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A WATER QUALITY MODEL OF AN URBAN STREAM

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SYNOPSIS

A simulation model is presented to describe the water quality in a river flowing through an urban area. The model is composed of two submodels: one for calculating a non-uniform flow and the other a water quality. The water quality submodel can describe longitudinal distributions of the particulate BOD, the dissolved BOD, SS and dissolved oxygen. This model successfully represented the present state of the water quality in the Kaki River in Nagaoka and was applied to examine the effect of a reduction of BOD loads on the future water quality. The predicted feature was that a planned sewage system would remarkably improve the water quality.

INTRODUCTION

Streams flowing through urban areas receive high pollutant loads into their small drainage areas. Therefore, the water quality of urban streams is generally very sensitive to variations in the pollutant load and it often shows a diurnal or a seasonal change. This means also that the effect of cutting off the pollutant load by constructing a sewerage system is expected to be remarkable.

In order to predict water quality in urban streams, firstly, evaluation of the pollutant load into the drainage area is necessary. This is carried out using the pollutant load factor, which expresses unit amount of the pollutant load per capita or area and so on. Secondly, the estimation of the purification process of the pollutant in a river is necessary. This is often made in terms of the stream input-output ratio, which is defined as a pollutant load ratio of the output at the lower-stream point of the river to the input at the upper point. Conventionally, overall input-output ratio of pollutant load is also used. This is defined as the ratio of pollutant load arriving at a specific point in the river to that generated in the drainage area.

The analysis by the overall input-output ratio or stream input-output ratio has a defect in that processes in the river, especially settling and decomposition, are difficult to treat separately. The settling process does work to purify water, although it is not a true purification but an apparent one. In general, the amount of settling is not small enough to be insignificant in discussing the water quality in urban streams. Therefore, an accurate estimation of the purification should include an evaluation of the settling process.

The amount of settling, or sediment deposit, can, in principle, be estimated by either direct measurement or observation during a storm runoff. However, both methods are reported to be inaccurate as Kawashima and Suzuki (7) pointed out. It is difficult for a sediment trap used in lakes and oceans to catch settling materials in a flowing river water. At a storm runoff, non-point sources from road surfaces, farm fields and mountainous areas join with the accumulated sediment on a river bed as pollutant sources. Additionally, it is difficult to make precise observations within a short period of the runoff duration. Therefore, even if sediment deposit is completely flushed out at the storm runoff, it is difficult to estimate the amount of sediment deposit accurately.

In order to overcome such difficulties and to distinguish the processes of settling and decomposition, a model to describe these processes in a river is required.

In Nagaoka City, the Kaki River flows through its urban area and merges with the Shinano River. As a combined sewerage system had already been completed in the lower reach of the Kaki River, the stream input-output ratio under a dry-weather condition is easily obtained from observation. The averaged value is 0.6 to 0.8 for the lowest 2.5 km of the river. Therefore, the stream purification process is important in a description of the longitudinal change of the water quality. However, the degree of the contribution of true purification by decomposition is not evaluated accurately by the above method.

In the upper drainage area of the Kaki River, a sewerage system is currently under construction and it will be completed in 1995, reducing pollutant load as well as wastewater flow rate. In such a situation, it is uncertain if the present state of the overall and stream input-output ratios will be maintained. In order to estimate the effect of the sewerage system on the water quality, a model which can describe physical and biochemical processes in the river is more suitable than that described in terms of the input-output ratio. Therefore, we will construct a mathematical model to describe the water quality of an urban stream and will predict the effect of a reduction of BOD load by the sewerage system on the water quality of the Kaki River.

Ever since the classical BOD-DO model was presented by Streeter-Phelps (13), many water quality models have been proposed, e.g. Aiba et al. (1), Kawashima and Suzuki (6), etc. However, the response of the water quality to a change in the flow rate of rivers has seldom been discussed. As the flow rate in the future will be reduced by the sewerage system and the reduction of the flow rate may affect the water quality there, it is important to describe the flow precisely. For that purpose, we will construct a model which calculates the non-uniform flow, as well as water quality.

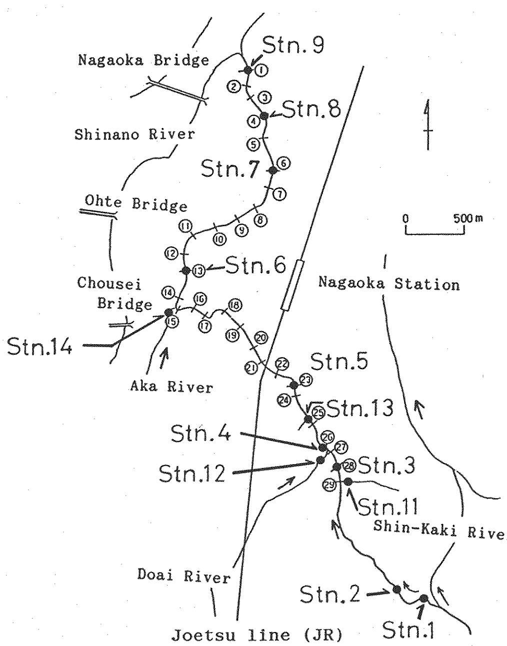

Fig. 1 A plan view of the Kaki-River basin. Circled numbers denote surveying points. Flow rate, BOD, SS, DO and nutrients are observed at nine fixed stations in the Kaki River and four stations in tributaries.

DESCRIPTION OF THE STUDY AREA

The plan view of the Kaki River basin is shown in Fig. 1. The Kaki River is a typical urban stream which flows through Nagaoka City. As the Kaki River reaches the plain area, the Shin-Kaki River branches off just upstream of Stn. 1 in Fig. 1, and more than half of the flow rate is diverted to the Shin-Kaki River. The drainage area is 17.8 km^2 and the length is 6.5 km from the branching point. At the upper reach of the Kaki River from Stn. 6, many irrigation channels merge with or diverge from the river. The average flow rate in the lower reach of the Kaki River from Stn. 4 is 1.34 m^3/s at the low-water level. Main tributaries are the Doai and Aka Rivers, which merge with the Kaki River at Stn. 11 and Stn. 14, respectively. Among the tributaries, the Doai River has the largest flow rate and the worst water quality, and is the main source of pollutant load as a sewerage system has not been constructed in its drainage area. In contrast, a sewerage of combined system had already been constructed in the north-western district of the city and no pollutants pour into the lower reach of the Kaki River at Stn. 6.

Construction of the sewerage system is planned to be completed progressively, in four blocks of the whole area as shown in Fig. 2. The construction had already been completed in S-1 and S-2-1 in 1978. These blocks are located in the downtown area of Nagaoka City. As urbanization has been developing recently in S-2-2, a new sewerage system is under construction. Therefore, pollutant load will be reduced almost completely in the end, when the sewerage starts to work. As a large part of S-3 and S-4 areas are mountains and forests and the population density in these areas is small, no sewerage is planned at present.

Using the pollutant load factor, the BOD load at the present state is estimated to be 4,200 kg/day as shown in Table 5. As 81.5 % of the total BOD is generated in S-2-2 where the Doai River flows, this area is considered to be the main source of pollutant loading. The domestic waste is 47.5 % of the total BOD load in the whole Kaki River basin. Almost the same ratio is estimated to be generated in S-2-2. Details of the estimation of pollutant loads will be described in the following chapter.

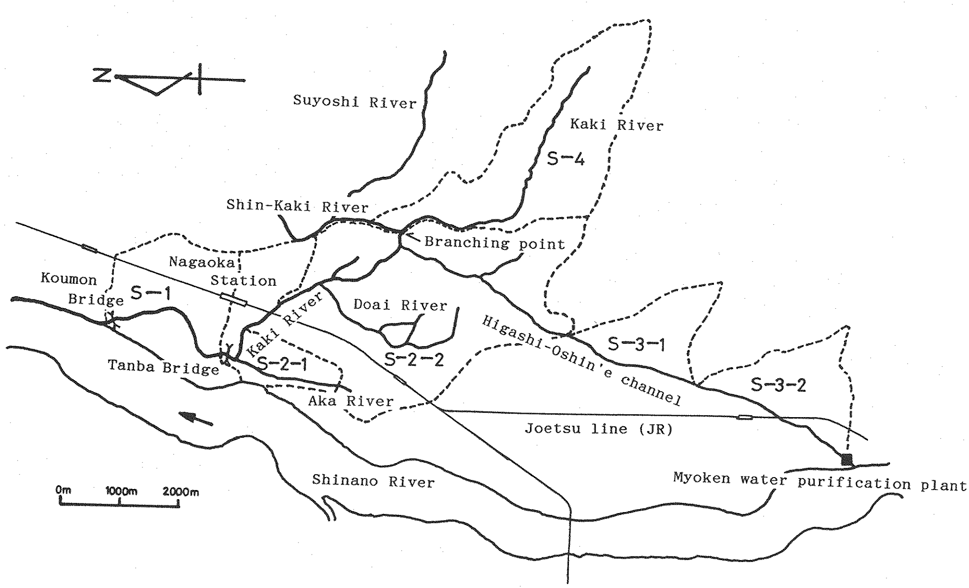

Fig. 2 Division of the drainage area of Kaki River basin. The sewerage construction has already been completed in S-1 and S-2-1. The sewerage system is now being constructed in S-2-2 which is the major source of pollutants to the river.

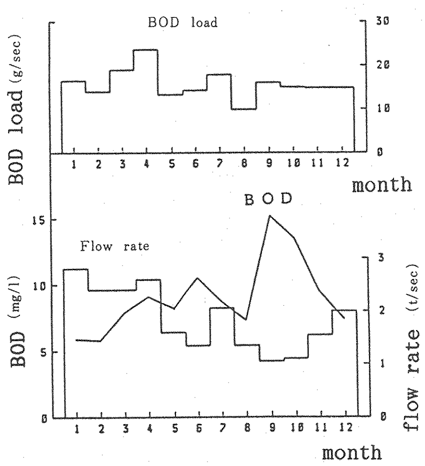

Fig. 3 Seasonal variation of BOD concentration, flow rate and BOD load observed at Stn. 6 in the Kaki River.

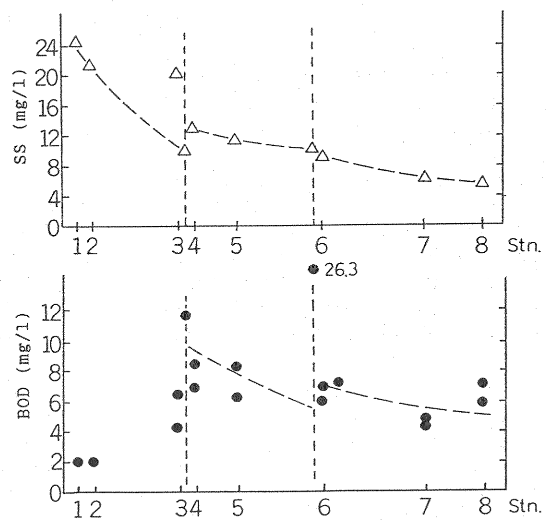

Fig. 4 A typical example of longitudinal distribution of SS and BOD observed in October 1984.

The actual amount of load which arrives at a specific point of the river is ordinarily less than the above values. For example, only 58.2 % of the total BOD load in S-2-2 is estimated to reach the Kaki River at the low-water level condition.

The wastewater flow rate is estimated to be 21,500 m^3/day (0.25 m^3/sec), while the natural discharge is 1.09 m^3/sec at the low-water level. As 86 % of the total wastewater flow rate is generated in S-2-2, the reduction of wastewater flow rate due to the construction of the new sewerage will affect the total flow rate. In order to estimate the effect of the sewerage on the water quality, therefore, a calculation of the non-uniform flow is necessary.

Nagaoka City (9) has been measuring the water quality at three stations of the Kaki River since 1971. Both the BOD and flow rate had been measured monthly from 1973 until 1975. Their monthly averaged values at Stn. 6 are shown in Fig. 3. A clear intra-annual cycle of the flow rate and BOD concentration is observed. The water quality is worst in September and October, when the flow rate is the lowest. From October to December, the water quality recovers as flow rate increases. This is due to the merging of cleaner water from the Higashi-Ohsin'e Channel with the upper part of the Kaki River in non-irrigating seasons. On the contrary, a seasonal change of BOD load is rather small, except in April and August.

Considering the characteristics of the seasonal change of the water quality, we have observed the water quality of the river once a month in autumn since 1984, at the stations shown in Fig. 1. A typical result is shown in Fig. 4. Concentrations of SS and BOD decrease toward downstream in a similar way. As much as 50 % of SS and 20 % of BOD is lost within the lowest 2.5 km of the river, where no pollutant load enters. This fact suggests that, in spite of such a relatively short distance, the purification process (settling and/or decomposition) cannot be ignored in the whole description of the water quality.

WATER QUALITY MODELING

A predictive water quality model should be able to describe the effect of reductions of both the pollutant load and wastewater flow rate due to the construction of a sewerage system. Therefore, a model to describe the flow as well as the water quality is required. Here we propose a simulation model which is composed of two submodels: one calculating the non-uniform flow, the other, the water quality.

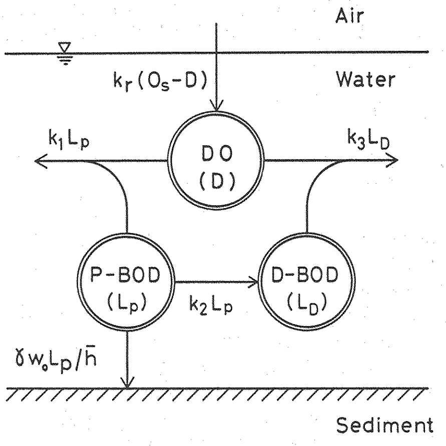

Fig. 5 Processes and Variables of the water quality submodel.

Modeling of the non-uniform flow

Integration of the equation of motion for fluid flow over the cross section leads to the basic equation for the non-uniform flow as follows:

$$-i + dh/dx + (1/2g)(d(Q/A)^2/dx) + (n^2/R^{4/3})(Q/A)^2 \tag{1}$$

where: i = slope of a river bed, h = depth, x = downstream distance, g = acceleration of gravity, Q = flow rate, A = cross sectional area, R = hydraulic radius and n = Manning's roughness coefficient.

To calculate h, information for i, A and R is necessary. We obtained these values by a field survey at the twenty-nine sections along the river as shown in Fig. 1. The values of A and R are then expressed as the polynomials of h given as follows:

$$A = a_1h^3 + a_2h^2 + a_3h + a_4 \tag{2}$$

$$R = r_1h^3 + r_2h^2 + r_3h + r_4 \tag{3}$$

where $a_1,...,a_4$, $r_1,..,r_4$ = coefficients which are determined at each cross section.

Water quality submodel

As mentioned previously, the settling and decomposition of particulate matter are principal mechanisms of the purification of rivers. In order to distinguish the purification processes responsible for particulate matter from those for dissolved matter, we divide BOD into two components: the particulate BOD (P-BOD) and the dissolved BOD (D-BOD). Model variables are, in addition, SS and DO.

The physico-chemical processes taking place among these variables are schematically shown in Fig. 5. The mineralizations of the particulate and the dissolved BOD are assumed to be first-order reactions. The solubilization of the particulate BOD into the dissolved BOD is assumed to be a first-order reaction without consumption of dissolved oxygen. The particulate BOD is also removed by sedimentation. DO is consumed in both decomposition processes and is reaerated from the atmosphere at a rate proportional to the oxygen deficit.

In the calculation of SS, the chemical composition of a decomposable portion of SS is necessary. Though the chemical compositions of algae and bacteria are proposed (e.g. Somiya et al. (12)), the chemical composition of easily decomposable

SS in urban streams is different from them and is similar to carbohydrates or sugars. Therefore, we assume that a part of SS has a chemical composition as CH_2O which decomposes itself by consuming DO as follows;

$$CH_2O + O_2 \rightarrow CO_2 + H_2O \tag{4}$$

If we define the decomposable SS as the particulate BOD, the rate of consumption of SS per unit uptake rate of DO, β(=30/32), must be considered in the calculation of SS.

As Dobbins (3) summarized, numerous other processes are taking place in natural streams: liberation of partly decomposed organic products, an increase of BOD from scoured bottom deposits, oxygen uptake by sediments, respiration and detachment of attached algae (Kawashima and Suzuki (6)) and photosynthesis by phytoplankton. However, we have observed in the Kaki River that the net transfer of BOD and SS was from the overlying water to the sediments except during the storm runoff and that a diurnal change of DO was small because the biomass of phytoplankton and attached algae was not so large. Therefore, we assume that the above processes could be neglected. Furthermore, the flow condition was considered to be such that the shear velocity is lower than the proposed critical velocity for sediment erosion (Otsubo (11)), leaving settling to be the dominant process.

The basic equations of conservation of the variables are as follows:

$$u(dL_P/dx) = (1/A)(d[AD_x(dL_P/dx)]/dx) - \gamma w_0 L_P/h - (k_1+k_2)L_P \tag{5}$$

$$u(dL_D/dx) = (1/A)(d[AD_x(dL_D/dx)]/dx) - k_3 L_D + k_2 L_P \tag{6}$$

$$u(dD/dx) = (1/A)(d[AD_x(dD/dx)]/dx) - k_1 L_P - k_3 L_D + k_r(O_s - D) \tag{7}$$

$$u(dS/dx) = (1/A)(d[AD_x(dS/dx)]/dx) - \gamma w_0 S/h - (k_1+k_2)\beta L_P \tag{8}$$

where: L_P , L_D = particulate and dissolved BOD concentrations; S = SS concentration; D = dissolved oxygen concentration; u = flow velocity; D_x = longitudinal dispersion coefficient; w_0 = settling velocity; O_s = saturation concentration of DO; k_r = reaeration rate coefficient; k_1, k_2 and k_3 = decomposition rate constants; and γ = concentration ratio of the particulate BOD immediately above the sediment surface to the average over the cross section. As for SS, the same ratio, γ, was assumed. In these equations, u, h, L_P, L_D D and S are all averaged values over the cross section.

Many earlier models, e.g. QUAL I (15), Dobbins (3) and Aiba et al. (1), dealt with losses of BOD and SS by settling as the first order kinetics. In our model, a similar term appears at the second term on the right hand side of Eqs. (5) and (8). The removal rate constant of this term, say k_s, can be expressed as

$$k_s = \gamma w_0/h \tag{9}$$

which involves the water depth and the concentration ratio γ. The earlier models do not include these values.

Model parameters

Model parameters except for the reaeration rate coefficient were all determined from the in-situ measurement in the Kaki River. Parameters thus determined are the decomposition rate constants, settling velocity, concentration ratio and the dispersion coefficient.

Decomposition rate of BOD

The decomposition rate constants were obtained by the dark-bottle method. River water was sampled at Stns. 5 and 6. The sampled water was filtered immediately, and both unfiltered and filtered samples were incubated for five days in dark condition at the sampling temperature. From Eqs. (6) and (7), DO concentration in the bottle filled with filtered water can be expressed as

$$dD/dt = - k_3L_D = dL_D/dt \tag{10}$$

The solution can be obtained immediately as

$$D - D_5 = L_{D_0} \exp(-k_3t) \tag{11}$$

where L_{D0} = initial concentration of L_D and D_5 = DO after five days of incubation. Using Eq. (11) and the experimental result with the filtered water, we can determine the value of k_3.

For the bottle with the unfiltered water, L_P, L_D and DO can be expressed as follows;

$$dL_P/dt = - (k_1+k_2)L_P \tag{12}$$

$$dL_D/dt = - k_3L_D + k_2L_P \tag{13}$$

$$dD/dt = - k_1L_P + k_3L_D \tag{14}$$

These simultaneous differential equations are easily integrated to obtain DO as a function of t as

$$D = D_0 - L_{P_0} - L_{D_0} + \frac{k_1-k_3}{k_1+k_2-k_3} L_{P_0} \exp\{-(k_1+k_2)t\} + (L_{D_0} + \frac{k_2}{k_1+k_2-k_3} L_{P_0}) \exp(-k_3t) \tag{15}$$

where L_{P0} = initial concentration of L_P. Thus the decomposition rate constants, k_1 and k_2, can be obtained from the experimental result of the unfiltered sample, if the ratio, k_1/k_2, and the value of k_3 are known.

Little data is available for the ratio, k_1/k_2. Ishikawa and Nishimura (15) showed a method to evaluate the mineralization of the particulate and dissolved organic matters. They applied it to the data of Osaka Bay and found that the first-order rate coefficients ranged from 0.132 to 0.434 day^{-1} for the direct mineralization (k_1) and 0.034 to 0.189 day^{-1} for the solubilization (k_2). Considering these results, we assumed the ratio, k_1/k_2, to be 2. The sensitivity of the model to this ratio was small as long as the sum of k_1 and k_2 was kept constant.

In the following chapter, we will validate our model by comparing the calculated results with observed data including several temperature conditions. For that purpose, water samples were collected in different seasons, and then were incubated in a laboratory at the field temperatures. Assuming the Arrhenius-type dependence of the rate constants on temperature, we calculated the apparent value of the activation energy. An averaged value was 18 kcal/mol, which was slightly larger than that observed by Kawashima and Suzuki (7).

Settling velocity and the concentration ratio, γ

The concentration ratio, γ, can be evaluated from the vertical distribution of SS. The value of γ as well as the settling velocity could be estimated from the Rouse profile (see, for example, Ishihara (4)), if the shear velocity, u_*, is known. However, observed profiles do not always obey this profile. While settling and scouring depend largely on local conditions of the bed slope and bed material, the vertical distribution of SS at a specific point depends on the cumulative effect of the upper stream conditions as well. As the geometry of the river is rather complicated, SS is not necessarily distributed at the equilibrium profile as is assumed with the Rouse profile.

Sugiki (14) gave a typical settling velocity of organic matter with specific weight of 1.25 as a function of diameter. The settling velocity was evaluated from repeated observation with the medium diameter of suspended solids in the Kaki River, and the average value of 1.3×10^{-5} m/s was obtained. The value of γ was also obtained from the observed profile of SS. The value fluctuated widely but the average was 1.5.

The value of γ for BOD is, in general, different from that for SS, as chemical compositions are different each other. If the particulate matter has a uniform size and a simple chemical composition, the sufficient condition under which both values of γ coincide with each other is one where the water column is well mixed ($\gamma \approx 1$) or the settling of particles is much faster than their decomposition ($w_0/h >> k_1 + k_2$). The latter condition is almost satisfied in our calculation.

Dispersion coefficient

The dispersion coefficient was evaluated from the in situ measurement with floats. Cylindrical floats with diameters of 6 cm and heights of 9 cm were released from specific points of the river at a constant time interval, and then the time, t_i, at which the ith floats passed the specific point x m downstream was measured. The variance σ^2 was obtained from the following formula as

$$\sigma^2 = x^2\{\sum(\bar{t}/t_i)^2 - N\} \tag{16}$$

where N is the total number of floats and $\bar{t}$ is the averaged time defined as

$$\bar{t} = N / \sum(1/t_i) \tag{17}$$

The dispersion coefficient was calculated from the variance of the distributed floats using the following equation as

$$D_x = (1/2)(d\sigma^2/dt) \tag{18}$$

The experiments were conducted at two different flow rates; 0.6 m^3/s in 1985 and 2.0 m^3/s in 1986. The results were expressed as

$$D_x/ hu_* = 10 \text{ or } 190 \tag{19}$$

Considering the flow condition, we used 0.17 (m^2/s) for the dispersion coefficient.

As the analysis of dispersion of floats cannot account for the vertical shear, the dispersion coefficient obtained by the above method could be an underestimated value. Therefore, we made a sensitivity analysis of the coefficient as shown in Fig. 6. The results show that the difference in the coefficient at one order of magnitude did not affect the calculation results very much.

Reaeration rate coefficient

O'Conner and Dobbins (10) formulated the reaeration rate coefficient as a function of flow velocity and water depth. The modified formula (Committee on Sanitary Engineering Research (2)) accounting for temperature dependence as

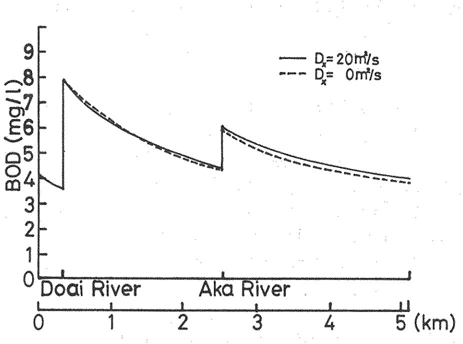

Fig. 6 A sensitivity of the dispersion coefficient to BOD in the model.

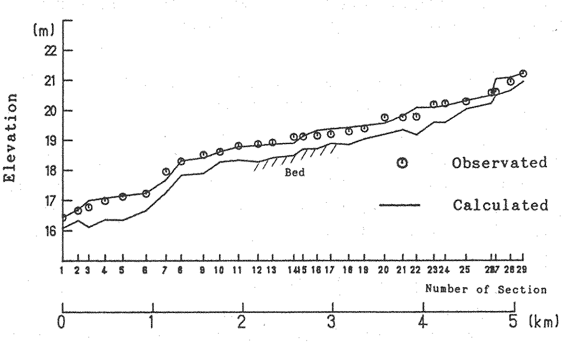

Fig. 7 Comparison of the observed and calculated water surface profile.

$$k_r = \frac{(D_M u)^{1/2}}{2.303h^{3/2}} 1.204^{(T-293)} \qquad (20)$$

was used in this model, where D_M = molecular diffusivity of oxygen gas in pure water, and T = absolute temperature.

Validation of the model

The present model is validated if it can simulate the observed distribution of the flow depth and water quality of the Kaki River. Two confluences to the river were considered: the Doai River, and the Aka River. The observed concentrations of the constituents and flow rates at the confluences were given as the boundary conditions. The same longitudinal division of flow sections as in the survey was adopted.

At first, a water level profile was simulated by means of the non-uniform flow submodel. As the flow of the present concern was subcritical, the observed depth at the downstream end was used as the boundary condition. Manning's n was so evaluated as to minimize the difference in water level between the observed and the calculated. The calculated result is given in Fig. 7, which shows a good agreement with the observed profile. In this calculation, n was assumed constant at 0.06 throughout the river and this value was used for other flow conditions.

Secondly, we validated the water-quality submodel. The observed values of concentration of BOD, SS and DO at the upstream boundary were given as the boundary condition. Another boundary condition was that their gradients at the downstream end were constant.

The observed ratio of the particulate BOD to the dissolved one in the two tributaries is shown in Fig. 8. The correlation suggests that the ratio is about 2. Therefore, we used this value for the calculation of 1984, although BOD in 1984 was not separately analyzed. For the calculation of other years, the observed values of the individual constituent were given.

Calculated results are shown in Fig. 9. Model parameters and their values are listed in Table 1. The longitudinal changes of SS and DO coincide well with the observed ones except for one SS data of 1 km downstream from the confluence point of the Doai River. This observed value may be erroneous, compared with other observed values. The DO slightly recovers toward downstream from the confluence point of the Aka River, and this situation was well reproduced in the calculation. The total BOD was also reproduced well except for a couple of points. In contrast, dissolved BOD is poorly reproduced. This may partly be due to the effluent loads from small tributaries. Note that the agreement was satisfactory at the downstream from the confluence point of the Aka River where pollutant loads can be practically neglected. As a conclusion, our model satisfactorily reproduces the observed profiles of the model variables. The degree of agreement of the calculated results

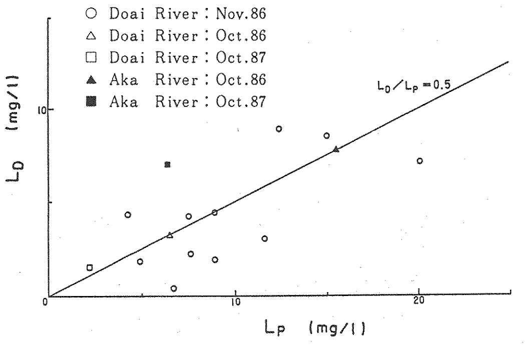

Fig. 8 Correlation of dissolved BOD with particulate BOD observed in tributaries.

Table 1. Parameters in the water quality submodel (1987)

Parameters	Symbol	Unit	Value
Water temp.	t	°C	13.5
Decomposition rate const.	k_1	1/day	0.52
Decomposition rate const.	k_2	1/day	0.26
Decomposition rate const.	k_3	1/day	0.41
Dispersion Coefficient	D_x	m^2/sec	0.17
Reaeration rate const.	k_r	1/day	2.0 (averaged value)
Concentration ratio	γ	-	1.5
Settling velocity	w_0	m/s	1.3×10^{-5}
Saturation DO	O_s	mg/l	10.1

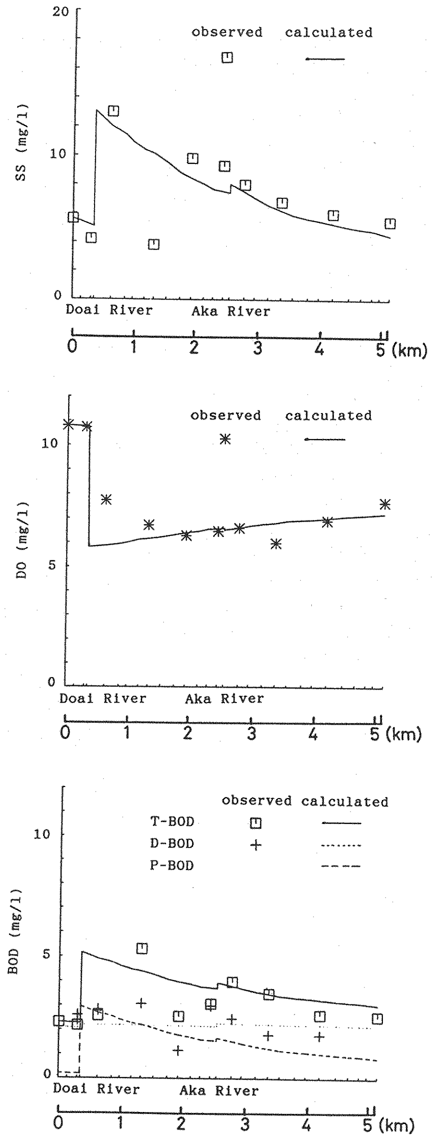

Fig. 9 Results of the simulation of SS (upper), DO (middle) and BOD (lower). Circles are observed values in October 1987.

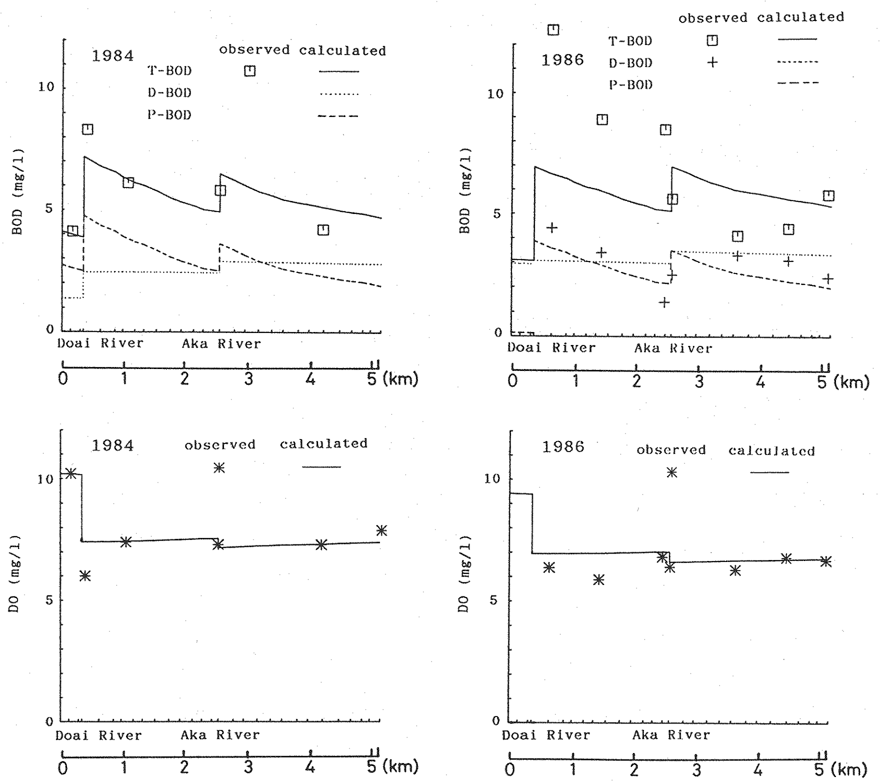

Fig. 10 Results of the simulation of BOD and DO in 1984 and 1986.

with observations for another years, was almost the same as that of this year, which validates our model. The calculated results of BOD and DO are shown in Fig. 10.

Let us consider the controlling factor which determines the distribution of BOD. As the longitudinal variation of D-BOD is small, we will discuss the distribution of P-BOD. In the basic equation (5), we can compare the relative contributions of the dispersion, settling and decomposition processes. Among these, the contribution of the dispersion was small, as shown in Fig. 6. Therefore, the ratio of the decomposition and settling,

$$r = (k_1+k_2)/(\gamma w_0/h) \quad (21)$$

is a measure of the relative importance. From the simulations of 1984, 1986 and 1987, the ratio at each year was calculated to be 0.26, 0.32 and 0.21, respectively. Thus, we can conclude that the settling process is the controlling factor determining the longitudinal variation of BOD in the Kaki River.

ANALYSIS OF POLLUTANT LOAD

In Nagaoka City, a combined sewerage system has been under construction since 1988 and it is due to be completed in 1995. As the planned area almost covers S-2-2 where the largest amount of pollutant load is generated, the effect of the construction of the sewerage is expected to be remarkable. In this chapter, we will predict how river water quality will be recovered by the sewerage. Firstly, we estimate the present state of the pollutant load in the drainage area of the Kaki River, using the statistics of Nagaoka City such as population and shipping output of factories (the Nagaoka City (9)) and unit amount of BOD load per capita

Table 2. Population, area and population density in the drainage area of the Kaki River in 1985

	S-1	S-2-1	S-2-2	S-3	S-4	Total
Population (persons)	30,845	18,008	23,915	3,659	2,127	78,554
Area (km^2)	3.67	2.57	11.54	4.64	6.55	28.97
Density (persons/km^2)	8,405	7,007	2,072	789	345	2,712

Table 3. Pollutant load per capita or unit area assumed in the analysis

Wastewater Component	BOD	Wastewater flow rate
(unit)	(kg/capita/day)	(m^3/capita/day)
Man (domestic area)	0.0665	0.352
(commercial area)	0.0665	0.860
(industrial area)	0.0665	0.313
Cattle	0.64	0.09
Swine	0.20	0.01
(unit)	($kg/km^2/day$)	($m^3/km^2/day$)
Farm field	17.3	0

or per unit area (the Ministry of Construction (8)). Secondly, we predict the pollutant load in the future by estimating these statistics. Thirdly, we calculate the longitudinal distribution of river water quality, using the estimated loads and wastewater flow rates as the boundary conditions in our model described in the preceding chapter.

Division of the drainage area

Based on a new sewerage system plan, the whole drainage area was divided into four blocks as shown in Fig. 2. The blocks named S-2 and S-3 are further divided into two sub-blocks, as shown in the figure. A sewerage was already constructed in S-1 and S-2-1 in 1978. In S-2-2, a sewerage system is under construction, with the expected results that the pollutant load will be reduced almost completely in the end, after it begins operation. As a large part of S-3 and S-4 is mountains and forests and the population density in these areas is small, no sewerage is planned at present. The Higashi-Ohsin'e Channel, which is an irrigation channel flowing through S-3, merges with the Kaki River only in the non-farming season, so that the pollutant load in S-3 was considered only in the non-farming season in the simulation. In Table 2, the population, area and population density in the drainage area are listed.

Pollutant load at the present state

For all blocks, the population, the number of livestock, the shipping output of factories and the area of farmland have been investigated by the Nagaoka City (9) and they were multiplied by the pollutant load factors to obtain the total amount of the pollutant loads. The estimated values of the BOD load and the pollutant discharge per capita or unit area were published by the Ministry of Construction (8) and they were tabulated in Table 3. Using these values, we calculated the wastewater flow rate and BOD load at the present state, and they are tabulated in Tables 4 and 5. The values in the tables denote the daily production rates of the discharge and BOD in each study area. As listed in Table 5, domestic waste is as much as 47.5 % of the total daily production of BOD in the Kaki River basin. The industrial, agricultural and natural wastes are estimated to be 38.1, 4.8 and 9.5 %, respectively. As 81.5 % of the total BOD is generated in S-2-2, this area is considered to be the main source of pollutants.

Table 4. Estimated wastewater flow rate (m^3/day) in 1985

Wastewater Component	S-1	S-2-1	S-2-2	S-3	S-4	Total
Domestic	0	0	10764	1289	749	12802
Industrial	0	0	7613	971	60	8644
Agricultural	0	0	26	1	0	27
Total	0	0	18403	2261	809	21473

Table 5. Estimated BOD load (kg/day) in 1985

Wastewater Component	S-1	S-2-1	S-2-2	S-3	S-4	Total
Domestic	0	0	1590	243	141	1974
Industrial	0	0	1405	179	1	1585
Agricultural	0	0	191	11	0	202
Natural	0	0	200	80	113	393
Total	0	0	3386	513	255	4154

The real amount of the load which arrives at a specific point of the river is ordinarily less than the above values. For example, only 58.2 % of the total BOD load in S-2-2 is estimated to reach the Kaki River in the low-water level condition of the river.

Pollutant load in the future

We estimated the pollutant load variation until 1995 when the sewerage system will be completed, assuming that the pollutant load to the Kaki River basin will be linearly reduced owing to the sewerage construction. The population, the number of livestock, the shipping output of factories and the area of farmland in the future were estimated from the recent trends of these items. As the change of the pollutant load per capita (kg/capita/day) or unit area (kg/m^2/day) is also given by the Ministry of Construction (8), we used these values for our prediction.

The calculated results for 1995 are listed in Tables 6 and 7. The total amount of the BOD load was estimated to be 2,372 kg/day, which is almost a half of the amount in 1985. Especially, the BOD load in S-2-2 in 1995 is only 18.4 % of that in 1985. As a result, the contribution of the BOD load in the area is as low as 45.4 % of the total BOD load in 1995. In comparison, the load in S-3 will be

Table 6. Predicted wastewater flow rate (m^3/day) in 1995 when sewerage system will be completed

Wastewater Component	S-1	S-2-1	S-2-2	S-3	S-4	Total
Domestic	0	0	3094	1700	1865	6659
Industrial	0	0	0	2520	80	2600
Agricultural	0	0	61	1	0	62
Total	0	0	3155	4221	1945	9321

Table 7. Predicted BOD load (kg/day) in 1995

Wastewater Component	S-1	S-2-1	S-2-2	S-3	S-4	Total
Domestic	0	0	445	300	329	1074
Industrial	0	0	0	465	2	467
Agricultural	0	0	434	4	0	438
Natural	0	0	200	80	113	393
Total	0	0	1079	849	444	2372

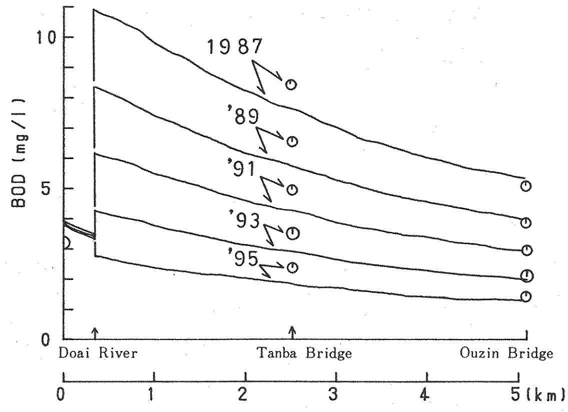

Fig. 11 Predicted distribution of BOD in future. Planned sewerage system is to be completed in 1995. Open circle denotes calculated result by assuming the overall input-output ratio at two specific points.

35.8 % in 1995, so the pollutant load in this district cannot be ignored in the near future.

Prediction of water quality in the future

Using the developed model described in the preceding chapter, we calculated the water quality in October (18 °C) when the flow rate is at the low-water level. This condition means the worst condition of the future water quality.

Since a part of the pollutant load is self-purified in tributaries or removed in waste channels, the overall input-output ratio is less than unity under a dry weather condition. This ratio can be evaluated by comparison of the observed amount of the BOD load at the merging point of the Kaki River with the total amount of BOD load estimated at section 4-2. For example, this ratio is 0.58 in S-2-2 in 1995 on the low-water basis.

If the Doai River basin itself is considered, the self-purification in the Doai River is considered to be the stream input-output process. Let us estimate this ratio at the present and in the future. As we have seen in the simulation in the preceding chapter, the apparent purification of P-BOD is much faster than that of D-BOD. Therefore, we only have to consider the P-BOD in the stream input-output process in the Doai River. If particulate matter flows down in the distance x with an average velocity of u, the concentration ratio at the upper to lower stream ends is given as $\exp\{-(k_1+k_3+k_s)x/u\}$. In the purification process of the Doai River (x = 2.0 km, u= 0.3 m/s), the stream input-output ratio of the P-BOD is 0.75 in 1985. The ratio in 1995 is easily obtained at 0.8 because the wastewater flow rates are given.

For the prediction of the future water quality, a change in the ratio of the pollutant load arriving at the Doai River to that generated in the drainage is also important. However, a reliable value for the future is not available. Therefore, we assumed the ratio to be constant.

The calculated result of longitudinal change of the total BOD is shown in Fig. 11. The effect of the sewerage on the water quality is remarkable. The BOD is estimated to be less than 2 mg/l at the downstream end of the Kaki River in 1995. This value is below the set standard of the water quality in the Shinano River.

The BOD in the upper reach is, however, larger than 2 mg/l even in 1995 and it is worse than that of the Doai River. Thus, a counterplan is needed to reduce pollutant loads especially in S-3 and S-4 in the future.

CONCLUSION

A simulation model was developed to describe the water quality of an urban stream. The model consists of two submodels; one for calculating a non-uniform flow, and the other a water quality distribution. The latter submodel is a modified version of the classical Streeter-Phelps model. In order to distinguish the decomposition of organic matter from the apparent BOD removal by settling of SS, the particulate and the dissolved BOD were considered as model variables. We applied our model to the Kaki River and found that the model was able to finely reproduce the observed longitudinal profiles of the particulate BOD, the dissolved one, as well as SS and DO.

The pollutant load in the Kaki River basin was estimated and the major source of pollutants was identified. Furthermore, the reduction of the pollutant load in the future due to a new sewerage system construction was investigated to predict its effect on the water quality.

The predicted pollutant load was applied to our model to simulate the longitudinal change of the water quality in the future. According to the simulation, a remarkable effect of the sewerage system on the water quality should be expected.

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APPENDIX - NOTATION

The following symbols are used in this paper:

a_i = constant, Eq. (2);
A = area of a cross section;
D = dissolved oxygen concentration;
D_0, D_5 = dissolved oxygen concentration at the initial and after five days' incubation;
D_x = longitudinal dispersion coefficient;
D_M = molecular diffusivity of oxygen in water;
g = acceleration of gravity;
h = flow depth;
i = slope of the river bed;
k_1, k_2, k_3 = decomposition rate constant;
k_r = reaeration rate coefficient;
k_s = rate constant for BOD removal by sedimentation;
L_D = concentration of dissolved BOD;
L_P = concentration of particulate BOD;
L_{D_0}, L_{P_0} = initial concentration of dissolved and particulate BOD;
n = Manning's roughness coefficient;
N = number of floats;
O_s = saturation concentration of dissolved oxygen;
Q = flow rate;
r = ratio of BOD removal by decomposition and that by settling;
r_i = constant, Eq. (2);
R = hydraulic radius;
S = cross-sectional mean concentration of suspended solid;
t = time;
t_i = travel time of ith float;
$\bar{t}$ = mean travel time of float;
T = absolute temperature;
u = cross-sectional mean velocity;
u_* = shear velocity
w_0 = settling velocity;
x = coordinate of longitudinal direction;

β = rate of consumption of SS per unit uptake rate of DO;

γ = concentration ratio of particulate BOD immediately above the sediment to the averaged one over the cross section; and

σ = variance.

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