Mathematical simulation on accumulation process of a blooming plankton Peridinium bipes (Dinophyceae) in a dam reservoir

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Abstract The accumulation process of the blooming plankton Peridinium bipes was studied in this paper using a mathematical model based on a horizontal one-dimensional multi-layered flow model coupled with a vertical migration model of the Peridinium bipes community. The estimated accumulation process consisted of three processes: upward swimming and dispersion of Peridinium bipes cells, advection of the cells with the countercurrent of surface water, and entrainment and effluent of the cells with the plunging flow of inflow river water. The numerical analysis has revealed that the accumulation process helps Peridinium bipes to avoid hydraulic washout and it contributes to a contribution to a concentration of Peridinium bipes cells on the upper side of the reservoir.

Keywords Accumulation process; bloom; dinoflagellate; Dinophyceae; eutrophication; freshwater red tide; mathematical model; numerical simulation; Peridinium bipes; reservoir

Introduction
Water blooms caused by dinoflagellate Peridinium spp. have appeared frequently since the 1970s in Japan (Fukuju et al., 1998; Somiya and Kishimoto, 1998). Similar blooms were observed in Clear Lake, California (Horne et al., 1970), Lake Berryessa, California (Herrgesell et al., 1976) and Lake Kinneret, Israel (Pollinger and Serruya, 1976; Berman-frank and Erez, 1996; Zohary et al., 1998). These blooms mainly appear in oligotrophic and mesotrophic reservoirs and lakes causing several problems such as foul odor and taste, spoilage of the scenery, choking of filter beds, killing of fish and negative influence on recreation activities (Fukuju et al., 1998). Therefore, much interest is given to how to restrain the bloom of Peridinium spp. in such above mentioned clear water bodies. Formation of the blooms will be composed of four processes: appearance, multiplication, accumulation and deterioration processes. The appearance process, in which new seeds are provided for multiplication, consists of the germination of cyst (hypozygote) and re-multiplication of vegetative cells of Peridinium spp. The disappearance process, by which vegetative cells are decreased, consists of death, decomposition, predation, sedimentation and hydraulic washout of living cells of Peridinium spp. The other two processes, multiplication and accumulation processes, will be related to development and sustenance of the bloom. The multiplication process is a sexual reproduction of the vegetative cells. Reports such as Nishihori et al. (1991), Ikeda et al. (1997) and Kishimoto et al. (1998a) have been published on the multiplication process of Peridinium spp. In these reports, Peridinium spp. has a relatively small maximum growth rate and small half saturation constant of Monod’s equation on concentrations of nitrogen and phosphorus. This may indicate that Peridinium spp. may adapt to oligotrophic and/or mesotrophic water bodies. However, Kishimoto et al. (1998b) has pointed out that the small half saturation constants are only useful for increasing the growth rate of Peridinium bipes to the extent that it is nearly equal
to the growth rate of coexistence phytoplanktons in low concentrations of nutrients. Accordingly, it is not possible to explain a reason why *Peridinium* spp. is more dominant to other phytoplankton only in the multiplication process.

**Objectives**

It is well known that *Peridinium* spp. has two flagella and can swim at will using these flagella. Therefore, we speculated that the accumulation process related to the swimming ability of *Peridinium* spp. plays an important role in formation of a bloom. The purpose of this paper is to understand the accumulation mechanism of the bloom and its role in the appearance of blooms within a mathematical model.

We selected Asahi Reservoir in Okuyoshino Pumped-storage Power Plant as a study site. The Okuyoshino Power Plant is capable of generating electric power of 1,206 MW using the 526 m difference of elevation between Asahi Reservoir, which is a lower dam, and Seto Reservoir, which is an upper dam (Fig. 1). Some features of Asahi Reservoir are shown in Fig. 1. Umuno River is an influent river and its ordinary flow rate is in the range of 0.5 to 1.0 m$^3$ s$^{-1}$. The catchment area of 39.2 km$^2$ is covered with forest and no houses.

Therefore, concentrations of dissolved nitrogen and dissolved phosphorus in Umuno River water are relatively low, about 0.2 mgN l$^{-1}$ and 0.004 mgP l$^{-1}$ in ordinary conditions.

The dinoflagellate bloom of *Peridinium bipes* has been observed since 1980 in the Asahi Reservoir (Table 1). Although the pattern of appearance of blooms is different each year, the ordinary blooming season is summer and autumn. There were severe blooms of *Peridinium bipes* in 1995, especially in July and August. Therefore, accumulation processes of the bloom during August 16 to 17 in 1995 were estimated through the following mathematical model.

**Methods**

To evaluate only the accumulation process, the mathematical model handled only hydrodynamics and migration of *Peridinium bipes* communities. Multiplication and predation were not handled in it. The state variables, horizontal current, vertical current, water temperature, turbidity, light intensity and population density of *Peridinium bipes*, are all considered in this model.

A horizontal one-dimensional multilayered flow model has been applied to simulate water current in Asahi Reservoir. Fundamental differential equations are shown in Table 2. Table 2 also shows difference equations deduced from the differential equations using the staggered scheme (Iwasa et al., 1979) which is a type of explicit scheme. Some assumptions
were introduced into the modeling: establishment of hydrostatic pressure distribution in the reservoir and uniform water surface profile. Inflow and outflow through discharge gates for hydraulic power generation (which is peculiar in this reservoir) was handled as a side-overflow. Size of a control volume was set at a 1 m height and 100 m length. Figure 2 shows the manner of numbering control volumes.

In Asahi Reservoir, daily fluctuation of water levels may reach over 10 m due to hydraulic power generation. Therefore, the height of a surface control volume has been decided to be under 1.5 m yet over 0.5 m by the following rules: if the height of a surface control volume is less than 0.5 m, new surface control volume is created by joining of a surface control volume and next lower control volume; if the height of a surface control volume is more than 1.5 m, the surface control volume is divided into two control volumes, a new surface control volume which has the height of less than 1 m and a lower control volume which has the height of 1 m.

The upper reach of the reservoir was determined to be a depth of over 2.5 m. Vertical numbers for the most upstream control volumes were more than three by this operation. If the upper reach of the reservoir moves upstream, newly generated control volume has the same values of the static variables in a next downstream control volume except for a value of population density of *Peridinium bipes*. If the upper reach of the reservoir moves downstream, the value of the static variables except the variables of population density of *Peridinium bipes* in the disappeared control volumes are discarded. The population of *Peridinium bipes* in the most upstream control volume is set to zero in the case of generation and adds to the population in the next downstream control volume in the case of disappearance of control volumes. In this operation, the biomass of *Peridinium bipes* were conserved before and after the boundary processing.

### Vertical migration model of *Peridinium bipes* community

*Peridinium bipes* has negative geotaxis and positive phototaxis (Kishimoto *et al.*, 1999). Therefore modeling of vertical migration of *Peridinium bipes* communities is important for a precise evaluation of the accumulation process. In this study, the vertical migration model

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Source: Asahi Dam Office
Table 2  Fundamental differential equations and difference equations in an intermediate control volume

\[ \begin{align*}
\text{equation of continuity} & \quad \frac{\partial U_x}{\partial x} + \frac{\partial U_z}{\partial z} = 0 \\
\text{material balance equation} & \quad \frac{\partial C}{\partial t} + U_x \frac{\partial C}{\partial x} + (U_z + W_C) \frac{\partial C}{\partial z} = \frac{\partial}{\partial x} \left( D_{Cx} \frac{\partial C}{\partial x} \right) + \frac{\partial}{\partial z} \left( D_{Cz} \frac{\partial C}{\partial z} \right) + S_C \\
\text{equation of motion} & \quad \frac{\partial U_x}{\partial t} + U_x \frac{\partial U_x}{\partial x} + U_z \frac{\partial U_x}{\partial z} = -\frac{1}{\rho} \frac{\partial P}{\partial x} + \frac{1}{\rho} \frac{\partial \tau_{xx}}{\partial x} + \frac{1}{\rho} \frac{\partial \tau_{zz}}{\partial z} \\
\text{heat balance equation} & \quad \frac{\partial T}{\partial t} + U_x \frac{\partial T}{\partial x} + U_z \frac{\partial T}{\partial z} = \frac{\partial}{\partial x} \left( D_{T_x} \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial z} \left( D_{T_z} \frac{\partial T}{\partial z} \right) + \frac{H}{\rho C_w}
\end{align*} \]

\[ \begin{align*}
U_{i \left( \frac{1}{2} + \frac{i}{2} \right)}^{n+1} & = \frac{1}{B_{i \left( \frac{1}{2} + \frac{i}{2} \right)}} \left( U_{i \left( \frac{1}{2} + \frac{i}{2} \right)}^{n} B_{i \left( \frac{1}{2} + \frac{i}{2} \right)} - U_{i \left( \frac{1}{2} + \frac{i}{2} \right)}^{n+1} A_{i \left( \frac{1}{2} + \frac{i}{2} \right)} + U_{i \left( \frac{1}{2} + \frac{i}{2} \right)}^{n} A_{i \left( \frac{1}{2} + \frac{i}{2} \right)} \right) \\
C_{i \left( \frac{1}{2} + \frac{i}{2} \right)}^{n+1} & = C_{i \left( \frac{1}{2} + \frac{i}{2} \right)} - \frac{\Delta t}{V_{i \left( \frac{1}{2} + \frac{i}{2} \right)}} \left[ \left( U_{i \left( \frac{1}{2} + \frac{i}{2} \right)} \right) \left( C_{i \left( \frac{1}{2} + \frac{i}{2} \right)} A_{i \left( \frac{1}{2} + \frac{i}{2} \right)} - \left( C_{i \left( \frac{1}{2} + \frac{i}{2} \right)} A_{i \left( \frac{1}{2} + \frac{i}{2} \right)} \right) \right) \right] \\
U_{i \left( \frac{1}{2} + \frac{i}{2} \right)}^{n+1} & = U_{i \left( \frac{1}{2} + \frac{i}{2} \right)} - \frac{\Delta t}{V_{i \left( \frac{1}{2} + \frac{i}{2} \right)}} \left[ \left( U_{i \left( \frac{1}{2} + \frac{i}{2} \right)} \right) \left( C_{i \left( \frac{1}{2} + \frac{i}{2} \right)} A_{i \left( \frac{1}{2} + \frac{i}{2} \right)} - \left( C_{i \left( \frac{1}{2} + \frac{i}{2} \right)} A_{i \left( \frac{1}{2} + \frac{i}{2} \right)} \right) \right) \right]
$$\left( \frac{U_{x(i,j)} - U_{x(i,j-1)}}{\Delta z} - \frac{U_{y(i+1/2,j)} - U_{y(i-1/2,j)}}{\Delta z} \right) B_{(i,j-1/2)} \right] + \Delta t \left( \frac{T_{(i+1/2,j)} - T_{(i,j-1/2)}}{\Delta x} A_{(i+1/2,j)} - \frac{T_{(i,j-1)} - T_{(i,j-1/2)}}{\Delta x} A_{(i+1/2,j)} \right) - \Delta t \left( \frac{T_{(i,j+1/2)} - T_{(i,j-1)}}{\Delta z} B_{(i+1/2,j)} - \frac{T_{(i,j-1/2)} - T_{(i,j-1)}}{\Delta z} B_{(i+1/2,j)} \right) + H \Delta t$$

$$W_{TB} = \frac{(\rho_w - \rho_0) g d_{TB}^2}{18 \eta}$$

$$D_z = D_{TB}; \quad D_s = 0.0001 \exp(-0.6 Ri) \quad 0 \leq Ri \leq 12$$

$$D_s = D_{TBz}; \quad D_{x} = 0.0001$$

$U_x, U_y$: horizontal and vertical current (m s$^{-1}$); $TB$: turbidity (NTU); $Per$: Peridinium bipes (cells m$^{-3}$); $T$: water temperature (°C); $D_x, D_y$: horizontal and vertical turbulent eddy viscosity (m$^2$ s$^{-1}$); $D_{Cx}, D_{Cz}$: horizontal and vertical turbulent diffusion coefficient of $C$ (m$^2$ s$^{-1}$); $D_{Tx}, D_{Ty}$: horizontal and vertical turbulent diffusion coefficient of water temperature (m$^2$ s$^{-1}$); $\tau_{xx}, \tau_{zz}$: normal stress (N m$^{-2}$); $P$: pressure (N m$^{-2}$); $W_C$: surfacing velocity of $C$ (m s$^{-1}$); $\nu$: coefficient of kinematic viscosity (m$^2$ s$^{-1}$); $\eta$: coefficient of viscosity (m$^2$ s$^{-1}$); $S_C$: production rate of $C$ ($= 0$ in this study) (NTU m$^{-3}$ s$^{-1}$ or cells m$^{-3}$ s$^{-1}$); $H$: generated heat (K m$^{-3}$ s$^{-1}$); $\rho_0$: standard water density (kg m$^{-3}$); $\rho_w$: water density (kg m$^{-3}$); $\rho_{TB}$: density of turbid material ($= 2.6$ kg m$^{-3}$); $d_{TB}$: diameter of turbid particle ($= 1$ µm); $C_w$: specific heat of water ($= 1,000$ kcal m$^{-3}$ K$^{-1}$); $\Delta z$: height of control volume ($= 100$ m); $\Delta t$: time step for calculation ($= 30$ s); $g$: gravitational acceleration ($= 9.8$ m s$^{-2}$); $Ri$: local Richardson number; $i, j$: control volume number.
proposed by Kishimoto et al. (1999) was used (Table 3). In his model, the critical population density of *Peridinium bipes* should be set at double the maximum population density observed. Maximum population density during the bloom of *Peridinium* spp. generally reaches tens of billions cells per m$^3$ within the water surface. However, the high density layer is usually limited at water surface to a depth of several centimetres and the population density decrease to under the billions of cells per m$^3$ at the depth of several tens of centimetres. Accordingly, the critical population density was set to $1.0 \times 10^{10}$ cells per m$^3$ in this study.

**Results and discussion**

**Reproduction of the bloom**

The target period of numerical analysis was August 1995 when the most severe bloom was observed every day. Data were collected for the mathematical model with hourly atmospheric temperature, hourly precipitation, daily solar radiation, daily relative humidity,
daily wind velocity, duration of sunshine, hourly elevation of water surface, hourly influent, hourly water temperature of river water, hourly turbidity of river water, hourly effluent from Asahi dam and hourly generation flux data. All information was obtained from the Asahi Dam Office. At Okuyoshino Power Plant, the hydroelectricity is usually generated throughout the daytime and Seto Reservoir water flows through a headrace channel to Asahi Reservoir during generation. However, it seems improbable that *Peridinium bipes* cells would pass through the head gate of Seto Reservoir, as the vegetative cells of *Peridinium bipes* are accumulated in the water surface during the daytime. Accordingly, it was assumed that there would be no *Peridinium bipes* cell in the influent from Seto Reservoir with hydroelectric power generation.

The hydrodynamic simulation had been started on August 1, 1995. Water temperature and turbidity observed at station A was input in initial state variables under an assumption of horizontal uniformity. Initial water current was set to zero. The hydrodynamic simulation was continued until 12:00, August 16, with the mathematical model being computed for 7 days with the weather and water use conditions of August 16 used for reproduction of freshwater red tide after 10 cells m$^{-1}$ of *Peridinium bipes* cells were input into all control volumes. The simulated results are shown in Fig. 3. In Fig. 3, water temperature has stratified and two thermoclines are observed in the water surface and under an elevation of 409 m where the orifice gates are installed. This is a typical distribution of water temperature in Asahi Reservoir. Influent river water has plunged into the reservoir on an elevation of 440 m for the difference between density of warm surface water and density of cold river water. Countercurrent to the plunging flow has been formed near the water surface. Figure 4 shows observed and computed sketches of the bloom on August 16, 12:00. In Fig. 4,
standard population densities for judging magnitude of the bloom were determined from
the relationship between apparent magnitude of the bloom and observed population density
of *Peridinium bipes* at the depth of 0.5 m (Fig. 5). Both sketches illustrate the formation of
dense bloom in the upper side of the reservoir. Thus, this model has been considered to
reproduce the phenomenon of the dinoflagellate bloom adequately.

Evaluation of accumulation process

In deducing that the situation shown in Fig. 3 was to be an initial condition, two separate
simulations were investigated, with and without generation of electricity, for the evaluation
of the accumulation process of the dinoflagellate bloom. The simulations started at 12:00,
August 16 and ceased at 12:00, August 17. Inflow flux from Umuno River had been at a
constant value of 0.64 m$^3$ s$^{-1}$ and discharge flux from Asahi Dam had ranged from 0.58 to
0.60 m$^3$ s$^{-1}$ during calculation. The operation of hydraulic power generation was conducted
from 14:00 till 18:00 on August 16 and from 8:00 till 10:00 on August 17 and the pumping
operation was continued from 3:00 till 7:00 on August 17. Influent flux with generation had
varied from 12.6 to 78.2 m$^3$ s$^{-1}$ and intake flux with pumping was in the range of 34.5 to
62.5 m$^3$ s$^{-1}$. It had been fine during simulation period and atmospheric temperature
had been observed in the range from 20.5 to 31.5°C. Wind velocity and relative moisture at
10:00 were 0 m s$^{-1}$, 94 % on August 16 and 0 m s$^{-1}$, 93 % on August 17 respectively.

Once, *Peridinium bipes* without generation. The simulated distributions of
*Peridinium bipes* are shown in Fig. 6. The vector diagram of water current and the distribution
graph of water temperature were omitted from Fig. 6, as they were similar to the distri-
butions in Fig. 3. The simulation results showed that *Peridinium bipes* cells were
accumulated to the upper side of the reservoir from 12:00 till 18:00. However, the accumu-
lated cells dispersed downward and were carried downstream along the interface between
the plunging flow of influent river water and surface countercurrent in the nighttime.
Therefore, the bloom had almost disappeared before sunrise. On the addition of direct sun-
light, *Peridinium bipes* rapidly migrated upward and the bloom reappeared (from 6:00 till
12:00). This diurnal migration pattern was similar to that observed in Shorenji Dam
Reservoir (Yamada *et al*., 1998). Figure 7 illustrates the diurnal migration pattern and domi-
ninating factors on the accumulation process. In the daytime, *Peridinium bipes* cells swim
upward by their negative geotaxis and positive phototaxis and are carried to the upper end
of the reservoir with upstream countercurrent of surface water. In the nighttime, however,
Figure 6: Diurnal transitions of population density of *Peridinium* spp. (cells ml$^{-1}$) in the Asahi Reservoir without pumping-up and generation by the hydroelectric power plant.

Figure 7: Estimated accumulation mechanism of *Peridinium bipes*. 

- advection with the outercurrent of surface water
- dispersion and entrainment
- upward swimming
- effluent with plunging flow of influent river water
Figure 8  Water current in the Asahi Reservoir with pumping-up and generation by the hydroelectric power plant. Discharge gates for generation are located at 1,700 m from the dam site and 424 - 428 m in elevation.

Figure 9  Diurnal transitions of population density of Peridinium spp. (cells ml⁻¹) in the Asahi Reservoir with pumping-up and generation by the hydroelectric power plant. Discharge gates for generation are located at 1,700 m from the dam site and 424 - 428 m in elevation.
*Peridinium bipes* disperses vertically with a decrease of swimming velocity and spreads downstream along the interface between the plunging flow and the upstream countercurrent. This accumulation process plays the role of concentrating *Peridinium bipes* cells on the upper side of the reservoir.

Although effluent water from Asahi Dam amounted to 0.7% of the total volume, the decreased biomass of *Peridinium bipes* was only 0.1% of the initial biomass throughout the simulation. Thus, it is successful for *Peridinium bipes* to avoid the hydraulic washout by staying at the upper side of the reservoir.

**Behavior of Peridinium bipes with generation.** Vector diagrams of water current under generation and pumping are demonstrated only at 15:00 in generation and at 6:00 in pumping by generators in Fig. 8. The simulated distributions of *Peridinium bipes* are shown in Fig. 9. The jet flow from the discharge gates for generation occurs at 15:00. However, the countercurrent of surface water in the upper side of the reservoir remained and *Peridinium bipes* kept forming the blooms (Figs 8 and 9). Water current toward the discharge gates was observed at 6:00 and a part of the plunging flow was streaming toward the gate. *Peridinium bipes* cells were also drawn through the discharge gate. As the result of the pumping operation, water current toward the discharge gate partly prevented *Peridinium bipes* cells from accumulating in the water surface. However, the bloom reappeared in the upper side of the reservoir at 9:00 and 12:00. Total biomass of *Peridinium bipes* in the reservoir decreased to 98.0% of the initial biomass through the simulation. However, effluent water from the orifice gate of Asahi Dam and intake through the discharge gate for generation were 0.7% and 8.6% of the total volume of Asahi Reservoir respectively. These results show that the accumulation process contributes to diminish the hydraulic washout of *Peridinium bipes* cells, even if the pumped-storage power generation is operating.

**Conclusion**

In this study a mathematical model has been presented that combines a horizontal one-dimensional multi-layered flow model with a vertical migration model of *Peridinium bipes* communities. The model has been applied to the analysis of the accumulation process of *Peridinium bipes* cells in Asahi Reservoir. The preliminary calculation’s results have demonstrated that the model reproduces the phenomenon of the dinoflagellate bloom adequately. As the result of numerical simulations, the accumulation mechanism of *Peridinium bipes* has been estimated to be constituted of three processes: upward swimming and dispersion of *Peridinium bipes* cells, advection of the cells with the countercurrent of surface water, and entrainment and effluent of the cells with the plunging flow of inflow river water. During daytime, *Peridinium bipes* cells swim upward by their negative geotaxis and positive phototaxis and the upstream flow of surface water carries *Peridinium bipes* cells to the upper end of the reservoir. During nighttime, however, *Peridinium bipes* disperses vertically with decrease of swimming velocity and spreads downstream along the interface between the plunging flow and the upstream countercurrent of surface water by entrainment with the plunging flow. It is concluded that the above accumulation process helps *Peridinium bipes* to avoid hydraulic washout and contributes to concentration of *Peridinium bipes* cells on the upper side of the reservoir. *Peridinium bipes* is thought to succeed in oligotrophic and mesotrophic reservoirs through the accumulation process combined with the multiplication process, which is adapted to poor nutrient circumstances.

**References**


