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Relationship between the Characteristics and Water Quality of Irrigation Ponds in Japan

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Abstract

This study dealt with the relationship between the characteristics of irrigation ponds and water quality. We conducted a statistical analysis of 556 irrigation ponds located in urbanized rural areas and flat rural areas throughout the country, and examined a number of indicators of water quality such as pH, chemical oxygen demand (COD), contents of total phosphorus (T-P) and total nitrogen (T-N). There were no strong correlations between the characteristics of the irrigation ponds and water quality. We then conducted a similar analysis of the ponds after classifying them into 4 groups based on hydraulic and meteo rological characteristics. In this analysis, a strong relationship was found for the water quality in each group of ponds. We also studied the nitrogen load in the effluent from the catchment basins and found that diffuse non-point-source nitrogen was the major constituent. Relative intensity of the factors affecting water quality was investigated by multiple regression analysis and box plot analysis.

Discipline: Irrigation, drainage and reclamation
Additional key words: basin characteristics statistical analysis, diffuse non-point-source, water quality preservation, load management

Introduction

In Japan, there are about 213,890 irrigation ponds. Of these, the irrigation area of 68,850 ponds is larger than 2 ha and together they cover a total area of 1,235 thousand ha and contain an effective volume of 4,769 million m^3 of water[6]. This volume of water amounts to about 16% of the 30,470 million m^3 of the effective volume of water contained in dams in Japan[4] and about 8% of the 58,700 million m^3 used yearly for agriculture[3]. The ponds are an important source of water for agriculture. They are also considered to be closed and are a valuable component of local open-spaces, fulfilling multiple purposes in many areas.

With increasing development and a tendency toward crowded living, the inflow of gray water to irrigation ponds may cause pollution and the resultant abnormal algal bloom may lead to environmental problems, for example the death of fish, stench, and destruction of scenery. This deterioration of water quality by factors such as water inflow and nitrogenous and phosphorus sediments is a result of socioeconomic activity in the catchment basins. It is essential to analyze the basin characteristics, including land utilization, agricultural practices, weather, and sources of pollutant loading for the preservation of the water quality in irrigation ponds. An understanding of how the characteristics of the basins and the hydraulic properties of the ponds influence the water quality may provide effective information to promote the preservation of the water quality in future.

Method of analysis

We examined the water quality of irrigation ponds from 1991 to 1993. Nationwide, approximately 25,000 irrigation ponds have an irrigation area of more than 5 ha in urbanized agricultural areas or agricultural areas[5]. From these, 852 were sampled from prefectures across the nation in proportion to the number of ponds in each prefecture.

In principle, sampling was carried out 5 times at

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sluice gates and from a depth of approximately 50 cm at each pond during the irrigation season (May through October).

Of the 852 irrigation ponds, in some, river water was introduced except for basin use, others were used for other purposes, such as aquaculture, golf courses, industries and farming, and for some of them the information we collected could not be used. The data from these types of ponds were excluded in the analysis of water quality characteristics because the actual conditions were not clarified and it was difficult to estimate the occurrence of nutrient loading. Therefore in principle, we examined 556 irrigation ponds in the present study.

These 556 irrigation ponds were then classified into groups to analyze the influence of major environmental factors, such as water depth, retention time, and hours of sunlight on the fluctuation of water quality. Although it was possible to group the ponds by combining each factor, considering the shallow irrigation ponds studied in this report, the hours of sunlight were found to be the factor that influences primary productivity, such as growth of plant plankton. Retention time and water depth were also used as a measure to group the ponds. The uses of the irrigation ponds were other factors that influenced the water quality. Based on these factors, the following 4 groups were analyzed in this report.

For the water depth and retention time, median values were determined by statistical analysis of whole irrigation ponds.

- Group I: Long period of sunlight (≥ 1,900 h/year) and shallow irrigation ponds (< 4.0 m).
- Group II: Short period of sunlight (< 1,900 h/year) and shallow irrigation ponds (< 4.0 m).
- Group III: Long retention time (≥ 60 days) and deep irrigation ponds (≥ 4.0 m).
- Group IV: Short retention time (< 60 days) and shallow irrigation ponds (< 4.0 m).

General conditions of irrigation ponds

Table 1-a shows the statistical values of the characteristics of the irrigation ponds. The average values of the indicators of water quality of the irrigation ponds were as follows: COD, 9.02 mg/L; T-N, 1.36 mg/L; T-P, 0.10 mg/L; pH, 7.6; and EC, 143 μS/cm. Of these values, pH, COD, and T-N exceeded the standards for water for agricultural use (paddy rice, Table 1-b). When the average nutrient concentrations in summer exceeded 0.5–1.5 mg/L for T-N and 0.02–0.10 mg/L[1] for T-P, eutrophic conditions were likely to prevail.

Table 1-a. Statistical values of characteristics of irrigated ponds and catchment basins

	Number of ponds	Mean	STD
Available storage capacity ($10^3 m^3$)	555	94.5	260.2
Catchment area (ha)	556	66.0	179.4
Depth (m)	467	5.1	3.9
Retention time (day)	555	114.1	190.2
Available storage capacity/catchment area (m)	555	2.7	4.2
Available storage capacity/depth (ha)	467	19.4	43.0
Area rate of arable land (%)	556	25.6	29.9
Beef cattle density (head/ha)	39	1.0	1.6
Dairy cattle density (head/ha)	25	0.8	1.1
Pig density (head/ha)	20	3.0	6.4
Domestic fowl density (head/ha)	22	327.7	837.0
Application of N fertilizer to the field (kg/10a)	288	1.2	7.2
Application of P fertilizer to the field (kg/10a)	289	1.0	5.4
Application of K fertilizer to the field (kg/10a)	288	1.1	6.2
Population density (persons/ha)	271	18.1	71.0
Extension rate of sewerage (%)	271	22.4	38.0
Ratio of night soil treatment (%)	271	77.6	38.3
Mean precipitation (mm/year)	556	1,482	371
Mean temperature of air (°C)	556	14.4	2.2
Yearly daylight hours (hour)	556	1,893	171
COD (mg/L)	553	9.02	10.19
T-N (mg/L)	552	1.36	1.78
T-P (mg/L)	528	0.10	0.19
pH	553	7.6	0.8
EC (μS/cm)	553	143	198

Table 1-b. Standard values for water for agricultural use (paddy rice)

Item	Standard value
pH	6.0~7.5
Chemical oxygen demand (COD)	below 6 mg/L
Suspended solids (SS)	below 100 mg/L
Dissolved oxygen (DO)	below 5 mg/L
Total nitrogen (T-N)	below 1 mg/L
Electric conductivity (EC)	below 300 μS/cm
As	below 0.05 mg/L
Zn	below 0.5 mg/L
Cu	below 0.01 mg/L

The average retention time ([effective storage capacity of the pond]/[volume of inflow water into the pond]) was 114.1 days, which is approximately equivalent to 1/4 of the general retention time of lakes and marshes in Japan (approximately 1.2 years).

Land use in the catchment basins of the irrigation ponds was as follows: 70% for forests, 8% for paddy fields, 6% for farms, 4% for orchard areas, and 2% for grasslands (Fig. 1). Non-agricultural land use accounted for the remaining 10%. Consequently, land use was characterized by a high ratio of forests.

Water quality in irrigation ponds and characteristics of catchment basins

1) Correlation between water quality in irrigation ponds and catchment basin characteristics

Our data failed to reveal a strong correlation between the hydraulic properties of the irrigation ponds or basin characteristics (such as agricultural practices, land use, and environmental conditions) and pond water quality. For example, there was no strong correlation between the retention time and T-N value (Fig. 2 (1)) or between the proportion of forests in the basins and the T-N value in the ponds (Fig. 2 (2)). We performed single correlation analyses between the indicators of water quality and each of these characteristics, but the results were identical.

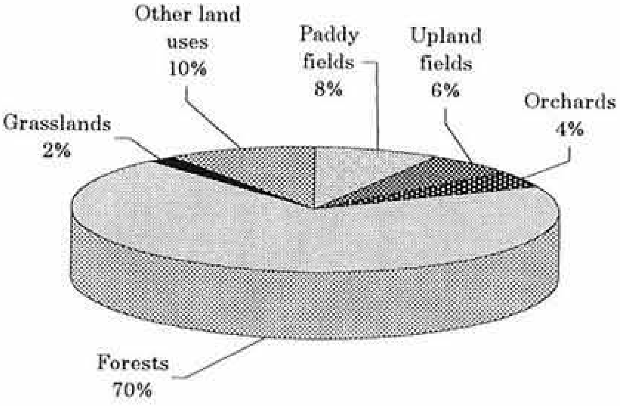

Fig. 1. Land utilization in the catchment basins of the irrigation ponds

When classified into 4 groups, however, the irrigation ponds showed a correlation between each pond property and water quality indicators (Tables 2 and 3). In Group I, average values of COD, T-N, and T-P exceeded the averages for all the irrigation ponds and also the aver-

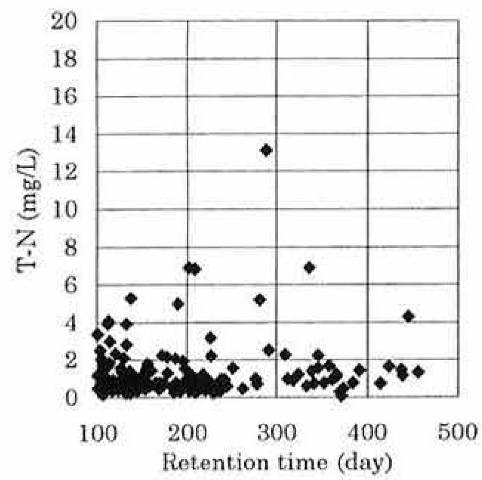

Fig. 2(1). Relationship between the retention time and T-N in the irrigation ponds

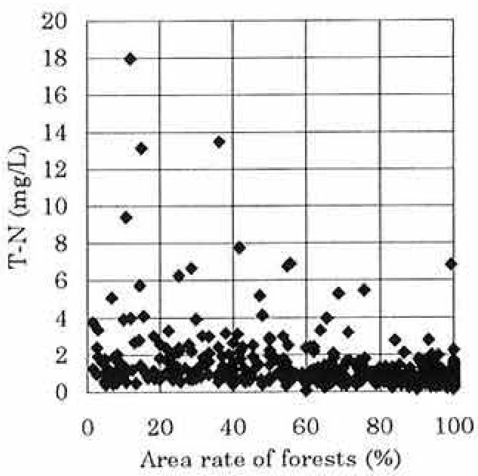

Fig. 2(2). Relationship between the proportion of forests in the catchment basins and T-N in the irrigation ponds

Table 2. Mean values of depth, daylight hours, retention time, and water quality indicators calculated for each group of irrigation ponds

	All irrigation ponds	Group I	Group II	Group III	Group IV
Number of ponds	556	99	85	153	115
Available storage capacity (10^3m^3)	94.5	40.1	64.0	199.0	23.6
Depth (m)	5.1	2.5	2.4	7.1	2.3
Retention time (day)	114.1	108.2	61.5	216.2	22.4
Yearly daylight hours (hour)	1,893	2,003	1,771	1,915	1,878
COD (mg/L)	9.02	11.36	10.51	8.20	8.98
T-N (mg/L)	1.36	1.96	1.28	1.28	1.42
T-P (mg/L)	0.10	0.13	0.11	0.08	0.09
pH	7.6	7.7	7.5	7.7	7.5
EC (μS/cm)	143	166	173	144	175

Table 3. Correlation coefficients between irrigation pond characteristics and water quality indicators classified into 4 groups

	COD				T-N				T-P			
	G. I	G. II	G. III	G. IV	G. I	G. II	G. III	G. IV	G. I	G. II	G. III	G. IV
Available storage capacity (10^3m^3)	0.212	−0.057	−0.218	−0.013	0.254	−0.065	−0.093	−0.029	0.131	−0.017	−0.160	0.003
Catchment area (ha)	0.028	0.099	−0.143	0.149	0.077	0.030	−0.058	0.009	0.092	0.051	−0.107	0.177
Depth (m)	−0.061	−0.117	−0.281	−0.129	−0.043	−0.237	−0.045	−0.129	−0.122	−0.142	−0.189	−0.203
Retention time (day)	0.411	0.035	−0.029	−0.020	0.077	0.117	−0.087	−0.005	0.282	0.172	−0.052	−0.001
Available storage capacity/depth (ha)	0.215	−0.049	−0.112	0.012	0.248	−0.045	−0.056	0.007	0.143	−0.009	−0.088	0.052
Mean precipitation (mm/year)	−0.210	−0.029	−0.222	−0.021	−0.007	−0.172	−0.122	−0.092	−0.157	−0.032	−0.095	−0.058
Mean temperature (°C)	0.225	0.131	0.254	0.031	−0.084	0.061	0.092	−0.013	0.157	0.114	0.148	−0.048
Yearly daylight hours (hour)	−0.023	0.202	0.409	0.013	−0.021	0.141	0.189	0.110	−0.021	0.061	0.266	−0.024
COD (mg/L)	1.000	1.000	1.000	1.000	0.286	0.243	0.312	0.078	0.792	0.343	0.605	0.423
T-N (mg/L)	0.286	0.243	0.312	0.078	1.000	1.000	1.000	1.000	0.391	0.684	0.196	0.313
T-P (mg/L)	0.792	0.343	0.605	0.423	0.391	0.684	0.196	0.313	1.000	1.000	1.000	1.000
pH	0.595	0.234	0.515	0.230	0.228	0.386	0.318	0.134	0.638	0.355	0.343	0.404
EC (μS/cm)	0.271	−0.023	0.166	−0.001	0.643	−0.010	0.448	0.090	0.401	−0.033	0.003	−0.002

ages for each of the other groups. In Group III, average COD and T-P values were lower than in the other groups.

In Group I, there was a low correlation between the retention time and COD compared with all the irrigation ponds and the other groups. In Group I there was a strong correlation between the COD and the T-P value compared with all the irrigation ponds and the other groups. Group II showed a strong correlation between the T-N and T-P values, suggesting that the N/P ratio was relatively stable. In Group III there was a strong correlation between the COD and the T-P value, indicating that phosphorus may be the limiting factor for eutrophication. In Group IV, no strong correlation was found between any of the indicators of water quality.

The correlations between the water quality indicators in each group suggest that they affect the variation of water quality in irrigation ponds.

2) Outflow characteristics of nitrogen load from the catchment basins

The proportion of nitrogen load in the catchment basins of irrigation ponds (Fig. 3) was determined by the unit method. The nitrogen load from paddy fields, forests, and areas with non-agricultural land use was calculated by multiplying the T-N concentration of rainfall by

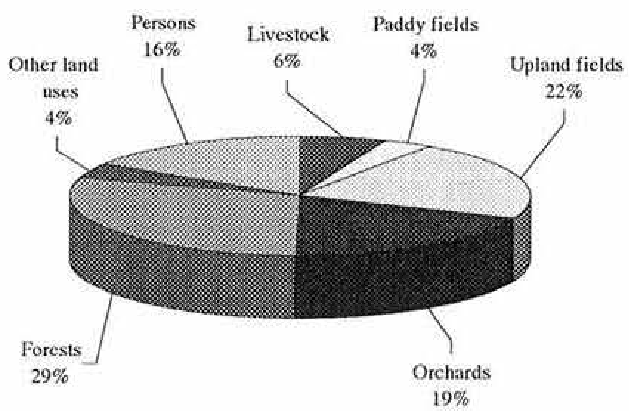

Fig. 3. Nitrogen load from effluent in the catchment basins

the amount of precipitation during the period of irrigation.

The nitrogen load from farms and orchards was calculated by multiplying the amount of fertilizer applied during the irrigation period by the discharge rate of 30%[2].

The nitrogen load from livestock was estimated by using the documented value for cattle/head/day and the documented value for pigs/head/day[8]. The nitrogen load from the households in the basins was estimated from the documented[7] value of 6.0 g/person/day of treated household drainage from septic tank (mixed drainage and urine) and 1.45 g/person/day of untreated mixed household drainage.

Although land use in the basins of the irrigation ponds consisted of forests (70%), farmland (20%), and other land uses (10%) (from Fig. 1), agricultural land use accounted for about 51% of the nitrogen load, indicating that agriculture exerts a major influence on water quality in irrigation ponds. The nitrogen load per unit area in the basins was 90 g/ha/d (standard deviation 153 g/ha/d; median value 36 g/ha/d). Since 78% of the nitrogen load was derived from diffuse non-point sources, such as farmland and forests, it might be difficult to control or manage the load.

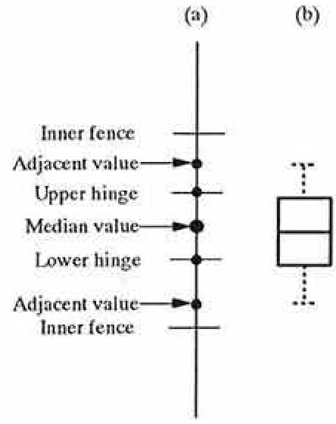

Fig. 4. Concept of box plot

3) Multiple regression analysis of water quality and catchment basin characteristics

Variables were selected by multiple regression analysis taking the indicators of water quality as the objective variables and the characteristics of irrigation ponds and their catchment basins as explanatory variables. Because the number of cattle raised in the basins was relatively low, we excluded the density of farm animals from the variables before performing the analysis. The standard of variable selection was set up as $F_{in} = F_{out} = 2.0$ for the F

Table 4. Standard regression coefficients in multiple regression model for prediction of the water quality of irrigation ponds

		COD	T-N	T-P
Hydraulic characteristics	Available storage capacity			
	Catchment area			
	Depth	–0.175		–0.111
	Retention time			
	Available storage capacity/catchment area		–0.070	
	Available storage capacity/depth	0.071	0.054	
Agricultural characteristics	Area rate of arable land			
	Application of N fertilizer to the field			
	Application of P fertilizer to the field			
	Application of K fertilizer to the field			
Land use characteristics	Area rate of paddy fields	0.075	–0.095	
	Area rate of upland fields		0.109	
	Area rate of orchards		0.085	
	Area rate of forests	–0.044	–0.335	–0.095
	Area rate of grasslands			
	Area rate of other land uses			0.096
Social characteristics	Population density			
	Extension rate of sewerage		–0.085	
Meteorological characteristics	Mean precipitation	–0.116		
	Mean temperature	0.163		
	Yearly daylight hours		0.119	0.103

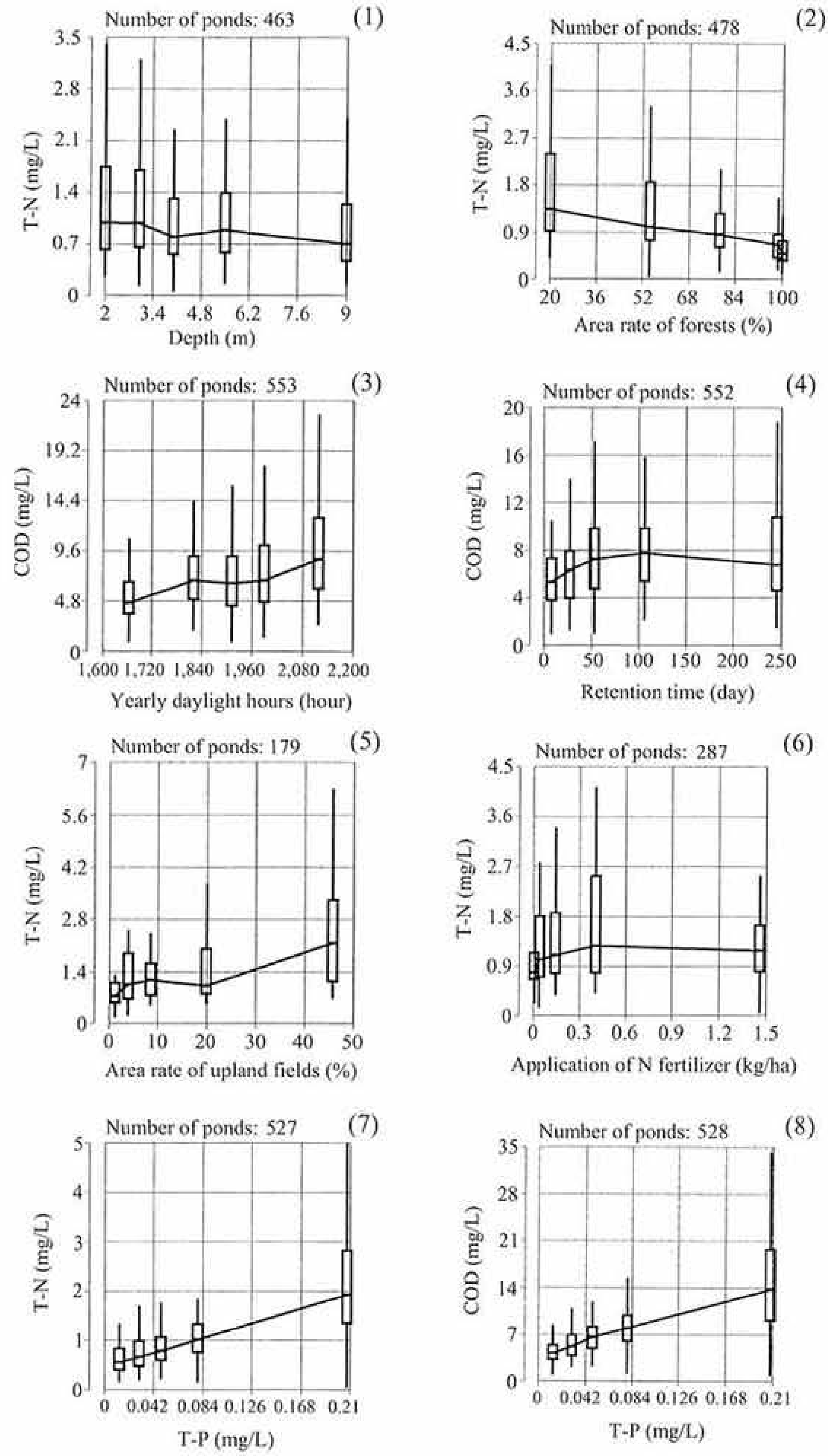

Fig. 5. Parallel box plots

(1) Depth and T-N.
(2) Proportion of forests in the catchment basins and T-N.
(3) Yearly daylight hours and COD.
(4) Retention time and COD.
(5) Proportion of upland fields in the catchment basins and T-N.
(6) Nitrogen fertilizer application and T-N.
(7) T-P and T-N.
(8) T-P and COD.

value of the variance ratio, and was estimated by the methods of forward selection and backward elimination. Table 4 shows the standardized partial regression coefficients between the indicators of water quality (objective variables) and the characteristics selected as a result of variable selection. The proportion and Variance Inflation Rate (VIF) were calculated by carrying out a multiple regression analysis taking the individual explanatory variables selected from Table 4 as the objective variables and the other variables as the explanatory variables. The value of VIF was 1.0–2.7 and the explanatory variables were found to be independent. The absolute values from Table 4 are considered to reflect the degree to which individual indicators of water quality were influenced.

Based on these considerations, the characteristics of irrigation ponds and their catchment basins that most affected water quality were as follows:

for COD, depth of water, annual average temperature, and annual precipitation;

for T-N, proportion of forests in basins, yearly hours of daylight, and proportion of farmland in basins;

for T-P, depth of water, yearly hours of daylight, and non-agricultural land uses.

Land use characteristics influence water quality, particularly the T-N. Compared with the T-N, COD and T-P values are affected by a variety of characteristics other than land use. However the proportion of forests in basins affected all of the above indicators of water quality: i.e. the values of all the indicators of water quality tended to decrease in proportion to the increase of the forest areas in basins.

4) Analysis by box plot

When there are biases or outliers in the distribution of research data, the correlation coefficient is not always an appropriate index to describe the correlation among variables. We used parallel box diagrams[9] to analyze the relationships among variables in these cases.

In this analysis, all the data of the variables on the horizontal axis were arranged from minimum to maximum values and then divided into 5 sets, each containing an equal number of data. A box diagram of the variables on the vertical axis was made for each of the 5 data sets. The position of each box plot on the horizontal axis corresponded to the position of the central value in each horizontal data set. The central horizontal line in the box plot represented the 50% value (median), and the upper and lower hinge values were 75 and 25%, respectively; thus 50% of all the data were included within the height of the box. The maximum and minimum values in each set were represented by the upper and lower vertical lines (Fig. 4).

In the parallel box plots, the correlations are not indicated quantitatively with a coefficient, but the relative tendencies among the variables can be observed.

We analyzed the relationships between each water quality indicator (COD, T-N, and T-P) and irrigation pond characteristics by this method. The characteristics derived from this analysis coincided with the results of the multiple regression analysis as follows:

(1) The pond depth and the proportion of forests in the catchment basins showed a negative correlation with all the water quality indicators (Figs. 5 (1) and 5 (2)).
(2) A positive correlation was found between yearly daylight hours and COD. Although there was a positive correlation between the COD and retention time up to about 100 days, there was no correlation with the COD for longer retention times (Figs. 5 (3) and 5 (4)).
(3) T-N showed a positive correlation with the area of upland fields. There was a positive correlation between T-N and nitrogen applied as fertilizer up to about 0.4 kg/ha. However, there was no clear correlation at levels of application beyond that value (Figs. 5 (5) and 5 (6)).
(4) No significant correlation could be found between T-P and any irrigation pond characteristics except for the positive correlation with the pond depth and the proportion of forests in the catchment basins.
(5) There were positive correlations among the water quality indicators, such as COD, T-N, and T-P (Figs. 5 (7) and 5 (8)).

Conclusion

Although the mechanisms responsible for the fluctuations of water quality cannot be clearly determined by statistical analysis alone, the following information is necessary to preserve the water quality in irrigation ponds.

Since current agricultural practices result in COD, nitrogen, and phosphorus load mostly occurring from diffuse non-point sources, it is difficult to control or manage the load. And we consider that the improvement of the methods of fertilizer application and water management in the fields may not drastically decrease the occurrence of pollutants in a short period of time.

Water quality in irrigation ponds can be improved by reducing the source materials, pollutant runoff into the irrigation ponds, and the amount of pollutants in the irrigation ponds. Although many engineering methods involving the construction of drainage treatment facilities, by-passing the waterways, compact oxidizing of the waterways, use of aquatic plants, and dredging of the ponds can be applied, it is difficult to achieve effective and long-term control by a single method at this time.

When a comprehensive evaluation of the situation is taken into consideration, on a long-term basis, it will be important that the basin characteristics of each irrigation pond be thoroughly analyzed and appropriate engineering steps be taken for water quality preservation. These steps should include the use of load management to structurally remove the sources of pollutants.

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