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Application of a Two Dimensional Model to Predict the Effects of the Curtain Method on Algal Blooming in Reservoirs

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As one of the ways of reducing algal blooming in T-Dam reservoir, two vertical curtains, having depths to cover the epilimnion thickness, are installed across the reservoir in order to curtail the nutrient supply from nutrient-rich inflow to the downstream epilimnion of the reservoir. The physical and biological process in the reservoir ecosystem have been modelled, by assuming stratified layered and parcels structure, to predict the water quality and algal species composition in the reservoir. The state variables, temperature, four types of phytoplankton as chlorophyll-*a*, soluble phosphorus, nitrate, ammonium, dissolved oxygen, biochemical oxygen demand, internal nitrogen, internal phosphorus, and when diatoms are modelled explicitly silica, are considered in the model.

Keywords: Curtain; Entrainment; Epilimnion; Eutrophication; Reservoir; Riverine

1. Introduction

This research work is concerned with a simulation study of the new eutrophication control technique called curtain method introduced to T-Dam Reservoir, one of the largest reservoirs in Kyushu, Japan (Asaeda et al., 1996). T-Dam Reservoir has shown a serious deterioration of water quality caused by cultural eutrophication especially during summer.

T-Dam reservoir is located in the northern part of Kyushu, the west island of the Japanese archipelago, 33^0 25' N in latitude, and 130^0 43' E in longitude. The reservoir is 2.5 km long, 400 m wide, 900 ha of total water surface area, and 35 m of maximum depth. The total volume of the reservoir is 18 million m^3. Three rivers enter the reservoir. The main river called Sata River, enters the upstream end of the reservoir, whereas Teishakuji River and Small River enter the middle of the reservoir (Fig. 1). Small River has the highest concentration of nutrients but its discharge is small compared with the other two rivers. Phosphate phosphorus concentration in Sata River and Teishakuji River is around 0.1 mg l^{-1} whereas in Small River it amounts to 0.2 mg l^{-1} (Saitoh and Gotoh, 1994). The morphology of the reservoir is such that it has an elongated shape as shown in Fig. 1.

As a means of reducing entrainment of nutrient-rich inflow into the downstream epilimnion, two plastic curtains were installed across the reservoir, having depths to cover the epilimnion thickness, in March 1994. The plan view of T-Dam Reservoir and the location of the curtains are shown in Fig. 1. The curtains were mounted on floating buoys to maintain a constant depth of 5 m below the water surface and installed much towards the riverine zone in which most of the inflow enters the reservoir. The most upstream curtain was placed to cut off nutrient supply from Sata River and Teishakuji River and the other curtain was installed to block the nutrients from Small River. This method reduced algal blooming in the withdrawal zone of the Terauchi Dam Reservoir especially during spring and summer (Asaeda et al., 1996).

The three parts of the reservoir separated by the two curtains were named as Zone A, Zone B, and Zone C (Fig. 1). Chlorophyll-*a*, phosphorus, nitrate nitrogen, ammonium, DO, and BOD were measured at four depths; 0.5 m, 2.0 m, 4.0 m, and 6.0 m in each zone. Temperature at the three zones were measured at 1 m intervals of the depth. The experiments were conducted over three months from the beginning of March to the end of June, 1994. The withdrawal level of Terauchi Dam reservoir was maintained at 1.5 m below the water level from March 3 to March 22, then was lowered to 12 m on March 23, 15 m from March 25, then

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was raised to 10 m on April 25, and from June 13 it was changed daily between 6-9 m to supply warmer water for irrigation.

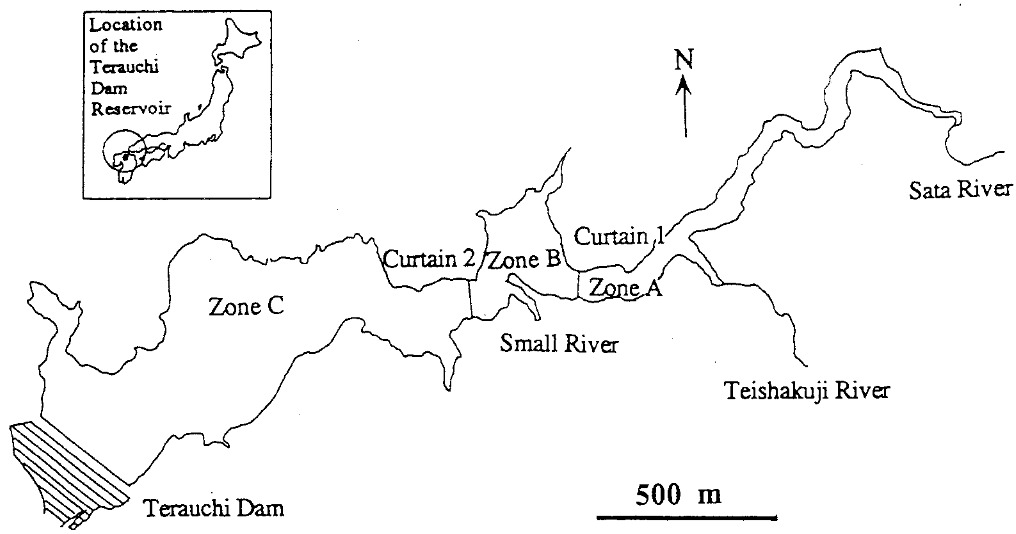

Figure 1: Plan view of Terauchi Dam Reservoir.

The experimental results of this study identified some of the possible mechanisms and reasons for the reduction of algal blooming at the downstream zone of the reservoir (Asaeda et al., 1996). During early spring up to the middle of April, inflow was lighter than the water at the surface and floated over the reservoir surface. Thus, the presence of curtains prevents the direct intrusion of the high level of nutrients to the downstream. Algal concentration was higher in the upstream zones. Thus, within these zones, algae consume large amount of inflow nutrients, which cause a reduced nutrient supply to the downstream zone of the reservoir. Moreover, water in the upper layers gradually settled down to the bottom of the as it was replaced by lighter inflowing water. During this process, water below the curtain bottom flows from the upstream side to the downstream side and flows up along the curtain entraining cool heavy water in the downstream zone. This entrainment leads to an increase in the density of the upward flow, which increases the submergence level of nutrient-rich interflow. During late spring and summer, the presence of the curtains prevents the dispersion of nutrient from upstream zones to the downstream zones. It was also found that the inflow penetration level reduced close to the withdrawal level which played a major role by withdrawing nutrient rich interflow (Nimal et al. 1996a and Nimal et al. 1996b).

Thus the two dimensional simulation model has been developed with two distinct objectives. The first was to gain insight into the functional and quantitative relations in the T-Dam Reservoir ecosystem from the points described above related to eutrophication. The second objective was to give a sound and reasonable foundation for this new technique of reservoir water quality control.

2. Numerical Simulations

The numerical simulations described in this paper were performed with the two dimensional version of the reservoir simulation software DYRESM (Imberger and Patterson 1989, Patterson and Imberger, 1989). Daily values of meteorological, inflow and withdrawal quantities are input to drive the algorithms which model the processes occurring, in the reservoir. The model uses a set of layers of variable thickness to model the vertical, physical processes within the lake. The layers combine, separate, get thicker or thinner or rise and fall in response to physical processes of mixing, inflow, withdrawal and turbulent diffusion. The horizontal structure is maintained by using a set of horizontal parcels within each layer. The properties of temperature, salinity, density and several other relevant quantities are uniform within each parcel. The parcels adjust in a manner similar to the layers to represent various horizontal, physical processes. The parcels and layers are allowed to adjust within the framework of a reservoir shape which is incorporated via a table of volumes and areas at each height. A much more complete description of this model is provided in Hocking and Patterson (1991), and Hocking and Patterson (1994).

In order to perform the simulations for this particular situation, it was necessary to make the following additions to the model.

3. Adaptations to include flow under the curtains

The effect of the curtains on the flow is to prevent horizontal passage of water through them, so that it is effectively blocked, or forced to travel underneath. In the model, the location of each parcel is variable, and depends upon the sequence of events leading up to the current time. Therefore, to implement a model of these processes, the original locations of parcel boundaries were chosen so that when appropriate they coincided with the location of the curtains. Those parcels at those locations were then flagged. In all subsequent calculations, horizontal mixing of these flagged parcels with the ones downstream was prohibited. However, while this prevents mixing through the curtain, it does not prevent horizontal motion as when an inflow or withdrawal occurs at any point in the reservoir.

In the field, if a withdrawal occurs, the level of the water surface drops with the result that water on the upstream side of the curtain is forced under the curtain to the downstream side. If there is an inflow, the level rises and there is a flow under the curtain to conserve volume, the direction of which depends on the location of the inflow source. In the model, therefore, it was necessary to implement an algorithm which calculates the mass imbalance between the two sides of the one or more installed curtains at the end of the day after all of the physical processes have occurred, and rectify this imbalance by some transport of this water from the "credit" side to the "debit" side. This flow should in effect be treated as a local selective withdrawal from under the curtain, and then as a stratified intrusion on the deficit side. The flow around the curtain is likely to cause some small local mixing, so as the required amount is taken from the surplus side it is mixed into a single parcel which is then deposited on the deficit side with some local mixing with the nearby parcels.

Inflows are prevented from intruding beyond the curtains if the intrusion falls within one curtain depth of the surface, and similarly withdrawals are prevented from pulling water from beyond the curtains.

4. Water Quality model

An ecological sub-model described the phytoplankton production, dissolved oxygen budget, and nutrient cycling. Vertical diffusion of biological state variables in the hypolimnion was estimated using the turbulent diffusion algorithm described by Imberger and Patterson (1989). Four major groups of phytoplankton are identified in Terauchi Dam Reservoir. Hence, the model considers four phytoplankton groups; diatoms, cyanobacteria, green algae, and flagellates. The state equations of the ecological sub- model are given below (After Riley and Stefan, 1987, and Hamilton and Schladow 1994).

$$\frac{\partial Py_i}{\partial t} = \left(G_i - R_i - M_i\right)Py_i - G_{Z_i} \qquad (1)$$

where, Py_i= phytoplankton concentration of group i(mg m^{-3}); G_i= gross growth rate of phytoplankton (day^{-1}); R_i= respiration of phytoplankton (day^{-1}); M_i= natural mortality except grazing by zooplankton (day^{-1}); G_{Z_i} = loss of phytoplankton from zooplankton grazing per day ((mg m^{-3} day^{-1})

$$\frac{\partial IP_i}{\partial t} = Up_{max}\theta_p^{T-20}\frac{IP_{max} - IP_i}{IP_{max} - IP_{min}} f(P)Py_i - R_i IP_i - M_i IP_i - k_{gz}\theta_{gz}^{T-20}\frac{Py_i}{K_{gz} + Py_i}P_i\frac{IP_i}{Py_i}Z_p \;;\; f(P) = \frac{PO_4}{K_{PO_4} + PO_4} \qquad (2;3)$$

where, IP = internal phosphorus concentration (mg m^{-3}) ; Up_{max} = maximum rate of phosphorus uptake (day^{-1}) ; K_{PO_4} = half saturation constant for phosphorus uptake (mg m^{-3})

$$\frac{\partial PO_4}{\partial t} = \sum_{i=1}^{4} -Up_{max}\theta_P^{T-20}\frac{IP_{max} - IP_i}{IP_{max} - IP_{min}} f(P)Py_i + R_i IP_i + M_i\left(IP_i - IP_{min}\right) + k_{gz}\theta_{gz}^{T-20}\frac{Py_i}{K_{gz} + Py_i} P_i \frac{IP_i - IP_{min}}{Py_i} Z_P$$
$$+S_P\theta_s^{T-20}\frac{DO + K_{DO}}{DO}\frac{A_s}{V_L} + k_{OP}\theta_{bod}^{T-20} Yp_{bod} BOD \tag{4}$$

where, PO_4 = concentration of soluble reactive phosphorus (mg m^{-3}); S_P = sediment phosphorus release rate (mg m^{-2}); K_{DO} = factor regulating sediment nutrient release with dissolved oxygen concentration(mg m^{-3}) ; A_S = area of sediment in contact with a layer (m^{-2}) ; V_L = volume of layer (m^{-3}) ; k_{op} = rate coefficient for organic decay of phosphorus (day^{-1}); Yp_{bod} = ratio of phosphorus release to oxygen utilised in organic decay ; BOD = biochemical oxygen demand (mg m^{-3})

$$\frac{\partial NO_3}{\partial t} = \sum_{i=1}^{4} -Un_{max}\theta_P^{T-20}\frac{IN_{max} - IN_i}{IN_{max} - IN_{min}} f(N)\left(1 - P_{NH}\right)Py_i + k_{NO}\theta_{NO}^{T-20}\frac{DO}{K_{NO} + DO} NH_4 \tag{5}$$

where, NO_3 = concentration of nitrate (mg m^{-3}) ; k_{NO} = rate coefficient for nitrification (day^{-1}); K_{NO} = half saturation constant for dependence of nitrification or denitrification on dissolved oxygen (mg m^{-3})

$$P_{NH} = \frac{NH_4 NO_3}{\left(NH_4 + K_N\right)\left(NO_3 + K_N\right)}\frac{NH_4 K_N}{\left(NH_4 + NO_3\right)\left(NO_3 + K_N\right)} \tag{6}$$

where, K_N = half saturation constant for nitrogen uptake (mg m^{-3})

$$\frac{\partial NH_4}{\partial t} = \sum_{i=1}^{4} -Un_{max}\theta_P^{T-20}\frac{IN_{max} - IN_i}{IN_{max} - IN_{min}} f(N)P_{NH}Py_i + R_i IN_i + M_i\left(IN_i - IN_{min}\right) + k_{gz}\theta_{gz}^{T-20}\frac{Py_i}{K_{gz} + Py_i} P_i \frac{IN_i - IN_{min}}{Py_i} Z_P$$
$$+S_n\theta_s^{T-20}\frac{DO + K_{DO}}{DO}\frac{A_s}{V_L} - k_{NO}\theta_{NO}^{T-20}\frac{DO}{K_{NO} + DO} NH_4 + k_{On}\theta_{bod}^{T-20} Yn_{bod} BOD \tag{7}$$

where, S_n = sediment nitrogen release rate (mg m^{-2}) ; k_{on} = rate coefficient for organic decay of nitrogen (day^{-1}) ; Yn_{bod} = ratio of nitrogen release to oxygen utilized in organic decay

$$\frac{\partial DO}{\partial t} = W_S - W_E - k_{NO}\theta_{NO}^{T-20}\frac{DO}{K_{NO} + DO} NH_4 Y_{on} + \sum_{i=1}^{4}\left\{G_{max}\theta_P^{T-20}\min\left[f(P); f(N); f(I)\right]Py_i Y_{OP} - R_i Py_i Y_{OP}\right\}$$
$$-k_{BOD}\theta_{bod}^{T-20}\frac{DO}{K_{bod} + DO} BOD \tag{8}$$

where, W_S = Oxygen flux from surface applies only when considering surface layer of depth Δz (mg m^{-3} day^{-1}) ; W_E = Oxygen demand in sub-euphotic zone applies only wen considering sub-euphotic zone for a layer of depth Δz (mg m^{-3} day^{-1}) ; DO = dissolved oxygen concentration (mg m^{-3}) ; Y_{On} = stoichiometric ratio of oxygen to nitrogen for nitrification ; G_{max} = maximum growth rate (day^{-1}) ; Y_{OP} = ratio of mass of oxygen produced or respired to mass of chlorophyll-*a*

$$\frac{\partial BOD}{\partial t} = k_{BOD}\theta_{bod}^{T-20}\frac{DO}{K_{bod} + DO} BOD - \sum_{i=1}^{4} k_m\theta_m^{T-20} Py_i Y_{OP} \tag{9}$$

where, K_{bod} = half saturation constant for dependence of detrial decay on dissolved oxygen (mg m^{-3}) ; k_{bod} = rate coefficient for detrial decay on dissolved oxygen (day^{-1}).

5. Results of simulations

Simulations were performed on T-Dam reservoir using the model with the curtains incorporated over the period March-June, 1994. Comparison with the field data shows the model to be accurately reproducing the behaviour of the temperature structure in the reservoir (Fig. 2). The curtains were placed at a distance of 1335 m and 1670 m from the dam wall and extended to a depth of 5 m. Once the physics of the model was verified, it was necessary to calibrate the biological/biochemical components in the water quality model. Measured and simulated total chlorophyll-*a* concentration at the surface layer of the Zone C are shown in Fig. 3. Estimated chlorophyll-*a* values showed variation from some measured values. This variation could be due to several reasons. One reason is that it may be due to chlorophyll-*a* concentration of the inflow. The inflow chlorophyll-*a* was measured once a month, hence interpolated values between two months were used. These interpolated values might have significant deviation from their real values. Another reason could be the use of average parameter values. One parameter represents the average values of several species. As each species has its own characteristic parameters, the variation in the species composition inevitably gives a corresponding variation in the average parameter used in the model.

The model can be used to examine the physical processes which lead to the effects described on the chlorophyll levels in the lake near to the dam wall. The simulations show that early in the period, warmer inflows were flowing over the surface of the lake, and were blocked by the two curtains, thus causing the newly arrived water to remain upstream, although there was some leakage past the curtains in a downstream direction (see Fig. 4). In early April, the tilting of the isotherms downward at the upstream end indicates that the inflow is now plunging deeper into the lake, and intruding at a level beneath the bottom of the curtains. This is well below the photic zone, so although nutrients may be carried into the lake, they may be too deep to be utilised until there is a mixing event.

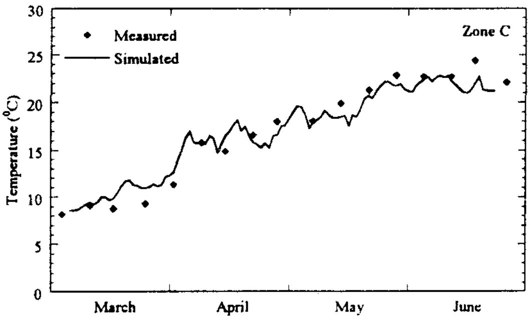

Figure 2 Measured and simulated temperature distributions in the top layer of zone C of T-Dam Reservoir in 1994.

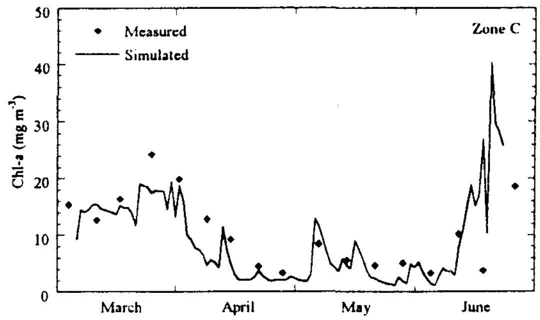

Figure 3 Measured and simulated chlorophyll-*a* distributions in the top layer of zone C of T-Dam Reservoir in 1994.

These effects are seen more clearly in the plots of residence time (a measure of the time individual parcels have spent in the reservoir). Figure 5 shows very clearly how the inflows and intrusions have been inhibited near the surface by the installation of the curtains. The first curtain acts to isolate the epilimnion behind the curtain from the inflow, and anything which does pass under the curtain is effectively blocked by the second (downstream) curtain. Any nutrients carried into the lake are therefore stored at deeper levels downstream of the curtain, so that no new nutrients are added to the euphotic layer. The trapping of this water beneath the thermocline means that much of the nutrient load is unavailable until the occurrence of a mixing event.

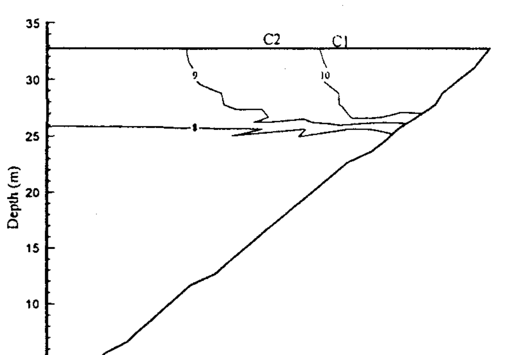

Figure 4 Simulated temperature distribution on March 11th, 94

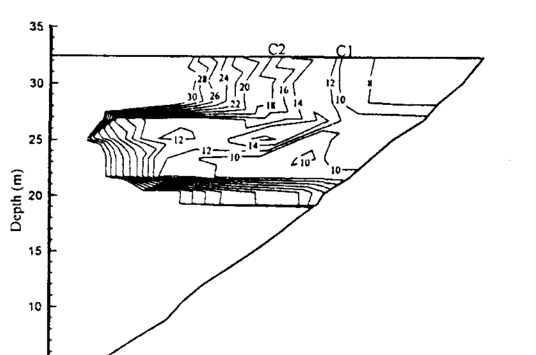

Figure 5 Simulated residence time on April 08th, 94

The simulations of Chl-a further strengthen our conclusions. Early in April, there is low concentration in the surface layer downstream of the second curtain, while the level between the curtains and upstream of both is relatively high. The intrusion of some of the upstream water under the curtains has shown some blooming at the upstream end of the main basin at the level of curtain bottom (Fig. 6). Over the period of the simulation this effect is maintained. Higher concentrations are restricted to the upper reaches of the reservoir and to below the mixed layer in the regions nearer to the dam wall; exactly the locations at which the inflows and hence nutrient inputs have occurred (see Fig. 7).

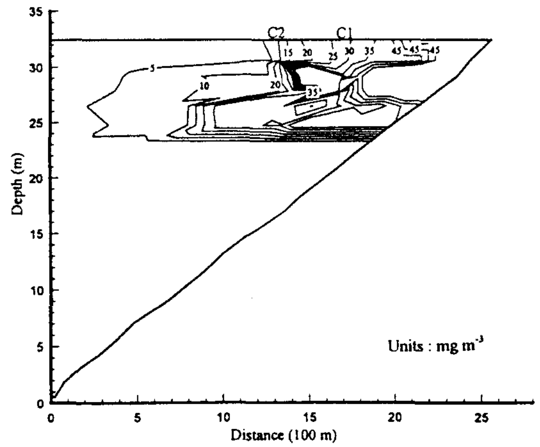

Figure 6 Simulated chl-*a* distribution on April 08th, 94

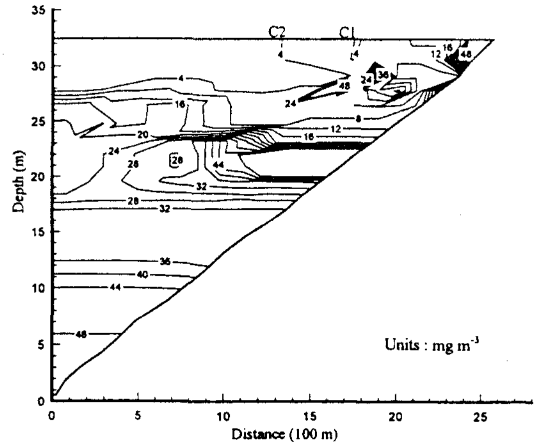

Figure 7 Simulated phosphorus distribution on April 08th, 94

6. Conclusion

This study has presented a model that combines the mixing dynamics of a stratified lake with the biological processes, diffusion, and flow under the curtains. The model has been run using lake data from the T-Dam Reservoir in Kyushu, Japan. The ecological sub-model is calibrated over 115 days available data, from the beginning of March to the end of June, 1994. The model simulates the chlorophyll-*a* concentration in the three zones of the reservoir with reasonable accuracy. Curtain method can best be applied for a reservoir or lake having an elongated shape. In particular, the method is a low cost technique with a high degree of reliability and simplicity when compared to existing control measures.

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