WATER ENVIRONMENT IMPROVEMENT IN AN ORGANICALLY POLLUTED CLOSED WATER BODY BY ARTIFICIAL WATER SURFACE COOLING

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ABSTRACT

This study focused on water-surface cooling and cool-water-mass downwelling processes to restore the aquatic environment in an organically polluted reservoir. This study was aimed at acquiring fundamental knowledge concerning the improvement of the aquatic environment using two experimental scenarios. First, we measured the impacts of cold-water supply on the physical and biochemical dynamics of water quality in the thermally stratified water column; algae growth was suppressed through limited photosynthesis induced by a low water temperature and poor oxygenation at the lowest depth with high nutrients. Second, the effectiveness of the proposed technique to improve the actual reservoir was estimated via scenario analyses using a vertical one-dimensional water-quality-dynamics model that considered thermal convection stemming from water-surface cooling, resulting in the suppression of both algae overgrowth in the hypolimnion as well as long-term anoxification of the epilimnion. The findings of this study indicate that artificial water-surface cooling for conservation and restoration in an organically polluted closed water body was effective.

Keywords: Recovery from anoxification, Suppression of algae over-growth, One-dimensional water quality model, Heat convection

1. INTRODUCTION

In an organically polluted water body, algae overgrowth in the hypolimnion and the anoxification of the epilimnion can lead to serious disruption of the aquatic habitat. The conservation and restoration of reservoirs polluted in such a manner require the development of techniques to not only recover from the anaerobic state but also suppress the abnormal proliferation of phytoplankton. Recently, deep-water reservoirs experiencing organic pollution and eutrophication have been treated using aquatic environmental measures that require large amounts of physical and energy-intensive mitigation techniques. However, such physical countermeasures are typically not cost effective owing to steep initial and on-going costs and a spatially limited improvement effect; they have problems concerning real-world application. 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. Two different possible impacts on water quality were measured by artificially cooling the water surface using cold-water injection below the thermocline. The first possibility studied is the early disappearance of anoxification due to increased vertical transport of dissolved oxygen (DO) from the surface layer along a cold-water-mass downwelling route, even in hot seasons. The early disappearance of anoxification should lead to both a reduction in the internal nitrogen and phosphorus load from the bottom mud and the restraint of sulfide generated under the strong reductive condition. The second possibility is concerned with controlling algal overgrowth by controlling the temperature required for photosynthesis in the epilimnion via water-surface cooling. The most significant effect expected when the water surface is cooled down is a suppression in cyanobacterial bloom; at high temperatures exceeding 25 °C, remarkable cell proliferation generally occurs due to active photosynthesis.

The purpose of this study was to acquire fundamental knowledge about how to improve aquatic environments from two experimental processes. One method was to measure the impacts of cold-water supply on the physical and biochemical dynamics of water quality in the thermally-stratified water column using indoor cylindrical water tanks. The other method numerically estimated water quality improvement based on a one-dimensional water quality dynamics model. In order to consider the mass transport of heat convection due to water surface cooling, the conventional diffusion model was modified with the advection-diffusion model by introducing both the estimation method of the sinking velocity of the cold water and by applying the operator-splitting method to the numerical solution of the partial differential equation. In addition, the water-quality-dynamics model was represented by an advection-diffusion model in the ecosystem model; the equation corresponding to the inhibition of phytoplankton growth with respect to water temperature was corrected to account for the ecological characteristics of algae such that cyanobacterial growth is strongly suppressed at low temperatures. The proposed advection-diffusion model was verified by applying it in the numerical simulation of water-quality dynamics, which are dependent on thermal convection from the radiative-cooling process at the water surface in a thermally stratified reservoir. Finally, we computationally analyzed the impacts of artificial water-surface cooling on water-quality dynamics in actual organically polluted reservoirs by scenario analysis and quantitatively estimated the effects of the improved water quality from two viewpoints, viz. long-term inhibition of anoxification in the epilimnion and suppression of algal overgrowth in the hypolimnion.

2. WATER QUALITY EXPERIMENT FOR ARTIFICIAL SURFACE COOLING

2.1 Outlines of water quality experiment

Laboratory experiments were conducted using water sampled at the surface of the reservoir where the organic pollution had been detected owing to an inflow of humic (Thach et al. 2017). First, the sampled water was stored at a depth of 110 cm inside two cylindrical tanks with a 30-cm diameter and 120-cm height in a thermostatic chamber, as illustrated in Figure 1. This chamber was controlled at a relatively high temperature of 30 °C without illumination. We irradiated the uppermost layer of the tanks from two sides using the fluorescent lamps for aquatic plant growth with approximately 70 μmol/(m² s) light quantum. By using direct lighting under the dark condition in the thermostatic chamber, the photic and aphotic zones for phytoplankton growth could be generated in the upper layer at a depth of approximately 20 cm and in the lower layer at a depth of approximately 90 cm in the tank.

The water-quality dynamics in the two water tanks, with the indoor environment maintained at 30 °C, were monitored for 22 days under the irradiation of fluorescent lamps with a 24-hour cycle (12 hours on and off each). The varied experimental conditions between the two tanks consisted of whether the water surface was only forcibly cooled by the cold-water supply. The first tank served as a control, and the cold-water supply was not varied. The water surface of the second tank was cooled by spraying cold water through four horticultural watering nozzles. Water-surface cooling was achieved by conveying 15 °C water through a container stored in a low-temperature room to the 30 °C room using a timer-controlled submersible pump, as shown in Figure 1. To clearly grasp the impact of surface cooling on water quality dynamics, cold water was applied with spray intensity equivalent to a rainfall intensity of 50 mm/d, and the cooled water supply was added for one hour after the start of fluorescent lighting. Water depth was maintained through the use of a drain outlet on the side wall and below the water surface, irrespective of the cold-water supply. The experimental system, which cyclically provides cold water to the cylindrical tank in the high-temperature thermostatic chamber, was set up by automatically returning the water overflow from the drain outlet to the container in the thermostatic chamber at low temperature. DO and water temperature near both the surface and the bottom of the two tanks were continuously measured at 20-min intervals by using a fluorescent DO meter. Additionally, scheduled measurements for surface-level chlorophyll-a (Chl-a), phosphate-phosphorus (PO_4-P), nitrate-nitrogen (NO_3-N), and ammonia-nitrogen (NH_4-N) were recorded twice per week over a period of 22 days.

2.2 Results and discussion

Figure 2 shows time series data of water temperature and DO continuously measured at the surface and bottom depths in each experimental condition. The results of the scheduled measurements for Chl-a, dissolved inorganic

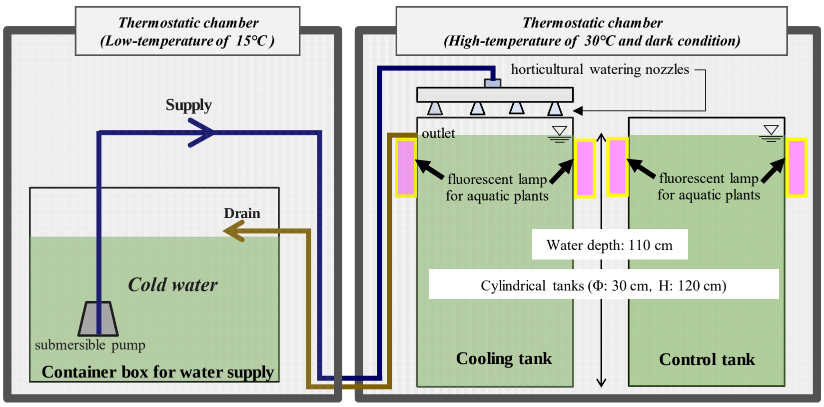

Figure 1. Schematic diagram of experimental apparatus for water surface cooling.

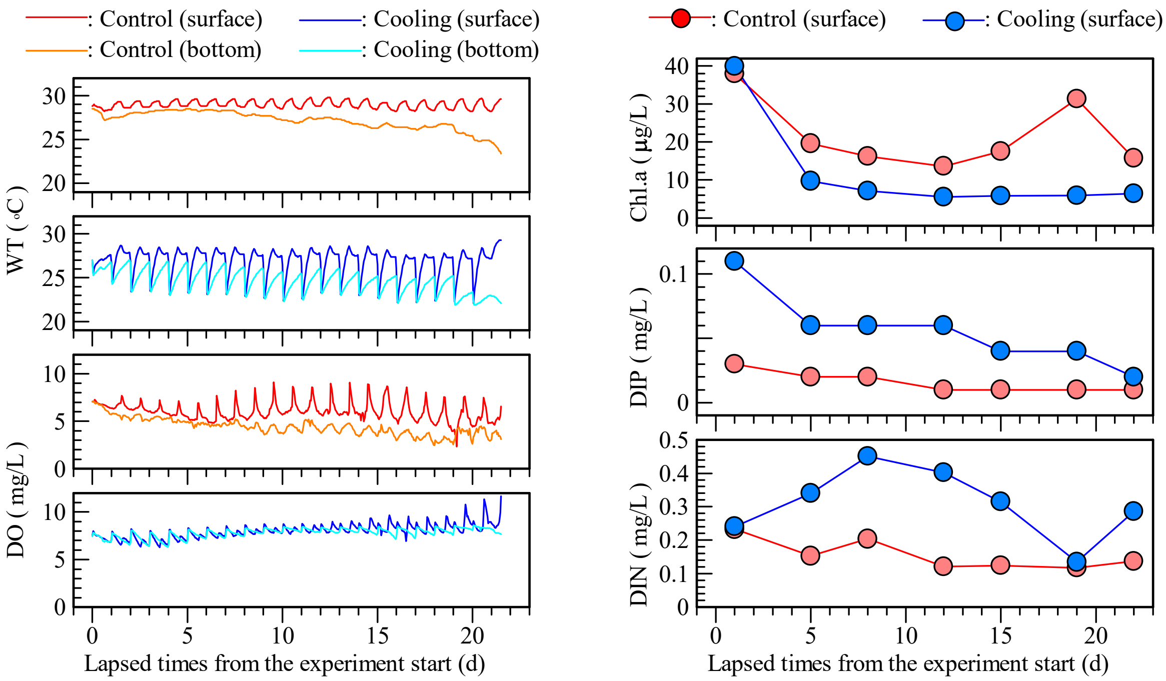

Figure 2. Results of continuous measurements of water temperature (WT) and DO, and the scheduled measurements of Chl-a, DIP (=PO_4-P) and DIN (= NO_3-N + NH_4-N) in the water quality experiment for water surface cooling.

phosphorous (DIP: PO_4-P), and dissolved inorganic nitrogen (DIN: sum of NO_3-N and NH_4-N) at the bottom are also shown. First, the basic characteristics of water quality dynamics without surface cooling were considered from the measurement results of the control condition. The water temperature at the surface fluctuated in conjunction with the 24-hour cycle as the water in the upper layer was heated by the fluorescent lamp and its temperature rose to above room temperature. Conversely, the water temperature at the bottom layer began to fall slowly after the eight day of the experiment without the variation of 24-hour cycle. Because we conducted our experiments 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. As a result, the thermal stratification occurred with a weak stability resulting in deviations between the surface and bottom of 2~4 °C in the control condition. DO measured at the surface varied with the 24-hour light cycle and an increase in concentration with lights on and a decrease with lights off, with the amplitude value increasing by about 4 mg/L. At the surface of the control tank, there was a significant variation in DO associated with the large stroke linked to high Chl-a concentration. This is manifested in terms of maintaining a eutrophic state level and the low concentrations of DIN and DIP. These results indicate that active photosynthesis occurs in phytoplankton when there is no limitation on algal growth. DO at the lowest measured bottom depths decreased to poorly oxygenated levels. Such a low concentration of DO would result from not only the aphotic state in the lower layer of cylindrical tank, but also from the thermal stratification that began on the eighth of the experiment. From these results, we could reproduce eutrophic phenomena, such as the presence of highly-concentrated Chl-a in the upper layer and poor oxygenation in the lower layer. These effects could be confirmed in closed water bodies with large depths, such as those in cylindrical tanks.

In the cooling tank, the water temperature at the surface lowered sharply when cold water was injected for one hour after the light exposure, resulting in a cooling effect of approximately 5 °C. As a result, the surface-water temperature exhibited periodic variations that differed from the fluctuations of the 24-hour cycle in the control tank. The deepest-water-temperature measurement decreased to match the surface measurement after supplying cold water, and it was confirmed that thermal convection led to a mixing between the upper and lower layers in the cylindrical tank. At the surface in the cooling tank, Chl-a temporally decreased in concentration while both DIP and DIN were kept at high concentrations, in comparison with the results of the control experiment. This result points to the inhibition of phytoplankton growth. In addition, the fluctuating DO levels at the water surface in the cooling tank were less than those observed in the control tank. This result confirmed that photosynthesis of phytoplankton was negatively influenced by lowering water temperature. DO in the bottom layer did not decrease significantly at poor oxygen levels but was maintained at the initial concentration, and the temporal change in DO at the bottom was similar to that at the surface. Therefore, the bottom layer received the hydraulic supply of DO from the surface layer through the cold-water-mass downwelling process. The above observations indicate that water-surface cooling can lead to not only the suppression of phytoplankton growth due to low water temperature limitation for photosynthesis but also the avoidance of a poor oxygen level in the lower layer because of the vertical mixing stemming from the thermal convection.

3. NUMERICAL ESTIMATION OF WATER ENVIRONMENTAL IMPROVEMENT EFFECTS BY WATER SURFACE COOLING

3.1 One-dimensional water quality dynamics model considering thermal convection by surface cooling

The one-dimensional water-quality dynamics model is one in which the constructive formula can be represented by the vertical turbulent diffusion equations used in the numerical simulation of water-environment dynamics in a deep-water reservoir with a shallow surface area. One of the governing equations in the water-quality-dynamics model is the diffusion equation concerning water temperature as follows (Thach et al., 2018a):

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

$$K_v=K_{v0}\left(1+\frac{10}{3}R_i\right)^{-3/2} \quad (2)$$

$$K_{v0}=\kappa u_{*s} z\cdot\exp(-k_* z),\ u_{*s}=\sqrt{(\rho_a/\rho_w)C_D}\cdot U \quad (3)$$

$$R_i=\frac{-1+\sqrt{1+40\zeta}}{20},\ \zeta=\frac{\kappa^2 z^2 N^2}{u_{*s}^{\ 2}\exp(-2k_* z)} \quad (4)$$

where, T and A_z denote respectively the water temperature and the horizontal section area at depth z, ρ_w is the water density, and c_w is the specific heat of water. The first term on the right side of Eq. (1) denotes the mass transport by vertical turbulent diffusion in which the driving force is the wind stress acting on water surface. Here, K_v is the vertical turbulent diffusion coefficient and can be generally represented by Eq. (2) in order to consider the restraint of vertical mass transport due to thermal stratification (Henderson-Sellers 1985). In this equation, K_{v0} given by Eq. (3) denotes the turbulent diffusion coefficient in neutral conditions with a uniform water density, and R_i defined as Eq. (4) represents the local Richardson number. Here, κ is the Karman constant, u_{*s} is the friction velocity above the water surface, k_* is the attenuation coefficient of u_{*s}, ρ_a is the density of air, C_D is the drag coefficient for the surface wind velocity U, and N is the Brunt-Vaisala frequency calculated from the gradient of water density. Using the observed wind data, values of C_D and k_* can be respectively estimated by Web-Deacon's equation and Nakamura's calculation formula (Nakamura and Hayakawa, 1991). The last term on the right side of Eq. (2) denotes the generation of water temperature by the transmitted beam of sunlight through water surface. Also, q_z is the underwater light intensity at depth z and can be generally expressed by $q_z=(1-\beta)\cdot Q_0\cdot\exp(-\eta z)$, in which Q_0 is the net solar radiation at the water surface (Dake and Harleman 1969). The one-dimensional vertical diffusion model has an advantage in that the calculation of current by the momentum equations is not required because the advection effect in the mass transport can be ignored as a negligible amount compared to the turbulent diffusion effect. However, the numerical analysis of water quality impacted by water surface cooling requires the vertical one-dimensional advection-diffusion model, which can consider the advective mass transport in the vertical direction due to cold-water mass downwelling. Therefore, the basic equation for the water quality model was modified as follows;

$$\frac{\partial T}{\partial t}+\frac{1}{A_z}\frac{\partial(A_z wT)}{\partial z}=\frac{1}{A_z}\frac{\partial}{\partial z}\left(A_z K_v\frac{\partial T}{\partial z}\right)-\frac{1}{\rho_w c_w}\frac{\partial q_z}{\partial z} \quad (5)$$

where w denotes the vertical current velocity and is a function of water depth. In order to solve the above equation, it is necessary to evaluate, in advance, the current velocity of thermal convection stemming from the water surface cooling.

This study focused on the estimation of sinking velocity for a cold-water mass with a vertical one-dimensional model (Kimura et al., 1993). The numerical analysis model for thermos-convection due to water surface cooling could be derived from the heat conservation principle of the water column considering both the convective and diffusive heat flux. When the vertical profile of water temperature and its temporal change would be acquired by the observation, the sinking velocity of the cold water $w(z)$ could be analyzed as follows;

$$\begin{aligned} &w(z)=\alpha\cdot q'_z\\ &q'_z=\sqrt{\frac{q'_m}{T_m-T'_m}\left\{(z-z_m)\frac{\partial\overline{T}(z)}{\partial t}+(T_m-T'_m)\cdot q'_m-\lambda\frac{\partial T}{\partial z}\right\}}\\ &q'_z=\frac{q'_m}{T_m-T'_m}\left\{\lambda\left.\frac{\partial\theta}{\partial z}\right|_{z_b}-(z_b-z_m)\frac{\partial\overline{T}(z_b)}{\partial t}\right\} \end{aligned} \quad (6)$$

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, $\overline{T}(z)$ 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. Also, T'_m represents the water temperature of the cold water as it sinks at the depth of z_m, and it can be regarded as the surface water temperature. From the premise of estimating the velocity of thermal convection, the water-temperature variables of $\partial T/\partial z$, $\overline{T}$, and $\partial\overline{T}/\partial t$ in Eq. (6) can be evaluated by continuously measuring the vertical water-temperature profile.

The operator splitting method was applied for the solution to Eq. (5). For this method, the advection term and the diffusion term in Eq. (5) would be separated in one time-step, and the numerical solution could be calculated in the two steps. In the first step, the approximate values were obtained by solving the diffusion equation where only the advection term was omitted from Eq. (5). The Crank–Nicholson method was applied to solve the diffusion equation with boundary conditions at the water surface. Values of $\partial T/\partial z$, $\overline{T}$, and $\partial\overline{T}/\partial t$ in Eq. (6) could be calculated by using the vertical water temperature profile, calculated as the first approximation, and could provide the estimation of $w(z)$ by Eq. (6). In the second step, the approximate values were corrected for $T(z)$ by solving the advection equation that was obtained by omitting all of the terms on the right-hand side of Eq. (5). Because the values of $w(z)$ in advection term are known from the first step, $T(z)$ could be calculated by solving the advection equation by the explicit method.

The ecosystem model could be incorporated as a sub-model into the water quality dynamics model, where the biochemical reaction among plankton and microorganisms would be mathematically formulated, to make a one-dimensional vertical turbulent diffusion equation. The ecosystem model generally includes nine state variables: phytoplankton, zooplankton, particulate non-living organic matter, dissolved organic matter, PO_4-P, NH_4-N, NO_3-N, and DO. Although the general one-dimensional ecosystem model would be based on the diffusion equation, this study required the consideration of the advective transport of water quality due to the cold-water mass downwelling with the change in water temperature. Therefore, the governing equation for the water quality dynamics model would be given as the vertical advection-diffusion equation, in which the vertical current velocity was already known in the calculation process of the water temperature profile, as follows;

$$\frac{\partial C_{\mathrm{X}}}{\partial t}+\frac{\partial\left(wC_{\mathrm{X}}\right)}{\partial z}=\frac{\partial}{\partial z}\left(K_v\frac{\partial C_{\mathrm{X}}}{\partial z}\right)-\left(\frac{dC_{\mathrm{X}}}{d\,t}\right)_{\mathrm{Bio}} \tag{7}$$

where, C_{X} is the concentration of a state variable X. The last term on the right side of Eq. (7) corresponds to the ecosystem model and denotes the biochemical change with time of state variables. Generally, the biochemical change with time in the state variable can be formulated using the first-order kinetics represented as $\left(dC_{\mathrm{X}}/dt\right)_{\mathrm{Bio}}=v\cdot C_{\mathrm{X}}$. Here, v is the first-order rate constant. For example, when defining the concentration of phytoplankton as C_{PP}, the growth of phytoplankton by photosynthesis can be represented as $L_{\mathrm{T}}\cdot L_{\mathrm{L}}\cdot L_{\mathrm{N}}\cdot v_{\mathrm{photo}}\cdot C_{\mathrm{PP}}$ where v_{photo} is the growth rate, and L_{T}, L_{L} and L_{N} denote the limitation function of water temperature, underwater light intensity, and nutrients, respectively. The limitation functions range from 0 to 1, representing the positive influence against the maximum growth of phytoplankton. For example, the smaller the value of L_{T}, the greater the inhibition of growth due to water temperature. The definition of the limitation function L_{T} was an especially important factor because this research focused on the suppression of phytoplankton overgrowth by water surface cooling. Generally, the function L_{T} can be expressed by the upward convex quadratic function such that the maximum value (=1) when the water temperature is optimal, as follows (Harada et al., 2013);

$$L_{\mathrm{T}}=\left\{\frac{T}{T_{\mathrm{opt}}}\exp\left(1-\frac{T}{T_{\mathrm{opt}}}\right)\right\}^{a} \tag{8}$$

where, T_{opt} is the optimal water temperature for the photosynthesis and a is a power index. Generally, $a = 3$ should be adopted (Harada et al., 2013). This study takes the above-described experimental results into account by using the lowering of the water temperature as a successful method for the suppression of phytoplankton growth. We correct the value of a based on the ecological characteristic of cyanobacteria, for which the favored environment would be the high-water temperature in the warm season. When the water temperature would be lower than optimal, $T < T_{\mathrm{opt}}$, the power index would be set to larger value of $a = 7$ because cold water may strongly inhibit the occurrence of photosynthesis. The power index would be set to $a = 3$ under the condition of $T > T_{\mathrm{opt}}$, because the inhibition of cyanobacteria growth at high temperature would be relatively small in the natural environment.

3.2 Validity of improved one-dimensional water quality dynamics model

To verify the validity of the proposed advection-diffusion model, it 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. The target water body was a regulating reservoir with a water surface area of ca. 19300 m^2 and pondage of ca. 63000 m^3 on the Ito Campus of Kyushu University, Japan. This reservoir, located in the deforestation area, was created for rainfall storage, and the water level was maintained at a maximum water depth of ca. 8 m. During rainfall, a large amount of water flows into the reservoir through two box culverts from the catchment area and the stored water is discharged simultaneously from the spillway. The area was mostly forestland before the campus was developed and logged wood chips were subsequently covered over by the developed land, including the area of the targeted reservoir. As a result, excessive levels of dissolved organic matter from the humified wood chips flowed into the pond through two box culverts during rainfall and high inflow of humic acid resulted in a dark reddish-brown colored water. The insufficient underwater light caused by dissolved organic matter led to thermal stratification from spring to autumn, resulting in the formation of the hypolimnion with the decline of DO levels. Anoxic water could occur in depths > 2 m by strong thermal stratification in summer, and the anoxification above the bottom bed could be maintained over six months (Harada et al., 2009; Harada et al., 2014). The thermal stratification would also cause seasonal increases in ammonium, phosphate, and sulfide levels in the hypolimnion and deposition of mud at the bottom (Nguyen et al., 2015; Thach et al., 2018b).

In the target reservoir, weekly field observations have been carried out at the center of the water body from April to December since 2009 with the aim of understanding seasonal changes to the vertical profiles of water quality parameters in relation to organic pollution and eutrophication. The observation period corresponded to the season when the water temperature had a non-uniform distribution in the vertical direction, and the anoxic water occurred above the bottom bed. In the field observations, the on-site measured water quality items such as DO and water temperature were recorded at 0.5 m intervals, from the water surface to just above the bottom sediment, using the multi-parameter water quality meter and the transparency was measured using a Secchi disk. In addition, water samples collected at 1 m intervals were analyzed for Chl-a, PO_4-P, NO_3-N, NH_4-N, total organic carbon, dissolved organic carbon, and so on. In this study, the weekly observed data in 2016 was used for model verification. The target reservoir in 2016 was the most organically polluted and eutrophic phenomena when assessed by the following measurements. First, the water above the bottom of the reservoir was in a long-term anoxic state over 8 months, resulting in an increase in concentrations of PO_4-P, NH_4-N and sulfide caused by anaerobic biochemical reactions. Also, the Chl-a in the surface layer notably increased to a high concentration of about 50 μg/L in autumn, and the cyanobacteria blooms spread across the entire water surface in middle of November. The seasonal changes in vertical profiles of water quality items in the observation period from April to December were simulated by using metrological data of air temperature, relative humidity, solar radiation, and wind velocity as calculation conditions, and this simulation was applied to both the newly proposed advection-diffusion model and the conventional diffusion model.

Figure 3 shows comparisons of the observed results (marks) and the calculated results (lines) by the advection-diffusion model (the upper graph) and the conventional diffusion model (the lower graph). The left side of the graph in Figure 3 denotes the comparison of results for the water temperature at 0 m, 2 m and 6 m. Both the advection-diffusion model and the conventional diffusion mode could satisfactorily simulate the temporal dynamic of water temperature in the period from April to middle October so as to reproduce the seasonal change. However, there was a difference in reproducibility during the middle of October between the models. The advection-diffusion model differed from the conventional diffusion model in that the calculated results of the water temperature at the surface did not contain the short-cycle vibration with a large amplitude, with the deviations from those observations being relatively small. The advection-diffusion model could also provide the 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 middle graph in Figure 3 shows the comparison of observations and calculations concerning Chl-a concentrations at the water depth of 0 m, 1 m and 2 m in the epilimnion. Both the advection-diffusion model and the conventional diffusion model could satisfactorily reproduce the peak values that occurred at the beginning of May, August, and November. However, the two models differed in that the advection-diffusion model could reproduce the rapid decline in the observed vales of Chl-a during November,

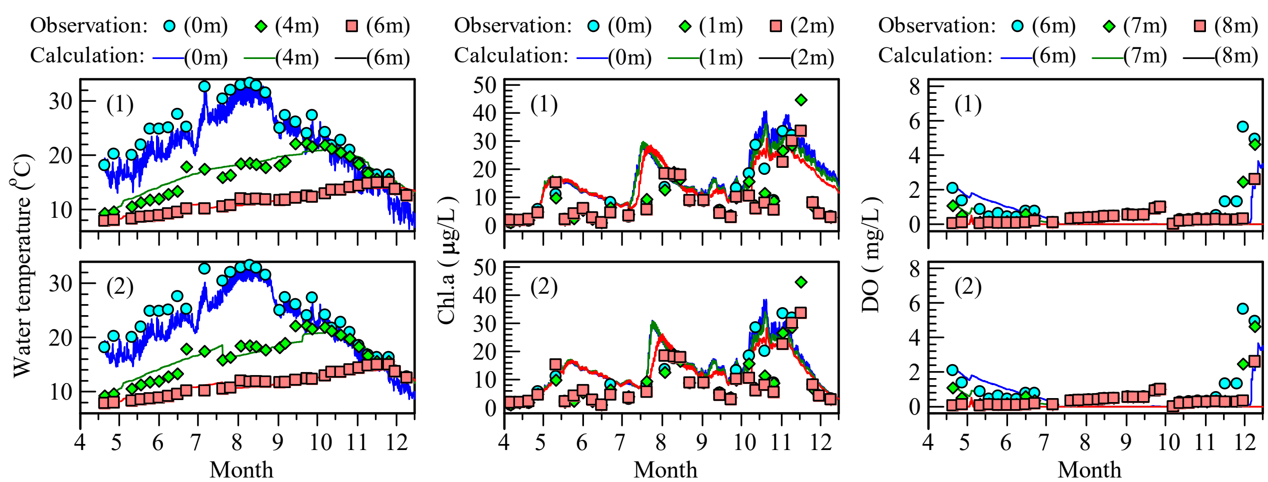

Figure 3. Comparison of the measurements for water temperature (WT), Chl-a, and DO, with the calculated results using the conventional diffusion model (1) and advection-diffusion model (2).

unlike the conventional diffusion model. This reproducibility by the advection-diffusion model would reflect the modifications of the limitation function of the water temperature concerning the phytoplankton growth rate. The right graph in Figure 3 shows the calculation results of two models and the observed DO data at 6 m, 7 m and 8 m in the hypolimnion. Between the observed results and the simulated results in both the advection-diffusion model and the conventional diffusion model, there were gaps concerning the point in time at which DO conditions recovered from the anoxic state due to the hydraulic supply of oxygen associated with the vertical heat convection. However, the deviations between the observations and the calculations in the advection-diffusion model were smaller compared to the conventional diffusion model, and it could be confirmed that the reproducibility of DO in this model was improved by considering the advection effect which the cold water mass downwelling would cause in a cool season.

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

To estimate the effect of water quality and environmental improvement by artificially cooling the water surface a closed water body, scenario analyzes were applied to the numerical simulation for water quality dynamics in the above-referenced reservoir. In this scenario analysis, the water quality data and the meteorological data in 2016 were used as the initial and calculating conditions similar to the reproduction calculation for verifying the advection-diffusion model. It was assumed that cold water, which is at the same temperature as the water at the bottom, will contribute to 20% of the total water surface at a water-sprinkling intensity of 50 mm/d from the outside of the reservoir. Also, 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. Therefore, the influences of the inflow and the outflow of water stemming from the cold water supply were considered in Eq. (2) as the boundary condition in the upper layer, including the water surface. 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. These conditions were divided into 3 cases; Case 1 (zero time, non-supply). Case 2 (12 times, supply amount: 2070 m^3/d), and Case 3 (24 times, supply amount: 4140 m^3/d).

Figure 4 shows the simulated results for Chl-a concentration at the water surface as well as the deviation of water temperature between the surface and the bottom. The maximum deviation of water temperature in Case 2 was about 23 °C, while those in Case 2 and Case 3 were respectively about 15 °C and 10 °C. Also, 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. Therefore, it was confirmed in Case 2 and Case 3 that long-term stable thermal stratification (such as that in Case 1) can be restrained by continuously supplying cold water. In the summer season (July to September), Chl-a in Case 2 and Case 3 increased to a concentration higher than in Case 1. This result implies that the reduction in water temperature at the surface in summer can be linked to the elimination of high-temperature inhibition, resulting in an increased proportion of Chl-a, as demonstrated in Case 2 and Case 3. However, 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. Table 1 shows the duration of the anoxic state in the hypolimnion and the date on which anoxification at the bottom recovered, as calculated from the simulated DO results. Since anoxic duration at depths greater than 5 m was remarkably shortened in Case 2 and Case 3 as

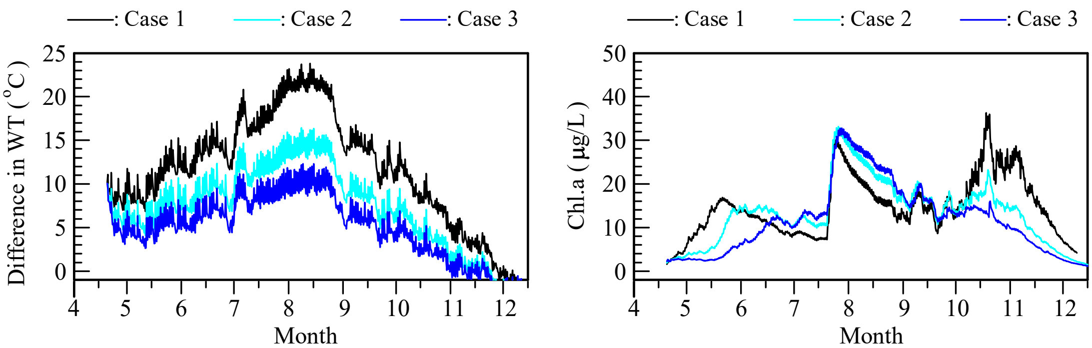

Figure 4. Results of scenario analyses concerning the difference in water temperature between the surface and bottom, and the Chl-a concentration at water surface.

Table 1. Results of scenario analyses concerning the anoxic durations in the epilimnion

Case	5 m	6 m	7 m	8 m	Date on which anoxification at the bottom recovered
1	52	129	156	242	December 21
2	0	36	105	224	December 5
3	0	0	0	212	November 29

compared to Case 1, it could be confirmed that the thermal convection stemming from the cold water supply should promote the vertical transport of oxygen from the upper layer. Particularly, the anoxic state at the bottom in Case 3 recovered about 3 weeks earlier than in Case 1. Such an early anoxic recovery limits the increase in nitrogen, phosphorous, and sulfide levels originating from anaerobic biochemical reactions in the bottom sediment and also leads to an early recovery of the bottom sediment from the reduced state.

4. CONCLUSIONS

This study investigated the ability of artificial water surface cooling to produce improvement in the aquatic environment of an organically polluted reservoir using two different methods. In the first method, we 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. Second, 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.

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