Research article

Influences of Land Use during the Puddling Period on Water Balance and Quality in a Rice Farming Area

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Abstract The study was carried out on the Shinotsu Canal agricultural watershed of Hokkaido, Japan from 2003 to 2008. This study was conducted to evaluate the nutrients fluxes after using irrigation into the paddy fields and the effectiveness of the paddy fields in removing nutrients load of the Shinotsu Canal watershed. Upper part of the Shinotsu Canal is dominated by paddy field and lower part is dominated by upland field. Water samples were collected with an automatic sampler at pump station (inflow) and end of drainage channel (outflow) of both block, and measured volume of inflow and outflow at puddling period (May). The concentration of suspended solids (SS) was determined by gravimetrically through suction filtration, total nitrogen (TN) and total phosphorus (TP) were determined by UV spectrophotometric methods, respectively. Water balance is higher at lower part of Mihara drainage block (MDB) than upper part of Tsukigata drainage block (TDB) due to high percentage of upland that caused losses of water by leakage and percolation. TN, TP and SS concentrations in drainage water are higher in MDB than that of TDB. The net loads of TN and TP are showed negative and lower values in TDB whereas MDB is positive and higher values, due to a combination of nitrification and denitrification, sedimentation reactions and sorption by soil is more in high percentage of paddy field in TDB. TN, TP and SS concentrations outflow load and net load are decreasing from 2003 to 2008 due to changed of water management by progress of pipe line. From the viewpoint of reducing the outflow of nutrients, it may be stated that the paddy field dominated area showed good performance in purification function for nutrients compounds.

Keywords land and water use, water balance, puddling period, water quality, Hokkaido

INTRODUCTION

In Japan, paddy fields cover 55% of the land used for agriculture. They require abundant water and account for 95% of the total agricultural water demand (Tabuchi and Hasegawa, 1995). Paddy fields therefore play a significant role in the overall agricultural watershed. Most paddy fields are located along lower reaches of rivers, use rivers as their main source of water, and discharge their outflow back into the river. The Shinotsu Canal watershed has a significant role in agriculture in Hokkaido, Japan. Water quality of the Shinotsu Canal is influenced by nonpoint source pollutants arising from land-based agricultural activities (Hasan et al., 2010). In some paddy fields along the lower parts of the Ishikari River basin in the Shinotsu Canal, irrigation water is reused as means of maximizing water utilization, and the water may contain higher levels of pollutants from surface and subsurface drainage compared with usual irrigation water. Several researchers have reported that cyclic irrigation may increase the hydraulic retention time of nutrients, and thereby, enhance water purification in paddy field districts (Feng et al., 2004, 2005; Takeda and Fukushima, 2006). Cyclic irrigation may not only save water but also reduce the concentration of nutrients in agricultural areas (Kudo et al., 1995). The ability of cyclic irrigation to reduce nutrient load is directly proportional to the quantity of water reused (Kaneki et al., 2003). Tong and Chen (2002) examined the hydrologic effects of land use in Ohio and observed a significant relationship between land use and stream water quality, especially with respect to nitrogen and phosphorus.

In irrigation practices, especially puddling and transplantation period (May), require abundant water during the whole irrigation period (May to August) in paddy fields, and have strong influence on the water environment. Furthermore, many studies on nutrient fluxes in paddy fields have been outperformed in the irrigation period, but the flow of nutrients out of paddy fields has not been studied adequately in Hokkaido in instances of abundant water use. Therefore, this study aimed to assess the influences of land use and water management on water balance and quality during the puddling period at the Shinotsu Canal watershed in Hokkaido.

MATERIALS AND METHODS

The investigation was performed in the Shinotsu Canal in the Shinotsu district (43°57′N, 141°4′E), which is located at southern Ishikari River basin in west-central Hokkaido prefecture in northern Japan (Fig. 1). The Shinotsu Canal is 23 km long and passes through 10,864 hectares of agricultural watershed where the main cultivated crops are rice, wheat, corn, onions, and vegetables. Agricultural irrigation is controlled by five pumping stations from upstream to downstream. The lower stream pumping stations provide irrigation water derived through drainage channels from the outflow or runoff from upstream paddy fields. The study area comprised the Tsukigata drainage block (TDB) in the upper stream and Mihara drainage block (MDB) in the lower stream of the Shinotsu Canal (Fig. 2).The soil is peat-dressed mineral soil, and most land is flat. The annual average precipitation is 1024 mm, most is in the form of rain occurring from July to September. The annual temperature ranges from a minimum of −7.4°C in January to a maximum of 23°C in August. Fertilizer is applied to paddy fields in this region (N, 60–75 kg/ha; P, 80–90 kg/ha) during puddling to transplantation period (May) and the flowering stage (middle of July).

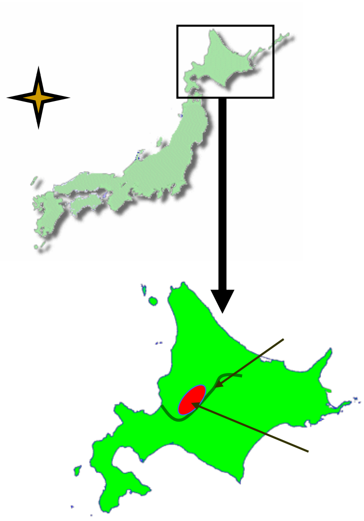

Fig. 1 Location map of study area

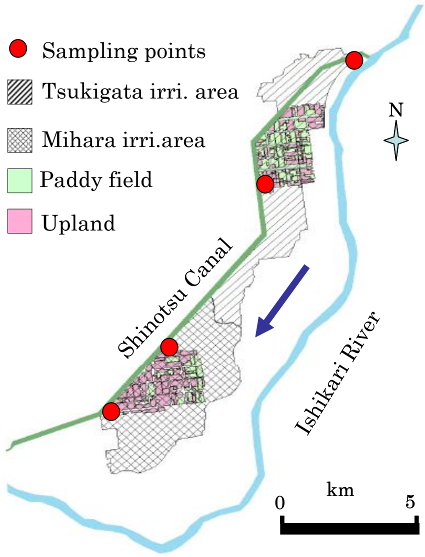

Fig. 2 Investigated area of Shinotsu

Inflow and outflow water samples (composite water samples) were collected from TDB and MDB. Composite water samples (two mixture samples obtained at intervals of 6 h for 24 h) were collected with an automatic water sampler (ISCO Model 3700) during the puddling and transplantation periods (May) in 2003, 2004, 2006, 2007, and 2008. Inflow water samples were collected at each pumping station, and outflow samples were collected at the end of the TDB and MDB drainage channels. Inflow water volume of TDB and MDB were calculated from data on pump discharge and water level in the delivery tank; these data were collected from the management office of the Tsukigata and Mihara pumping stations (Shinotsu-chuoh Land Improvement District). Outflow water volumes were calculated from continuous records of water levels using an automatic water gauge, and flow velocity was measured when the water was sampled. Channel renewal (open to pipe) data were collected from the Shinotsu-chuoh Land Improvement District. Precipitation was estimated from the Shin-shinotsu and Tsukigata rainfall records using the Automated Meteorological Data Acquisition System (AMeDAS). Areas of paddy fields and uplands in the study watersheds were calculated using GIS Arc-View software from 1:25,000 scale digital maps. The concentration of suspended solids (SS) was determined gravimetrically by suction filtration, and total nitrogen (TN) and total phosphorus (TP) were determined by UV spectrophotometric methods. The concentrations of SS, TN, and TP were determined as described in the Japanese Industrial Standard (JIS).

RESULTS AND DISCUSSION

The Tsukigata and Mihara irrigation and drainage blocks were investigated from 2003 to 2008, and the areas of their paddy fields and upland fields were calculated. The Tsukigata pumping station irrigated 1948 hectares in the upstream agricultural watershed of the Shinotsu Canal (Table 1). TDB forms part of the irrigation area for Tsukigata pumping station and covers an area of 743 hectares (Table 1). Mihara pumping station lies in the downstream agricultural watershed of the Shinotsu Canal and irrigates 2018 hectares (Table 1). MDB is part of the irrigation area of Mihara pumping station and covers 747 hectares (Table 1). During the study period, the paddy field area was greater in TDB than in MDB, but the upland field area was greater in MDB than in TDB. A high percentage of the paddy field area was found in TDB (41–46%). In contrast, the percentage of upland was higher in MDB (56–63%) than in TDB (30–36%). TDB was dominated by paddy fields and MDB by upland fields; land use pattern did not change substantially during the study period.

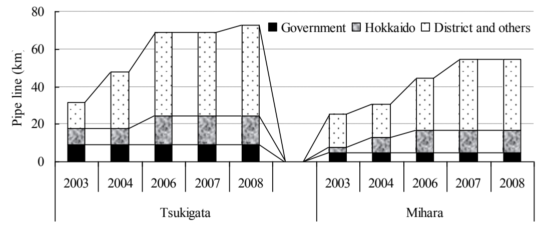

Fig. 3 Renewal of pipe line at Tsukigata and Mihara irrigation block

The form of irrigation channels is an important factor in water management in the agricultural watershed of the Shinotsu Canal. The pipeline irrigation channels are constructed from open channels in the Tsukigata and Mihara irrigation blocks. Lengths of the pipeline irrigation channels of the Tsukigata and Mihara irrigation blocks were calculated for every year from 2003 to 2008, except for 2005. The total pipeline length in the Tsukigata irrigation block was larger than that in the Mihara irrigation block for every year (Fig. 3). Pipelines are constructed as part of projects operated by the national government, the Hokkaido prefecture government, and the Shinotsu-chuoh Land Improvement District. The length of pipeline constructed under the national government project was constant during the study period, whereas the length of pipeline constructed under the Hokkaido project increased from 2003 to 2006 in both blocks. Pipelines constructed under other projects gradually increased in length from 2003 to 2008 in both blocks. The condition of these pipelines is evaluated at each drainage block. The water balance of each block was calculated using Eq. (1):

$$\textit{Water balance} = \textit{total inflow} - \textit{total outflow} \quad (1)$$

where *total inflow* is the volume of pumped water plus precipitation, and *total outflow* is surface plus subsurface drainage water per day. Inflow and outflow water volumes of TDB and MDB were calculated for the years 2003 to 2008. Irrigation water is distributed from about May 7 every year in the Shinotsu district. Average daily inflow water volume was greater for MDB than for TDB for every year. In contrast, outflow water volume of MDB was lower than that of TDB. Inflow and outflow volumes gradually decreased due to increasing pipeline length in both blocks. The form of irrigation channel is changing gradually from open to pipeline, and farmers now control irrigation water for each paddy block to ensure proper water utilization. In contrast, the land use pattern of each block did not change significantly during the study period. The water balance of MDB was higher than that of TDB for every year (Fig. 4), because the percentage of upland was higher in MDB than in TDB, and paddy fields were scattered. Abundant water was therefore lost from the paddy fields to adjacent uplands by leakage and percolation. Water balance in TDB and MDB did not change significantly during the study years except in May, 2006 at MDB (Fig. 4).

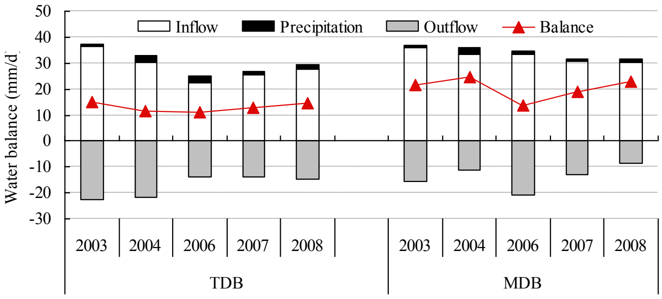

Fig. 4 Water balance of TDB and MDB

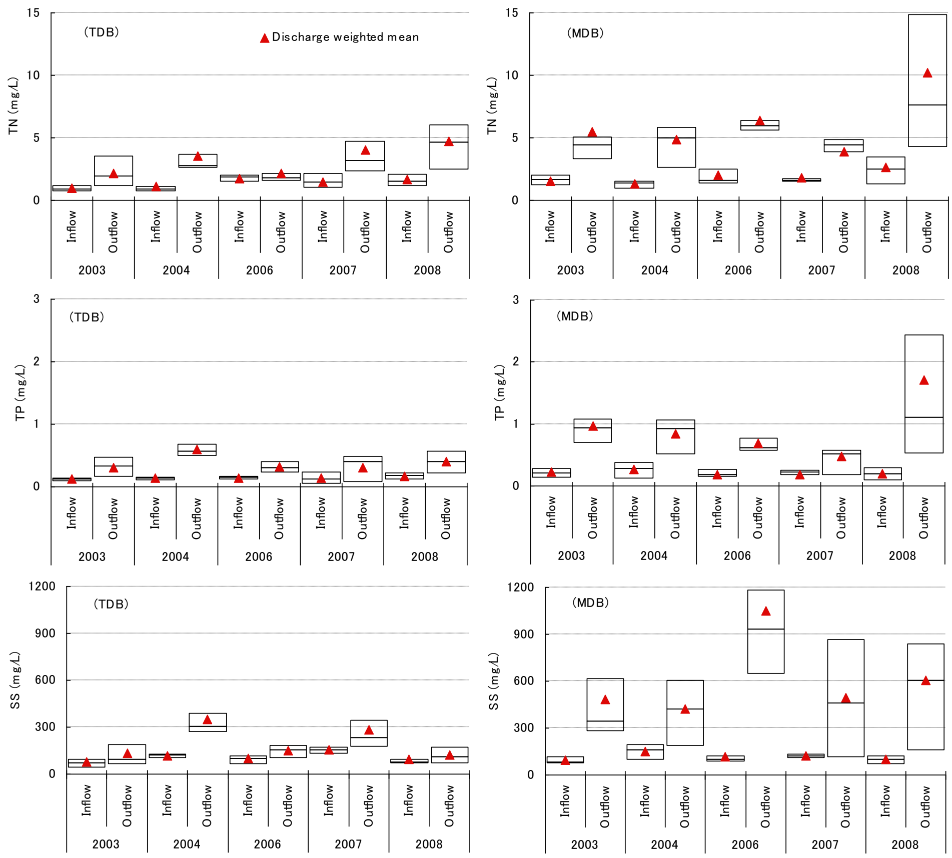

Fig. 5 Concentarions of TN, TP and SS in TDB and MDB in May

The discharge weighted mean concentrations of TN, TP, and SS of inflow and outflow water of TDB and MDB in May for every year are shown in Figure 5. The box plots of TN, TP, and SS concentrations represent 75% and 25% quartiles, medians, and weighted mean values for TDB and MDB. Mean TN, TP, and SS concentrations were higher in outflow than in inflow water in both drainage blocks. Variations in TN, TP, and SS concentrations were larger in outflow than in inflow water. These variations are thought to be caused by agricultural activities, i.e., puddling and transplantation. In the initial stages of rice cultivation, abundant irrigation water is used in paddy fields for puddling, and it mixes with soil and fertilizer. Nutrient-rich flooded water is released through surface drainage before transplantation. A high load of pollutants accumulates through subsurface drainage and is subsequently discharged into drainage ditches. The concentrations of nitrogen and phosphorus in drainage water increase during puddling and transplantation, and also when fertilizer is applied (Takeda et al., 1997; Feng et al., 2004). Several studies of water quality indicators in drainage water from paddy fields in Japan showed that the concentrations of these contaminants increased significantly during puddling periods (Kondoh et al., 1992). Also, nutrient concentrations are generally higher in drainage water than in irrigation water (Takeda et al., 1997). In the present study the concentrations of TN, TP, and SS in outflow water were higher in MDB than in TDB due to the land use pattern, i.e., low percentage of paddy fields in every year (Table 1). Outflow discharge was lower in MDB than in TDB during the study period (Fig. 4), and nutrient concentrations were decreased by the high outflow discharge in the TDB drainage. Tabuchi and Takamura (1985) reported that outflows from paddy fields contained much less pollutants than upland fields because nutrients are easily absorbed by soil particles in paddy fields. The concentrations of TN, TP, and SS showed large variation due to puddling, transplantation, and initial use of fertilizers, which runoff by surface and subsurface drainage from paddy fields in both blocks. Nutrient concentrations of drainage water increased rapidly when the puddling process began, and high concentrations continued to be present during subsequent farming activities.

The net outflow nutrient load is one of the most important factors to consider when evaluating the role of paddy fields in reducing levels of pollutants from agricultural watersheds (Tabuchi and Takamura, 1985). The net nutrient load associated with irrigation is defined as the outflow nutrient load minus the inflow nutrient load (e.g., Takeda et al., 1997). The net load indicates increase or decrease in the nutrient load discharged from the paddy field when irrigation is compared with drainage water. A positive net load indicates that the paddy field area is a nutrient source, whereas a negative value indicates that the area is a nutrient sink, i.e., nutrients are absorbed by the paddy soil. The nutrient load is the product of average nutrient concentration and water flow volume. The daily nutrient load is calculated using the L-Q power Eq. (2):

$$L = aQ^b \tag{2}$$

where L is the load in kg ha^{-1} d^{-1}, Q is the flow rate m^3 ha^{-1}d^{-1}, and a and b are coefficients. Thus, the net nutrient load, L_{net} (kg ha^{-1}d^{-1}) is given by the following Eq. (3):

$$L_{net} = aQ_{out}^{\ b} – a'Q_{in}^{\ b'} \tag{3}$$

TN, TP, and SS loads were greater in MDB than in TDB for every year except for the outflow SS load of MDB. The net TN and TP loads were negative and lower values were found in TDB than in MDB (Table 2), because TDB contained a higher percentage of paddy field than MDB, causing greater nitrification and denitrification, sedimentation reactions, and sorption by soil. Misawa (1987) and Shiratani et al. (2002) reported that paddy field areas in Japan caused net removal of nutrients due to a combination of nitrification and denitrification, sorption by soils, and sedimentation reactions.

Table 1 Land use of research areas

Study block		Tsukigata	Mihara
Irrigation block (ha)		1948	2018
Drainage block (ha)		743	747
Paddy (ha)	2003	303 (40.8%)	161 (21.6%)
	2004	308 (41.5%)	208 (27.8%)
	2006	311 (41.9%)	184 (24.6%)
	2007	310 (41.7%)	188 (25.2%)
	2008	343 (46.2%)	177 (23.2%)
Upland (ha)	2003	269 (36.2%)	467 (62.5%)
	2004	264 (35.5%)	420 (56.2%)
	2006	261 (35.1%)	444 (59.4%)
	2007	262 (35.3%)	440 (58.9%)
	2008	224 (30.1%)	425 (56.9%)

Table 2 Nutrients loads of TDB and MDB in May

Load (kg ha^{-1})	Year	TDB			MDB		
		Inflow	Outflow	Netload	Inflow	Outflow	Netload
TN	2003	10.25	-11.86	1.61	18.21	-23.94	5.73
	2004	10.13	-11.48	1.36	15.35	-17.29	1.94
	2006	9.54	-9.21	-0.33	14.68	-33.53	18.85
	2007	10.03	-9.27	-0.77	13.76	-15.66	1.90
	2008	10.06	-9.49	-0.57	13.30	-13.28	-0.02
TP	2003	1.54	-1.24	-0.31	2.51	-3.78	1.26
	2004	1.23	-1.15	-0.08	2.06	-2.83	0.77
	2006	0.84	-0.48	-0.36	1.98	-5.07	3.09
	2007	1.04	-0.47	-0.57	1.81	-2.93	1.12
	2008	1.12	-0.55	-0.57	1.75	-2.25	0.50
SS	2003	105.39	112.35	6.96	61.33	26.22	-35.10
	2004	96.53	102.00	5.47	48.68	24.99	-23.69
	2006	92.51	56.57	-35.94	49.42	56.20	6.78
	2007	90.35	53.90	-36.45	40.67	23.97	-16.70
	2008	88.08	50.83	-37.26	33.09	21.04	-12.05

Net SS loads were negative in both TDB and MDB. TN, TP, and SS loads decreased between 2003 and 2008 due to changes in water management activities, i.e., progress in pipeline construction. However, progress in pipeline construction reduced outflow water volume, which affects the outflow and net load of nutrients. Water discharge is closely related to nutrient load. Our data on net nutrient loads indicate that areas dominated by paddy fields promote the purification mechanisms for nitrogen and phosphorus compounds in the water environment of agricultural watersheds.

CONCLUSION

In this study, we evaluated the land use pattern, renewal of irrigation channels by pipeline construction, water balance, water quality, and mass balance of nutrient loads in drainage blocks. The data on land use pattern indicated that TDB is dominated by paddy field areas whereas MDB is dominated upland fields. The water management system changed from open channels to pipelines in each block during the study period. Water balance was higher in MDB than TDB because MDB had a larger proportion of upland, which caused greater losses of water by leakage and percolation. The concentrations of TN, TP, and SS in outflow water were higher in MDB than in TDB, because pollutant outflow from paddy fields was much less than that from upland fields. Paddy fields act to purify pollutants such as nitrogen and phosphorus. The net loads of TN, TP, and SS were negative in TDB, where the lower values indicated nutrient uptake by TDB paddy soil, whereas MDB paddy fields had positive loads and higher values; i.e., they were nutrient sources. By reducing the outflow of nutrients, blocks dominated by paddy fields showed good purification performance for nutrient compounds. The reasons for this were the relatively low nutrient concentrations in irrigation water and the change in the water management system in TDB. Upstream (TDB) water is therefore cleaner than lower stream (MDB) water because of the effects of agricultural land use and the water management systems of the Shinotsu Canal watershed.

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