(25) **Water Quality and Simulation by the Box Model in the Ariake Sea**

有明海の水質とボックスモデルを用いたシミュレーション

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Abstract; The Ariake Sea is a typical semi-closed water body surrounded by lowlands. The area of tidal flat accounts for 40% of all those in Japan and both the tidal flat and the sea has high fishery production. In recent decades, there are progressive developments such as new harbor, land reclamation and enclosure of a bay. Recent fishery production is abruptly decreasing, and thus it is necessary to investigate the environmental status. In this study, after developing a two-dimensional water quality model in the Ariake Sea, the characteristics of water quality through the observed data and simulation results were examined. As a result, it was indicated that the tidal flat plays an important role especially in nutrients. The discharged pollutant loads affect the concentrations of COD in summer. However, these high concentrations occur for a short period before being flushed out to the open sea.

Keywords; The Ariake Sea; Water Quality; Field Survey; Finite-volume Model; Simulation.

1. Introduction

The Ariake Sea is a typical shallow sea in Japan. Its total area is about 1,700 km^2 with 100km gulf axial length, 16 km of average width, and 20 m of average water depth. The Ariake Sea has the largest tidal range in Japan, which is about 6 m at a spring tide in the gulf inner part. A tidal flat appearing with such large tidal range is also the greatest, that is 207 km^2 or about 40% of a total tidal flat area in Japan. The estuarine areas and tidal flat are very rich habitation and suitable for spawning. Many typical species can be observed along coastal areas. The fishery and laver productivity in the Ariake Sea and its tidal flat are very high.

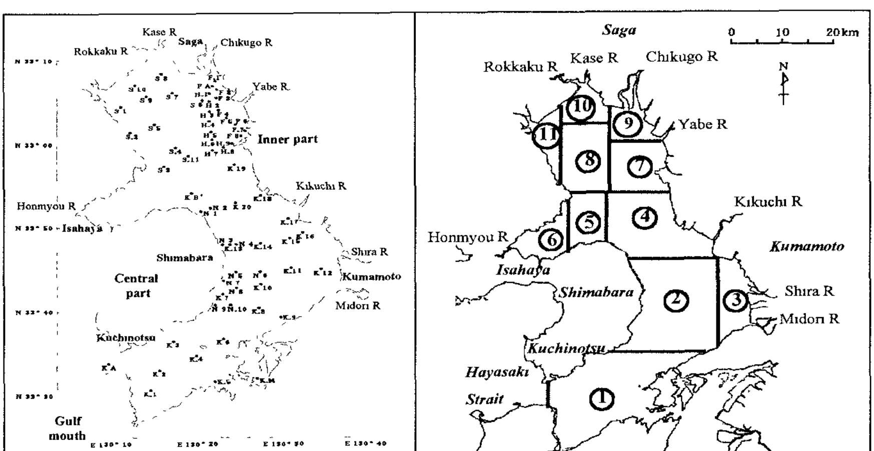

Figure 1 (a) The Ariake Sea, and (b) box element in the model.

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For this several decades, various kinds of human activities have been rapidly developed in this area. The effects of these activities on water quality, characteristics of the seabed and ecosystem are the keen concern of people.

The objective of this study is to develop numerical model based on the finite-volume model for water quality analysis in the Ariake Sea and to examine the characteristics of water quality through the observed data and numerical simulation.

2. Methodology

2.1 Monitoring data of water quality

There are 57 fixed observation points in the Ariake Sea as shown in Fig. 1(a). At these points, regular monitoring and sampling at the high tide of every spring tide have been carried out for 10 to 37 years by related four prefectures. In this study, the selected water quality (salinity, COD, DIN, and PO_4-P), among the observed data are shown with results of numerical simulation.

2.2 Water quality modeling

Based on natural transport, the two-dimensional finite-volume model is developed for water quality simulation in the Ariake Sea. The finite-volume model is widely used[1),2),3),4)] to represent the transport of conservative and non-conservative materials in the water body where the water movement varies significant like the Ariake Sea.

Each divided element is considered to be complete mixing state. Focusing on the overall water quality and bottom sediment in the Ariake Sea, in this study it is assumed that there is no effect of density currents in water movement.

The mass balance equation of material transported across any element is described[5)] in Eq.(1).

$$\frac{dV_i c_i}{dt} = \sum_j (G_{ji} + D_{ji}) \pm S_i \tag{1}$$

where $dV_i c_i/dt$ = mass change in element i $[M/T]$
V_i = volume in element i $[L^3]$
G_{ji} = mass transport from element j to element i by advection $[M/T]$
D_{ji} = mass transport from element j to element i by dispersion $[M/T]$
S_i = reaction in element i $[M/T]$

Advection term (G_{ji}) and dispersion term (D_{ji}) are given in Eqs.(2) and (3).

$$G_{ji} = Q_{ji}[\delta_{ji} c_j + (1-\delta_{ji}) c_i] \tag{2}$$

where Q_{ji} = net flow rate from element j to element i $[L^3/T]$
δ_{ji} = net advection factor [-]

$$D_{ji} = E'_{ji}(c_j - c_i) \tag{3}$$

where E'_{ji} = mixing coefficient $[L^3/T]$

By substituting advection term and dispersion term with Eqs.(2) and (3), Eq.(1) can be written as

$$\frac{dV_i c_i}{dt} = \sum_j \{Q_{ji}[\delta_{ji} c_j + (1-\delta_{ji}) c_i] + E'_{ji}(c_j - c_i)\} \pm S_i \tag{4}$$

Both advection factor (δ_{ji}) in advection term and mixing coefficient (E'_{ji}) in dispersion term are assigned to be constant in this study. The reaction parameters are summarized in Table1.

The water quality in the finite-volume model is defined as averaged value over the finite volume and specific time constant. The specific time in this study is one day (two tidal cycles). Therefore, observed concentration in each element is treated as an averaged value. This averaged value can be mathematically defined under the assumption of no density currents even if concentration distribution exists.

Table 1 Reaction equations and parameters used in water quality simulation in the Ariake Sea.

Algae (diatom and green algae)

$S_{tAlgae} = Algae_{Growth} - Algae_{Decay} - Algae_{Settling}$

$Algae_{Growth} = \mu \cdot Chl\text{-}a_t \;\; T_A \;\; V_t$

$Algae_{Decay} = K_d \;\; \theta^{(Tt-T0)} \;\; Chl\text{-}a_t \cdot V_t$

$\mu = \mu_{Max} \cdot DIN_t / (K_N + DIN_t) \cdot PO_4\text{-}P_t / (K_P + PO_4\text{-}P_t)$

SS (Suspended Solids)

$S_{tSS} = - SS_{Settling} + SS_{Resuspension}$

$SS_{Resuspension} = \gamma_S \cdot Am_t / H_t$

$SS_{Algae} = \gamma_{SS} \;\; Chl\text{-}a_t$

$TSS_t = SS_t + SS_{Algae}$

DIN (Dissolved Inorganic Nitrogen)

$S_{tDIN} = - DIN_{Ag} + DIN_{Ad} + DIN_{Release}$

$DIN_{Ag} = \gamma_{AN} \cdot Algae_{Growth}$

$DIN_{Ad} = \gamma_{AN} \;\; Algae_{Decay}$

$L_{Settling} = K_{Sj} \cdot C_t \cdot A_t \quad (j = 1,2,3)$

C_t = concentration in fluid volume

A_t = area

H_t = depth

V_t = volume

COD (Chemical Oxygen Demand)

$COD_t = DCOD_t + PCOD_t + COD_{Algae}$

DCOD (Dissoved Chemical Oxygen Demand)

$S_{tDCOD} = DCOD_{Release}$

PCOD (Particulate Chemical Oxygen Demand)

$S_{tPCOD} = - PCOD_{Settling} + PCOD_{Resuspension}$

$PCOD_{Resuspension} = \gamma_{SC} \cdot SS_{Resuspension}$

COD_{Algae} (Chemical Oxygen Demand of algae)

$COD_{Algae} = \gamma_{AC} \cdot Chl\text{-}a_t$

PO_4-P (Orthophosphate)

$S_{tPO4\text{-}P} = - PO_{4\,Ag} + PO_{4\,Ad} + PO_{4\,Release}$

$PO_{4\,Ag} = \gamma_{AP} \cdot Algae_{Growth}$

$PO_{4\,Ad} = \gamma_{AP} \;\; Algae_{Decay}$

$L_{Release} = K_{Rj} \;\; (C_{mud} - C_t) \cdot Am_t \cdot T_R \quad (j = 1,2,3)$

C_{mud} = concentration in bottom mud

Am_t = mud area

T_A = temperature factor for algal growth

T_R = temperature factor for release

μ_{max}	maximum specific growth rate diatom green algae	 0.35 0.25	1/day	γ_{AC}	COD / Chl-a diatom green algae	 0.035 0.035	mg-COD/μg-Chl-a
K_N	saturation constant (DIN) diatom green algae	 0.05 0.05	g/m³	γ_{AN}	N / Chl-a diatom green algae	 0.006 0.010	mg-N /μg-Chl-a
K_P	saturation constant (PO_4-P) diatom green algae	 0.01 0.02	g/m³	γ_{AP}	P / Chl-a diatom green algae	 0.0007 0.0007	mg-P/μg-Chl-a
Kd	specific decay rate diatom green algae	 0.005 0.005	1/day	γ_{SS}	SS / Chl-a diatom green algae	 0.1 0.1	mg-SS/μg-Chl-a
θ	temperature coefficient diatom green algae	 1.04 1.06	-	γ_{SC}	PCOD / SS	0.05	mg-COD/mg-SS
K_{S1}	settling velocity (Chl-a) diatom green algae	 0.1 0.1	m/day	K_{S2} K_{S3}	settling velocity (PCOD) settling velocity (SS)	0.2 0.5	m/day
K_{R1} K_{R2} K_{R3}	release coefficient (DCOD) release coefficient (DIN) release coefficient (PO_4-P)	0.03 0.042 0.045	m/day	γ_S	resuspension coefficient (SS)	0.0001	g/m-s

Setting small elements in the finite-volume model may cause instability during the period of high loading inflow due to strong rainfall. As shown in Fig.1(b), the whole area of the Ariake Sea is divided into 11 discrete elements of various sizes.

The connection point between the Ariake Sea and the open sea at the Hayasaki Strait (element ①) is set as an open boundary where seawater flows in and out under tidal cycles. Through water quality analysis of observed data, three zones of the Ariake Sea; near the mouth of the gulf, the central area and the innermost part can be classified.[6),7)] Pollutant loads from surrounding area, discharged through the river flows, are also taking into account as a continuous source of substances.

3. Verification of advection factor and mixing coefficient

In this study, simulation of conservative substance such as chlorides is used to estimate the advection and mixing coefficient of each volume. The net flow rate (Q_{ji}) was employed by rearranging the calculation results from water movement model.[6)]

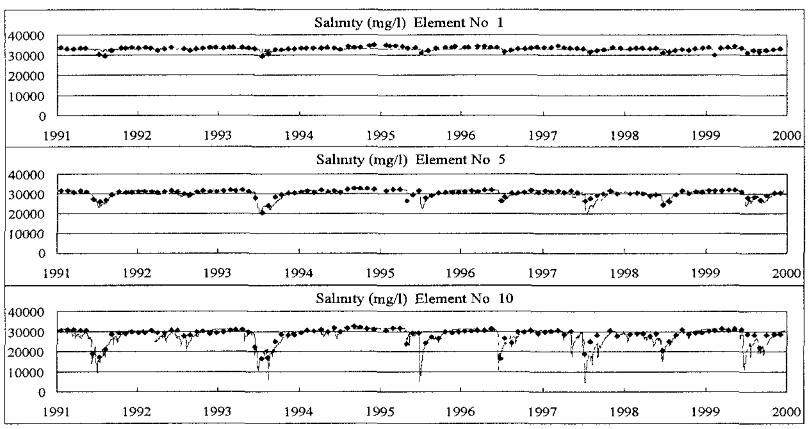

Figure 2 Calculated salinity in the calibration of advection factor and mixing coefficient.

The calibration results during nine years are exampled in Fig. 2 together with observed data of salinity. From these figures, the calculation results almost agree with the observed data. Also, it indicates that the developed model can simulate overall dilution process by discharged freshwater from the main rivers.

The advection factor ranges[5)] between 0.5 and 1.0. The value of mixing coefficient ($E'ji$) can be estimated through the calibration of salinity. As listed below, the obtained mixing coefficient ranges between 200 to 15,000 m^3/ s. [$E'_{ij} = E'_{ji}$]

$E'_{1,2} = 15000$	$E'_{2,3} = 2500$	$E'_{2,4} = 15000$
$E'_{4,5} = 3000$	$E'_{4,7} = 5000$	$E'_{5,6} = 750$
$E'_{5,8} = 2000$	$E'_{7,8} = 3000$	$E'_{7,9} = 500$
$E'_{8,9} = 500$	$E'_{8,10} = 1000$	$E'_{8,11} = 1500$
$E'_{9,10} = 200$	$E'_{10,11} = 200$	

4. Validation of the water quality model in the Ariake Sea

Through calibrating the advection and dispersion parameters, other parameters for water quality simulation, for example, reaction rate, growth factor and decay rate can be examined as shown in Tables 1. Three water quality parameters, COD, DIN (dissolved inorganic nitrogen) and PO_4-P; are used for the developed model. The simulated results of COD, DIN and PO_4-P are demonstrated in Figs. 3, 4 and 5, respectively. Simulated results of each water quality parameters show good agreement with the observed data at all of the volume elements, the mouth of the gulf (element 1), the central area (element 5) and the innermost part (element 10).

In Fig. 3, on an average, COD is 0.4 mg/l in the gulf mouth, 1.5 mg/l in the central part and 2 mg/l in the innermost part. A tendency of a slight rise of COD concentration in nine years may be recognized near the coastal area, however COD in all elements can be considered rather constant except the summer period. High concentrations in summer (rainy season) are mainly caused by the discharged loads from the rivers. In summer season, other phenomena of release/resuspension from sea bottom and rapid COD production by algae may also affect on mass change as discussed later. The simulated results also represent this effect.

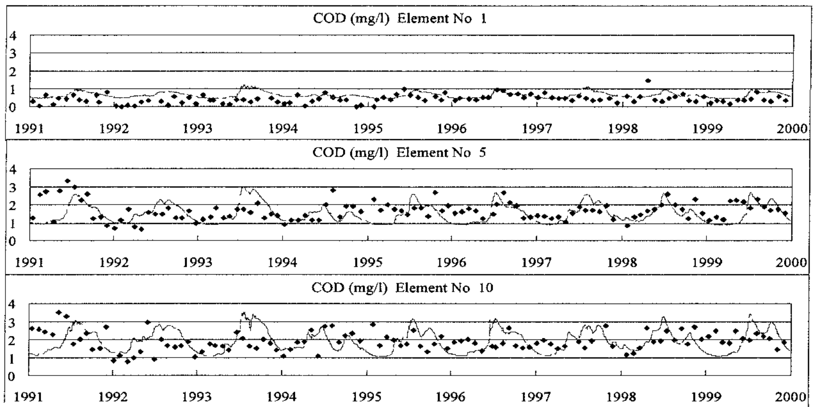

Figure 3 Simulated results and observed data of COD.

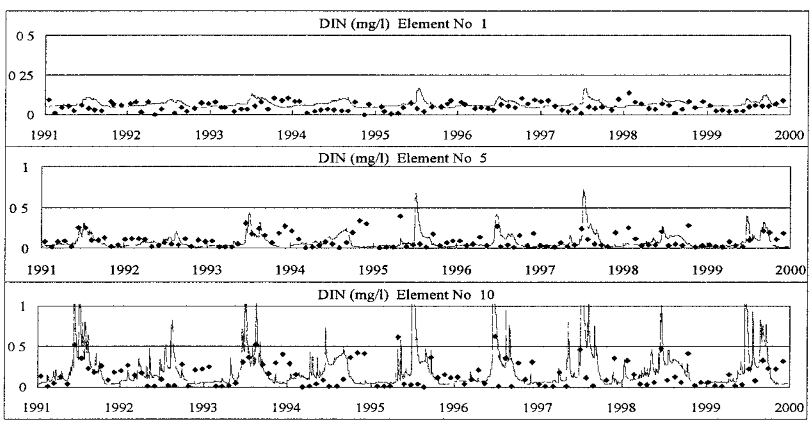

Figure 4 Simulated results and observed data of DIN.

As shown in Figs. 4 and 5, nutrients concentrations are also higher, as COD is higher, in the innermost part due to discharged loads and resuspension and release from bottom mud.[6)] There is a distinct seasonal pattern in a change of nutrients. Nutrients concentrations become low during winter to early summer, which coincides with the period when the influence of aerobic area in the tidal flat increases, and become high during summer to fall. This is because nutrients consumption is accelerated under the condition of aerobic and anoxic/anaerobic in the bed mud. Thus, it is clearly recognized that besides advection and dispersion, other natural phenomena such as sedimentation, release and biomass production, as well as the discharged loads from the rivers, affect the water quality and mud quality of the Ariake Sea. Detail examination on the effects of these phenomena is described in another article.[8)]

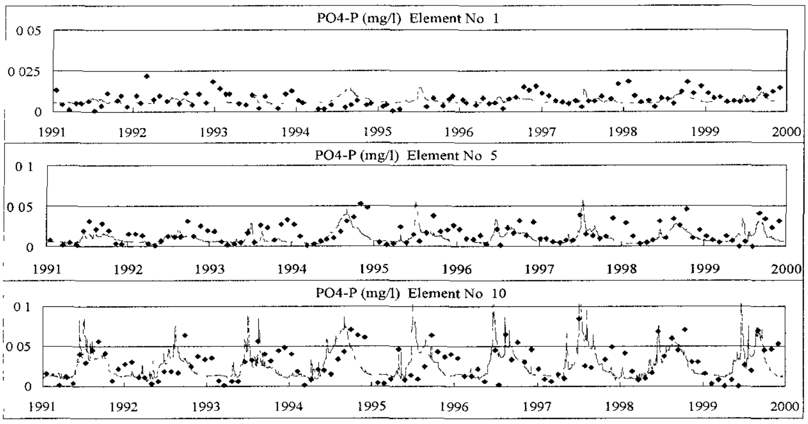

Figure 5 Simulated results and observed data of PO_4-P.

5. Conclusions

1) In the numerical analysis, the functional finite-volume model with fundamental and important parameters was established through validation by means of comparison between calculated results and observed data.
2) The simulated results show the good agreement with observed data for a long term, nine years, with the same parameter value. This model can be applied to simulate water quality in the Ariake Sea from macroscopic view point.
3) The basic environmental characteristics of the Ariake Sea were revealed through numerical simulation and existing observational data without contradiction. That is, higher concentrations are observed in the innermost part of the Ariake Sea. During a year, summer is the period of high concentration in the Ariake Sea. Main causes in high COD and nutrients concentrations are high discharged loadings from the rivers and high release and resuspension from bottom mud, respectively. Nutrients concentrations in the Ariake Sea change in a seasonal pattern according to nutrient consumption and the phenomena of release and resuspension.

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