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Effect of Aquaculture on Material Cycles in Otsuchi Bay, Japan

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A numerical physical-biological coupled model is developed for the study of coastal material cycles including aquaculture. The model calculates spatial distributions of PON (Particulate Organic Nitrogen), POP (Particulate Organic Phosphorus), DON (Dissolved Organic Nitrogen), DOP (Dissolved Organic Phosphorus), *Chl*-a, zooplankton, NO_3-N, NH_4-N and PO_4-P using simulated current. It also takes into consideration the effects of shellfish feeding and excretion, seaweed photosynthesis, and the loading of DIN from rivers. The model is applied to Otsuchi Bay, in Iwate Pref., in Japan. The model elucidated the cycling of nitrogen among ecological compartments. If the amount of cultured shellfish is extremely increased, the feeding by shellfish is large enough to change the lower trophic level ecosystem, reducing concentration of phytoplankton and POM (Particulate Organic Matter) around the cultured region, while phytoplankton increases far from the culture due to the increase of recycled nutrient by the excretion of shellfish.

Key words: aguaculture, numerical model, oyster, scallop

INTRODUCTION

Aquaculture fisheries especially for scallop, oyster and sea grasses in northern Japan have become important socioeconomic activities in the past twenty years. Consequently, pollution of the bay areas by accumulated faecal pellets, leftover food and other physiological excretions have become more and more serious to the environment of the aquacultures and to human life (e.g. odors and pollution of bathing resorts). Numerical models have been proposed to assess the influence of the location or the area of the aquaculture rafts on the ecological and/or environmental system (e.g., the one box model by Takeoka et al. (1988) or the three dimensional model by Kishi et al. (1994, 1995)). Takeoka et al. (1988) paid attention to the flow of dissolved oxygen and carbon content between the bay area where aquaculture is conducted and the outer region. They calculated the sources and sinks of dissolved oxygen in the bay, and concluded that using their model they could access the rough features of the carbon and oxygen flows between the bay and the outer region. The three dimensional model by Kishi et al. (1993, 1995) showed the spatial distribution of dissolved oxygen (DO), chemical oxygen demand (COD), and accumulated matter in the bay based on the carbon cycle, and focus on the role of cultured shellfish on the nutrient cycle of the bay.

Here we introduce a numerical model for aquaculture in Otsuchi-Bay based on nitrogen and phosphorus cycles.

Otsuchi Bay is a semi-enclosed bay, 8 km long and 2 km wide, on Sanriku Ria coast in northeastern Japan. The bay opens onto the Pacific Ocean (39°20′N,141°56′E). Three small rivers Otsuchi, Unosumai, and Kozuchi river flow into the bay, contributing a total influx of approximately 3–10 m^3/sec (Hirano and Hayakawa 1976). During the spring, runoff into the bay is derived from melting snow in the surrounding mountains as well as local rainfall.

Two dominant patterns of water flow are observed in Otsuchi bay. In the first, the seaward outflow of the surface water passes over the landward inflow of denser, more saline water, which enters the bay at the bottom. This circulation is caused by westerly wind stress and is considered to be prominent in winter and spring when west to northwest wind prevails (Hasunuma et al. 1977, Shikama 1990). Second, an inflow of surface water over outflow of deeper water is observed during summer (Shikama 1990). However, both the circulation pattern may be seen in summer, depending on difference in water density between inside and outside the bay (Shikama 1990).

In this paper we present results of simulations using the physical-biological model of Kawamiya et al. (1996), and we demonstrate that it can simulate the time dependent features of the ecosystem in Otsuchi Bay (shown in Fig. 1).

The biological submodel has the same structure as in Kawamiya et al. (1995) expect for minor changes associated with adding shellfish and sea grass ecosystems. Specifically, the model estimates the distribution of nitrate, ammonium, phosphate, dissolved oxygen, phytoplankton (chlorophyll-a), zooplankton, particulate organic nitrogen, and dissolved organic nitrogen. The model reproduced the effect of shellfish aquaculture in the material cycle in the bay.

MODEL CONCEPTION

A schematic view of the material flows in the ecological

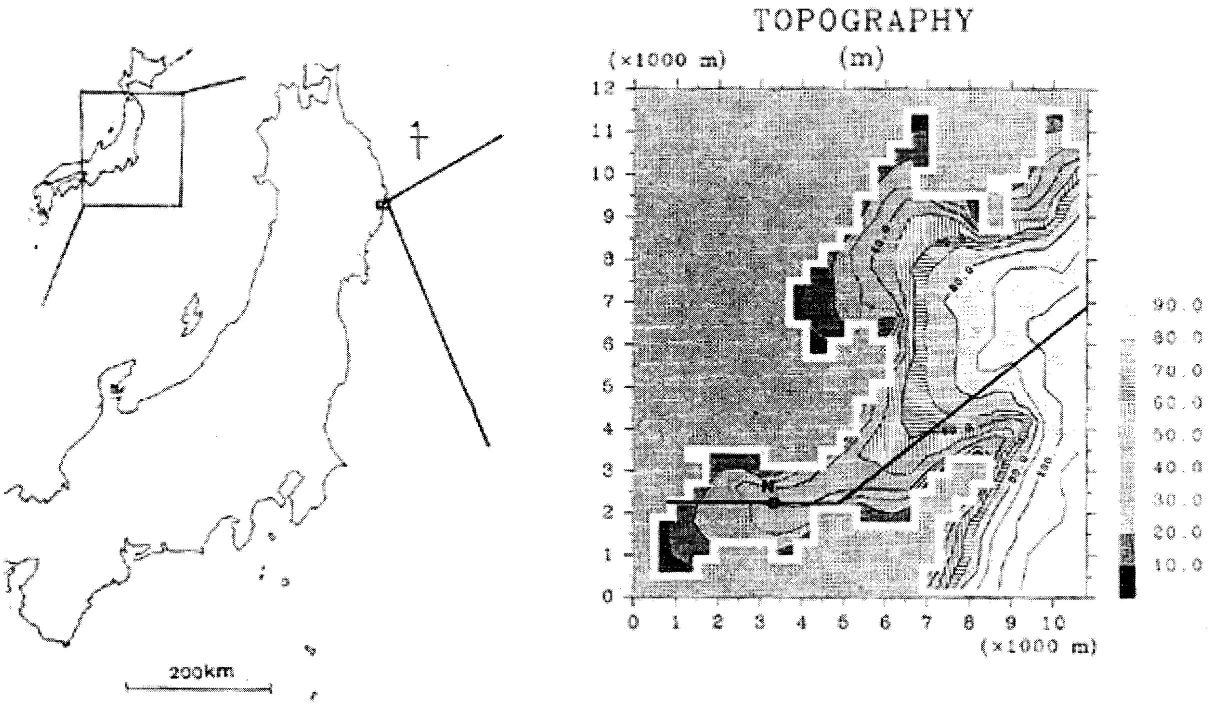

Fig. 1. Schematic view of Otsuchi Bay, Japan.

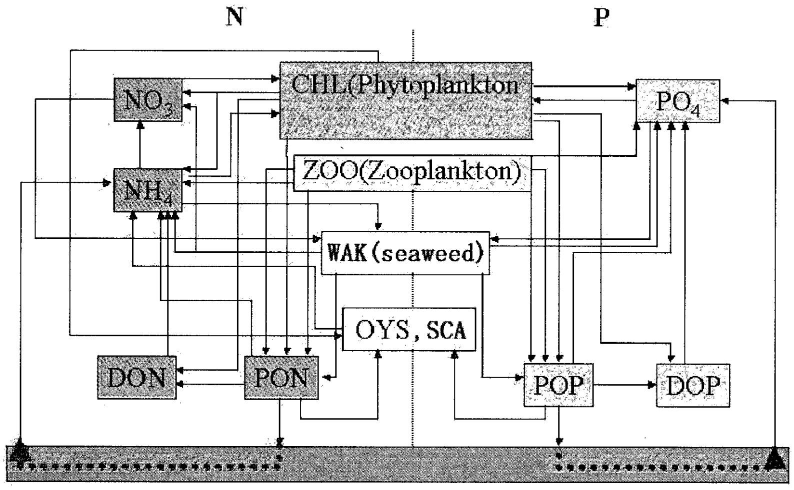

Fig. 2. Schematic view of material cycles of ecological model.

parts of the model is shown in Fig. 2. In Fig. 2 the compartments shown as squares are independent variables (calculated numerically), except for WAK (Wakame sea weed), OYS (Oyster) and SCA (Scallop), which are assigned concentrations based on the statistics of fisheries.

Current simulation model

The model requires circulation fields around the area of aquaculture. Usually tidal, wind induced and/or density currents are calculated using three-dimensional primitive equations and an equation of state after Kawamiya et al. (1995) and Fujihara et al. (1992).

Biological model

The detailed equations coupling the compartments are after Kawamiya et al. (1995, 1996) except for the shellfish ecosystem. The sink-source terms are as follows;

(1) Phytoplankton (Chl)

dChl/dt = Photosynthesis − Extracellular excretion
− Respiration − Mortality − Grazing by ZOO
− Grazing by OYS and SCA

(2) Zooplankton (ZOO)

dZOO/dt = Grazing − Egestion − Excretion − Mortality
− Grazing by OYS and SCA

(3) Nitrate (NO_3)

dNO_3/dt = − Photosynthesis by Chl
+ Nitrification − Photosynthesis by WAK

(4) Ammonium(NH_4)

dNH_4/dt = − Photosynthesis by Chl + Respiration by Chl
− Nitrification + Excretion by ZOO

+Decomposition of PON
+Decomposition of DON
+Respiration by WAK
+Excretion by OYS and SCA
−Photosynthesis by WAK

(5) Phosphate (PO_4)

$dPO_4/dt = -$Photosynthesis by Chl+Respiration by Chl
+Egestion by ZOO+Decomposition of POP
+Decomposition of DOP
−Photosynthesis by WAK

(6) Particulate Organic Nitrogen (PON) and Particulate Organic Phosphorus, (POP)

d(PON or POP)/dt
=Mortality of Chl+Mortality of ZOO
+Excretion of ZOO
−Decomposition from PON(POP) to DON(DOP)
−Decomposition from PON(POP) to $NH_4(PO_4)$
−Grazing by OYS and SCA

(7) Dissolved Organic Nitrogen (DON) and Dissolved Organic Phosphorus (DOP)

d(DON or DOP)/dt
=Extracellular excretion
+Decomposition from PON(POP) to DON(DOP)
−Decomposition from DON(DOP) to $NH_4(PO_4)$

(8) Wakame seaweed (WAK)

The standing stock of Wakame seaweed is estimated based on catch data from aquaculture and given implicitly.

(9) Oyster (OYS) and Scallop (SCA)

The standing stocks of these shellfish are also estimated based on catch data from aquaculture in 2000 and given implicitly. Generally speaking oyster culture is set around two to five meters depth and scallop culture is around six to fifteen meters. In the model, oyster culture is set from surface to four meters (i.e., level one and two) and, scallop culture is set from four to ten meters (i.e., level three and four).

Following Kishi et al. (1995) grazing by oysters is represented as follows;

$$\text{Grazing of PON(POP)} = r_1 \times r_2 \times r_3 \times \text{PON(POP)} \times \text{OYS}$$

Where r_1 is the amount of filtered water by shellfish,
r_2 is the food catch rate of shellfish (0.4),
r_3 is the ingestion rate by shellfish (0.9),

and

$$r_1 = 0.066T - 0.308$$

where T is water temperature.

$$\text{Grazing of Chl} = r_1 \times r_2 \times \text{Chl} \times \text{OYS}$$

$$\text{Grazing of ZOO} = r_1 \times r_2 \times \text{ZOO}/2 \times \text{OYS}$$

That is, oysters prefer phytoplankton to zooplankton.

On the other hand, excretion from shellfish is only to ammonium (NH_4) as follows;

$$\text{Excretion of shellfish} = k_2 \times k_2' \times \text{OYS(SCA)}$$

Where k_1 is excretion/respiration ratio for excretion (0.05 [gN/gO_2]) and k_2' is respiration 1.98×10^{-8}[gO_2/g(wet)/sec] the value of which are followed after Kishi et al. (1995).

Parameters and conditions for the model

The other values of biological parameters are the same as in Kishi et al. (1995). There are ten vertical levels consisting of the 2, 3, 5, 5, 5, 5, 10, 15, 20 and 50 m. This spacing corresponds to the vertical height of the shellfish cultures, that is, oysters are cultured in the upper two levels (shallower than 5 m), and scallops are cultured in the third and fourth levels (i.e., between five and fifteen meters) those of scallop are kept. The horizontal grid spacing is 400 m. The horizontal grid size is not enough to distinguish individual rafts but it is enough to grasp the characteristics of aquaculture in this bay. The horizontal diffusion coefficient is $1.0 \times 10^6\,cm^2\,s^{-1}$ and viscosity is $7.5 \times 10^6\,cm^2\,s^{-1}$. The vertical diffusion and viscosity coefficients are estimated according to Pacanowski and Philander (1981).

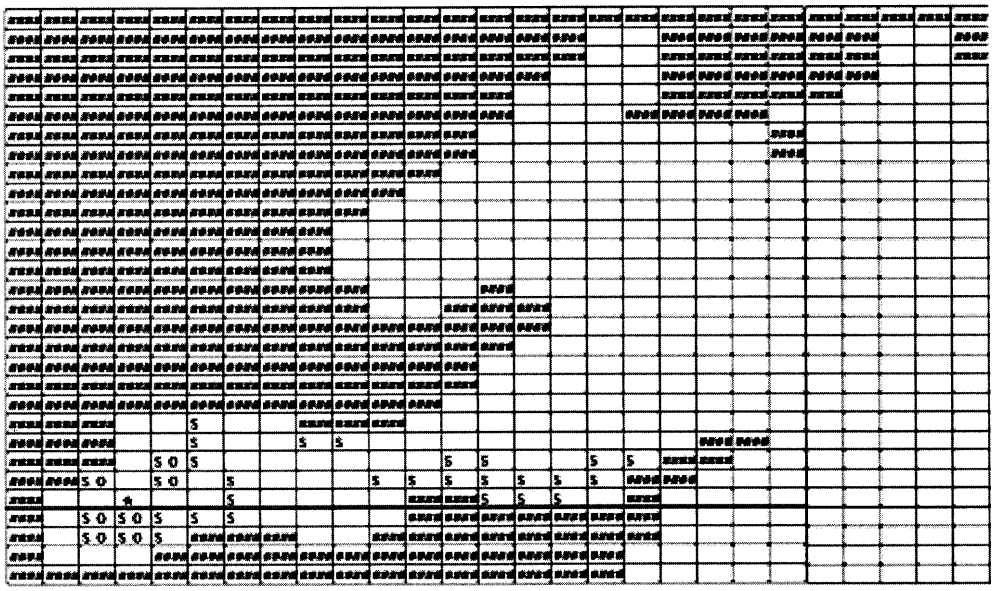

Fig. 3. Distribution of aquaculture rafts. S: scallop culture; O: oyster culture.

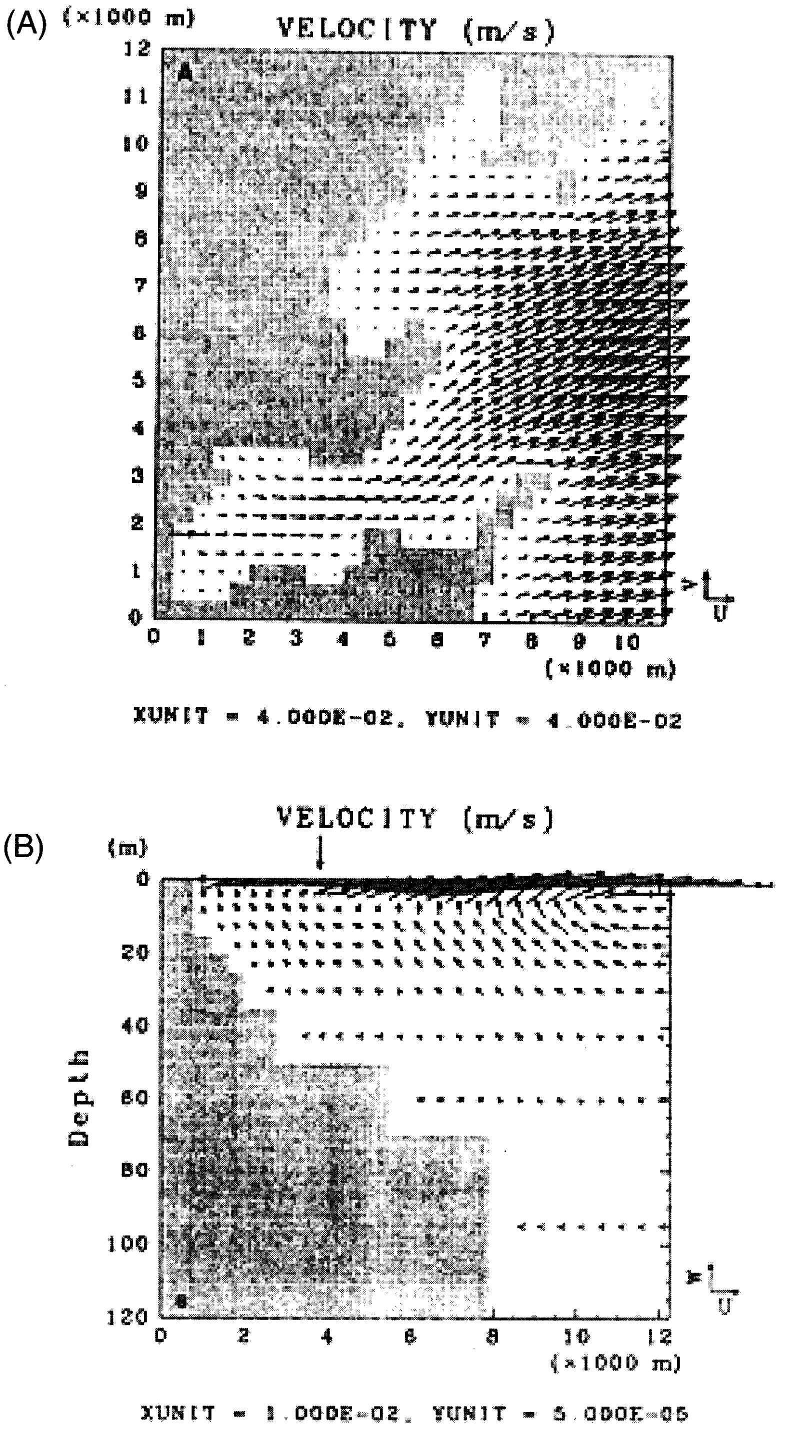

Fig. 4. Velocity fields: (A) horizontal view of the first level (1 m); (b) zonal view.

As for the current, we consider only the tidal current (M2) and wind stress because the inflow from the outer region changes from hour to hour and it is hard to evaluate their effects on nitrogen/phosphorus flow among the organisms. Figure 4 shows a horizontal velocity field for level 1 (i.e., 1.0 m depth) and zonal flow along the bay axis after 10 days from the initial state under wind forcing in March. As westerly winds drag surface water (down to 10 m) toward the mouth of the bay and a compensating current occurs toward the end of the bay in the deeper portion.

The model was calculated using the wind stress from 1st of March 2000 to 15th of March (at the boundary of the bay, temperature, salinity and biological compartments are fixed as described above). The basic equation is as follows;

$$\frac{\partial C}{\partial t} = -(v\nabla_h)C - w\frac{\partial C}{\partial z} + \nabla_h (K_h \nabla C) + \frac{\partial}{\partial z}\left(K_v \frac{\partial C}{\partial z}\right) + Q(C)$$

where C is arbitrary biological compartment and Q(C) is biological terms after Kawamiya et al. (1995).

Based on the observed values, the horizontally and vertically uniform values are set as initial and boundary conditions (initial conditions and boundary conditions are the same) as follows; in March, phytoplankton: 1.0 mg Chl.a

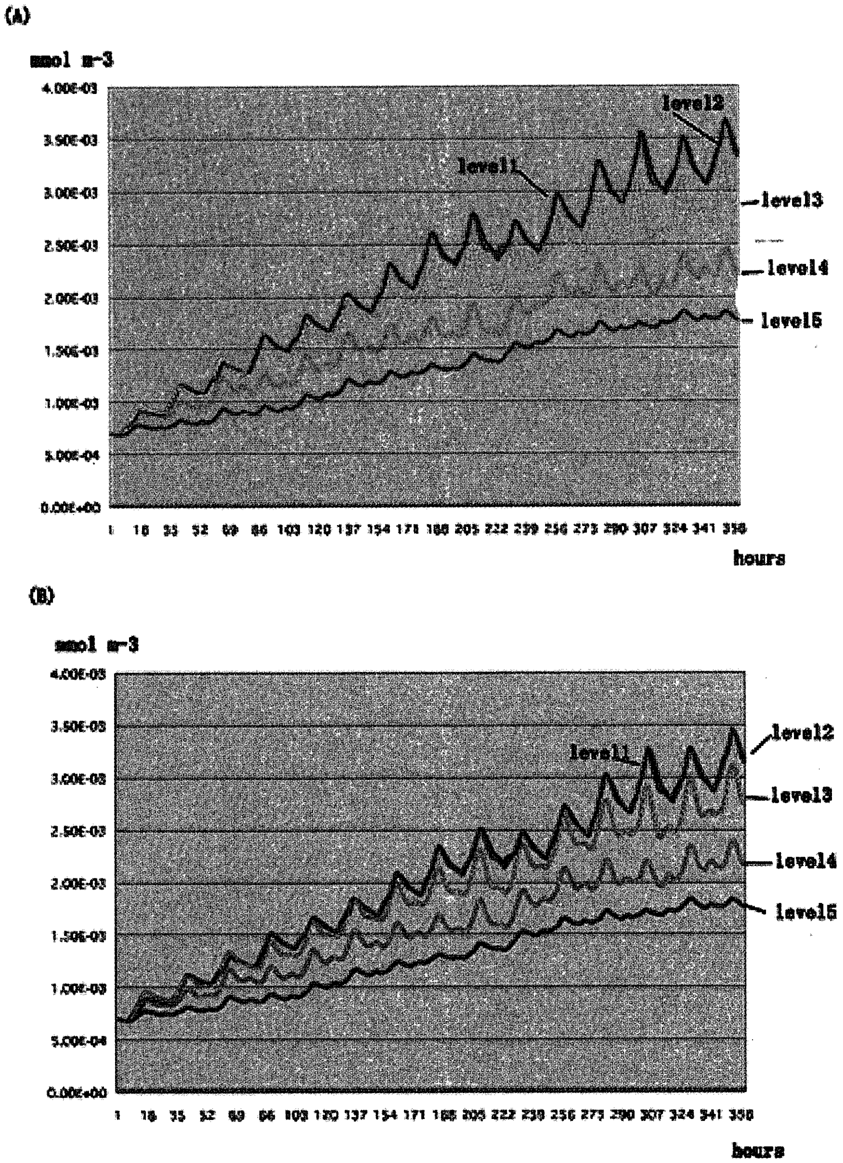

Fig. 5. Time dependent features of vertical distribution of phytoplankton (mmol N/m^{-3}): (A) in case of without shellfish culture; (B) in case with shellfish culture.

m^{-3} (50 mg C m^{-3}), zooplankton: 0.5 mmol N m^{-3}, PON: 0.4 mmol N m^{-3}, DON: 4.0 mmol m^{-3}, NO_3: 5.0 mol m^{-3}, NH_4: 0.5 mmol m^{-3}, water temperature 10.0°C, salinity: 34.8 psu.

The ecological part of the model was run for thirty days. The horizontal distribution of the aquaculture preserve is shown in Fig. 3. Oysters are introduced in November and grown up for one year and four months or two years. They are harvested from February to October of next year. Wakame sea grass is introduced in September, grown for 2 to 4 months and harvested from the next January to May. Consequently from December to May shellfish and seaweed are both in the bay area. Our calculation is carried out in March to investigate the competition and/or symbiotic relationships among these species and other organisms in the bay. The monthly averaged weight of shell fish and the other organisms in the preserves, river loading and also horizontal distributions of Chl.a, nutrients, water temperature and salinity were all collected by a fisheries experiment station (unpublished) in 2000 and 2001. Based on these data, the horizontal distributions of nutrients and phytoplankton at different levels for March in 2000 are calculated and discussed.

RESULTS AND DISCUSSION

Figure 5 shows time dependent features of the vertical distribution of Chl.a at the end of the bay where aquaculture is conducted intensively (indicated by the star in Fig. 3). The effect of the initial conditions seems to be diminished by day 15 (360 hrs). We discuss after day 15. Figure 5(A) shows the case without shellfish culture and Fig. 5(B) shows the case with shellfish culture. There is no big difference between two cases. In the shallower region, phytoplankton decreases with case without shellfish culture although it is not grazed by shellfish. In Fig. 6, however, ammonium in the same point increases in case with shellfish culture due to excretion. This means phytoplankton increases by using recycled nutrient in case with shellfish. In the upper layer NH_4 decreases due to the uptake by phytoplankton. In case with shellfish culture (Fig. 6(B)), the concentra-

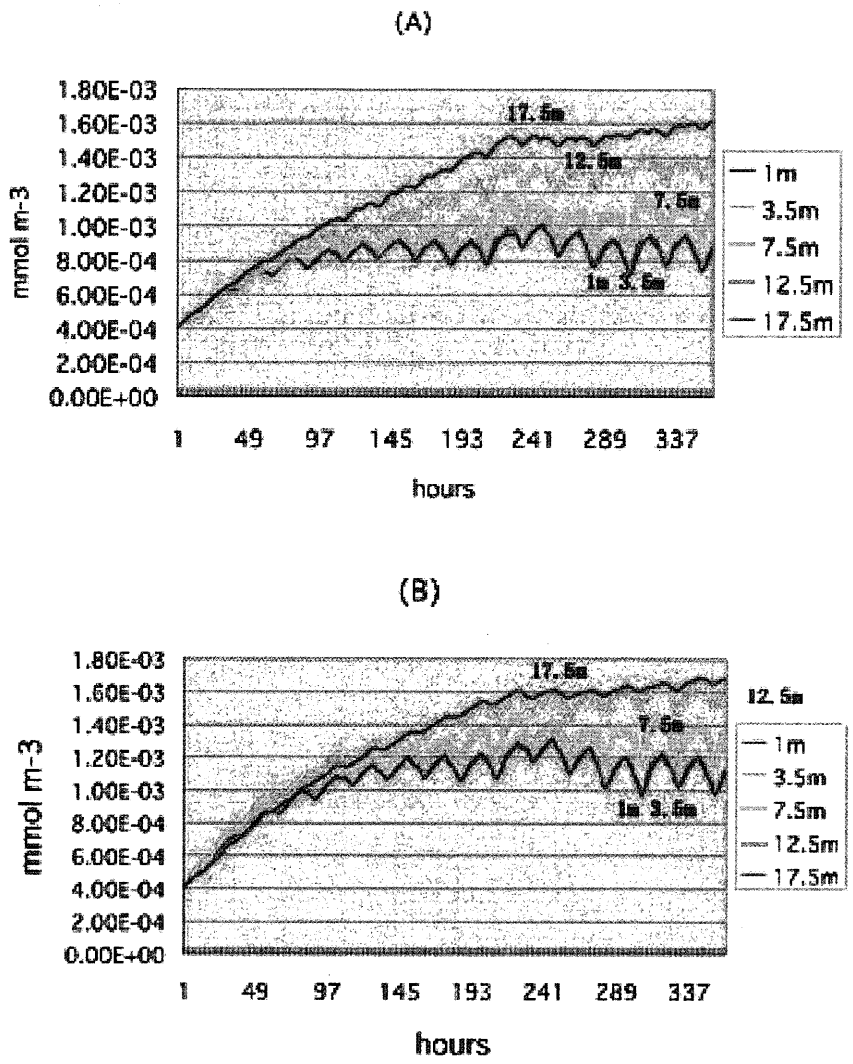

Fig. 6. Time dependent features of vertical distribution of ammonium (NH_4) (mmol N/m^{-3}): (A) in case of without shellfish culture; (B) in case with shellfish culture.

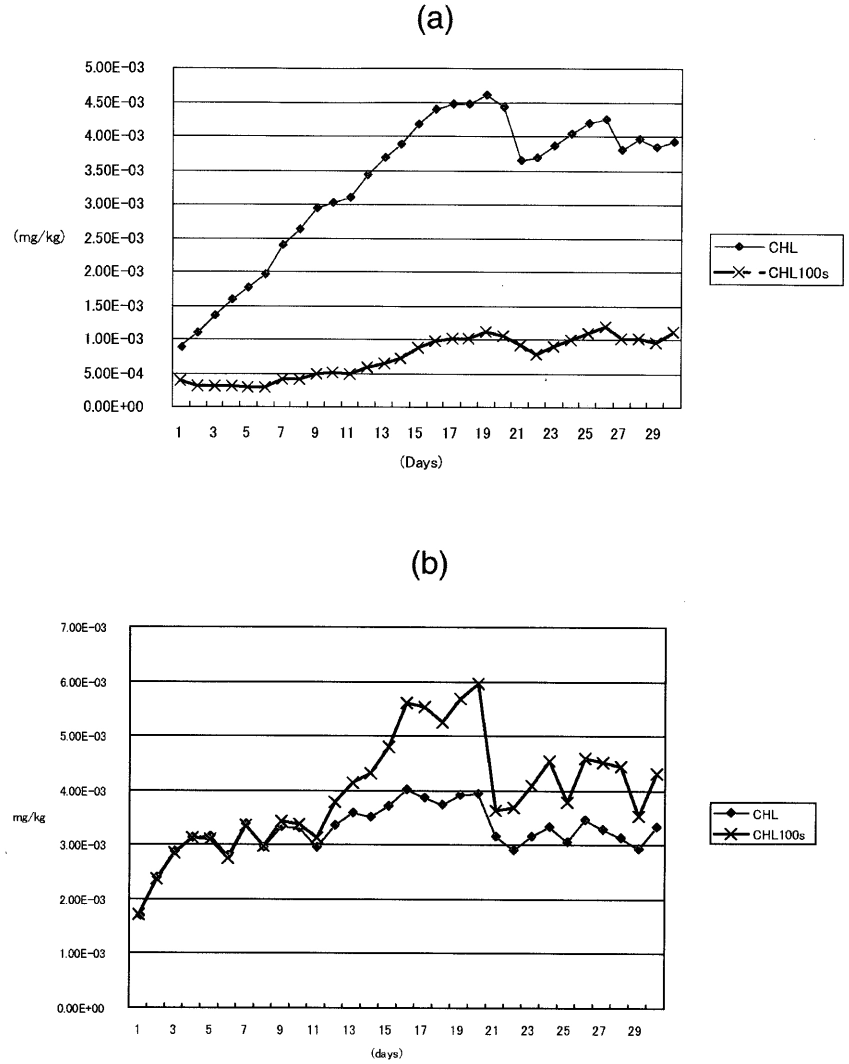

Fig. 7. Time dependent features of phtoplankton (mg chl a/m^{-3}) at sea surface. (a) Near the culture (shown in Fig. 3). (b) Outside the bay. (X: in case with 100 times shellfish culture)

tion of upper layer is much less than that in case without shellfish culture (Fig. 6(A)), because phytoplankton stock decreases due to grazing by shellfish as described above.

Oyster, for instance, filters water $1.57T-7.392$ (ℓ/d/g(wet)). When T is 8°C this amount reaches 1.16×10^6 (m^3/d), for the total amount of cultured oyster is guessed to be 2.2×10^5 (kg). The rough estimation of the total volume of Otsuchi Bay is 3.8×10^9 (m^3). This means that cultured oyster filters 0.03% of sea water of the bay per day. So the effect of cultured shellfish is very small for the nutrient cycle of the bay. If we set the amount of cultured shellfish to be 100 times, the effect must be considerable. In fact, Fig. 7 shows the comparison with normal case and 100 times cultured case. Figure 7(a) shows the time dependent features of phytoplankton of the surface near the culture and Fig. 7(b) shows that at the mouse of the bay. At the inner part of the bay, phytoplankton decreases due to the grazing of shellfish while it increases outside of the bay because of increased recycled nutrient by excretion of shellfish.

CONCLUSION

Using this model, we can assess the influence of the location or area of aquaculture preserves on the ecological and/or environmental system. However the ecosystem model only with the nutrient cycle has the limitation for the above purpose. We have to include the other compartments like oxygen, COD for the precise prediction of the environment. The effect of aquaculture on the lower trophic ecosystem can be found through this model.

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