Water Quality Analysis in the Ariake Sea

有明海の水質解析に関する研究

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ABSTRACT: Two-dimensional water quality model has been developed and applied in water quality analysis in the Ariake Sea. The contributions of three major phenomena; (1) algal production, (2) release and resuspension from mud bed and (3) discharged loadings from the basin area through the rivers; on the water quality in the Ariake Sea have been examined using the developed model. The obtained results indicate that summer is a period of high concentration in the Ariake Sea. High concentrations of COD and suspended solids caused by high discharged loadings exist only for a short period before being transported out to the open sea by tidal movement. Release and resuspension from the bottom sediments also increase COD, SS and orthophosphate concentrations in the innermost area during summer. Nutrient concentrations in the innermost area are influenced by algal growth especially in the low discharged loadings period. Though short-term contribution of discharged loadings appears to be insignificant, it shows that evaluation of their long-term contribution on the water quality and bottom sediments is necessary.
KEYWORD; the Ariake Sea, Algal Production, Finite-volume Model, Resuspension, Bottom Sediments

1 Introduction

The Ariake Sea is the semi-closed shallow sea located in the west of Japan. With 100 km of length and 16 km of average width, its total area is about 1700 km^2. The average depth of the Ariake Sea is about 20m. The Ariake Sea is connected to the open sea at Hayasaki Strait, shown in Figure 1(a). The Ariake Sea has the greatest tidal range in Japan. At a spring tide, it reaches almost 6 m at head of the bay. Large tidal flat appears under such a high tidal range. The tidal flat of the Ariake Sea is 207 km^2, which is approximately 40% of total tidal flat area in Japan. The estuarine areas and tidal flat of the Ariake Sea are very rich habitation and suitable for spawning and nursery. Many typical species can be observed along the coastal areas. The fishery and laver productivity in the Ariake Sea and its tidal flat are very high.

Nowadays, various kinds of activities like land reclamation, constructions of harbors and bay closure are developed in the area of the Ariake Sea. The impacts of these activities on water quality, characteristics of the seabed and ecosystem in the Ariake Sea must be examined.

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 investigate the effects of pollutant loads from drainage areas and some natural phenomena, i.e. release and resuspension from mud bed, on its water quality.

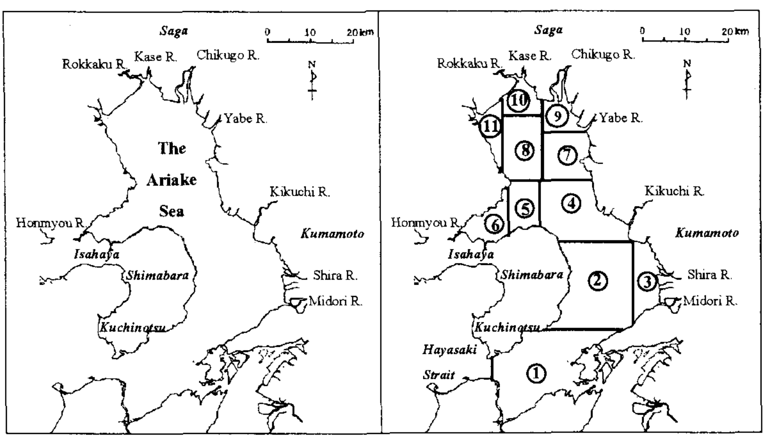

Figure 1 (a) Map of the Ariake Sea and (b) its water quality simulation model.

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2 Water quality simulation modeling

In this study, two-dimensional water quality model is developed for water quality simulation and analysis in the Ariake Sea with the basis of the finite-volume model. The finite-volume model is frequently applied to describe the transport mechanism of conservative and non-conservative materials in the water body where the water movement varies significantly. Many researchers had developed the finite-volume model for water-sediment quality modeling in the typical sea areas like the Seto inland sea (Lee *et al.* 1996) and Tokyo port (Matsunashi and Imamura 1998).

The water quality analysis in this study focuses on the overall water quality and bottom sediments. The water quality model is developed on the assumption that there is no effect of density currents . Each element is considered to be complete mixing state.

The mass balance equation of material transported between two elements (Rich 1973) is defined in Eq.(1).

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

where dV_ic_i/dt = mass change in element i $[M/T]$
V_i = volume of 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 $[M/T]$

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

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 (G_{ji}) and dispersion term (D_{ji}) by Eqs.(2) and (3), Eq.(1) can be written as

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

The water quality in the finite-volume model is averaged over the specific time constant and finite volume. The specific time constant used in this study is one day (two tidal cycles). Thus, observed concentration is also treated as an averaged value in each element. Even if the concentration distribution exists, the averaged value can be mathematically defined on the assumption of no density currents. High loadings discharged during heavy rain originate instability in calculation if small elements are used in the finite-volume model. Both advection factor (δ_{ji}) in advection term and mixing coefficient (E'_{ji}) in dispersion term used in the developed model are constant in this study. The reaction term (S_i) of each water quality in Eq.(1) is described in Table1.

As shown in Figure 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 Hayasaki Strait is set as an open boundary where seawater flows in and out under tidal cycles. Materials are transported between the Ariake Sea and the open sea through this open boundary. Pollutant loads from surrounding area, discharged through the river flows, are also taken into account as a continuous source of substances.

3 Estimation of advection factor and mixing coefficient

In this study, simulation of conservative material such as chlorides is used to estimate the advection and mixing coefficient of each element. The net flow rate (Q_{ji}) can be estimated by rearranging the calculation results from water movement model, MIKE21 (Araki *et al.* 2001). The advection factor ranges between 0.5 and 1.0 (Rich 1973). The mixing coefficients obtained from the calibration of salinity range between 200 to 15000 m^3/s.

The calibration results are shown in Figure 2 together with observed salinity. It is obvious that the developed model can simulate overall dilution process by discharged freshwater from the main rivers and direct runoff. Figure 2 shows good agreement between the obtained results and the observed data.

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

Algae (diatom and green algae)

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

$Algae_{Growth} = \mu \cdot Chl\text{-}a_i \cdot T_A \cdot V_i$

$Algae_{Decay} = K_d \cdot \theta^{(Ti-T0)} \cdot Chl\text{-}a_i \cdot V_i$

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

SS (Suspended Solids)

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

$SS_{Resuspension} = \gamma_S \cdot Am_i / H_i$

$SS_{Algae} = \gamma_{SS} \cdot Chl\text{-}a_i$

$TSS_i = SS_i + SS_{Algae}$

DIN (Dissolved Inorganic Nitrogen)

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

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

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

$L_{Settling} = K_{sj} \cdot C_i \cdot A_i \quad (j = 1,2,3)$

C_i = concentration in fluid volume

A_i = surface area

H_i = depth

V_i = volume

COD (Chemical Oxygen Demand)

$COD_i = DCOD_i + PCOD_i + COD_{Algae}$

DCOD (Dissoved Chemical Oxygen Demand)

$S_{iDCOD} = DCOD_{Release}$

PCOD (Particulate Chemical Oxygen Demand)

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

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

COD_{Algae} (Chemical Oxygen Demand of algae)

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

PO_4-P (Orthophosphate)

$S_{iPO4\text{-}P} = - PO_{4\,Ag} + PO_{4\,Ad} + PO_{4\,Release}$

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

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

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

C_{mud} = concentration in bottom mud

Am_i = 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/m^3	γ_{AN}	N / Chl-a diatom green algae	 0.006 0.008	mg-N /μg-Chl-a
K_P	saturation constant (PO_4-P) diatom green algae	 0.01 0.02	g/m^3	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

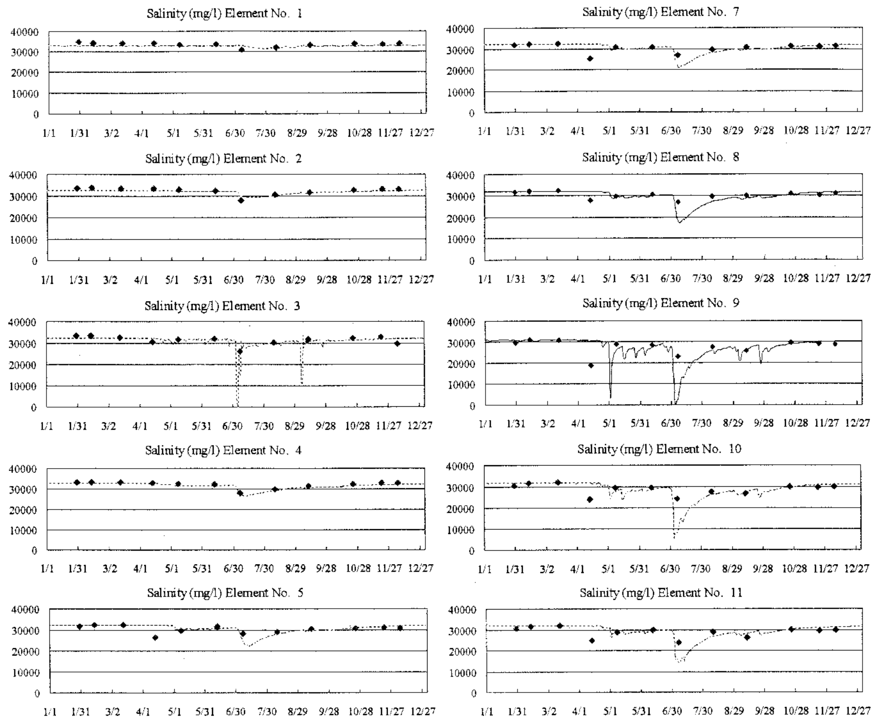

Figure 2 Simulated salinity in the calibration of advection factor and mixing coefficient.

4 Calibration of water quality parameter in the Ariake Sea

Through calibrating the advection and dispersion parameters, other parameters for water quality simulation, i.e. reaction rate, growth factor, decay rate, etc. can be examined (see Table 1). Four water quality parameters COD, SS, dissolved inorganic nitrogen (DIN) and orthophosphate (PO_4-P); in 1995 are considered in this study. The simulated results of COD, SS, DIN and PO_4-P at the gulf inlet (element 1), the central area (element 5) and the innermost part (element 10) are demonstrated in Figures 3 and 4, respectively.

Simulated results have good agreement with the observed data. High concentrations within 1-2 month in summer (rainy season) are caused by the mass transportation of dispersion and advection with discharge from rivers. In summer season, other phenomena such as release/resuspension from sea bottom and rapid COD production by algae affect on mass change with longer term as described later.

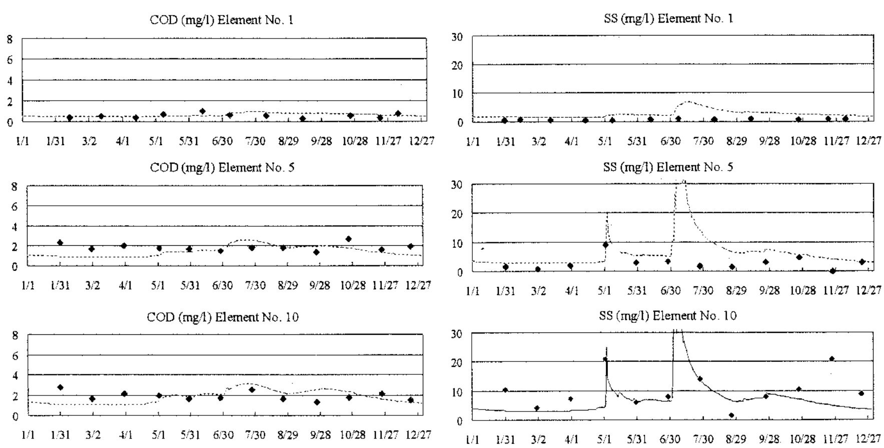

Figure 3 Simulated COD and SS concentrations in 1995.

Setting the big element capacity with well-mixed state derives slower response of SS concentration than observed data especially in summer season. If some elements will be more divided with smaller capacity, then faster response can be given. However, the first and important step in this study focuses on overall water quality analysis in the Ariake Sea.

Figure 4 shows the seasonal pattern of nutrient concentrations in the Ariake Sea. Nutrient concentrations are low during winter to summer. According to Araki et al. (2001), the observation in the Ariake Sea indicates that low tide level is lower between winter to early summer. As a result, the area of tidal flat increases in this period. The period of low DIN and PO_4-P concentrations coincides with tidal flat expansion period when nutrients consumption is accelerated under aerobic and anoxic/anaerobic condition in the mud bed. Comparing with those in the central area and near the gulf inlet, nutrient concentrations in the innermost area are higher.

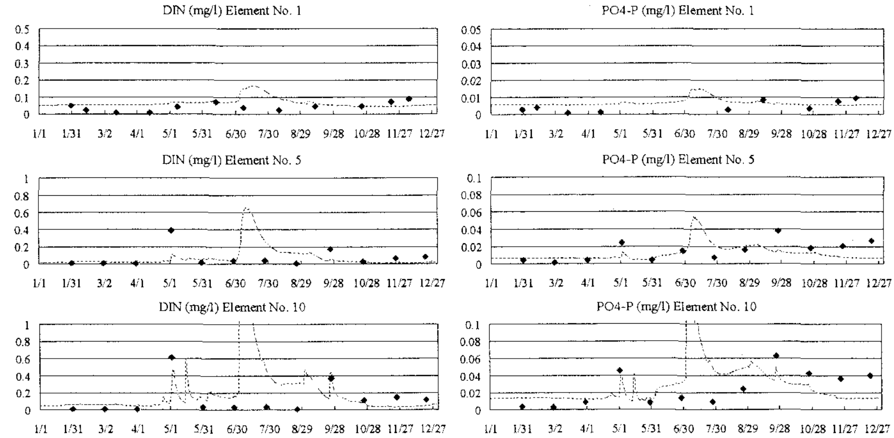

Figure 4 Simulated DIN and PO_4-P concentrations in 1995.

5 Water Quality Analysis in the Ariake Sea

Besides advection and dispersion, other natural phenomena such as resuspension, release from sea bottom and biomass production, as well as the discharged loads from the rivers, affect the water quality and sediment quality in the Ariake Sea. In order to examine the influence of the factors mentioned above, the developed model is performed to simulate water quality under various conditions.

5. 1 Effect of algal production

The total amount of algae present in a body of water at a given time can be measured as suspended solids, by algal cell count, by cell volume, or by the quantity of chlorophyll present in the water. Algae utilize carbon, nitrogen and phosphorus for growth and release nutrients substances back to the water during the decomposition. Some of those nutrients will be stored in the mud bed. They will be released back to the water when tidal movement disturbs the mud bed.

According to two sample results shown in Figure 5, water quality simulation is carried out with the assumption of no existing of algae.

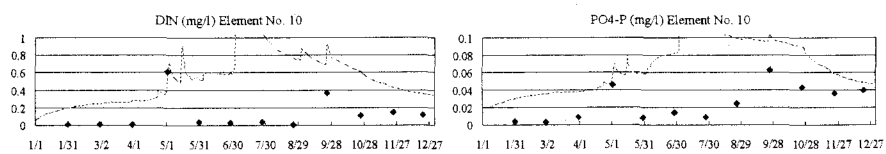

Figure 5 Concentrations of DIN and PO_4-P without the existing algae in 1995.

Without the growth and decomposition of algae, it is shown that the concentrations of DIN and PO_4-P increase. In other elements, same results of the increase in the nutrient concentrations are recognized. It can be pointed out that, except in the high discharged loadings period, the existing of algae can be one of major factor to keep the concentrations of nutrients low in the whole year.

5. 2 Effect of resuspension and released substances from bottom sediments

To investigate the effect of resuspension and the release from the bottom sediments, the water quality is simulated under the following assumptions; 1) there is no initial sediment at the sea bottom, 2) after the material settles, it will not leave the bed and 3) the entrapped nutrients will not be released back to the water.

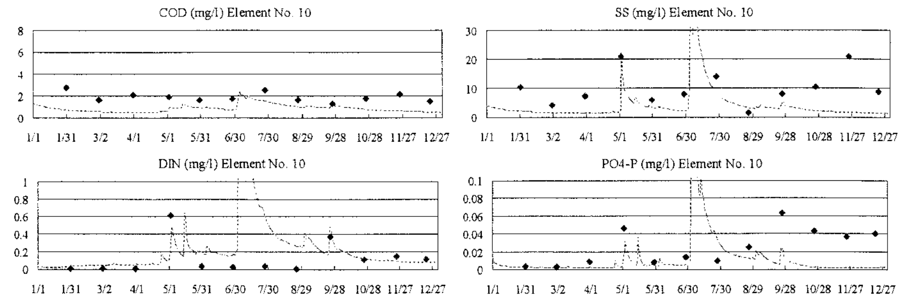

Figure 6 Simulated water quality in 1995 neglecting the effects of the bottom sediments.

In the shallow area like element 10, resuspension and released substances from bottom sediments significantly affect the concentrations of COD, SS and PO_4-P. As shown in Figure 6, most of suspended solids are produced by the resuspension from bottom sediments caused by tidal movement. Comparing with other parameters, DIN decreases slightly.

5. 3 Effects of pollutant loads from the rivers

It indicates that high discharged pollutant loads in summer (rainy season) affect COD and SS concentrations in the Ariake Sea. Except the summer period, concentrations of COD and SS in all elements are almost constant.

The contribution of discharged loadings from the rivers on DIN and PO_4-P concentrations is considered to be less than those on COD and SS concentrations because the main causes of high nutrient concentrations in summer are released nutrients from bottom sediments and decomposition of dead algae, not the loadings discharged from the rivers. High concentrations caused by high discharged loadings usually occur for a short period before being flushed out to the open sea. From the long-term viewpoint, the discharged loadings may form the bottom deposit, which contains non-organic/organic material and nutrients. Therefore, long-term deposition process should be assessed in connection with discharged loadings from the rivers and human activities.

6 Conclusions

1. After parameter calibration, developed finite-volume model can simulate water quality in the Ariake Sea, which shows good agreement with field data.
2. From water quality analysis, the bottom deposit is one of the main sources of suspended solids and nutrients in the shallow area.
3. The nutrients released from bottom sediments and decomposition of algae result in high nutrients concentration in summer while high concentrations of COD and SS are mainly caused by high discharged loadings from the rivers during summer period.
4. Although the discharged loads from the rivers may give less influence on the water quality in short-term analysis, there might be some long-term impacts on its bottom sediments. With the application of developed model, the research on the long-term impacts of discharged loads from the rivers on the water quality and bottom sediments in the Ariake Sea will be carried out in the future.

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