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Three-Dimensional Water Quality Modeling of Chinhae Bay
진해만의 3차원 수질 모델링

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Abstract □ A three-dimensional hydrodynamic-ecosystem model was developed and applied to Chinhae Bay which is located in the southeastern sea of Korea. The model includes a three-dimensional hydrodynamic model and an eutrophication model, and the model operates on the same grid system. The agreement between predicted and measured results is reasonably encouraging. The concentrations of the calculated COD, DIN and DIP are appeared to be very high due to the phytoplankton production and the wastewater input in the northern part of Chinhae Bay. Anoxic and hypoxic water masses in the bottom layer occur in the northern part of the bay due to the excess loading of wastewater and strong stratification, and in the western inner part of the bay due to high oxygen consumption in densely populated aquaculturing facilities. DO concentration contours show parallel to the bay entrance line, which means the importance of supplying DO by physical process from the mouth of the bay. Although both the hydrodynamic and biochemical processes play important role to form the hypoxic waters in the bottom of the inner bay, it is suggested that the hydrodynamic conditions such as the vertical and the horizontal eddy diffusivity are primarily important factors.

Keywords : ecosystem model, eutrophication, hypoxia, anoxia, hydrodynamic processes

要 旨 : 해수유동 모델과 부영양화 모델로 구성된 3차원 생태계 모델을 수립하여 진해만에 적용하였으며, 해수유동 모델과 부영양화 모델은 동일한 격자상에서 운영된다. 수치계산결과를 관측결과와 비교하였으며, 그 결과 비교적 잘 일치하였다. 계산된 COD, DIN 및 DIP의 농도는 오폐수의 과다유입과 식물성 플랑크톤의 생산에 의해 진해만의 북부 지역(마산만)에서 높게 나타났다. 저층에서 저산소 및 무산소 수괴는 오폐수의 유입량이 많고 성층이 강하게 형성되는 진해만의 북부해역과 성층형성과 양식장이 밀집되어 있는 진해만의 서부 내만에서 발생하고 있다. DO 농도의 등분포선은 만 입구로부터 DO 공급과 물리적 작용에 의해 만 입구에서 만 내로 DO의 수송으로 인해 만의 입구와 평행하게 나타났다. 저층 저산소 수괴의 형성에 물리적, 생화학적 과정이 대단히 중요한 역할을 하며, 이 중에서 해수의 수평적·연직적 확산에 의한 물리적 작용이 제일 중요한 요소인 것으로 판단된다.

핵심용어 : 생태계 모델, 부영양화, 저산소, 무산소, 동역학적 과정

1. INTRODUCTION

Chinhae Bay is one of the most polluted coastal bay in Korea (Fig. 1), and the productivity has declined significantly. The bay is plagued with problems that accompany agricultural and industrial development and population growth along its shore and headwaters. The increased loading of contaminants into water bodies has resulted in hypoxic and anoxic water masses and frequent red tide problem in Chinhae Bay during summer season. The concentrations of nitrogen and phosphorus which are the main nutrient sources of eutrophication have rapidly in-

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creased since 1985 (Kang and Lee, 1992). Many of these problems including bottom-water anoxia, red tide and decline in fisheries are associated with the eutrophication of the bay. Therefore the present study is focused mainly on the processes affecting the eutrophication and the hypoxic water in the bay.

A combined hydrodynamic and ecological model is needed to understand the processes contributing to the formation of the anoxic and hypoxic water masses. It was acknowledged that ecosystems are extremely complex systems and the difficult part of modelling is therefore to select the ecologically relevant components and processes in a given problem context, which requires a profound ecological knowledge. Much more modelling experience has been gained since 1980 (Cerco and Cole, 1993; Nakata, 1993; Cerco, 1995; Lung *et al.*, 1995; Cho and Chae, 1999; KORDI, 1999). Water quality models mainly deals with the physical transport of chemical constituents in the water, using the simulated oxygen concentration as an indicator of water quality. They are usually based on nutrient and phytoplankton submodels, since primary production and mineralization of the produced biomass are the main determinants of oxygen saturation in the water. Models of this type have been further developed into the direction of general eutrophication models (Bach, 1993; Baretta and Ruardij 1987); good examples of this category are MIKE21 EU (Vested *et al.*, 1991), ERSEM (ERSEM, 1993) and CE-QUAL-ICM (Cerco and Cole, 1993). The MIKE21 EU model system consists of an advanced 2D circulation model in combination with modules describing advection-dispersion, oxygen dynamics and carbon/nutrient cycling in the lower trophic levels. The model is depth-integrated and thus cannot resolve any vertical structure in the water column. It therefore cannot be used reliably in stratified areas. ERSEM is a comprehensive ecosystem model which dynamically simulates the large-scale cycling of organic carbon, oxygen and the macronutrients N, P and Si over the seasonal cycle. Horizontal transport is prescribed by daily exchange volumes between boxes, derived from the results of a 3D physical circulation model. Vertical mixing is prescribed by time-varying exchange coefficients across the boundary between the surface and deep boxes. The model has limitation of coarse spatial resolution in horizontal and vertical directions. The ERSEM model was indirectly coupled between hydrodynamic and ecological submodels. CE-QUAL-ICM is a three-dimensional eutrophication model, and the model incorporates 22 state variables that include physical properties; multiple forms of algae, carbon, nitrogen, phosphorus, silica, and dissolved oxygen. The CE-QUAL-ICM model solves the conservation of mass equation for each grid cell.

This paper is in focus in development of ecological model and its applicability to Chinhae Bay. Effective management of water quality in Chinhae Bay requires understanding of the mechanism that lead to the appearance of the anoxic and hypoxic water masses. We investigate these mechanisms using a 3D model that consists of hydrodynamic model and eutrophication model. The present study advances the state of the art in eutrophication modeling. It is coupling of the eutrophication model and a 3D time-variable hydrodynamic model. Thus, the hydrodynamic and eutrophication models operate on a grid that provides lateral and vertical resolution, and the models is run on PC. Prior to application to this model, most of eutrophication models were commonly run in steady-state.

2. OBSERVATIONS AND RESULTS

To obtain hydraulic and water quality parameters, field observations of temperature, salinity, dissolved oxtgen (DO), NO_2-N, NO_3-N, NH_4-N, PO_4-N, chemical oxygen demand (COD), total suspended solids (TSS), Chlorohyll-a, pH etc. were carried out at stations shown in Fig. 1 from

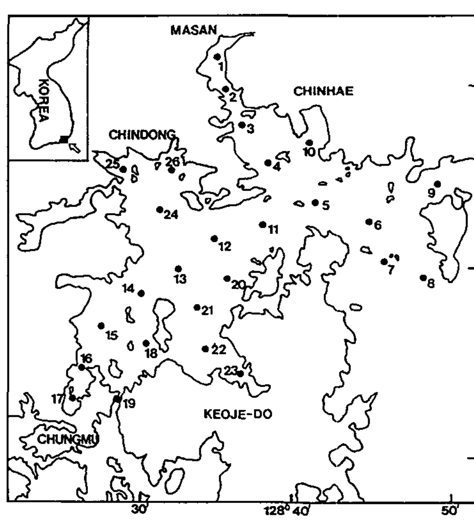

Fig. 1. Observation stations in Chinhae Bay.

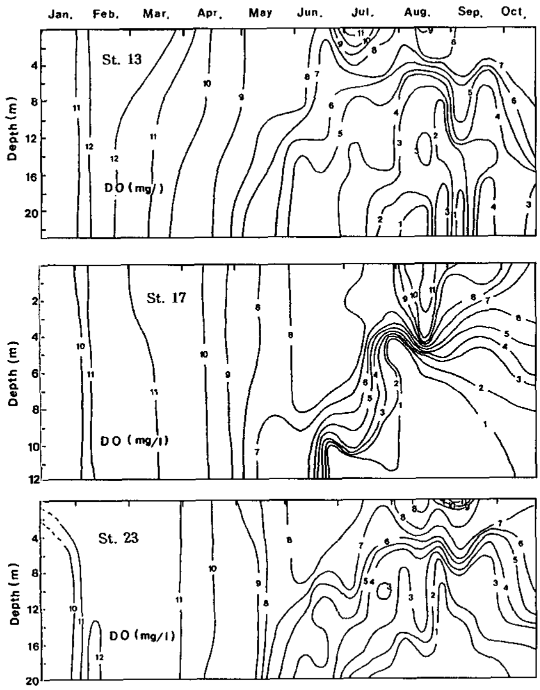

Fig. 2. Monthly depth profiles of DO measured at Sts. 13, 17 and 23 in 1993.

1990 to 1994. The bay consists of fifty minor-streams, and the major sources of freshwater to the bay are located at the northern part (Masan Bay) of the bay. External loads to the system were observed on April 25~26 and July 23~24, 1994 using 3 surveying ships, and the results of hydraulic and water quality parameters are given in NFRDA (1995).

The observed results at Sts. 13, 17 and 23 in 1993 are shown in Fig. 2. It is surprised the anoxic water masses (DO 1.0 mg/) were extended to 9 m depth at St. 17 and to 9 m at St. 23, and the anoxia lasted from June to September. The problem of the anoxia in the inner bay can be attributed to the presence of strong stratification due to weak vertical mixing.

3. NUMERICAL MODEL

3.1 Model Description

To investigate the mechanism producing the anoxic and hypoxic water masses in Chinhae Bay, three-dimensional hydrodynamic water quality model is developed and applied to the field. The model consists of two submodules: a three-dimensional hydrodynamic model (Kim and Lee, 1994) and an eutrophication model.

3.1.1 Hydrodynamic Model

Hydrodynamic model produces three-dimensional predictions of velocity, diffusion, surface elevation, salinity and temperature. The finite difference form of the governing equations is solved using ADI integration scheme.

Assuming hydrostatic pressure distribution and Boussinesq approximation, the governing equations for an incompressible fluid in a three-dimensional (x, y, z) coordinate system with the z-axis vertically upwards are:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \tag{1}$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=fv-\frac{1}{\rho_o}\frac{\partial p}{\partial x}+\frac{\partial}{\partial x}\left(\varepsilon_x\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(\varepsilon_y\frac{\partial u}{\partial y}\right)+\frac{\partial}{\partial z}\left(\varepsilon_z\frac{\partial u}{\partial z}\right) \tag{2}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}=-fu-\frac{1}{\rho_o}\frac{\partial p}{\partial y}+\frac{\partial}{\partial x}\left(\varepsilon_x\frac{\partial v}{\partial x}\right)+\frac{\partial}{\partial y}\left(\varepsilon_y\frac{\partial v}{\partial y}\right)+\frac{\partial}{\partial z}\left(\varepsilon_z\frac{\partial v}{\partial z}\right) \tag{3}$$

$$\frac{\partial p}{\partial z}=-\rho g \tag{4}$$

$$\frac{\partial(hT)}{\partial t}+\frac{\partial(huT)}{\partial x}+\frac{\partial(hvT)}{\partial y}+\frac{\partial(hwT)}{\partial z}=\frac{\partial}{\partial x}\left(k_xh\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_yh\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_zh\frac{\partial T}{\partial z}\right) \tag{5}$$

$$\frac{\partial(hS)}{\partial t}+\frac{\partial(huS)}{\partial x}+\frac{\partial(hvS)}{\partial y}+\frac{\partial(hwS)}{\partial z}=\frac{\partial}{\partial x}\left(k_xh\frac{\partial S}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_yh\frac{\partial S}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_zh\frac{\partial S}{\partial z}\right) \tag{6}$$

where u, v and w are the velocities in x, y and z directions respectively, p is the pressure, ρ_o is the reference density, f is the Coriolis parameter as $2\omega\sin\phi$ where ϕ is the latitude, ω is the angular speed of earth rotation, t is the time, g is the gravity, ρ is the density, ε_x, ε_y and ε_z are the eddy viscosity coefficients in x, y and z directions respectively, and k_x, k_y and k_z are the diffusion coefficients in x, y and z directions, respectively. For k_x and k_y, we assume a value, $k_x=k_y=a\,l^{4/3}$, after Richardson (1926), where a=0.01 and l=grid size of simulation, and k_z is given by Kim (1994). The equation of state is

$$\rho=\rho\,(\mathrm{Cl},\,T) \tag{7}$$

Knudsen's (1931) equation is applied here. The above equations are numerically solved after Kim and Lee (1994). The open boundaries are forced with O_1, K_1, M_2 and S_2 tidal constituents using the data at Kaduk and Kyunnaeryang channels (Kim, 1994).

3.1.2 Eutrophication Model

At an arbitary point in the sea, the time change of the standing stock or biomass in each compartment can be described by the following diffusion equation:

$$\frac{\partial(hB)}{\partial t}+\frac{\partial(huB)}{\partial x}+\frac{\partial(hvB)}{\partial y}+\frac{\partial(hwB)}{\partial z}=\frac{\partial}{\partial x}\left(k_x h\frac{\partial B}{\partial x}\right)$$
$$+\frac{\partial}{\partial y}\left(k_y h\frac{\partial B}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_z h\frac{\partial B}{\partial z}\right)+RSST \quad (8)$$

Where B is the biomass of the compartment, u, v, and w are velocities in x, y and z directions, respectively, k_x, k_y and k_z are diffusion coefficients in x, y and z directions, respectively, and RSST represents external loads and kinetic sources and sinks in each compartment. To estimate the material flux in the bay or coastal area, this equation should be coupled with a 3D hydrodynamic model. The magnitudes of u, v, and w computed from the hydrodynamic model are used to predict temporal and spatial variations in the biomass of each compartment.

In this model, the organic components of the ecosystem are divided into 4 compartments: phytoplankton, zooplankton, detritus and dissolved organic matter, and phosphate and inorganic nitrogen is considered as inorganic compartments. The benthic system in this model is treated as a boundary condition. In addition, DO and COD can be incorporated into the model as water quality compartments if necessary. The processes included in nutrient cycle model are the production of organic nitrogen and phosphorus, and decomposition of these to inorganic nutrients. Sinking processes are also incorporated into the model. The parameter values chosen for the eutrophication model are obtained from measurements (NFRDA, 1995; Kim, 1997).

3.1.3 Biological Processes

1) Phytoplankton (P: mgC/m^3)

The time change of phytoplankton biomass is described as follows:

dP/dt=growth - extracellular release - respiration - grazing by zooplankton - grazing by benthos - mortality - sinking

2) Zooplankton (Z: mgC/m^3)

The time change of zooplankton biomass is described as follows:

dZ/dt = grazing - egestion - excretion - mortality ± vertical migration

3) Particulate Organic Matter (POC: mgC/m^3)

This compartment refers to organic detritus and is expressed in carbon units such as POC. PON or POP are determined from the POC concentration using the C/P and C/N ratios of the detritus. The time change of the POC compartment is described by the following equation:

dPOC/dt = mortality of phyto-P + mortality of zoo-P + egestion - biodegradation - by production of DOC-sinking + loading

4) Dissolved Organic Carbon (DOC: mgC/m^3)

Dissolved organic matter is calculated on the basis of dissloved organic carbon, thus the concentration or biomass expressed in the unit of nitrogen or phosphorus are converted to carbon using C/N or C/P ratios. The time change of DOC is described as follows:

dDOC/dt = extracellular release + input from POC - degradation + loading

5) Phosphate (DIP)

Dissolved inorganic phosphorus (DIP) is considered in the model as phosphate PO_4-P, and the behavior of phosphorus in biological processes is represented as follows:

dDIP/dt = -uptake by phytoplankton + phytoplankton respiration + zooplankton excretion + mineralization of POC + mineralization of DOC + regeneration from the bottom + loading

6) Dissolved Inorganic Nitrogen (DIN)

Inorganic nitgrogen here represents the total of NH_4-N, NO_2-N and NO_3-N, and the biological processes of DIN are represented as follows:

dDIN/dt = -uptake by phytoplankton + phytoplankton respiration + excretion from zooplankton + mineralization of organic suspension release from the bottom + loading

7) Dissolved Oxygen (DO)

The time change of DO is described as follows:

dDO/dt = supply by phytosynthesis - consumption by phytoplankton respiration - consumption by zooplankton respiration - consumption by detritus mineralizations - consumption by DOM mineralizations - consumption by sediment + reaeration

8) Chemical Oxygen Demand (COD)

dCOD/dt = input from phytoplankton compartment +

input from zooplankton compartment + input from POC compartment + input from DOC compartment

The above detailed descriptions and the formula governing the bio-chemical processes are given in Nakata (1993).

3.2 Numerical Solution

Hydrodynamic model and eutrophication model operate on the same grid, and the integration time is 2 months. Model grid resolution is 500 m in the horizontal, and is discretized by 78×81 horizontal points and 5 levels in the vertical, the depth varies from 3 to 20 m. The computational time step is 30 s (Table 1). The amount of discharges, nitrogen, phosphorus, and COD loading etc. from fifty streams were obtained from measurements (NFRDA, 1995). Most of fresh water inflow occurs in the northern part of the bay. The parameter values used for the computations presented in this paper are summerized in Table 1. The finite difference form of the governing equations was solved using ADI integration scheme. The model BACHOM-3 (Kim and Lee, 1994) was run with horizontal viscosity of 24 m^2/s, bottom friction coefficient of 0.005 and internal friction coefficient of 0.0025 throughout the bay.

The available water quality data for Chinhae Bay were restricted to measurements of temperature, salinity, COD, DO, DIN, DIP, and chrolophyll. Due to the data limitations, we could only develop a simple biochemical model that considers the inorganic-organic nutrient cycle. The processes included in this model are the production of organic nitrogen and phosphorus, and decomposition of these to inorganic nutrients. Sinking processes were also incorporated into the model. The parameters used in the model and their initial status are shown in Tables 2~4. Table 2 shows the initial vertical profiles for all compartments, and table 3 shows the open boundary conditions of

Table 2. Initial values of ecosystem compartment.

Compartment	Level 1	Level 2	Level 3	Level 4	Level 5
Phytoplankton (mgC/m^3)	500	500	500	500	500
Zooplankton (mgC/m^3)	50	50	50	50	50
POC (mgC/m^3)	400	400	400	400	400
DOC (mgC/m^3)	700	700	700	700	700
DIP (μg-at/*l*)	1.3	1.3	1.3	1.3	1.3
DIN (μg-at/*l*)	10	10	10	10	10
DO (mg/*l*)	8.0	8.0	7.0	7.0	7.0
COD (mg/*l*)	1.3	1.3	1.3	1.3	1.3

Table 3. Open boundary condition of ecosystem model.

Compartment	Level 1	Level 2	Level 3	Level 4	Level 5
Phytoplankton (mgC/m^3)	500	500	500	500	500
Zooplankton (mgC/m^3)	30	30	30	30	30
POC (mgC/m^3)	400	400	400	400	400
DOC (mgC/m^3)	600	600	600	600	600
DIP (μg-at/*l*)	1.0	1.0	1.0	1.0	1.0
DIN (μg-at/*l*)	8.0	8.0	8.0	8.0	8.0
DO (mg/*l*)	9.0	8.0	8.0	7.0	7.0
COD (mg/*l*)	0.8	0.8	0.8	0.8	0.8

Table 1. Computational conditions of flow and eutrophication model.

Parameters	Values
Horizontal grid interval	$\Delta x=\Delta y=500$ m
Time interval in the hydrodynamic model	$\Delta t=30$ s
Time interval in the diffusion model	$\Delta t=300$ s
Vertical grid interval	Level 1: 3 m (0~3 m)
	Level 2: 5 m (3~8 m)
	Level 3: 5 m (8~13 m)
	Level 4: 5 m (13~18 m)
	Level 5: below 18 m
Horizontal eddy viscosity coefficient	$\varepsilon_x=\varepsilon_y=24\ m^2/s$
Horizontal eddy diffusion coefficient	$k_x=k_y=24\ m^2/s$
Vertical eddy diffusion coefficient	$k_z=3\ cm^2/s$
Initial salinity concentration	33.0‰
Salinity concentration at open boundary	33.0‰
Internal friction coefficient	$\gamma_i^2=0.0025$
Bottom friction coefficient	$\gamma_b^2=0.0050$
Coriolis parameter	$f=8.37\times10^{-5}$

Table 4. Parameter values used in ecosystem model.

Parameter	Value
Maximum growth rate of phytoplankton (1/day)	0.893 exp (0.0633T)
Respiration rate of phytoplankton (1/day)	0.01 exp (0.0524T)
Maximum grazing rate of zooplankton(1/day)	0.18 exp (0.0693T)
Half saturation constant for phosphate (μg-at/l)	0.1
Half saturation const. for inorganic nitrogen(μg-at/l)	3.0
Settling velocity of phytoplankton (m/day)	0.173
Mortality of phytoplankton(1/day)	0.01
Mortality of zooplankton (1/day)	0.054
Ivlev index for grazing$(m^3C/m^3)^{-1}$	0.01
Optimum light intensity for photosynthesis (cal/m^2 day)	200
Chl-a/C ratio of phytoplankton	0.021
P/C ratio of phytoplankton	0.001403
N/C ratio of phytoplankton	0.01171
P/C ratio of zooplankton	0.000704
N/C ratio of zooplankton	0.0132
Gross growth efficiency of zooplankton (%)	30
Digestive efficiency of zooplankton (%)	70
P/C ratio of particulate organic matter	0.0005048
N/C ratio of particulate organic matter	0.009921
P/C ratio of disolved organic matter	0.0002581
N/C ratio of disolved organic matter	0.007143
Reaeration coefficient (1/day)	0.15
Settling velocity of POC (m/day)	0.432
Mineralization rate of DOC (1/day)	0.02 exp (0.0693T)
Half saturation constant of DO for minera. of DOC (mg/l)	1.0
Mineralization rate of POC (1/day)	0.2 exp (0.07T)
Half saturation constant of DO for minera. of DOC (mg/l)	1.0
Fraction of POC decomposition to DOC to minera. of POC (%)	25.0
Release rate of P from bottom (mg/m^2/day)	2.45
Release rate of N from bottom (mg/m^2/day)	24.5
Oxygen consumption rate at bottom (mg O_2/m^2/day)	1,500 exp (0.0377T)

the model. The initial and boundary conditions were determined from data observations taken by NFRDA (1995). The typical summer distribution(NFRDA, 1995; Kim, 1997) was used as the initial and boundary values. Values assigned to ecosystem model parameters are listed in Table 4.

3.3 Results and Discussion

Since the flow fields generated by the hydrodynamic model are to be used in the long-term computation of water quality parameters, it is important to demonstrate the ability of the model to compute the proper residual circulation of the bay. Fig. 3 shows the computed monthly averaged near-surface currents in the bay. The typical gravity induced circulation pattern in Chinhae Bay is reproduced by the model. The simulated circulation patterns show outflow from the bay in the upper most level. The magnitude of the computed near-surface residual currents is in the range of 5 to 15 cm/s, and the currents in the western central part of the bay are rotating anti-clockwise.

The results of the validation at the monitoring stations in summer are shown in Fig. 4. Summer is a critical season for bay water quality due to the occurrence of bottom-water anoxia. Comparisons between measured and modelled concentrations of DIN, DIP, COD and DO are presented for these monitoring sites. The monitoring results were published by NFRDA (1995) for the purposes of these comparisons. The comparisons exhibit a high degree

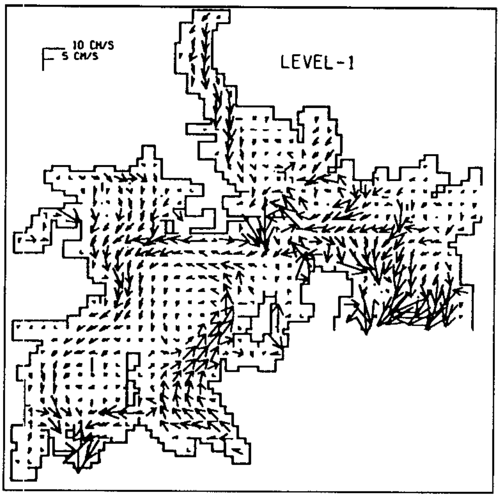

Fig. 3. Computed tidal residual currents in level 1.

of correlation. The correlation coefficients of DIN, DIP, COD and DO are 0.75, 0.79, 0.90 and 0.75, respectively. The concentrations of observed DIN are higher than those of the simulations, whereas the concentrations of the monitored DIP, COD and DO are lower than those of the simulations. Discrepancies between predictions and observations are attributable to degree of stratification in the model and field, which is derived from hydrodynamic effects.

The simulated distributions of DIN, DIP and COD in near-surface and near-bottom are shown in Figs. 5, 6 and 7, respectively. The concentrations of the simulated COD, DIN and DIP are found to be very high in the northern coast (Masan Bay) of Chinhae Bay. The region of high concentration corresponds to the region in which there is the largest source of loading, and also the region has weak tidal currents. This area is receiving wastewater from the cities of Changwon and Masan. These concentrations from the inner bay toward the bay entrance decrease gradually, and the concentrations in Kaduk channel (bay entrance) are very low because of the dilution by the strong water mixing in the horizontal and vertical directions and the small amount of DIN and DIP inputs from open sea. The model yields encouraging results. The concentration of COD in the surface layer becomes over 4 ppm in the northern bay area, and this highly organic polluted water

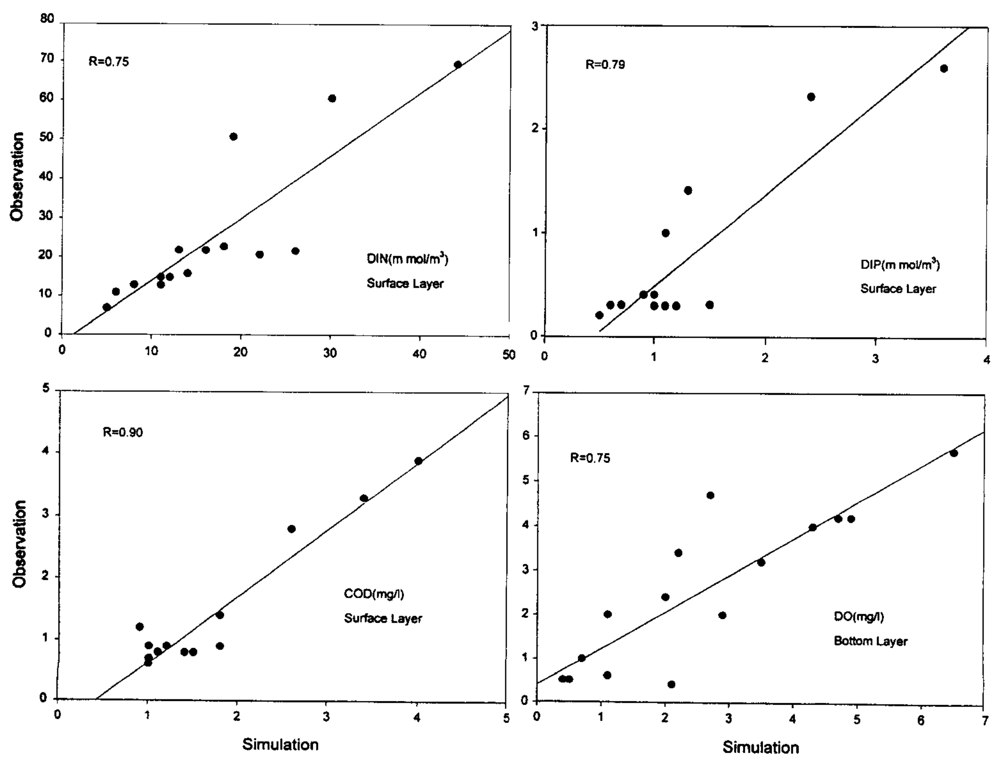

Fig. 4. Comparisons of simulated and observed results.

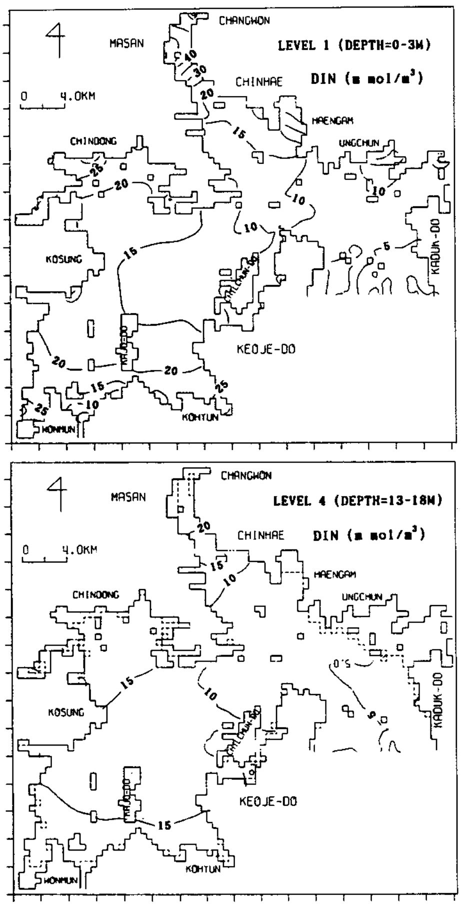

Fig. 5. Computed DIN distributions in near surface and bottom.

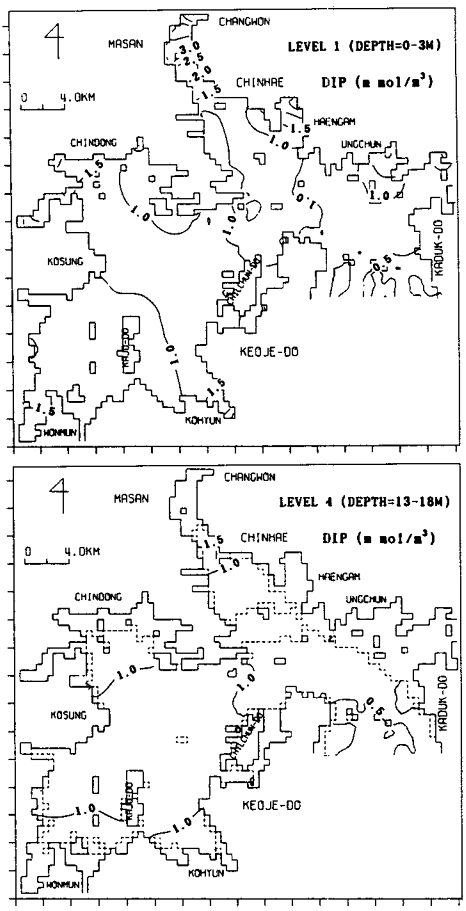

Fig. 6. Computed DIP distributions in near surface and bottom.

is presumably attributed to the phytoplankton production and the wastewater input from urban area. The organic rich particulate pollutants input at the northern part of the bay can be accumulated in the inner part of the bay. The contribution of phytoplankton abundance to the COD concentration is sometimes more than the contribution of the physically dispersed one from the loading of land origin. High concentration of COD in the northern area of the bay is presumably attributed to abundant phytoplankton, which relates to nutrient loading from land.

The distributions of DO concentration in the surface and the bottom are shown in Fig. 8. The values are on the whole larger in the upper layer than those in the lower layer because of photosynthesis. Bottom DO concentration around the northern part of the bay having large wastewater and the western part of the bay having aquaculture-farm shows a lower value compared with the other area. Regions of anoxia (DO$\leq$1.0 mg/l) and hypoxia (DO $\leq$2.0 mg/l) occur almost in the inner bottom bay due to the wastewater input, weak mixing and the increment of the oxygen consumption in high density of culturing facilities.

Our model agrees with observation (Lee *et al.* 1993; NFRDA, 1995; Kim, 1997) that low-DO waters occur in the western inner bay and the nothern bay. The simulated DO concentrations in the bottom layer of the bay entrance channel are usually more than 4.0 mg/l, whereas the concentrations in the inner part of the bay in summer are less than 2 mg/l. The formation of the anoxic and hypoxic waters in the inner part of the bay may be attributed to the existence of strong stratification, the weak mixing and the excess loading of organic and inorganic pollutants from land (Kim, 1994; Kim, 1997). Thus, we need to consider what processes remove inorganic nitrogen from these areas. DO concentration contours show parallel to the bay

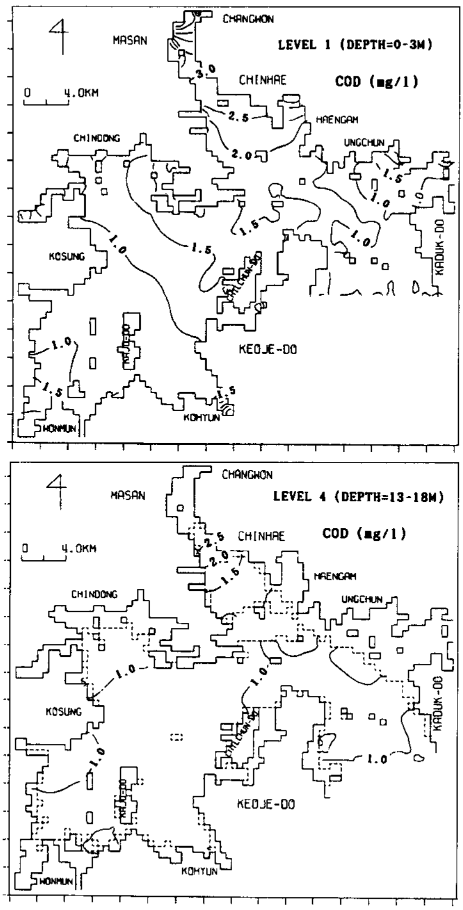

Fig. 7. Computed COD distributions in near surface and bottom.

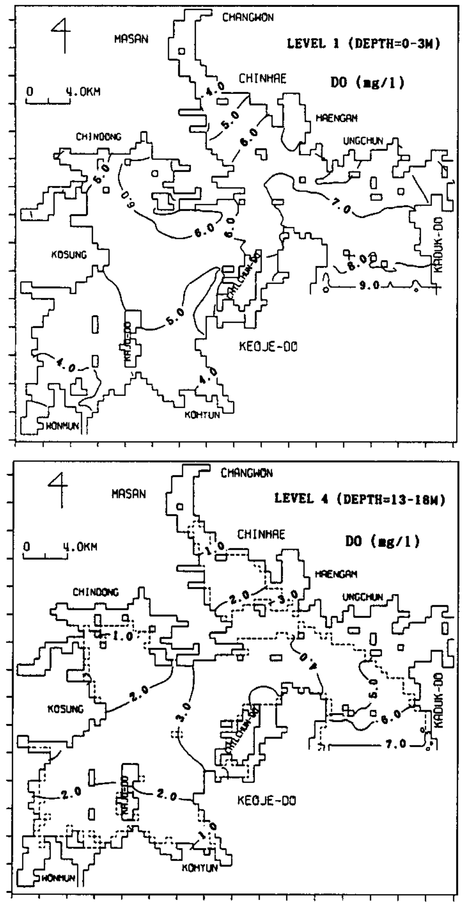

Fig. 8. Computed DO distributions in near surface and bottom.

entrance line, which means the importance of the supplying DO by physical process from the mouth of the bay. DO could be consumed on the bottom water-sediment complex in the transporting process toward the inner bay and might be disapeared until the water mass reached the inner bay. This fact may be closely related to the large amount of oxygen consumption in the inner bay. Also from these results, the gravity induced circulation by the fresh water inflow can act to maintain the favorable oxygen condition in the bottom water by promoting the water exchange process between the bay water and the outer boundary water. As the gravity induced circulation become stronger associated with the increasing of fresh water inflow, the oxygen rich water along the bottom layer could be supplied. This result implies that although the microbiological processes in the sediment-water interface also plays important role on the formation of the hypoxic water masses in the inner part of the bay, it is not primary important. For the verification of these mechanisms we must need further investigation. Improvements in model-data agreement require new estimates of loads to the system and reformulation of model principles.

4. CONCLUSIONS

In order to analyze the water quality of Chinhae Bay which is located in the southeastern sea of Korea, an ecosystem model has been developed and applied to the bay. The model includes a three-dimensional hydrodynamic model and an eutrophication model, and the model operates on the same grid. The computed results have been compared with field measurements, and the agreement between predicted and measured results are reasonably encouraging. The concentrations of the simulated COD, DIN and DIP are found to be very high in the northern part of Chinhae Bay having large amounts of domestic and industrial wastes. This highly organic polluted water is presumably attributed to the phytoplankton production and the wastewater input from urban area.

Bottom DO concentrations in the northern part of the bay having large waste water and the western part of the bay having aquaculture-farm are lower than those of the other area. The formation of the anoxic and hypoxic waters in the inner part of the bay may be attributed to the existence of strong stratification and the excess loading of organic and inorganic pollutants from land and the increment of the oxygen consumption in high density of culturing facilities. DO concentration contours show parallel to the bay entrance line, which means the importance of the supplying DO by physical process from the mouth of the bay. This result implies that although both of the hydrodynamic and biochemical processes play important role to form the hypoxic waters in the bottom of the inner bay, it is suggested that the hydrodynamic conditions such as the vertical and the horizontal eddy diffusivities are primary important factors. To obtain better understanding on the bay ecosystem, the detailed study on the biochemical processes will be needed.

REFERENCES

Bach, H.K., 1993. A dynamic model describing the seasonal variation in growth and distribution of eelgrass. I. Model Theory, *Ecological Modelling*, **65**(1), pp. 31-51.

Baretta, J.W and Ruardij, P., 1987. Evaluation of the Ems estuary ecosystem model, *Cont. Shelf Res.*, **7**, pp. 1471-1476.

Cerco, C.F. and Cole, T., 1993. Three-dimensional eutrophication model of Chesapeake Bay, *J. Envir. Engrg.*, ASCE, **119** (6), pp. 1006-1025.

Cerco, C.F., 1995. Simulation of long-term trends in Chesapeake Bay eutrophication, *J. Envir. Engrg.*, ASCE, **121**, pp. 298-310.

Cho, H.Y. and Chae, J.W., 1999. Water quality modeling for environmental management in Chinhae Masan Bay, *J. Korean Society of Coastal and Ocean Engrg.*, **11**(1), pp. 41-49 (in Korean).

ERSEM, 1993. An overview of the European Regional Seas Ecosystem Model (ERSEM), In: K.-G. Barthel, M. Bohle-Carbonell, C. Fragakis and M. Weydert (Editors), *Marine Science and Technologics.* MAST Days and Euromar Market, Vol. 1. Commission of the European Communities, Luxembourg, pp. 339-354.

Lee, P.Y., Park, J.S., Kang, C.M., Choi, H.G. and Park, J.S., 1993. Studies on oxygen-deficient water mass in Chinhae Bay, *Bulletin of National Fisheries Research Development and Agency*, Report No. 47, pp. 25-38 (in Korean).

Lung, W.S. and Larson, C.E., 1995. Water quality modeling of upper Mississippi River and Lake Pepin, *J. Envir. Engrg.*, **121**, pp. 691-699.

Kang, S.W. and Lee, J.C., 1992. On the development of water quality prediction model for enclosed seas, *Proc. 1992 Int. Oceans Space and Resources Utilization Seminar and 29th Ocean Engrg. Res. Workshop*, Underwater Technology, Ulsan, Korea (in Korean).

Kim, C., 1994. Three-dimensional numerical model experiments of tidal and wind-driven currents in Chinhae Bay, *J. Oceanol. Soc. Korea*, **29**, pp. 95-106.

Kim, C., 1997. A shallow water front and water quality in Chinhae Bay, *J. Korean Society of Coastal and Ocean Engrg.*, **9**(2), pp. 86-96.

Kim, C. and Lee, J., 1994. A three-dimensional PC-based hydrodynamic model using an ADI scheme, *Coastal Engrg.*, **23**, pp. 271-287.

Knudsen, M., 1931. Hydrographical tables, GEC Gad. Copenhagen, London.

KORDI, 1999. Development of coastal water quality assessment and prediction technology (in Korean).

Nakata, K., 1993. Ecosystem model; its formulation and estimation method for unknown rate parameters, *J. Adv. Mar. Tech. Soci.*, **8**, pp. 99-131 (in Japanese).

NFRDA, 1995. Study on the phenomena of coastal eutrophication and red tide (in Korean).

Vested, H.J., Jensen, O.K., Ellegaard, A.C., Bach, H.K., and Rasmussen, E.K., 1991. Circulation modeling and water quality prediction, *Proc. 2nd Int. Conf. on Estuarine and Coastal Modeling*, ASCE, Florida, pp. 317-331.

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