LOWLAND TECHNOLOGY INTERNATIONAL Vol. 10, No. 2, 68-75, December 2008
International Association of Lowland Technology (IALT), ISSN 1344-9656

STUDY ON ALGAL GROWTH IN ISAHAYA RESERVOIR

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ABSTRACT: Isahaya reservoir was constructed at the innermost sea of Isahaya Bay, Japan, in 1997 for preventing natural disasters and developing water resources. Algal growth in this reservoir has been changed since the beginning of the Isahaya-Bay Sea Reclamation Project. As the result, the main purpose of this study is to investigate the effect of algae growth in the Isahaya reservoir using a water quality model. In mass balance equation of this model, several interactions among water quality parameters, namely chlorophyll-*a* (Chl-*a*), chemical oxygen demand (COD), suspended solid (SS), total nitrogen (TN), dissolved inorganic nitrogen (DIN), total phosphorus (TP), dissolved inorganic phosphorus (DIP) and chloride (Cl^-), are incorporated. Sensitivity analysis reveals that nutrients in the Isahaya reservoir are contributed from land area, resuspension-release from mud bed, and coagulation-flocculation-precipitation by seawater. This study found that, before fiscal year 2000, lime (calcium hydroxide, $Ca(OH)_2$) which is used for soil improvement was one of algal growth inhibition in the Isahaya reservoir. Since fiscal year 2000, diatom is the most dominant algal species in this reservoir.

Keywords: Water quality model, Isahaya reservoir, algal growth, diatom, lime

INTRODUCTION

Changing in environmental conditions may affect survival of living organisms. The environmental conditions in the Isahaya Bay have been changed since the beginning of the reclamation project. The physical, chemical and biological changes in the Isahaya Bay have happened and affected to each other. Water quality in this reservoir has been deteriorated by the enrichment of nutrients, and these nutrients have accelerated the growth of algae in the reservoir since the initiation of the reclamation project. Furthermore, 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] (Fisheries Agency of Japan 2001). Algal productivity in Isahaya Bay has been changed. Low algal productivity appeared from the beginning of project until fiscal year 2001. Detailed study on the effect on algal productivity is required. The aim of this study is to investigate the effect on algal growth in the Isahaya reservoir using a water quality model. From the beginning of the project, lime treatment was implemented in order to increase the strength of soil in the reclamation area. From this study, it is found that addition of chemical for improving the reclamation land area affected algal growth in the Isahaya reservoir during the early phase of the Isahaya project.

GENERAL OUTLINE OF ISAHAYA RESERVOIR

Isahaya Bay is located in the western part of the Ariake Sea. In April 1997, the inner part of the bay was separated from the sea by a 7 km long and 200 m wide dike as shown in Fig. 1. Construction of this dike has enclosed 35 km^2 of the Isahaya Bay's tidal flat which is 2% of total area of the Ariake Sea. The polder in Isahaya Bay is approximately 8.16 km^2 in area, including the

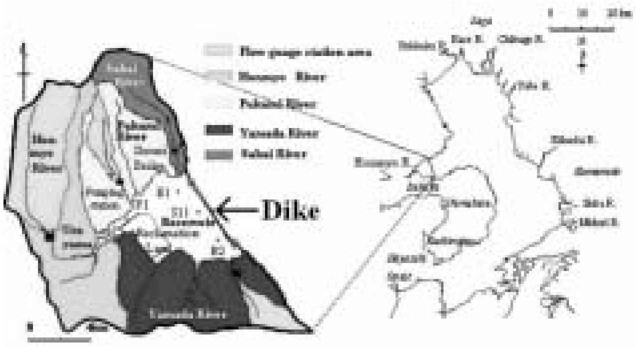

Fig. 1 Isahaya reservoir and its watershed

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Note: Discussion on this paper is open until June 2009

Table 1 Details of Isahaya reservoir watersheds

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: 2900x10^4 m^3			

central area (7.06 km^2) and the Oe (1.1 km^2). Isahaya reservoir was constructed for irrigation and flood prevention on lowland areas located around the construction site and on the reclaimed lands. Water level in the reservoir has been maintained at 1 m below sea level to sustain enough potential water storage volume for flood control. Major rivers flowing into the reservoir are Honmyo, Fukami, Yamada and Sakai Rivers. Total basin area of these rivers is 249 km^2, which is 3% of the Ariake Sea basin area. Total amount of water discharged from all rivers are around 430 million m^3/year. Details of the river basins are described in Table 1.

METHOD AND METHODOLOGY

Algal Productivity Analysis

The Fisheries Agency of Japan, Ministry of Agriculture, Forestry and Fisheries reported in 2001 that the chemical oxygen demand (COD), total phosphorus (TP), and total nitrogen (TN) were higher than the goal levels for a reservoir (Fisheries Agency of Japan, 2001). For Isahaya reservoir, these goals cannot be maintained because high algae production. Water quality in the Isahaya reservoir has been deteriorated by nutrients loading, which have accelerated the growth of algae in the reservoir since the initiation of the reclamation project.

Based on the observed data of the Committee of Water Quality in the Isahaya-Bay Land Reclamation 16th (2007), the scatter diagram between cell number and ratio of Chl-*a* from diatom and blue green algae of fiscal year 1997 to 2000 and 2001 to 2004 are illustrated in Figs. 2 and 3, respectively. Relationship between cell number and Chl-*a* in Fig. 3 has more strength of an association than Fig. 2 which indicates that there is a close relationship between cell number and Chl-*a* during fiscal year 2001 to 2004. This close relationship means there are cause-and-effect between cell number and Chl-*a* during these periods. It means that there is high possibility for diatom and blue green algae growth in the reservoir. From the results shown in Fig. 3, it is found that after 2001, two kinds of algae, diatom and blue green algae, have grown up and become the typical species in the Isahaya reservoir.

The results from Fig. 3 are consistent with the ratio of diatom from observation data shown in Fig. 4. Before fiscal year 2000, many kinds of algae with low cell numbers appeared in region A (before fiscal year 2000) of Fig. 4; but after fiscal year 2000, most of algae are diatom with high cell number as shown in region B.

As shown in Fig. 5, in the beginning of the Isahaya Project (region A), lime input per year was high and it gradually decreased since 2000 (region B). The relation between algae cell number in Fig. 4 and lime input shows that algae cell number has increased with decreasing lime input. From this relationship, it can be

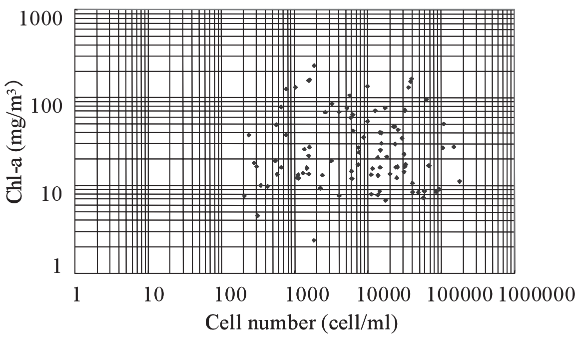

Fig. 2 Relationship between cell number and chlorophyll-*a* from diatom and blue green algae of the fiscal year 1997-2000

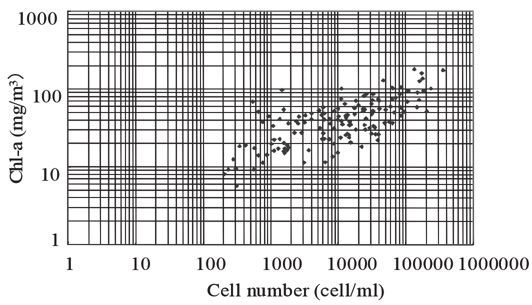

Fig. 3 Relationship between cell number and chlorophyll-*a* from diatom and blue green algae of the fiscal year 2000-2004

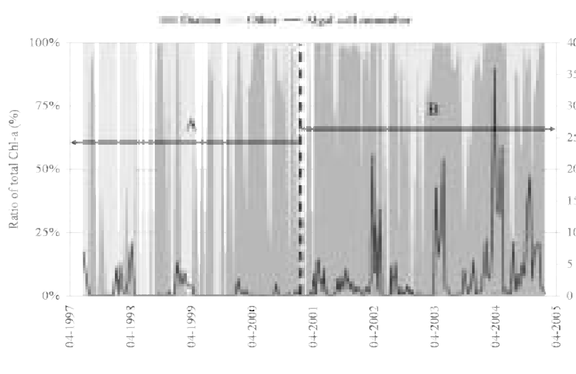

Fig. 4 Ratio of diatom and other kind of algae and algal cell number (average value at station B1 and B2)

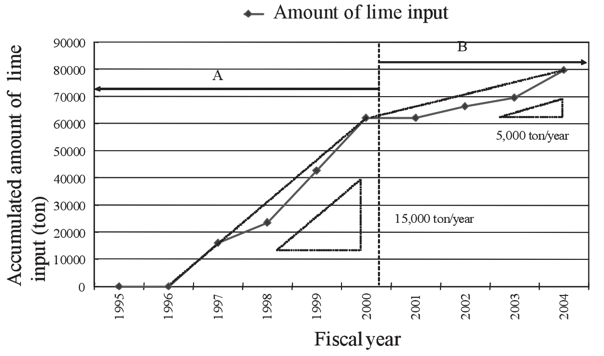

Fig. 5 Amount of lime input for soil improvement (Prime Minister Koizumi Junichiro response in the Diet 2005)

said that lime which is used for soil improvement is one of algal growth inhibitors in the Isahaya reservoir, especially diatom. In fact, silica (SiO_2) is a major soil component. There are 3 phases of silica that contained in soil and water column, i.e., soluble, colloidal and particulate silica. When soil is stabilized by lime, (calcium hydroxide ($Ca(OH)_2$) to improve strength and stiffness of reclamation foundations, silica reacts with lime. From this reaction, calcium makes bond with silicate producing stable calcium silicate hydrates, which will coagulate and precipitate. As a result, the amount of silica in water column will decrease. Decreasing of silica can inhibit the growth rate of diatoms, as diatoms accumulate silica as a structural element in their cell walls. It can be concluded that, amount of lime input influences algal productivity and their species in the beginning of the reclamation project. After 2000, algae in the reservoir can grow with only small effect of lime input.

Water Quality Model of the Isahaya Reservoir

The developed water quality model is based on completely mixed reservoir because there is almost no spatial distribution of observed water quality (Koga et al. 2003). This water quality model is applied to simulate water quality in the reservoir from 2003 to 2005. Water quality constituents in this model are chlorophyll-*a* (Chl−*a*), chemical oxygen demand (COD), suspended solid (SS), total nitrogen (TN), dissolved inorganic nitrogen (DIN), total phosphorus (TP), dissolved inorganic phosphorus (DIP) and chloride (Cl^-). The available data for this model consist of Isahaya reservoir water quality data from Kyushu Regional Agricultural Administration Office (2006), annual record of each river discharge from Japan River (2003), and meteorological data from Automated Meteorological Data Acquisition System – AMeDAS (2007).

Continuity equation for water quality model which states the change in the Isahaya reservoir's storage is shown in Eq. 1:

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

where
V : Isahaya reservoir capacity (L^3)
Q_{in} : Inflow from the watersheds (L^3/T)
Q_{out} : Outflow from the Isahaya reservoir (L^3/T)
Q_m : Seawater seepage from the Ariake Sea (L^3/T)
Q_r : Direct inflow by rainfall (L^3/T)

Inflow loading from each watershed is determined from loading (L), (g/s) and flow rate (Q), (m^3/s) relationship. Coefficients of L-Q relationship ($L = aQ^b$) for SS, COD, TN and TP are listed in Table 2.

Inflow from the Ariake Sea $Q_m(t)$ as shown in Fig. 6 is estimated by Darcy's law shown in Eq. (2):

$$Q_m(t) = K \cdot [h_i(t) - h(t)] \qquad (2)$$

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 simulated chloride concentration with observed values. The simulated results are presented in Fig. 7. Good correlation between simulated chloride and

Table 2 Coefficients of 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

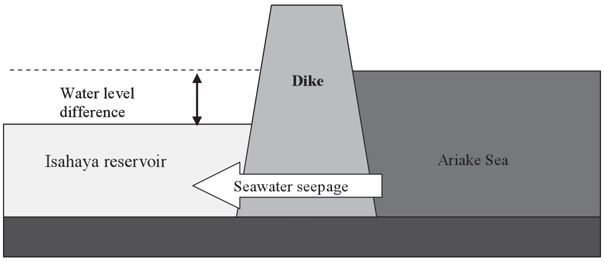

Fig. 6 Inflow from the Ariake Sea

observed chloride means that the amount of seawater seepage computed by Darcy's law is satisfactory.

The equations of water quality model are shown in Eq. (3) to (10). The simulation period is from 2003 to 2005. Concentration of algae is estimated in terms of Chl-*a*. As mentioned in algal productivity analysis, two kinds of algae productivity, namely, diatoms and blue green algae are considered. Chl-*a* accumulation is calculated by using Eq. (3). Chl-*a* accumulation can be generated by algal growth in water body and resuspended from mud bed with suspended soilds, minus outflow loading, decay and settlement.

Chlorophyll-a

$$\underbrace{\frac{d(CH_i(t)\cdot V(t))}{dt}}_{\text{(Chl-a accumulation)}} = \underbrace{-L_{out(CH_i(t))}}_{\text{(Outflow loading)}} \underbrace{-w_i\cdot CH_i(t)\cdot A}_{\text{(Settlement)}}$$

$$\underbrace{+\alpha\cdot J_{res}(t)}_{\text{(Resuspension)}} \underbrace{+P_{i(CH_i)}\cdot V(t)}_{\text{(Growth)}} \underbrace{-F_{i(CH_i)}\cdot V(t)}_{\text{(Decay)}} \qquad (3)$$

where

CH_i : Chlorophyll-*a* concentration (M/L^3)

w_i : Algae settling velocity (L/T)

A : Isahaya reservoir area (L^2)

α : Coefficient regarding algae in resuspended solids from the mud bed (-)

J_{res} : Resuspension flux (M/L^2/T)

P_i : Growth rate (M/T/L^3)

F_i : Decaying rate (M/T/L^3)

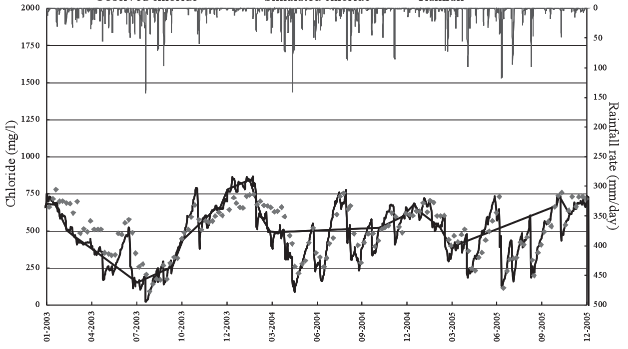

Fig. 7 Chloride simulation result

A basic governing equation for this algal growth is Monod equation. In this equation, the growth rate of algae depends on the concentration of limiting nutrient. This model is developed as a relatively simple model for the effect of temperature, light intensity and salinity on algal growth rates into Monod equation. With this model the combined effects of temperature, light intensity, salinity concentration and nutrient limitation can be described. The temperature function, nutrients, light intensity and chloride relationship with the Monod model are described as:

Growth and decay

$$P_{i(CH_i)} = \mu_{\max i}\cdot f_{Tm1i}\cdot\frac{DIN(t)}{DIN(t)+KN_i}\cdot\frac{DIP(t)}{DIP(t)+KP_i}$$

$$\cdot\frac{Lu(t)}{Lu(t)+K_{Lu}}\cdot CH_i(t)\cdot\left(1+\frac{\beta\cdot Cl}{M}\right) \qquad (4)$$

Decaying rate, *FF*, is defined as the factor describing all biological processes leading to a decrease in algal biomass due to respiration, cell death, and predation by higher organisms in food chain, and etc. The temperature dependence of algal decay rate is also taken into account in this model. An increase in water temperature can lead to increased algal growth rates. As water temperatures increase, growth of algae are slowed down or terminated. The first order decay equation for diatom and blue green algae in the Isahaya reservoir water quality model is shown in Eq. (5).

$$F_{i(CH_i)} = FF_i\cdot f_{Tm2i}\cdot CH_i(t) \qquad (5)$$

in which

μ_{max} : Maximum specific growth rate (1/T)

f_{Tm1} : Temperature correction function for growth (-)

f_{Tm2} : Temperature correction function for decay (-)

FF : Decaying rate coefficient (1/T)

DIN : Dissolve inorganic nitrogen concentration (M/L^3)

DIP : Dissolve inorganic phosphorus concentration (M/L^3)

KN : DIN saturation coefficient (M/L^3)

KP : DIP saturation coefficient (M/L^3)

Lu : Solar radiation (cal/L^2/T)

K_{Lu} : Solar radiation saturation constant (cal/L^2 /T)

β : Chloride coefficient (-)

Cl : Chloride concentration (M/L^3)

M : Chloride concentration in the Ariake Sea (M/L^3)

Subscript i: (1: diatom, 2: blue-green algae)

Temperature correction function for algal decay, f_{Tm2}, is calculated following the effect of temperature on reaction rate, θ_i^{T-20}. Resuspension of algae within resuspension particles from mud bed is included in this model. In Eq. (3), α is the ratio of algal productivity to resuspended solids from mud bed. The resuspension flux of SS due to wind from the mud bed, J_{res}, is calculated by wind functions as expressed in Eq. (6). Wind velocity and wind direction data are observed at Shimabara station.

$$J_{res}(t) = \gamma \cdot \left(\frac{U_*^2(t)}{U_{*c}^2} - 1\right)^m \cdot f_w(w_d(t)) \quad (U_* \geq U_{*c})$$
$$= 0 \quad (U_* < U_{*c}) \tag{6}$$

where
γ: Resuspension coefficient ($M/L^2/T$)
$U_*(t)$: Wind velocity (L/T)
$U_{*c}(t)$: Critical wind velocity (L/T)
$f_w(w_d(t))$: Wind direction coefficient $0 \leq f_w \leq 1$ (-)
w_d : Direction of wind velocity (-)
m : Constant (-)

Wind direction coefficient is shown in Eq. (7).

$$f_w(w_d) = 1 - 0.5 \cdot w_c \cdot (1 - \cos(w_m - w_d(t))) \tag{7}$$

where
w_c : Wind direction factor $0 \leq w_c \leq 1$ (-)
w_m : Critical wind direction for resuspension (-)

The settlement flux of SS, J_{SS} , and the settlement flux of adsorbed DIP with SS, J_{DIP}, are explained in Eq. (8) and (9), respectively (Koga et al., 2003).

$$J_{SS}(t) = u_{SS} \cdot (1 + \alpha_{SS} \cdot Cl(t)) \cdot SS(t) \tag{8}$$

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 solid concentration (M/L^3)

$$J_{DIP}(t) = \alpha_{DIP} \cdot J_{SS}(t) \cdot (DIP(t)) \tag{9}$$

Where
α_{DIP} : Settlement coefficient (L^3/M)
$DIP(t)$: DIP concentration (M/L^3)

COD, TN, TP

COD, TN and, TP concentrations in this water quality model are considered as particulate and dissolved COD, N and P and nutrient regarding to algae as shown in Eq. (10):

$$\underset{}{\frac{d(C_j(t)\cdot V(t))}{dt}} = \underset{\text{(Particulate)}}{\frac{d(P_j(t)\cdot V(t))}{dt}} + \underset{\text{(Dissolved)}}{\frac{d(D_j(t)\cdot V(t))}{dt}} + \underset{\text{(Regarding algae)}}{\frac{d(\Sigma(CH_i(t)\cdot K_{Eij}\cdot V(t)))}{dt}} \tag{10}$$

Definition and value of parameter using in this model are listed in Table 3.

RESULTS AND DISCUSSION

Chlorophyll-*a*

Figure 8 demonstrates the temperature coefficients for algal productivity in the Isahaya reservoir obtained from the developed model. Simulation results of total Chl-*a*, Chl-*a* from diatoms and blue green algae are shown in Fig. 9. From Chl-*a* simulation results, it can be seen that diatoms are predominant species in the Isahaya reservoir. The diatoms are dominant during spring and fall, while blue green algae are dominant during summer.

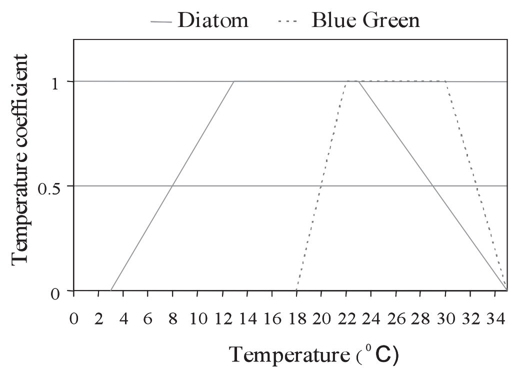

Fig. 8 Optimal temperature for algal productivity

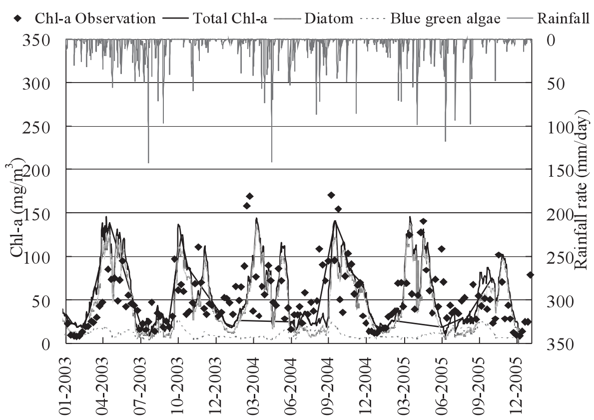

Fig. 9 Total chlorophyll-*a* concentration, chlorophyll-*a* from diatom and blue green algae

Table 3 The parameters obtained from the calibration results

Parameter	Description			Value
μ_{max}	Maximum specific growth rate (1/day)		Diatom	0.47
			Blue-green algae	0.17
FF	Decaying rate (1/day)		Diatom	0.05
			Blue-green algae	0.02
f_{Tm1}	Temperature(Growth) (lower, optimum, optimum, upper) Limited temperature ::Use optimum value::		Diatom	(3,13,23,35)
			Blue-green algae	(18,22,30,35)
f_{Tm2}	Temperature correction function(Death) θ_i^{T-20}		Diatom	1.04
			Blue-green algae	1.04
KN	Saturation constant of DIN (mg/l)		Diatom	0.1
			Blue-green algae	0.08
KP	Saturation constant of DIP (mg/l)		Diatom	0.008
			Blue-green algae	0.008
K_{Lu}	Solar radiation saturation constant (cal/cm^2/day)			200
U_{SS}	Settling velocity(m/day)		SS	0.18
W_{C1}			Diatom	0.07
W_{C3}			Blue-green algae	0.05
W_{SSC}			COD	0.1
W_{SSN}			Nitrogen	0.1
W_{SSP}			Phosphorus	0.15
$K_{Ei,1}$	Conversion coefficient from CHL to COD (mg-COD/μ g-CHL)		Diatom	0.015
			Blue-green algae	0.015
$K_{Ei,2}$	Conversion coefficient from CHL to N (mg-N/μ g-CHL)		Diatom	0.0035
			Blue-green algae	0.0035
$K_{Ei,3}$	Conversion coefficient from CHL to P (mg-P/μ g-CHL)		Diatom	0.0005
			Blue-green algae	0.0005
$J_{D,J}$	Release flux		COD	0.035
			DN	0.0025
			DP	0.01
α_{SS}	Coagulation coefficient of SS (mg/l)$^{-1}$			0.004
$\alpha_{D\text{-}IP}$	Settlement coefficient (mg/l)$^{-1}$			0.002
J_{res}	Resuspension flux (m=1)	Critical wind Speed	U_{*C}(m/s)	2.5
		Resuspension coefficient	γ (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)			20560

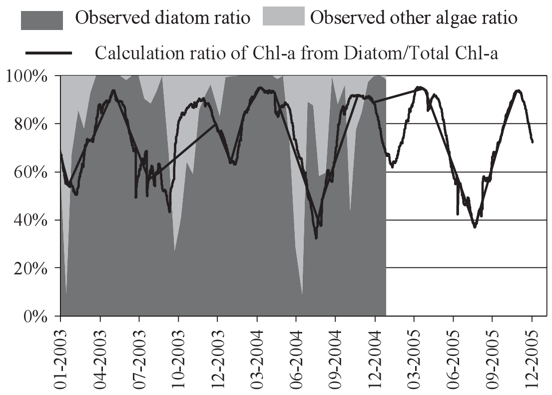

Fig. 10 Ratio of chlorophyll-*a* from diatom to total chlorophyll-*a* between observed data and calculation results

Ratio of Chl-*a* from diatom to total Chl-*a* between observed data and simulation results are demonstrated in Fig. 10. Simulation results of diatoms concur with the observed data. High ratio of diatoms in simulation results appear in the same time as the observed data. It can be said that Chl-*a* simulation in this water quality model are satisfied and diatoms are the most dominated species in the Isahaya reservoir from 2003 to 2005.

COD

COD simulation results are presented in Fig. 11. There is relationship between COD and algae growth. That is, during high growth of algal productivity, COD are gradually increased. It means algal productivity contributes to COD concentration. During spring 2005, although Chl-*a* simulation results have good agreement with the observed data but the values are lower than the observed data. This can be suggested that there are other living cells contributing COD to water column. During fall of 2005, COD simulation results are higher than the observed data, this occurs because particulate COD from SS is high in this period.

DIN and DIP

DIN simulation results are shown in Fig. 12. DIN decreases during high algal productivity because algae uptake DIN in water column. High DIN occurs due to release process of algae after decaying. DIP simulation results are shown in Fig. 13. It is found that, DIP decreases due to precipitation and increases due to release process. High DIP concentration can be seen even during high algal growth rate which means DIP is not the limiting nutrient for algal productivity in the Isahaya reservoir. Dissolved phosphorus and magnesium (Mg^{2+}) in intruded seawater can be adsorbed by suspended solids and settled by coagulation and chemical precipitation (Koga et al. 2003). When intrusion of seawater occurs, dissolved phosphorus can settle to the bottom with solid particles. During summer,

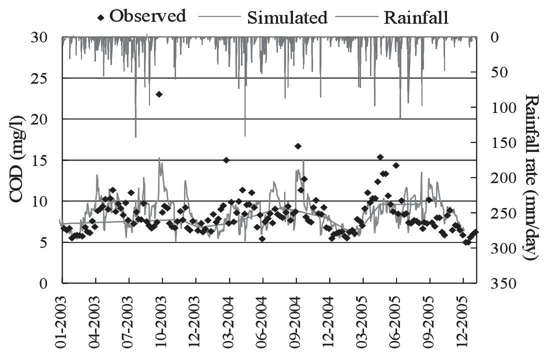

Fig. 11 COD concentration

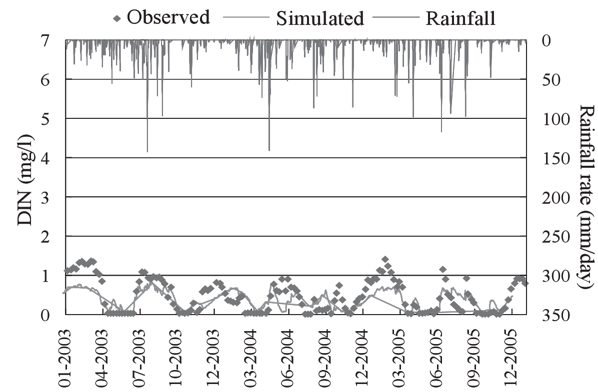

Fig. 12 DIN concentration

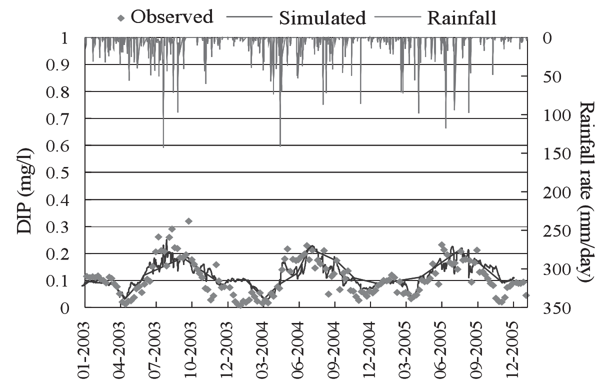

Fig. 13 DIP concentration

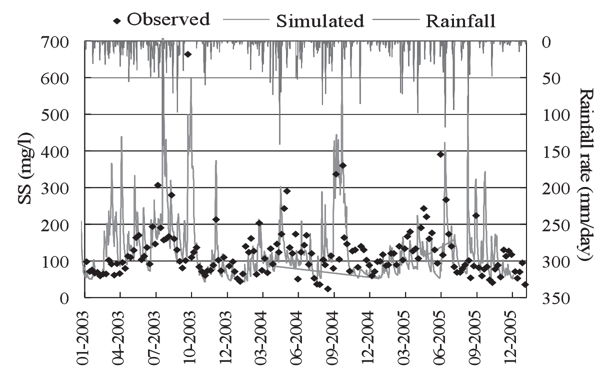

Fig. 14 Suspended solids concentration

high DIP concentration occurs due to high release rate of DIP from bottom mud. In this model, these precipitation and release of DIP are taken into account. From DIP simulation results, good relationship with observed data is found, which means DIP is controlled by release, resuspension, coagulation and precipitation processes. It shows that temperature and salinity play an important role on DIP in the Isahaya reservoir. Tendency of simulation results of DIN is fluctuated following the observed data, but the accuracy are not good as DIP simulation results. In the region where DIN simulation results differ from the observed data, simulation results of Chl-*a* also have poor agreement with the observed data, which indicates that Chl-*a* plays an important role on DIN concentration. For further study, Chl-*a* should be concerned more in details in order to get better results of DIN.

Simulation results of suspended solids are shown in Fig. 14. High SS concentration occurs in 2003 because of high discharge loading during high rainfall period. It is pointed out that land loading has a very strong influence on SS concentration. In summer of 2004, high SS concentration occurred because of high resuspension rate from mud bed due to high wind speed. That is, wind speed plays an important role on SS in the Isahaya reservoir. When low water transparency occurs during high resuspension period, light intensity decreases in water column and algal photosynthesis decreases. However, as the Isahaya reservoir is shallow, light intensity does not have strong impact on algal productivity. For chloride concentration, it is found that salinity concentrations slightly affect the growth rates of diatoms and blue green algae. As diatoms and blue green algae in the Isahaya reservoir are brackish species, both diatoms and blue green algae can grow up during this salinity concentration range.

CONCLUSIONS

From this study, it reveals that after fiscal year 2000, algae species and their growth have changed from the initial of reclamation project by environmental changes. It is found that two kinds of algae, diatoms and blue green algae are predominant in the Isahaya reservoir after fiscal year 2000. The effect on algal growth can be described from Chl-*a* simulation result. That is, in the Isahaya reservoir, light intensity and salinity concentration have small effect on algal growth, but temperature and nutrients, especially DIN, play an important role on algal growth. The nutrient simulation results reveal that DIN uptake increases during algal growth but DIP is affected by resuspension, release, coagulation and precipitation processes. Temperature and salinity levels also influence DIP in the Isahaya reservoir. At this moment, there is almost no effect on algal growth by lime input, but water quality goals in the Isahaya reservoir are not maintained because of high algal productivity.

ACKNOWLEDGEMENTS

Authors gratefully thank all colleagues in the Laboratory of Water Resources Engineering, Saga University for their cooperation.

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