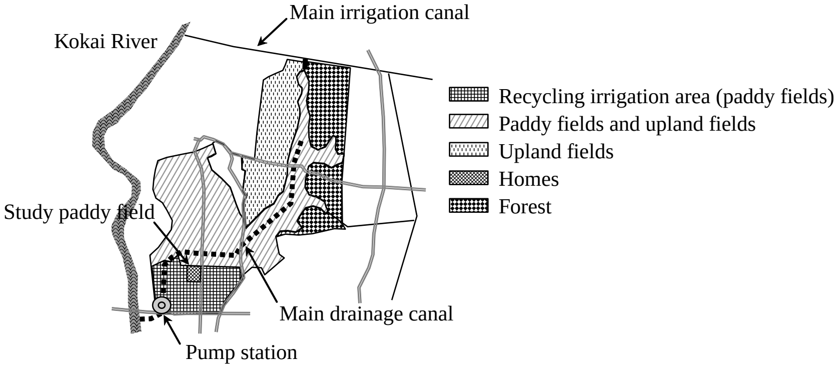

Figure 1 Outline of the study catchment

Table 1 Land uses

Land use	Area (ha)	Percentage (%)
Paddy fields	36.5	57.1
Recycling irrigation area	8.9	13.9
Upland fields	11.6	18.1
Homes	2.7	4.2
Forest	13.1	20.5
Total	63.9	

Sampling and water quality measurements

River water, ponding water in the study paddy field at three points (inlet, centre and outlet), and the outflow water at the pump station were sampled once a week during the irrigation period. The outflow water in the main drainage canal at the pump station, which was the irrigation water applied to the recycling irrigation area, was sampled at 12-h intervals by an automatic sampler (ISCO 6700, ISCO, USA). Water temperature, pH, electrical conductivity (EC), dissolved oxygen (DO) and turbidity were measured at each sampling point with a water quality meter (U-21XD, HORIBA, Japan). The concentration of total nitrogen (T-N) was measured with a T-N analyser (TN-301P, Yanaco, Japan).

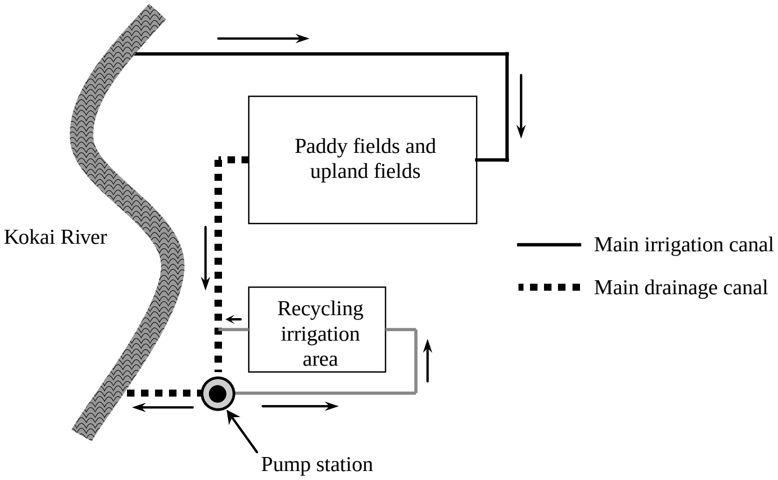

Figure 2 Outline of the recycling irrigation system

Table 2 Farming schedule of study paddy field in 2003

Dates	Farming practices
April 19	Basal fertilizer application (N 3.2 gm^{-2})
April 20	Start of irrigation
April 27	Puddling and weeding
April 29	Transplanting
May 17	Weedicide application
June 10–June 25	Mid-summer drainage
July 13	Topdressing (N 2.2 gm^{-2})
August 3	Pesticide application
August 30	End of irrigation
September 14	Harvesting

Results and discussion

Characteristic of N removal in the paddy field

Water balance in paddy field. The water balance in a paddy field is expressed by the following equation:

$$H_i = H_{i-1} + I_i + R_i - E_i - P_i - S_i,$$

where $H_i =$ ponding water depth (mm), $I_i =$ amount of irrigation water (mm), $R_i =$ amount of rainfall (mm), $E_i =$ amount of evapotranspiration (mm), $P_i =$ amount of percolation (mm) and $S_i =$ amount of surface drainage (mm) at time i (d).

We did not measure the amount of surface drainage or percolation. So we calculated the water balance on the basis of the observation that the maximum value of the sum of percolation and evapotranspiration was $10\,\mathrm{mm\,d^{-1}}$.

1. The amount of rainfall (R_i) was estimated from AMeDAS data.
2. The amount of evapotranspiration (E_i) was calculated by the Makkink method.
3. The amount of surface drainage on the ith day (S_i) was calculated as:

$$S_i = 0\,\mathrm{mm} \text{ when } (H_{i-1} - H_i) + I_i + R_i < 10\,\mathrm{mm};$$

$$S_i = (H_{i-1} - H_i) + I_i + R_i - E_i - P_i \text{ when } (H_{i-1} - H_i) + I_i + R_i \geq 10\,\mathrm{mm}.$$

4. The amount of percolation on the ith day (P_i) was calculated as:

$$P_i = 0\,\mathrm{mm} \text{ when } (H_{i-1} - H_i) + I_i + R_i < 0\,\mathrm{mm};$$

$$P_i = (H_{i-1} - H_i) + I_i + R_i - E_i \text{ when } 0\,\mathrm{mm} < (H_{i-1} - H_i) + I_i + R_i < 10\,\mathrm{mm};$$

$$P_i = 10 - E_i\,\mathrm{mm} \text{ when } (H_{i-1} - H_i) + I_i + R_i \geq 10\,\mathrm{mm}.$$

Figure 3 shows the seasonal variations of the inflowing and outflowing water. The water requirement (evapotranspiration + percolation) during the irrigation period was $8.8\,\mathrm{mm\,d^{-1}}$. The optimum water requirement rate in Japan is $20–25\,\mathrm{mm\,d^{-1}}$. Thus, the study paddy field saved irrigation water.

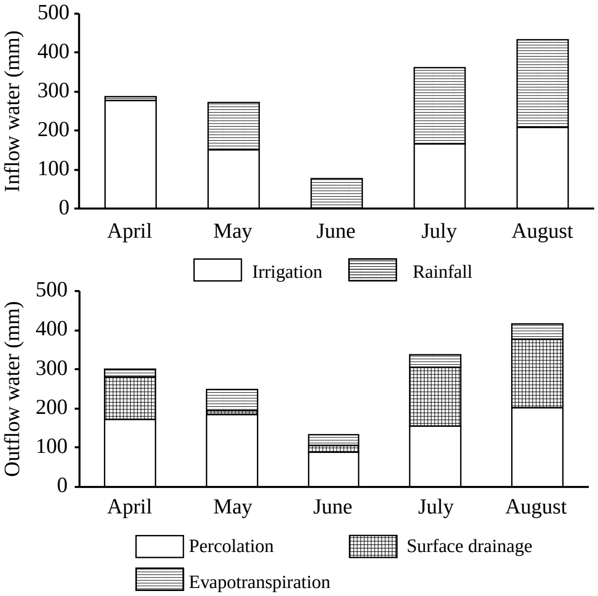

Figure 3 Seasonal variations in inflowing and outflowing water

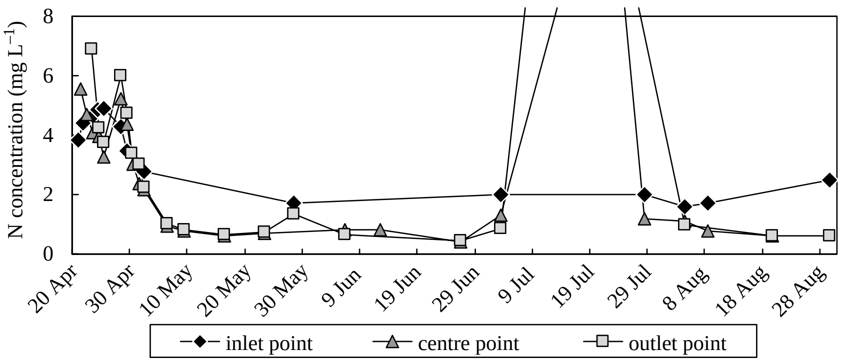

Figure 4 N concentrations of ponded water at inlet and outlet

N balance in paddy field. Figure 4 shows the N concentrations of ponded water at the inlet, centre and outlet points during the irrigation period. Most of the time, the N concentration at the centre and outlet was lower than that at the inlets, except during the start of irrigation, puddling and fertiliser topdressing.

Figure 5 shows the seasonal variations in the inflowing and outflowing N loads. These loads were calculated by multiplying the N concentration by water volume. The total N loads during the irrigation period were 30.7 kg ha^{-1} inflowing and 27.8 kg ha^{-1} outflowing (Table 3). The net outflow load of N (outflow minus inflow) was -2.9 kg ha^{-1}. The negative value means that this paddy field removed N.

N removal rate constant. In paddy fields, N is removed by denitrification, sedimentation and absorption by plants and algae. In general, this N removal is expressed by the following exponential formula:

$$N = N_0 \exp(-at/h),$$

where $N =$ N concentration in the ponded water (mg L^{-1}), $N_0 =$ initial N concentration (mg L^{-1}), h = ponded water depth (m), a = N removal rate constant (m d^{-1}) and $t =$ time (d).

N removal rate constant means the potential for N removal. Figure 6 shows the decrease in N concentrations in the ponded water between two periods. In the first period, from 23 to 25 April, water with a high N concentration (4.73 mg L^{-1}) was supplied, and nutrients were dissolved from basal fertiliser and soil. In the second period, from 16 to 22 July, nutrients were dissolved from the topdressing. To calculate the N removal rate constant, we assumed that the ponding water depth was 0.05 m, the usual depth in Japanese paddy fields, and applied the above formula. The N removal rate constants were, respectively, 0.017 and 0.024 m d^{-1}. These values are close to previous results in the same field, 0.016 to 0.021 m d^{-1} (Yoshinaga *et al.*, 2003).

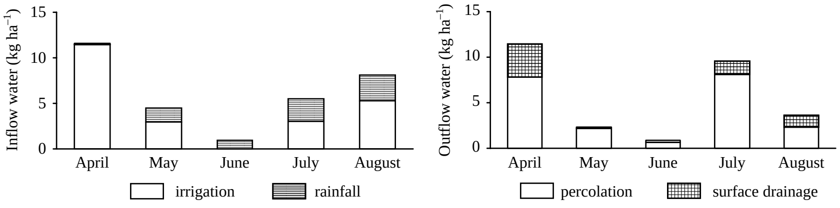

Figure 5 Seasonal variations in the inflow and outflow loads of N

Table 3 N loads of inflowing and outflowing water

	Inflow		Outflow		Net outflow
	Irrigation	Rainfall	Percolation	Surface drainage	
April	11.46	0.14	7.80	3.65	−0.16
May	2.95	1.55	2.21	0.13	−2.16
June	0.00	0.96	0.68	0.16	−0.12
July	3.05	2.46	8.13	1.45	4.08
August	5.30	2.82	2.31	1.27	−4.53
Total	22.76	7.92	21.13	6.66	−2.90

Tabuchi (2001) calculated N removal rate constants of some soil types at constant temperature in the dark, and found values of 0.007 to 0.014 m d^{-1}. In actual paddy fields, N is removed by absorption by vegetation and algae in the light as well, so actual values would be higher. Yamaguchi and Hata (1993) clarified the relationship between the N concentration of irrigation water and N removal. The N concentration dropped from an initial 20 mg L^{-1} to 1.0–2.0 mg L^{-1} by 7 d. Thus, the removal rate constant was around 0.03 m d^{-1}. Judging from these results, our study paddy field had a comparable potential for N removal.

N removal functions in catchment equipped with recycling irrigation system

Figure 7 shows the N concentrations of the river and main drainage canal. During most of the irrigation period, the N concentration at the outflow was lower than that at the inflow. During late April and late June to early July, however, the N concentration at the outflow was higher. Those results were due to nutrient enrichment in the paddy fields. Generally, during late April, the beginning of the irrigation period, a large amount of water is applied to paddy fields, and puddling and transplanting are carried out. These actions mix the water, basal fertiliser and soil, allowing nutrient-rich water to drain from the fields. In June, fields are drained to dry the soil as standard farming practice in Japan to maintain the condition of the rice roots. There was no water in our study paddy field during 10 to 25 June. In these aerobic conditions, organic matter breaks down quickly, and the nutrient concentrations in the soil become high. Irrigation began again in late June, and nutrient-rich water consequently drains from the paddy fields. Thus, the high N concentrations at the outflow were due to agricultural practices, and the paddy fields became a pollutant source.

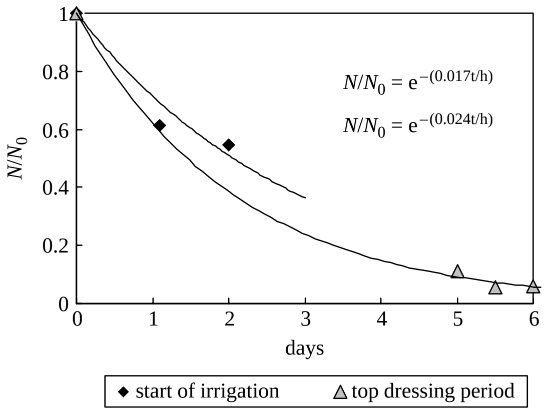

Figure 6 Decrease of N concentrations in the ponded water

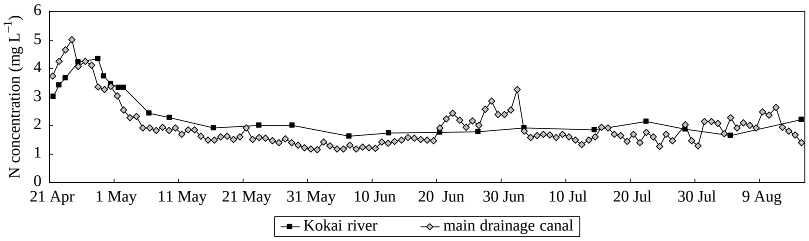

Figure 7 N concentrations in Kokai River and main drainage canal

Factors of N removal in recycling irrigation system. The recycling irrigation system removes N in two ways. First, reusing drainage water increases the retention time. Retention time has a great influence on nutrient removal. Retention time is calculated as follows:

$$RT = V/(Q_{in} + P),$$

where RT = retention time (d), V = water volume retained in the catchment (m^3), Q_{in} = flow of irrigation water to the catchment (m^3 d^{-1}) and P = precipitation (m^3 d^{-1}).

Takeda *et al.* (1997) found that nutrients were removed when retention time was 5 to 7 days. A higher recycling ratio requires less irrigation water to increase retention time. Feng *et al.* (2005) reported a retention time of 5–9 days (except in April) in the same paddy field as ours.

Second, a recycling irrigation system accumulates nutrients. To achieve this, a regulating reservoir is needed from which water is pumped up to the fields. The reservoir collects water and nutrients from the whole catchment and accumulates the nutrients in the recycling irrigation system by preventing the outflow of nutrient-rich water. It could be suggested that sedimentation of particle nitrogen in the catchment plays a great role in reducing nitrogen effluent load, because average turbidity was comparatively high (98.4 mg/L at the main drainage canal). In addition, paddy fields remove nutrients from nutrient-rich irrigation water (Kunimatsu, 1983). In our study catchment, the main drainage canal played the role of reservoir, and nutrient-rich water was reused on the upper fields. The average N concentration of the water in the main drainage canal, which was the source of recycled irrigation water, was 2.0 mg L^{-1}, a comparatively high concentration.

Relationship between recycling ratio and N removal. Our results show that a recycling irrigation system is effective at removing N (Figure 8). To evaluate the efficiency of our study site, we calculated the recycling ratio and difference in N concentration. The recycling ratio was calculated as follows:

$$R = 100\,V_p/(V_p + V_s),$$

where R = recycling ratio (%), V_p = volume of reused water supplied through the recycling irrigation system (m^3), and V_s = volume of runoff from the catchment (m^3).

We estimated the N removal function from the difference in N concentration:

$$D = -\Delta N/t,$$

$$\Delta N = (N_o - N_i),$$

where D = difference in N concentration (mg L^{-1} d^{-1}), N_o = N concentration of outflow water in the main drainage canal (mg L^{-1}), N_i = N concentration of inflow water in Kokai River (mg L^{-1}), and t = time (d).

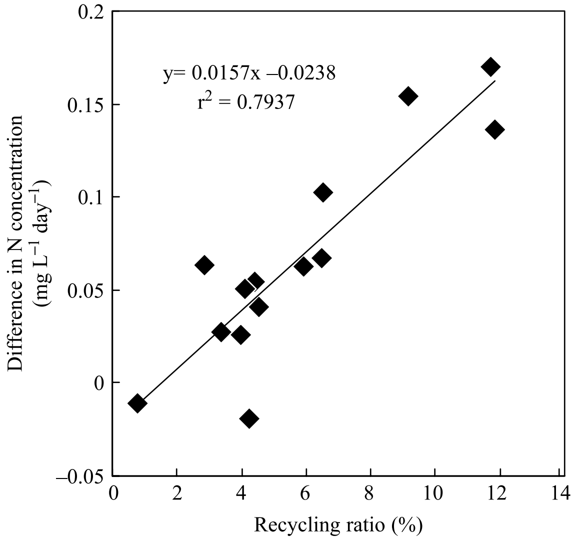

Figure 8 Relationship between recycling ratio and difference in N concentration

To reveal the effect of the recycling irrigation system on N removal, we calculated the recycling ratio and difference in N concentration for the period excluding when the paddy field was a pollutant source. Figure 8 shows the relationship between the two. A positive difference means that the N concentration at the outflow was lower than that at the inflow. This figure indicates that the N removal efficiency is proportional to the recycling ratio. Consequently, it is possible to raise the N removal effect of this recycling irrigation system by keeping the recycling ratio high. The mean recycling ratio was 5.7%, and the mean difference in N concentration was $0.066\,\mathrm{mg\,L^{-1}\,d^{-1}}$.

Conclusions

Recycling irrigation systems can remove N. Thus we found the system plays an effective role for nutrient load management in catchments. In this study, we evaluated the effect of the recycling irrigation system on N removal. We came to the following conclusions.

1. The total inflow and outflow loads during the irrigation period in the study paddy field were 30.7 and $27.8\,\mathrm{kg\,ha^{-1}}$ respectively. Therefore, the net outflow load was $-2.9\,\mathrm{kg\,ha^{-1}}$, indicating that this paddy field removed N.
2. The N removal rate constant was $0.017\,\mathrm{m\,d^{-1}}$ at the start of irrigation and $0.024\,\mathrm{m\,d^{-1}}$ during topdressing.
3. The difference in N concentration (inflow minus outflow) increased in proportion to recycling ratio.

The recycling irrigation system purifies water by accumulating N in the system. This function has a significant role to play in reducing the N load from rice-growing areas.

References

Feng, Y.W., Yoshinaga, I., Shiratani, E., Hitomi, T. and Hasebe, H., (2005). Nutrient balance in a paddy field with a recycling irrigation system. *Wat. Sci. Tech.*, **51**(3–4), 151–157.

Kaneki, R. (1991). Water quality of return flow and purification by using paddy fields. *J. Jpn. Soc. Irrig. Drain. Reclam. Eng.*, **59**(11), 31–36 (in Japanese).

Kudo, A., Kawagoe, N. and Sasanabe, S. (1995). Characteristics of water management and outflow load from a paddy field in a return flow irrigation area. *J. Jpn. Soc. Irrig. Drain. Reclam. Eng.*, **63**(2), 49–54 (in Japanese).

Kunimatsu, T. (1983). Crop land – recycling of nutrients and purification function in paddy fields. Research Report. Lake Biwa Research Institute, Shiga, Japan, pp. 28–35 (in Japanese).

Nagai, A. (1993). Estimation of pan evaporation by Makkink equation. *J. Jpn. Soc. Hydrol. & Wat. Resour*, **6**(3), 238–243 (in Japanese with English abstract).

Shiratani, E., Yoshinaga, I., Feng, Y.W. and Hasebe, H. (2004). Scenario analysis for reduction of effluent load from an agricultural area by recycling the run-off water. *Wat. Sci. Technol.*, **49**(3), 55–62.

Tabuchi, T. (2001). Nitrate removal in the flooded paddy field. *Proc. Int. Workshop on Efficiency of Purification Process in Riparian Buffer Zones* (edited by the organizing committee for international workshop of riparian buffer zones), pp. 81–90.

Tabuchi, T. and Takamura, Y. (1985). *Nitrogen and Phosphorus Outflow from Catchment Area*. Tokyo University Press, Japan.

Takeda, I., Fukushima, A. and Tanaka, R. (1997). Non-point pollutant reduction in a paddy-field watershed using a circular irrigation system. *Wat. Res.*, **31**, 2685–2692.

Yamaguchi, Y. and Hata, K. (1993). Change of water quality on nitrogen and phosphorus in surface of fallow paddy fields. *J. Jpn. Soc. Irrig. Drain. Reclam. Eng*, **61**(10), 7–12 (in Japanese).

Yoshinaga, I., Feng, Y.W., Hasebe, H. and Shiratani, E. (2003). Nitrogen removal function of paddy field in a circular irrigation system. *Proceedings of 7th International Conference on Diffuse Pollution*, 17–21 August 2003, Dublin, Ireland, pp. 56–61.