Sustainable and Safe Dams Around the World – Tournier, Bennett & Bibeau (Eds)

Development of a prediction model used in measures for reducing mold odor in dam reservoirs

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ABSTRACT: The introduction of water quality conservation facilities is an effective measure for reducing mold odor in dam reservoirs. However, depending on the hydraulic and water quality conditions, the countermeasures of changing the dam operations both by shortening detention time and by lowering surface water temperatures may be efficient and effective. This paper analyzes the results of field investigation and past surveys, clarifies the mechanism of mold odor occurrence in T dam, and develops a simple model that enables prediction and prevention of mold odor occurrence. The model makes it possible that dam administrators pre-vent mold odor by entering daily dam management data (inflow, outflow, and reservoir water temperature).Main factor of mold odor occurrence in T Dam is growth of Cyanobacteria in dam reservoirs. And we clarified Cyanobacteria could grow under certain situation, such as long detention time, a lot of nutrient salts and higher water temperatures. The developed simple model can estimate the degree of risk of mold odor. Therefore, it enables to predict the effects of the countermeasures by the revised dam operation.

RÉSUMÉ: L'introduction d'installations de maintien de la qualité de l'eau est une mesure efficace pour atténuer les odeurs de moisissure dans les réservoirs. Toutefois, selon les conditions hydrauliques et celles de la qualité de l'eau, les contre-mesures liées à l'exploitation du barrage comme la réduction du temps de rétention et l'abaissement de la température de surface de l'eau peuvent être efficaces. Cet article analyse les résultats des investigations de terrain et les relevés antérieurs; il clarifie le mécanisme d'apparition des odeurs de moisissure à la digue T et il développe un modèle simple permettant de prévoir et de prévenir l'apparition d'odeurs de moisissure. Le modèle permet aux exploitants de barrages d'empêcher les odeurs de moisissure en saisissant les données de gestion quotidiennes du réservoir (débit entrant et sortant ainsi que température de l'eau). Le principal facteur d'apparition des odeurs de moisissure à la digue T est la croissance des cyanobactéries dans le réservoir. Il a été démontré que celles-ci pouvaient se développer sous certaines conditions, comme une longue période de rétention, un grand apport de sels nutritifs et des températures d'eau élevées. Un modèle simple a été développé pour estimer le degré de risque d'avoir des odeurs de moisissure. Par conséquent, il permet de prévoir les effets des contre-mesures obtenues en révisant le mode d'exploitation du barrage.

1 INTRODUCTION

The mold odor occurrence (caused by 2-methylisoborneol (2-MIB)) in the water in the T dam reservoir caused some problems, for example forbiddance of supplying water, in August 2015. The dam administrator has been provided to predict the mold odor occurrence and take effective preventive measures against it. Although it is very important to predict the mold odor occurrence with high accuracy with such methods as the numerical simulation, a simple prediction method is required for daily dam reservoir management.

Against this background, we elucidated the mechanism of the mold odor occurrence in the T dam Reservoir and developed a model that could be used for simple prediction of the mold odor occurrence in this study.

2 MECHANISM OF MOLD ODOR IN T DAM

2.1 *Validation field*

The T dam is located in the middle reaches of the Sorachi River in the western part of the Hokkaido Island of Japan. The construction of this dam for the flood control and water utilization (for tap water supply, power generation and irrigation) was completed in 1999. The major specifications of the dam and meteorological data at the dam site are given below (Figure 1).

■ Reservoir capacity: 108,000,000 m^3 ■ Maximum reservoir surface area: 680.0 ha
■ Dam height: 50.0 m ■ Crest length: 445.0m ■ Catchment area at dam site: 1662.0km^2
■ Yearly average rainfall: Around 1,200 mm ■ Average air temperature: 7.1℃

(Source: The management data of T dam in 2007-2016)

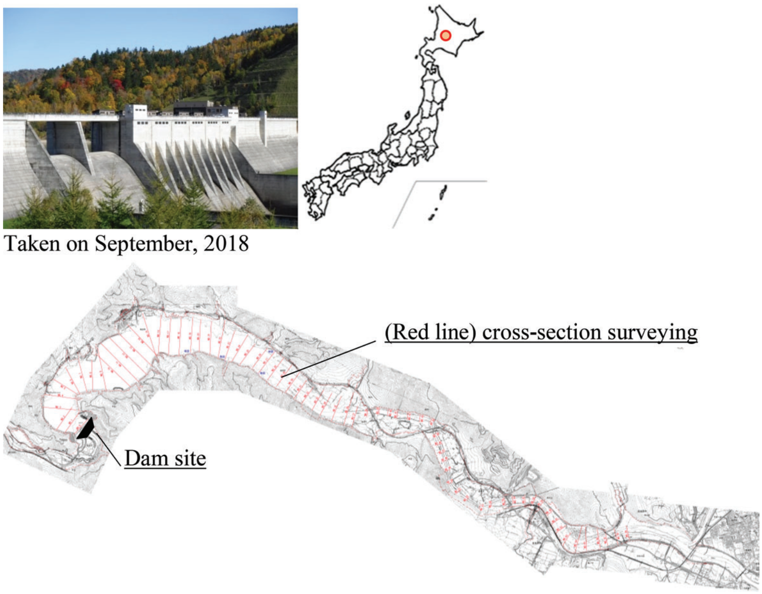

Figure 1. T dam location map and aerial view

2.2 *Generating Mechanism of Mold Odor*

2.2.1 *Past Appearance of Mold odor*

The mold odor (2-MIB) occurrence (2-MIB generation) in the T dam Reservoir was observed in the summer, between June and September, in four years, i.e., 2002, 2003, 2004 and 2015 (Figure 2).

The strongest-ever mold odor occurrence was observed in 2015. Figure 3. shows the chronological changes in the odor measured at the dam site and three points downstream of it. The maximum 2-MIB concentration observed at the most downstream point (50 ng/L) was approx. 40 % of the maximum 2-MIB concentration (116 ng/L) observed at the dam site (Figure 3) presumably because of the degradation and dilution of 2-MIB in water while it was flowing down the river. Therefore, the dam reservoir is considered the source of the mold odor.

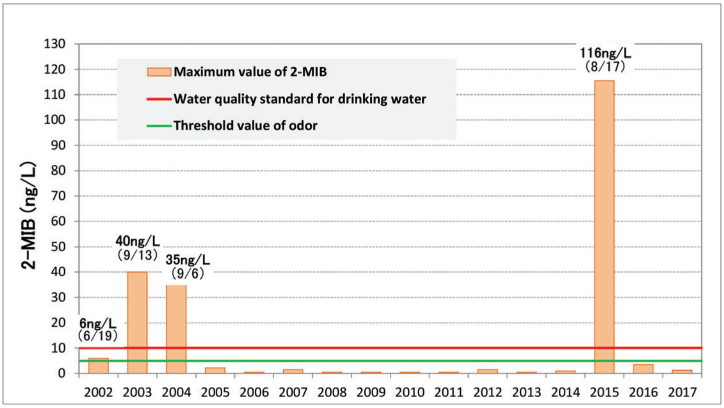

Figure 2. Annual maximum 2-MIB concentration in the T Dam Reservoir (2002 – 2017)

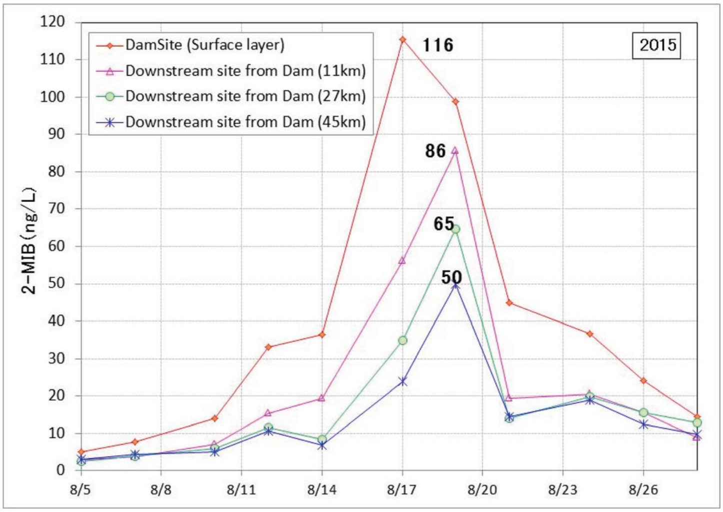

Figure 3. Changes in the 2-MIB concentration observed at the site of the T dam and three points downstream of it (in 2015)

The positive correlation observed between the concentration of 2-MIB and the density of cyanobacteria (blue-green algae) in the surface layer in the dam reservoir (Figure 4) suggests that the growth of the bacteria was the cause of the mold odor occurrence.

The microscopic identification and genetic analysis of the 2-MIB-producing algae of the attachment in the water in the reservoir revealed that the mold odor occurrence in 2003 and 2004 had been caused by Phormidium tenue and that in 2015 had been caused by *Phormidium sp.* (cf.*tergestinum*) or *Pseudanabaena catenata* (Figure 5).

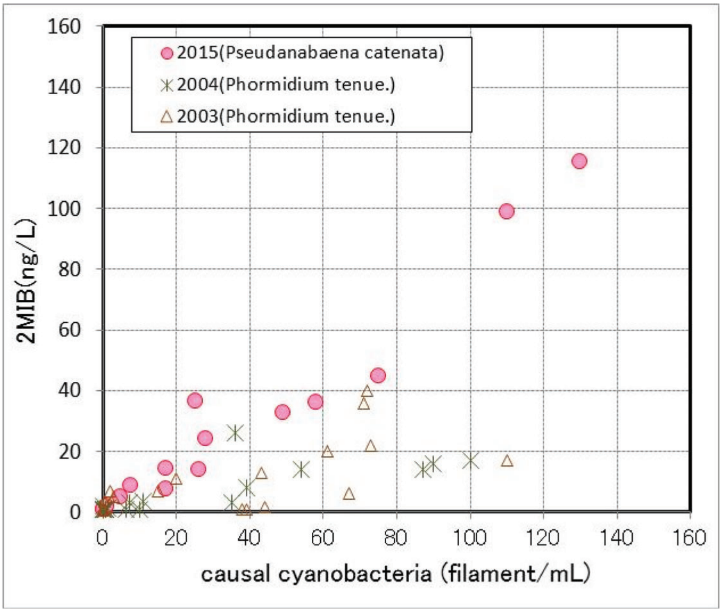

Figure 4. Correlation between 2-MIB and causal cyanobacteria (in the surface layer at the dam site)

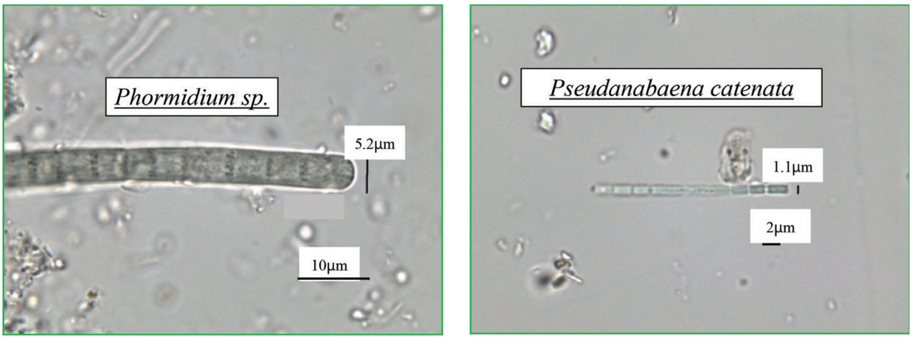

Figure 5. Photomicrographs of cyanobacteria producing 2-MIB

2.2.2 *Generating Mechanism of Mold Odor*

We estimated the sources of the mold odor in the dam reservoir in 2015 from the results of the field survey that we had conducted in 2016 and other surveys in the past (Figure 6). As seen in Figure 6., it was estimated that 2-MIB dissolved in the river water flowing into the reservoir and that produced by attached cyanobacteria in the reservoir had accounted for only 2 % and 1% of 2-MIB dissolved in the water in the reservoir, respectively and the remaining 97 % of 2-MIB had been produced by planktonic cyanobacteria in the reservoir.

Then, we compared the data on the occurrence of the mold odor (including the maximum concentration of 2-MIB produced by the causal cyanobacteria) and the water quality monitoring data in the reservoir in the period between 2002 and 2017 (Table 1). The comparison revealed that a high 2-MIB concentration is closely related to the "high surface water temperature," "long detention time," and "high nutrient salt concentration (PO_4-P)".

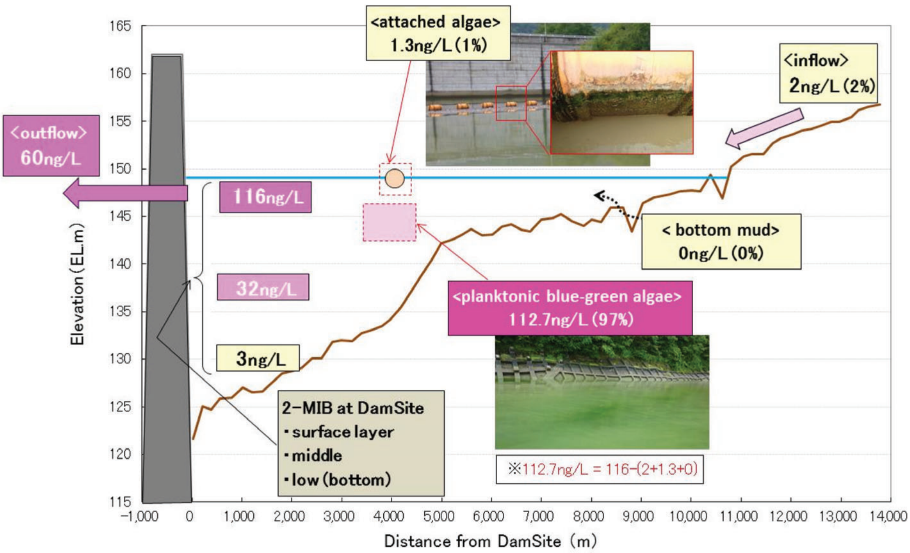

Figure 6. Estimation of the sources of 2-MIB in the T dam Reservoir

Table 1. Results of cause with or without mold odor (2-MIB)

year	Developmental period and Observation (2-MIB)			Water Temperature	Detention Time	Nutrients (PO4-P)	With Mold Odor	Reason of Without Mold odor			
	Over 1ng/L	Over 5ng/L	Maximum of Observation	℃	day	mg/L		Low Water Temperature	Shorten Detention Time	Without Nutrients	Washout
2002	6/11～6/26	6/15～6/20	6	16～20	13.2	0.003	●				
2003	7/17～10/2	8/1～9/25	40	16～22	11.3	0.003	●				
2004	8/5～9/30	8/26～9/30	35	19～25	12.3	0.005	●				
2005	8/4～8/11	–	2.2	19～26	6.9	0.007			✓		
2006	–	–	<1	19～27	10.4	0.004					✓
2007	8/8～9/12	–	1.5	18～26	19.1	0.002				✓	
2008	–	–	<1	21～25	13.3	0.002				✓	
2009	–	–	<1	18～25	6.8	0.006			✓		
2010	–	–	<1	18～23	4.1	0.021			✓		
2011	–	–	<1	20～25	7.3	0.019			✓		
2012	6/6～7/4	–	1.5	16～19	10.8	0.008		✓			
2013	–	–	<1	21～24	10.5	0.003				✓	
2014	7/2	–	1	17～22	10.1	0.0015				✓	
2015	7/29～10/2	8/5～9/4	115.5	22～25	10.8	0.003	●				
2016	6/16～7/15	–	<1		6.2				✓		✓
2017	8/2～8/9	–	1.3	22～24	10.4	0.002				✓	

The above-mentioned analysis has revealed that the mold odor occurrence has been observed when the three conditions, i.e., "daily average temperature of the water in the surface layer in the dam reservoir at 22°C or above," "water detention time of nine days or longer" and "within 30 days of flooding with an hourly average inflow rate of 150 m^3/s or more," are met and that the odor (2-MIB) production increases as the number of consecutive days on which the three conditions are met increases (Figure 7).

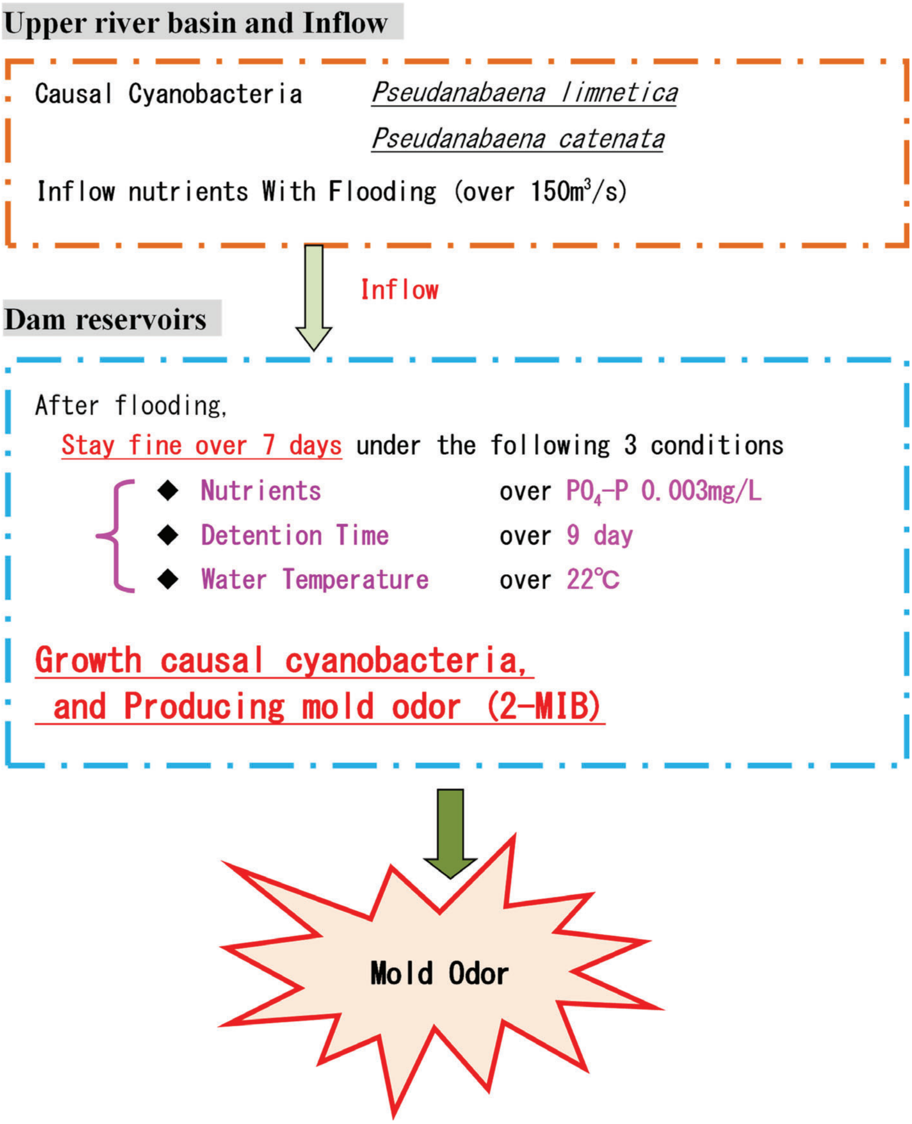

Figure 7. Mechanism of the mold odor occurrence (2-MIB production) in the T dam reservoir

3 DEVELOPMENT OF A SIMPLE MODEL

3.1 *Development of a Simple Model*

We developed a model that provided the dam administrator with a simple method to predict the mold odor occurrence and prepare measures to prevent the occurrence (hereinafter referred to as "the Simple Model").

Figure 8. shows the use of the model developed in this study in the workflow of the dam management for reducing the mold odor.

The Simple Model allows the dam administrator to predict the mold odor occurrence by entering daily dam management data (inflow rate, outflow rate and water temperature of surface layer in the reservoir) and prepare preventive measures based on the prediction result.

Figure 9. shows the result of the retrospective prediction of the mold odor occurrence in 2015 with the Simple Model.

The Simple Model successfully reproduced the mold odor occurrence, as the probability of the occurrence predicted by the model began to increase before the production of 2-MIB began and decreased rapidly when the 2-MIB concentration had reached its peak, resulting in the decrease in the concentration thereafter.

3.2 *Dam Management of Reducing Mold Odor*

We used a quasi-three-dimensional numerical model to verify the effect of various efficient dam management methods on the mold odor reduction (Figure 10). The verification has revealed that "increasing water discharge from the dam" at the time of the occurrence of the mold odor are effective in reducing the mold odor as preventing the rise of the surface water temperature and shorting the detention time.

3.3 *Use of Simple Model*

The Simple Model enables the estimation of the mold odor reduction effect of various dam reservoir management methods. In this study, its effectiveness in numerical simulation has

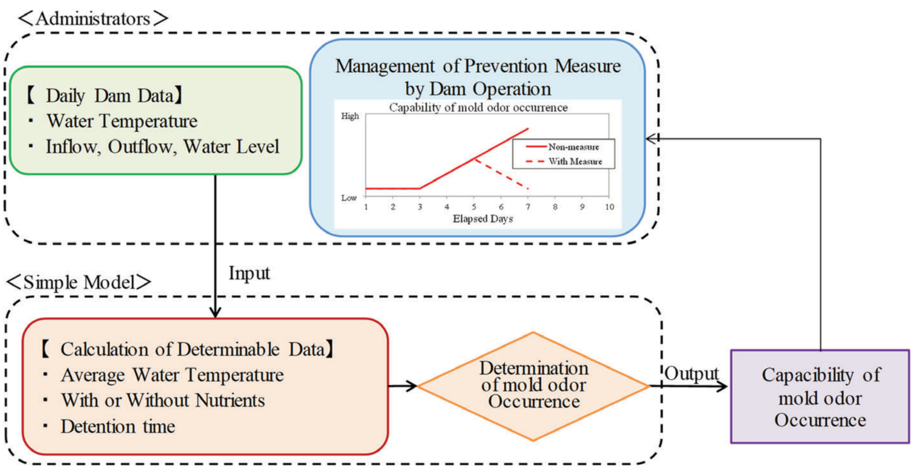

Figure 8. Concept of dam management for reducing mold odor

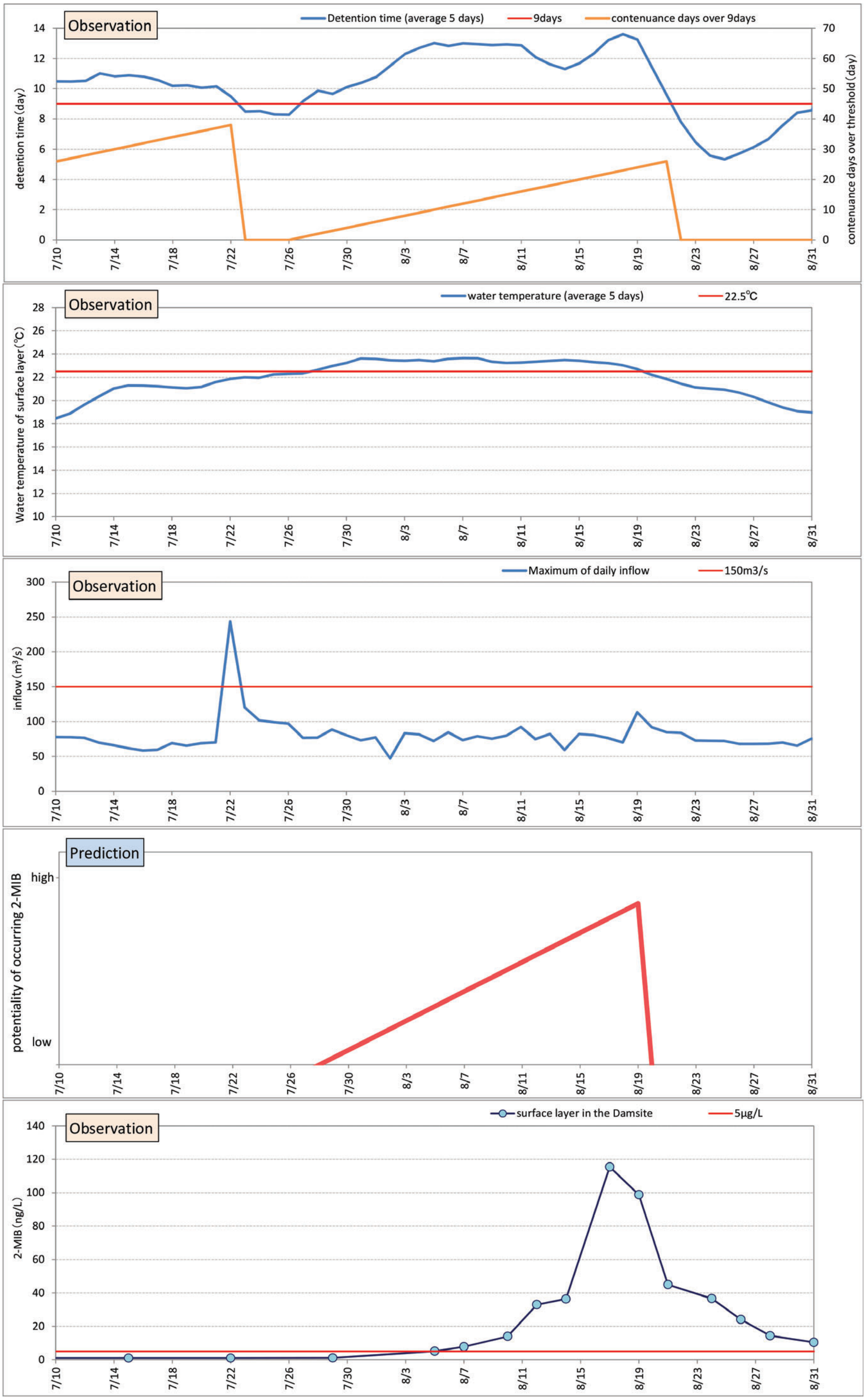

Figure 9. Result of the prediction of the mold odor occurrence in 2015 with the Simple Model

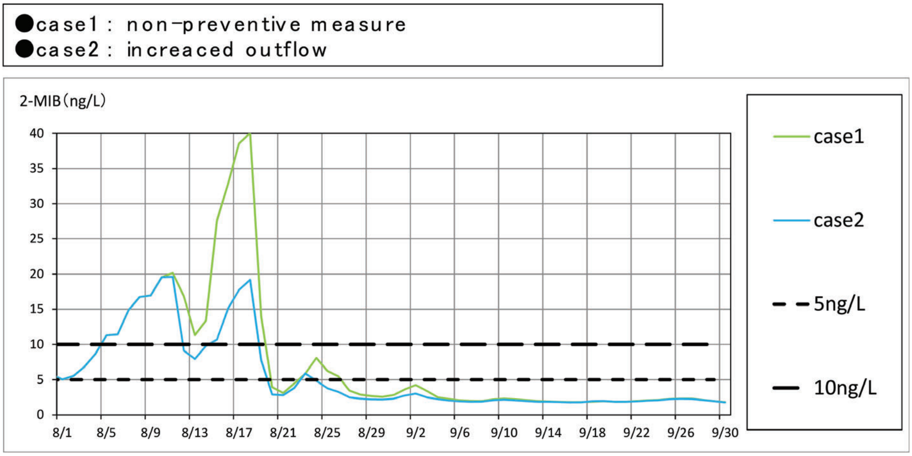

Figure 10. Result of the verification of the mold odor reduction effect of various dam reservoir management methods with a quasi-three-dimensional numerical model

been proved. Figure 11. shows the result of the estimation of the effect of increasing water discharge from the dam on the mold odor reduction.

The result has proved that the use of the developed Simple Model enables the prediction of the mold odor occurrence as part of the daily dam reservoir management work and rapid response to the risk of the occurrence with preventive measures prepared in advance.

4 CONCLUSIONS

The analysis conducted in the study has suggested that the growth of 2-MIB-producing cyanobacteria (Phormidium tenue and Pseudanabaena catenata) in the water in the T dam Reservoir is the cause of the mold odor occurrence.

We have identified “the surface water temperature of 22°C or above, the water detention time of nine days or longer and the concentration of nutrient salt (PO4-P) of 0.003 mg/L or more” as the conditions for the growth of these bacteria and revealed that, if these conditions continue longer, the probability of the mold odor occurrence will increase.

We have developed a simple model that enables the prediction of the possibility of the mold odor occurrence from the observation data taken daily at the dam Management Office, with the above-mentioned mechanism of the occurrence taken into consideration.

This model can also be used for the estimation of the mold odor reduction effect of various reservoir management methods.

A huge amount of facility construction and maintenance costs will be required if the growth of algae that produce the mold odor in a large-capacity dam reservoir like the T dam Reservoir is to be controlled with the structural measure of constructing and operating facilities for water quality control such as a reservoir water circulation system. Therefore, the prevention of the mold odor occurrence in the daily reservoir management based on the results of predictions (or the use of non-structural measures) is expected to lead to a large reduction in the cost.

Prevent status

Input data

necessary outflow of preventive measure

date	input data: daily data: water level, daily averaged (EL.m)	inflow, daily averaged (m^3/s)	inflow, daily maximum (m^3/s)	outflow, daily averaged (m^3/s)	data: water temp, daily averaged (°C)	water quality survey: 2-MIB surface layer, survey (ng/L)	water quality survey: D-PO4-P surface layer, survey (mg/L)	results of the simple model and preventive measures: potentiality of occurring 2-MIB, days (day)	preventive measures: necessary outflow, daily averaged (m^3/s)	preventive measures: possibility of outflow (day)
H27.7.28	149.81	43.82	76.97	60.43	23.3			0	62.77	over 10
H27.7.29	149.60	57.54	88.44	63.93	23.2	1.1		0	61.52	3
H27.7.30	149.61	54.86	80.51	50.49	24.2			1	61.58	3
H27.7.31	149.63	42.32	73.24	46.16	24.6			2	61.70	3
H27.8.1	149.69	48.29	77.35	43.49	22.6			3	62.06	3
H27.8.2	149.64	31.89	47.20	42.23	22.7			4	61.76	3
H27.8.3	149.43	44.30	83.41	43.51	23.1			5	60.52	2
H27.8.4	149.56	50.56	81.73	42.60	24.4			6	61.29	2
H27.8.5	149.67	46.42	72.21	40.93	24.1	5.1		7	61.94	3
H27.8.6	149.78	50.36	84.67	47.32	23.6			8	62.59	4

After preventive measure

date	input data: daily data: water level, daily averaged (EL.m)	inflow, daily averaged (m^3/s)	inflow, daily maximum (m^3/s)	outflow, daily averaged (m^3/s)	data: water temp, daily averaged (°C)	water quality survey: 2-MIB surface layer, survey (ng/L)	water quality survey: D-PO4-P surface layer, survey (mg/L)	results of the simple model and preventive measures: potentiality of occurring 2-MIB, days (day)	preventive measures: necessary outflow, daily averaged (m^3/s)	preventive measures: possibility of outflow (day)
H27.7.28	149.81	43.82	76.97	60.43	23.3			0	62.77	over 10
H27.7.29	149.60	57.54	88.44	63.93	23.2	1.1		0	61.52	3
H27.7.30	149.61	54.86	80.51	50.49	24.2			1	61.58	3
H27.7.31	149.63	42.32	73.24	61.70	24.6			2	61.70	3
H27.8.1	149.69	48.29	77.35	61.70	22.6			3	62.06	3
H27.8.2	149.64	31.89	47.20	61.70	22.7			0	61.76	3
H27.8.3	149.43	44.30	83.41	43.51	23.1			1	60.52	2
H27.8.4	149.56	50.56	81.73	42.60	24.4			2	61.29	2
H27.8.5	149.67	46.42	72.21	40.93	24.1	5.1		3	61.94	3
H27.8.6	149.78	50.36	84.67	47.32	23.6			4	62.59	4

Preventive measure

Improvement of 2-MIB

Figure 11. Result of the prediction of the effect of a preventive measure with the Simple Model

These non-structural measures can be promising water quality control measures in future because the mold odor occurrence can be predicted and prevented in advance in the daily reservoir management work of drinking water suppliers, which leads to a lower maintenance cost.