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REEVALUATION FOR EFFECTIVENESS OF THE GUIDELINE FOR AN AERATION DESTRATIFICATION SYSTEM AS A MEASURE FOR CONTROLLING WATER-BLOOM AND MUSTY ODORS WITH BASED ON OBSERVATIONAL DATA

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INTRODUCTION

One of the problems related to water quality of reservoirs is the bloom of cyano-bacteria due to eutrophication. Flowing into reservoirs with a relatively high concentration of nutrients, bloom of cyano-bacteria or other types of phytoplankton occurs when the period of water retention or water temperature reaches a certain level. The bloom of cyano-bacteria causes the coloring of surface water and obnoxious odors of drinking water, and thus has adverse effects on landscape and water use. Numerous cases of water quality risk have been reported in Japan, so measures are urgently required for protecting water quality in reservoirs.

Reservoir aeration destratification systems are one of the tools for controlling eutrophication in reservoirs and have recently been employed in great numbers. Nagayoshi et al. (2006) analyzed the effects of aeration destratification systems installed at ten reservoirs in Japan, and proposed an effective method for operating the facilities to control water-bloom and musty odors. The method has been designated as a standard operating method applicable to actual reservoirs. To verify its practicability, its applicability should be examined in numerous reservoirs.

In this study, the validity of the proposed method of operation was verified for reservoirs where aeration destratification systems were in operation in Japan through questionnaire surveys and analysis of operation results. Data were also collected on the quality and temperature of reservoir water and on cyano-bacteria, and parameters serving as the bases for operating aeration destratification systems were reevaluated.

OUTLINE OF AERATION DESTRATIFICATION SYSTEMS

Functions of aeration destratification systems

Aeration destratification systems produce circulating flow by causing water masses to move in the reservoir using the buoyancy of air bubbles. Thus, the thermocline in the reservoir can be transformed. Much has yet to be known about the bloom of cyano-bacteria in reservoirs.

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The effectiveness of aeration systems for controlling the bloom of cyano-bacteria has not yet been fully verified, either. The mechanism of control of cyano-bacteria's bloom is assumed to be as shown in Figure 1 based on the generally known characteristics of cyano-bacteria and the characteristics of flow formation in the reservoir (formation of circulated and mixed layers).

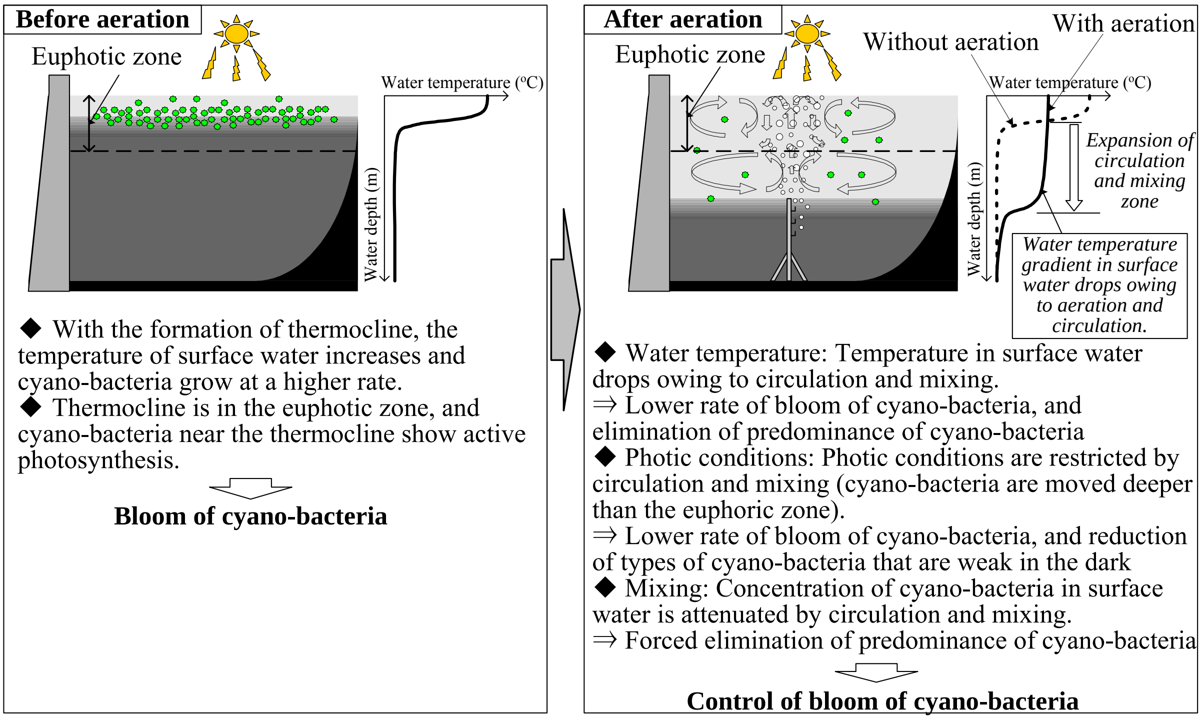


Figure 1 Mechanism of controlling the bloom of cyano-bacteria using an aeration destratification system

Type of aeration destratification system

The aeration destratification system used in this study was of air diffusion type. Air sent from the compressor at the ground level is discharged via an underwater diffusion outlet to produce ascending current using the buoyancy of air bubbles for circulating and mixing reservoir water. The circulation and mixing capacity (energy efficiency) is said to be higher than in any other type (Asaeda and Imberger, 1989). Air diffusion type aeration systems account for a large percentage of aeration systems recently installed in Japan.

ANALYSIS OF INDICATORS OF THE EFFECTS OF AERATION DESTRATIFICATION SYSTEMS

Quantitative identification of conditions for water quality risk

Principle of data analysis

Dam managers or water users often regard specific phenomena in respective water bodies as the deterioration of water quality. No indicators or criteria are available for generally determining the occurrence of water quality risk. Quantifying water quality risk is, however, necessary for properly operating aeration destratification systems or evaluating their effects.

Nagayoshi et al. (2006) investigated the maximum annual number of cells of cyano-bacteria and the occurrence of water quality risk using the results of quantitative investigations of cyano-bacteria conducted by dam managers in ten damsites in Japan where eutrophication occurred and aeration destratification systems were installed. As a result, they concluded that there existed certain relationships between the number of cells of cyano-bacteria and deterioration of reservoir water quality (Table 1).

Table 1 Number of cells of cyano-bacteria and water quality risk (results of evaluation at ten damsites)

Cyano-bacteria species	Type of problem	Relationships between number of cells and water quality risk	
		Number of cells	Corresponding Condition
Microcystis	Water-bloom	≥ 10,000cells/mL	Outbreak of water quality risk
		≥ 1,000cells/mL	High possibility for outbreak of water quality risk
Anabaena	Water-bloom	≥ 100cells/mL	High possibility for outbreak of water quality risk
Phormidium	Musty odor	≥ 1,000cells/mL	High possibility for outbreak of water quality risk

In this study, similar analysis was made using additional data recently made available at 23 damsites in Japan including those covered by the investigations of Nagayoshi et al. Then, the relationships listed in Table 1 were re-evaluated.

Analysis results

In relation to water quality risk owing to Microcystis, the relationship between the maximum annual number of cells of Microcystis and the occurrence of water-bloom identified at the site is shown in Figure 2. The maximum annual number of cells was the value obtained from monthly observation. The figure separately shows the cases of water-bloom that occurred locally and throughout the reservoir. Where the number of cells of Microcystis was less than 1,000 per mL, water-bloom occurred only a few times. Water-bloom occurred in a wide area only once. Where the number of cells were more than 1,000 per mL and less than 10,000 per mL, on the other hand, water-bloom occurred in a wide area in about 30% of cases. Where the number of cells exceeded 10,000 per mL, water-bloom occurred in about 80% of cases. Thus, water-bloom was highly likely to occur.

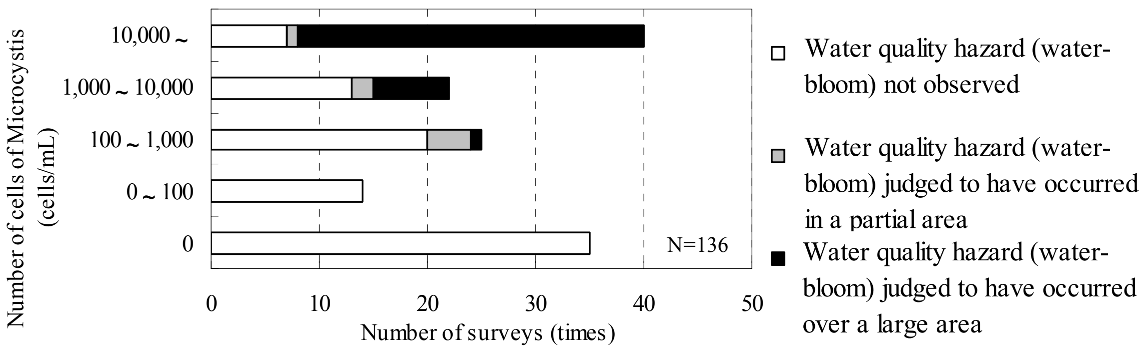


Figure 2 Number of cells of Microcystis and occurence of water quality risk (as judged on-site)

In order to examine water quality risk owing to Anabaena, the relationship between the maximum annual number of cells of Anabaena and the occurrence of water-bloom is shown in Figure 3. No water-bloom occurred in the case where the number of cells of Anabaena was below 100 per mL. Where the number of cells exceeded 100 per mL, water-bloom occurred several times. The possibility of the occurrence of water-bloom increased when the number of cell exceeded 10,000 per mL.

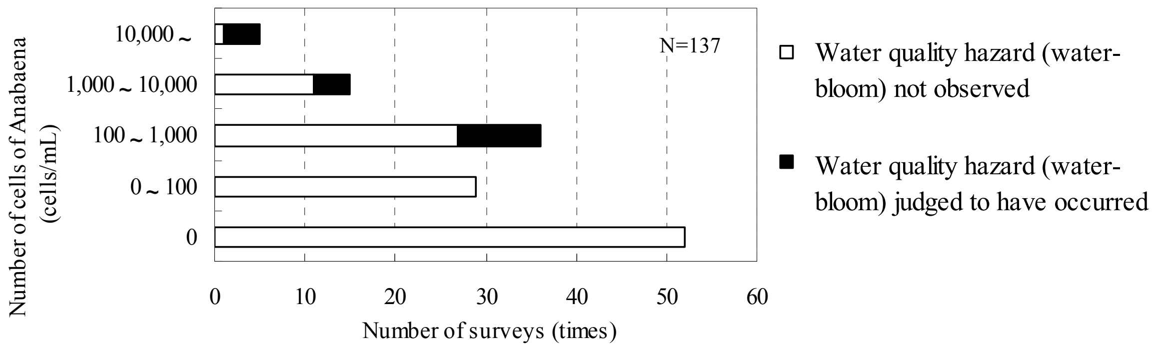


Figure 3 Number of cells of Anabaena and occurence of water quality risk (as judged on-site)

In relation to water quality risk owing to Phormidium, the relationship between the maximum annual number of cells and the occurrence of musty odors is shown in Figure 4. No musty odors were generated where the number of cells was below 1000 per mL. Musty odors, however, developed in the case where the number of cells exceeded 1,000 per mL.

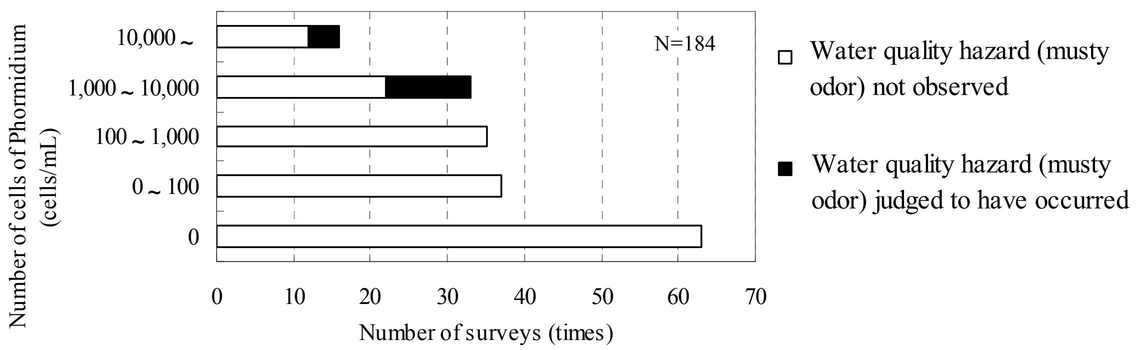


Figure 4 Number of cells of Phormidium and occurence of water quality risk (as judged on-site)

The relationship between the number of cells of cyano-bacteria and water quality risk was organized based on the above results (Table 2). Water quality deteriorated in the cases where the maximum annual number of cells of cyano-bacteria exceeded 1,000 per mL for Microcystis, 100 per mL for Anabaena and 1,000 per mL for Phormidium. The results were in agreement with those obtained by Nagayoshi et al. (Table 1). In this study, however, no water deterioration occurred in some cases at the same number of cells as in the study of Nagayoshi et al.

In the study of Nagayoshi et al., water-bloom occurred in all of the cases if the maximum annual number of cells of Microcystis exceeded 10,000 per mL. In this study, water-bloom also occurred at a high rate, or in about 80% of cases, where the maximum annual number of cells exceeded 10,000 per mL. Thus, the results of both studies were nearly in agreement with each other.

Table 2 Number of cells of cyano-bacteria and water quality risk (results of evaluation at 23 damsites)

cyano-bacteria species	Type of problem	Relationships between cell number of cells and water quality risk	
		Number of cells	Corresponding Condition
Microcystis	Water-bloom	≥ 10,000cells/ml	High possibility for outbreak of water quality risk
		≥ 1,000cells/ml	Possibility for outbreak of water quality risk
Anabaena	Water-bloom	≥ 100cells/ml	Possibility for outbreak of water quality risk
Phormidium	Musty odor	≥ 1,000cells/ml	Possibility for outbreak of water quality risk

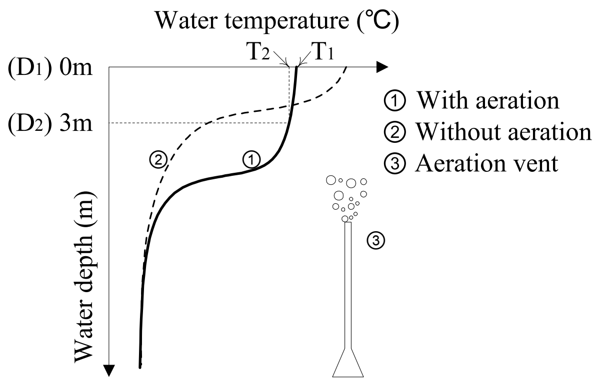
Indicators based on the hydraulic conditions at the time of water quality risk

Principle of data analysis

Bloom of cyano-bacteria generally occurs in the surface water of the reservoir. Then, thermocline develops at shallow depths in surface water and cyano-bacteria often dominate the area. Nagayoshi et al. paid attention to the point and analyzed the relationship between the maximum annual number of cells of cyano-bacteria and temperature gradient in the surface water of reservoir on the same date in ten reservoirs in Japan. As a result, they found that water quality was highly likely to deteriorate once the water temperature gradient exceeded 0.5°C/m. Then, they concluded that water quality risk could be avoided by operating the aeration destratification system so as to hold the water temperature gradient in the surface water of reservoir below 0.5°C/m.

In this study, data collected at 28 damsites were used to analyze the relationship among the water temperature gradient, maximum annual number of cells of cyano-bacteria and water quality risk by a method similar to that of Nagayoshi et al. Verification was made of using water temperature gradient as a parameter for controlling the operation of aeration destratification systems. The water temperature gradient at which water quality risk could be avoided was re-evaluated.

Water temperature gradient (°C/m) was calculated by dividing the variance between the water temperatures measured in surface water (at a depth of 0.1 m) and at a depth of 3.0 m by the variance in depth (Figure 5). However, water temperature at the depth correlated with stratification should be used for the examination of opereation of aeration destratification systems in each dam.



Temperature gradient calculation method

$K = (T_1 - T_2)/(D_1 - D_2)$

Here:

K : water temperature gradient (℃/m)

T_1: surface water temperature (at depth of 0.1m) (℃)

T_2: water temperature at depth of 3m (℃)

D_1: depth at which T_1 was measured (m)

D_2:depth at which T_2 was measured (m)

Figure 5 Schematic illustration of water temperature gradient calculation method

Analysis results

The relationship between the maximum annual number of cells of Microcystis and the water temperature gradient on the same date is shown in Figure 6. The number of cells increased with the water temperature gradient. Water quality was highly likely to deteriorate where the water temperature gradient was more than 0.5°C/m and the number of cells of Microcystis was larger than 10,000 per mL. Reducing water temperature gradient below 0.5°C/m is therefore expected to control water quality risk induced by Microcystis.

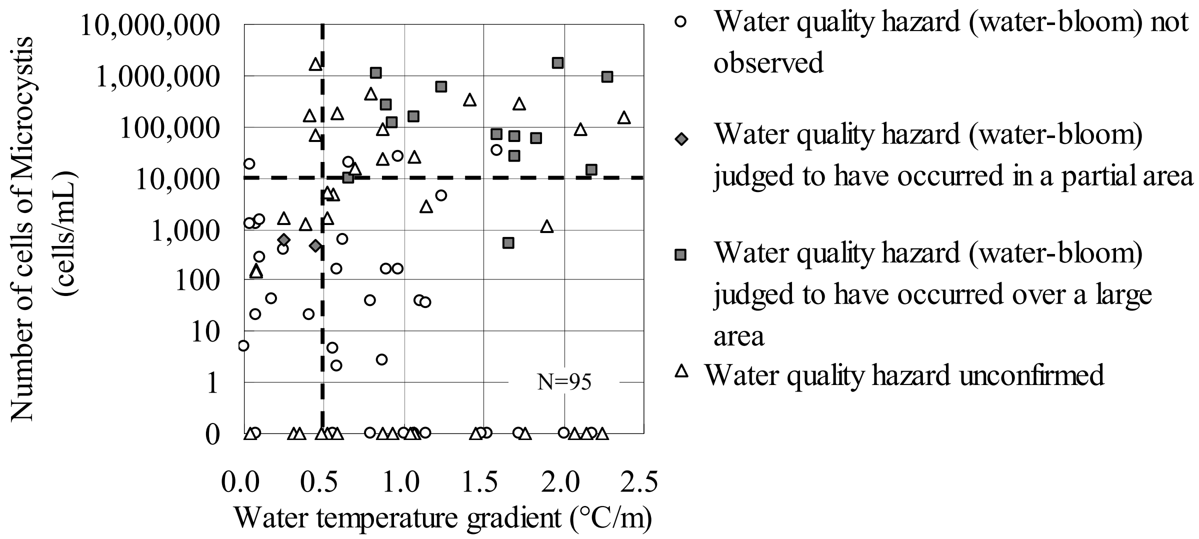


Figure 6 Water temperature gradient and the maximum annual number of cells of Microcystis

The relationship between the maximum annual number of cells of Anabaena and the water temperature gradient on the same date is shown in Figure 7. The number of cells increased with the water temperature gradient. Water quality was highly likely to deteriorate where the water temperature gradient was more than 0.5°C/m and the number of cells of Anabaena was larger than 100 per mL. Reducing water temperature gradient below 0.5°C/m is therefore expected to control water quality risk induced by Anabaena.

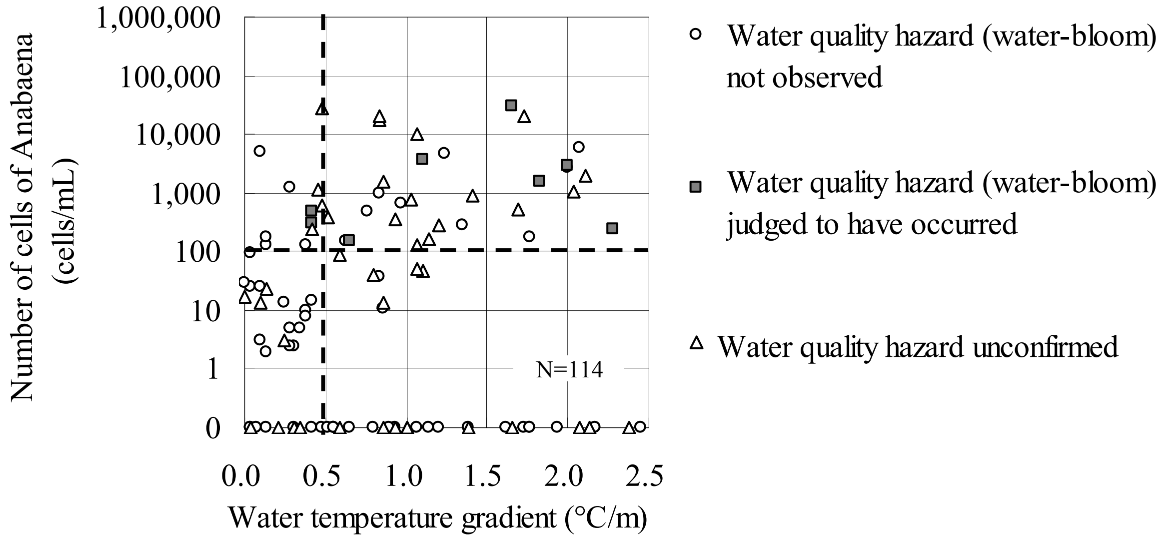


Figure 7 Water temperature gradient and the maximum annual number of cells of Anabaena

The relationship between the maximum annual number of cells of Phormidium and the water temperature gradient on the same date is shown in Figure 8. The number of cells increased with the water temperature gradient. Water quality was highly likely to deteriorate where the water temperature gradient was more than 0.5°C/m and the number of cells of Phormidium was larger than 1,000 per mL. Reducing water temperature gradient below 0.5°C/m is therefore expected to control water quality risk induced by Phormidium.

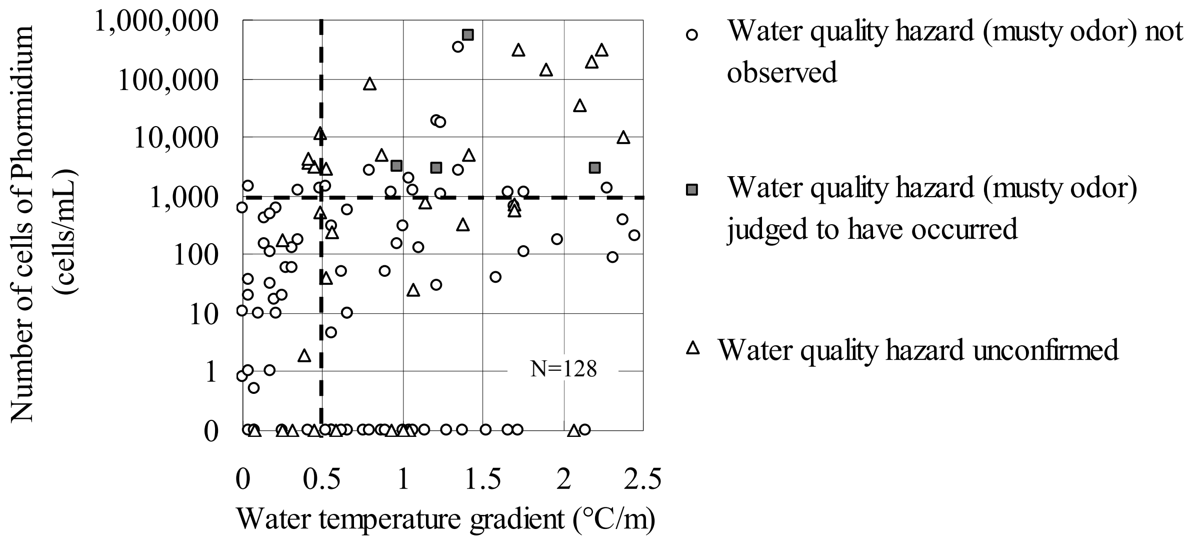


Figure 8 Water temperature gradient and the maximum annual number of cells of Phormidium

It was found based on the results described above that the probability of occurrence of water quality risk was low where the water temperature gradient was less than 0.5°C/m and that the probability was high where the water temperature gradient was more than 0.5°C/m. Then, the conclusion of Nagayoshi et al. proved valid that holding the water temperature gradient below 0.5°C/m was expected to control water quality risk.

VERIFICATION OF THE EFFECTIVENESS FOR IMPROVING WATER QUALITY

Effective operation of aeration destratification systems

Nagayoshi et al. proposed an effective method for operating aeration destratification systems based on the results of analysis of the effects of aeration destratification systems installed at damsites in Japan (Table 3).

Table 3 Conditions for effective operation of aeration destratification systems obtained from case analyses

Operating period	Beginning	April
	End	September - October
Operation during a flood		Continuous running as a fundamental rule (however, it should be stopped depending on the situation.)
Depth of aeration		15 - 20m

In this study, the effects of operation of aeration destratification systems installed at damsites were analyzed to verify the validity of the operation method shown in Table 3.

Evaluation of the effects of water quality improvement

<u>Outline of the effects of water quality improvement at respective damsites</u>

Analysis was made of the results of operation of aeration destratification systems installed for controlling eutrophication at 14 damsites in Japan under the control of the Ministry of Land, Infrastructure and Transport or Japan Water Agency. The objective was to verify the validity of the operation method proposed by Nagayoshi et al.

The effects of aeration destratification systems at the damsites were identified on a year-to-year basis in 1997 through 2006 based on the water temperature, number of cells of cyano-bacteria observed and mode of operation of the facilities. Then, water quality improvement effects were compared in cases where an operation method similar to the one proposed by Nagayoshi et al. or another method was employed.

Defined as the "operation method similar to the one proposed by Nagayoshi et al." was that implemented in cases where the facility was operated at a mean operating rate of 80% and the mean depth of water aeration was more than 15 m in April through September. The aeration effect was evaluated based on the mean water temperature gradient and mean frequency of occurrence of water quality risk in April through September after the commencement of aeration. The mean frequency of water quality risk was obtained by averaging in the period after the commencement of aeration. The value was calculated by dividing the number of days water quality risk occurred in the April-September period by the total number of days.

The results of evaluation of the effects of water quality improvement in different dams are listed in Table 4.

An operation method similar to the proposed method was adopted at six damsites. The mean water temperature gradient ranged from 0.2 to 0.6°C/m in April through September at the damsites. At five damsites out of the six, the mean water temperature gradient was below 0.5°C/m, in other words it was the range where water quality risk could be avoided.

The mean frequency of occurrence of water quality risk was 0 to 6% except at the K Dam. Aeration destratification systems therefore proved effective. Thus, the operation method proposed by Nagayoshi et al. was found to be nearly valid.

A method other than the proposed method was adopted at eight damsites out of 14 where verification was made. The mean water temperature gradient was 0.3 to 1.1°C/m at these damsites in April through September. The water temperature gradient exceeded 0.5°C/m at five damsites out of eight.

The mean frequency of occurrence of water quality risk was rather high: 17% in the B Dam, 28% in the I Dam and 19% in the L Dam. In the B Dam, water-bloom occurred in the period between 1998 and 2000 when the depth of aeration was low 12-15 m. In the other period, the depth of aeration was 18-20 m. And the reservoir of B dam was complicated shape. Therefore it was inferred that the effect of aeration failed to reach far in the reservoir.

In the I and L Dams, high mean water temperature gradients 1.0°C/m and 1.1°C/m led to the occurrence of water quality risk.

No water quality risk occurred in other five dams than the B, I and L Dams. The mean water temperature gradient was relatively low in these reservoirs. Operating an aeration and circulation method properly according to the characteristics of the reservoir, although not the proposed method, holds the mean water temperature gradient nearly to 0.5°C/m and proves effective for controlling water quality risk.

Table 4 Conditions of aeration destratification systems operation and water quality improvement effects

No.	Dam	To be controlled	Year full-scale operation of aeration	Total air diffused (as of 2006) (m^3/min)	Operation during a flood	Results of operation		Parameters for evaluating aeration effects	
						Average rate of operation[1]	Average depth of aeration[1] (m)	Mean water temperature gradient[1] (°C/m)	Mean frequency of water quality risk[1]
1	A	Musty odors	2004	23.3	Discontinued	93%	20.2	0.5	5%
2	B	Water-bloom	1997	17.2	Discontinued	85%	16.8[2]	0.3	17%
3	C	Musty odors	1997	12.0	In operation	52%	14.9	0.5	0%
4	D	Water-bloom	2004	22.4	In operation	100%	26.0	0.2	0%
5	E	Water-bloom	1997	12.4	Discontinued	94%	21.0	0.3	6%
6	F	Water-bloom	2002	29.6	Discontinued	64%	14.9	0.5	0%
7	G	Water-bloom	2005	14.8	Discontinued	85%	21.3	0.4	0%
8	H	Water-bloom	2006	11.1	Discontinued	90%	10.7	0.9	0%
9	I	Water-bloom	2006	3.7	Discontinued	38%	25.0	1.0	28%
10	J	Water-bloom	1993	7.2	Discontinued	69%	19.3	0.7	0%
11	K	Water-bloom	2003	7.4	In operation	89%	18.0	0.5	22%
12	L	Water-bloom	2006	5.1	In operation	9%	15-20[3]	1.1	19%
13	M	Water-bloom	2006	7.4	In operation	96%	26.4	0.6	1%
14	N	Water-bloom	1998	3.6	Discontinued	67%	13.4	0.7	0%

(shaded) : Method similar to the proposed method used

[1] Mean value in April-September period when the aeration destratification system was in operation on a full-scale between 1997 and 2006.

[2] Depth of aeration is lower in 1998 through 2002.

[3] No details are known

Evaluation of the effects of aeration and circulation based on the water temperature gradient

The relationship among mean depth of aeration, rate of operation of aeration system and mean water temperature gradient in April through September each year is shown in Figure 9. The larger the depth of aeration and the higher the rate of operation, the lower the water temperature gradient. When the rate of operation was more than 80% and at a depth of aeration of 20 m or larger, the mean water temperature gradient was generally below 0.5°C/m.

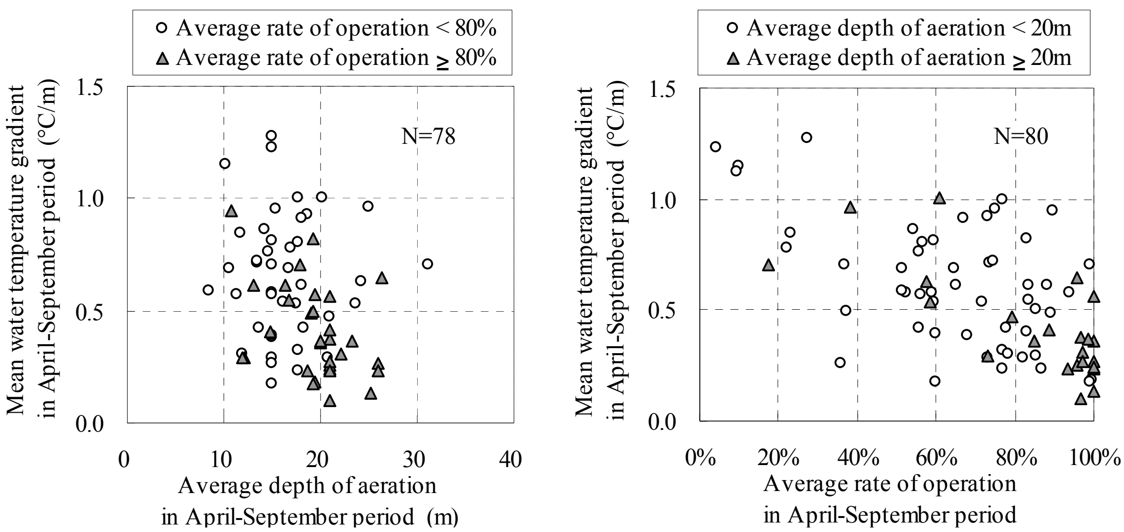


Figure 9 Depth of aeration, rate of operation of aeration systems and mean water temperature gradient

Evaluation of the effects of aeration and circulation based on the number of cells of cyano-bacteria that deteriorates reservoir water quality

The relationship among mean depth of aeration, rate of operation of the aeration system and maximum annual number of cells of Microcystis in the April-September period is shown in Figure 10. The larger the depth of aeration, the lower the maximum annual number of cells of Microcystis. When the depth of aeration was more than 20 m, the maximum annual number of cells of Microcystis was generally below 1,000 per mL. When the average rate of operation was more than 80%, the maximum annual number of cells of Microcystis except in the K dam was generally below 1,000 per mL.

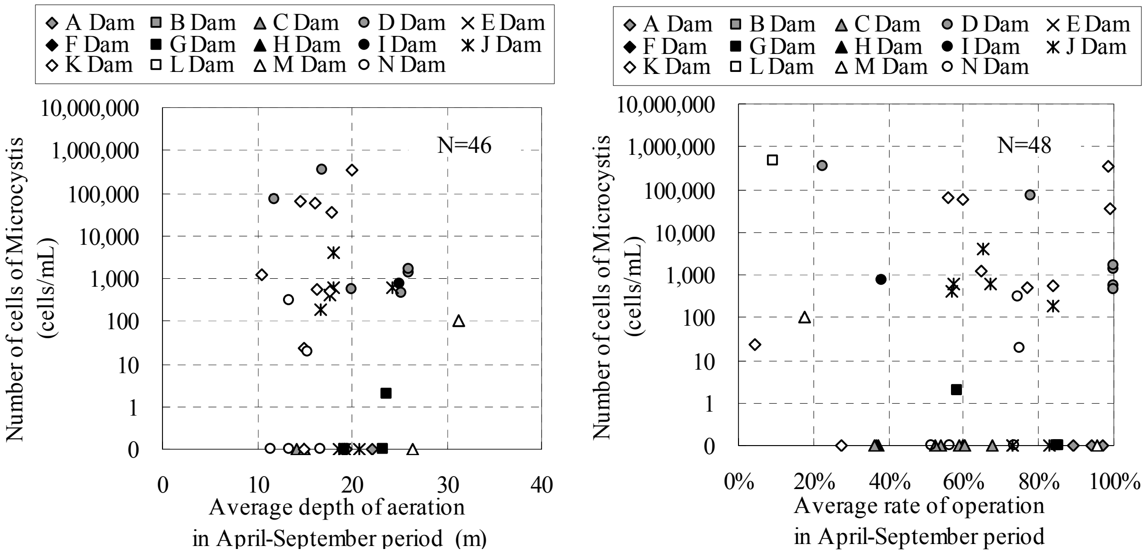


Figure 10 Depth of aeration, rate of operation of aeration system and the number of cells of Microcystis

Similar analysis was also made for Anabaena and Phormidium. As a result, when the mean depth of aeration in the April-September period was more than 20 m, the maximum annual number of cells was generally less than 100 per mL for anabaena, and was less than 1000 per mL for Phormidium in all the cases.

Results of verification of the effects of water quality improvement

The effects of water quality improvement by aeration destratification systems are described below.

(1) The occurrence of water quality risk can be controlled where the mean depth of aeration is larger than 15 m and the rate of operation of the facility is higher than 80% in the April-September period.

(2) The larger the depth of aeration and the higher the rate of operation of the facility, the lower the water temperature gradient. The mean water temperature gradient is generally lower than 0.5°C/m where the depth of aeration is larger than 20 m if the rate of operation is sufficiently high.

(3) In most of the cases with a depth of aeration of higher than 20 m, the maximum annual number of cells of cyano-bacteria is below the level at which deterioration is likely to occur.

Thus, the conditions of operation proposed by Nagayoshi et al. were found to be valid.

FUTURE TASKS

In this study, it was found that the indicators of the effects of aeration destratification systems and the method of operation proposed by Nagayoshi et al. were valid. The method is considered generally applicable for controlling water-bloom in particular numerous cases of adopting the method. Only a few cases are, however, available of using aeration destratification systems mainly for controlling musty odors produced by Anabaena or Phormidium. Continuing verification are therefore necessary by collecting more data.

Water-bloom occurred in some cases even when the proposed method was adopted. On the other hand, there has been cases where a method other than the proposed method of operating the aeration destratification system helped control the occurrence of water quality risk. When selecting the operation method, therefore, the proposed method should basically be used and appropriate parameters for controlling operation and operation method should be specified according to the characteristics of the dam reservoir. To that end, studies should be made on the methods for selecting effective operation conditions according to the characteristics such as the shape of the reservoir, quality of inflow, hydraulic conditions and meteorological conditions, and on the methods for specifying appropriate air volume and facility layout.

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