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FUNDAMENTAL PROPERTIES AND ANALYSIS OF WATER QUALITY IN A RESERVOIR AFFECTED BY LITTLE WATER USE AND TEA PLANTATION

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ABSTRACT: There are many reservoirs in trouble on eutrophication problem. This paper focused on a reservoir whose water has rarely been used for agriculture or drinking. The many tea plantations distributed in the dam basin are suspected to be the cause of the reservoir's eutrophication. It was investigated that eutrophication components such as nitrogen and phosphorus and how they relate to the tea plantations in the basin. With reference to phosphorus, trophic levels were determined with Vollenweider plots and Carlson indices. With reference to nitrogen, a field survey was carried out to investigate the properties of sulfate and then sulfate concentration was analyzed with a simple model. The various activities to improve the water quality of the reservoir are introduced. In conclusion, the dam reservoir water is typically eutrophic, and might be affected by the fertilizer in tea plantations. The motion of surface water in the dam reservoir is similar with the property of river, and then the sulfate concentration was analyzed with simple model.

Keywords: Reservoir, Eutrophication, Tea Plantation, Sulfate, Improvement Activities

1. INTRODUCTION

The K dam reservoir in the north of Nara Prefecture, Japan, has an eutrophication problem causing a lot of blue-green algae to bloom every summer and needs to be protected from mold odors in the water because this water is used as drinking water. The many tea plantations distributed in the dam basin are suspected to be the cause of the reservoir's eutrophication.

It has been reported that the overfertilization to almost of the domestic tea plantations resulted that the surface water and groundwater surrounding the tea plantations had problems on water quality besides the K dam basin [1]-[3]. In order to improve the situation, many researchers tried to reduce the amount of applied fertilizer and improve the fertilization method. A rare successful water quality improvement of groundwater and river water was reported recently [4]. The K dam management office also has taken various steps to combat the water quality problem in the reservoir. For example, they have mown weeds on the slopes surrounding the reservoir, planted purification grasses around the tea plantations, planted buckwheat crops instead of tea tree crops, and created a floating island with aquatic plants for the purification of reservoir water, among other activities.

In this paper, the author gives a basic overview of the water quality of the K dam reservoir and discusses the concrete actions that have been taken to improve it. Of particular interest to us are eutrophication components such as nitrogen and phosphorus and how they relate to the tea plantations in the basin. With reference to phosphorus, trophic levels were determined with Vollenweider plots and Carlson indices and performed comparisons with other domestic reservoirs, and with reference to nitrogen, a field survey was carried out to investigate the properties of sulfate and then sulfate concentration was analyzed with a simple model.

2. METHOD

2.1 Parameters of Dam Reservoir and Basin

Table 1 shows the parameters of the K dam reservoir and its basin. The K dam was built as a concrete gravity dam in 2001 and, according to the management officer, the sediment level at the bottom of the reservoir remains low even ten years after the completion. Water from the reservoir has rarely been used for agriculture or drinking in the past and a downturn in tea leaf consumption has significantly lowered what little water use there originally was. Ideas and activities for increasing the water usage of the reservoir are required besides as follows; water supply stations around the dam are available in the form of automatic vending machines, and farmers can buy reservoir water with coins and pour it into the tanks of pickup trucks to use the water more conveniently.

The basin area of the reservoir is 18.9 km^2, the

Table 1 Parameters of the K dam and basin

Parameters	Value
Type of dam	Concrete gravity dam
Basin area	18.9 km^2
Total reservoir capacity	5.6×10^6 m^3
Water surface area	0.329 km^2
Mean depth	17.0 m
Residence time	0.31 year
Phosphorus load in 2008	683,553 $gP \cdot yr^{-1}$
Phosphorus load in 2009	997,690 $gP \cdot yr^{-1}$
Phosphorus load in rain*	15,500 $gP \cdot yr^{-1}$

*value estimated by author

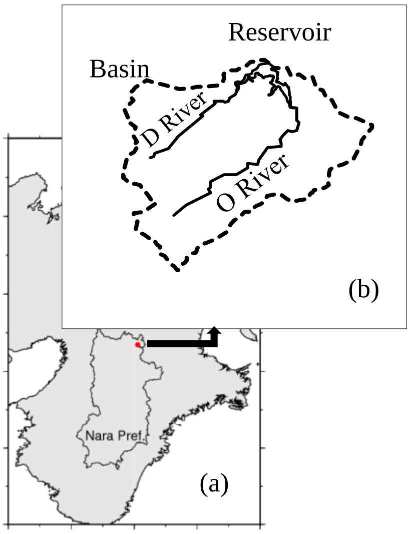


Fig.1 Location of the (a) K dam reservoir and (b) basin

total reservoir capacity is 5.6×10^6 m^3, and the water surface area is 0.329 km^2, as shown in Table 1. Since the K dam was originally intended for irrigation and the provision of drinking water, the basin area and the reservoir capacity are small compared to dams with other purposes.

Two main rivers, D River and O River, flow into the dam reservoir, as shown in Fig. 1. A discharge channel M also flows into the reservoir between these main rivers. This channel is not included on the map due to its small discharge, but information pertaining to it is mentioned as necessary.

2.2 Data

Data used in this paper were provided by the dam office and the part of data was measured and analyzed by the author. Dam control items were water temperature, inlet, and outlet flow, and weather data were precipitation and air temperature.

2.3 Determination of Trophic Level in Reservoir

As nutrition issues have been linked to phosphorus, the trophic level in the reservoir was determined using a Vollenweider plot with phosphorus data. Trophic state index (TSI) was used as an additional index.

There are various methods of determine the trophic level, and in this work the Vollenweider method was selected due to its popularity [5]. There are two ways to make a Vollenweider plot: one, a flame method based on unit load data, and two, a method based on actual observed concentration and discharge data. The latter method was adopted and phosphorus concentration data was used from between 2008 and 2009.

TSI values were calculated using chlorophyll *a* and total phosphorus due to a lack of transparency data on the reservoir.

2.4 Field Survey on Sulfate

Tea trees prefer sulfur and can grow in suitably acidic soil [6], [7]. Ammonium sulfate is often top-dressed into tea plantations during tea-picking season. Ammonium sulfate is the major quick-impact fertilizer described by $(NH_4)_2SO_4$ as a chemical formula [7]-[9]. Sulfur component circulates through the primary production process and accumulates in the sediment as hydrogen sulfide [10]. Fertilizer run-off from tea plantations causes severe water quality problems that have a national impact, which is why the author focuses on the sulfate in water here.

Sulfate is not measured by the dam office, so the author measured it specifically for this study. A monthly field survey was conducted between August and December 2011 during the formation of thermo-stratification.

Since the reservoir water is not used in great quantities, water turnover is small, so the motion of the reservoir water could be regarded as the same as river water during the formation of stratification.

The water in the field survey was sampled and measured at the surface layer in the reservoir and at the points where two rivers and the discharge channel flow into the reservoir. Water temperature, pH, dissolved oxygen, and electric conductivity were measured onsite as soon as sampling. Water samples were taken and sulfate was then measured in our laboratory. Other observed items included inorganic phosphoric acid, turbidity, chemical oxygen demand, and inorganic nitrogen such as nitrate-nitrogen, nitrite-nitrogen, and ammonia-nitrogen.

3. RESULTS AND DISCUSSION

3.1 Properties of Water Quality in the Reservoir

Figure 2 shows the changes of water temperature, pH, chlorophyll *a*, and dissolved oxygen (DO) with time for each layer in the reservoir. The water temperature results show that while the reservoir water was stratified in during summer, winter corresponded approximately to circulation.

The amount of phytoplankton in the summer increased at the sunlit surface layer of the reservoir, as shown in the results for chlorophyll *a*. Carbonic acid assimilation by phytoplankton caused the high value of pH and super saturation of DO. Upon rearranging the data in terms of the relationship between the water temperature and kinds of phytoplankton, while Bacillariophyceae tended to be dominant in water with a temperature below 15 degrees, Cyanophyceae was dominant over 15 degrees. This is in agreement with the general consensus that low water temperature is adequate for Bacillariophyceae while Cyanophyceae grows at high temperature [11], [12].

3.2 Trophic Level in the Reservoir

Figure 3 plots data of other Japanese reservoirs [13] as well as a Vollenweider model of the K dam reservoir. The K dam reservoir was plotted using information from the 2008–2009 circulation seasons, and as shown, was obviously eutrophic.

Furthermore, the K dam reservoir was classified using the trophic state index (TSI) proposed by Carlson [14]. Data on chlorophyll *a* and total phosphorus at the surface layer between June and August was only used to determine TSI due to the lack of transparency data. The trophic level of the reservoir was classified as rank E in terms of the highest frequency, as shown in Table 2. Rank E was also given to the eutrophic level in the Vollenweider model, as in [14], [15].

The land use for each basin is shown in Fig. 4. Although the areas of the tea plantations are very small compared to the basin areas, a typical turbid water problem caused by blue-green algae occurred every summer. Since tea tree crops are grown commercially on the mountainsides, cultivation conditions could be responsible for fertilizer running off from the plantations. Figure 5 shows the change of phosphorus load calculated from the concentration in each river. Phosphorus load peaks appeared in April and October. According to the

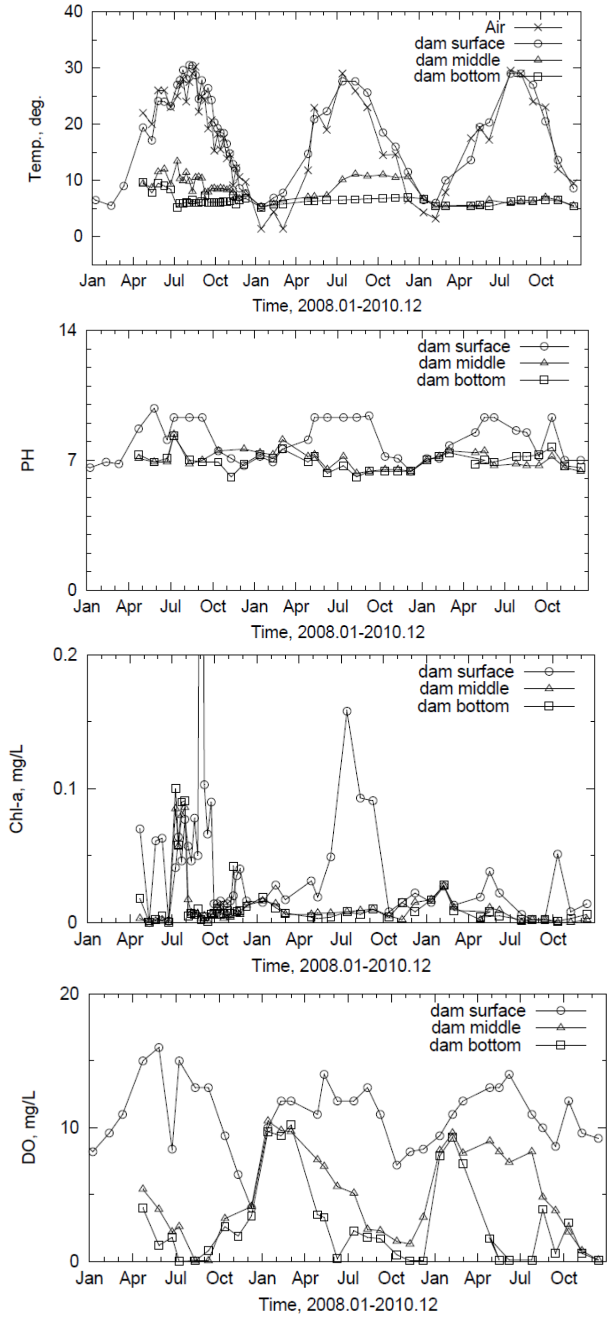
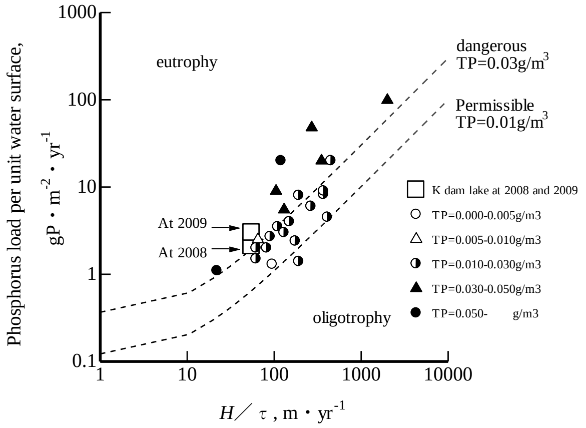


Fig.2 Changes of water temperature, pH, chlorophyll-*a*, and dissolved oxygen with time



H is mean depth of dam reservoir, τ is residence time.

Fig.3 Plot of Vollenweider model on dam reservoirs

Table 2 Frequency of trophic state index of the K dam reservoir

Rank	Score of TSI	Frequency		Vollenweider model [15]
		TSI(chlorophyll *a*)	TSI(Total Phosphorus)	
A	Below 37	1	1	Oligotrophy
B	37 - 47	0	0	Oligotrophy - middle
C	47 - 53	0	1	Middle
D	53 - 61	0	2	Middle - eutrophy
E	Over 61	7	4	Eutrophy

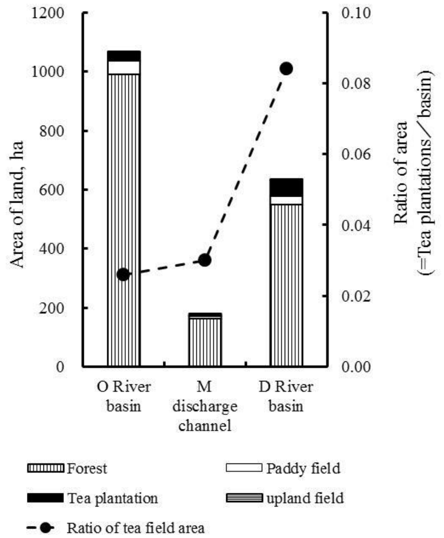


Fig.4 Land use for each basin and area ratio of tea plantations compared with basin (rearranging data provided by dam office)

standard of fertilizer for agricultural crops [16], base fertilizer is spread in the period running from late February through the middle of March and in early September. Rapeseed oil cake, an organic manure, is often used as a base fertilizer. It takes three weeks for rapeseed oil cake to decompose. The peaks of phosphorus load shown in April and October correspond to the decomposing stage of rapeseed oil cake. In general, phosphorus is absorbed in the soil and kept in the field. However, the sloped nature of tea tree fields causes soil particles with phosphorus to run off from the field and flow into the reservoir. While the soil in the field retains the nitrogen component in the form of ammonium, ammonium sulfate changes into nitrate nitrogen relatively quickly and the nitrogen component might run off

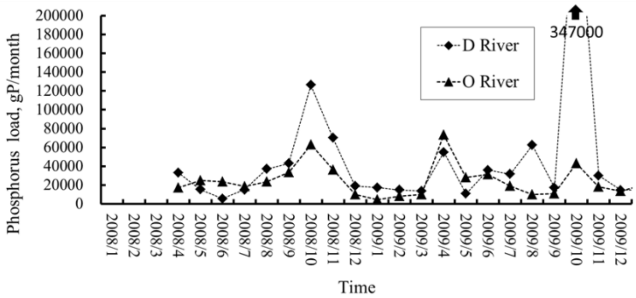


Fig.5 Changes of phosphorus load in river water with time

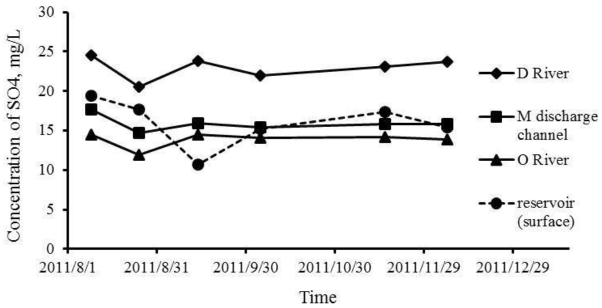


Fig.6 Changes of sulfate concentration observed in dam reservoir and rivers with time

from the tea plantation. As a result, ammonia fertilizers such as ammonium sulfate contribute to the water quality problem in the reservoir.

Attempts at improving the water quality in the reservoir include planting certain grasses around tea plantations that prevent soil from running off and placing floating plant islands in the reservoir itself to absorb nutrients.

3.3 Sulfate Concentration and Its Analysis in Surface Layer

3.3.1 Results of field survey

Figure 6 shows the change of sulfate concentration observed at the reservoir's surface and at the rivers. The concentration of sulfate is larger in D River than the other rivers, as shown. According to Fig. 4, which illustrates the land use for each basin, the area ratio of a tea plantation compared with the basin area is 8.4 % on the D River basin, 3.0 % on the M discharge channel, and 2.6 % on the O River basin. Therefore, in light of the nutrient load mechanism discussed in previous section, the large ratio of the tea area on the D River basin seems to be connected to the high concentration of sulfate in the D River water.

Figure 7 shows the relationship between sulfate

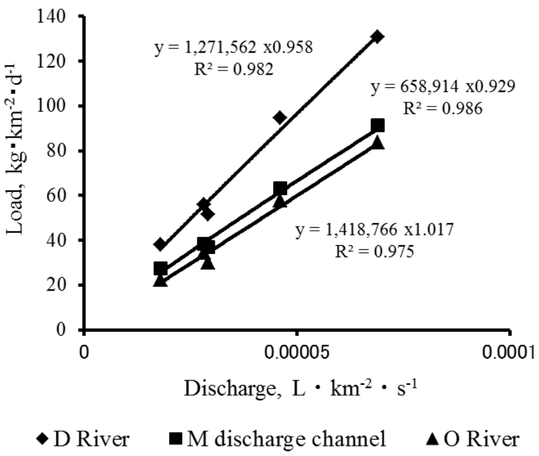


Fig.7 Relationship between sulfate load and river discharge

load L and discharge Q. The L-Q values for each basin are calculated as

$$L_1 = 1,271,562 \cdot {Q_r}^{0.958} \quad (1)$$

$$L_2 = 658,914 \cdot {Q_r}^{0.929} \quad (2)$$

$$L_3 = 1,418,766 \cdot {Q_r}^{1.017} \quad (3)$$

where L_1 is the load of sulfate in D River, L_2 is the load of M River, L_3 is the load of O River, and Q_r is the river discharge.

Since the concentration of sulfate increases along with the area of a tea plantation, it is reasonable to assume that load might run off from the plantations.

3.3.2 Analysis of sulfate concentration

Sulfate concentration was analyzed using a simple water quality model defined with river water inlet and reservoir outlet as shown in equation (4). This simple model was used because, although the author originally intended to use a circulation model of sulfur in water without an input-output system, the author wanted to investigate the rough validity. Little water use of the reservoir and reservoir stratification means that reservoir properties will remarkably agree with those of a river. Furthermore, biological processes and vertical mobility could be conversely estimated from the difference between the calculation result and the field survey measurements.

Water temperatures at each depth were measured at an intake tower of the reservoir and vertical profiles of water temperatures were used to estimate

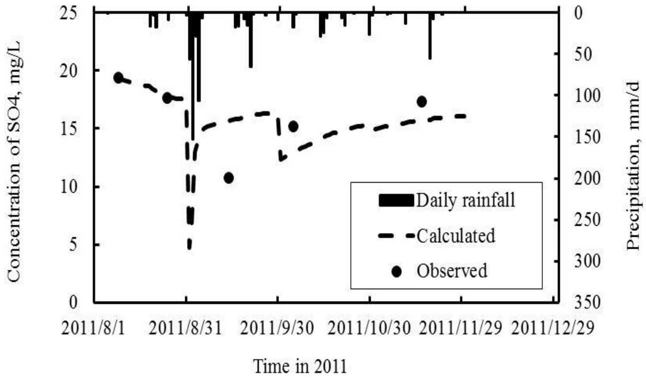


Fig.8 Comparison with calculated and observed data on concentration of sulfate

the depth of the surface layer as stratification depth. The reservoir was assumed to be stratified between August and December. Since the layer depth was varied with time, the model equation was naturally considered with the depth change.

$$\frac{d(VC)}{dt} = L_1 + L_2 + L_3 - QC \quad (4)$$

where C is the concentration of sulfate at the reservoir surface layer, V is the water volume of the surface layer given by multiplying water surface area by the depth of the surface layer, t is time, and Q is reservoir outlet.

Figure 8 shows the calculation result of sulfate concentration and daily rainfall. Sulfate concentration in the surface layer of the reservoir was calculated during stratification.

When the simple model was used to analyze the sulfate concentration, the calculated concentration value was in good agreement with the observed value. Our simulation was performed after the concentration of sulfate decreased in early September, and the concentrations of sulfate gradually increased until November. Concentration was quite low in early September. It seems that large typhoon No.1112 (TALAS) passed through the area at that time, and there was heavy rainfall.

4. CONCLUSIONS

A great deal of effort has been made by many Nara Prefecture officials and members of land improvement organizations to improve the water quality in the K dam reservoir. The author and laboratory members have also participated in these improvement activities as volunteers. In this paper, the fundamental properties of the K dam reservoir are reported using examples from the eutrophication mechanism and various water quality improvement methods.

The surface layer water of the K dam reservoir indicated approximately pH 10 during summer. Carbonic acid assimilation by much phytoplankton caused super saturation of dissolved oxygen in addition to high pH.

The value of mean depth divided by residence time was 55 m per year. Phosphorus load per unit water surface was 2.1 $g \cdot m^{-2} \cdot yr^{-1}$ in 2008, and 3.1 $g \cdot m^{-2} \cdot yr^{-1}$ in 2009. The TSI was the rank E level.

The reservoir water is typically eutrophic, and might be affected by the fertilizer in tea plantations.

The area ratios of tea plantations for each basin were less than 10 %. The concentrations of phosphorus and sulfate in rivers were described in order of the area ratios.

The motion of surface water in the dam reservoir is similar with the property of river, and then the concentration was analyzed with simple model.

It was observed that much rainfall brought about by typhoons decreased the concentration of sulfate and then the concentration gradually increased. The change of the concentration was simulated with the simple model.

5. ACKNOWLEDGEMENTS

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