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Plan of Controlling Freshwater Red Tide Outbreak by a Vertical Fence in a Reservoir

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ABSTRACT:
Freshwater red tide is a phenomenon that changes the color of the water surface of reservoirs red or yellowish brown. The freshwater red tides found at dams managed by the Japan Water Agency are mostly caused by the genus *Peridinium*. Several countermeasures against freshwater red tides have been implemented up to now, but there is not yet one established countermeasure. This paper will summarize the information acquired to date concerning the red tides caused by *Peridinium*, and report on a new countermeasure against freshwater red tides with vertical fences in the reservoir, which was prepared based on the collected information. Sameura Dam with large water level fluctuations and Tomisato Dam with rather small water level fluctuations were selected as experimental field sites, and countermeasure experiment plans suitable to the respective water level fluctuations were created.
This experiment tries to suppress the dormant cells (cysts) of *Peridinium* to reduce their competitiveness with other phytoplankton for the purpose of slowly eliminating red tide.

Keywords: Freshwater red tide, Peridinium, Cyst, Vertical fence

1. INTRODUCTION

Freshwater red tide is a phenomenon that changes the color of the surface of lakes red or yellowish brown. It is caused by a massive outbreak and accumulation of phytoplankton, and impairs the scenery of reservoirs. Various species of phytoplankton cause freshwater red tides, but one of the most representative causative species is the dinoflagellate *Peridinium*. Freshwater red tides emerging in dams managed by the Japan Water Agency (hereinafter, the "JWA") are mostly caused by *Peridinium*.

At Sameura, Shingu and Tomisato Dams, which are managed by the Ikeda Comprehensive Dams Operating and Maintenance Office, freshwater red tides by *Peridinium* take place almost every year. To suppress the red tides, surface water has been removed to prevent water temperature from rising in the reservoir, and algiciding devices utilizing ultraviolet rays were installed on a trial basis. However, their effects are unclear. It is therefore imperative to establish a countermeasure against red tides.

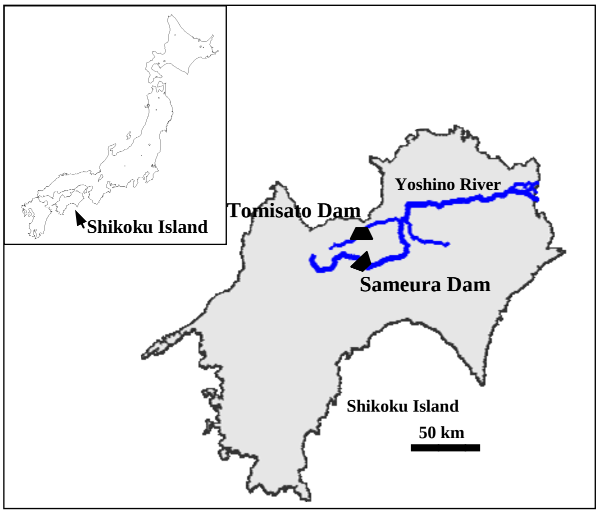


Figure 1. Map of Samaura and Tomisato Dams

2. FRESHWATER RED TIDES EMERGED AT THE RESERVOIRS OF IKEDA COMPREHENSIVE CONTROL OFFICE

2.1. Freshwater Red Tides at Sameura Dam

Sameura Dam is located in Kochi Prefecture. It is a multiple-purpose gravity dam constructed on the main river of the Yoshino River, with a basin area of 472 km^2, total reservoir capacity of 316 × 10^6 m^3, water surface area of 7.5 km^2, and dam height of 106 m. Administration of Sameura Dam commenced in April 1975.

The nutrient salts in the Sameura Dam reservoir are classified as oligotrophic to mesotrophic. Furthermore, freshwater red tides have been observed at Sameura Dam since 1993. The causative specie is *Peridinium*. Freshwater red tides emerge from November to January more often than in summer time (Fig. 2). In addition, they often take place in the main river or tributaries of the Yoshino River, 10 km or more above the dam. Local residents claim the red tides impair the local scenery.

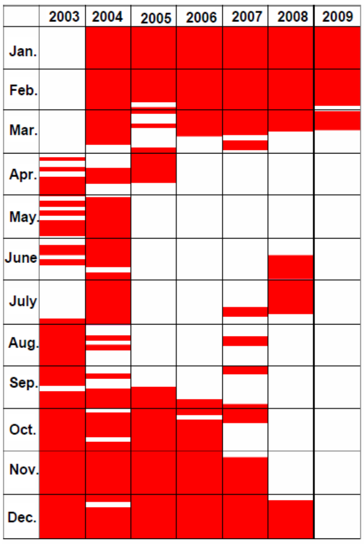


Figure 2. Times of observed freshwater red tides at Sameura Dam

2.2. Freshwater Red Tides at Tomisato Dam

Tomisato Dam is located in Ehime Prefecture. It is a multiple-purpose gravity dam constructed on the Dozan River of the Yoshino River system, with basin area of 101 km^2, total reservoir capacity of 52 × 10^6 m^3, water surface area of 1.5 km^2, and dam height of 106 m. Administration of Tomisato Dam commenced in April 2001. The nutrient salts at the Tomisato Dam reservoir are classified as oligotrophic to mesotrophic. Freshwater red tides have been observed from the year commencing administration. Just like Sameura Dam, it was discovered that *Peridinium* was the dominant species. *Peridinium* is often observed from summer to autumn (Fig. 3). Furthermore, freshwater red tides are mainly observed on the main river of the Dozan River and at inflow areas of its tributaries.

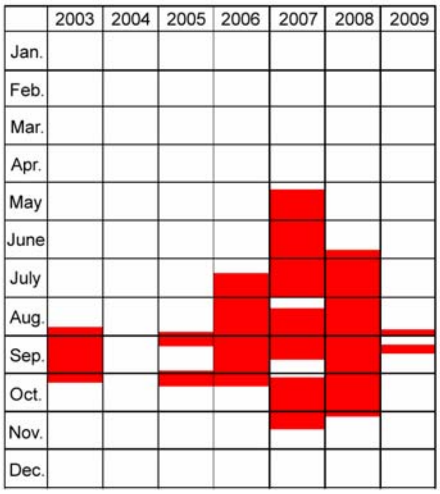


Figure 3. Times of observed freshwater red tides at Tomisato Dam

3. MECHANISM OF FRESHWATER RED TIDES OCCURRENCE

3.1. Life History of *Peridinium*

Peridinium is a type of phytoplankton whose cell size in 15–60 × 10^{-6} m. Each cell is covered by a cellulosic hull and it has a flagellum. The main feature of *Peridinium* is that it swims toward light by utilizing its flagellum in order to photosynthesize.

Peridinium's life cycle comprises both asexual and sexual reproduction (Fig. 4). In addition, it creates dormant cells (cysts) through sexual reproduction.

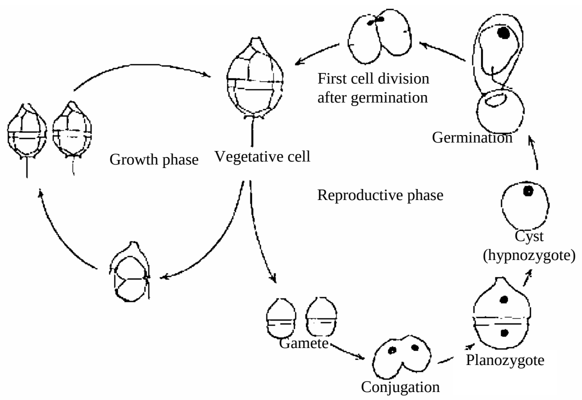


Figure 4. Life cycle of *Peridinium cunningtonii* (Kadota, 1987)

3.3. Proliferation Characteristics of *Peridinium*.

The proliferation speed of *Peridinium* is slower than other phytoplankton. Therefore, *Peridinium* is considered to have some factor that enables it to defeat other phytoplankton, principally because it is generated in large numbers to create freshwater red tide.

Regarding the condition of generating *Peridinium* at the dams managed by the JWA, it was observed at many dams that the number of generations increased with each passing year exponentially. As a result of sampling and number counting, the same trend can be seen at Sameura and Tomisato Dams (Fig. 5). We can infer from this that the generation of *Peridinium* accelerates its proliferation in the following year.

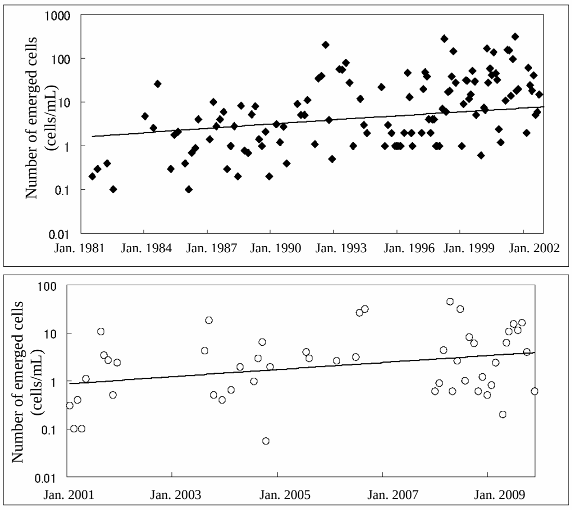


Figure 5. Annual number of *Peridinium* sp. cells at Sameura Dam (upper) and Tomisato Dam (lower)

3.3. Accumulation Mechanism of *Peridinium*

Peridinium senses light and swims toward it. Accordingly, *Peridinium* gathers near the surface layer of the dam lake in the daytime, when the sun is shining, but at night when there is no light it sinks to the bottom of the lake. The freshwater red tides from *Peridinium* often accumulate upstream of the reservoir because of *Peridinium*'s habit of moving toward light, and in addition, because of the wind drift current on the surface of the reservoir and entraining flow caused by the river inflow.

3.4. Cyst Characteristics

Dinoflagellates are reproduced by asexual reproduction. However, some species reproduce sexually depending on environmental changes such as the water temperature and light, and create motile zygotes. A cyst (dormant cell) refers to a cell with a stout membrane formed on the surface of cell membrane after a motile zygote has lost its flagellum over time. Because a cyst is not able to swim, it sinks to the sediment at the bottom of the lake and becomes deposited. After the cyst is dormant for a certain period, when placed in a more suitable environment it germinates and transforms into a vegetative cell.

Peridinium is said to create cysts at the peak of its generation. From this we can consider that *Peridinium* overpowers other species of phytoplankton in the early stages of generation because the cysts of the former generation germinate all at once under suitable conditions.

Furthermore, based on germination experiments of *Peridinium* cysts, environments with low concentrations of nutrient salts such as nitrogen and phosphorus do not affect germination. But cysts are not able to germinate in water at low temperatures or in locations without light. Moreover, in places deep underwater, where light may shine through but where the water temperature rises too slowly during the daytime, germination is delayed.

This shows that if cysts can be made to sink to the deeper layers, then cyst germination can be suppressed and, as a result, freshwater red tides can be suppressed.

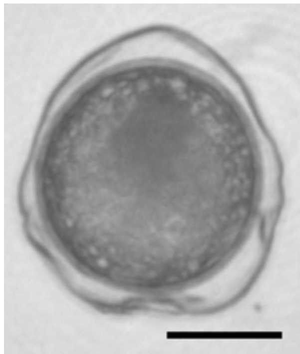
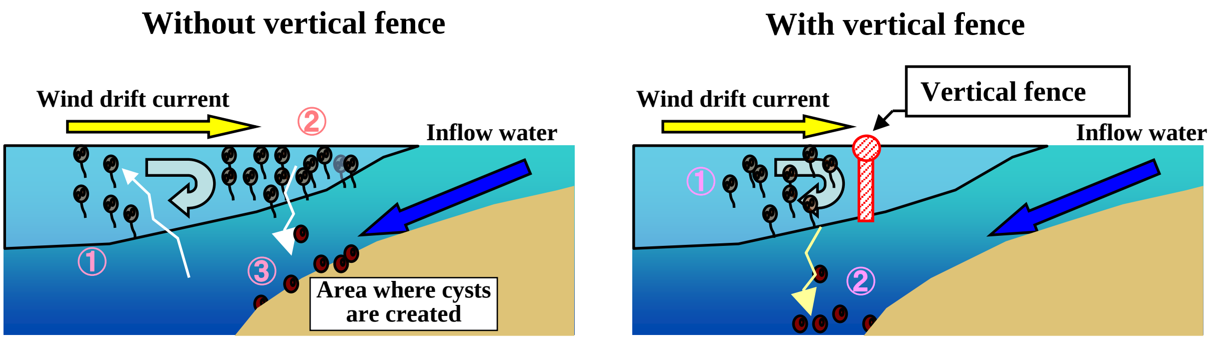


Fig. 6 *Peridinium bipes* cyst
(Scale: 20 μm)

4. VERTICAL FENCE MECHANISM AS A COUNTERMEASURE AGAINST FRESHWATER RED TIDES

A vertical fence for preventing freshwater red tides is a water-stop sheet that is placed cross the surface layer of the reservoir. The fence can block the movement of water between the upper stream and lower stream in the surface layer. Previously used vertical fences for freshwater red tide prevention separated the freshwater red tide accumulated in the upper stream region from other unaffected regions in order to prevent the red tide from spreading into the lower stream region.

On the other hand, the mechanism of this vertical fence is explained as follows; Step [1] stops water flow from the lower stream to the upper stream due to entraining flows or wind drift currents near the water surface, for the purpose of preventing vegetative *Peridinium* cells from spreading to the upper stream. This method is completely opposite from former methods, however. Step [2] utilizes currents created by the inflow water from the upper stream to the lower stream near the thermocline to lead vegetative *Peridinium* cells to the lower stream region and cause the created cysts to sink to deeper layers. Step [3] deprives the competitiveness of *Peridinium* against other planktons, because deep layers without light are not suitable to cysts' germination, and then finally freshwater red tides disappear. (Fig. 7 right).



① Vegetative cells move toward surface layer (cursoriality).
② Vegetative cells accumulate in upper stream region of reservoir by wind drift current and entraining flows.
③ Sunken cysts accumulate in bottom mud (causing generation of next generation).

① Fences interrupt movement between the upper and lower stream (accumulation in upper stream region is suppressed).
② Cysts flow to a deeper location in the reservoir (cysts move to an environment not suitable for germination).

Figure 7. Accumulation mechanism of *Peridinium* and vertical fences
(Somiya et al., revised from 1995 version)

5. DEMONSTRATION EXPERIMENT PLAN FOR COUNTERMEASURES AGAINST FRESHWATER RED TIDES AT SAMEURA DAM

5.1. Purpose of Demonstration Experiment at Sameura Dam

Figure 8. shows the reservoir water levels at Sameura Dam. The average levels from the commencing administration to 2009 indicate that the water level gradually decreases after the flood season, reaching its lowest level around February. The water level then rises from the inflow of melted snow and other factors. Furthermore, because the water level of the reservoir goes up and down from the influence of fronts, typhoons and drought, the reservoir water level fluctuates throughout the year. As a result, the demonstration experiment at Sameura Dam focused on investigating methods where the fence position could be easily altered according to the water level fluctuations.

5.2. Setup Positions and Shape of Vertical Fences

As Fig. 9 shows, the bases of vertical fences should be located at 3 locations each in the main branch of the Yoshino River and the inflow section of its tributary, called the Seto River. These fences should be relocated according to reservoir water level changes and the location of freshwater red tide generation. The total length of the fences is 105–255 m on the Yoshino River, and 110–200 m on the Seto River.

To facilitate fence relocations, vertical fences should be set to a depth of 1 m at Sameura Dam. Relocating the vertical fences is a way to respond to reservoir water level fluctuations.

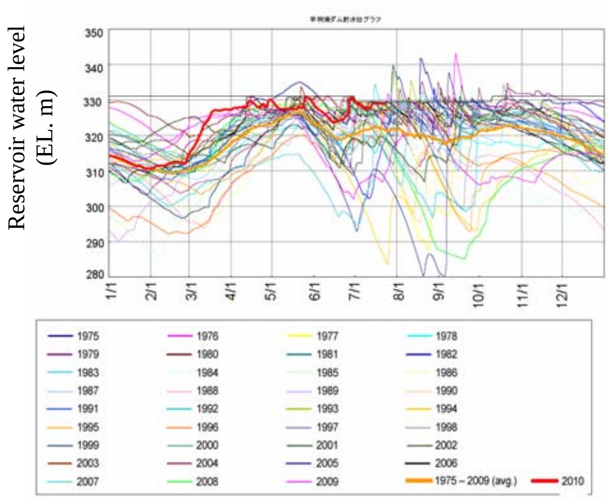


Figure 8. Reservoir water levels at Sameura Dam

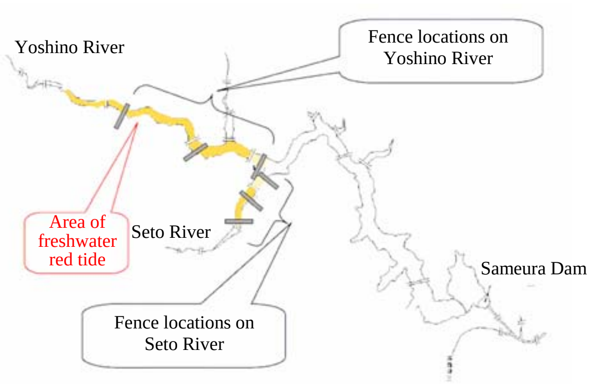


Figure 9. Vertical fence setup plan for Sameura Dam

5.3. Experiment Image at Sameura Dam

Because the reservoir water level greatly fluctuates throughout the year at Sameura Dam, this dam is well-suited for verifying fence relocations to meet the fluctuations. When the reservoir water level is highest, the vertical fences should be installed on a base prepared in the uppermost stream; when the water level drops, the fences should be moved to a base in the second uppermost stream region and the conditions should be monitored (Fig. 10). If flooding occurs, the fences should be removed.

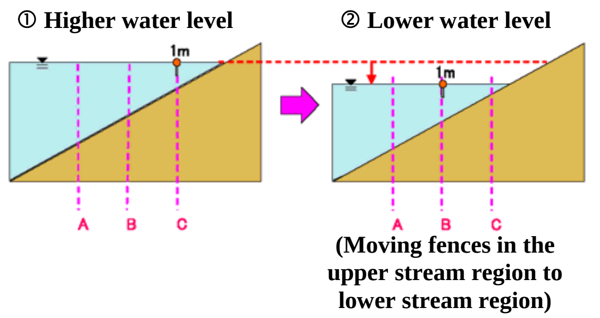


Figure 10. Experiment image at Sameura Dam

5.4. Problems and Solutions Regarding Vertical Fence Setup

At Sameura Dam, the general public often ride boats on the lake. Therefore, vertical fences crossing the lake could obstruct the boats' movements. This problem concerning lake surface users should be solved by reducing the diameter of some of the floats used for the vertical fences and preparing a clearly marked passage for boats covered with rubber sheets, as shown in Fig. 11. Furthermore, several signs indicating the location of the passage and other signs stating which areas are off limits need to be installed to secure the safety of general lake users.

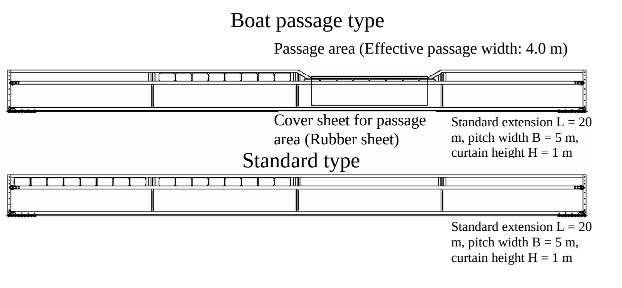


Figure 11. Vertical fence shapes

6. DEMONSTRATION EXPERIMENT PLAN FOR COUNTERMEASURES AGAINST FRESHWATER RED TIDES AT TOMISATO DAM

6.1. Purpose of Demonstration Experiment at Tomisato Dam

In previous uses of the vertical fence method, it is necessary to block currents from the upper stream to the lower stream. Therefore, fences were required to be installed at a depth of over 5 m. Comparatively, in this method the currents from the lower stream to the upper stream near the surface must be blocked, but some currents from the upper stream to the lower stream must be generated in the layer immediately below the fences. In this context, the most suitable depth for the vertical fences must be confirmed through demonstration experiments.

The annual water level fluctuations in the Tomisato Dam reservoir are somewhat small (Fig. 12). Accordingly, the demonstration experiments focused on placing fences whose depth could be changed as deep as 5 m, utilizing the smaller water level fluctuations, in order to determine the most suitable depth using this method.

6.2. Setup Positions of Vertical Fences

Regarding the setup positions of fences at Tomisato Dam, field research was conducted on the basis of records of past occurrences of freshwater red tides. As a result, setup positions have been determined as shown in Fig. 13, avoiding places with steep revetment or places that could damage the vertical fences.

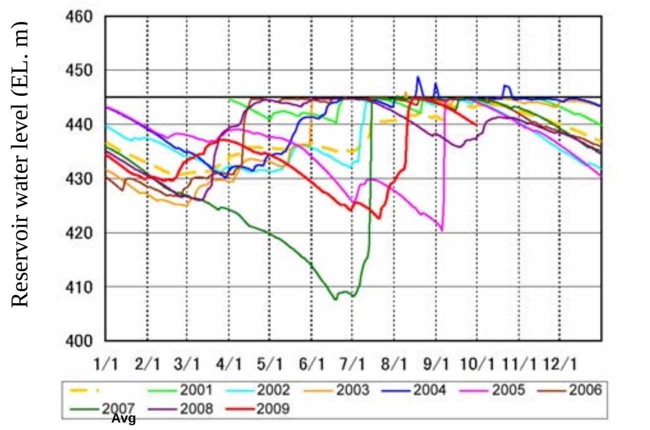


Figure 12. Reservoir water levels at Tomisato Dam

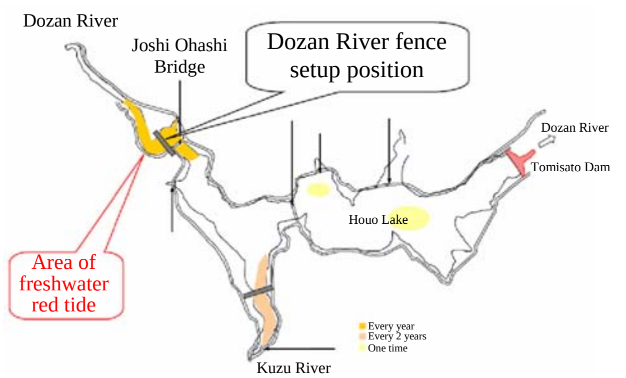


Figure 13. Vertical fence setup plan for Tomisato Dam

6.3. Vertical Fence Structure

The vertical fences at Tomisato Dam can be folded into a smaller size. Ropes fixed to the fence belts can be used to adjust the fence height (Fig. 14).

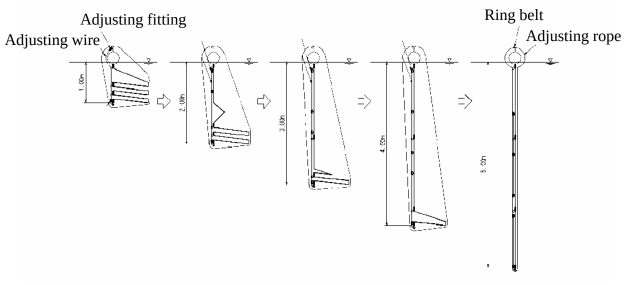


Figure 14. Structure of depth-adjustable fence

6.4. Relationship with Reservoir Water Levels

Freshwater red tides mostly emerge from summer to autumn at Tomisato Dam. During this time the dam often maintains near normal water levels, so therefore the lake may be regarded as having a certain water depth. However, it has been observed that the water levels decreased several times. If the water level drops, the vertical fences would be folded as needed, or other necessary arrangements would be taken.

6.5. Experiment Image at Tomisato Dam

Because the fluctuation range of reservoir water levels at Tomisato Dam is rather small, the dam is well-suited for verifying the depth adjusting mechanism of the fences. When starting this experiment, the fence depth should be set at 1 m and the conditions should be monitored. If no freshwater red tide accumulation is observed in the lower stream region of the vertical fences, the conditions should be monitored further, keeping the fence depth at 1 m. If any freshwater red tide accumulation is observed, the fence depth should be extended by 1 meter at a time up to a maximum of 5 m (Fig. 15). If flooding occurs, the fences should be removed.

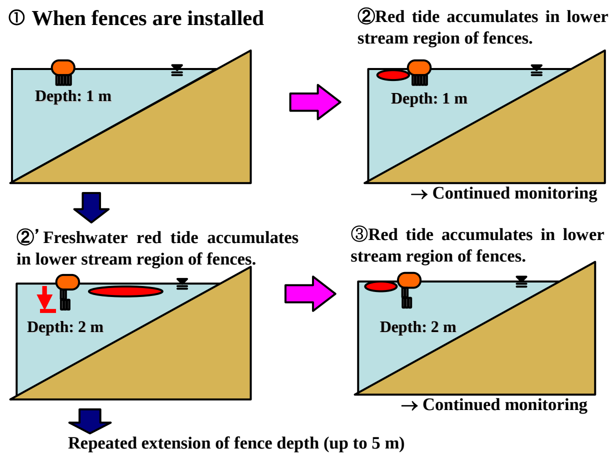


Figure 15. Experiment image at Tomisato Dam

7. CONCLUSIONS

Countermeasures against freshwater red tides using vertical fences have already been started at some dams managed by the JWA. However, all of them originally aimed to prevent freshwater red tide from spreading to the lower stream region. The vertical fence method discussed in this paper is a new method that focuses on *Peridinium* cysts and makes good use of past information of the JWA. But there is no knowledge yet about the most suitable fence depth required to achieve the purpose of this measure. Moreover, this measure has a disadvantage of troublesome maintenance and difficult controllability of vertical fences in dams with large water level fluctuations. This demonstration experiment enables us to investigate solutions to these problems, as well as naturally seek ways to suppress freshwater red tides.

Moreover, in research the vertical fences, it is necessary to measure the level of chlorophyll a in the reservoir. In the future, it is planned to investigate the conditions before occurrence of red tide, onsite flows including flow directions and speed at the time red tide occurs, turbidity near the vertical fences, and the dominant species of phytoplankton. Through these investigations we will be able to quantitatively understand the conditions of freshwater red tide occurrence and clarify more details of countermeasure mechanisms.

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