Water Environment Improvement in an Organically Polluted Closed Water Body by Artificial Water Surface Cooling

KYUSHU UNIVERSITY

Masayoshi Harada*, Kosuke Hayami**, Kazuaki Hiramatsu* and Toshinori Tabata*
*Faculty of Agriculture, Kyushu University, Fukuoka, Japan **Kajima Corporation, Tokyo, Japan

INTRODUCTION: Background & Purposes in This Study

Serious disruption of the aquatic habitat in an organically polluted reservoir

The conservation and restoration of organically polluted reservoirs with strong thermal stratification require the development of techniques to not only **recover from the anaerobic state** but also **suppress the abnormal proliferation of phytoplankton.**

The aim of this study was to propose a new physical technique to overcome such problems in a deep-water reservoir with small surface area and where the anoxification of the hypolimnion would be elongated owing to thermal stratification with strong stability

Artificially cooling the water surface using cold-water injection below the thermocline

→ **Suppression in algal bloom via water-surface cooling**

→ **Early disappearance of anoxification due to a cold-water-mass downwelling**

This study focused on water-surface cooling and cool-water-mass downwelling to restore the aquatic environment in organically polluted reservoirs, and was aimed at acquiring fundamental knowledge for the improvement effects by two approaches.

① Water Quality Experiment for Artificial Surface Cooling

➲ To measure the impacts of cold-water supply on the physical and biochemical dynamics of water quality using thermally-stratified water column using indoor water tanks.

② Numerical Estimation of Improvement Effects via Scenario

➲ To modify the conventional diffusion model with the advection-diffusion model by introducing both the estimation method of the sinking velocity of the cold water and numerical solution by operator-splitting method

WATER QUALITY EXPERIMENTS FOR ARTIFICIAL SURFACE COOLING

- ✓ Taking sample water in the organically polluted reservoir owing to an inflow of humic substance.
- ✓ Storing sampled water at a depth of 110 cm inside two cylindrical tanks in a thermostatic chamber controlled at a high temperature of 30 °C.
- ✓ **Irradiating the upper layer of the tanks using the fluorescent lamps** with about 0.07 mol/(m² s) light quantum **with a 24-hour cycle (12 hours on and off each)** for 3 weeks.
- ✓ Monitoring water quality parameters such as WT, DO, Chl.a, NH_4-N, NO_3-N and PO_4-P.
- ✓ Cooling the water surface **by supplying cold water of 15 °C through horticultural watering nozzles with spray intensity of 50 mm/d** for one hour after the start of fluorescent lighting.
- ✓ Setting the same water tank **without supplying the cold water** under irradiating the upper layer as **a control tank.**

◆ **Because this experiments were conducted in winter, external cold air intruded into the lowest part near the floor in the high-temperature room through a gap between the water-supply hose and chamber door, resulting in a decrease in water temperature in the bottom layer of the cylindrical tank.**

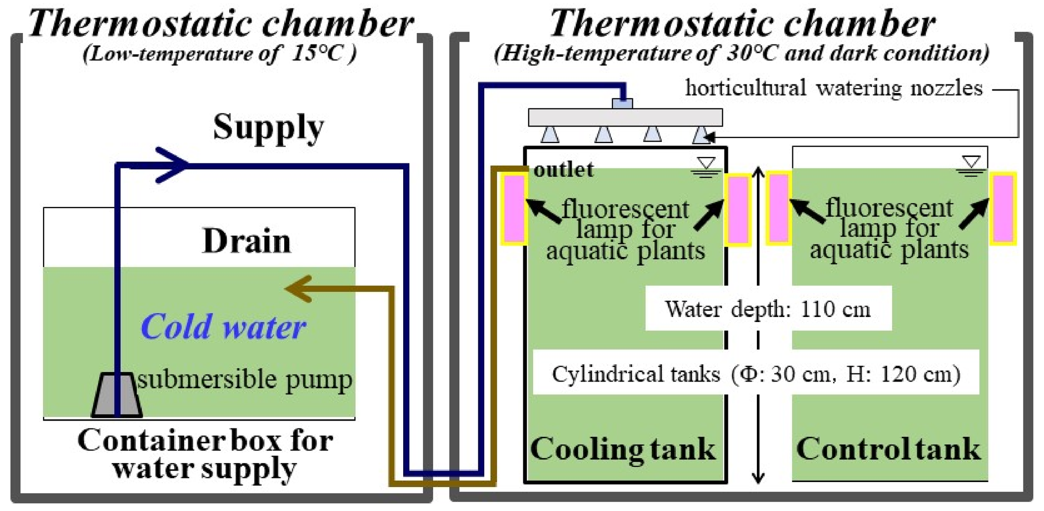
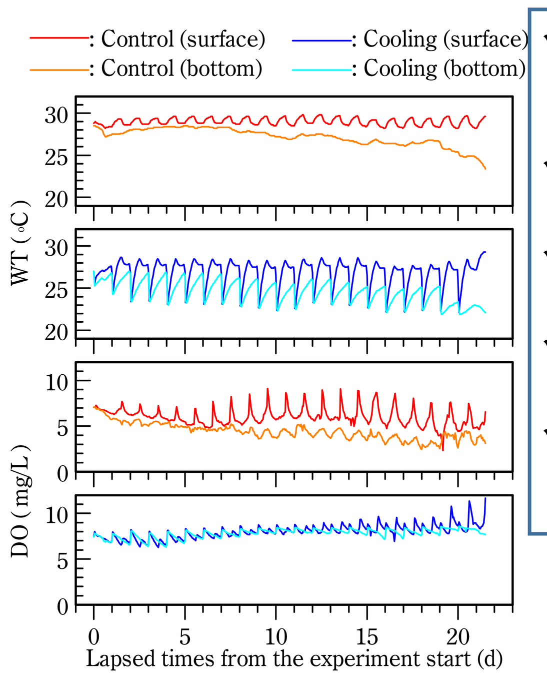
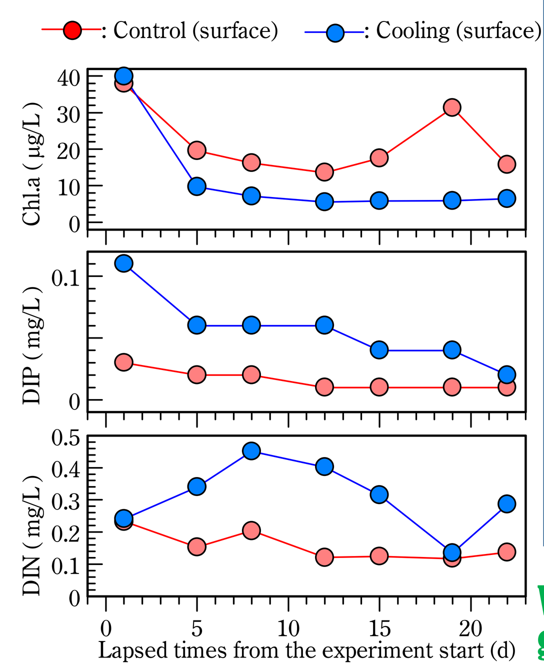


Fig. Schematic diagram of experimental apparatus for water surface cooling



- ✓ WT fluctuated with the 24-hour cycle as the surface water was heated by the fluorescent lamp regardless of supplying cold water.
- ✓ WT at the surface lowered due to injection of cold water, resulting in a cooling effect of 5 °C.
- ✓ WT at the bottom decreased to match the surface's WT after supplying cold water.
- ✓ Temporal change of DO at the bottom in the cooling tank corresponded to that at the surface.
- ✓ The bottom in the cooling tank received the hydraulic supply of DO from the surface layer through the cold-water-mass downwelling.

Water-surface cooling led to the avoidance of a poor oxygen level due to the vertical thermal mixing.



At the surface in the control tank

- ✓ Chl-a maintained a eutrophic state level, and such a high concentration linked to a significant variation in DO associated with the large stroke.
- ✓ The low concentrations of DIN and DIP indicate that active photosynthesis occurs in phytoplankton when there is no limitation on algal growth

At the surface in the cooling tank

- ✓ Chl-a temporally decreased in concentration while both DIP and DIN were kept at high concentrations.
- ✓ Photosynthesis of phytoplankton was negatively influenced by lowering water temperature.

Water-surface cooling led to the suppression of algal growth due to low limitation of WT for photosynthesis.

Fig. Results of continuous measurements of water temperature (WT) and DO, and the scheduled measurements of Chl-a, DIP (=PO_4-P) and DIN (= NO_3-N + NH_4-N) in the water quality experiment for water surface cooling.

NUMERICAL ESTIMATION OF WATER ENVIRONMENTAL DYNAMICS: Outline of One-dimensional Advection-diffusion Model

Numerical simulation of water-environment dynamics in a deep-water reservoir with a shallow surface area

The one-dimensional water-quality dynamics model represented by the vertical turbulent diffusion equations

The numerical analysis of water quality impacted by water surface cooling

It required the vertical one-dimensional advection-diffusion model, which considered the advective mass transport in the vertical direction due to cold-water mass downwelling

It is necessary to evaluate the current velocity of thermal convection stemming from the water surface cooling.

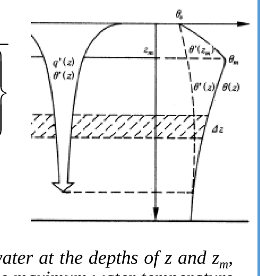
The estimation of sinking velocity for a cold-water mass

When acquiring the vertical profile of WT and its temporal change rate, the sinking velocity of the cold water $w(z)$ could be analyzed based on the heat conservation principle of the water column considering the convective and diffusive heat flux as following

$$w(z) = \alpha \cdot q'_z$$

$$q'_z = \sqrt{\frac{q'_m}{T_m - T'_m}\left\{(z - z_m)\frac{\partial \bar{T}(z)}{\partial t} + (T_m - T'_m)\cdot q'_m - \lambda\frac{\partial T}{\partial z}\right\}}$$

$$q'_m = \frac{q'_m}{T_m - T'_m}\left\{\lambda\left.\frac{\partial \theta}{\partial z}\right|_{z_b} - (z_b - z_m)\frac{\partial \bar{T}(z_b)}{\partial t}\right\}$$



where α is a constant value, q'_z and q'_m denote the sinking flux of the cold water at the depths of z and z_m, T_m is the water temperature at the depth of z_m, z_m is the water depth taking the maximum water temperature in the vertical profile, is the averaged water temperature in the depth range of [z_m, z], λ is a thermal transmission rate of water, and z_b is a water depth at the bottom.

◆ **Application of the operator splitting method for the solution of advection-diffusion equation of WT**

$$\frac{\partial T}{\partial t} + \frac{1}{A_z}\frac{\partial (A_z w T)}{\partial z} = \frac{1}{A_z}\frac{\partial}{\partial z}\left(A_z K_v \frac{\partial T}{\partial z}\right) - \frac{1}{\rho_w c_w}\frac{\partial q_z}{\partial z}$$

- ✓ The advection term and the diffusion term **were separated** in one time-step by **the operator splitting method**.
- ✓ **First, the approximate values of WT** were obtained **by solving the diffusion equation** where only the advection term was omitted with the Crank–Nicholson method.
- ✓ **Sinking velocities of the cold water** $w(z)$ were estimated using **vertical profile of WT** calculated as the first approximation
- ✓ **Second, approximate solutions of** $T(z)$ were **corrected** by **solving the advection equation.**

The numerical analysis of vertical profiles in water quality

- ➢ **State variables: Phytoplankton, POC, DOC, NH_4-N, NO_3-N, PO_4-P, DO**
- ➢ **Based on one dimensional vertical diffusion equation in which biochemical reactions are represented by the first order kinetics as ecosystem model**
- ➢ **Considering vertical advective transport due to cold-water mass downwelling**

$$\frac{\partial C_X}{\partial t} + \frac{\partial (w C_X)}{\partial z} = \frac{\partial}{\partial z}\left(K_v \frac{\partial C_X}{\partial z}\right) - \left(\frac{dC_X}{dt}\right)_{Bio}$$

Temporal change term | Advection term | Turbulent diffusion term | Biochemical reaction term

Term of phytoplankton growth by photosynthesis can be represented as the production of the maximum growth rate and phytoplankton concentration by multiplying the limitation functions of WT, underwater light intensity, and nutrients. The limitation functions range from 0 to 1, representing the positive influence against the maximum growth of phytoplankton.

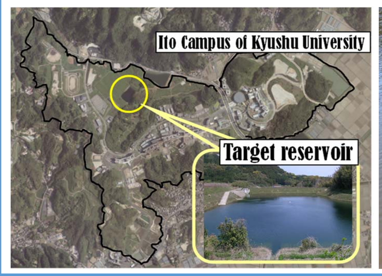
$$L_T = \left\{\frac{T}{T_{opt}}\exp\left(1 - \frac{T}{T_{opt}}\right)\right\}^a$$

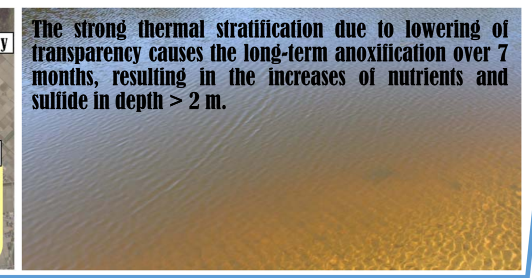
Limitation function of WT

T_{opt}: optimal water temperature of photosynthesis
$T<T_{opt}$: a=7 (strong inhibition by cold water)
$T>T_{opt}$: a=3 (weak inhibition at high temperature)

Validity of proposed one-dimensional water quality dynamics model

- ✓ The proposed model was applied to the numerical simulation of water quality dynamics in an actual water body where the vertical heat convection should occur due to the strong radiative cooling at the water surface in autumn.
- ✓ A regulating reservoir with a water surface area of ca. 19300 m² and pondage of ca. 63000 m³ on the Ito Campus of Kyushu University, Japan.
- ✓ The water level was maintained at a maximum water depth of ca. 8 m.
- ✓ Excessive levels of DOM from the humified wood chips have flowed into this reservoir, resulting in a dark reddish-brown colored water.
- ✓ **Model verification by reproducing the weekly observed data in 2016**





Scenario analysis concerning water quality improvement effect by artificial water surface cooling

➢ **Basic numerical conditions**

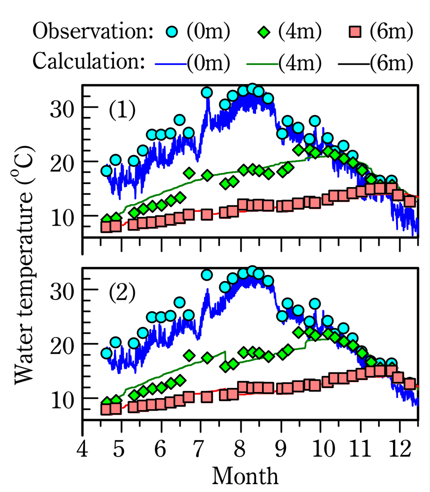
1. The water quality data and the meteorological data in 2016 were used as the initial and calculating conditions.
2. Cold water, which is at the same temperature as the water at the bottom, was supplied to 20% of the total water surface at an intensity of 50 mm/d from the outside of the reservoir.
3. It was supposed that the reservoir would be at its full water level of 8 m, and that the water volume corresponding to the supply quantity would flow out through the water surface.

➢ **Scenario conditions:**

Assuming that cold water is supplied for one hour in one run, the number of water sprinkling in one day was set to specific conditions.

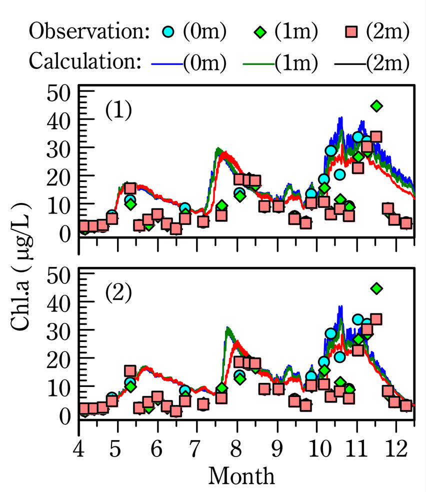
Case 1: zero time, non-supply
Case 2: 12 times, supply amount of 2070 m³/d
Case 3: 24 times, supply amount of 4140 m³/d

NUMERICAL ESTIMATION OF WATER ENVIRONMENTAL DYNAMICS: Validity of Proposed Advection-diffusion Model



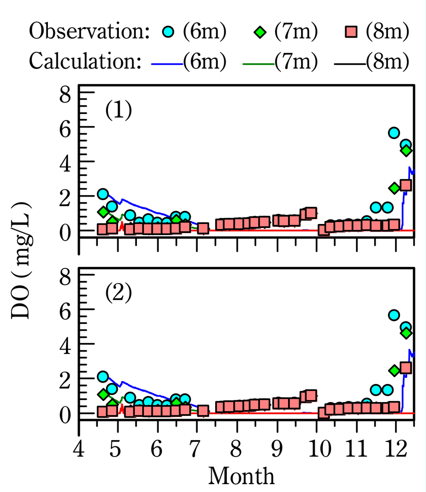
➲ In the proposed model, the short-cycle vibrations contained in calculations as well as the deviations between calculated and observed results at water surface since November were relatively small compared to the convention model.

➲ The proposed model could provide the well calculated results at depths of 4 m and 6 m in which the water quality seasonally changed while receiving the influence of the thermocline



➲ The two models differed in that the advection-diffusion model could reproduce the rapid decline in the observed vales of Chl-a during November, unlike the conventional diffusion model.

➲ The reproducibility by the advection-diffusion model was reflected by the modifications of limitation function of WT for the algal growth rate.



➲ Deviations between two results in the advection-diffusion model were smaller compared to the conventional diffusion model.

➲ The reproducibility of DO in the proposed advection-diffusion model was improved by considering the advection effect which the cold water mass downwelling would cause in a cool season.

Fig. Comparisons of observations of WT, Chl.a and DO with the calculated results by (1) the conventional diffusion model and (2) the proposed advection-diffusion model

NUMERICAL ESTIMATION OF WATER ENVIRONMENTAL DYNAMICS: Scenario Analyses

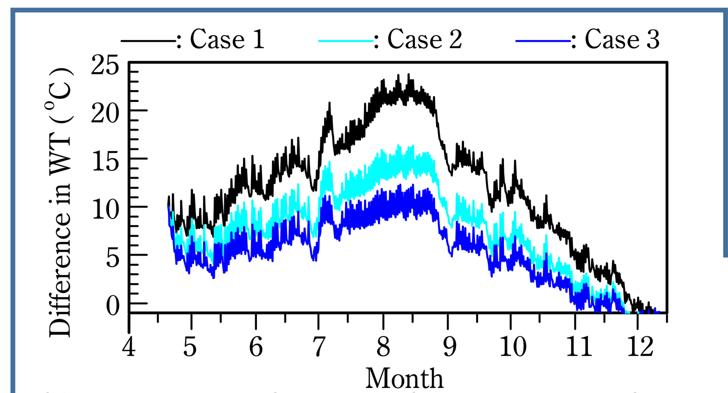


Fig. Results of scenario analyses for the difference in WT between the surface and bottom

Table Results of scenario analyses concerning the anoxic durations in the epilimnion

Case	5m	6m	7m	8m
1	52	129	156	242
2	0	36	105	224
3	0	0	0	212

- ✓ The maximum deviation of WT in Case 2 was about 23 °C, while those in Case 2 and Case 3 were respectively about 15 °C and 10 °C.
- ✓ The period over which the temperature difference was more than 10 °C exceeded 5 months in Case 1, but those in Case 2 and Case 3 were shortened to a few months.
- ✓ Anoxic duration at depths greater than 5 m was remarkably shortened in Case 2 and Case 3 as compared to Case 1
- ✓ The thermal convection stemming from the cold water supply promoted the vertical transport of oxygen from the upper layer.
- ✓ The anoxic state at the bottom in Case 3 recovered about 3 weeks earlier than in Case 1, resulting in inhibition of increase in nutrients and sulfide originating from anaerobic biochemical reactions in the bottom sediment.

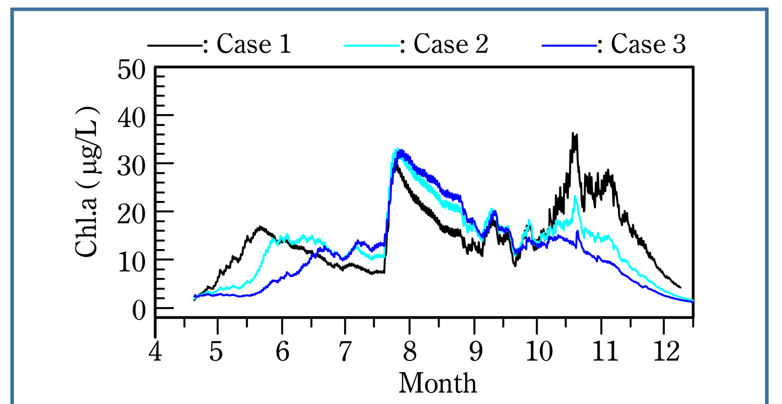


Fig. Results of scenario analyses for Chl.a concentrations at the water surface

The promotion of algal growth in Case 2 and Case 3 decreased during July and September. In particular, the peak concentration in the middle of October lowered as compared to the results in Case 1, and the proportion of Chl-a decreased rapidly in autumn.

CONCLUSIONS

This study proposed the ability of artificial water surface cooling to produce improvement in the aquatic environment of an organically polluted reservoir using two different methods.

1. It was experimentally found that the supply of cold water at the water surface could inhibit the increase of Chl-a concentration as well as poor oxygenation at the bottom depth. In particular, it was found that surface cooling suppressed algal growth by limiting photosynthesis at low water temperatures.
2. The effectiveness of the proposed technique was numerically estimated for the actual reservoir using scenario analyses. For the scenario analyses, we constructed a vertical one-dimensional water quality model to take into account vertical thermal convection mass transport stemming from water surface cooling, as verified by applying the numerical calculation to the actual water body. The results of scenario analyses showed that the cold-water supply could be linked to the suppression of both the algae over-growth in the hypolimnion and the long-term anoxification in the epilimnion.

In conclusion, the artificial water surface cooling would be an effective method for the conservation and restoration of the aquatic environment in organically polluted closed water bodies.