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Long-term Prediction of Water Quality in Osaka Bay

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As an effort to clarify the ecosystem of Osaka Bay, a semi-enclosed coastal area under the influence of stratification, a three-dimensional water quality model with combination of the baroclinic flow model and primitive eco-system model was constructed. The proposed model succeeded in simulating the time-depending flow and density structure and the baroclinic residual currents in Osaka Bay. In present study, we tried to improve the model by taking account of the benthic-pelagic interaction and exchange of nutrients between sea bottom sediments and overlaying water. On vertical structure, the model consists of 13 layers of water and eight layers of sediments.

Long-term prediction of water quality was conducted from 1964 to 1985. This period is characterized by rapid water pollution and its decrease by the cutoff reduction of COD and P flowed into Osaka Bay. By combining the sediment model into original model, the numerical model was confirmed to shows more reasonable results in simulating the water quality in Osaka Bay.

Key Words : Water quality model, Release of nutrients, Sediments

1. Introduction

The rapid industrialization and urbanization around Osaka Bay area have produced much serious water pollution since 1950's. A symbolic phenomenon is the increase of red tide (algal bloom) appearance throughout the year. Since 1960's, eutrophication became so serious that the Japanese government set up Law Concerning Special Measures for Conservation of the Seto Inland Sea in 1973, to reduce the pollution loads from land. By analyzing the field data in Osaka Bay, the cutoff reduction of COD and P loads produced significant effects on the recovery of water quality; however it is found that there is four or five years delay in time series of COD and P between estimated pollution load and observed concentration. It has not been clarified why such a delay takes place.

It is well known that in enclosed waters like reservoirs and lakes, the reduction of inflow nutrients from lands could improve the water quality. However, the water quality improvement in water body has a tendency to be delayed in time after the reduction of inflow nutrients. The same phenomenon had been observed in Osaka Bay as shown in Fig. 1. In a study about water quality of lakes, Larsen et al.[1] pointed out that such a phenomenon might be induced by the exchange of nitrogen and phosphorus between the

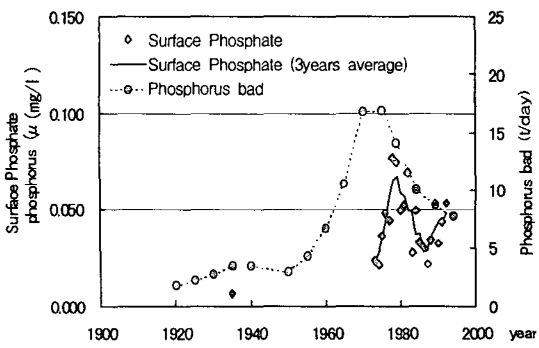

Fig. 1. The change of phosphorus loading from land and phosphorus concentration observed at surface layer in the head of Osaka Bay.

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sea bottom sediment and the overlying water.

The objective of the present study is to get better understanding of the nutrient release from the sea bottom sediment using numerical models. The Water System Lab of Osaka University developed the three-dimensional water quality model, which coupled the baroclinic flow model and primitive eco-system model. The baroclinic flow model had been successfully simulating the time-dependent 3-D flow and density structure, as well as the baroclinic residual currents in Osaka Bay under the fresh water influence.[2,3] In addition, 3-D water quality model based on primitive ecosystem also succeeded to predict the time change of nutrients.[4] Here we take into account the chemical/biological interaction and exchange of nutrients in the benthic-pelagic system, namely sea bottom sediment and overlaying water.

2. The flow structure and the change of pollutant loading in Osaka Bay

2.1. The flow structure

Osaka Bay is an oval-shaped bay with a 60km major axis from northeast to southwest and a 30km axis from northwest to southeast as shown in Fig. 2. The sea bottom of the bay is composed of soft clay and gravel sediment, which have been mainly transported by the Yodo and Yamato Rivers located at the head of the bay. In the past 40 years 6,300ha of coastal sea area in Osaka Bay have been reclaimed and a lot of development projects are still under construction. Most bay areas of less than 10m depth has been reclaimed. While, at least 90% of coastal line has been covered by artificially constructed breakwater. As a result, the seawater has been polluted due to poor exchange of water between outer oceans and inner bay coupled with the load of nutrients from rivers and industrial facilities. Algal bloom has occurred regardless of season and anoxia has appeared near the sea bottom especially in summer. From the physical viewpoints, the eastern bay area is stratified due to large amounts of river discharge with weak velocity, while in the western bay area, the flow velocity through Akashi and Kitan straits are very strong which cause the seawater well mixed in the vertical direction. As a result, a tidal front can be seen obviously along the boundary between stratified eastern sea area and well mixed western sea area.

The 3-D baroclinic simulation in Osaka Bay was conducted by Nakatsuji et al.[2] The result is shown in Fig. 3 and Fig. 4. In Fig. 3, one predominant residual current is the Okino-se circulation, which is produced the coalescence of headland eddies occurring at the cape of Awaji Island. Another circulation, called the off-Nishinomiya circulation, was clearly observed in the layer from depths of 3 m-5 m near the bay head. The circulation is quasi-geotropic. It is driven by the horizontal divergence of the upper layer water under the effects

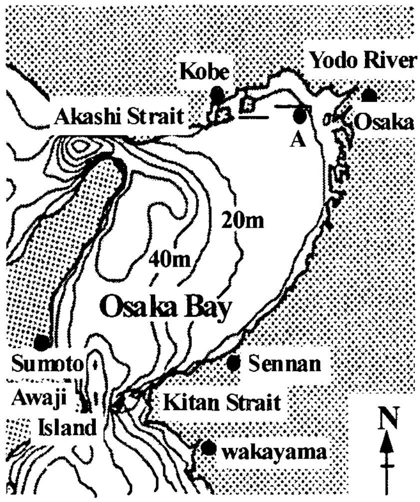

Fig. 2. Topography of Osaka Bay and computation domain.

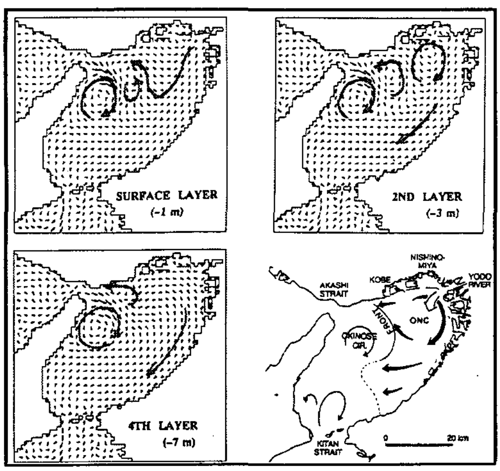

Fig. 3. The residual circulation in Osaka Bay; Lower and Right-hand side figure shows schematic view of anti-cyclonic circulation accompanied with estuarine vertical circulation based on field surveys and numerical simulation.

of the earth's rotation. Upwelling action of lower water is found to play an important role in anticyclonic circulation. That is to say, the vertical estuarine circulation results in promoting the anticyclonic circulation appearing at the head of Osaka Bay. Schematic illustration of above-mentioned residual circulation can be shown in the lower and right-hand side figure of Fig. 3.

Fig. 4 shows the 3D displacement of particles discharged from Yodo River with respect to time. Here the Lagrangian particle tracking method was used. Trajectories of 30,000 particles demonstrated the existence of residual circulation system and also its role on mass transport processes. We can find that Osaka Bay has a very complicated but interesting current system affected by independent external forces like tidal current, wind, atmospheric pressure, and streamflow.

2.2. The changes of pollutant loading

Red tide often occurred around 1970 as a result of eutrophication of seawater. The lack of policy to control pollutant loads caused serious pollution to the Seto Inland Sea including Osaka Bay. In such circumstance, the Law Concerning Special Measures for Conservation of the Seto Inland Sea was enacted in 1973, which is called Seto Inland Sea Law for short. This law contributed to a cut-off of COD loading from the land in half, reduction of P and N loads from land area, and restriction of reclamation of coastal seas. On the other hand, industrial plants and local governments made efforts to improve the water treatment facilities and residents living around Osaka Bay areas. People became more aware of the need for environmental conservation. As an example, laundry detergent without phosphorus has been widely used.

Fig. 5 shows the changes of the estimated pollution loads flowed from Osaka Prefecture into Osaka Bay. The loads could be estimated by multiplying the

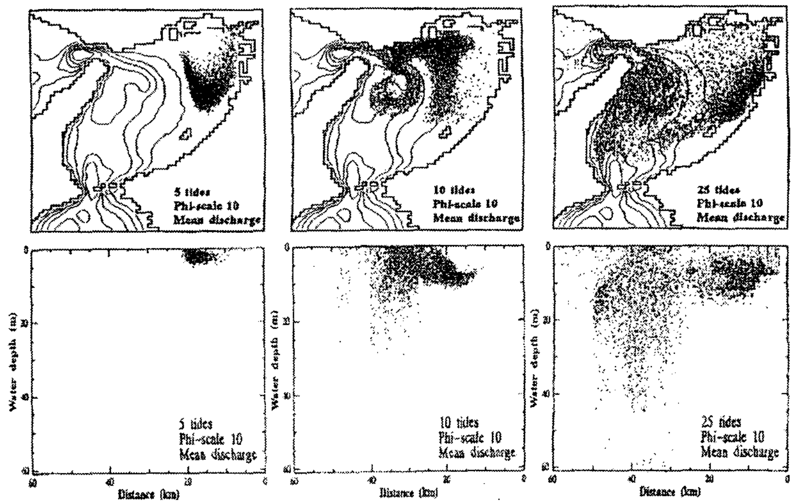

Fig. 4. The variation of 3D movement of particles released from Yodo River; Upper is horizontal view of tracer particles plotted independently of depths; lower is vertical view of particles projected at right angle to east-west cross section The particles behaviors are related with residual current system. In particular, estuarine circulation can be seen under the stratified interface.

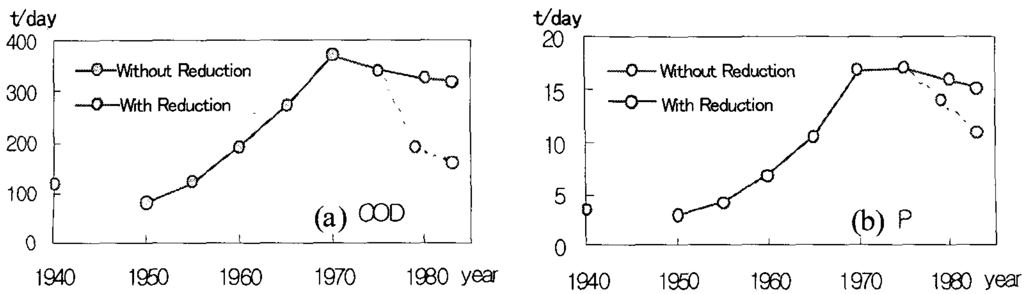

Fig. 5. The changes of pollutants loading from 1940 to 1983. ((a):COD, (b):Phosphorus).

volume of wastewater by the rate of loading, following the method used by Joh[5]. The sources of pollutants were wastewater from domestics, industries, agriculture and livestock.

The dotted line in Fig. 5(a) shows the change of the estimated COD loading. Factories with discharge more than 50ton/day of wastewater were regulated. In addition, many sewage treatment plants were constructed. For these efforts, the level of COD loading in 1970 successfully decreased into half of that in 1983. In Fig. 5(b), the dotted line demonstrates the change of estimated P loading. Although the Seto Inland Sea Law did not include regulation for P reduction, P decreased after 1970, as the same result of the improvement of wastewater treatment facilities for livestock and other industries. In addition, reduction of P also was accelerated by individual factory for social demand of less pollution.

3. Long-term prediction of water quality in Osaka Bay

3.1. Numerical Model

The three-dimensional water quality model has developed in cooperation with baroclinic flow model and primitive ecosystem model. The benthic and pelagic interaction and exchange of nutrients between sea bottom sediment and overlying water were carefully considered in this model.

The three dimensional baroclinic flow model is based on the conservation of volume, momentum and dispersion of salinity and temperature under hydrostatic and Bussinesq assumptions. Eddy viscosity and diffusivity are used for representing turbulence transport of momentum and scalar variables. Empirical formulas are used for the stratification influence.

The three dimensional water quality model based on primitive ecosystem is driven by physical, chemical, and biotic processes. The conceptual diagram of the model is shown in Fig. 6. Seven state variables are set in pelagic zone of water flowing: namely, phytoplankton; dissolved oxygen DO; dissolved inorganic nitrogen DIN; dissolved inorganic phosphorous DIP; organic nitrogen ON; organic phosphorous OP and COD. The advection and dispersion of such nutrients depend on flow and density structures in pelagic zone. Individual phytoplankton grows based on ingestion, respiration, excretion, and digestion.

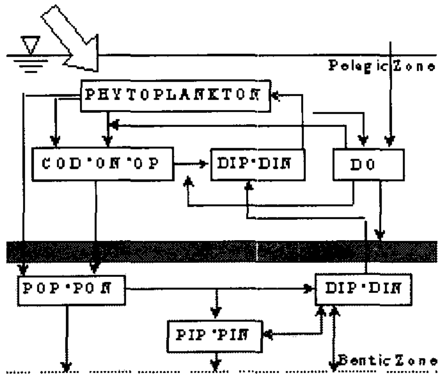

Fig. 6. Conceptual diagram of the model.

Population dynamics of phyto-plankton occurs according to migration, mortality, and reproduction.

The basic equations are shown as follows:

Process of Migration and Diffusion

$$\frac{\partial C_i}{\partial t} = -\frac{\partial UC_i}{\partial x} - \frac{\partial VC_i}{\partial y} - \frac{\partial WC_i}{\partial z} + kx\frac{\partial^2 C_i}{\partial x^2} + ky\frac{\partial^2 C_i}{\partial y^2} + kz\frac{\partial^2 C_i}{\partial z^2} + \Sigma s_i(C_j) \tag{1}$$

Where, C_i = concentration of substance, i

U, V, W = components of velocity in X (East-West), Y(north-south) and Z(up-down) direction respectively

K_x, K_y, K_z = vortex diffusion coefficients in X(East-West), Y(north-south) and Z(up-down) direction respectively, for which computational results of 3-D baroclinic flow are adopted and these terms are time-dependent varying at a different location in the space.

$S_i(C_j)$ = amount of changing from substance j to substance i representing the process of internal change

Process of Internal Change

$$\frac{\partial PP}{\partial t} = \{G_p - R_p - D_p\}PP + U_{pp}\frac{\partial PP}{\partial z} \tag{2}$$

$$G_p = \mu_{\max} \times F_N \times F_I \times F_T$$

$$F_{NU} = Min\left[\frac{IP}{K_{IP}+IP}, \frac{IN}{K_{IN}+IN}\right]$$

$$F_I = \frac{I}{I_s}\exp\left[1-\frac{I}{I_s}\right]$$

$$F_T = \frac{T}{T_s}\exp\left[1-\frac{T}{T_s}\right]$$

$$\frac{\partial IN}{\partial t} = -F_N G_N PP + K_N ON + \frac{W_{IN}}{H_b} \quad (3)$$

$$\frac{\partial IP}{\partial t} = -F_N G_N PP + K_P OP + \frac{W_{IP}}{H_b} \quad (4)$$

$$\frac{\partial OP}{\partial t} = -F_P\{R_P + D_P\}PP - K_P OP + U_{OP}\frac{dOP}{dz} \quad (5)$$

$$\frac{\partial ON}{\partial t} = -F_N\{R_P + D_P\}PP - K_N ON + U_{ON}\frac{dON}{dz} \quad (6)$$

$$\frac{\partial COD}{\partial t} = -F_c\{R_P + D_P\}PP - K_C COD + U_{COD}\frac{dCOD}{dz} + \frac{W_c}{H_b} \quad (7)$$

$$\frac{\partial DO}{\partial t} = -F_{PDO}\{G_b - R_P\}PP - F_{COD}K_C COD + K_s(DOS - DO_s) - \frac{W_{DO}}{H_b} \quad (8)$$

where, PP = concentration of phytoplankton (chlorophyll a)

G_P = multiplication rate of PP

R_P = respiration rate of PP

D_P = withering rate of PP

F_{NU}, F_I, F_T = terms dependent respectively on nutrients, radiation and temperature of water for multiplication rate

IP, IN = concentration of inorganic phosphorus and nitrogen respectively

K_{IP}, K_{IN} = half-saturated coefficients of phosphorus and nitrogen respectively

U_{PP}, U_{OP}, U_{ON}, U_{CD} = sedimentation rate of PP, OP, ON, COD respectively

OP = organic phosphorus

ON = organic nitrogen

COD = concentration of COD

DO = concentration of oxygen

K_P, K_N, K_C = decomposition rate of phosphorus, nitrogen and oxygen respectively

K_S = aeration coefficient

H_b = thickness bottom layer

W_{IP}, W_{IN}, W_C = quantity of release of phosphorus, nitrogen and oxygen from sea bottom mud respectively

W_{DO} = oxygen consumption by sea bottom mud

DOS = concentration of saturation dissolved oxygen

DO_S = concentration of dissolved oxygen on surface layer

F_P, F_N, F_C, F_{PDO}, F_{COD} = converted coefficients from chlorophyll-a respectively

As for sediment model, six state variables are considered in benthic (sea bottom sediment) zone: DIN; DIP; particulate organic nitrogen PON; particulate organic phosphorous POP; particulate inorganic nitrogen PIN; particulate inorganic phosphorous PIP. The PIP, however, consists of two constituents: exchangeable and non-exchangeable.[6,7] Initial values of those state variables are given on the basis of empirical data in Osaka Bay.

The sediment model is based on the following assumption: (1) OP and ON are divided into biodegradable and stable fractions. (2) Exchangeable PIP represents Fe-phosphorus fraction, non-exchangeable particulate phosphorus represents the sum of Ca- and Al-phosphorus fractions. (3) Denitrification is considered for pore water nitrogen. (4) Degradation rates of POP and PON are in proportion to temperature and dissolved oxygen concentration in overlying water. (5) Release rates of DIP and DIN are in proportion to temperature in overlying water. Especially release rate of DIP depends on dissolved oxygen concentration in overlying water.

The benthic-pelagic coupling is carefully considered in the present model. Organic detritus settle onto benthic zone while mineralization of organic matter in the sediment is included. After mineralization, diffusion of nutrient occurs based on the nutrient flux between water column and bottom sediment. The proposed model is characterized by taking account of detailed mechanism of nutrient dynamics in benthic zone.

3.2. Outline of Computation

As computation domain, Osaka Bay is divided into 32×32 grids in the horizontal direction. The size of each grid is 2 km. It is minimum resolution for representing the baroclinic residual currents peculiar to physical processes in Osaka Bay.

Water column is also divided into 13 layers in the vertical direction. The thickness of layer is 2m for 10 layers, 10m for 2 layers and 15m for 13th layer from sea surface to bottom. The sea bottom sediments consists of 8 segments. The size and shape of each segment is different corresponding to the characteristics of fluid dynamics and topography of the bay. The bottom sediment is also divided into 8 layers in the vertical direction, the thicknesses of the layer is a range from 2cm to 40cm.

Based on meteorological condition, fluid dynamics through the year can be classified to four terms corresponding to the four seasons, namely March-May, June-Aug., Sept.-Nov. and Dec.-Feb.. Flow pattern for each season was computed by using 3-D flow model(ODEM;Osaka Daigaku Estuary Model). The computed velocity and eddy diffusivity was transferred into water quality model.

Table 1. Model Variables

Variables		Value (unit)
Pelagic Zone	Maximum growth rate	2.4 (1/day)
	P nutrient half saturation	0.005 (g/m3)
	N nutrient half saturation	0 025 (g/m3)
	P decomposition rate	$0.02 \times 1.09^{T-20}$(1/day)
	N decomposition rate	$0.02 \times 1.09^{T-20}$(1/day)
	Reaeration coefficient	0.1 (1/day)
Benthic Zone	P decomposition rate	1.0×10^{-3}(mg/g/day)
	N decomposition rate	1.0×10^{-3}(mg/g/day)
	Distribution coefficient for P	12.5
	Distribution coefficient for N	89
	Diffusion coefficient.	5.4×10^{-3} (cm^2/s)

Table 2. The boundary conditions for flow and water quality model

Boundary Condition				Spring	Summer	Autumn	winter
Flow model	Surface of seawater	Temp. (℃)		16.3	26.7	15.2	5.5
		Amount of Clouds		6.2	6.3	5.4	5.8
		Wind Velocity (m/s)		3.2	3.0	3.2	3.2
		Vapor Pressure (hPa)		12.2	25.8	12.1	5.8
		Amount of Insolation (W/m2)		184.6	193.4	109.0	96.6
	Fresh water	Stream flow (m^3/s)	Yodo River	273.8	367.9	165.7	142.1
			Yamato River	23.8	27.2	21.2	16.1
		Temp. (℃)		18.0	28.9	18.0	7.0
		Salinity (psu)		21.5	20.0	21.5	23.0
	Seawater	Tide		M2			
		Temp. (℃)		13.0	22.0	22.0	11.0
		Salinity (psu)		32.0	32.0	32.0	32.0
Water quality model	Seawater	COD (mg/l)		* 2.0 **1.5	* 2.6 **1.9	* 2.0 **1.5	* 1.3 **1.1
		T-N (mg/l)		* 0.36 **0.36	* 0.38 **0.38	* 0.36 **0.36	* 0.34 **0.34
		T-P (mg/l)		* 0.034 **0.030	* 0.039 **0.031	* 0.034 **0.030	* 0.029 **0.029
		Chl. a (mg/l)		* 0.004 **0.004	* 0.005 **0.005	* 0.004 **0.004	* 0.005 **0.005
		DO (mg/l)		* 8.6 **8.6	* 8.1 **8.1	* 8.5 **8.5	* 9.0 **9.0
				* Akasi strait ** Kitan strait			

The computation started by using the distribution of water quality in 1965 as an initial condition. And the computation was repeated by taking the time change of nutrient loading from land as boundary conditions into account until 1988. The time increment was 60 seconds. Parameters used in the model are summarized in Table 1.

The decomposition rates of nitrogen and phosphorus were decided by the experiment. Other variables were decided referring to the references.[6,8] Boundary conditions for four seasons are shown in Table 2. Loads from land area was given by collecting 21 rivers flowing into Osaka Bay. The loads were computed by multiplying the concentration of water quality by amount of water at the boundary of entrance of each river. Water quality of outside sea boundary was based on the field data.

3.3. Verification of the Model

To examine the validity of the proposed model, it is necessary to compare predicted data with observed one. Fig. 7 shows the comparison of the release rate of DIP from the sea bottom. The white circles mean field data observed at the head of Osaka Bay by Horie and Hosokawa.[8] The observation point is indicated by symbol 'A' in Fig. 2. It is near the Yodo River estuary in bay head and at the front of long breakwater off Port Nishinomiya. The release rate of DIP might be proportional to the water temperature, and it might be in inverse proportion to the DO concentration of the overlying water.; hence its value is 5 mg/m^2/day in winter, while about 25 mg/m^2/day in summer. Change of predicted release rate over time is also shown by solid line. The prediction result shows a good agreement with observed data.

Fig. 8 shows a comparison of total phosphorus concentration between predicted and observed data. Osaka Prefecture Fisheries Experimental Station has conducted regular monthly observations in 20 stations in Osaka Bay since 1972. Main nutrients have been measured every three months at every single station. T-P is measured at the surface layer. The predicted T-P concentration has a tendency to increase with time until 1973 and to gradually decrease after 1973. On the other hand, the observed values of T-P seem to be a little scattered. However, their time-moving average give s a good agreement with the time change of predicted results.

3.4. Results and Disscussion

The predicted results of T-P concentration from 1964 to 1988, were compared with the loading of P discharged from land. The reductions of COD and P were discussed in Section 2. As shown in Fig. 9, the predicted T-P concentration rapidly increased before 1970 accompanied with increase in P loading. After its value attained the peak, T-P concentration decreased gradually. The rate of decrease in T-P was affected by the regulation by The Seto Inland Sea Law. The decreasing rate of T-P with cutoff reduction of COD and P loading is higher than that without cutoff reduction. Compared to the level of T-P concentration in 1975, T-P concentration reduced by 37% in 1985 while the cutoff reduction was practiced. On the other hand, estimated T-P concentration

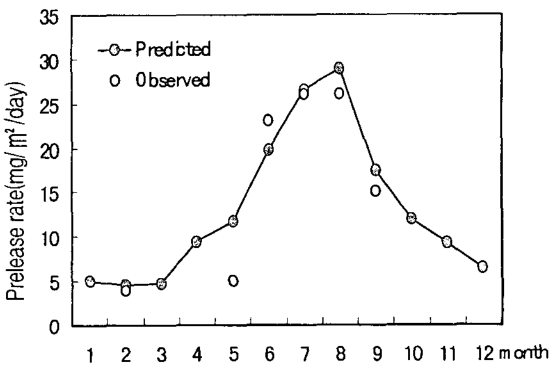

Fig. 7. Comparison between measured and calculated data for the release rate of DIP(Left fig.).

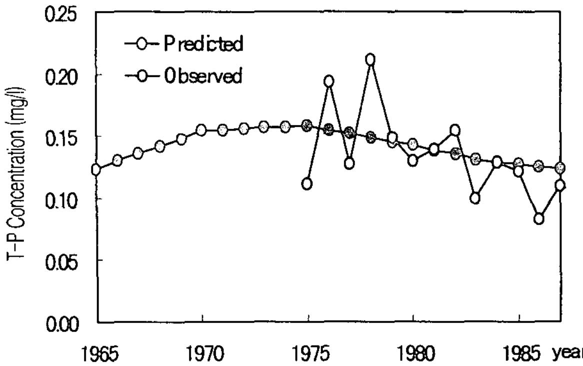

Fig. 8. Comparison between calculated and measured data for T-P concentration in the head of Osaka Bay(Right fig.).

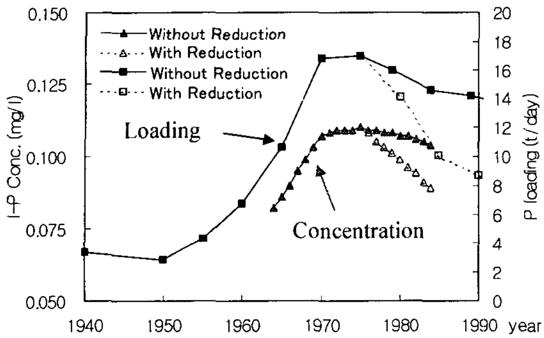

Fig. 9. T-P concentration for long-term computation assuming the loading of P from 1964 and 1985 depending on reduction.

without cutoff reduction decreased by 11% in 1975. It is obvious from the fact that the regulation of reduction of nutrient loading enforced strong effects on improvement of water quality.

These computation results, however, could not predicted the time difference between the reduction of P loading and the decrease in T-P concentration as demonstrated in Fig. 1. One of the reasons is that the point 'A' is located inside the Off-Nishinomiya Circulation and the resident time of nutrients is only eight days or more. In addition, entrainment of lower water into stratified upper layer is very large as expected. It is necessary to analyze the computation results and to discuss the complicated mechanism of pelagic and benthic interaction including exchange of nutrients between sea bottom sediment and overlaying water.

4. Conclusions

In the present study, the three-dimensional water quality model with the baroclinic flow model and the primitive eco-system model is improved on taking account of the exchange of nutrients between pelagic and benthic zones. By enclosing the sediment part, the water quality model shows reasonable results in seasonal variation of release rate of DIP and the change of T-P concentration at stratified upper layer in the bay head in Osaka Bay.

Then, the long-term period computation was carried out using the model with 13 levels in water pelagic column and 8 levels in benthic (sediment) zone during period from 1964 to 1988. In this period, rapid industrialization and urbanization brought out water pollution in Osaka Bay and The Japanese Government put the cutoff reduction of COD and P loading was conducted through practice of The Seto Inland Sea Law. The computation results show that the cutoff reduction of nutrients has effects on the recovery of water quality.

However, it still cannot explain the time delay between the loading P and observed T-P concentration, which was obviously appeared in observation results. For clarifying the mechanism of water quality in Osaka Bay, more efforts of field survey and the refined modeling are required.

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