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Impact of Inflow Loading and Algal Productivity on Water Quality in the Chikugo Barrage Reservoir, Japan

Narumol Vongthanasunthorn*[*], Hiromitsu Sasaki*, Kenichi Koga,**
Mayuko Sakata* and Kensuke Tabira******

*Department of Civil Engineering and Architecture, Faculty of Science and Engineering,
Saga University, Saga, Japan
**Professor Emeritus, Saga University, Saga, Japan
***Fuji P.S Corporation, Fukuoka, Japan
****The Shinwa Bank, Ltd., Nagasaki, Japan
[*]E-mail : si4430@cc.saga-u.ac.jp

Abstract

The Chikugo Barrage is located at 23 km upstream from the mouth of the Chikugo River, which is the largest river in the Northern Kyushu Region of Japan. Main purposes of the Chikugo Barrage are flood control, water supply, maintaining flow of the Chikugo River and preventing effect of seawater intrusion from the Ariake Sea. There are two rivers flowing into the reservoir, the Chikugo River (the main stream) and the Homan River (a tributary). According to water intake for urban area and irrigation and the operation of the Chikugo Barrage, previous researches reported that the hydraulic retention time (HRT) in the reservoir of the Chikugo Barrage became longer and resulted in high growth of phytoplankton in the reservoir during 1985-2008, while inflow loading was a cause of high phytoplankton when HRT was short. In this study, relationship between loading from upstream, HRT, algal productivity and water quality in the Chikugo Barrage Reservoir was analyzed by using water quality model. Calculated results confirm that chlorophyll-a (Chl-a) in the reservoir increased when inflow loading was high or when the HRT in the reservoir was long. Algal productivity significantly affected on the nutrient level and also led to the increase in COD and SS in the reservoir. Without loading from the Homan River, simulated result of COD in the reservoir became lower indicating that loading from the Homan River has subsidiary impact on concentration of algae in the reservoir. Since the result of loading analysis shows that ratio of Chl-a loading from the Homan River to the main stream tends to increase, loading control in the Homan River Basin is suggested as an effective measure for water quality management in the Chikugo Barrage Reservoir.

Keywords : Chikugo Barrage; Homan River; inflow loading; algal productivity; finite volume model

Introduction

When considering about water resources in one country especially an island country like Japan, precipitation is a valuable source of freshwater in that country. Based on the data of FAO [1] in June 2018, average annual precipitation in Japan is 1,668 mm which is around 1.6 times of the world average. On the other hand, total renewable water resources per capita of Japan is 3,373 m^3/capita-year which is less than half of the world average [2]. Despite of high precipitation, small amount of water resources is available for one person in Japan because of its large population.

After the World War II, economic development and population growth resulted in the rapid increase in water demand in Japan. In order to secure stable water supply, water resources development became necessary [3, 4].

According to the Water Resources Development Promotion Law, the Water Resources Development Basic Plans were issued for seven river systems namely Tone River, Arakawa River, Toyokawa River, Kiso River, Yodogawa River, Yoshino River and Chikugo River, so-called river systems for water resources development [4, 5]. Facilities including dams, barrages and water channels have been constructed to stabilize water flow at downstream and, at the same time, some of them also pay important roles in flood control, power generation and conservation of water environment [3, 4].

Designated as one of the river systems for water resources development, the Chikugo River is the largest river located in the Northern Kyushu Region. Length of the main stream is 143 km and the river basin covers 2,860 km^2 in Kumamoto Prefecture, Oita Prefecture, Fukuoka Prefecture and Saga Prefecture (Figure 1) [6].

Figure 1 Watershed of the Chikugo River [6]

According to the Water Resources Development Basic Plan of the Chikugo River System [7], the Chikugo Barrage was constructed at 23 km upstream from the river mouth and the operation has been conducted since April 1985. The purposes of the Chikugo Barrage are flood control, water supply, compensation for flow fluctuation in the Chikugo River and prevention of seawater intrusion [6]. At present, the Japan Water Agency (JWA) is responsible for operation and maintenance of the Chikugo Barrage. The JWA is an independent administrative agency established in 1962 under Water Resources Development Public Corporation Law, which has engaged in development and management of water resources in the seven river systems [4, 8].

The Chikugo Barrage is about 500 m long and consists of 5 main gates, a lock for ship passage and 2 fish ladders. Total capacity of the reservoir of this barrage is around 5.5 million m^3 [6]. Water is withdrawn from the reservoir by large pumping stations and distributed to water users in both sides of the Chikugo River. Water quality environmental standards of the Chikugo River [6] is shown in Figure 2. Water quality from Mamezu Bridge located at upstream of the Chikugo Barrage until the mouth of the Chikugo River is classified as B Class.

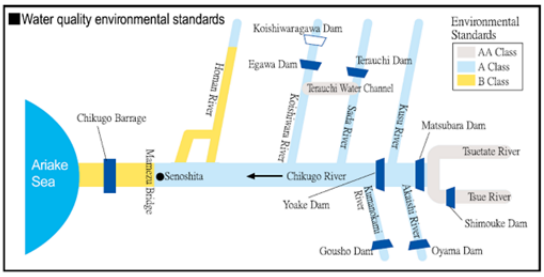

Figure 2 Water quality environmental standards of the Chikugo River [6]

Since 1977, the Chikugo Barrage Environmental Monitoring Liaison Council was established in order to monitor the environmental impact of the construction and to periodically assess the impact of the barrage operation on the environment of the main stream, tributaries and the Ariake Sea [6]. Figure 3 shows sites of environmental survey around the Chikugo Barrage.

Since water quality in the reservoir of the Chikugo Barrage is required to meet water quality environmental standards and demand of water users, several researches were conducted focusing on water quality in this reservoir and pollutant loading from upstream. It was found that loading of COD, T-N and T-P at upstream of the Chikugo Barrage had linear relationship with population and paddy field area [9]. Unit loading of COD from forest, urban area and paddy field area at upstream of the Chikugo Barrage were obtained from water quality simulation by the tank model [10] and the tank model sufficiently simulated pollutant loading of the Chikugo River at Senoshita Station [11]. According to the water intake for downstream and the operation of the Chikugo Barrage, the hydraulic retention time (HRT) in the reservoir became longer and resulted in the increase in phytoplankton in the reservoir during 1985-2008 [12], while the analysis result in [13] showed that loading from upstream was a cause of high concentration of phytoplankton in the reservoir during the period of short HRT.

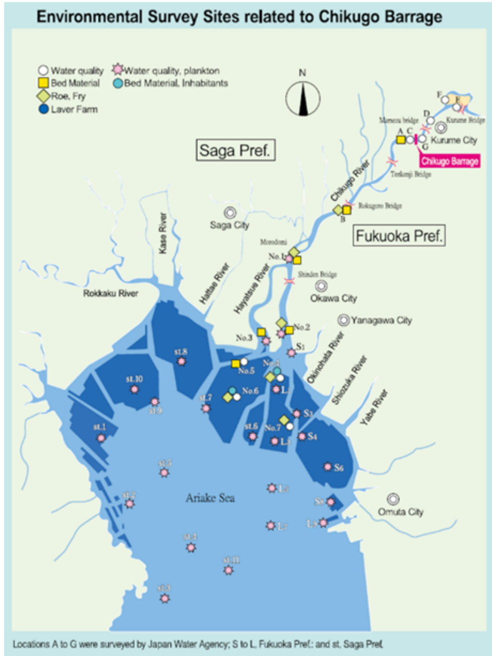

Figure 3 Environmental survey sites related to the Chikugo Barrage [6]

In order to provide useful information for water quality management in the Chikugo Barrage Reservoir, relationship between inflow loading, HRT, algal productivity and water quality in the Chikugo Barrage Reservoir from 2009 to 2014 was examined in this study by using water quality model.

Materials and Methods

Study Area

The study area consists of the reservoir of the Chikugo Barrage and two inflow rivers; the Chikugo River (the main stream) and the Homan River (a tributary). Map of the study area and monitoring stations are shown in Figure 4.

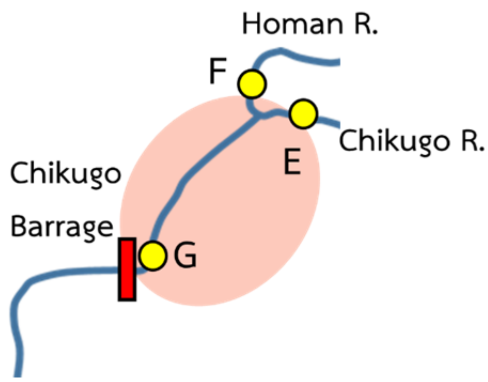

Figure 4 Study area and location of monitoring stations

Station E and Station F are the monitoring stations of the Chikugo River and the Homan River respectively while water quality in the reservoir is monitored at Station G. Flow rate and water quality in the study area are monitored by Chikugo Barrage Operation and Maintenance Office (Japan Water Agency) and Kyushu Regional Development Bureau (Ministry of Land, Infrastructure, Transport and Tourism).

In this study, characteristics of water quality in the reservoir and upstream rivers were examined based on the monitoring data. After that, impact of inflow loading, HRT and algal productivity on water quality in the reservoir was analyzed by using the finite volume model.

Data Analysis

Monitoring data related to flow and water quality in the reservoir and upstream rivers was analyzed to examine a trend of each water quality parameter and to find the relationship among the parameters. Water quality parameters considered in this study are chlorophyll-a (Chl-a), dissolved inorganic nitrogen (DIN), orthophosphate (PO4-P), Chemical Oxygen Demand (COD), suspended solids (SS) and dissolved oxygen (DO). Period of the study is 1985-2014.

Loading Analysis

Loading of the Chikugo River and the Homan River was estimated from monitoring data of Station E and Station F, respectively. Relationship between loading and flow rate (L-Q equation) of each river was examined. The L-Q equations were applied as boundary condition of the water quality model and impact of loading on water quality in the reservoir was analyzed.

Water Quality Model

Since water depth is shallow and spatial difference of concentration is small, the reservoir of the Chikugo Barrage can be considered as a completely-mixed water body. The water quality model was developed based on a finite volume model [16]. Inflow loading from upstream (main stream of the Chikugo River and the Homan River) was estimated from L-Q equations. Calculation period is 2009-2014. Time step of calculation is 1 day. Continuity equation and governing equations of water quality are listed below [13-15].

$$\frac{dV}{dt} = \sum Q_{in} - \sum Q_{out} \quad (1)$$

where V: Volume (m^3); Q_{in} : Inflow (m^3/s); Q_{out} : Outflow (m^3/s)

Governing equations of Chl-a are described in equations (2) – (4). Monod equation was adopted for growth rate of Chl-a [17]. Based on the monitoring data, three types of phytoplankton; namely diatom, green algae and blue-green algae were considered in this study.

$$\frac{d(V \cdot CH)}{dt} = \sum L_{in(CH)} - \sum L_{out(CH)} + G - D - w_{CH} \cdot CH \cdot A \quad (2)$$

$$G = \mu_{max} \cdot f_G \cdot \frac{N}{N+K_N} \cdot \frac{P}{P+K_P} \cdot \frac{I}{I+K_I} \cdot CH \cdot V \quad (3)$$

$$D = k_d \cdot \theta_{CH}{}^{(T-20)} \cdot CH \cdot V \quad (4)$$

where CH: Chl-a (μg/l); $L_{in(CH)}$: Chl-a inflow loading (g/s); $L_{out(CH)}$: Chl-a outflow loading (g/s); G: Growth; D: Decay; w_{CH} : settling velocity of Chl-a (m/d); A: surface area (m^2); μ_{max} : maximum specific growth rate (1/d); f_G : temperature coefficient of growth (-); N: dissolved inorganic nitrogen (mg/l); P: orthophosphate (mg/l); I: light intensity (cal/cm^2); K_N : half-saturation constant of nitrogen (mg/l); K_P : half-saturation constant of phosphorus (mg/l); K_I : half-saturation constant of light intensity (cal/cm^2); k_d: decay rate (1/d); θ_{CH} : temperature coefficient of decay; T: water temperature (°C)

Governing equations of DIN and PO4-P are shown in equation (5) and equation (6), respectively.

$$\frac{d(V \cdot N)}{dt} = \sum L_{in(N)} - \sum L_{out(N)} + Y_N(D - G) + r_N \cdot f_N \cdot B_N \cdot A_B - K_{DN} \cdot \theta_N^{(T-20)} \cdot N \cdot V \quad (5)$$

$$\frac{d(V \cdot P)}{dt} = \sum L_{in(P)} - \sum L_{out(P)} + Y_P(D - G) + r_P \cdot f_P \cdot B_P \cdot A_B \quad (6)$$

where $L_{in(N)}$: DIN inflow loading (g/s); $L_{out(N)}$: DIN outflow loading (g/s); Y_N : mass ratio of DIN to Chl-a; r_N : release rate of DIN (m/d); f_N : temperature coefficient of release; B_N : DIN in river bottom (mg/l); A_B : bottom area (m^2); K_{DN}: denitrification rate (1/d); θ_N : temperature coefficient of denitrification; $L_{in(P)}$: PO4-P inflow loading (g/s); $L_{out(P)}$: PO4-P outflow loading (g/s); Y_P : mass ratio of PO4-P to Chl-a; r_P : release rate of PO4-P (m/d); f_P : temperature coefficient of release; B_P : PO4-P in river bottom (mg/l)

COD is composed of dissolved COD, particulate COD and COD content of phytoplankton, while SS includes suspended solids and SS content of phytoplankton. Governing equations of COD and SS are as follows:

$$TCOD = DC + PC + Y_C \cdot CH \quad (7)$$

$$\frac{d(V \cdot DC)}{dt} = \sum L_{in(DC)} - \sum L_{out(DC)} - K_{DC} \cdot DC \cdot V \quad (8)$$

$$\frac{d(V \cdot PC)}{dt} = \sum L_{in(PC)} - \sum L_{out(PC)} - w_{PC} \cdot PC \cdot A \quad (9)$$

$$TSS = SS + Y_S \cdot CH \quad (10)$$

$$\frac{d(V \cdot SS)}{dt} = \sum L_{in(SS)} - \sum L_{out(SS)} - w_{SS} \cdot SS \cdot A \quad (11)$$

where TCOD: total COD (mg/l); DC : dissolved COD (mg/l); PC : particulate COD (mg/l); Y_C : mass ratio of COD to Chl-a; $L_{in(DC)}$: DC inflow loading (g/s); $L_{out(DC)}$: DC outflow loading (g/s); K_{DC} : degradation rate of DC (1/d); $L_{in(PC)}$: PC inflow loading (g/s); $L_{out(PC)}$: PC outflow loading (g/s); w_{PC} : settling velocity of PC (m/d); SS: suspended solids (mg/l); Y_S : mass ratio of SS to Chl-a; $L_{in(SS)}$: SS inflow loading (g/s); $L_{out(SS)}$: SS outflow loading (g/s); w_{SS} : settling velocity of SS (m/d)

Results and Discussion

Characteristics of Water Quality in the Chikugo Barrage Reservoir and Inflow Rivers

Ratio of flow rate of the Homan River at Station F (QF) to the flow rate of the Chikugo River at Station E (QE) is shown in Figure 5. The ratio QF/QE increased from 2009 and the average ratio was around 0.25. The increase in the ratio QF/QE indicates that impact of inflow loading from the Homan River on the water quality in the reservoir might increase when compared with the inflow loading from the main stream [15]. In loading analysis, inflow loading from each river was evaluated and relationship between loading and flow rate was examined.

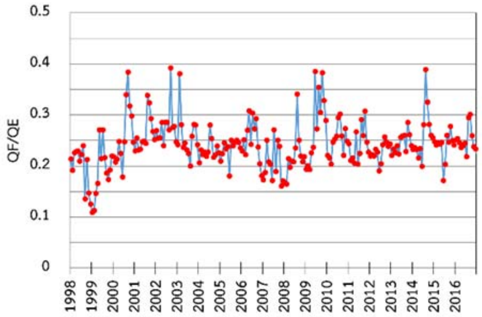

Figure 5 Ratio of flow rate of the Homan River (QF) to the Chikugo River (QE)

Chl-a observed at Station E, F and G are shown in Figure 6. Since Chl-a at all stations was high in the period of high rainfall, it can be said that high inflow loading resulted in high Chl-a in the reservoir. Chl-a in the Homan River was much higher than that in the main stream. Based on flow ratio of 0.25, Chl-a loading of the Homan River could be as high as half of the main stream. Moreover, Chl-a at Station G also increased when HRT in the reservoir was long. It indicates that both loading from upstream and HRT were the causes of the increase in Chl-a in the reservoir.

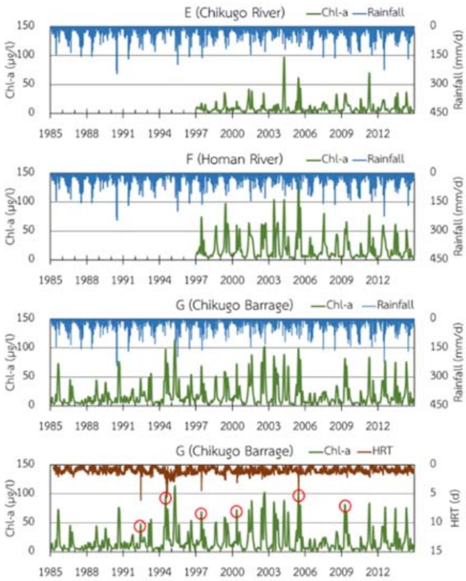

Figure 6 Chl-a in the Chikugo Barrage Reservoir and inflow rivers

In Figure 7, DO in the reservoir exceeded the saturated DO (Cs) when Chl-a was high which shows that large amount of oxygen was supplied by photosynthesis. Figure 8 shows COD at Station E, F and G. COD at Station G had the same trend with inflow rivers which represents the impact of inflow loading on COD in the reservoir. On the other hand, COD in the reservoir also increased in the period of high Chl-a. It indicates that growth of phytoplankton and inflow loading affected on COD in the reservoir.

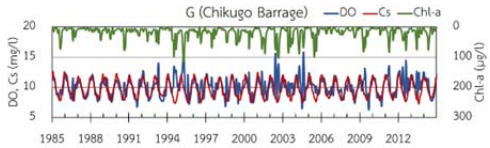

Figure 7 DO and Chl-a in the Chikugo Barrage Reservoir

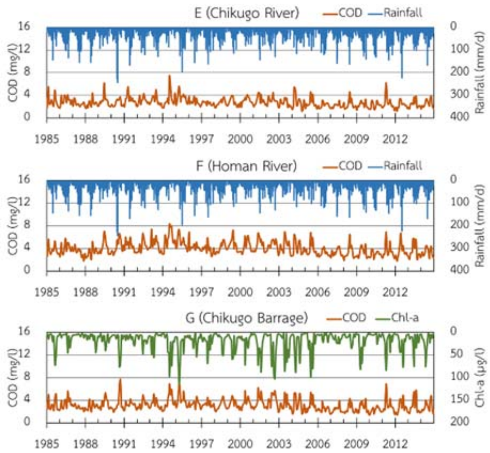

Figure 8 COD in the Chikugo Barrage Reservoir and inflow rivers

Figure 9 shows DIN at Station E, F and G. Trend and level of DIN in the reservoir were same with DIN of the main stream (Station E), while DIN of the Homan River was higher than other stations and changed seasonally. It can be said that DIN in the reservoir was affected by inflow loading from the main stream. Compared with Chl-a, DIN in the reservoir decreased when

Chl-a was high, which confirmed the consumption of DIN by algal growth.

PO4-P at each station is shown in Figure 10. Similar to DIN, POP4-P in the reservoir was raised by loading from upstream. The decline of PO4-P in the period of high Chl-a also confirms phosphorus consumption by phytoplankton in the reservoir.

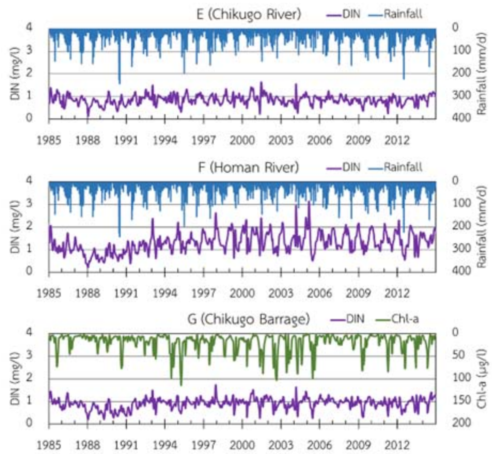

Figure 9 DIN in the Chikugo Barrage Reservoir and inflow rivers

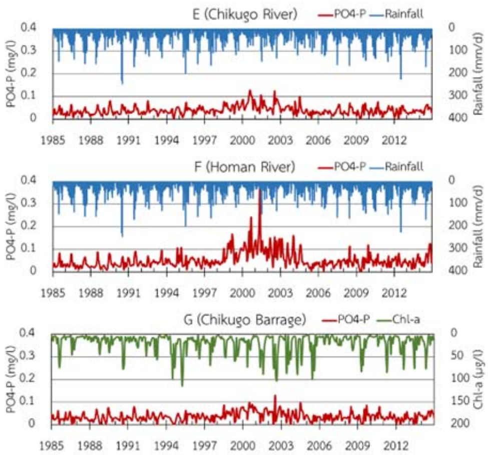

Figure 10 PO4-P in the Chikugo Barrage Reservoir and inflow rivers

From Figure 11, SS at each station increased when the rainfall was high. It indicates that high inflow loading resulted in high SS in the rivers and the reservoir. Since the period of high SS in the reservoir was different from the period of high Chl-a, it can be said that impact of algal growth on SS in the reservoir was less significant than the inflow loading. On the other hand, long HRT in the reservoir probably resulted in large settling amount of SS.

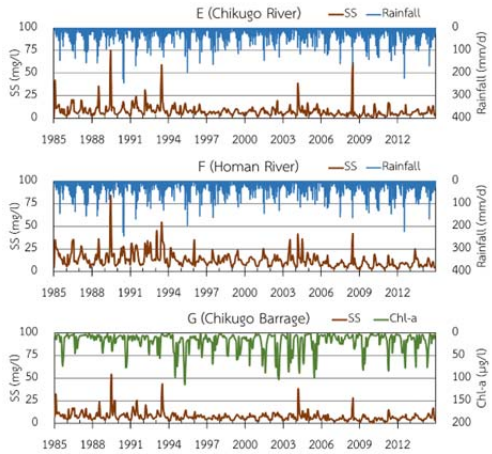

Figure 11 SS in the Chikugo Barrage Reservoir and inflow rivers

Loading Analysis

Loading of the main stream (LE) and the Homan River (LF) was estimated from the observed data. As shown in Figure 12, loading of COD in both rivers proportionally related to the flow rate.

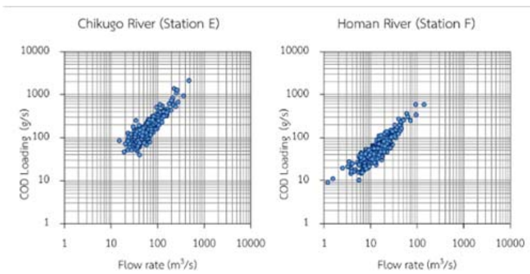

Figure 12 COD loading and flow rate of the Chikugo River and the Homan River

Other loading also had the similar relationship with flow rate. The L-Q equations of the main stream and the Homan River are listed in Table 1.

Table 1 L-Q equations of the Chikugo River and the Homan River

$L = aQ^b$	Chikugo River (Station E)		Homan River (Station F)	
	a	b	a	b
Chl-a	0.1	2.0	1.5	1.75
DIN	0.8	1.07	1.3058	0.9527
PO4-P	0.008	1.3648	0.033	1.1088
COD	1.8	1.0811	2.0	1.1913
SS	0.6	1.5454	4.5	1.2372

As shown in Figure 5, monthly average flow rate of the Homan River from 2009 to 2016 was around 25% of the flow rate in the main river. Loading of each river in 2009-2016 was estimated by using L-Q equations (the result of 2012 was excluded because of inadequate data). Ratio of loading of the Homan River to loading of the Chikugo River is summarized in Table 2.

Table 2 Ratio of loading of the Homan River (LF) to loading of the Chikugo River (LE)

Loading	LF / LE
Chl-a	0.39
DIN	0.25
PO4-P	0.25
COD	0.34

It was found that nutrient loading (DIN and PO4-P) of the Homan River was 25% of the main river. On the other hand, Chl-a loading and COD loading were 39% and 34%, respectively. Despite of its low flow rate, loading ratio of Chl-a and loading ratio of COD of the Homan River were larger than the ratio of flow rate. It is necessary to pay attention to the impact of the loading of the Homan River on the water quality in the reservoir especially concentration of phytoplankton and organic matter.

Contribution of Inflow Loading on Water Quality in the Chikugo Barrage Reservoir

Water quality in the reservoir was calculated by considering only the inflow loading from upstream and neglecting other mass transport and transformation terms. Calculated results are shown in Figure 13. Chl-a increased during the period of high rainfall (high flow rate). Except in the period of high rainfall, DIN in the reservoir was almost constant. At the same time, it also indicates that the low level of observed DIN was a result of nutrient consumption by algal growth in the reservoir.

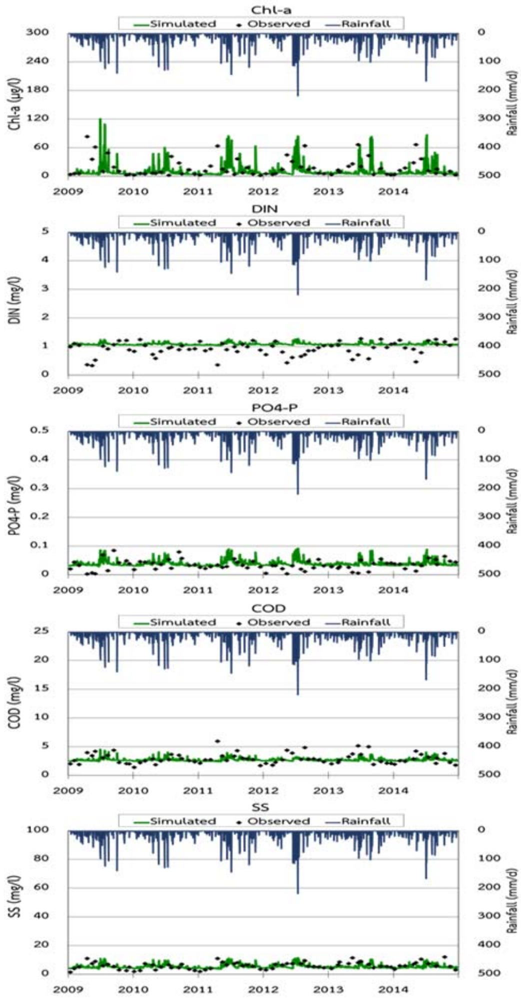

Figure 13 Contribution of inflow loading on water quality in the Chikugo Barrage Reservoir

Calculated result of PO4-P was high in the period of high flow rate which confirmed the impact of inflow loading on PO4-P in the reservoir. Similar to DIN, reduction of PO4-P according to productivity of algae in the reservoir was also confirmed.

Calculated results of COD and SS during the period of high loading were lower than observed data, which indicates that the effect of algal productivity on COD and SS could not be neglected.

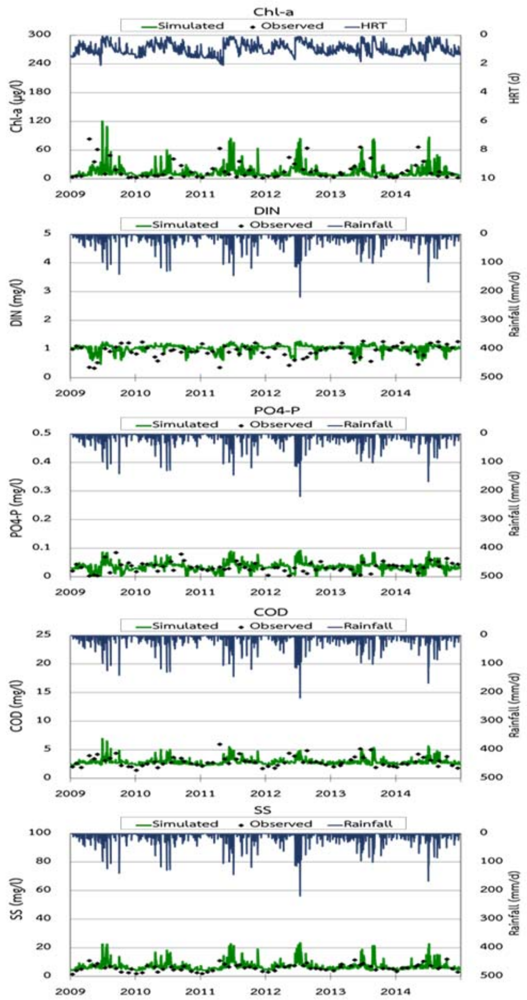

Figure 14 Simulated results considering inflow loading and algal productivity in the Chikugo Barrage Reservoir

Contribution of Algal Productivity on Water Quality in the Chikugo Barrage Reservoir

Productivity of algae was taken into account in the calculation together with the inflow loading from upstream. Figure 14 shows the calculated results. By including the impact of algal productivity, calculated results of all water quality parameters have good agreement with the observed data. Moreover, simulated result of the Chl-a also showed good agreement with observed data in the period of long HRT. The increase of Chl-a, COD and SS and the consumption of nitrogen and phosphorus by algal productivity were confirmed. Algal productivity and HRT placed significant impact on water quality in the reservoir. The parameters used in the water quality model are listed in Table 1.

Contribution of Loading of the Homan River on Water Quality in the Chikugo Barrage Reservoir

Calculated result without loading of the Homan River is shown in Figure 15. The calculated result in the reservoir is lower than the result in Figure 14. It is shown that loading of the Homan River also had subsidiary effect on concentration of phytoplankton in the reservoir. Reduction of loading of the Homan River can contribute to eutrophication control in the Chikugo Barrage Reservoir.

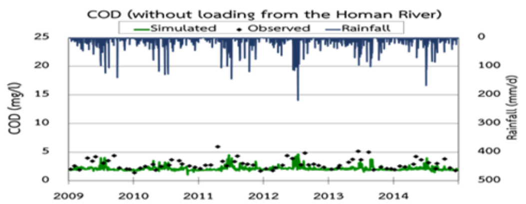

Figure 15 Simulated result by neglecting loading of the Homan River

Table 3 Parameters used in the water quality model of the Chikugo Barrage Reservoir

μ_{max}	maximum specific growth rate	1.3 – 1.8	1/d
K_N	half-saturation constant of nitrogen	0.02	g/m^3
K_P	half-saturation constant of phosphorus	0.002	g/m^3
K_I	half-saturation constant of light intensity	100	cal/cm^2
k_d	decay rate	0.05	1/d
θ_{CH}	temperature coefficient of decay	1.05	-
w_{CH}	settling velocity of chl-a	0.05	m/d
w_{PC}	settling velocity of PCOD	0.5	m/d
w_{SS}	settling velocity of SS	0.5	m/d
r_N	release rate of DIN	0.15	m/d
r_P	release rate of PO4-P	0.01	m/d
K_{DN}	denitrification rate	0.015	1/d
θ_N	temperature coefficient of denitrification	1.05	-
K_{DC}	degradation rate of DCOD	0.08	1/d
Y_N	DIN: Chl-a	0.02	mg DIN /µg Chl-a
Y_P	PO4-P: Chl-a	0.0015	mg PO_4-P /µg Chl-a
Y_C	COD: Chl-a	0.015 – 0.03	mg COD /µg Chl-a
Y_S	SS: Chl-a	0.1 – 0.18	mg SS /µg Chl-a

Conclusions

In this study, water quality analysis was conducted to define the impact of inflow loading from upstream and HRT regarding to the operation of the barrage on water quality in the Chikugo Barrage Reservoir. It was found that Chl-a in the reservoir increased when loading from upstream was high or when the HRT in the reservoir was long. Calculated results confirmed that algal productivity significantly affected on nutrient level (both DIN and PO4-P) in the reservoir while PO4-P also highly depended on the supply from upstream. Growth of phytoplankton also played an important role on increasing COD and SS in the reservoir. Since the effect of loading from the Homan River on concentration of algae in the reservoir was confirmed and ratio of Chl-a loading from the Homan River to the main stream tends to increase, loading control in the Homan River Basin is suggested as an effective measure for water quality management in the Chikugo Barrage Reservoir.

Acknowledgement

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