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LONG-TERM CHANGE OF WATER QUALITY IN THE RESERVOIR OF THE ISAHAYA BAY RECLAMATION PROJECT

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ABSTRACT: In 1997, the Isahaya Reservoir was constructed at the innermost part of Isahaya Bay, Japan to prevent natural disasters and to develop water resources for large-scale farm lands. The main purposes of this study were to analyze the mechanisms underlying the water quality changes observed and to collect significant information for water quality management at the reservoir. Observed water quality parameters on *chlorophyll-a,* suspended solids, total nitrogen, dissolved inorganic nitrogen, total phosphorus, dissolved inorganic phosphorus and chloride ion were analyzed by using a water quality model. It was found that the results obtained from the developed water quality model agreed with the observed data. After calibrating the observed data, a simple sensitivity analysis was conducted to demonstrate the mechanisms of the water quality changes. The major water quality problems were suspended solids that had been resuspended by strong wind and eutrophication due to the enrichment of nutrients. The major mechanisms of water quality changes in the Isahaya reservoir were a coagulation and flocculation by brackish water and the transformation process of phosphorus. The coagulation affected the settling velocity of suspended solids and dissolved phosphorus. It was also revealed that the resolution process of dissolved phosphorus from suspended solids was controlled by the salinity.

Keywords: Reclamation project, suspended solids, nutrients, coagulation, salinity, water quality model.

INTRODUCTION

Isahaya Bay is located in the western part of the Ariake Sea in southwestern Japan. The water quality in the Isahaya Reservoir has been deteriorated due to the enrichment of nutrients which have accelerated the growth of algae in the reservoir since the initiation of the reclamation project. In addition, the chemical oxygen demand (COD), total phosphorus (TP), and total nitrogen (TN) have been higher than the goal levels for the reservoir (COD 5 mg/L, TN 1 mg/L and TP 0.1 mg/L). It is of great concern and importance to identify the mechanisms underlying the adverse water quality changes in the reservoir; the eutrophication process seems to be the most important issue.

SUMMARY OF THE ISAHAYA RESERVOIR

The Isahaya reservoir and its watersheds are shown in Fig. 1. In general, the water level of the reservoir has been maintained at around 1 m below the average sea level to prevent damages from high tides and flooding. Details of the watersheds of the Isahaya reservoir are listed in Table 1.

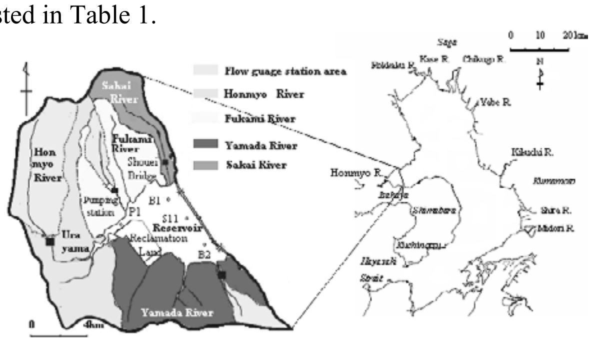

Fig. 1.The Isahaya Reservoir and its watersheds

Table 1. Details of the Isahaya Reservoir

Watershed	Honmyo River	Sakai River	Fukami River	Yamada River
Watershed area (km^2)	88.5	19.2	42.6	62.8
Isahaya Reservoir	Reservoir area: 26 km^2 Storage capacity: 2900×10^4 m^3			

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Note: Discussion on this paper is open until December 2013

CONTINUITY EQUATION OF THE ISAHAYA RESERVOIR

Water quality model of the Isahaya Reservoir based on the following continuity equation Ittisukananth et al. (2008)

$$\frac{dV(t)}{dt} = Q_{in}(t) - Q_{out}(t) + Q_m(t) + Q_r(t) \quad (1)$$

where, $V(t)$: water volume of Isahaya Reservoir (L^3)
$Q_{in}(t)$: inflow from the watersheds (L^3/T)
$Q_{out}(t)$: outflow from Isahaya Reservoir (L^3/T)
$Q_m(t)$: inflow from the Ariake Sea (L^3/T) (Seawater seepage)
$Q_r(t)$: direct inflow by rainfall (L^3/T)

The capacity of the reservoir is calculated based on water level data. Inflow or seawater seepage from the Ariake Sea $Q_m(t)$ is estimated by Darcy's law as shown in Eq. (2).

$$Q_m(t) = K \cdot (h_i(t) - h(t)) \quad (2)$$

where K : overall permeability coefficient (L^2/T)
$h_i(t)$: daily seawater level (L)
$h(t)$: daily reservoir water level (L)

The overall permeability coefficient can be verified by comparing the simulated chloride concentration with the observed values. The good correlation between simulated chloride and observed data shown by Mitsugi et al. (2012) confirmed that the amount of seawater seepage can be determined by Darcy's law.

WATER QUALITY MODEL

The water quality model was developed assuming complete mixing in the reservoir. This assumption is already confirmed through analyzing observed data (Ittisukananth 2008). Water quality parameters in this model are *chlorophyll-a* (Chl-a), COD, suspended solids (SS), TN, dissolved inorganic nitrogen (DIN), TP, dissolved inorganic phosphorus (DIP) and chloride ion (Cl). The available data for this model consist of the water quality data of the Isahaya Reservoir (Kyushu Regional Agricultural Administration Office, 2006), the annual record of each river's discharge (River Bureau, Ministry of Land, Infrastructure, Transport and Tourism, Japan, 2005) and the relevant meteorological data (Automated Meteorological Data Acquisition System – AMeDAS, 2007).

Inflow loading from each watershed is determined from the loading [L (M/T)] and flow rate [Q (L^3/T)] relationship. The constants of the L-Q relationship, $L= aQ^b$, for SS, COD, TN and TP are listed in Table 2.

Table 2 Constants of the L-Q relationship for SS, COD, TN and TP

Water Quality Parameters	Honmyo River (P1 Station)		Sakai River (Syouei Station)	
	a	b	a	b
SS	2390	2.72	1410	2.64
COD	259	1.32	178	1.24
TN	150	1.02	56	1.01
TP	15	1.20	2.49	1.07
Water Quality Parameters	**Fukami River (Pumping Station)**		**Yamada River (Syuzuka Station)**	
	a	b	a	b
SS	2170	2.64	4060	2.95
COD	242	1.24	379	1.55
TN	69	1.05	149	1.13
TP	3.31	1.12	18	1.60

The settlement flux of SS, [J_{SS} (M/L^2T)] and the settlement flux of adsorbed DIP with SS, [J_{DIP} (M/L^2T)] are described in Eqs.(3) and (4), respectively. (Koga et al. 2003; Ittisukananth et al. 2008)

$$J_{SS}(t) = u_{SS} \cdot (1 + \alpha_{SS} \cdot Cl(t)) \cdot SS(t) \quad (3)$$

where,
u_{SS} : settling velocity of SS (M/T)
α_{SS} : coagulation coefficient of SS (L^3/M)
$Cl(t)$: chloride concentration (M/L^3)
$SS(t)$: suspended solids concentration (M/L^3)

$$J_{DIP}(t) = \alpha_{DIP} \cdot J_{SS}(t) \cdot (DIP(t)) \quad (4)$$

where,
α_{DIP} : settlement coefficient (L^3/M)
$DIP(t)$: DIP concentration (M/L^3)

The resuspension flux of SS due to wind [J_{res} (M/L^2T)] from the mud bed is calculated by wind functions as expressed in Eq. (5). The wind velocity and wind direction data were obtained from Shimabara Station, Nagasaki.

$$J_{res}(t) = \beta \cdot (\frac{U_*^2(t)}{U_{*c}^2} - 1)^m \cdot f_w(w_d(t)) \quad (U_* \geq U_{*c}) \tag{5}$$

$$= 0 \quad (U_* < U_{*c})$$

where, β : resuspension coefficient (M/L^2/T)

$U_*(t)$: wind velocity (L/T)

U_{*c} : critical wind velocity (L/T)

$f_w(w_d(t))$: wind direction coefficient $0 \leq f_w \leq 1$ (-)

w_d : wind direction (-)

m : constant (-)

The wind direction coefficient is expressed in Eq.(6).

$$f_w(w_d) = 1 - 0.5 \cdot w_c \cdot (1 - \cos(w_m - w_d(t))) \tag{6}$$

where, w_c : wind direction factor $0 \leq w_c \leq 1$ (-)

w_m : critical wind direction for resuspension (-)

The equations of the water quality model are shown as Eqs.7 to 12. The simulation period was from April 1998 to March 2002. To obtain the *chlorophyll-a* concentration which occurs during each season, three types of algae productivity were considered i.e. diatoms, green algae and blue-green algae.

Chlorophyll-a

$$\underset{\text{(Chl-a accumulation)}}{\frac{d(CH_i(t) \cdot V(t))}{dt}} = \underset{\text{(Outflow loading)}}{-L_{out}(CH_i(t))} \underset{\text{(Settlement)}}{-w_i \cdot CH_i(t) \cdot A} \underset{\text{(Growth)}}{+P_i(CH_i) \cdot V(t)} \underset{\text{(Decay)}}{-F_i(CH_i) \cdot V(t)} \tag{7}$$

Growth

$$P_i(CH_i) = \mu_{\max i} \cdot f_{Tm1i} \cdot \frac{DIN(t)}{DIN(t) + KN_i} \cdot \frac{DIP(t)}{DIP(t) + KP_i} \cdot \frac{Lu(t)}{Lu(t) + K_{Lu}} \cdot CH_i(t) \tag{8}$$

Decay

$$F_i(CH_i) = FF_i \cdot f_{Tm2i} \cdot CH_i(t) \tag{9}$$

COD, TN, TP

$$\frac{d(C_j(t) \cdot V(t))}{dt} = \frac{d(S_j(t) \cdot V(t))}{dt} + \frac{d(D_j(t) \cdot V(t))}{dt} + \frac{d(\Sigma(CH_i(t) \cdot K_{Eij} \cdot V(t)))}{dt} \tag{10}$$

Suspended Matter;

$$\underset{\text{(Accumulation)}}{\frac{d(S_j(t) \cdot V(t))}{dt}} = \underset{\text{(Inflow load)}}{L_{in(S_j)}(t)} \underset{\text{(Outflow load)}}{-L_{out(S_j)}(t)} \underset{\text{(Settlement)}}{-J_{S_j}(t) \cdot A} \underset{\text{(Resuspension)}}{+J_{res}(t) \cdot A} \tag{11}$$

Dissolved Matter;

$$\underset{\text{(Accumulation)}}{\frac{d(D_j(t) \cdot V(t))}{dt}} = \underset{\text{(Inflow load)}}{L_{in(D_j)}(t)} \underset{\text{(Outflow load)}}{-L_{out(D_j)}(t)} \underset{\text{(Release)}}{\pm J_{D_j}(t) \cdot A} \underset{\text{(Algae matter)}}{\pm R_{D_i}(t)} \tag{12}$$

Where,

CH_i: *chlorophyll- a* concentration (M/L^3)
V : capacity of Isahaya Reservoir (L^3)
L_{out}: outflow load (M/T)
w_i : algae settling velocity (L/T)
A : area of Isahaya Reservoir (L^2)
P : growth rate (M/T/L^3)
F : decay rate (M/T/L^3)
μ_{max}: maximum specific growth rate (1/T)
f_{Tm1}: temperature correction function for growth (-)
f_{Tm2}: temperature correction function for decay (-)
FF : decay rate coefficient (1/T)
DIN: dissolved inorganic nitrogen concentration (M/L^3)
DIP: dissolved inorganic phosphorus concentration (M/L^3)
KN: DIN saturation coefficient (M/L^3)
KP : DIP saturation coefficient (M/L^3)
Subscript i: (1: diatom, 2: green algae, 3: blue-green algae)
Lu : solar radiation (cal/L^2/T)
K_{Lu}: solar radiation saturation constant (cal/L^2 /T)
C : concentration (M/L^3)
Subscript j: (1: COD, 2: TN, 3: TP)
S : suspended matter (M/L^3)
D : dissolved matter (M/L^3)
K_{Eij}: conversion coefficient from CH_i to other parameters (-)
L_{in} : inflow load (M/T)
J_{Si} : settlement flux (M/L^2/T)
J_{res} : resuspension flux (M/L^2/T)
J_{Dj} : release flux (M/L^2/T)

R : transformation rate to algae from TN and TP (M/T)

Resolution of Phosphorus

In accord with the report by Tanaka (1994), a laboratory test was conducted under different salinity concentrations to reveal the behavior of phosphorus in an estuarine basin. The resolution of phosphorus which was adsorbed in SS was confirmed.

In the present study, the DIP resolution equations shown as Eqs.(13) and (14) were first developed based on the experimental results reported by Tanaka (1994), and the equilibrium concentration (c_∞) was determined.

The concentration of phosphate was normalized based on the difference between the equilibrium concentration and the phosphate concentration at each time step to describe the resolution process. The normalization of phosphate is shown in Fig. 2.

$$\frac{dc}{dt} = k(c_\infty - c) \tag{13}$$

$$\frac{c_\infty - c}{c_\infty - c_0} = e^{-kt} \tag{14}$$

where,

c : phosphate concentration (M/L^3)
c_∞ : equilibrium concentration (M/L^3)
c_0 : initial concentration (M/L^3)
t : time (T)
k : resolution rate from SS (1/T)

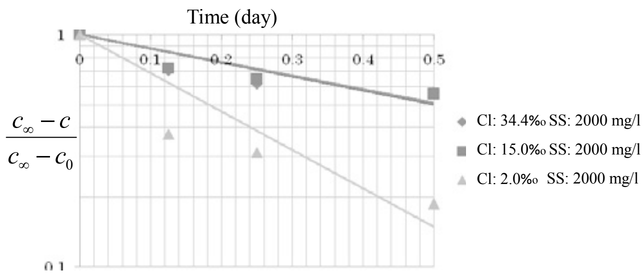

Fig. 2. Normalization of phosphate under different conditions of salinity and suspended solids

RESULTS AND DISCUSSIONS

SS Concentration

The simulated SS from April 1998 to March 2002 shown in Fig. 3 fluctuated widely over the simulation period. High SS concentrations occur due to high discharge loading during heavy rainfall periods and due to resuspension during strong winds. It is found that settlement flux and resuspension flux should be taken into account to obtain good agreement with the observed data. The settlement velocity is based on flocculant settlement under the brackish condition of the reservoir. The mud property taken into account in resuspension rate (β) in Eq. (5) is cohesive under the brackish condition (Ittisukananth et al. 2008). All parameters obtained from the model calibration in this study are summarized in Table 3. Some of these parameters refer to Iwasa (1990), PWRI (1987), Matsunashi (1998) and Vongthanasunthorn (2010).

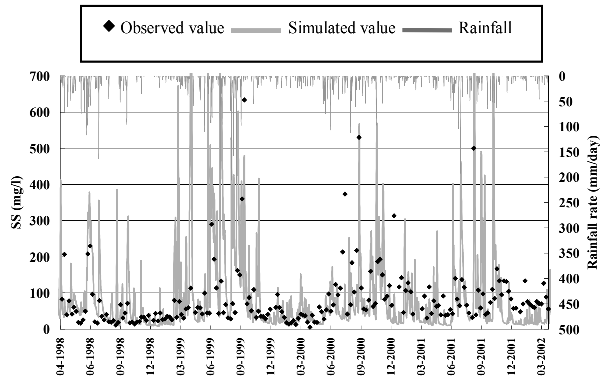

Fig. 3. Suspended solids (SS) in the Isahaya Reservoir.

The patterns of SS concentration in summer season (June to September) between 1999 and 2000 are quite different because a typhoon attacked this area. In 1999, during the summer season with very high typhoon activity, the higher SS concentration pattern occurs as well.

Table 3. Parameters obtained from the model calibration.

Parameter	Description		Value
μ_{max}	Maximum specific growth rate (1/day)	Diatom	0.469
		Green algae	0.45
		Blue-green algae	0.5
FF	Decay rate (1/day)	Diatom	0.11
		Green algae	0.08
		Blue-green algae	0.055
f_{Tm1}	Temperature (Growth) (lower, optimum, upper) limited temperature ::Use optimum value::	Diatom	(0,0,24)
		Green algae	(11,25,29)
		Blue-green algae	(23,28,34)
f_{Tm2}	Temperature correction function (Death) θ_i^{T-20}	Diatom	1.1
		Green algae	1.1
		Blue-green algae	1.05
KN	Saturation constant of DIN (mg/l)	Diatom	0.087
		Green algae	0.087
		Blue-green algae	0.087
KP	Saturation constant of DIP (mg/l)	Diatom	0.032
		Green algae	0.032
		Blue-green algae	0.032

Table 3. Parameters obtained from the model calibration (continued)

Parameter	Description		Value
K_{Lu}	solar radiation saturation constant (cal/ cm^2/day)		100
U_{SS}	Settling velocity (m/day)	SS	0.1
W_{C1}		Diatom	0.05
W_{C2}		Green algae	0.05
W_{C3}		Blue-green algae	0.05
W_{SSC}		COD	0.1
W_{SSN}		Nitrogen	0.1
W_{SSP}		Phosphorus	0.1
$K_{Ei,1}$	Conversion coefficient from CHL to COD (mg-COD/ μ g-CHL)	Diatom	0.05
		Green algae	0.05
		Blue-green algae	0.05
$K_{Ei,2}$	Conversion coefficient from CHL to N (mg-N/ μ g-CHL)	Diatom	0.007
		Green algae	0.007
		Blue-green algae	0.007
$K_{Ei,3}$	Conversion coefficient from CHL to P (mg-P/ μ g-CHL)	Diatom	0.0003
		Green algae	0.0007
		Blue-green algae	0.0007
$J_{D,j}$	Release flux	COD	0.05
		DN	0.0035
		DP	0.0185
α_{SS}	Coagulation coefficient of SS (mg/l)$^{-1}$		0.004
α_{D-IP}	Settlement coefficient (mg/l)$^{-1}$		0.0008
J_{res}	Resuspension flux (m=1)	Critical wind speed: U_{*c} (m/s)	2.5
		Resuspension coefficient: β (g/m^2 · day)	100
		Wind direction factor(-): W_c	0.75
		Critical wind direction for resuspension: W_m	NE
K	Overall permeability coefficient (m^2/day)		34560

In order to evaluate the accuracy of the simulation results of SS, a simple sensitivity analysis was performed. The results are shown in Figs. 4 and 5. These figures confirm that the SS transport parameters shown in Table 3 are appropriate from the view point of parameter fitting.

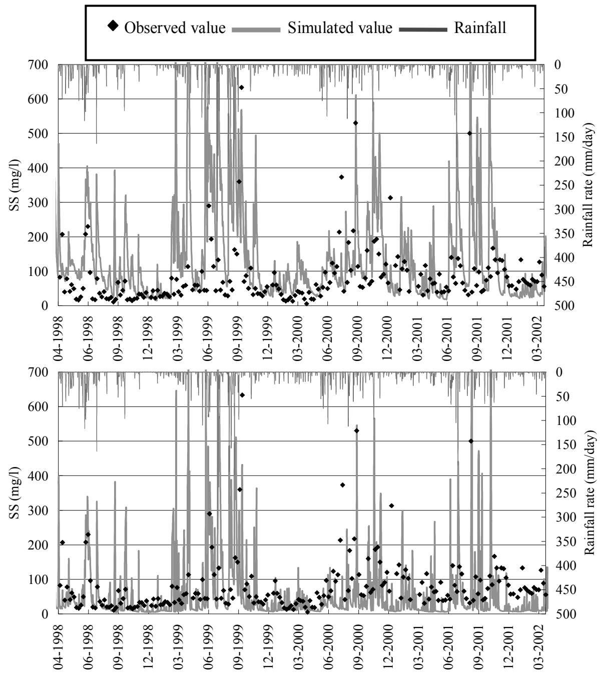

Fig. 4. Results of the sensitivity analysis with 0.5 settling velocity of SS (up) and 2.0 settling velocity of SS (down).

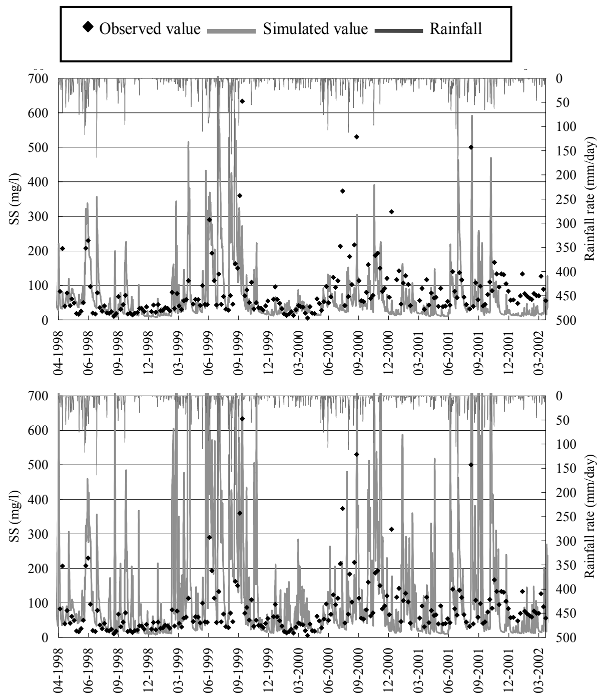

Fig. 5. Results from sensitivity analysis with 0.5 resuspension coefficient (up) and 2.0 resuspension coefficient (down).

TN and DIN Concentrations

Before obtaining the calibration results of the TN and DIN concentrations, a trial simulation was conducted to evaluate the effect of the land load. The results showed that loadings of TN and DIN from land have almost no contribution to the concentrations of TN and DIN in the reservoir, because the simulation results gave low and constant concentrations. This means that the release and resuspension should be taken into account in the fluctuating period in order to approach the observed data (Ittisukananth et al. 2008).

Finally, the TN and DIN calibration results are shown in Fig. 6. With algal productivity and bed load discharge, the TN and DIN calibration results are in good agreement with the observed data, indicating that internal sources such as algal growth and bed load discharge play an important role in the changes of nitrogen concentration and should be considered as sources of nitrogen in the Isahaya Reservoir.

In Fig. 6, the DIN level drops sharply during high algae growth. The simulated results in the spring of 2001, however, differ from the observed data. The lower observed data probably occurred because consumption of DIN was controlled by the specific algae. Thus, to evaluate TN and DIN for long-term simulation, more details regarding other biomasses and algal growth including their affecting factors should be obtained in future studies.

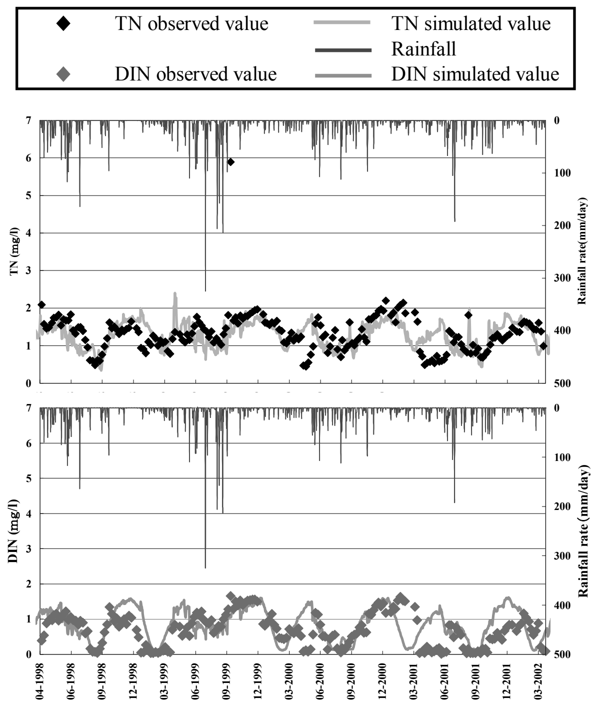

Fig. 6. Calibration results for TN and DIN concentrations.

TP and DIP Concentrations

In order to evaluate the effects of land load of TP and DIP, a trial simulation on TP and DIP was performed, the same as on TN and DIN. The trial simulation results revealed small effects of land load, similar to that obtained for TN and DIN.

As in the simulation for the TN and DIN concentrations, the resuspension of TP and the release of DIP from the mud bed should be taken into account in the fluctuating region. In addition, the nutrient consumption by algae is an important process to obtain calibration results of the algal growth process. Two types of calibration were conducted. First, the resolution from SS under the brackish condition was not introduced into the changes of the DIP concentration (Mitsugi et al. 2012). Overall agreement between the observed data and the simulation results was obtained except in the period of high concentrations of TP and DIP. These differences appear especially in the period of high SS and low river flow rate due to no rain or light rainfall. This tendency suggests that an additional process during a high SS concentration in the brackish condition is necessary to increase DIP and TP in the region. After this result, the simulation was incorporated with the resolution process reported by Tanaka (1994), and the simulation results are shown in Fig. 7. The concentrations of DIP and TP rose due to resolution effect during the period of high SS concentration and high salinity. The increased DIP in Fig. 7 is the adsorbed DIP which dissolves again from SS according to the salinity level. Some difference can be seen in the high concentrations of TP and DIP although the overall agreement with the observed data is good.

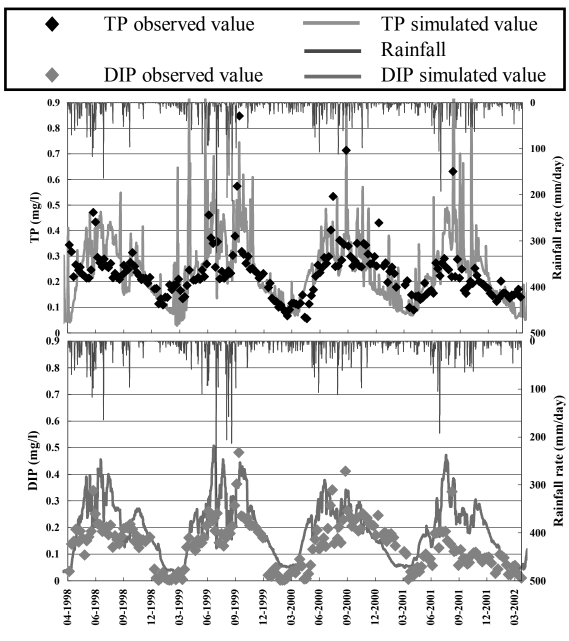

Fig. 7. TP and DIP concentrations.

To obtain better agreement of the TP and DIP simulation results, further study of the SS transport mechanisms such as flocculant settlement and resuspension under brackish condition is necessary. The adsorption of DIP by SS and the DIP resolution from SS will be studied in greater detail in the future.

COD and *Chlorophyll-a* Concentrations

As shown in Fig. 8, the concentration of algae was estimated in terms of *chlorophyll-a*. The calibration results of the *chlorophyll-a* concentration shows seasonal changes, and their agreement with the observed data is not always good.

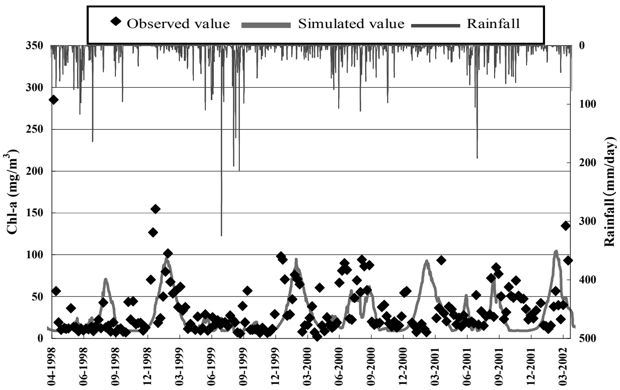

Fig. 8. *Chlorophyll-a* concentration.

Figure 9 shows the calibration results of the COD concentration, which includes the *chlorophyll-a* concentration because the biomass of algae is one type of organic matter. The agreement of the COD concentration was better than that of the *chlorophyll-a* concentration, though the two changing patterns are similar. This means that the reaction term on modeling of algal growth should be formulated by linking with nutrients and other water quality factors such as salinity and water temperature. In future studies, in order to develop this relationship, algae species and algal productivity factors should be examined in detail.

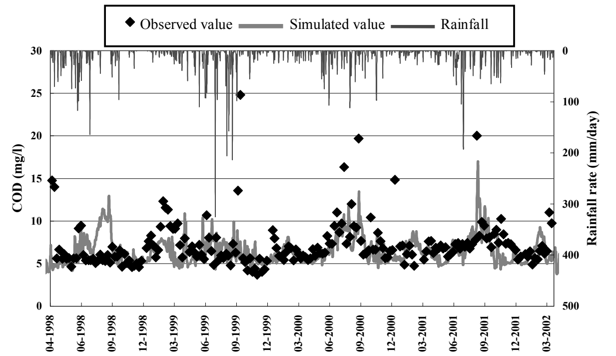

Fig. 9. COD concentration.

CONCLUSIONS

In this study, the mechanisms of the long-term change of water quality in the Isahaya Reservoir were examined based on the simulation results and the sensitivity analysis.

It can be concluded that the major sources of nutrient in the Isahaya Reservoir is not only the land load but also bed load. The characteristic change of water quality is suspended solids (SS) under the brackish condition

It is found that coagulation-flocculation by seawater affects the settling velocity of suspended solids (SS) and phosphorus. The simulation results also indicated that the resolution process of dissolved inorganic phosphorus (DIP) from SS is controlled by salinity.

These sources may play an important role as the nutrient supply for algae in the Isahaya Reservoir and can cause eutrophication in this reservoir. The interrelation between the algal productivity, the bed load, coagulation-flocculation and DIP resolution from SS should be taken into account to gain a greater understanding of the influence of discharged load from the Isahaya Reservoir on the nutrient content in the Ariake Sea.

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