(55) **Integrated Model for Water Quality Analysis in the Chikugo Basin and the Ariake Sea**

筑後川水系及び有明海における水質モデルの開発

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ABSTRACT; The water quality model for integrated water management in the Chikugo basin and the Ariake Sea is developed in this study. The integrated model is composed of three models: 1) the tank model; 2) the river model and 3) the two-dimensional box model of the Ariake Sea. Water quality parameters in this study are COD, SS and nutrient concentrations. Sensitivity analysis is carried out using the integrated model to evaluate the contribution of discharged loading from land area on water quality in the Ariake Sea from 1991 to 2000. It indicates that the nutrient concentrations in the vicinity of the mouth of the Chikugo River tend to increase during the period of high loading from the Chikugo basin while there is slightly effect of the discharged loading on COD and SS in the same area.

KEYWORDS; Integrated Water Quality Model; The Chikugo River; The Ariake Sea; Pollutant Loading; Sensitivity Analysis.

1. Introduction

In water quality management in the Chikugo basin, it is important to analyze the contribution of human activities in this basin on water quality in the Ariake Sea especially in the coastal area nearby the river mouth (element 9 in Fig.1) where fishery productivity is high. The water quantity and water quality models of the Chikugo basin[1), 2)] and the two-dimensional water quality model of the Ariake Sea[3), 4)] are modified and combined into an integrated model as the analytical tool in this study. Because the Chikugo River discharges directly into element 9, the discussion about the contribution of the discharged loading is focused on this element. Some general information of the Chikugo basin and the Ariake Sea is provided in this section.

1.1 The Chikugo basin

With the length of 143 km, the Chikugo River is the longest river in Kyushu Island, Japan. The Chikugo watershed covers 4 prefectures: Fukuoka; Saga; Kumamoto and Oita. The total area of this watershed is 2,860 km^2 with population of 1,064,000. Twenty percent of the Chikugo basin is agricultural area. The Chikugo River supplies freshwater for irrigation, drinking water, industry and power generation. The flow of the Chikugo River also plays an important role in the environmental preservation in its watershed and the Ariake Sea. Precipitation in the Chikugo basin is about 2,200 mm/y of which 65% occurs between June and September[5)]. With the catchment area of 2,315 km^2, annual average flow rate at Senoshita (Fig.1) is 120 m^3/s. High flow rate above 1,000 m^3/s can be usually observed at Senoshita during summer. In spite of high flow rate, water shortage tends to occur in the Chikugo basin in summer.

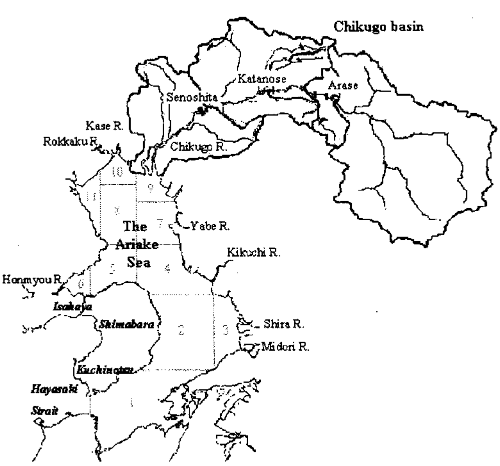

Figure 1 The Chikugo basin and the Ariake Sea

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To maintain the supply capacity, many projects viz. the construction of reservoirs, etc. are planned for water resources development and are still carrying out in this watershed.

1.2 The Ariake Sea

Total area of the Ariake Sea is about 1,700 km^2 with the length of 100 km, average width of 15 km and average water depth of 20 m. The tidal range of the Ariake Sea is the largest one in Japan. During the ebb tide, the tidal flat with the length of 6-10 km appears. The tidal flat area of the Ariake Sea is about 40% of total tidal flat in Japan. Total area of the watershed of the Ariake Sea is about 8,400 km^2 composing of 5 prefectures: Fukuoka; Saga; Kumamoto; Nagasaki and Oita. There are eight main rivers flowing into the Ariake Sea. Total basin area of these rivers is 6,852 km^2, which is around 80% of this watershed. Average annual discharge of the Chikugo River, the biggest one among these eight rivers, is more than 40% of total discharge from all rivers.

2. Integrated water quality model

After being modified, the developed models of the Chikugo basin and the Ariake Sea are combined. The integrated model is applied in the water quality analysis in the Chikugo basin and the Ariake Sea from 1991 to 2000. Time step of every model is 1 day. Runoff and loading discharged from the catchment area of the Chikugo River are calculated by the developed tank model. The obtained result is applied to the 1-D river model, which represents the Chikugo River, and the total amount of water and loading discharged from the Chikugo basin into the Ariake Sea are determined. Finally, water quality simulation is carried out in the Ariake Sea using the simulated result of the Chikugo basin. Outline of the integrated model is shown in Fig.2.

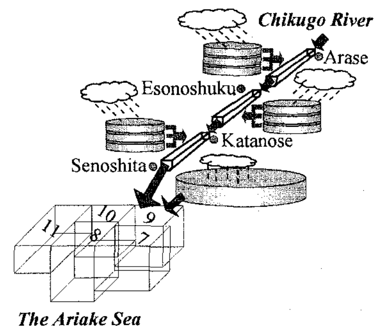

Figure 2 Integration of the developed tank model, the river model and the box model

2.1 The developed models of the Chikugo basin

The tank model and the river model are developed for the catchment area and the Chikugo River. Water quality parameters considered in the Chikugo basin are COD, SS, T-N and T-P.

(1) The tank model

The tank model developed by Sugawara[6] is a long-term rainfall-runoff model. Each tank has at least one lateral orifice at the side of the tank and one orifice at its bottom. Discharge through the lateral orifice represents surface and sub-surface runoff while the seepage flows down to a lower tank through the orifice at the bottom. The study area is the central and downstream area of the Chikugo basin, between Arase and the river mouth. Observed data of flow rate[7] and water quality[8] at Arase is given as the boundary condition. The study area is divided into 4 small basins. One basin is represented by a three-tank model[1]. Because the loading discharged from downstream area of Senoshita is considered to be directly discharged into the Ariake Sea, the tank model of this basin is one tank with a lateral orifice at the bottom as shown in Fig.2.

1) Water balance in the Chikugo basin

Most of the water amount in each basin comes from the precipitation and upper area (irrigation water) and is lost through the process of runoff and evapotranspiration, as shown in Eq.(1). Irrigation water is drawn from the river and distributed by the water structures such as weirs and open channels. Percentage of water intake from the open channels is around 75-90% during the irrigation period.

$$\frac{dY_{(k)}}{dt} = p_{(k)} - e_{(k)} - q_{T(k)} + i_{(k)} \tag{1}$$

where Y = water amount in the basin (m); p = precipitation (m/d); e = evapotranspiration (m/d); q_T = total runoff flowing into the river (m/d) and i = irrigation water (m/d). Subscript k is basin number.

2) Water balance in the tank model

Precipitation always enters the basin at the topmost tank while evapotranspiration occurs only in the topmost tank that is filled with water. Irrigation water is rapidly drained into the river through the outflow of the topmost tank and gradually discharged to the river as the groundwater from the last tank.

$$q_{L(i,j)} = a_{L(i,j)}(y_{(i)} - h_{(i,j)}) \quad (2)$$

$$q_{B(i)} = a_{B(i)} \cdot y_{(i)} \quad (3)$$

where q_L = runoff flowing through lateral orifice (m/d); a_L = discharge coefficient of lateral orifice (1/d); y = water depth (m); h = height of lateral orifice (m); q_B = seepage (m/d) and a_B = seepage coefficient (1/d). Subscripts i = tank number and j = lateral orifice number.

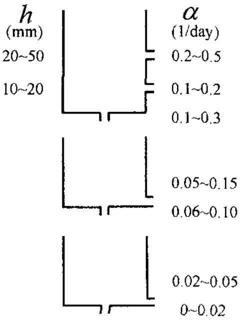

Figure 3 Height of lateral orifice, discharge coefficient and seepage coefficient used in the tank model

The values of h, a_L and a_B are shown in Fig.3. These parameters are calibrated with the observed flow rate at Esonoshuku, Katanose and Senoshita[7] by trial and error method. Generally, discharge coefficient is related to soil moisture but, in the area of frequent precipitation like Japan, the soil can be considered under the saturated condition and the soil moisture can be neglected[9].

3) Loading from the Chikugo basin

Total loading discharged from each basin is originated by three loading sources: 1) urban area; 2) forest area (mountainous area) and 3) agricultural area. It is assumed that the loadings from urban area and forest area are discharged constantly throughout the year while the loading from agricultural area is discharged during the irrigation period[1), 2)]. The unit loading rate of each source in the Chikugo basin and the estimation of loading discharged from this basin is shown in Table 1.

Table 1 The estimation of loading from the Chikugo basin[1)]

Tank	Forest area		Urban area		Agricultural area	
	Rainy day	Fine day	Rainy day	Fine day	Irrigation	Non-irrigation
1	$L = aQ^b$	-	$L = aQ^b$	-	70.0*	-
2	a = 1.0, b = 1.0	-	a = 2.0, b = 1.0	-		-
3	10.0*		5.0**			-

* : kg/ha-y, ** : g/capita-d

(2) The river model

As shown in Fig.2, the Chikugo River between Arase and Senoshita is divided into 3 segments. Daily flow rate and water quality in each segment are simulated by the one-dimensional model. Continuity equation and mass balance in each river segment are described in Eqs.(4) and (5).

$$\frac{dV_{R(k)}}{dt} = (Q_{R(k-1)} + Q_{T(k)} + Q_{D(k)}) - (Q_{R(k)} + Q_{W(k)}) \quad (4)$$

$$\frac{d\,c_{(k)} \cdot V_{R(k)}}{dt} = (c_{(k-1)} \cdot Q_{R(k-1)} + L_{T(k)} + L_{D(k)}) - c_{(k)}(Q_{R(k)} + Q_{W(k)}) \pm S_{(k)} \quad (5)$$

where V_R = water volume in river segment (m^3); Q_R = flow rate at downstream of river segment (m^3/s); Q_T = total runoff from the basin (m^3/s); Q_D = discharge from reservoir(s) (m^3/s); Q_W = water intake at weir(s) (m^3/s); c = concentration in the river segment (g/m^3); L_T, L_D = total loading discharged from the basin and reservoir(s) (g/s), respectively and S = reaction term (g/s). Subscript k is the number of river segment. L_T are obtained from the developed tank model using Table1. In this study, it is assumed that the reaction is negligible because of short detention time in the river segment.

In Fig.4(a), simulated flow rate at Senoshita in 1991-2000 shows good agreement with daily-observed data. All the observed data and simulated result are summarized in Fig.4(b). The seasonal change of flow rate in the Chikugo River can be reproduced by the application of the developed model.

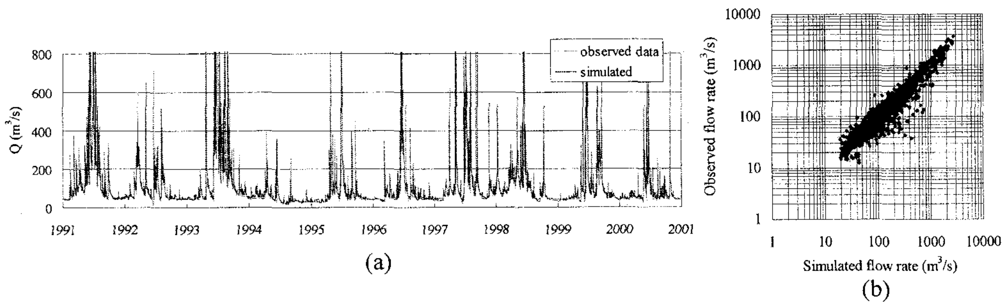

Figure 4 (a) Flow rate at Senoshita and (b) Relationship between simulated and observed flow rate

Loading rate at Senoshita simulated by the river model is compared with the monthly-observed data in Fig.5. The obtained loading rate is high during June to September and low during the winter as same as the observed data. It shows that the developed model can effectively estimate the loading rate in the Chikugo River especially in the low flow period.

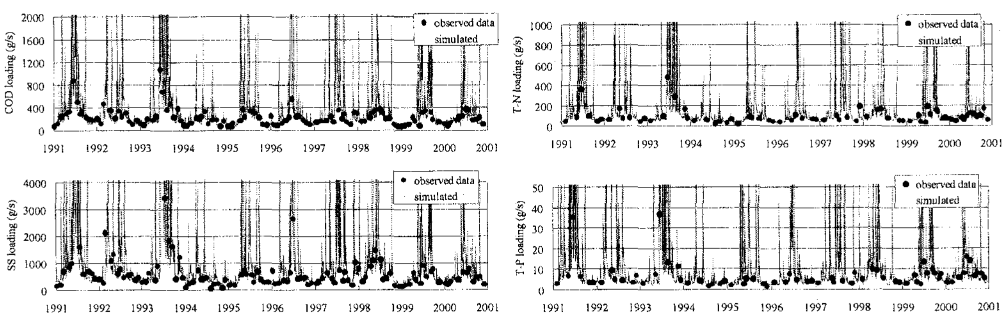

Figure 5 Loading rate in the Chikugo River at Senoshita from 1991-2000 (COD, SS, T-N and T-P)

2.2 Water quality model of the Ariake Sea

Nutrient budgets in many bays in Japan are evaluated using the box model. Budget models[10] are applied in nutrient budgets analysis in Hakata Bay[11] and compared with those in Mikawa Bay[12] and Tokyo Bay[13]. The reduction effects of pollutant load on water quality in Tokyo Bay are estimated using the box model[14]. In the integrated model, the Ariake Sea is divided into 11 elements (Fig.1). River water and loading from the Chikugo River are discharged into the Ariake Sea in element 9. Water quality parameters in the Ariake Sea in this study are COD, SS, dissolved inorganic nitrogen (DIN) and orthophosphate (PO_4-P)[15]. In this study, the prototype model[3), 4)] is improved by taking into account the influence of the property of bottom mud and the effect of wind on the resuspension. The release rate of dissolved material from the mud bed in each element is defined as a function of the water temperature. By using the observed data of all rivers[7], the modified box model can simulate water quality in the Ariake Sea efficiently. In the integrated model of this study, the observed data of the Chikugo River is replaced by flow rate and water quality obtained from the developed models of the Chikugo basin.

The mass balance in each element[16] is described in Eq.(6). The reaction term (S) of each parameter is explained below. The parameters used in this model are listed in Table 2.

$$\frac{dc_{(n)} \cdot V_{(n)}}{dt} = \sum \left\{ Q_{nm} \left[\delta_{nm} \cdot c_{(m)} + (1-\delta_{nm}) c_{(n)} \right] + E'_{nm} (c_{(m)} - c_{(n)}) \right\} \pm S_{(n)} \tag{6}$$

where c = average concentration in the element (g/m^3); V = volume of element (m^3); Q_{nm}, δ_{nm}, E'_{nm} = net flow rate (m^3/s), net advection factor (-) and mixing coefficient (m^3/s) between element n and m, respectively and S = reaction term (g/s). Subscripts n and m denote the considered element and the adjacent element, respectively. In this study, δ_{nm} and E'_{nm}, are constant for each element.

(1) Nutrients (DIN, PO_4-P)

Algae consume nutrients during the growth process and those nutrients will be released when algae are decomposed after decay. In this study, two kinds of algae, diatoms and green algae, are considered. The reaction terms of DIN (S_N) and PO_4-P (S_P) of element n are described in Eqs.(7) - (10). The explanation of the substantial change in biomass of algae (AG) is given in Eq.(9).

$$S_N = -\sum_{x=1}^{2} Y_{N(x)} \cdot AG_{(x)} + K_{RN} \cdot A_M \tag{7}$$

$$S_P = -\sum_{x=1}^{2} Y_{P(x)} \cdot AG_{(x)} + K_{RP} \cdot A_M \tag{8}$$

$$AG_{(x)} = (\mu_{(x)} - K_{D(x)} \cdot \theta_{(x)}{}^{(T-T_D(x))}) CH_{(x)} \cdot V \tag{9}$$

$$\mu_{(x)} = \mu_{MAX(x)} \cdot T_{G(x)} \frac{DIN_{(x)}}{(K_{N(x)} + DIN_{(x)})} \frac{PO4_{(x)}}{(K_{P(x)} + PO4_{(x)})} \tag{10}$$

where Y_N = DIN: Chl-a (mg DIN/μg Chl-a); Y_P = PO_4-P: Chl-a (mg PO_4-P/μg Chl-a) ; K_{RN}, K_{RP} = release rate of DIN and PO_4-P (g/m^2-d); A_M = mud area of element (m^2); K_D = specific decay rate (1/d); θ = temperature coefficient for decay (-); T_D = critical temperature for decay (°C); T = water temperature (°C); μ_{MAX} = maximum specific growth rate (1/d); T_G = temperature coefficient for algal growth (-); K_N, K_P = saturation constant of DIN and PO_4-P (g/m^3); CH = Chl-a (μg/l); DIN = dissolved inorganic nitrogen (g/m^3) and $PO4$ = orthophosphate (g/m^3). Subscript x refers to species of algae.

Growth rates of these algae are maximum at the optimal temperature and become zero when water temperature is lower than the minimum temperature or higher than the maximum temperature. To represent the growth pattern of both algae, T_G used in this study is a function of optimal temperature, maximum and minimum temperatures[17]. The growth temperature used in this model ranges from 0 to 30°C for diatoms and 10 to 30°C for green algae. The optimal temperature is 15°C and 25°C for diatoms and green algae, respectively. K_{RN} and K_{RP} depend on the water temperature.

(2) Suspended solids (SS)

The concentration of suspended solids especially in the area near the river mouth is an important water quality parameter in the relationship between water quality in the river and the sea. Most of the suspended solids in the sea are originated and discharged from land area and some of them are likely to deposit near the river mouth. In this study, new resuspension term (SS_{RS}) is adopted by taking the effect of wind into account. SS are composed of suspended material discharged from land area, like silt and sand, and algal form. Eqs.(11) - (13) show the reaction term of SS (S_S) of element n.

$$S_S = SS_{RS} - K_{SS} \cdot B_S \cdot SS \cdot A \tag{11}$$

$$SS_{RS} = (R_T \cdot K_{RT} + K_{RW}) \frac{A_M}{D} \tag{12}$$

$$v_W > v_W^* ; \qquad K_{RW} = K_W [(\frac{v_W}{v_W^*})^2 - 1]$$

$$v_W \le v_W^* ; \qquad K_{RW} = 0 \tag{13}$$

where K_{SS} = settling velocity of SS (m/d); B_S = settling coefficient (-); A = area of element (m^2); R_T, K_{RT} = resuspension coefficient (-) and resuspension rate (g/m-d) due to tidal movement; D = water depth (m); K_W = resuspension coefficient due to wind (g/m-d); v_W = maximum wind velocity (m/s) and v_W^* = critical wind velocity (m/s).

R_T represents the sensitivity to tidal movement of mud bed in each element. v_W is daily observed data from five observation stations around the Ariake Sea[18]. Settling velocity of different kind of particles can be adjusted by using B_S. The content of coarse particles e.g. sand and silt in suspended solids is normally high during the rainy season. Therefore, high value of B_S is used in this period.

Suspended solids in algal form (SS_{ALGAE}) are considered in this model. The calculated results in Figs.6 and 7 are total suspended solids including SS_{ALGAE}.

$$SS_{ALGAE} = \sum_{x=1}^{2} Y_{S(x)} \cdot CH_{(x)} \tag{14}$$

where Y_S = SS: Chl-a (mg SS/μg Chl-a). Subscript x refers to species of algae.

(3) COD

COD is considered as particulate COD (PCOD) and dissolved COD (DCOD). PCOD includes PCOD discharged from land area and in algal form. The reaction terms of PCOD (S_{CP}) and DCOD (S_{CD}) are described in Eqs.(15) - (17), respectively. Resuspended PCOD is related with resuspended solids from the mud bed using PCOD content in SS (Y_{SC}). The settling of PCOD in algal form ($SCOD_{ALGAE}$) is explained in Eq.(16).

$$S_{CP} = Y_{SC} \cdot SS_{RS} - (K_{SC} \cdot PCOD + SCOD_{ALGAE})A + \sum_{x=1}^{2} Y_{C(x)} \cdot AG_{(x)} \tag{15}$$

$$SCOD_{ALGAE} = \sum_{x=1}^{2} Y_{C(x)} \cdot K_{SA(x)} \cdot CH_{(x)} \tag{16}$$

$$S_{CD} = K_{RC} \cdot A_M \tag{17}$$

where Y_{SC} = PCOD: SS (mg COD/ mg SS); K_{SC} = settling velocity of PCOD (m/d) ; Y_C = PCOD: Chl-a (mg COD/μg Chl-a); K_{SA} = settling velocity of algae (m/d) and K_{RC} = release rate of DCOD (g/m^2-d). Subscript x refers to species of algae.

Table 2 Parameters used in the two-dimensional box model of the Ariake Sea

μ_{MAX}	maximum specific growth rate	0.25* (0.20)	1/d
K_N	saturation constant of nitrogen	0.05* (0.05)	g/m^3
K_P	saturation constant of phosphorus	0.01* (0.02)	g/m^3
K_D	specific decay rate	0.005* (0.005)	1/d
θ	temperature coefficient for decay	1.04* (1.06)	-
T_D	critical temperature for decay	25.0* (30.0)	°C
K_{SS}	settling velocity of SS	0.1	m/d
K_{SC}	settling velocity of PCOD	0.1	m/d
K_{SA}	settling velocity of algae	0.1* (0.1)	m/d
K_{RT}	resuspension rate due to tidal movement	10.0	g/ m-d
K_W	resuspension coefficient for wind	2.0	g/ m-d
v_W^*	critical wind velocity	4.0	m/s
K_{RN}	release rate of DIN	0.06 - 0.12	g/ m^2-d
K_{RP}	release rate of PO_4-P	0.002- 0.02	g/ m^2-d
K_{RC}	release rate of DCOD	0.01 - 0.5	g/ m^2-d

Table 2 Parameters used in the two-dimensional box model of the Ariake Sea (continued)

Y_N	DIN: Chl-a	0.015* (0.015)	mg DIN /μg Chl-a
Y_P	PO_4-P: Chl-a	0.0012* (0.0012)	mg PO_4-P /μg Chl-a
Y_S	SS: Chl-a	0.1* (0.1)	mg SS /μg Chl-a
Y_C	PCOD: Chl-a	0.035* (0.035)	mg COD /μg Chl-a
Y_{SC}	PCOD: SS	5.0	%

* diatoms; ( ) green algae

3. Result and discussion

As well as in the Chikugo River, water quality simulated by the integrated model in all elements in the Ariake Sea has good agreement with the observed data. Figure 6 shows water quality in the Ariake Sea near the mouth of the Chikugo River (element 9) obtained from the integrated model. High concentration in the innermost area of the Ariake Sea can be observed during the period of high discharge from land area. Besides the discharged loading, there are many factors such as algal growth, release from the mud bed, etc., which can affect on water quality in the Ariake Sea. Sensitivity analysis is carried out in the Ariake Sea using the integrated water quality model. To examine the contribution of discharged loading from land area, water quality is simulated by neglecting other reaction terms such as mass transformed by algae and mass transported between the seawater and the mud bed, etc. Simulated COD and SS shown in Fig.7 are lower than the observed data. It shows that loading discharged from the Chikugo basin does not result in high COD and SS in element 9. Without other phenomena, the simulated nutrient concentrations increase especially during June and September. It indicates that nutrients discharged from the Chikugo basin affect water quality in element 9 under the condition of limited capacity of element. Not only the influence of the discharged loading, the contribution of nutrient consumption by algae and nutrient supply from the mud bed on the nutrient concentrations are also implicitly revealed in Fig.7. The comparison between the obtained result and the observed data refers to the contribution of algal productivity and release from the mud bed on the nutrient concentrations in the coastal area of the Ariake Sea. Because all phenomena interrelate to each other, it is important to determine the contribution of discharged loading from the Chikugo basin referring to the contribution of other phenomena. To evaluate the interrelation between all phenomena, another sensitivity analysis is necessary.

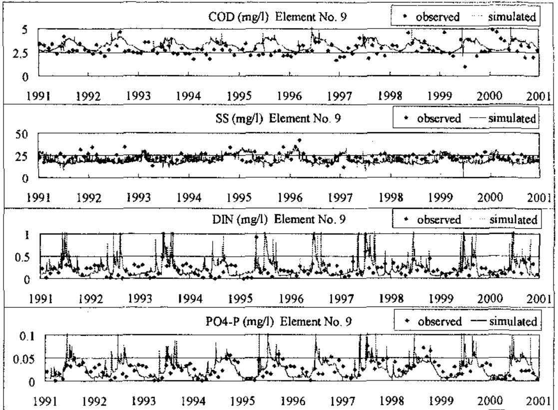

Figure 6 Water quality in the Ariake Sea (element9) simulated by the integrated water quality model

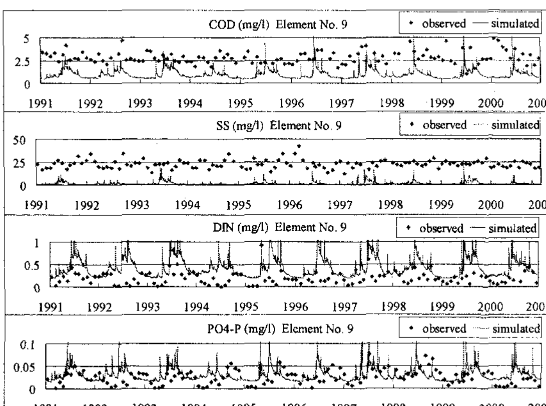

Figure 7 Contribution of the discharged loading on water quality in the Ariake Sea (element9)

4. Conclusions

Receiving discharge from the Chikugo River, the coastal area with high fishery productivity in the Ariake Sea such as element 9 is a sensitive area. As a basic study for water resources management, the contribution of loading from the Chikugo basin on water quality in the Ariake Sea is evaluated in element 9 using the integrated model. Sensitivity analysis indicates that COD and SS in this area are slightly affected by the loading from the Chikugo basin. The possible causes of high COD and SS in the shallow sea like element 9 are release and resuspension from the mud bed. Nutrient concentrations in element 9 are influenced by the discharged loading under the condition of limited element volume. Referring to the observed data, the nutrients in the Ariake Sea are balanced by the nutrient demand of the phytoplankton and the release from the mud bed. The interrelation with the algal productivity and the nutrient supply from the mud bed should be taken into account to gain more detail of the contribution of the discharged loading from the Chikugo basin on the nutrient content in the Ariake Sea. The study on the contribution of these phenomena will be carried out in the future.

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