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RESTRAINT EFFECTS OF 2-MIB CONCENTRATION INCREASES DUE TO TOTAL PHOSPHORUS MANAGEMENT IN THE UPPER KINOKAWA WATERSHED

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ABSTRACT: The off-flavor taste of tap water due to 2-methylisoborneol (2-MIB) is caused by blue-green algae. This is one of the water quality problems associated with high nutrient loads, such as those found in the Kinokawa River, with drains the southwestern part of the Kii peninsula in Japan. Water quality monitoring data showed that 2-MIB tended to increase when total phosphorus (TP) concentration exceeded 0.02 mg/L. This study employed mass load and river water quality analyses coupled with water runoff analyses to examine ways of mitigating TP load in river water. In this study, it was revealed following things. (1) TP mass load could be reduced by approximately half if the industrial drainage volume standards defined in the Water Pollution Control Law were more stringent. (2) TP concentration could be decreased by 41% in response to TP mass load reduction and by 5% in response to an increase in river flow rate. (3) TP mass load reduction combined with an increase in river flow rate could reduce TP concentration to less than 0.015 mg/L and prevent increases in 2-MIB in tap water.

Keywords: Kinokawa River; Off-flavor tap water; Total phosphorus; Mass load analysis; River water quality analysis; Distributed hydrological model

1. INTRODUCTION

In the Kinokawa River watershed (Fig. 1), off-flavor tap water due to 2-methylisoborneol (2-MIB) produced by blue-green algae had been a water quality problem since 2004 [1]. 2-MIB was first detected downstream from Hashimoto City (monitoring point (9) in Fig.1), and off-flavor tap water started to be reported upstream after 2006 (monitoring points (10) to (12)).

In research on the relationship between blue-green algae and nutrient concentrations, total nitrogen (TN) and total phosphorus (TP), along with the nitrogen phosphorus ratio (N/P ratio) are often used. For example, Yokoyama and Yamashita [2] showed that an increase in *Phormidium tenue*, a causative organism of 2-MIB, was markable higher under high N/P ratio. Other research showed that the growth of blue-green algae remained restrained under nitrogen limitation [3]. Therefore, the control of nutrient concentrations in a watershed is considered to be one of the important strategies for solving the problem of off-flavor tap water [4].

In the Kinokawa River watershed, the total maximum daily loading is set in order to reduce COD, TN and TP inputs to the Seto Inland Sea. That is, control of TP in the Kinokawa River watershed is needed in order to solve the problem of off-flavor tap water and to reduce TP inflow to the Seto Inland Sea.

This study simulated changes of TP concentration in upstream by using a numerical modeling and examined the control policy in place to decrease TP concentration. The study area is upstream of Kinokawa River from Gojo City to Oyodo Town (Fig. 2) and the period of evaluation was from 2004 to 2006.

2. STUDY AREA

Points (1) - (12) in Fig. 1 are water quality monitoring points set by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) or Wakayama City. The Kinokawa River is about 136 km in length and has a watershed area of about 1,750 km^2. The river flows northwest and changes course to flow west-southwest into the Seto Inland Sea. There are 23 cities, towns and villages in Wakayama and Nara prefectures in 2004. The population is approximately 700,000, which is about half of Wakayama City located downstream from monitoring point (1) to the Seto Inland Sea (Fig. 1). Forest covers about 70% of the watershed, but the land use along the river is different.

The upper reaches of the river are mainly covered by forest but paddy field and orchard gradually increase from Gojo City (monitoring point (10) in Fig. 1) to downstream. Near the river mouth Wakayama

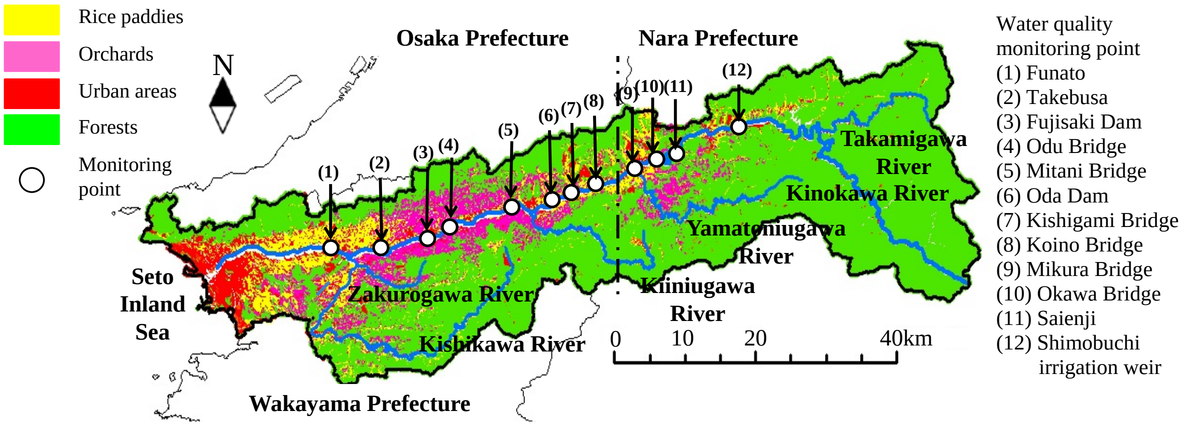

Fig. 1 Figure of land use of the Kinokawa River watershed
(The Ministry of Land Numerical land information in 1997)

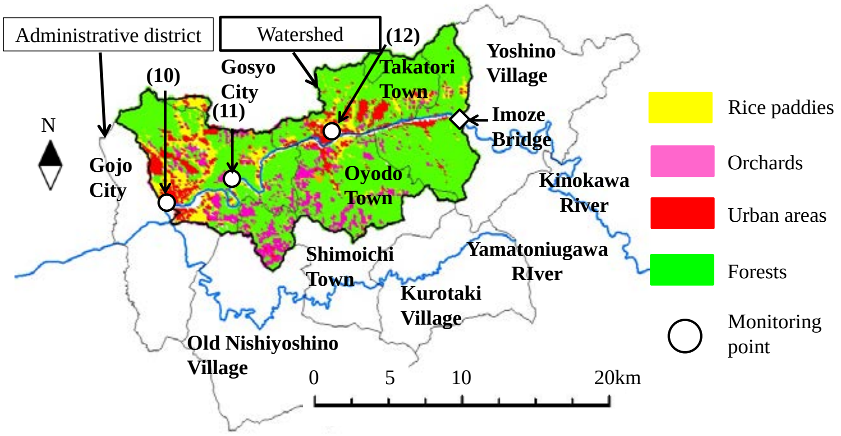

Fig. 2 Study area

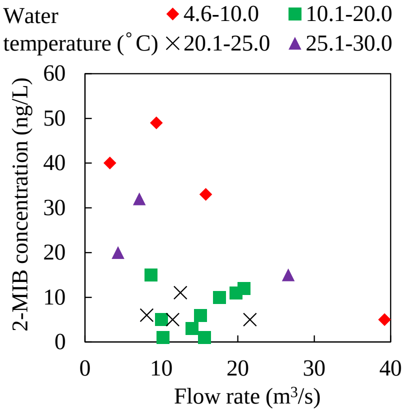

Fig. 3 Correlation of 2-MIB and flow rate by water temperature at Okawa Bridge

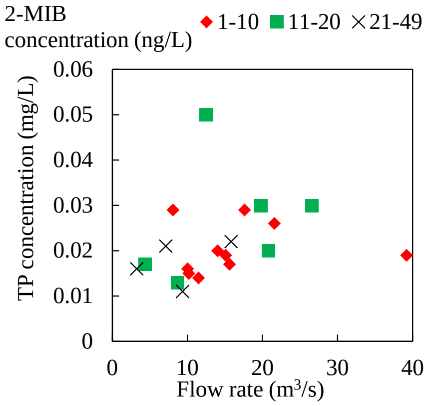

Fig. 4 Correlation of TP concentration and flow rate by 2-MIB at Okawa Bridge

City, urban area is the main land use.

In the study area shown in Fig. 2, the river is about 20 km in length and has a watershed area of about 220 km^2. The population is approximately 115,000, and about the half population lives in Gojo City, which is located immediately downstream of monitoring point (10). Forest covers about 60% of the watershed.

Fig. 3 and Fig. 4 show the relationships between 2-MIB and flow rate by water temperature and between TP and flow rate by 2-MIB concentration at the Okawa Bridge (monitoring point (10)) for data from 2004 through 2011. TP concentration was determined by the molybdenum blue method (potassium peroxodisulfate decomposition). 2-MIB concentration was assayed by these methods: gas chromatography mass spectrometry (GC-MS) of headspace gas in 2004, GC-MS of purge and trap samples from 2005 through 2006, and GC-MS of solid-phase extractions from 2007 through 2011. As shown in Fig. 3 and Fig. 4, the 2-MIB concentration

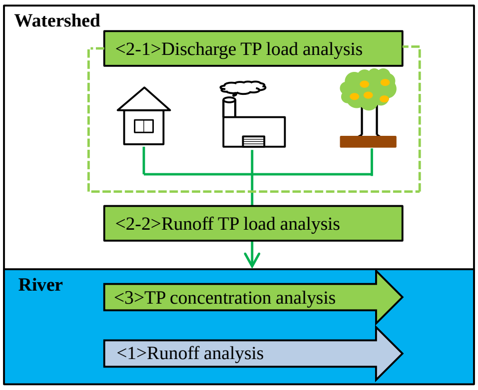

Fig. 5 Model conception diagram

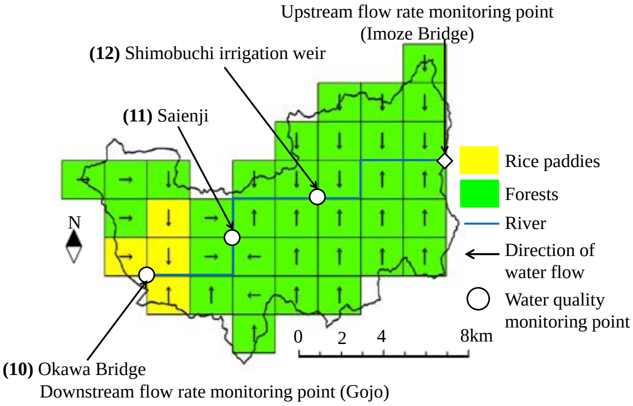

Fig. 6 Watershed mesh model (2km × 2km)

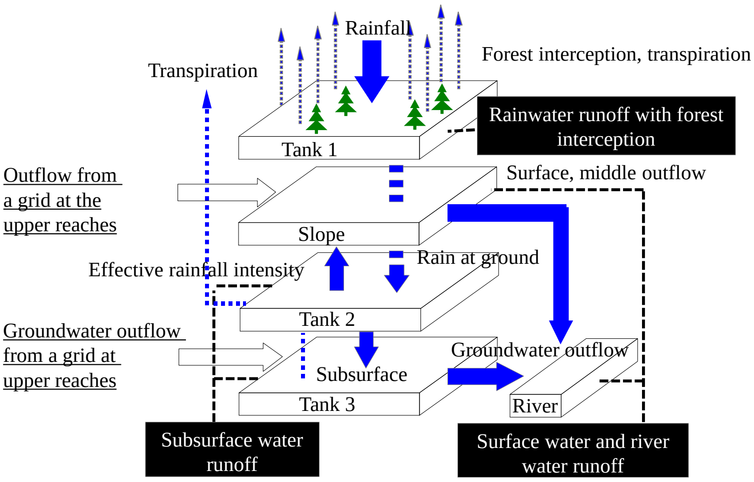

Fig. 7 Structure of the water outflow model

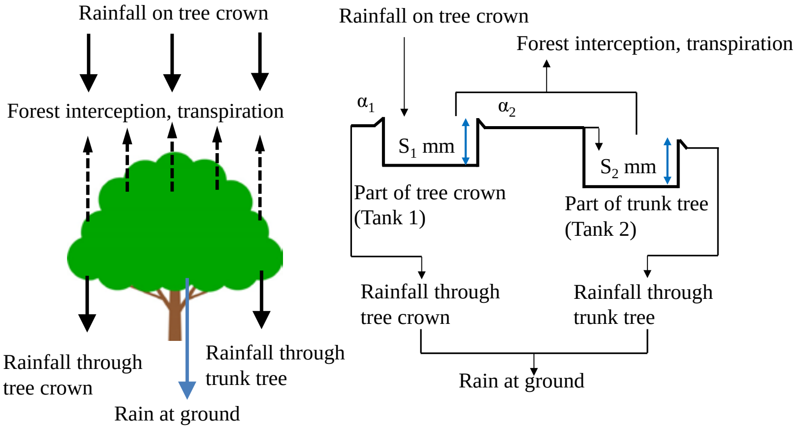

Fig. 8 Sub model for rain water runoff with forest interception

tends to increase when the flow rate of the river is low and TP concentration exceeds the eutrophication standard (0.02 mg/L, [2]).

3. STUDY METHOD

3.1 Model description

The models and analytical procedures employed in this study are as follows (Fig. 5).

<1> River flow rate and runoff rate of surface and subsurface water to the river are simulated by a distributed hydrological model.

<2> TP loading from point and non-point sources is simulated by a macro model using unit load ratios of TP along with the runoff rate of surface and subsurface water to the river.

<3> TP concentration in the river is simulated by a

one-dimensional steady state advection equation.

The study area was divided by 2 km × 2 km grid (Fig. 6).

Table 1 Load ratios of household wastewater and non-point sources

Source	TP load ratio	Source	TP load ratio
1) Household wastewater	1.3	4) Rice paddy	165
2) Urban area	190	5) Vegetable farm	72
3) Forest	34	6) Orchard	186

Unit 1) : g/(day・person) 2) : kg/(year・km^2)

Table 2 Load ratios of industrial wastewater

Source	TP load ratio	Source	TP load ratio	Source	TP load ratio
9 Food	0.67	17 Chemicals	0.22	25 Metals	0.33
10 Drink, tobacco, livestock feed	0.14	18 Oil, coal	0.00	26 Machines	0.05
11 Textiles (except for cloth)	1.12	19 Plastics	0.07	27 Electric machines	0.12
12 Cloth, others	0.11	20 Rubber	0.08	28 Communication equipment	0.04
13 Food (except for furniture)	0.00	21 Leather	0.20	29 Electric device	0.13
14 Furniture	9.04	22 Ceramic	0.20	30 Transport equipment	0.23
15 Pulp, paper	0.01	23 Steel	0.03	31 Precision machine	0.00
16 Publication, printing	0.02	24 Nonferrous metals	0.00	32 Other	2.11

Unit : (g/(day・million yen))

3.2 Runoff analysis using distributed hydrological model

The distributed hydrological model proposed by Ishizuka and Egusa [5] was used to calculate the river flow rate and the runoff rates of surface and subsurface water to the river (Fig. 7). This model consists of three sub models: 1) surface water and river water runoff, 2) subsurface water runoff, and 3) rain water runoff with forest interception. In this study, the water intake rate from the weir (Shimobuchi irrigation weir in Fig. 6) was used for the river water runoff sub model. The kinematic wave method is applied for the sub model of surface water and river water runoff.

Continuous equation

$$\frac{\partial h}{\partial t}+\frac{\partial q}{\partial x}-I=r_e \tag{1}$$

Motion equation

(river channel)

$$q=\frac{\sqrt{\sin\theta}}{n}h^{\frac{5}{3}} \tag{2}$$

(slope)

$$q=\begin{cases}\dfrac{k\cdot\sin\theta}{\gamma}h & (h<D)\\[2ex] \dfrac{k\cdot\sin\theta}{\gamma}h+\dfrac{\sqrt{\sin\theta}}{n}(h-D)^{\frac{5}{3}} & (h>D)\end{cases} \tag{3}$$

Where, h: height of runoff (mm), q: flow rate per unit width (mm^2/sec), t: time (sec), I: water intake rate from the weir, r_e: effective rainfall intensity (mm/sec), x: distance from the top of slope mesh (mm), θ: gradient of river channel or slope (degrees), n: roughness coefficient of Manning (mm$^{-1/3}$/sec), k: coefficient of permeability (mm/sec), and γ: effective porosity. A two-cascade storage function method was applied for the sub model of subsurface water runoff.

Continuous equation

$$\frac{dS_i}{dt}=r_i-Q_i \tag{4}$$

Motion equation

$$S_i=K_i\cdot Q_i^{P_i} \tag{5}$$

Where, S_i: storage height of watershed (mm), t: time (sec), r_i: inflow intensity (mm/sec), Q_i: height of runoff (mm/sec), K_i: storage parameter of watershed, P_i: model parameter, and i: tank number.

A tank model was applied for the sub model of rain water runoff with forest interception (Fig. 8) [5].

3.3 Macro model using unit loading of TP and runoff rate of surface and subsurface water to the river

TP discharge load from point and non-point sources was simulated using unit load ratios. This method is useful for identifying the causes of changes in water quality or water pollution and has been used for the design of water basin-wide sewage treatment strategies in Japan [6]. Table 1 and Table 2 show the unit load ratios used in this study. Household and industrial wastewater, forests, orchards, rice paddies, vegetable farms and urban areas were considered to be the main sources, and most of the unit load ratios were obtained from published literature [7]. The unit load ratio for industrial wastewater was calculated using the value written in published literature and the value of the industrial shipment for Wakayama and Nara prefectures [7].

The TP load ratio of the orchards was calculated by subtracting the production of each fruit crop from the amount of fertilizer applied to the orchards [8]. This was necessary because the discharge of phosphorous from the orchards is greatly dependent upon the type of fruit, the crop of fruit, and the amount of fertilizer applied, and it was therefore impossible to obtain the proper load ratio for orchards from previous literature. Daily TP discharge load values from point sources were calculated by dividing the annual TP discharge load by 365.On the other hand, daily TP runoff load from non-point sources was calculated by using the macro model [9].

$$DL_{1\sim4,j} = \sum_{n=1}^{2} k_{1\sim4,n} A_i R_{j,n}^{a} \tag{6}$$

$$DL_{5,j} = \sum_{n=1}^{2} k_{5,n} A_5 R_{j,n}^{a} M_{j,n}^{b} \tag{7}$$

Where, *DL*: daily TP runoff load (kg/day), subscript *i*: land use (*1*: urban area, *2*: rice paddy, *3*: vegetable farm, *4*: forest, *5*: orchard), *j*: date (1-365 days), *A*: land use area ratio, *R*: precipitation, *M*: amount of TP load in orchard (kg/day), *k*, *a*, *b*: model parameter.

3.4 One-dimensional steady state advection equation

The TP concentration in the river was calculated by using a one-dimensional steady state advection equation.

$$v\frac{dc}{dx} = -\lambda c + S \tag{8}$$

Where, *c*: TP concentration in river (mg/L), *x*: distance (mm), *v*: river flow velocity (mm/sec), *λ*: self-purification coefficient (1/sec), *S*: TP runoff load calculated by the macro model (mg/(L･sec)).

The river flow velocity was calculated by using river flow rate on a target day (14.1 m^3/sec in 2004, 7.4 m^3/sec in 2005, 13.5 m^3/sec in 2006). The self-purification coefficient used in this study is shown in Table 3. In this model, the self-purification coefficient tends to be large when runoff load is large and river flow rate is small. For example, in February, the self-purification coefficient in 2004 was larger than in other years because the ratio of river flow rate per runoff load in 2004 was smallest. It was 0.038 m^3/kg in 2004, 0.077 m^3/kg in 2005, and 0.073 m^3/kg in 2006. On the other hand, in August, the self-purification coefficient in 2004 was smaller than in other years because the ratio of river flow rate per runoff load in 2004 was the largest. It was 0.154 m^3/kg in 2004, 0.104 m^3/kg in 2005, and 0.038 m^3/kg in 2006. As a result, the self-purification coefficients were expected to differ for 2004 compared to those for other years.

4. RESULTS

Fig. 9 shows the river flow rate at Okawa Bridge (monitoring point (10) in Fig. 1 and Fig. 2). The simulated river flow rate (A) considers the water intake at the Simobuchi irrigation weir (point (12) in Fig. 1 and Fig. 2), while (B) does not consider the water intake. Particularly, in the period of irrigation (June to September), simulation result (A) better reflects the decrease in river flow rate than simulation result (B). Thus, the river flow rate obtained by

Table 3 Self-purification coefficient

Date		Self-purification coefficient (1/min)	Date		Self-purification coefficient (1/min)
2004	February 4	0.060	2006	February 1	0.030
	August 18	0.008		July 12	0.028
2005	February 2	0.027		August 2	0.023
	August 3	0.022		December 6	0.034
Age unit		0.022			

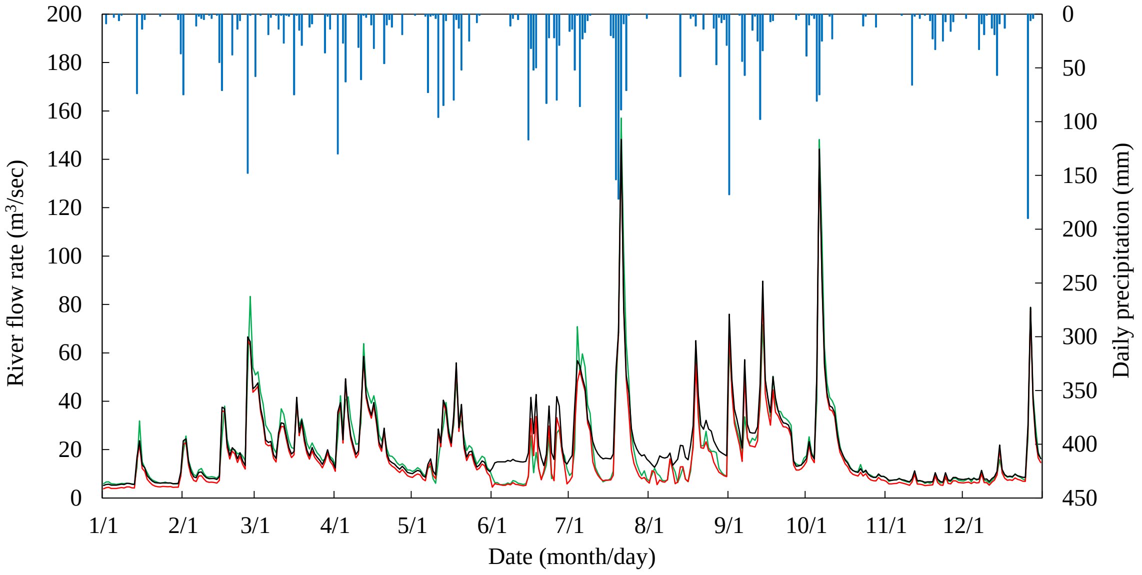

Fig. 9 River flow rate (Okawa Bridge in 2006)

Table 4 Simulated result (TP runoff load, river flow rate and TP concentration, Okawa Bridge)

Year	Date	TP runoff load (kg/day)	River flow rate (m^3/day)	TP concentration	
				simulated (mg/L)	observed (mg/L)
2004	February 4	109.6	4.18	0.010	0.010
	August 18	109.6	16.92	0.024	0.024
2005	February 2	107.5	8.35	0.015	0.015
	August 3	107.5	11.14	0.020	0.020
2006	February 1	300.3	22.08	0.028	0.028
	July 12	123.7	9.40	0.024	0.024
	August 2	123.7	11.30	0.021	0.021
	December 6	123.7	6.25	0.017	0.017

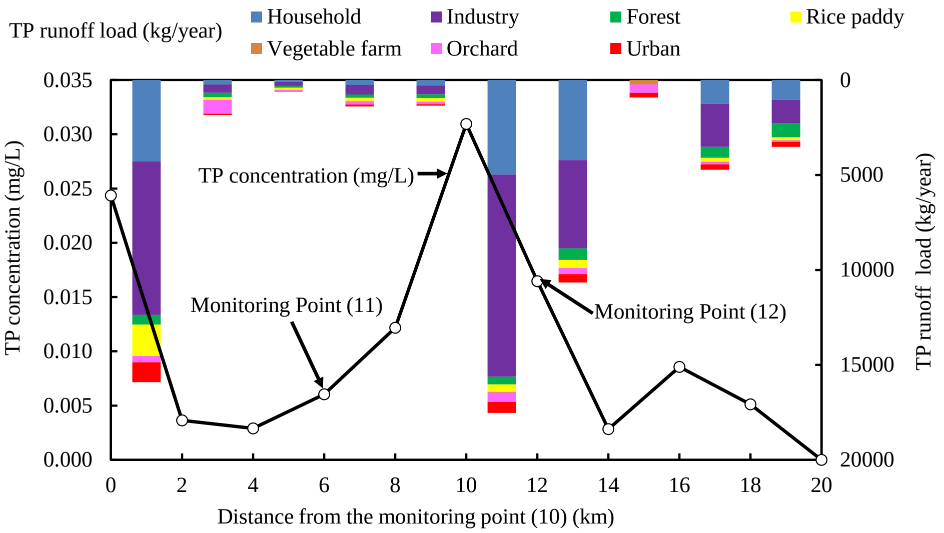

Fig. 10 Concentration analysis result with a direction flowing down (2006, Okawa Bridge)

simulation result (A) is used in the distributed hydrological model.

Table 4 shows the results for the TP runoff load, river flow rate, and TP concentration at Okawa Bridge. The simulated TP concentration is in good agreement with the value obtained by monitoring point observations.

Fig. 10 shows the TP concentration analysis results in the direction of moving to the Okawa Bridge, 2006. The TP runoff loads from household and industrial sources near the monitoring points (10) and (12) are much larger than the others. As a result, the TP concentration rapidly increases in these two sections. That is to say, the TP runoff load from household and industrial sources is considered to have a greater impact on the TP concentration than inputs from other sources.

5. DISCUSSION

In this chapter, TP concentration control policy based on the reduction of TP runoff load and river flow rate is examined. Fig. 11 shows the result of sensitive analysis of TP concentration in February 1, 2006. In this analysis, reduction effects of TP runoff load and river water intake to the TP concentration were evaluated. In Fig. 9, water intake at the Simobuchi irrigation weir was shown to greatly influence the river flow rate, so the water intake was adopted as a method to control the river flow rates. In addition, the self-purification coefficient in Table 3 was used in this analysis.

The TP concentration becomes 0.03 mg/L, which is more than the eutrophication standard (0.02 mg/L), when the TP runoff load and river water intake are not reduced. However, when the quantity of TP runoff load is reduced by 40%, the TP concentration can be maintained lower than the eutrophication standard. On the other hand, when the quantity of water intake is reduced by 30%, the TP concentration can be reduced to 0.026 mg/L, but this cannot satisfy the eutrophication standard.

However, the results of the sensitive analysis show that TP concentration can be controlled effectively and efficiently by simultaneously reducing TP runoff load and water intake. For example, the TP concentration can be controlled to less than 0.02 mg/L by reducing water intake by 20% and TP runoff load by 30%.

Thus, the policies for reducing TP discharge load from point sources were examined first because the discharge loads from households and industry were much larger those from non-point sources. In 2006 in

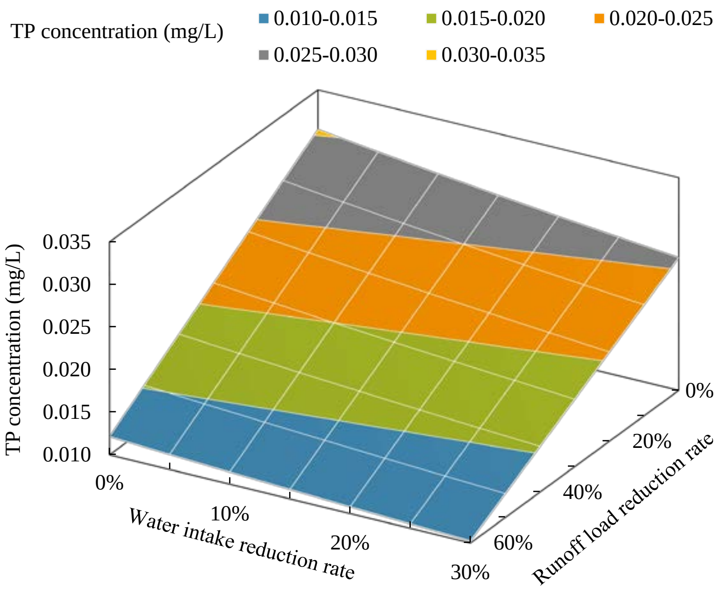

Fig.11 Sensitivity analysis (February 1, 2006, Okawa Bridge)

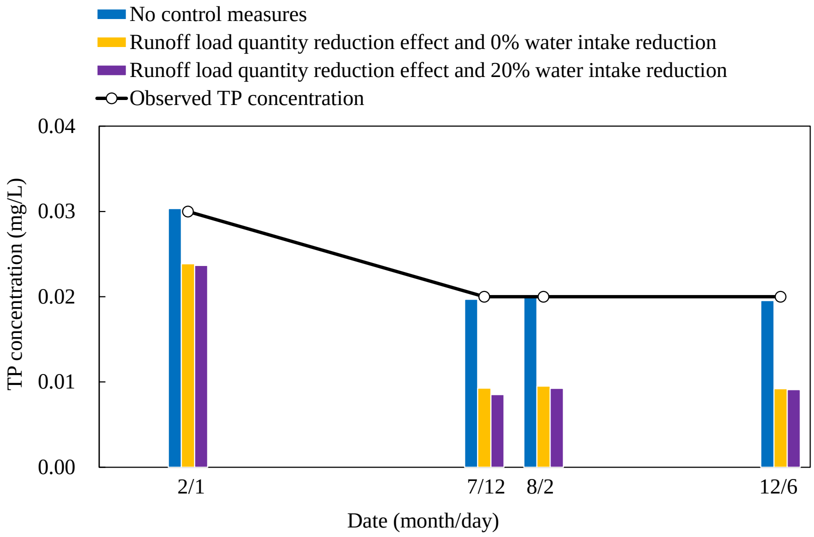

Fig. 12 Rise in river TP concentration suppressant effect (2006)

the study area, sewage system coverage was 22%. Septic tank for treatment of all domestic wastewater were used in 20% of the area, and septic tank for individual treatment of wastewater from toilets only were used in 23% of the area. The remaining 35% of the area had neither the sewage system nor the sewage treatment tanks. Therefore, the wastewater from toilets was treated in outside treatment plants and the other domestic wastewater was exhausted in rivers without treatment. In this area, the implementation of sewage systems was promoted by a Yoshinogawa River basin sewerage plan, starting in 1982. Based on this, TP discharge load from households was calculated for the case of 100% sewage system implementation.

For industrial drainage, the Fifth Area-Wide Total Pollutant Load Control for water quality was implemented in 2003 to industrial sites in the Kinokawa River watershed with drainage exceeding 50 m^3/day. However, most industrial sites in this area had drainage that was less than 50 m^3/day. In this simulation, however, TP discharge load from industrial sites was calculated based on the assumption that the Fifth Area-Wide Total Pollutant Load Control was applied to all industrial sites. The simulation result shows that overall TP discharge load would be reduced by 46.1%, with 42.8% reduction coming from industry, and 3.3% reduction coming from households.

Next, as a test of the effect of controlling river flow rate, water intake at the Shimobuchi irrigation weir was reduced by 20% in the irrigation period, which increased the river flow rate by approximately 30%. The results of the simulation conducted with water intake reduced by 20% in addition to imposing a reduction of TP runoff load are shown in Fig. 12. When the average reduction of TP runoff load and river flow rate of the simulated days are applied, the TP concentration decreases 48%. The decrease achieved by TP runoff load control is 45%, but the effect of water intake control is only 3%. On the other hand, when focusing on the irrigation period (July 12 and August 2), TP concentration can be decreased by 46%. The contribution from TP runoff load control is 41% and that of water intake is 5%. This result demonstrates that TP runoff load control is effective for this study area. It should be noted that TP concentration is below 0.02 mg/L, which is the eutrophication standard, except for on February 1, 2006. The TP runoff load is markedly elevated on February 1, 2006 and the effect of concentration reduction is only 22% because TP runoff loading from non-point sources is large due to rainfall. If the amount of fertilizer application and runoff load from forests can be reduced, the TP concentration under conditions such as those on February 1, 2006 can be reduced to below 0.02 mg/L.

6. CONCLUSION

The results of this study could be summarized as follows:

1) The distributed hydrological model was applicable to this system.
2) The increase in TP concentration can be controlled by management of river flow rate and TP runoff load can be predicted by using a macro model and one-dimensional steady state advection equation.
3) The increase in TP concentration can be controlled by management of river flow rate and TP runoff load.
4) When focusing on the irrigation period (July 12 and August 2), the TP concentration could be decreased by 46%. The TP runoff load control effect is a 41% decrease and water intake effect is a 5% decrease when focusing on the irrigation period.
5) TP mass load reduction combined with an increase in river flow could reduce TP to less than 0.015 mg/L and prevent increases in 2-MIB in tap water.

7. ACKNOWLEDGEMENTS

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