Effects of Bubbling Operations on Algal Bloom in Lake

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ABSTRACT : In order to develop a method of predicting and assessing lake eutrophication, which is a serious environmental problem, and to propose effective measures for improvement of water quality, this paper presents a composite model of the mixing of a lake by an air bubble plume and lake phytoplankton model. The equations of heat and mass transfer in the lake were solved together with equations governing physical and biological processes in the lake under real atmospheric conditions coupled with an integrated model of bubble plume. The verification of the model conducted using data of the Lake Calhoun (USA). Using the developed model, numerical experiments were carried out for an imaginary lake in Hiroshima region with different gas flow rate of bubble plume, different number of bubble ports and different starting date of bubble plume. The optimization of the improvement of water quality in the lake can be obtained by using appropriate gas flow rate and number of bubble ports.

Keywords : Eutrophication, Destratification, Bubble Plume, Phytoplankton

1 INTRODUCTION

Eutrophication of lakes is a serious problem for the water supply as well as for aquatic ecosystems. Common indicator of lake eutrophication is phytoplankton population density and species (Gulliver and Stefan, 1982), which, in appearance, is accompanied by symptoms of deterioration of water, being green, turbid and smelling. Eutrophication also causes the generation of toxic algae as well as deoxygenation of water, being harmful for other organisms and destroying ecological balance. Among various kinds of mitigation, the artificial circulation to create the surface mixing layer is the most commonly used over the world.

Although the artificial circulation has been widely enrolled as a method of controlling algal blooms in lakes and reservoirs, the response of the phytoplankton to destratification has been quite variable. Changes in total algal biomass is variable, with some authors reporting an increase and others a decrease. These variant results originate under the balance of different mechanisms.

Recent studies suggest that, among various kinds of devices proposed, a bubble diffuser or bubble plume has a relatively high efficiency in destratification of lakes and reservoirs, indicating a high energy conversion rate from an artificial input energy to the potential energy gain of the stratification. However, biologically favorable condition does not always agree with the energetically optimum condition. Bubbling from the middle or bottom of water establishes a plume which carries the bottom water to the surface. However, it also brings up the high concentration of nutrients of the bottom water. Thus, once it is wrongly operated, the results turn out to be worse. However, the relation between the bubbling operation and the phytoplankton production has not been discussed quantitatively. Thus, this study is aimed at constructing model implying the destratification process due to bubbling and the primary production, then establishing a criterion for the effective operation. Although algal bloom depends on pH also but in this study phytoplankton growth was assumed dependent only on temperature and light intensity.

2 ANALYSIS

The analysis consists mainly of two steps. In the first step the vertical distributions of physical, chemical and biological quantities were evaluated: the transport due to bubble plume was quantified for water and other physical, chemical and biological quantities under a certain environment of the lake, obtained by a dynamic lake model, DYRESM. Then, the biological processes are evaluated under the physical condition.

Although the complex structure was observed in the flow system of lakes, simple diffusion model was incorporated for the analysis of the vertical temperature distribution. While, bubbling system operated, flows from and to bubble plume was added.

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2.1 BUBBLE PLUME MODEL

In this study, the major function of bubble plume is assumed as the stratification controller, although various other functions are also expected. Therefore, the water transport between layers is the major concern in the modeling. However, a sufficient accuracy is required for obtaining the relation between bubbling rate and the biological production. For this purpose, an integral model is supposed to be suitable. In the model, the lake is considered to consist of two parts: the small plume zone and the much larger lake zone outside the plumes.

An integral model of bubble plume in the stratified environments was first developed by McDougall (1978) based on either a single plume model or an annular double plume model comprised of central bubble core and the surrounding rising liquid. The single plume model was applied successfully by Schladow (1992) to understand the energetics of the destratification. The double plume model was, on the other hand, modified by Asaeda and Imberger (1993), choosing the inner plume as a rising part and the outer plume as a surrounding downdraft. This modelling was successfully applied to the destratification process of a step-stratification (Asaeda, Ikeda, Imberger and Vu, 1994) .

Assuming a top-hat velocity and buoyancy profiles, a constant horizontal pressure surface and negligible turbulent transport leads to the integral equations for the inner core as follows,

$$\frac{d(r_1^2 v_1)}{dz} = 2 r_1 \alpha_\beta (v_1 - v_2) - 2 r_1 \alpha_\gamma v_2 \tag{1}$$

$$\frac{d(r_1^2 v_1^2)}{dz} = r_1^2 g_1' + 2 r_1 \alpha_\beta v_2 (v_1 - v_2) + 2 r_1 \alpha_\gamma v_1 v_2 \tag{2}$$

$$\frac{d(r_1^2 v_1 g_1')}{dz} = \frac{r_1^2 v_1 g}{\rho_r}\frac{d\rho_a}{dz} - 2 r_1 \alpha_\beta (v_1 - v_2) g_2' + 2 r_1 \alpha_\gamma v_2 g_{1l}' + \frac{d(r_1^2 g v_1 A_B)}{dz} \tag{3}$$

and for the outer plume,

$$\frac{d(r_2^2 - r_1^2) v_2}{dz} = -2 r_1 \alpha_\beta (v_1 - v_2) - 2 r_1 \alpha_\gamma v_2 - 2 r_2 \alpha v_2 \tag{4}$$

$$\frac{d(r_2^2 - r_1^2) v_2^2}{dz} = -(r_2^2 - r_1^2) g_2' - 2 r_1 \alpha_\beta v_2 (v_1 - v_2) - 2 r_1 \alpha_\gamma v_1 v_2 \tag{5}$$

$$\frac{d(r_2^2 - r_1^2) v_2 g_2'}{dz} = -\frac{(r_2^2 - r_1^2) v_2 g}{\rho_r}\frac{d\rho_a}{dz} - 2 r_1 \alpha_\beta (v_1 - v_2) g_2' + 2 r_1 \alpha_\gamma v_2 g_{1l}' \tag{6}$$

$$g_{1l}' = g_1' - \frac{Q_0 g H_A}{\pi r_a^2 (H_T - z)(v_1 + u_B)} \tag{7}$$

where, $g_1' = g(\rho_a - \rho_1)/\rho_l$, $g_2' = g(\rho_2 - \rho_a)/\rho_l$, z is vertical coordinate, v denotes the vertical velocity; r is the plume radius, subscripts 1 and 2 denote the inner and the outer plume variables. ρ_a is the density of the ambient water; ρ_l is the representative density; u_B is the bubble slip velocity, r_a is the ratio of bubble core radius to inner plume radius, A_B is the total fraction occupied by gas; α_β, α_γ, α are the entrainment coefficients for the outer to inner plumes, the inner to outer plumes, and the ambient to the outer plume respectively. Q_o is the gas flow rate at the free surface, H_A is the atmospheric pressure head, H_T is the total pressure head at the source (=H+H_A), H is the depth of water column. Following Asaeda and Imberger (1993), α_β=0.5, α_γ=1.0, α =0.083 are utilized. Equations (1) to (6) after nondimensionalizing were integrated iteratively using Runge-Kutta procedure. First, the inner plume equations are integrated up with the same starting conditions used by Asaeda and Imberger (1993) until the upward momentum of the plume vanishes.

For the first integration up the inner plume, the presence of the outer plume was ignored. When the plume does not reach the free surface, the inner plume stops rising there, which is the beginning of the outer downdraft. In the model, however, the inner plume spreads out because the upward momentum vanishes faster than the volume flux. Thus, the criteria, $v_1^2 r_1^2 \leq 0$, was used for the determination of the position to stop the integration.

Then the outer plume equations are integrated down to the neutral buoyancy level. During this downward integration, the values used for r_1, v_1 and g_1 at each level are those derived by the previous integration up the inner plume. An intrusion forms at the neutral buoyancy level. This process was repeated until it has converged; the criterion was less than 1% difference in the buoyancy of the inner plume from the previous value.

When the inner plume reaches the free surface, the water flows out radially along the surface, then suddenly plunges into the water body. This sudden plunging is explained as follows: As long as the water flows out with sufficient kinetic energy, the equivalent pressure loss of which balances with the gravity force of the heavier water. With decreasing speed, however, this balance breaks down, accounting for the submergence of the water. The initial quantities of the surface outflow is governed by,

$$r_1^2 v_{1I} = 2 r_I h_I v_{SI} \tag{8}$$

$$r_I^2 v_{1I} g'_{1LI} = 2 r_I h_I v_{SI} g'_{SI} \tag{9}$$

$$\frac{1-K_L}{2} v_{1I}^2 + g'_{1I}(H-h_I) = \frac{1}{2} v_{SI}^2 + g'_{SI}\left(H-h_I/2\right) \tag{10}$$

where K_L is the energy loss coefficient, subscripts I and s denote the values at the impingement region and of the surface jet respectively; r_I is the radius of the point where the horizontal jet starts, h_I is the initial thickness of the horizontal jet, v_{1I}, g_{1I}, g_{1LI} are the velocity, reduced gravity of the inner plume and the reduced gravity of the water at $H-h_I$, v_{SI} and g_{SI} are the velocity and the reduced gravity at the beginning of the horizontal jet. The plunging occurs when the condition, F_S= Const. is satisfied. Where $F_S = V_S / \sqrt{g_S h_S}$ and $h_S = \varepsilon r$, which is the thickness of the horizontal jet at r, is assumed to increase linearly with distance. ε equals to 0.19, is the increase rate of the thickness .

2.2 BIOLOGICAL MODEL

The growth rate of phytoplankton depends on many environmental factors such as nutrient concentration, light intensity, light period and temperature. Thus modelling of the growth of the phytoplankton requires the consideration of all environmental factors as much as possible.

$$\frac{\partial Chla_i}{\partial t} = G_{\max}\theta^{T-20} Chla_i \min\{f(I_i), f(IP_i), f(IN_i)\} - k_r\theta^{T-20} Chla_i - k_m\theta^{T-20} Chla_i - k_z Z\theta_z^{T-20} P \frac{Chla_i}{K_z + Chla_i} \tag{11}$$

Where, $Chla_i$ is concentration of chlorophyll-a in layer I, θ is a non-dimensional temperature multiplier for growth, respiration and mortality, T is the temperature in layer i, k_r, k_m and k_z are rate coefficients for respiration, mortality and zooplankton grazing, Z is the zooplankton biomass, P is a grazing preference factor for specific phytoplankton groups, θ_z is a non-dimensional temperature multiplier for zooplankton grazing and K_z is the half saturation constant for grazing, G_{max} is maximum growth rate of phytoplankton. Expressions of light and nutrients limitation functions are given by,

$$f(I_i) = \frac{I_i}{I_s}\exp\left[1-\frac{I_i}{I_s}\right], \quad f(IP_i) = \frac{IP_i - IP_{\min}}{IP_i}, \quad f(IN_i) = \frac{IN_i - IN_{\min}}{IN_i}, \quad I_i = \frac{I[1-\exp(-\eta\Delta h)]}{\eta\Delta h}.$$

Where, I_i is the light intensity at a layer, I_S is the saturation light intensity, IN is the internal nitrogen of phytoplankton cell, IP is the internal phosphorus of phytoplankton cell, IN_{min} is the minimum internal nitrogen, IP_{min} is the minimum internal phosphorus, Δh is the thickness of a layer, η is the light extinction coefficient. The conservation of biological and chemical processes on soluble reactive phosphorus, PO; ammonium, NH; and nitrate, NO are given by,

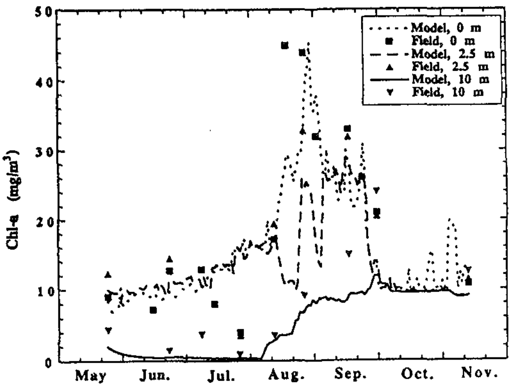
$$\frac{\partial PO_i}{\partial t} = k_r\theta^{T-20} IP_i + k_m\theta^{T-20}(IP_i - IP_{\min}) + k_{OP}\theta_O^{T-20} BOD.Y_{PBOD} + k_z Z\theta_z^{T-20} P\frac{Chla_i}{K_z + Chla_i}(IP_i - IP_{\min}) + S_P\theta_S^{T-20}\frac{AS_i}{V_i}\frac{DO_i + K_{DO}}{DO_i}$$
$$- Chla_i UP_{\max}\theta^{T-20}\frac{IP_{\max} - IP_i}{IP_{\max} - IP_{\min}}\frac{PO_i}{K_P + PO_i} \tag{12}$$

Where, k_{OP} is the coefficient for mineralization rate of organic phosphorus, S_p is the release rate of phosphorus from the sediment, BOD is the biochemical oxygen demand of water, Y_{PBOD} is the yield ratio of phosphorus to BOD due to organic decay, θ_o is the temperature multiplier for organic decay, DO is the dissolve oxygen in the water, UP_{max} is the maximum phosphorus uptake rate by phytoplankton, IP_{max} is the maximum internal phosphorus, K_p is the half saturation constant for external phosphorus uptake, K_{DO} is the adjustment factor for effect of oxygen on sediment nutrient release, θ_S is the non-dimensional temperature multiplier for sediment nutrient release, AS is the area of sediment in a layer, V is the volume of water in a layer.

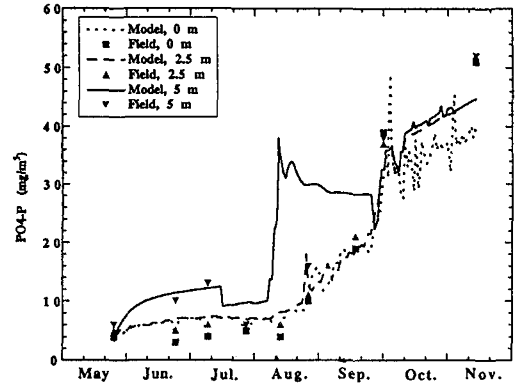
$$\frac{\partial NH_i}{\partial t} = k_r\theta^{T-20} IN_i + k_m\theta^{T-20}(IN_i - IN_{\min}) - k_{NO}\theta_{NO}^{T-20} NH_i\frac{DO_i}{K_{ON} + DO_i} + k_z Z\theta_z^{T-20} P\frac{Chla_i}{K_z + Chla_i}(IN_i - IN_{\min}) + k_{ON}\theta_O^{T-20} BOD.Y_{NBOD}$$
$$+ S_N\theta_S^{T-20}\frac{AS_i}{V_i}\frac{DO_i + K_{DO}}{DO_i} - Chla_i UN_{\max}\theta^{T-20}\frac{IN_{\max} - IN_i}{IN_{\max} - IN_{\min}}\frac{NH_i + NO_i}{K_N + NH_i + NO_i}P_{NH} \tag{13}$$

Where, k_{ON} is the coefficient for mineralization rate of organic nitrogen, Y_{NBOD} is the yield ratio of nitrogen to BOD due to organic decay, S_N is the release rate of ammonium from the sediment, UN_{max} is the maximum rate of nitrogen uptake by phytoplankton, k_{NO} is the rate coefficient for nitrification, K_N is the half saturation constant for nitrogen uptake, K_{ON} is the half saturation constant for effect of oxygen on nitrification.

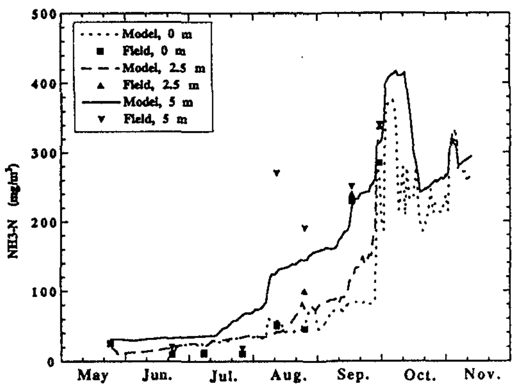
from hypolimnion layer broke through the metalimnion reaching the surface water layer. With large momentum impinging on to the water surface, it flows out radially then plunging at a certain distance entraining a lot amount of surface water and intrudes at a neutral level.



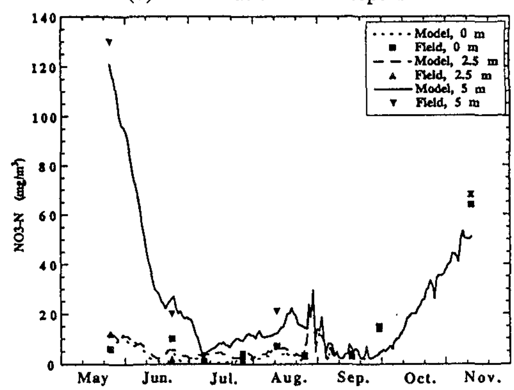
(a) Chl-a at different depths



(b) PO4-P at different depths



(c) NH3-N at different depths



(d) NO3-N at different depths

Fig.2 Comparison of Model Results with Field Data for Lake Calhoun

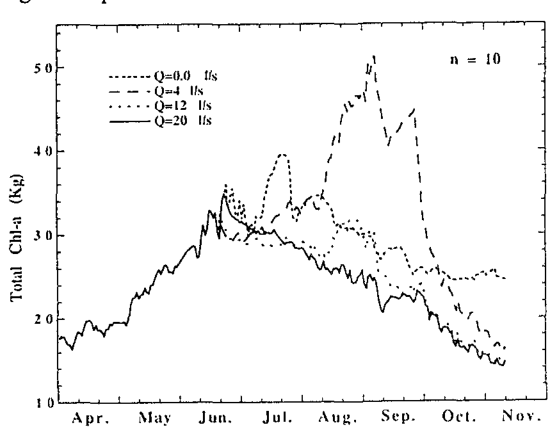


Fig.3 Effect of Gas Flow Rate (Q)

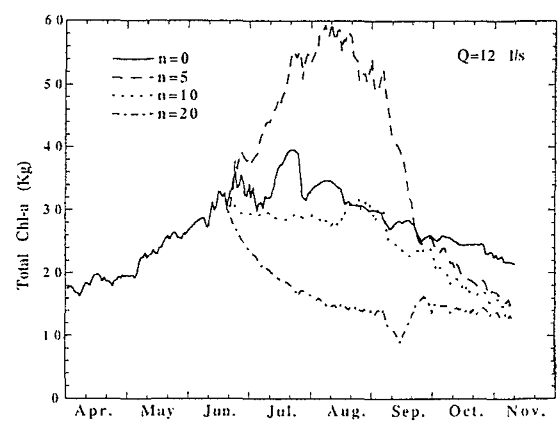


Fig.4 Effect of Number of Ports (n)

From Fig.4, when increasing the number of ports first phytoplankton population increases due to increasing the nutrient carried up, then decrease due to strong mixing by higher number of ports. The reason for this behavior is the nature of the entrainment process. Water is entrained in the wake of the bubbles rising in the fluid. If the number of bubbles is increased at high air flow rate, bubble wakes interfere with each other, especially in the core of the plume, and entrain relatively less per bubble, but with excessively increasing number of bubble ports, the buoyancy of each air release becomes too weak to form a coherent, rising water plume. Thus it is desirable to increase the number of bubble ports to obtain best results in a viewpoint of lake water quality management. Figs.3 and 4 confirms that, by selecting appropriate gas flow rate and number of bubble port, we can reduce the phytoplankton bloom in the lake significantly.

4.2 EFFECT OF STARTING TIME OF BUBBLING

The effects of starting time of bubbling are shown in Figs. 5 and 6. With gas flow rate (12 l/s), with three starting date of bubbling operation (May'30, June'19 and July'19) for different number of ports, the phytoplankton populations at the water surface were investigated. The results revealed that phytoplankton concentration with the later starting time of bubbling is higher for higher number of ports. The reason for this behaviour is as follows: with the later starting time of bubbling the nutrient concentration in the surface layer is higher due to nutrient inflow from rivers also due to higher phytoplankton concentration remains at the time of starting of bubbler. But for less number of ports by which phytoplankton population increases for bubbling, different starting dates results nearly same magnitude of bloom at different period.

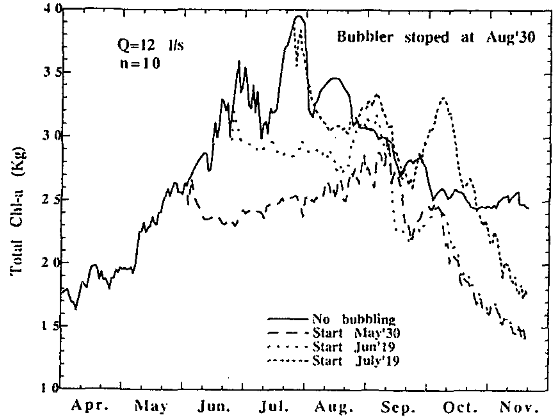


Fig.5 Effect of Starting Date of Bubbler(n=10)

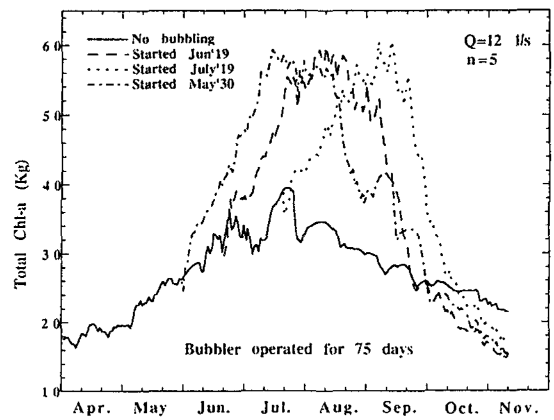


Fig.6 Effect of Starting Date of Bubbler(n=5)

5 CONCLUSION

Model can successfully simulate the biological quality of lake water including destratification process. Model predictions for imaginary lake with different conditions are reasonable. Model can be used to decide optimum number of ports, gas flow rate and starting date for a particular lake where bubbler will be used. Model can be used to predict effects of many other conditions.

6 REFERENCES

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