Estimation of Annual Runoff Pollutant Load and Its Reduction Efficiency

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Abstract: Storm runoff pollutant load has been evaluated by the unit-load-estimation method in water quality management planning of the local government. This method could not have a point of view about rainfall-runoff characteristics. Therefore, the model simulation in wet-weather condition can be estimated to be useful for the accurate evaluation of annual pollutant load. In this study, 3 types of basin, which are urban, agricultural and rural area, were investigated and the annual runoff pollutant load is calculated by the continuous simulation system which includes runoff load model, serial storage tanks model and time series data of rainfall during 10 years. And the surface load is calculated by using the saturation function model during dry-weather periods. The results of continuous simulation show that high values of pollutant load frequently occurs during rainy seasons. And relatively small rainfall events, whose return period is from once to 20 times per year, bring much runoff pollutant load. Finally, the control of detention pond is estimated to be available for not only flood control but runoff pollutant reduction in wet weather condition by the continuous simulation. Because the slight improvement of the existing drainage system or the small additional capacity of detention pond system can bring much efficiency for reduction of runoff pollutant.

Key words: Storm runoff, Pollutant runoff, Diffused pollution, Continuous simulation, Detention pond system, Stochastic analysis, Equivalent marginal benefit, Enclosed lake basin, Water quality management

1. INTRODUCTION

The unit-load estimation method, which roughly estimates pollutant load flowing into water environment, could not represent characteristics of rainfall-runoff(Kido et al. [1], Hosoi et al.[2],[3]). Therefore, the accurate evaluation of annual pollutant load by the model simulation during wet-weather condition is estimated to be useful for water quality management especially in eutrophicated lake. Objectives of this paper are development of the model simulation system, stochastic analysis of runoff pollutant load and estimation of its reduction efficiency by controlling the detention pond system.

2. STUDY AREAS AND FIELD SURVEY

The study areas are 4 rivers flowing into the lake KOYAMA shown in Fig.1. This enclosed lake has 2.8 m of average water depth, 45.2 km^2 of total basin area and about 21 thousand of inhabitants. The south part of this basin is almost covered by rural mountain area (A-3&4), the east part is covered by agricultural area (A-2) and the north part is covered by urban area (A-1). The separate sewerage system is planned only in north part and a few agricultural villages. Field survey and observation of storm runoff have been executed on at least twice in each sub-basin this three years. Observed items are rainfall intensity, river flow rate, COD, SS, T-N and T-P. Fig.2 shows first-flush of pollutant runoff which was observed especially in urbanized area (A-1). In this study, the observation data is utilized to develop some simulation models for forecasting the annual runoff load.

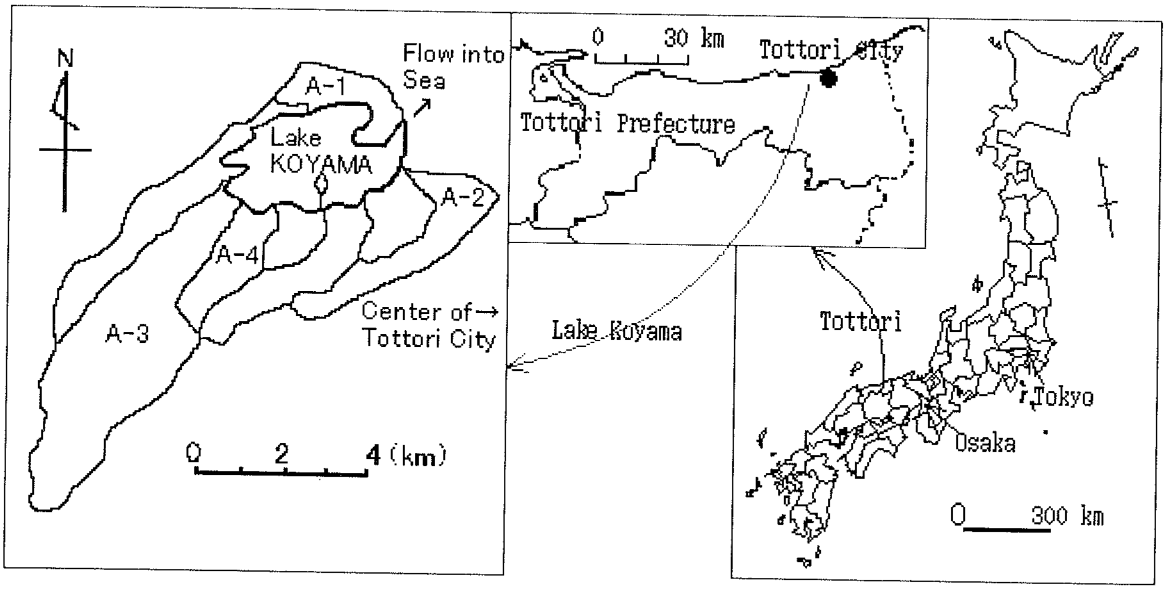

Fig.1 Location and Sketch of Study Area

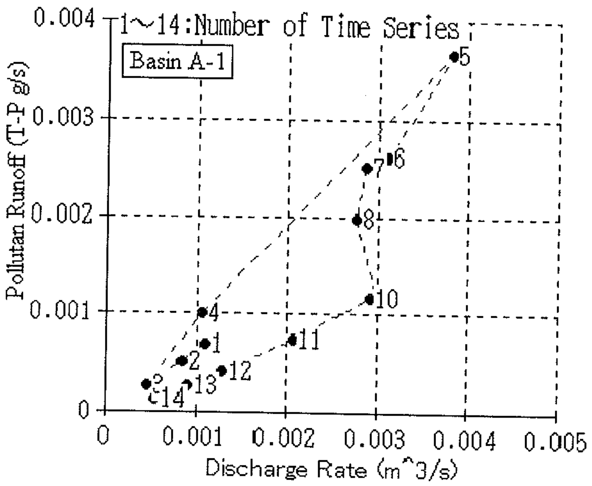

Fig.2 Observed first flush of Pollutant Runoff

3. STORM RUNOFF MODEL

Serial Storage Tanks Model (SSTM, Sueishi et al. [4]) shown in Fig.3 is used for forecasting time series data of storm runoff. The model are calibrated and verified based on two or more rainfall events investigated in each sub-basin and more suitable value of parameters is identified by trial and error method. Fig.4 shows example of SSTM simulation. The value of parameters indicates storm runoff characteristics of each basin.

Runoff ratio α of urbanized basin (A-1) is higher and height of storage is lower than any other basin. On the other hand, impermeable ratio β of rural mountain area (A-3,4) is higher than urbanized area. The storm runoff model of 4 sub-basins is evaluated to be adequate to forecast the time series data of rainfall runoff during 10 years.

Model equations are described as follows.

$$qa_{ij}=\alpha_{ij}\cdot(h-h_{ij})\cdot Sa \quad (1)$$

$$qb_i=\beta_i\cdot h\cdot Sa \quad (2)$$

$$Qa=\sum_i\sum_j qa_{ij} \quad (3)$$

where; q a: surface storm runoff, q b: permeable storm, α : coefficient of runoff ratio, β : coefficient of impermeable ratio, h : equivalent storage height in basin, S a: area of basin.

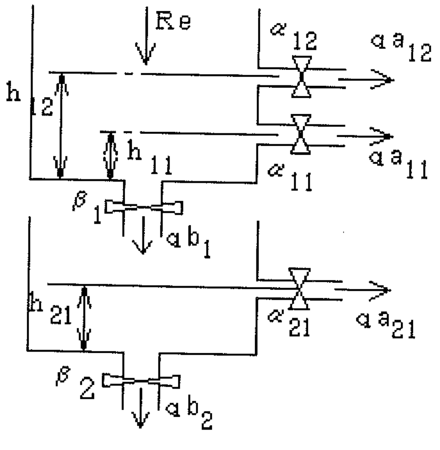

Fig.3 Sketch of Storm Runoff Model (SSTM)

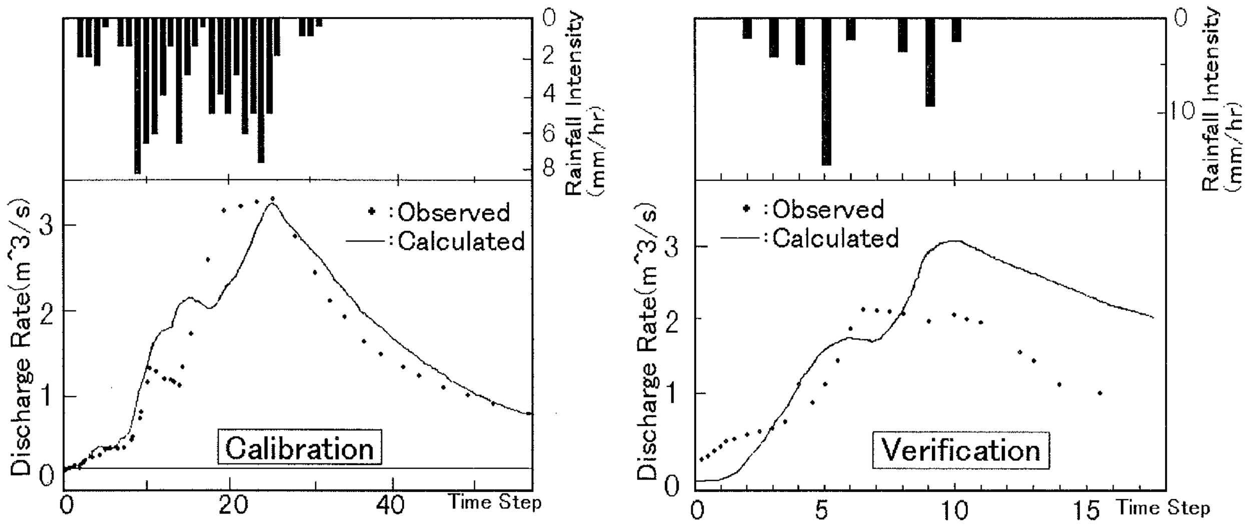

Fig.4 Example of Storm Runoff Simulation by SSTM

4. POLLUTANT RUNOFF MODEL

Two types of pollutant runoff model are applied to runoff simulation in each sub-basin. Model parameters of both models are identified by single or multiple regression analysis. And the saturate function model is applied to evaluate the accumulation of surface pollutant during dry-weather period (Public Works Research Institute Ministry of Construction [5]).

Model-1 : $L = k \cdot Q^n$ (4)

Model-2 : $L = k \cdot S^m \cdot Q^n$ (5)

where; L : Runoff Pollutant Load (g/s), Q : River Flow rate (m ^{3} /s), S : Surface Pollutant Load (g), k,n,m : Model Parameters

Fig.5 shows the example of comparison between calculation and observation of runoff pollutant load and Table 1 shows model parameters of both models. The parameter n shows the degree of dependence of the runoff load to the river flow rate. The value of n shows that the runoff load in rural and agricultural areas (A-2,3,4) exponentially grows corresponding with increasing of the flow rate and the runoff load in the urban area (A-1) linearly grows. Calculation of Model-2 can show good representation of the first-flush of pollutant load by introducing the variable of surface pollutant in its equation. Table 2 shows correlation coefficients of Model-2 are almost higher than ones of Model-1, especially about T-P. Therefore, Model-2 is estimated to be more available for simulation of runoff pollutant load, especially in the urban area.

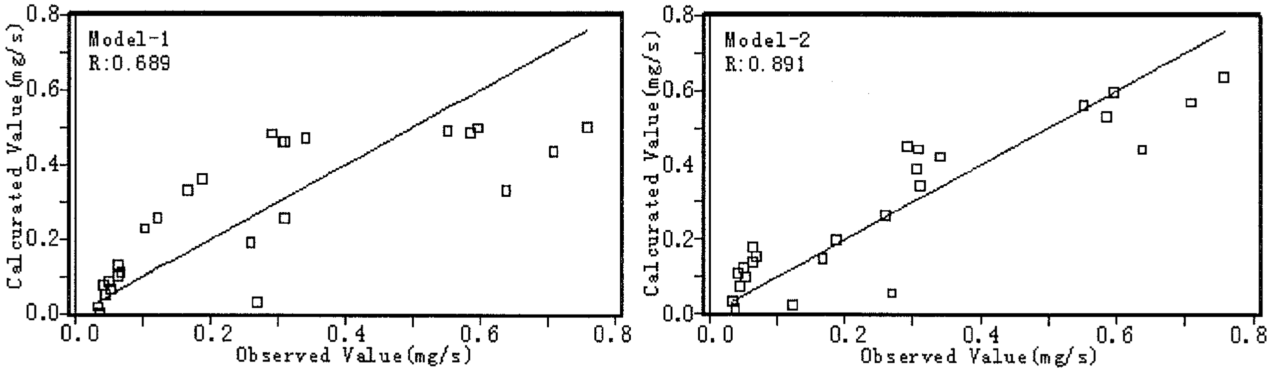

Fig.5 Estimation of Model Validity of Pollutant Runoff (Basin A-4, T-P, 92/10/20)

Table 1 Identified Model Parameters of Pollutant Runoff

Basin /Pollutant \ Model & para.		Model-1		Model-2		
		k	n	k	n	m
A-1	COD	2.54	0.84	1.02	0.87	0.12
	T-N	2.00	0.87	0.28	0.96	0.29
	T-P	0.46	1.06	0.05	1.23	0.47
A-2	COD	160.75	2.44	80.96	2.56	0.11
	T-N	11.73	1.73	5.24	1.91	0.16
	T-P	12.45	2.46	6.01	2.71	0.21

Basin/Pollutant \ Model & para.		Model-1		Model-2		
		k	n	k	n	m
A-3	COD	3.18	2.15	0.08	2.08	0.27
	T-N	0.81	2.15	0.34	1.79	0.07
	T-P	0.16	2.37	0.03	1.91	0.18
A-4	COD	5.75	1.04	1.11	1.51	0.16
	T-N	3.21	1.19	3.19	1.26	0.00
	T-P	0.58	1.05	0.07	1.48	0.25

Table 2 Correlation Coefficients between Observation and Calculation Values in Two Models of Pollutant Runoff

Basin	Pollutant	Model-1	Model-2
A-1	COD	0.959	0.965
	T-N	0.817	0.885
	T-P	0.719	0.820
A-2	COD	0.850	0.888
	T-N	0.889	0.944
	T-P	0.869	0.956

Basin	Pollutant	Model-1	Model-2
A-3	COD	0.858	0.918
	T-N	0.832	0.932
	T-P	0.784	0.879
A-4	COD	0.873	0.874
	T-N	0.961	0.971
	T-P	0.725	0.801

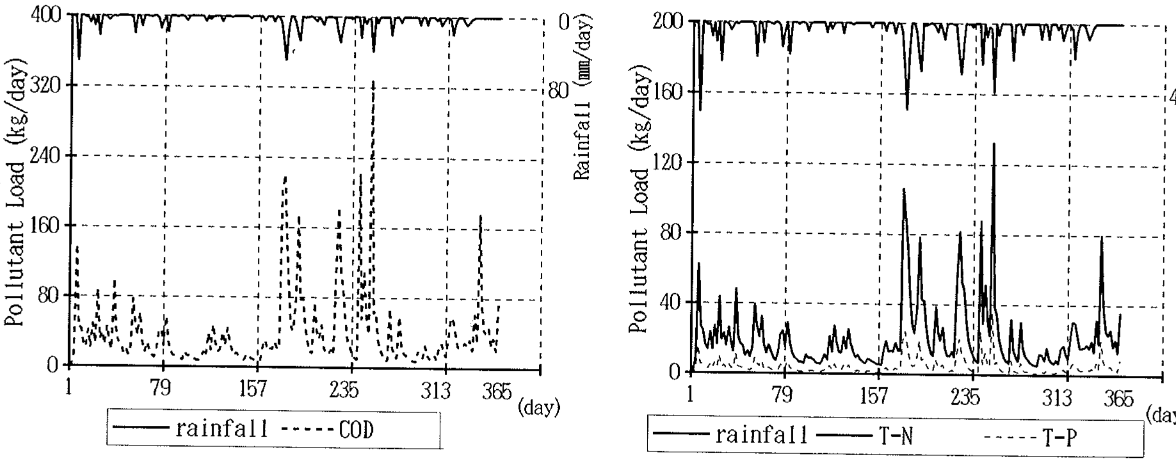

Fig.6 Example of Continuous Simulation to Estimate Annual Runoff Load (Basin A-4, 1993)

5. EVALUATION OF ANNUAL RUNOFF POLLUTANT LOAD

The annual runoff pollutant load is calculated by the continuous simulation system, which includes time series data of rainfall during 10 years, SSTM forecasting each river flow rate and runoff pollutant model (Model-2 mentioned above). And the surface load accumulation during dry-weather periods is calculated by the saturation function model.

Fig.6 is example of continuous simulation. It shows that high load of runoff pollutant frequently occurs during rainy seasons (June-July and Aug.-Sep.). It is supposed that the concentration of runoff load may influence the eutrophication of lake water in summer season.

Fig.7 shows annual runoff pollutant load calculated during 10 years. Annual runoff pollutant load is not directly proportional to annual precipitation, because of the non-linear relationship between runoff and rainfall, and because of accumulated surface load especially in urbanized area.

The unit value of runoff pollutant load(kg/km ^{2} /day) calculated by the continuous simulation is compared with diffused pollutant load by the unit-load estimation method in Table 3. Runoff load of COD and T-N by model simulation are much higher than ones by the unit-load estimation method in Basin A-1,2. But, calculated load of COD and T-N are a little less in basin A-3,4. This analysis shows that this runoff simulation model is useful for evaluation of runoff pollutant load especially in non-rural area.

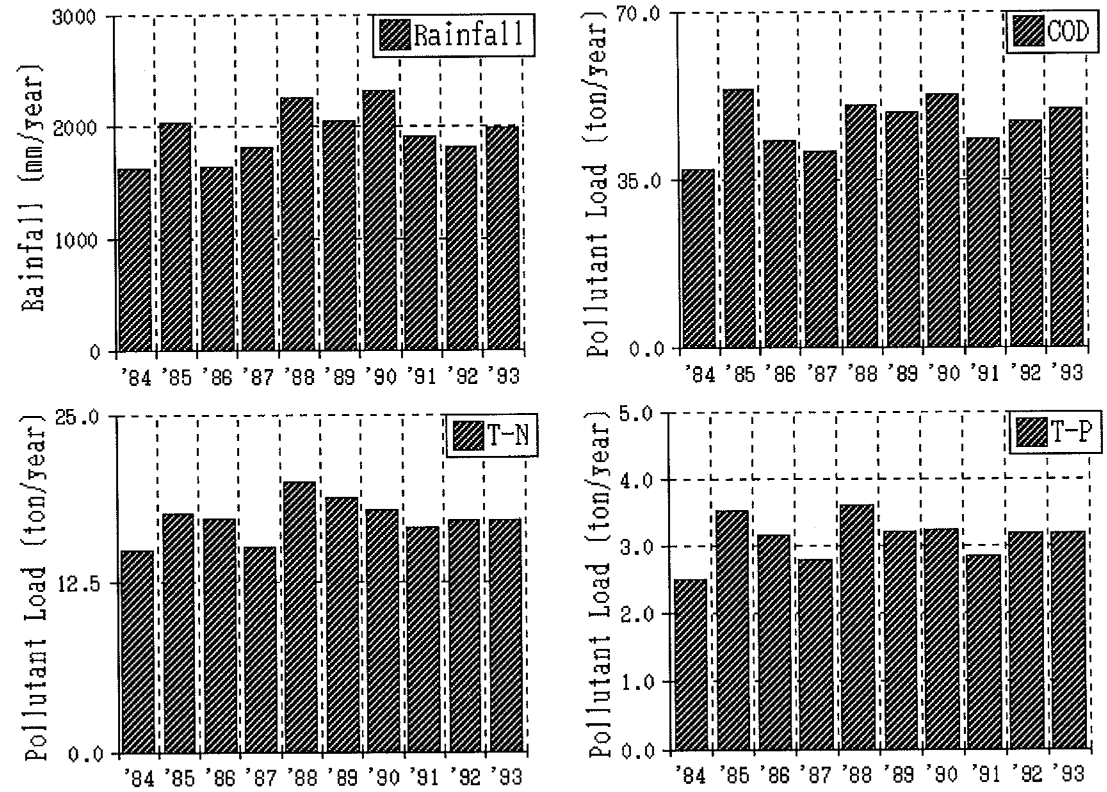

Fig.7 Annual Runoff Load in Wet-Weather Condition Estimated during 10 years

Table 3 Comparison of Unit Values of Runoff Pollutant Load by Two Method (kg/km ^{2} /day)

Basin	Unit-Load Estimation Method									Model Simulation (Model-2)		
	COD			T-N			T-P			COD	T-N	T-P
	Diffused*	Point**	Total	Diffused*	Point**	Total	Diffused*	Point**	Total			
A-1	13.8	24.8	38.6	4.2	8.2	12.4	0.21	1.04	1.25	35.1	30.8	5.36
A-2	10.0	22.2	32.2	3.3	5.2	8.5	0.17	0.96	1.13	24.6	6.0	0.77
A-3	6.1	1.0	7.1	2.3	0.3	2.6	0.10	0.03	0.13	3.1	0.8	0.17
A-4	20.9	1.7	22.6	2.7	5.3	8.0	0.14	0.76	0.90	12.2	6.6	1.38
Total	9.6	6.5	16.2	2.7	2.6	5.3	0.13	0.37	0.50	7.1	2.4	0.45

*Diffused : Runoff Pollutant from Diffused Source, **Point : Runoff Pollutant from Point Source (Tottori Prefectural Government [6])

And it shows that the expansion of urbanized area brings increasing of diffused pollution and the concentration of runoff nutrients in rainy season which cannot be directly reduced by the separate sewage system. Especially, annual runoff load of T-P by model simulation is more than three times as much as one by the unit-load estimation method.

6. STOCHASTIC ANALYSIS OF RUNOFF POLLUTANT AND ESTIMATION OF ITS REDUCTION

Fig.8 shows daily values of storm runoff and pollutant runoff sorted by the order of precipitation in sub-basin A-1 (Kido et al. [7]). This figure shows that the occurrence probability of runoff pollutant load is different from the occurrence probability of precipitation. It is estimated that rainfall events whose order is from 10th to 200th during 10 years bring a lot of runoff pollutant load. Occurrence probability values of these rainfall events are evaluated to be from once to 20 times per year. On the other hand, runoff pollutant load in relatively small rainfall less than 5 mm is estimated to become over 30 % of annual runoff pollutant load. It results from the first-flush of pollutant runoff from urban surface where accumulated surface pollutant load during short dry-weather period can be frequently washed off. And these results suggest that the storage control of storm runoff in small rainfall events is useful for reduction of runoff pollutant.

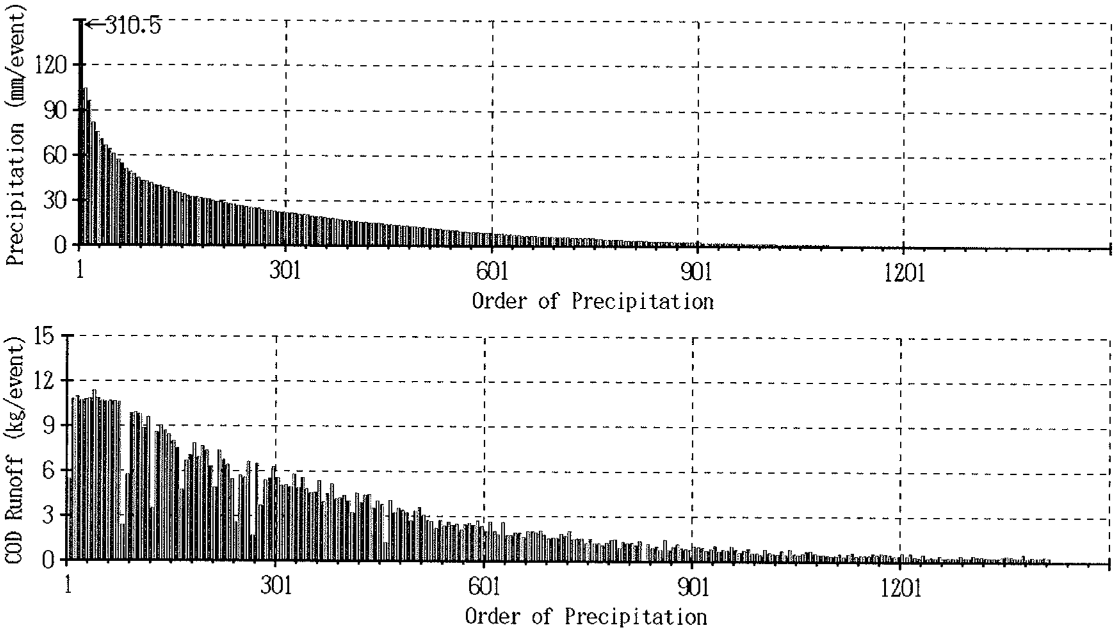

Fig.8 Storm and Pollutant Runoff Intensity Sorted during 10 years

It is discussed that the detention pond system mainly designed for flood control is utilized for reduction of runoff pollutant during early period in rainfall event when pollutant concentration is relatively high. First, the capacity of detention pond (Vd) is designed for storage of excess storm runoff beyond the capacity of the existing drainage canal system, when the rainfall event whose return period is 10 year is occurred. Secondly, designed Vd is allotted to Vd1 and Vd2 (Fig.9). Vd1 is immediately utilized from start of storm runoff event and Vd2 starts to be utilized when discharge rate of storm runoff is over the capacity of the existing drainage system. Both of Vd1 and Vd2 continue to be utilized until their capacity limit. This ratio of partition between Vd1 and Vd2 can be identified as setpoint of control variables in control strategy. Each setpoint control alternative with the constant partition ratio has different efficiency of flood control and pollutant reduction. The efficiency of flood control is evaluated as the ratio of avoiding flood and 100 % of this efficiency means non-flooding during 10 years. The potential of COD reduction is evaluated as the ratio of pollutant storage to total load of pollutant runoff during 10 years. 10 years continuous simulation estimates control strategies of detention pond system with eleven setpoints where the value of Vd1 is changed from 0 to 700 ton.

Fig.10 shows efficiency of flood control and potential of COD reduction evaluated by continuous simulation during 10 years(Kido et al. [8]). Any setpoint control of detention pond (Vd) having 700 m^3 designed for 10 years of return period cannot bring 100 % efficiency. Increasing potential of COD reduction by control of ratio of Vd1 brings slight decreasing of efficiency of flood control, while Vd1 is less than half of Vd . But, while Vd1 is bigger than half of Vd, the efficiency of flood control rapidly decreases. And Fig.10 shows the same trade-off relationship between flood control and pollutant reduction whenever the designed capacity of detention pond is increased to 1,000 m^3 or decreased to 400 m^3. Addition of storage capacity can bring about 30 % of potential of COD reduction under maintaining 100 % of efficiency of flood control.

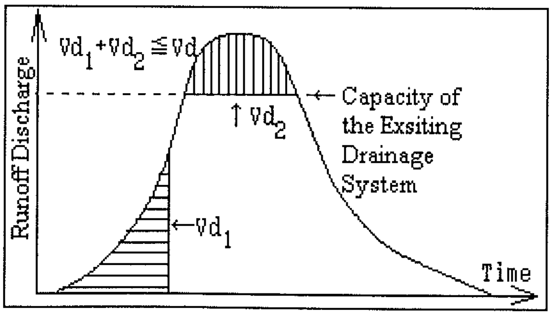

Fig.9 The Control Pattern of Detention Pond System for Flood Control and Pollutant Reduction

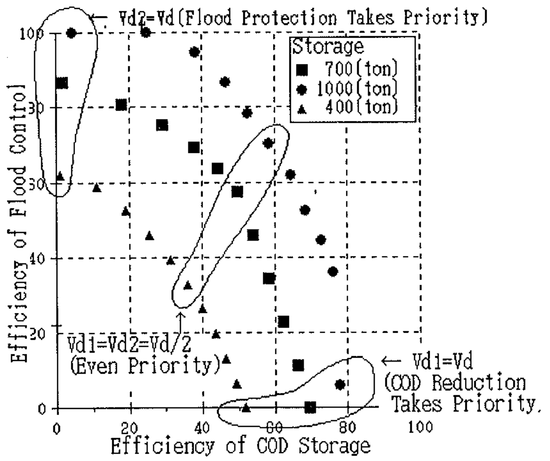

Fig.10 Efficiency of Flood Control and Potential of COD Reduction

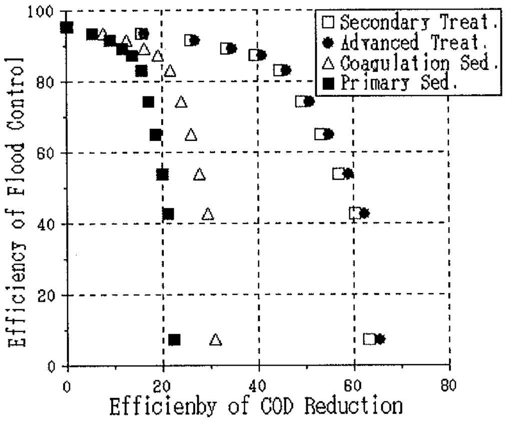

Fig.11 Efficiency of Flood Control and Potential of COD Reduction

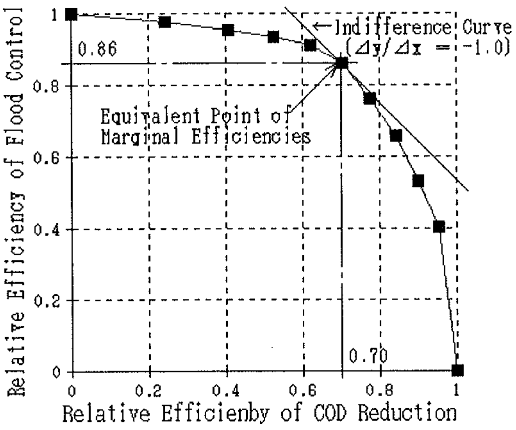

Fig.12 Relative Benefit of Flood Control and COD Reduction

Potential of pollutant reduction means total amount of pollutant load in storm water stored during 10 years according to each setpoint control alternative. Removal efficiency of 4 types of sewer treatment methods is adopted in order to estimate actual efficiency of pollutant reduction. Fig.11 shows that runoff COD is evaluated to be reduced more than 60 %, when storage of stormwater is transported to sewer treatment plant. And about 30 % reduction of runoff COD is evaluated when stored stormwater is treated by sedimentation processes in detention pond.

Strict risk/cost analysis and cost/benefit analysis should be done in order to determine the optimum proportion ratio to manage the detention pond system. But detailed risk analysis is difficult to apply to the problem of flood control and pollutant reduction. And simplified method converting risk into cost may bring under-estimation and/or over-estimation. If the maximum efficiency and the maximum potential displayed by one detention pond system could be evaluated as equivalent benefit, the setpoint can be estimated to be one of optimum control values when two marginal utilities are equal. Efficiency of flood control and potential of COD reduction are normalized by using each maximum and minimum value. Fig.12 shows relative benefits of flood control and pollutant reduction. The optimum point are defined by the analysis of the indifferential curve method. Estimated setpoint is 345:355 on the point of equivalent marginal benefit and Vd1 almost equals to Vd2 in this optimum setpoint control. And then, relative efficiency of flood control is 0.86 and relative potential of COD reduction is 0.70. This result shows the slight decrease of efficiency of flood control can bring much reduction of pollutant load. Therefore, a slight improvement of the existing drainage system or a little additional capacity of detention pond system can bring much benefit of reduction of runoff pollutant.

7. CONCLUSION

In this study, the simulation system was developed to calculate annual runoff pollutant load in wet-weather condition. Annual pollutant load was evaluated and it was estimated that relatively small rainfall events brought much amount of runoff pollutant load. And the control strategy of detention pond was estimated to be available for not only flood control but also runoff pollutant reduction in wet weather condition.

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