Key Issue: **5- Water Quality**

Climatic Zone:
Cf : Temperate humid climate

Subject:
- water quality conservation

Effect:
- Elimination of abnormal taste and smell
- Prevention of eutrophication

Project Name: The Kamafusa Dam
Country: Miyagi Prefecture, Japan (Asia) (N38°10' E140°38')

Implementing Party & Period
- Project: The Ministry of Land, Infrastructure and Transport
1970 (Operation Start) -
- Good Practices: The Ministry of Land, Infrastructure and Transport
Kamafusa Dam Control Office
1984 (Implementation of Good Practice) -

Key Words:
Water quality conservation measures, countermeasures against abnormal taste and smell, eutrophication

Abstract:
The reservoir water of the Kamafusa Dam, a multipurpose dam for flood control, water supply and power generation, failed to reach environmental quality standards for a long period of time. In addition, it frequently gave off an abnormal (musty) smell. In consideration of these conditions, the physical and biological effects of lake water circulation were investigated through pilot experiments on all-zone aeration carried out by means of intermittent air-pumping tubes and the operation of one large air-pumping tube, with the objective of attaining quality conservation of the lake water. At the same time, the mechanism for controlling abnormal proliferation of Phormidium was explicated. Based on the investigation results, measures for water quality conservation in the reservoir are proceeding.

1. Outline of the Project

The Kamafusa Dam, built at the upper course of the Goishi River of the Natori River System, is a multipurpose damn for flood control, water supply and power generation. Its particulars are shown in Table-1.

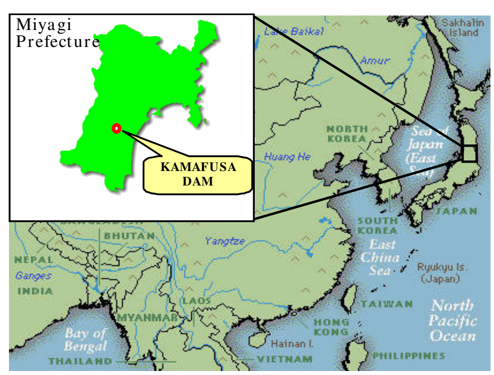
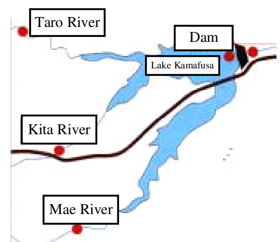


Fig.-1 Map of Dam Site

Table-1 Outline of the Kamafusa Dam

Item	Particulars
1) Dam	
Type	Gravity-type concrete dam
Height of dike	45.50 m
Crest length	177.00 m
Crest width	7.50 m
Cubic volume of dike	100,000 m^3
2) Storage level and storage capacity	
High water level when flooded	EL 150.60 m
Normal high water level	EL 149.80 m
Limited water level	EL 143.80 m
Lowest water level	EL 133.00 m
Total water capacity	45,300,000 m^3
Effective water capacity	39,300,000 m^3
Sedimentation capacity	6,000,000 m^3
Flood control capacity	21,000,000 m^3
3) Freshwater area and shape	
Catchment area	195.25 km^3
Reservoir surface	3.9 km^3
Extension of impoundment	Kita river course 4.0 km Mae river course 4.7 km
4) Intake/discharge facilities	
Intake for tap water	Selective intake (EL 137.0 m; Spare EL133.0 m) Surface intake
Intake for power generation	Surface intake
Discharge valve	4 gates (EL 144.6 m)
Crest gate	3 gates (EL 124.0 m)
Conduit gate	



2. Features of the Project Area

In the dam watershed, mountains and forests represent about 88% of the catchment area, fields and pastureland about 10% and the lake surface about 2%. Approximately 11,000 people live there. Major industries include primary industries, among which stockbreeding is particularly thriving; about 4,800

In September 1987, the Kamafusa Dam was designated under the Law concerning Special Measures for Conservation of Lake Water Quality for the purpose of reducing the pollution load from the catchment area. It was the first dam lake that received such designation. As a comprehensive preventive measure against water pollution, the “Plan for Conservation of Kamafusa Dam Lake Water Quality” was developed and executed for the first 5-year period ending in FY1991.

3. Major Impacts

The reservoir of the Kamafusa Dam is classified as an AA type lake, Type II of the water quality environmental standards, which have not yet been reached. Problems related to abnormal taste and smell (musty smell) arose at a frequency as high as 8 years in 13 between the start of impounding and 1983, and the following environmental impacts have been identified.

1) The 75% COD value ranges from 2.2 to 3.9 mg/l and is leveling off, exceeding the environmental standard of 1 mg/l.
2) Nitrogen and phosphor amounts correspond to those of lake types III to IV; these levels fall in the medium to high eutrophication period[s].

3) A musty smell was produced at a frequency as high as 8 years in 13 from 1970 when impounding of water was started to 1983, i.e., just before the experiment. The cause of the smell has been identified as 2-methylisoborneol, which Phormidium produces internally.
4) The Sendai City Waterworks Bureau treated the water with active carbon in powder as a countermeasure against the musty smell. The treatment, extending to an average period of about 130 days/year, cost ¥60 million/year, which represented a heavy financial burden on the water-use facility.

4. Mitigation Measures

With the circumstances being as described above, a pilot experiment for lake water quality conservation through all-zone aeration circulation by means of intermittent-type air-pumping tubes has been performed since 1984. Based on the investigation results on 9 tubes of 6 units including one larger air-pumping tube unit put into operation in 1990, this report sheds light on the physical and biological effects of lake water circulation and the mechanism for controlling abnormal proliferation of Phormidium, and proposes the direction of water quality conservation measures for dam lakes.
In the pilot experiment, intermittent-type aeration pumping tubes were installed at intervals of about 100 m depth of the dam lake. Air fed continuously from a compressor on shore intermittently turns to bullet-like air bubbles to produce an air lift action, that is, it forces the water in the pumping tubes upward, and bottom water is sucked from underneath. When mixed with surface water, the temperature of the bottom water rises and the water spreads horizontally into the equal-density zone. Details of the installation of experimental equipment and the specifications of the air-pumping tubes are shown in Tables 2 and 3, respectively. Fig.-2 is a view of installed air tubes.

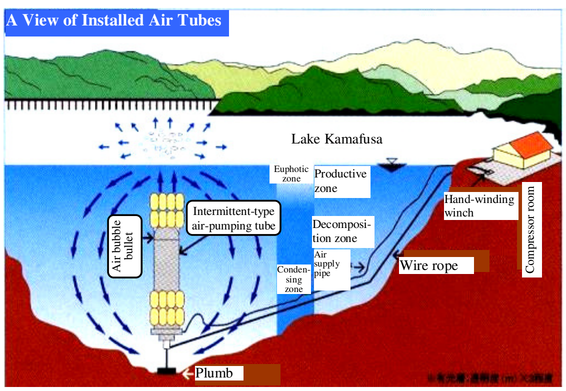


Fig.-2 A View of Installed Air Tubes

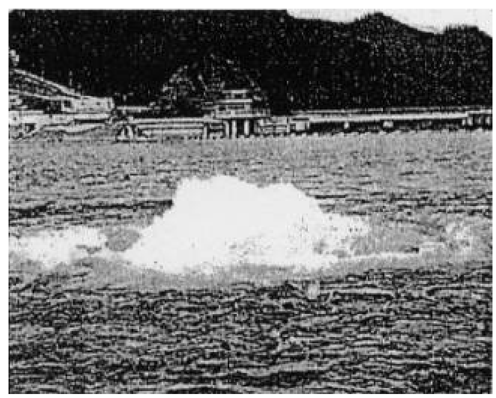


Fig.-3 View of aeration

Table-2 Specifications of Air-Pumping Tubes

		Specification
Air-pumping tubes (Nos. 1–5) 500 mm in diameter	Pumping tube	Inner diameter: 500 mm Tube length: 14–16 m (variable) Discharge water depth Normal full: 15.8 m Summer restriction: 9.8 m Pump discharge: 25,000 m^3/day (tube length: 16 m)
	Blower	Output: 7.5 kW Volume of air: 950 l/min
Larger pumping tube (No. 6) 500 mm in diameter × 4	Pumping tube	Inner diameter: 500 mm × 4 Tube length: 16 m Discharge water depth Normal full: 15.8 m Summer restriction: 9.8 m Pump discharge: 100,000 m^3/day (tube length: 16 m)
	Blower	Output: 22 kW Volume of air: 3,700 l/min

Table-3 Installation of Experimental Equipment

Date of Installation	Pumping Tube	Tube Length (m)	Depth of Installation	
			Suction port (EL)	Discharge port (EL)
June 1984	No. 1 No. 2	16 m	118	134
Sept. 1984	No. 3 No. 4	14 m	120	134
August 1987	No. 5	14 m	120	134
August 1989	No. 6	16 m	118	134

(1) Effect of Improvement by Lake Water Circulation

a) Lowering of Thermocline

The intersecting point of the upper and lower thermocline gradients was obtained from the vertical distribution of water temperatures in the lake. Water in the zone above this point was taken as epilimnion water. In the Kamafusa Dam, the strongest thermocline was usually formed in August and so the depth of the part above the thermocline, i.e., epilimnion water, was obtained from vertical distribution of water temperatures in August. The pumping tubes, which circulate the lake water, fulfill a physical function of lowering the thermocline. The actual results obtained are listed in the following.

1) Before the experimental equipment was put into operation, the epilimnion was as thick as 2–3 m. After the equipment began operations, it changed to 5–6 m with 5 tubes in operation, and 7 m with 9 tubes, indicating a lowering thermocline (Fig.-3).

2) In 1988, which experienced abnormal weather (low summer temperatures suddenly recovered to normal), a primary thermocline was temporarily formed at a depth of 1–2 m in the surface zone even with 5 tubes in operation, indicating insufficient capability for lowering the thermocline.

3) In 1990, in which 9 tubes were put into operation, the formation of a primary thermocline was weak despite rather similar weather conditions to those of 1988, and an increased capability was recognized.

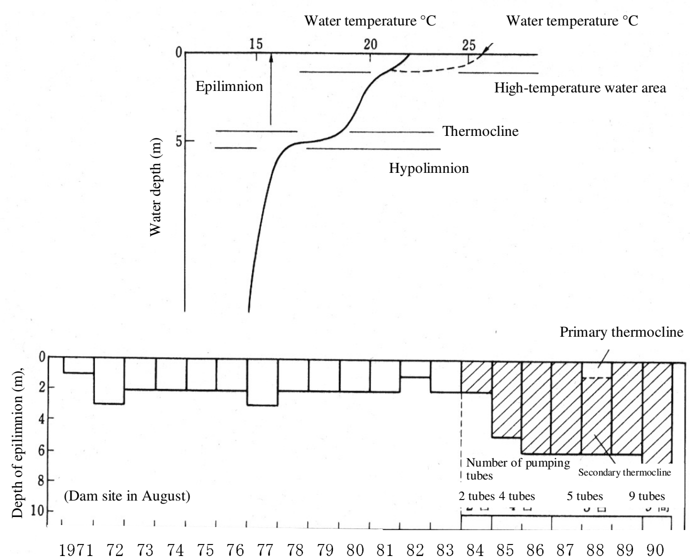


Fig.-4 Change in Depth of Surface Water Caused by Operation of Pumping Tubes

b) Control Effect on Phormidium

Table-4 compares the generation of Phormidium and musty smell before and after the experimental equipment was put into operation.

1) After pumping tubes were put into operation, Phormidium decreased remarkably and the water was completely free from the musty smell. Thus, the operation was considered effective in inhibiting the generation of Phormidium.

2) In August 1988, in which abnormal weather conditions prevailed, Phormidium increased to about 390 colonies/ml (maximum 1,500 colonies/ml) and so 5 tubes were assumed to be insufficient.

Table-4 Generation of Phormidium and Musty Smell

(Colonies/ml)

Month / Year	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990
Jan	0	680	(450)	60	80	60	40	40	290	-	134
Feb	0	920	(180)	0	-	-	30	10	320	20	45
Mar	0	150	190	30	-	150	110	10	620	10	22
Apr	0	320	70	0	20	30	20	0	260	-	0
May	0	320	130	30	60	210	110	90	40	20	65
Jun	0	0	0	0	(350)	150	0	0	0	0	0
Jul	0	0	10	0	(310)	240	0	0	0	0	0
Aug	0	(3600)	930	(14000)	(680)	20	0	0	390	10	0
Sep	(2700)	(2400)	(2300)	(2500)	390	0	0	0	0	10	28
Oct	(860)	(470)	(2300)	(150)	40	0	0	100	0	0	0
Nov	(100)	(580)	(200)	(310)	10	0	20	20		-	0
Dec	190	(3100)	(370)	90	50	10	0	80		-	0

( ) Period in which musty smell continued. ▭ Period in which air-pumping tubes were in operation

[Source: Sendai City Waterworks Bureau]

c) Control Effect on Total Volume of Plankton

Controlling the total volume of plankton leads to mitigation of an increase in internally produced COD. From this point of view, a change in chlorophyll "a", which expresses the total number and volume of plankton, is discussed below.

1) The concentration of chlorophyll "a" during the operation of 4 or 5 pumping tubes decreased to 8 μg/l or so from the level before the experiment (Fig.-5).
2) In 1990, the total number of plankton decreased remarkably to about 160 × 1,000 pieces. Due to the recognized effectiveness of the control, it is intended to continue investigations (Fig.-6).

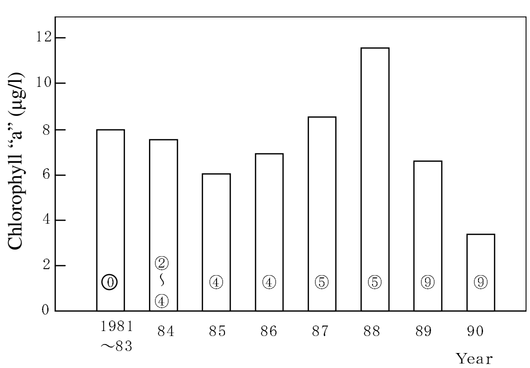


Fig.-5 Change in Chlorophyll "a"

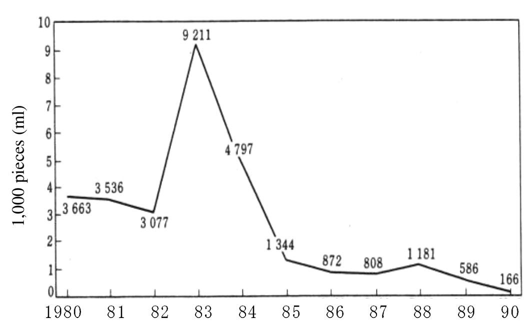


Fig.-6 Change in Plant Plankton

d) Conclusion

The effectiveness of the operation of 9 pumping tubes and the contents of earlier descriptions in this report are summarized in the table below.

Table-5　Results of Pilot Experiment

	Findings	Presumption
Range of impact	Pumped water does not form short current but is mixed with epilimnion water and spreads through the entire area of the lake mainly on drift current in 2 to 3 days. Water circulates through all zones over a long period of time.	
Lowering of thermocline; range of its impact	Thermocline lowered from 2–3 m to 5–6 m when 5 pumping tubes were operated and to about 7 m with 9 tubes.	In most years, 9 tubes seemed sufficient for suppressing the formation of primary thermocline.
Change in quality of water	After the operation, improvement of anaerobic tendency of hypolimnion water was observed. Temperature of epilimnion lowers less. Temperature of discharged water is higher than that of inflow water. The operation does prolong turbidity of water.	Cold-water phenomenon is not assumed to be presented. No adverse effect produced by lake water circulation is observed.
Biological phenomenon	Phormidium is apparently controlled. The total volume of algae decreased only when 9 tubes were put into operation.	Reduction of retention time of epilimnion resulted from lowering of thermocline is assumed to be a major element.

(2) Discussion on Algae Control Mechanism

Phormidium decreased dramatically when air-pumping tubes were put into operation. Following the operation of 9 tubes, a declining trend of plant plankton was observed.

To determine a suitable scale of equipment and a course of operation, further understanding of the mechanism of algae control is necessary. Therefore, results of on-site and indoor tests were included for discussion as a lead to explicating complex phenomena in the lake.

a) Factors Related to Control of Algae

Light, nutrition, water temperature, retention time in the epilimnion (proliferation period) and pH are considered as important factors allowing an increase in algae. Among them, the factors that changed substantially due to circulation of lake water in the experiment were restriction on light and retention time (proliferation period) in the epilimnion. Lowering of a thermocline vertically extends the range in which water mixing occurs, resulting in conveyance of algae into depths not reached by light. On the other hand, the circulation of lake water does not reduce nutrition and is assumed to be hardly involved in the algae control mechanism because of a smaller change in the temperature of surface water. Restriction on light and retention time in the epilimnion (the cycle of circulation in light and dark zones) are discussed in the following.

b) Restriction on Light to Mitigate Increase of Algae

The results of an indoor test using the epilimnion water of the Kamafusa Dam added with Phormidium and on-site testing on the amount of increase in algae ($1m^3$ flexible water mass equipment) show the following relation between proliferation of Phormidium and light.

1) Phormidium increased with more than 2,000 lux of light. The higher the luminous intensity, the more active its proliferation (Fig.-7).
2) In the on-site test on the amount of increase in algae, multiplication to 200–600 colonies/ml was seen at a depth between 0.5 and 1 m with more than 5,000 lux of light. At a depth of 3 m where underwater luminous intensity declined to about 1,000 lux, the increase was restrained (Fig.-8).
3) Disregarding limitations in test equipment that should have been considered in evaluating the above results, Phormidium is assumed to require a luminous intensity of about 2,000 lux for its active proliferation. Since the depth of water corresponding to this luminous intensity is approximately 2 m in the Kamafusa Dam, a depth from 1–2 m is believed to be the range of active increase in algae.

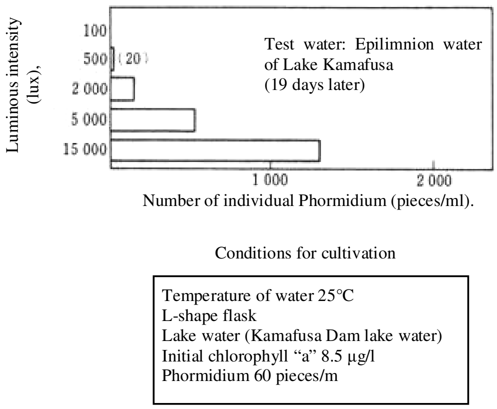


Fig.-7 Relation Between Proliferation of Phormidium and Luminous Intensity (Indoor)

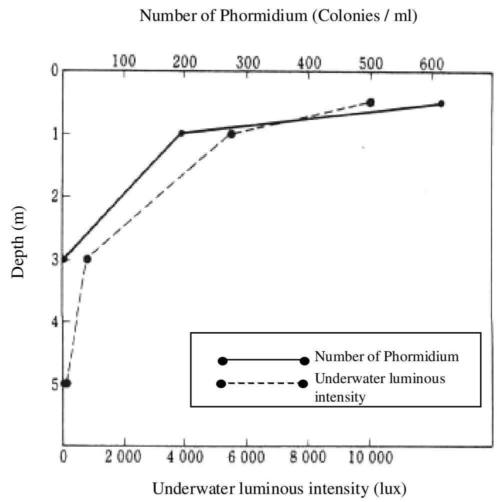


Fig.-8 Underwater Luminous Intensity of the Lake and the Number of Phormidium (On-site test on increase in algae)

c) Influence of Retention Time in Epilimnion

It is known from the results of tracer investigations and others that when a thermocline lowers, algae are distributed in the epilimnion and circulate in a light zone at a depth between 1–2 m in the epilimnion and a dark zone below it. Since such retention times in light and dark zones are believed to have a close relation to the control of increase in algae, discussion was made on the basis of the results of on-site and indoor experiments.

1) The effect of control on the increase when test equipment was installed in the epilimnion and induced circulation in a zone from 0–5 m and 0–10 m as obtained by the on-site test on the increase in volume of algae is shown in Fig.-9. The circulation in the 0–5m zone could suppress Phormidium and that in the 0–10m zone could also decrease the total volume of algae to about 1/3. It was confirmed that the larger the number of days of continuous retention under dark conditions, the higher the control effect (Table-6).
2) The indoor test also proved that longer retention period under dark conditions had a greater effect in controlling the increase of algae.
3) In an indoor cultivation test carried out by the Water Resources Development Public Corporation, too, there was no increase when retention in the dark continued for a week or so (Fig.-10).

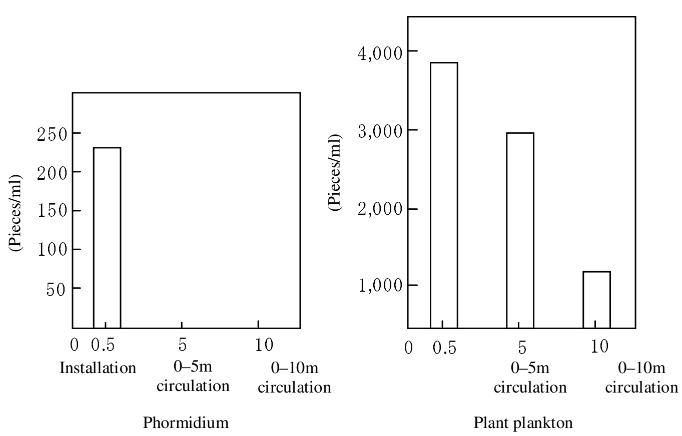


Fig.-9 Control Effect on Plant Plankton

Table-6 Increase in Phormidium and Light/Dark Conditions

Light/dark Conditions			Initial Period		Last Day	
			Chlorophyll "a"	Phormidium	Chlorophyll "a"	Phormidium
Control Light 12 hours Dark 12 hours			8.3	Piece/ml 100	μg/l 285	Piece/ml
1:1	Light	Dark				
	2 days	4 days	8.3	100	245	14,720
	5 days	10 days	8.3	10	79	690
1:2	2 days	4 days	8.3	100	187	14,600
	5 days	10 days	8.3	100	69	0

Conditions: 1 L-shape flask
Kamafusa Dam lake water (0.5 m) + vegetative salt
T-N 1.5 mg/l, T-P 0.05 mg/l

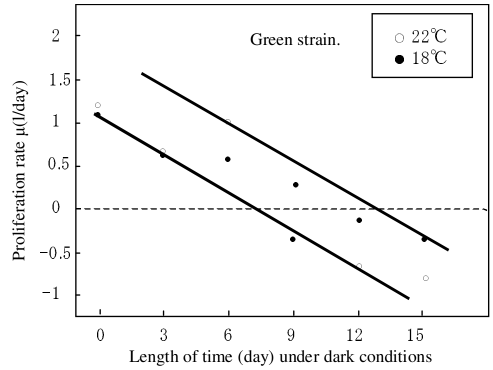


Fig.-10 Continuous Dark Conditions and Proliferation Rate of Phormidium

(Source: Water Resources Development Public Corporation's Indoor cultivation test on Phormidium)

d) Conclusion

The length of retention time in the dark zone
in water circulation through light and dark zones is assumed to be an important factor in controlling algae proliferation. The air-pumping tube functions to adjust the retention time of epilimnion water by circulating lake water to lower the thermocline. The position of the thermocline lowered from 2–3 m before the tube operation to about 7 m with 9 tubes in operation. According to an estimate based on the results of calculating simulation data, retention time at a depth of 2 m (the light zone) in the epilimnion was shortened from about 60 days before the operation to about 6 days with 9 tubes in operation. This leads to the assumption that the retention time of algae in the dark zone would be extended substantially. This is considered to have played an important role in controlling the multiplication of algae.

(3) Study of Required Scale to Lake Water Circulation Facilities

The cause of the eutrophication problem of the Kamafusa Dam was abnormal proliferation of plant plankton (Phormidium), a phenomenon heavily affected by nutritive conditions, water temperature and light as well as stagnancy of the epilimnion. Atmospheric temperature, insolation and other conditions of heat receiving, wind, inflow water, discharge operation and the effect of lake water circulation by means of air-pumping tubes all have some relation to stagnancy of the epilimnion. A lake water circulation model was built by appropriately modeling on these factors and was used to carry out the following analysis and study.

1) An estimate of the effectiveness of lake water circulation by means of air-pumping tubes and of the plankton control effect.
2) Study on an appropriate scale of pumping tubes.

a) Basic Structure of the Model

Although a change in the vertical section would need to be known by the use of a vertical two-dimensional model in the future, importance was attached to reproducing the effect of accelerating vertical mixing of water by means of pumping tubes, and a model was constructed as a one-dimensional one. Figure 11 is a schematic drawing of the model.

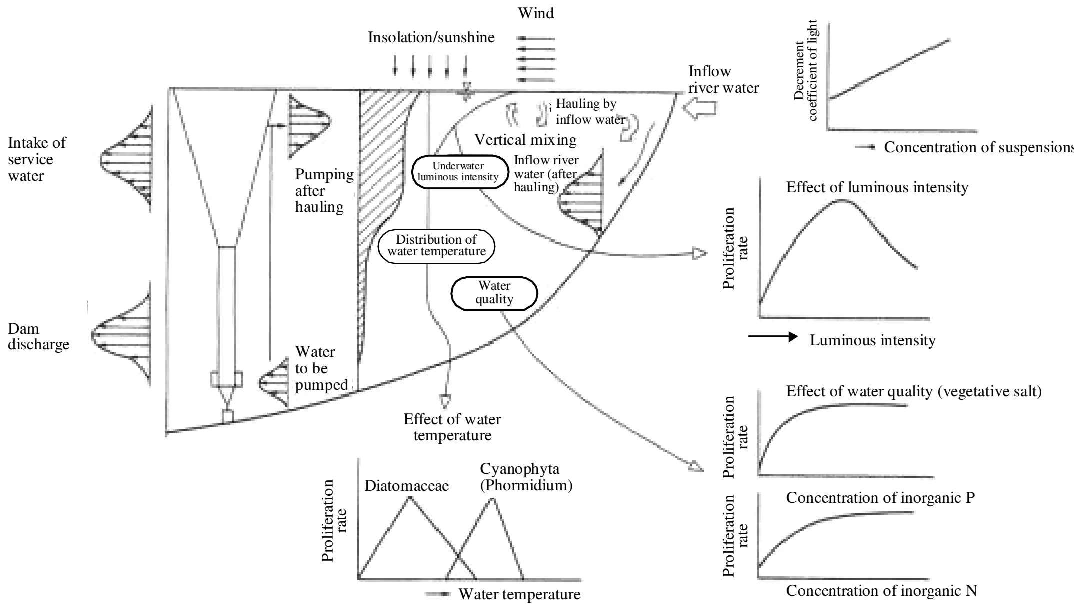


Fig.-11 Schematic Drawing of Lake Water Circulation

b) Result of Simulation to Reproduce Present State

1) Figure 12 shows the results of reproduction of water temperatures in 1988, which saw the highest development of a thermocline. The reproducibility of water temperatures is satisfactory with respect to the pattern of vertical distribution and that of daily variation; only a 1°C difference found at the time of a flood when no measurement of inflow water temperature was made.

2) With regard to abnormal proliferation of Phormidium, a model for quantitatively estimating a given species has not been developed to date. Then, for estimation, a combination of actual phenomena and the results of model computation was used as a quasi-empirical model with chlorophyll "a" and the thermocline as parameters. The reproducibility of the time of generation was satisfactory and the generated volume was also found to be reproducible as a general trend.

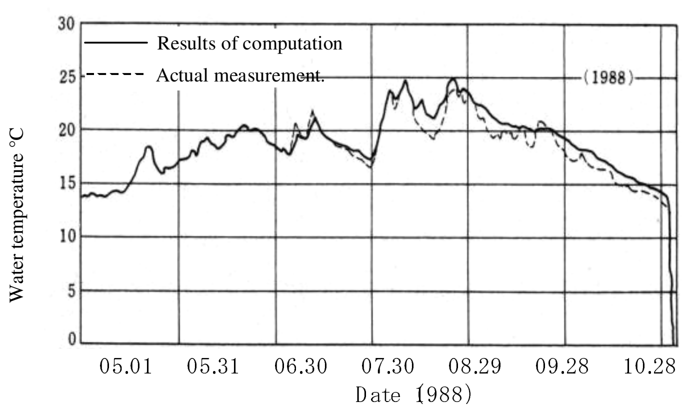


Fig.-12 Results of Estimation of Water Temperature

c) Study of Appropriate Number of Pumping Tubes

The operation of pumping tubes in the Kamafusa Dam could control the generation of Phormidium under the weather and water conditions of 1990. It could also lower the level of chlorophyll “a” in the total volume of plankton. Since 9 tubes were operated for a single year, however, evaluation should be made only after experimenting under other climatic and water conditions. Accordingly, simulation was made to determine an appropriate number of pumping tubes.

1) Case used for simulation

In designing the facilities, the required scale would depend on the year selected. Of a 10-year period from 1981 to 1990 for which various data was available, 1988 with its temporary generation of Phormidium was chosen as the object of simulation.

2) Results of Estimate

In Fig.-13 the result of computation for reproduction of chlorophyll "a" under the same conductions as in 1988 are shown.

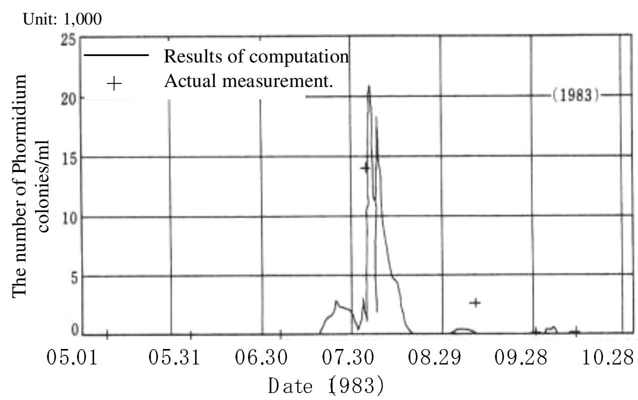


Fig.-13 Results of Computation of Phormidium (1983)

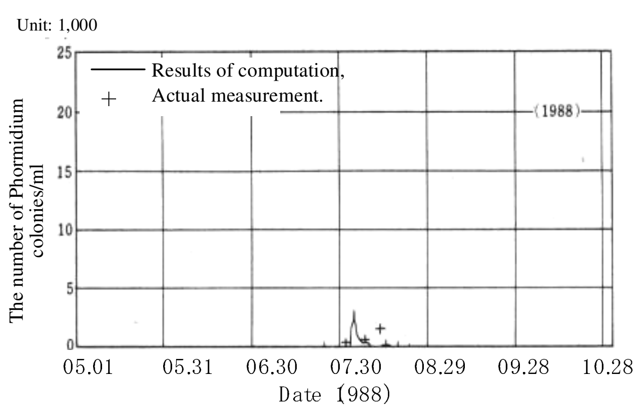


Fig.-14 Results of Computation of Phormidium (1988)

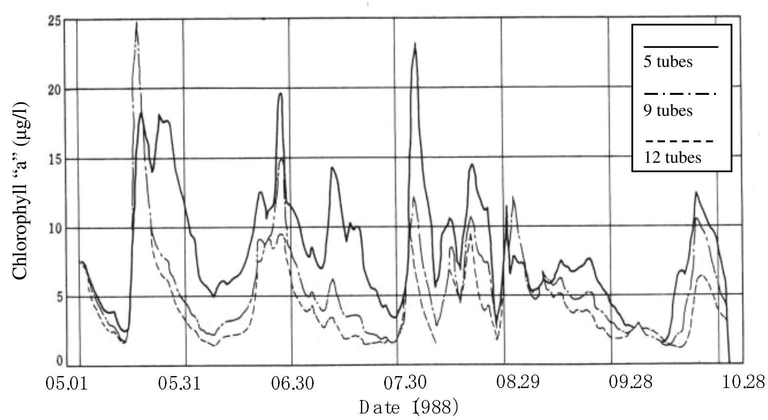


Fig.-15 Number of Pumping Tubes Put into Operation and Chlorophyll "a"

d) Problems Requiring Further Study

A vertical one-dimensional model of lake water circulation was built and effectiveness in controlling Phormidium (to eliminate abnormal taste and smell problems) and the total volume of algae (to reduce COD) resulted from improved strength and retention time of thermal stratification in the epilimnion was studied. Of the physical phenomena, simulation using the model could reproduce the effect of lowering thermal stratification. With respect to algae, it was possible to express the relation between the number of air-pumping tubes and effectiveness in controlling algae. In order to grasp the relation between complex flowing conditions in the lake and effectiveness in algae control, however, it is necessary to collect and evaluate results of investigations on the effect produced when 9 tubes are operated in different years having different weather and water conditions.

5. Results of the Mitigation Measures

The experiment performed since 1984 was capable of attaining the objective to solve the abnormal taste and smell problem in water utilization almost completely. As a result of various investigations, the mechanism for controlling the proliferation of plant plankton through circulation of lake water was significantly explicated. Furthermore, it would be necessary to determine an appropriate scale of lake water circulation in consideration of economic efficiency and effect suited to the characteristics of the reservoir.

6. Reasons for Success

As the service water-use entity was a direct victim of abnormal taste and smell, the administrator of the dam and the water-use entity jointly carried out investigations and were able to analyze the state of generation of Phormidium. On the other hand, as basic quality items had been periodically measured and recorded since the completion of the dam, sufficient basic materials were available for the analysis.

7. Outside Comments

1) Kahoku Shinpo: "Musty smell in Kamafusa Dam; Sendai City Waterworks Bureau begins investigation," September 17, 1981
2) Kahoku Shinpo: "Will musty water problem be solved successfully? Purification of the lake by pressurized air," June 11, 1984
3) Kahoku Shinpo: "Prefecture to Designate Lake Kamafusa," July 29, 1987

8. Further Information

8.1 References

1) *Dam Engineering*, Japan Dam Engineering Center, March 1992

8.2 Inquiries

International Affairs Department
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