Modelling of Individual Species of Phytoplankton in a Lake under Artificial Destratification

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ABSTRACT: A numerical model has developed to simulate water quality and algal species composition in a lake. As artificial destratification is widely used in the lakes, a bubble plume model has incorporated with the ecological model to simulate the dynamic responses of individual species under artificial mixing. Ecological model predicts concentrations of phosphate-phosphorus, ammonia nitrogen, nitrate nitrogen, dissolved oxygen and pH, which may have significant effect on the growth of certain species. Model was validated using data of U Lake (Japan).

Keywords : Eutrophication, Phytoplankton, Artificial destratification, Bubble plume

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 speciation (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 mitigations, the artificial circulation to create the surface mixing layer is the most commonly used over the world.

Although the artificial circulation has been widely used as a method of controlling algal blooms in lakes and reservoirs, the response of the phytoplankton to destratification has been quite variable. A number of observations have been reported; a shift predominant cyanobacteria algae to green species are often resulted, however, in some cases cyanobacteria species have increased following circulation attempts (Knoppert et al, 1970). With the formation of the mixed layer decreasing surface temperature reduces the phytoplankton activities, while the lowering pH provides the preferable condition for Green Algae rather than Cyanobacteria. At the same time, however, the high concentration of nutrients is lifted into the euphotic layer, where, otherwise, nutrients are gradually depleted.

As for Diatom, loss due to gravity settlement ceases during artificial mixing it often shows rapid rate of growth during mixing. Some water quality studies reported that artificial mixing may effect a change in the phytoplankton species composition, favouring non-motile species (Forsberg and Shapiro, 1981; Reynolds et al., 1984; Cowell et al., 1987). Considering total chlorophyll-a as the phytoplankton concentration some models were developed, validated and used for predictions (Gulliver and Stefan, 1982; Hamilton and Schladow, 1994; Imteaz and Asaeda, 1996). But as blooming season for different species is different and responses of different species to artificial mixing is not similar, it is necessary to develop, validate and use of model which considers different species of phytoplankton rather than total chlorophyll-a.

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. While, bubbling system operated, flows from and to bubble plume was added. DYRESM considers several layers along the depth fixed in a day but changing day by day.

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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 modelling. 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 model was successfully coupled with a lake hydrodynamic model, DYRESM and with an ecological model. Coupled model was calibrated and simulated for real lake conditions by Imteaz and Asaeda (1996). Bubble plume model divides each layer of physical model into ten sublayers as spatial spacing of numerical computation.

2.2 BIOLOGICAL MODEL

The growth rate of phytoplankton depends on many environmental factors such as nutrient concentration, pH, 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. Usually phytoplankton biomass is represented as the concentration of chlorophyll-a (Chla). The maximum potential growth rate is multiplied by the minimum value of expressions for limitation by light, internal phosphorus, internal nitrogen, silica (when diatoms are modelled explicitly) and pH. The conservation equation for chlorophyll-a is given by,

$$\frac{\partial Chla_i}{\partial t} = G_{max}\theta^{T-20}Chla_i \, min\{f(I_i), f(IP_i), f(IN_i), f(Si_i), f(pH_i)\}$$

$$-k_r\theta^{T-20}Chla_i - k_m\theta^{T-20}Chla_i - k_z Z\theta_z^{T-20}Pf\frac{Chla_i}{K_z + Chla_i} \qquad (1)$$

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 the rate coefficients for respiration, mortality and zooplankton grazing, Z is the zooplankton biomass, Pf 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 the maximum growth rate of phytoplankton, $f(I_i)$ is the light limitation factor, $f(IP_i)$ is the limitation factor for internal phosphorus, $f(IN_i)$ is the limitation factor for internal nitrogen, $f(Si_i)$ is the limitation factor for silica and $f(pH_i)$ is the limitation factor for pH. Expressions of light, nutrients and pH limitation functions are given by,

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

$$f(Si_i) = \frac{Si_i}{K_{Si}+Si_i}, \quad f(pH_i) = exp\left[-\frac{(pH-7)^2}{K_{pH}-(pH-7)*5}\right]$$

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, K_{Si} is the half saturation constant for silica uptake, K_{pH} is the factor regulating phytoplankton growth for higher pH. For pH lower than 7, $f(pH_i)$ is assumed to be unity as it is assumed that pH affects phytoplankton growth only at higher(>7) pH value. Characteristics of pH limitation factor has shown in Figure 1.

The conservation of biological and chemical processes on soluble reactive phosphorus, P; ammonium, NH; and nitrate, NO are given by,

$$\frac{\partial P_i}{\partial t} = k_r \theta^{T-20} IP_i + k_m \theta^{T-20}(IP_i - IP_{min}) + k_{OP}\theta_O^{T-20} BOD.Y_{PBOD} + S_P \theta_S^{T-20}\frac{AS_i}{V_i}\frac{K_{DO}}{K_{DO}+DO_i}$$

$$+ k_z Z \theta_z^{T-20} Pf \frac{Chla_i}{K_z + Chla_i}(IP_i - IP_{min}) - Chla_i UP_{max}\theta^{T-20}\frac{IP_{max}-IP_i}{IP_{max}-IP_{min}}\frac{P_i}{K_P + P_i} \qquad (2)$$

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.

$$\frac{\partial NH_i}{\partial t} = k_r \theta^{T-20} IN_i + k_m \theta^{T-20}(IN_i - IN_{min}) - k_{NO}\theta_{NO}^{T-20} NH_i \frac{DO_i}{K_{ON}+DO_i}$$

$$+ k_z Z \theta_z^{T-20} Pf \frac{Chla_i}{K_z + Chla_i}(IN_i - IN_{min}) + k_{ON}\theta_O^{T-20} BOD.Y_{NBOD}$$

$$+ S_N \theta_S^{T-20}\frac{AS_i}{V_i}\frac{K_{DO}}{K_{DO}+DO_i} - Chla_i UN_{max}\theta^{T-20}\frac{IN_{max}-IN_i}{IN_{max}-IN_{min}}\frac{NH_i+NO_i}{K_N + NH_i + NO_i}P_{NH} \qquad (3)$$

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.

$$\frac{\partial NO_i}{\partial t} = -Chla_i UN_{max}\theta^{T-20}\frac{IN_{max}-IN_i}{IN_{max}-IN_{min}}\frac{NH_i+NO_i}{K_N + NH_i + NO_i}(1-P_{NH}) + k_{NO}\theta_{NO}^{T-20} NH_i \frac{DO_i}{K_{ON}+DO_i} \qquad (4)$$

The term for preferential ammonium uptake, P_{NH}, is given by

$$P_{NH} = 1 - NO/(NO+NH)$$

Equation for dissolved oxygen (DO) is given by,

$$\frac{\partial DO}{\partial t} = \frac{W_g(C^*-DO_S)}{h} + G_{max}\theta^{T-20}Chla_i \min\{f(I_i),f(IP_i),f(IN_i),f(Si_i)\}Y_{OC} + k_m\theta^{T-20}Chla_i Y_{OC}$$

$$+ Chla_i UN_{max}\theta^{T-20}\frac{IN_{max}-IN_i}{IN_{max}-IN_{min}}\frac{NH_i+NO_i}{K_N + NH_i + NO_i}(1-P_{NH})Y_{NP} - k_r\theta^{T-20}Chla_i Y_{OC}$$

$$- k_{NO}\theta_{NO}^{T-20}NH_i\frac{DO_i}{K_{ON}+DO_i}Y_{ON}NH_i - k_B\theta_O^{T-20}\frac{DO_i}{K_{BOD}+DO_i}BOD_i \qquad (5)$$

Where, $C^* = 14.652 - 0.41022*T_S + 7.99E\text{-}3 * T_S^2 - 7.7774E\text{-}5 * T_S^3$, is the saturated oxygen concentration at the surface at temperature T_S, DO_S is the oxygen concentration at the surface, h is the depth of surface layer, W_g is the transfer velocity of oxygen at surface, Y_{OC} is the ratio of mass of oxygen produce to mass of Chl-a, Y_{NP} is the stoichiometric ratio of oxygen to nitrogen for nitrate reduction, Y_{ON} is the stoichiometric ratio of oxygen to nitrogen for nitrification, k_B is the rate coefficient for detrital breakdown, K_{BOD} is the half saturation constant for dependence of detrital decay on DO.

2.3 CALCULATION OF pH

Besides acidity the pH (hydrogen-ion concentration) also controls the chemical state of many lake nutrients, including carbon dioxide. Effects of pH on other important nutrients such as phosphate, ammonia are yet to find out. But there is established relationship between the various components of carbon and pH. Carbon dioxide gas dissolves in water to form soluble carbon dioxide. This reacts with water to produce undissociated carbonic acid (H_2CO_3), which dissociates and equilibrates as bicarbonate (HCO_3^-) and carbonate (CO_3^{-2}) according to the equation,

$$CO_2 \leftrightarrow CO_2 + H_2O \leftrightarrow H_2CO_3 \leftrightarrow HCO_3^- + H^+ \leftrightarrow CO_3^{-2} + 2 H^+$$
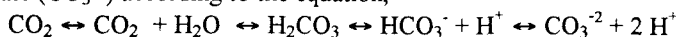
This series of reversible chemical changes is the most important of the several reactions that control pH in natural waters. As CO_2 is used up in photosynthesis or dissolves in from the air, the pH should change, since carbonic acid is either removed or added. However the pH shift is reduced or buffered by the huge amount of carbonate and bicarbonate present in the water body. The inorganic carbon equilibrium is the major pH buffering system for lakes. Horne and Goldman(1994) has shown the changes in three forms of inorganic carbon in a lake with changes in pH.

For pH calculation it was necessary to calculate alkalinity as pH, alkalinity and carbon is interrelated by, alkalinity = $[HCO_3^-] + 2[CO_3^{-2}] + [OH^-] - [H^+]$

As bicarbonate and carbonate can be related with total carbon, once total inorganic carbon and alkalinity have been determined, the hydrogen ion concentration can be calculated from the above relationship. But as we don't have measured data for both carbon and alkalinity an indirect method has used to calculate pH of the water body. By this method pH was calculated without calculating total inorganic carbon, rather it was calculated by the ratio of different forms of carbon. According to Harvey (1960) stoichiometric concentrations of carbonic acid (H_2CO_3), bicarbonate (HCO_3^-) and carbonate (CO_3^{-2}) are given as follows

$$x = [H_2CO_3] = \frac{ah^2}{k_1(h + 2k_2)} \tag{6}$$

$$y = [HCO_3^-] = \frac{ah}{(h + 2k_2)} \tag{7}$$

$$z = [CO_3^{-2}] = \frac{ak_2}{(h + 2k_2)} \tag{8}$$

where, a is the carbonate alkalinity of the water, h is the pH of the water, k_1 is the first apparent dissociation constant of carbonic acid, k_2 is the second apparent dissociation constant of carbonic acid. k_1 and k_2 are dependent only on the water temperature and given by,

$$k_1 = 10^{[14.8435 - 0.032786.T_K - 3404.71/T_K]}, k_2 = 10^{[6.498 - 0.02379.T_K - 2902.39/T_K]}$$

where T_K is the water temperature in Kelvin. From equations (6), (7) and (8) the ratio of carbonic acid to bicarbonate (x/y) can be expressed by h/k_1 and the ratio of bicarbonate to carbonate (y/z) can be expressed by h/k_2 which are independent of alkalinity. From the above ratio and the relationship between pH and above ratios given by Horne and Goldman (1994), pH was calculated by iteration.

2.4 SEDIMENTATION OF PHYTOPLANKTON

Loss due to sedimentation of phytoplankton cells from the euphotic zone is considered. Although it may not be significant all the time but because different species has different sedimentation rate it is preferable to consider sedimentation loss. For the calculation of sedimentation using Stokes law size, density and shape of individual species were considered. Stokes formulation for sinking rate is given as

$$S = \frac{2}{9}gr^2\frac{\Delta\rho}{\mu} \tag{9}$$

where r is the radius of individual cell which is defined by radius of a sphere of equivalent volume, $\Delta\rho$ is the excess density which is defined by the difference between the densities of the water and the sinking particle, μ is the dynamic viscosity of the water. The rate found by above equation was divided by a shape factor, as deviation from spherical geometry tends to increase structural viscosity and reduce sinking rate. Values of $\Delta\rho$, r and shape factor for different species are given by Scavia (1980).

From calculated sinking rate amount of sedimentation from a layer was calculated, deducted from the corresponding layer and subsequently added to the lower layer.

3. CALIBRATION AND COMPARISON WITH FILED DATA

At every 15 minutes, the set of equations describing mainly vertical transportation processes, settling, diffusion, mixing, and all transport due to bubbling is solved under the input of daily meteorological and

hydrological conditions. The simultaneous equations of biological processes are then calculated for the daily average conditions of temperature and nutrients distributions.
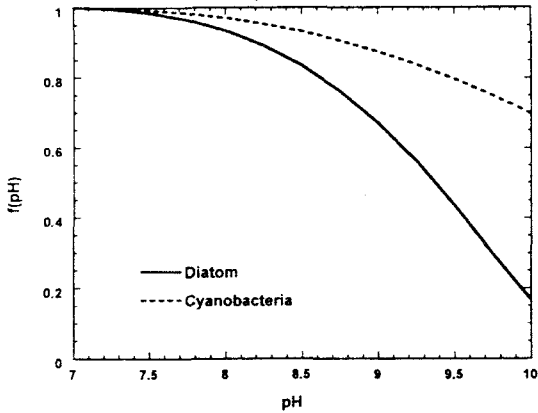
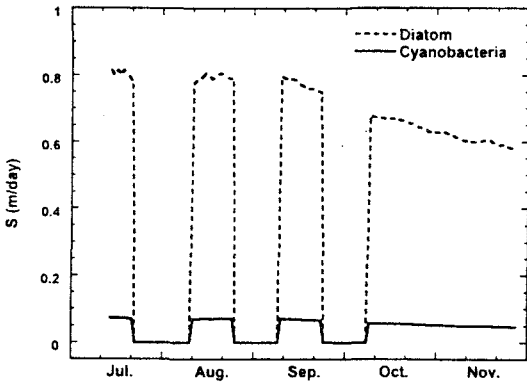Figure 1 Characteristics of pH limitation factor
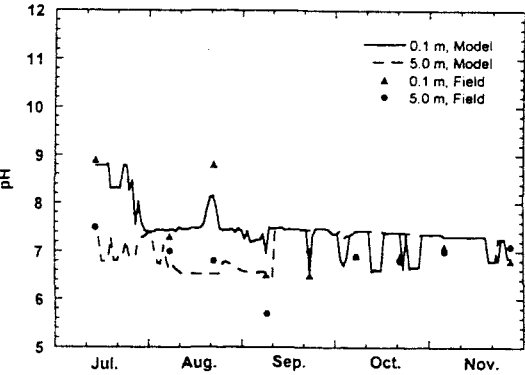
Figure 2 Sinking rate in the top layer
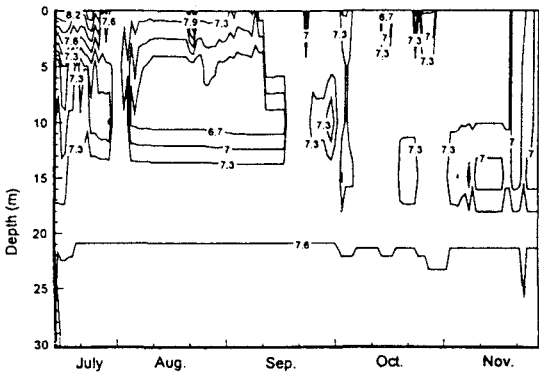
Figure 3 Comparison of model results for pH

Figure 4 Contour of pH produced by the model

Model was validated for U Lake (Japan) from July to November. In this lake the bubbler was operated intermittently from July'20 to Aug.'7, Aug.'22 to Sep.'5 and Sep.'20 to Oct.'4. Physical part of the model is free from calibration but for the biological part calibration is necessary. Appropriate values of biological parameters were chosen within specified range found in literature's to fit the field data. Among the various species of phytoplankton, in this lake only Cyanobacteria (Anabaena) and Diatom were dominating. Figure 2 shows the sinking rate for both the species in the top layer during computaion period. Figure 3 shows comparison of model results with field data for pH. Figure 4 shows the contour of pH for different depths and time of the year produced by the model. Figure 5 and 6 show the comparison with the field data for PO4-P and NH3-N respectively. The comparison with field data for Cyanobacteria and Diatom are shown in Figure 7 and 8 respectively.

4. CONCLUSION

Agreement of model results with the field data for different depths is good. Model can successfully simulate the individual species of phytoplankton, nutrients, pH as well as the effects of artificial destratification in the lake. During July pH was high. Since at high pH range(<10) proportion of HCO_3^- in the water is much higher than other form of carbon (carbonate and carbonic acid) which is utilised only by cyanobacteria, cyanobacteria became dominant in this period. However, with destratification pH decreased, then diatom increased, which caused to reduce cyanobacteria community in competition. Again during artificial mixing loss due to sedimentation of phytoplankton cell ceases. As diatom has higher cell volume loss due to sedimentation is significant for diatom. Cessation of this significant loss is another reason for increasing diatom during artificial mixing.
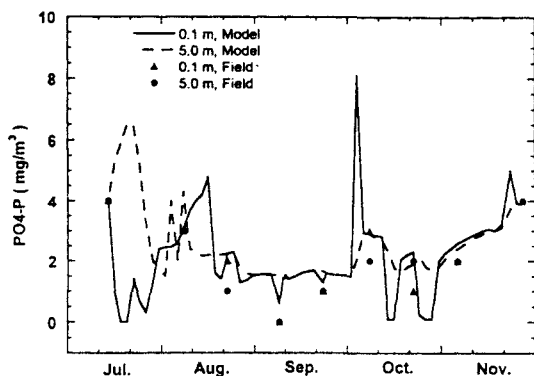
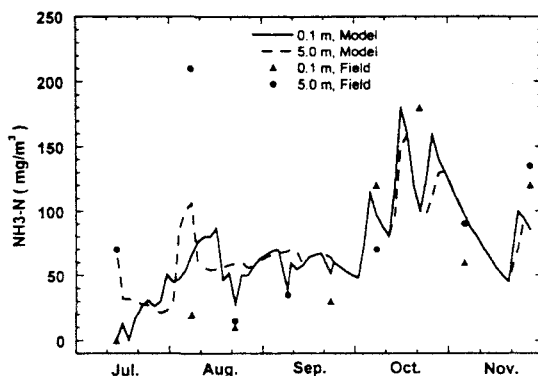Figure 5 Comparison of model results for PO4-P
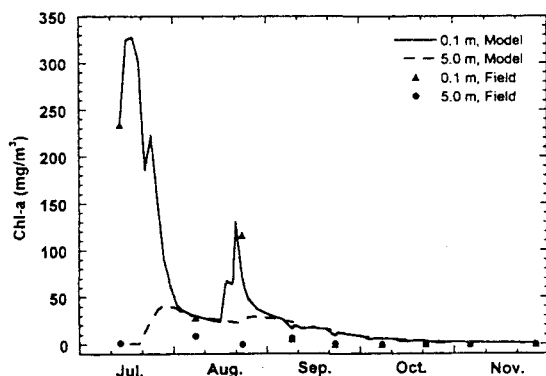
Figure 6 Comparison of model results for NH3-N
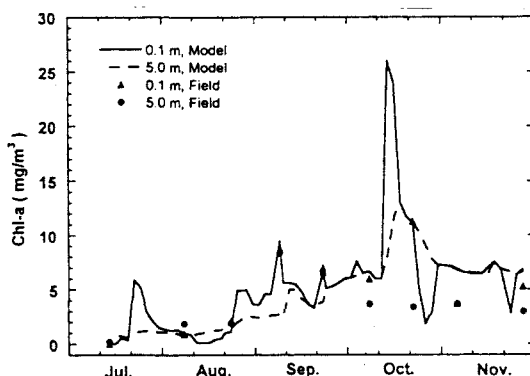
Figure 7 Comparison of model results for Cyanobacteria

Figure 8 Comparison of model results for Diatom

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