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Natural purification effects in the river in consideration with domestic wastewater pollutant discharge reduction effects

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Abstract

The first social experiment program in Japan to reduce domestic wastewater pollutant discharge by "soft interventions" in households has been conducted in the Yamato-gawa River drainage area since 2005. The Yamato-gawa River has been listed as one of the worst water quality rivers in Japan because of the larger annual average BOD. "Hard interventions" including deployment of wastewater treatment facilities and artificial installation of natural purification facilities in the river has been conducted in these years to improve river water quality. At the first Yamato-gawa River social experiment program (YR-SEP) in March 2005, BOD at the monitoring point near the river mouth decreased about 6% during the Program. Natural purification effect along the river was evaluated in this article with one-dimensional water quality model for the six river sections. Larger biological oxygen consumption rate, k_b, was estimated in the sections with artificially installed natural purification facilities. The effect of "soft interventions" in households in the YR-SEP was estimated as 25% BOD decrease in the nearest monitoring point to the river mouth, when all the households participate in the Program and BOD discharge reduction rate with "soft interventions" in households was 40%.

Key words: Yamato-gawa River; "soft interventions" in households; one-dimensional water quality model

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Introduction

The Yamato-gawa River, Japan, flows from Nara Prefecture through Osaka Prefecture into Osaka Bay (Fig. 1). The river length is 68 km and the drainage area is 1070 km^2. Population in the drainage area is over 2 million (Yamato-gawa River Local Office, 2009a). The Yamato-gawa River and its branches has been nominated as one of the worst deteriorated water quality rivers in Japan in these years because of the larger annual average BOD concentration. Artificial constructed facilities to enhance natural purification have been installed especially in the middle and lower sections of the river.

A social experiment program on domestic wastewater discharge reduction has been conducted in the Yamato-gawa River drainage area called Yamato-gawa River Social Experiment Program (YR-SEP) aiming at reducing domestic wastewater pollutant discharge with "soft interventions" in households since 2005, which has been led by the Yamato-gawa River Local Office of the Ministry of Land, Infrastructure, Transportation and Tourism (MLIT) (Tsuzuki, 2009; Tsuzuki et al., 2009a, 2009b; Yamato-gawa River Local Office, 2009a). This is the first river basin wide scale Program targeted water quality improvement in the river with community participation with "soft interventions" in households in Japan and the first one also in the world, at the most of the authors' knowledge. In this article, we focused on the natural purification effects in the Yamato-gawa River.

Pollutant discharge estimation was conducted for domestic, industrial and natural sources in the Yamato-gawa River drainage area (Yoneda et al., 2006). Natural purification effects of the river water purification facilities in the river were evaluated (Shimomura and Taniguchi, 2008). Water quality improvement evaluation derived from the "soft interventions" should be necessary.

Estimation of natural purification effect in the Yamato-gawa River, and domestic wastewater pollutant discharge reduction intervention effects of the YR-SEP on the river water quality were studied in this article. For the former purpose of the evaluation of natural purification effect in the river, biological oxygen consumption rate was evaluated for six sections in the river using one-dimensional water quality model. BOD and DO alternations in the river are a classical topic after Streeter and Phelps (1925). We have evaluated overall natural purification effect in the river section, some of which are with artificially installed natural

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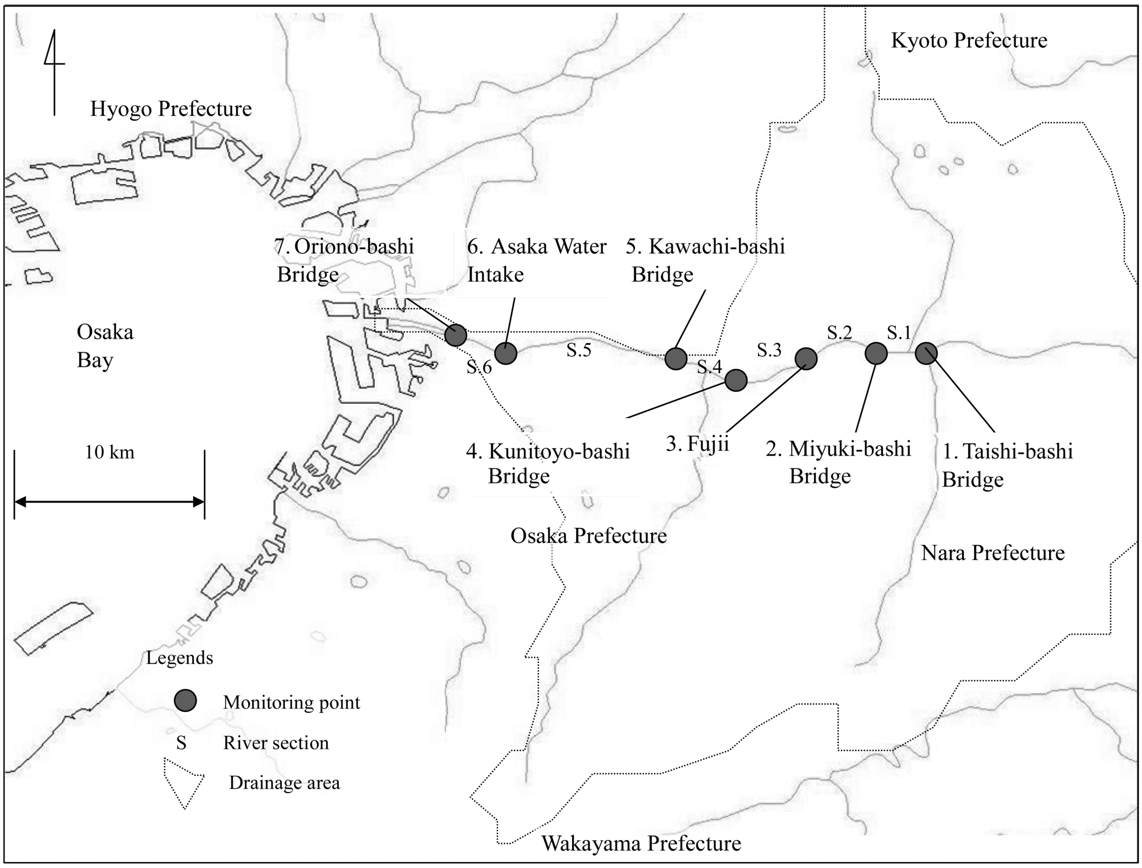

Fig. 1 Yamato-gawa River drainage area and monitoring points.

purification facilities. Moreover, water quality estimation has been conducted to evaluate the domestic wastewater pollutant discharge reduction with "soft interventions" in households.

1 Methods

1.1 Data collection

Water quality parameters, water temperature, pH, DO, turbidity, BOD, COD_{Mn}, $NH_4{}^+$-N, *Escherichia coli* and other water quality parameters are periodically, once a month, or continuously monitored at the monitoring points in the Yamato-gawa River. Additional monitoring of BOD and *E. coli* was conducted in the YR-SEP during the Program period and before or after the Program period to evaluate the water quality improvement effect of "soft interventions" in households in the Program by the Yamato-gawa River Local Office with community participation. We have collected typical water quality and quantity data to conduct analysis on the natural purification effect in the river (Yamato-gawa River Local Office, 2009b; Osaka Prefecture, 2009).

1.2 One dimensional water quality model

One dimensional water quality model of BOD and DO (Toda, 2001) was applied to evaluate natural purification effect in the six sections of the river (Fig. 1) including natural purification effect in the river and the effect of artificially provided natural purification facilities in the river.

BOD and DO concentrations along with the river flow can be explained with the following Eqs. (1) and (2) (Toda, 2001).

$$\text{BOD:}\quad u\frac{\mathrm{d}B}{\mathrm{d}x} = -k_\mathrm{b}B - k_\mathrm{p}B + L_\mathrm{B} \tag{1}$$

$$\text{DO:}\quad u\frac{\mathrm{d}D}{\mathrm{d}x} = -k_\mathrm{b}B + k_\mathrm{r}(D^* - D) - L_\mathrm{D} \tag{2}$$

where, B (g/m^3) is BOD concentration; D (g/m^3) is DO concentration; x (m) is distance; u (m/sec) is advection velocity; k_b (sec^{-1}) is biological oxygen consumption rate; k_p (sec^{-1}) is BOD removal rate with physical and chemical reaction; L_B (g/(m^3·sec)) is BOD loading; k_r (sec^{-1}) is re-aeration coefficient; D^* (g/m^3) is saturation oxygen concentration; and L_D (g/(m^3·sec)) is oxygen consumption rate with other reaction than biological.

Equations (3) and (4) can be developed with the analyses of Eqs. (1) and (2) (Toda, 2001). Equation (3) is the same as the Equation 3.2 of Jolánkai and Bíro (2000).

$$\text{BOD: } B = \frac{L_\mathrm{B}}{k_\mathrm{b}+k_\mathrm{p}} + \left(B_0 - \frac{L_\mathrm{B}}{k_\mathrm{b}+k_\mathrm{p}}\right)\exp\left(-\frac{k_\mathrm{b}+k_\mathrm{p}}{u}x\right) \tag{3}$$

$$\text{DO: } D = D_0\exp\left(-\frac{k_\mathrm{p}}{u}x\right) + \left(D^* - \frac{L_\mathrm{B}}{k_\mathrm{b}+k_\mathrm{p}}\frac{k_\mathrm{b}}{k_\mathrm{r}} - \frac{L_\mathrm{D}}{k_\mathrm{r}}\right)\left\{1-\exp\left(-\frac{k_\mathrm{r}}{u}x\right)\right\} + \frac{k_\mathrm{b}}{k_\mathrm{b}+k_\mathrm{p}-k_\mathrm{r}}\left(B_0 - \frac{L_\mathrm{B}}{k_\mathrm{b}+k_\mathrm{p}}\right)\left\{\exp\left(-\frac{k_\mathrm{b}+k_\mathrm{p}}{u}\right) - \exp\left(-\frac{k_\mathrm{r}}{u}x\right)\right\} \tag{4}$$

where, B_0 (g/m^3) is BOD concentration at x = 0 m and D_0 (g/m^3) is DO concentration at x = 0 m.

There are seven monitoring points in the main flow of the Yamato-gawa River (Fig. 1). Equations (3) and (4) were applied for six sections between these seven monitoring points. For the purpose of making the calculation easy and simple, some parameters in the equations were fixed for all the section: k_p is 8.3×10^{-6} sec^{-1} (0.72 day^{-1}), k_r is 3.3×10^{-5} sec^{-1} (2.9 day^{-1}), L_D is 3.3×10^{-6} (g/(m^3·sec)) (0.29 g/(m^3·day)), D^* is 11.0 g/m^3. Some parameters were determined for each section based on the collected data and water quality data of the branches including u, k_b, L_B, B_0 and D_0. Several cases of k_b were simulated and k_b was determined for each section, which should represent natural purification effect of the section in the river.

The model analysis results were compared for the evaluation purpose to the existing results on natural purification effects in the Yamato-gawa River (Yoneda et al., 2006; Shimomura and Taniguchi, 2008), and some rivers in Japan (Kunimatsu and Muraoka, 1986; Kusuda, 1986).

1.3 Effects of "soft interventions" in households

BOD and DO with and without "soft interventions" was calculated with the one dimensional water quality model to evaluate the effect of the community participation during the YR-SEP. BOD discharge by domestic wastewater, industry and land use were derived from Yoneda et al. (2006).

2 Results

2.1 Water quality and quantity data

The flow rate, DO and BOD at the seven monitoring points in Japanese Fiscal Year (JFY) 2004–2008 are summarized in Table 1. Flow rate was estimated from water depth data using the linear regression line between water depth and flow rate at each monitoring point when flow rate was not recorded.

2.2 One dimensional water quality model parameters

One dimensional water quality model parameters were estimated and demonstrated in Table 2 using average water quality and quantity data in Table 1.

Figure 2 shows an example of biological oxygen consumption rate, k_b, estimation process. DO and BOD at the lower monitoring point of the section were calculated with Eqs. (3) and (4). Then, k_b was estimated using interpolation method with the actual DO and BOD. Therefore, two values of k_b were estimated for each section, k_b estimated from DO ($k_{b\text{-DO}}$) and k_b estimated from BOD ($k_{b\text{-BOD}}$). The calculated $k_{b\text{-BOD}}$ was from -3.6×10^{-5} to 1.6×10^{-4} sec^{-1}, or from –3.1 to 14.3 day^{-1} and $k_{b\text{-DO}}$ was from 1.8×10^{-6} to 3.9×10^{-5} sec^{-1} or from 0.2 to 3.4 day^{-1} (Table 3 and Fig. 3). Estimation result of $k_{b\text{-BOD}}$ in the section 6 was below zero, which should be owing to a larger BOD concentration at the lower end of the section and smaller L_B in the section. Estimation result of $k_{b\text{-BOD}}$ in Section 1 was comparatively larger than those in other sections. Possible reasons for comparatively larger $k_{b\text{-BOD}}$ in Section 1 are due to a larger BOD difference between the monitoring points 1 and 2, and larger L_B in the section.

2.3 Effect of YR-SEP on water quality improvement

Effect of domestic wastewater pollutant discharge reduction in the YR-SEP on BOD in the river was simulated with estimated biological oxygen consumption

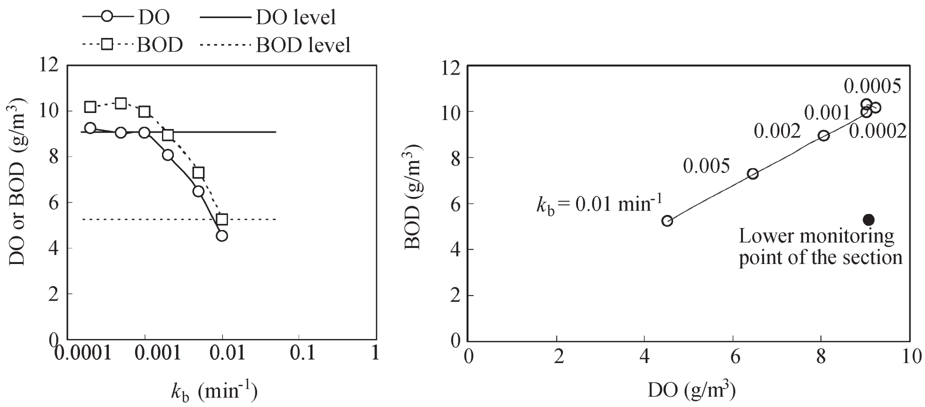

Fig. 2 An example of biological oxygen consumption rate, k_b, estimation process in Section 1.

Table 1 Flow rate, DO and BOD at the monitoring points of the Yamato-gawa River in JFY 2004–2008

Monitoring point		Distance[a] (km)	Flow rate (m^3/sec)			DO (g/m^3)			BOD (g/m^3)		
			Min[b]	Max[c]	Ave[d]	Min	Max	Ave	Min	Max	Ave
1	Taishi-bashi Bridge	36.6	2.56	9.10	4.93	7.4	11.0	9.09	2.8	22.0	7.26
2	Miyuki-ohashi Bridge	35.1	2.89	18.73	9.53	7.4	11.7	9.09	1.9	13.7	5.28
3	Fujii	28.6	6.61	19.29	11.48	7.8	11.7	9.29	2.0	15.3	5.41
4	Kunitoyo-bashi Bridge	22.6	5.36	34.32	11.91	6.6	10.6	8.41	1.1	12.5	4.51
5	Kawachi-bashi Bridge	18.1	4.25	22.43	11.88	7.4	12.1	9.54	1.4	8.6	3.54
6	Asaka	7.1	7.44	30.20	14.52	7.5	13.1	10.07	1.1	8.2	3.45
7	Oriono-bashi Bridge	5.3	8.24	30.92	14.64	7.1	12.7	9.64	1.8	9.1	4.09

[a] Distance from the river mouth; [b] Min: minimum; [c] Max: maximum; [d] Ave: average.

Table 2 Some parameters for each section of the Yamato-gawa River

River section	Monitoring points[a]	Width (m)	Depth (m)	Velocity u^b (m/sec)	Retention time (hr)	Inflow BOD[c] (g/m^3)	Flow rate[d] (m^3/sec)	Flow rate[e] (m^3/sec)	BOD loading (g/hr)	BOD loading (L_B) ($g/(m^3 \cdot hr)$)
1	1–2	50	0.51	0.29	1.45	6	4.60	4.60	99,313	2.622
2	2–3	50	0.52	0.41	4.43	10	1.95	1.95	70,204	0.419
3	3–4	50	0.53	0.44	3.78	10	0.43	0.43	15,466	0.097
4	4–5	100	0.55	0.22	5.73	2	–0.03	0.17	1200	0.005
5	5–6	100	0.53	0.25	12.16	15	2.64	2.64	142,358	0.247
6	6–7	80	0.52	0.35	1.41	10	0.12	0.17	6000	0.081

[a] Number of the monitoring point; [b] advection velocity; [c] inflow BOD was estimated as average BOD of inflow branches in the section, 10 g/m^3 was supposed for the section No. 3 besides there is no specific inflow branch; [d] total flow rate of inflow branches in each section estimated from the flow rate differences between the upper and lower monitoring points of the section; [e] for sections No. 4 and 6, flow rate for the BOD loading calculation was supposed to be 0.17 m^3/sec besides the calculation results were less than the value.

Table 3 Summary of biological oxygen consumption rate (k_b) estimations

River section	$k_{b\text{-BOD}}$		$k_{b\text{-DO}}$		Description of the section	Artificially installed natural purification facility
	sec^{-1}	day^{-1}	sec^{-1}	day^{-1}		
1	1.65E-04	14.24	6.81E-06	0.59	Winding and straight, with sand bar in about 30% of the section	
2	3.59E-06	0.31	8.58E-06	0.74	Winding and straight, with sand bar in about 50% of the section	
3	1.06E-05	0.92	3.18E-05	2.74	Winding and straight, with sand bar in about 50% of the section	Kamenose Ravine (natural environment)
4	3.78E-06	0.33	1.77E-06	0.15	Rather straight, with sand bar in about 70% of the section	Kashiwara Area purification facility
5	1.22E-05	1.06	5.76E-06	0.50	Rather straight, with sand bar in about 30% of the section	West Athletic Fields Area purification facility Dry Riverbed Fields Area purification facility Second Athletic Fields Area purification facility Chokichi-Nagahara Area purification facility
6	–3.56E-05	–3.08	3.90E-05	3.37	Winding and straight, with sand bar in about 80% of the section	Asaka-yama Area purification facility

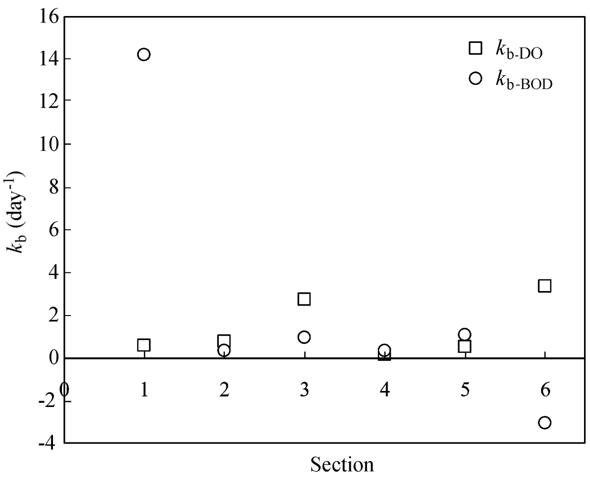

Fig. 3 Biological oxygen consumption rate (k_b), estimated from DO and BOD.

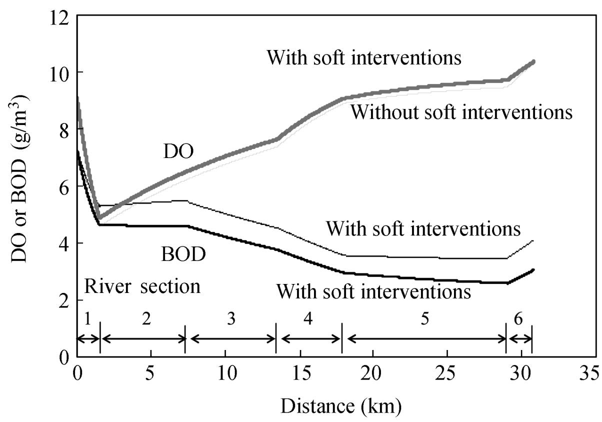

Fig. 4 BOD and DO estimation results of one dimensional water quality model with and without "soft interventions" in households to reduce pollutant discharge.

rate estimated from BOD, $k_{b\text{-BOD}}$, and other parameters in the sections. In the estimation, BOD loading, L_B, was reduced to some extent in accordance with possible domestic wastewater pollutant discharge reduction amount (Tsuzuki et al., 2009a) as shown in Table 4.

DO and BOD with and without "soft interventions" were simulated (Fig. 4). In the simulation, $k_{b\text{-BOD}}$ was applied for both BOD and DO concentration simulations. Therefore, final BOD concentrations in the upper sections are the same as initial BOD concentrations in the lower sections which were based on the monitoring data. However, there were a little discrepancy of final DO concentrations in the upper sections and the initial DO concentrations in the lower sections which were based on the monitoring data. In the simulation, final DO concentrations in the upper section were applied as initial DO concentrations in River sections 2–6 to maintain smooth connection of the simulation results between the upper and lower sections. Therefore, DO simulation results show a tendency of concentration besides the absolute values have some errors in River sections 2–6.

Calculation for "with soft interventions" cases, calculation results of BOD and DO in the upper sections were

Table 4 BOD loading (L_B) for water quality simulation of the effect of the YR-SEP

River section	MP[a]	Pollutant discharge (kg/day)						BOD loading (g/hr)		L_B (g/(m^3·hr))	
		Domestic wastewater		Industry	Land use	Total	Percentage of domestic wastewater (%)	Without SI[c]	With SI	Without SI	With SI
		WWTP[b]	On-site treatment								
1	1–2	254	3254	200	1649	5357	65.5	3720	2746	2.622	1.935
2	2–3	32	4764	1503	577	6876	69.7	4775	3443	0.419	0.302
3	3–4	23	449	115	31	618	76.4	429	298	0.097	0.068
4	4–5	2	5734	1917	951	8604	66.7	5975	4382	0.005	0.004
5	5–6	0	4886	1513	124	6523	74.9	4530	3173	0.247	0.173
6	6–7	803	1672	648	72	3195	77.5	2219	1531	0.081	0.056

[a] Monitoring points; [b] wastewater treatment plant; [c] soft interventions.

applied for the initial conditions for the next section. In the conditions that all the households participate in the YR-SEP, BOD concentration at the monitoring point nearest to the river mouth was estimated to decrease 25%, from 4.1 to 3.1 g/m^3.

3 Discussions

In Section 1, larger $k_{b\text{-BOD}}$ was estimated (Table 3, Fig. 3), the reasons for which should be owing to a larger flow rate of inflow branches (Table 2), a larger BOD difference between the upper and lower monitoring points (Table 1), and a larger L_B (Table 2). L_B was estimated as a product of inflow flow rate and average BOD of inflow branches (Table 2). The inflow branches flow rate was calculated as difference of flow rate of the upper and lower monitoring points of the section. In Section 1, comparatively larger spring water and groundwater inflow to the main river should exist because the section is near the mountainous area. Then, L_B should be smaller than the estimated value in Table 2, and the actual $k_{b\text{-BOD}}$ should be smaller than the estimated value. However, for the simulation result shown in Fig. 4, the effect of the spring water and groundwater is already included in k_b and L_B. Therefore, water quality simulation results should be supportive.

In Section 6, $k_{b\text{-BOD}}$ could not determined from the one dimensional water quality model, one of the reasons for which was L_B was not large enough to explain BOD increase in this section (Tables 1 and 2). One of the inflow branches in this section, Nishiyoke-gawa River, is one of the most water quality deteriorated branches in the Yamato-gawa River. More accurate estimation in consideration with seasonal effect should be necessary in the future research.

When we compare $k_{b\text{-BOD}}$ of the four sections other than Sections 1 and 6, larger k_b was estimated in Sections 3 and 5, and smaller k_b was estimated in Sections 2 and 4 (Table 3 and Fig. 3). The overall effects of the artificially installed natural purification facilities in the river can be evaluated as larger biological oxygen consumption rate, k_b, in Sections 3 and 5 in this study. Shimomura and Taniguchi (2008) evaluated BOD and nitrogen parameters in terms of the river purification facilities. Some detailed analysis was conducted for nitrogen parameters but for organic carbon parameters in their study. Our result should enhance understanding of the artificially installed natural purification facilities in the river.

Natural purification rate is sometimes evaluated as combination of biological effect and physical effect including sedimentation and absorption. Kusuda (1986) summarized the mixed natural purification rate, $k_1 + k_3$ (day^{-1}), measured with fields survey in the rivers in Japan, 12 cases for BOD, one case each for DOC, TOC and COD_{Mn}. In this article, $k_1 + k_3$ is corresponding to $k_b + k_p$. The measurement values of $k_1 + k_3$ for BOD in larger river were in wider range, e.g., 0.1–1.88 day^{-1} for the Tama-gawa River in Tokyo, 1.2–2.4 day^{-1} for the Chikuma-gawa River in Tohoku District, and 0.11–0.17 day^{-1} for the Chikugo-gawa River in Kyusyu Island. Total of $k_{b\text{-BOD}}$ and k_p in this study in Sections 2–5 was 1.03–1.78 day^{-1}. Therefore, total of hypothesized value of k_p and estimated value of k_b are within the existing measured values of the combination of biological and physical oxygen consumption rates in the rivers in Japan.

The effect of "soft interventions" in households in the YR-SEP was estimated as 25% BOD decrease in the nearest monitoring point to the river mouth, Oriono-bashi Bridge (Fig. 4). BOD decreased about 6% in the first Program in 2005 comparing to that before the Program at the monitoring point near the river mouth. The participant rate of the first Program was 15% according to the questionnaire survey. Yoneda et al. (2006) estimated BOD concentration reduction at the monitoring point near the river mouth, Oriono-bashi Bridge would be 6% if the participant rate is 15% under the conditions that BOD discharge derived from gray water can be decreased to the maximum level. Their estimation result is almost accordance with the YR-SEP water quality monitoring result at the first time of the Program. Our estimation result hypothesized the participation rate of the YR-SEP is 100%. More detailed estimation in consideration with the participation rates and possible pollutant discharge reduction amounts should be necessary in the future research.

The inflow from the Yamato-gawa River occupies around 15% of COD_{Mn} load flowing into the Osaka Bay (Ministry of Land, Infrastructure, Transportation and Tourism (MLIT) Kinki Regional Development Bureau, 2009; Hyogo Prefecture, 2009). With an assumption that percentages of BOD load and COD_{Mn} load flowing into the Osaka Bay are the same, BOD load inflow decrease of 25% from the Yamato-gawa River can be estimated as 3.8% of total BOD load inflow from all the rivers flowing into the Osaka Bay. If the “soft interventions” proliferate all the drainage area of the Osaka Bay, BOD load inflow decrease should be larger, which should be estimated river by river depending on the river characteristics.

4 Conclusions

We have investigated natural purification effect in the Yamato-gawa River, where the first social experiment program, YR-SEP, with community participation to reduce domestic wastewater pollutant discharge with “soft interventions” in households. Major conclusions in this study are: (1) larger biological oxygen consumption rate, k_b, was estimated in the sections with artificially installed natural purification facilities; and (2) the effect of “soft interventions” in households in the YR-SEP was estimated as 25% BOD decrease in the nearest monitoring point to the river mouth when the participation rate is 100%.

Acknowledgments

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