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Effects of Hydrological Factors on the Estimation of Storm Runoff Loading in a Large River Watershed

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Abstract

It is important to accurately evaluate storm runoff loading for preserving the water quality of stagnant water bodies. In this study, we analyzed the effects of hydrological factors on the estimation of storm runoff loading using hourly observed data (rainfall, river flow and water quality) at 2 points located in the center of the Yahagi River basin, and applied simple regression models to estimate the loading. Firstly, we observed close relationships among rainfall, river flow, water quality and loading. Secondly, by evaluating the differences between estimated and observed loading rates during the rainy season, we proposed conditions for upgrading the accuracy of loading estimation. Thirdly, we analyzed the factors that affect storm runoff loading from hydrological aspects, and identified relationships between the cumulative loading residual and factors such as preceding dry weather period. Finally, some conditions for the estimation of storm runoff loading are outlined, which include improving the application of the regression models to estimate the loading.

Discipline: Irrigation, drainage and reclamation
Additional key words: water quality, regression model, precision of loading estimation, residual value between estimated value and actual value, preceding dry weather period

Introduction

To conserve the national land with emphasis placed on drainage basins, various schemes for restoring and preserving sound hydrological cycles, including a new national comprehensive development plan, have been proposed by the administrative sector. Also for the preservation of the water environment, promotion of efficient measures for the conservation of drainage basins, is strongly required. Therefore, the authors published a report on the role of agricultural water utilization systems in environmental control of drainage basins based on water management and hydrological cycles[7)]. For such studies, it is important to analyze the actual discharge characteristics of pollution load materials in drainage basins. Proper evaluation of storm runoff loading during rainfall including annual total runoff loading, in particular, is important for promoting environmental control of water quality along with water quality conservation measures provided for drainage basins.

This paper presents the results of studies on the factors affecting the calculation of storm runoff loading, using conventional simple-runoff-loading calculation models based on unit-hour continuous rainfall observation data of flow rate and water quality, obtained at the intake of agricultural water in the midstream area of the Yahagi River.

Methods

Location of the survey points is shown in Fig. 1. The Yahagi River is one of the major rivers in the Nishi-Mikawa district with a population of approximately 1.2 million in the drainage basin 122 km in total length and 2,264 km^2 in area. In this drainage basin, although a large number of projects relating to water resources development have been carried out to meet the increase

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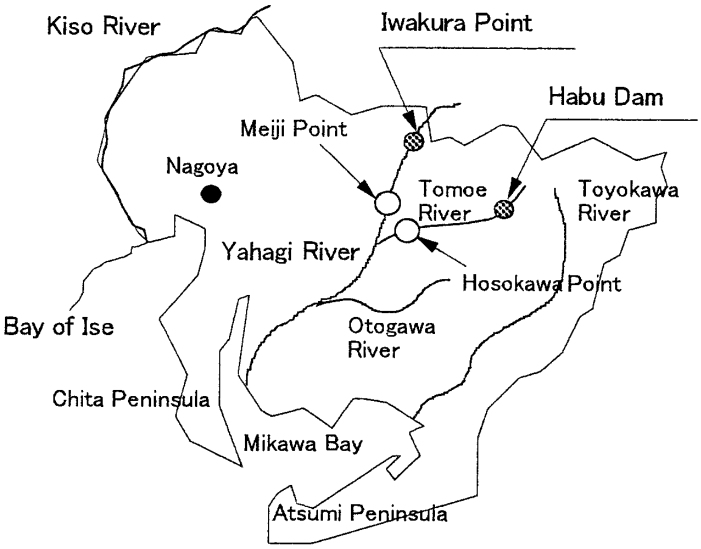

Fig. 1. Diagram of observation points

Table. 1 Land use of drainage basin upstream from the observation points

Point	Forests		Paddy fields		Upland fields and orchards		Others		Total (km^2)
	Area (km^2)	Area rate (%)	Area (km^2)	Area rate (%)	Area (km^2)	Area rate (%)	Area (km^2)	Area rate (%)	
Meiji Point	830.78	82.2	64.92	6.4	29.64	2.9	84.82	8.4	1,010.16
Hosokawa Point	290.65	82.4	13.81	3.9	3.65	1.0	44.53	12.6	352.64

in the water demand since the Meiji irrigation water channel was constructed in 1879, the area often experiences a shortage of water even presently. Meanwhile, adjacent areas have been rapidly industrialized since the 1960s and water pollution has increased along with the urbanization process. In 1969, the Yahagi River Drainage Basin Water Quality Conservation Committee was organized to develop measures for water quality conservation.

Continuous observation points for monitoring the flow rate and water quality are located at the Meiji irrigation water point (hereafter referred to as "Meiji point") of the Yahagi River main stream and the Hosokawa point (hereafter referred to as "Hosokawa point") of the tributary stream. Table 1 shows the type of land use of the drainage basin upstream from the observation points, estimated based on the information provided by the geographical survey. Areas covered by forest predominate in both drainage basins.

Table 2. Annual rainfall at drainage basin of the Yahagi River

Unit: mm/y

Year	Iwakura Point		Habu Dam Point	
	Rainfall	Rainy days	Rainfall	Rainy days
1992	1,206	114	1,459	117
1993	1,479	131	1,756	137
1994	923	77	1,309	89
1995	1,432	104	1,392	94
1996	1,165	97	1,150	94

Annual rainfall and number of rainy days observed during the period from 1992 to 1996 at rainfall gauging stations are shown in Table 2. The Table shows that 1994 was a year of drought and 1993 was a year of high water level at either points during the five-year period. For rainfall information in the drainage basin of the Yahagi River main stream, the unit-hour rainfall observation data taken at the Iwakura point were used as well as the data taken at the Habu dam point for the Tomoegawa drainage basin. For the flow rate, unit-hour flow rate data[6)] taken at the Hosokawa and the Meiji points (data taken from 1993 to 1996 for the Hosokawa point and from 1992 to 1993 and of 1996 for the Meiji point) were used, and for the water quality data, unit-hour observation data taken (1982 to 1986) by the automatic water quality monitor[2)] of Aichi Prefecture were used.

For estimating the storm runoff loading, the equations (1), (2)[1] and (3)[4]were used:

$$L = aQ^b \quad \text{.........} (1),$$
$$\Sigma L = a(\Sigma Q)^b \quad \text{.........} (2),$$
$$\Sigma L = a(\Sigma R)^b \quad \text{.........} (3).$$

Where L:loading, Q:river water flow, ΣL:cumulative load of one rainfall, ΣQ: cumulative rate of one rainfall outflow, ΣR:cumulative volume of one rainfall, and a, b:coefficients.

Actual and estimated values of storm runoff loading

Figs. 2–4 show the relationship between the river water flow rate ($m^3/km^2 \cdot d$) and its load ($kg/km^2 \cdot d$), that between the cumulative rate of one rainfall outflow (m^3/km^2) and its cumulative load (kg/km^2), and that between the cumulative volume of one rainfall (mm) and cumulative load (kg/km^2), obtained at the Hosokawa point with water quality represented as T–N drawn in plots on logarithmic graphs. Rainfall included that exceeding 5 mm per h observed each year. A series of continuous rainfall events is defined as continuous rainfall in excess of 5 mm/h and the absence of rainfall and continuous rainfall less than 5 mm/h over 12 h implied that continuous rainfall had ceased. For the duration of direct runoff due to rainfall, as shown in Fig. 5, runoff caused by one rainfall was represented on the graphs as hourly changes of the flow rate. It was also assumed that rainfall itself had stopped and the duration until the flow rate after the rainfall was restored to the level before the rainfall was assumed to correspond to the duration of direct rainfall. In addition, runoff due to rainfall not clearly recorded was excluded from the study and analysis. The flood caused by one rainfall, obtained as described above, covered wide areas both at the Hosokawa and the Meiji points.

For the relationship between the flow rate, rainfall and its load, as shown in Figs. 2–4, similar results were obtained for T–P at the Hosokawa point and T–N and T–P at the Meiji point. Where these results were considered together with the results obtained in the preceding paragraph, regression by either one of equations (1) – (3) was performed. Thus, coefficients 'a' and 'b' were obtained by the least squares of linear regression (hereafter referred to as the "linear regression equation") using the logarithm of equations (1) – (3). Identification period of the coefficients covered 4 years (1993 to 1996) for the Hosokawa point and 3 years (1992, 1993 and 1996) for

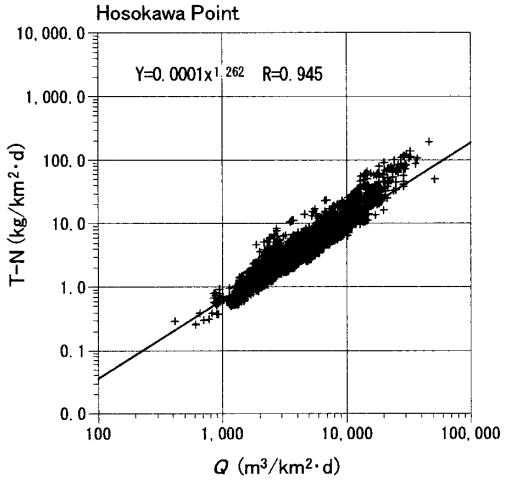

Fig. 2. Relationship between streamflow and T–N storm runoff loading

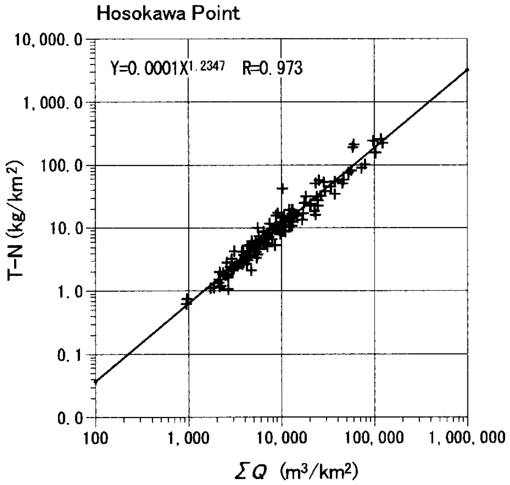

Fig. 3. Relationship between one rainfall cumulative outflow discharge and T–N storm runoff loading

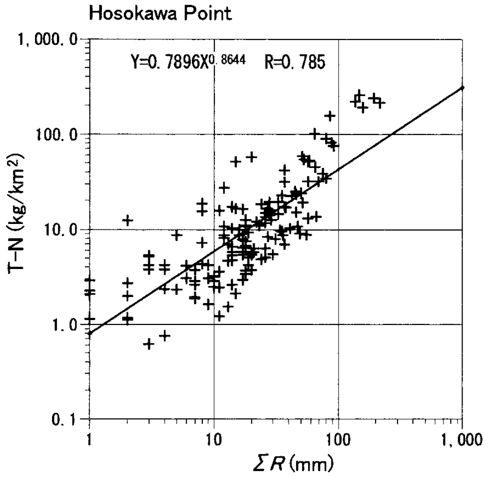

Fig. 4. Relationship between one rainfall cumulative volume and T–N storm runoff loading

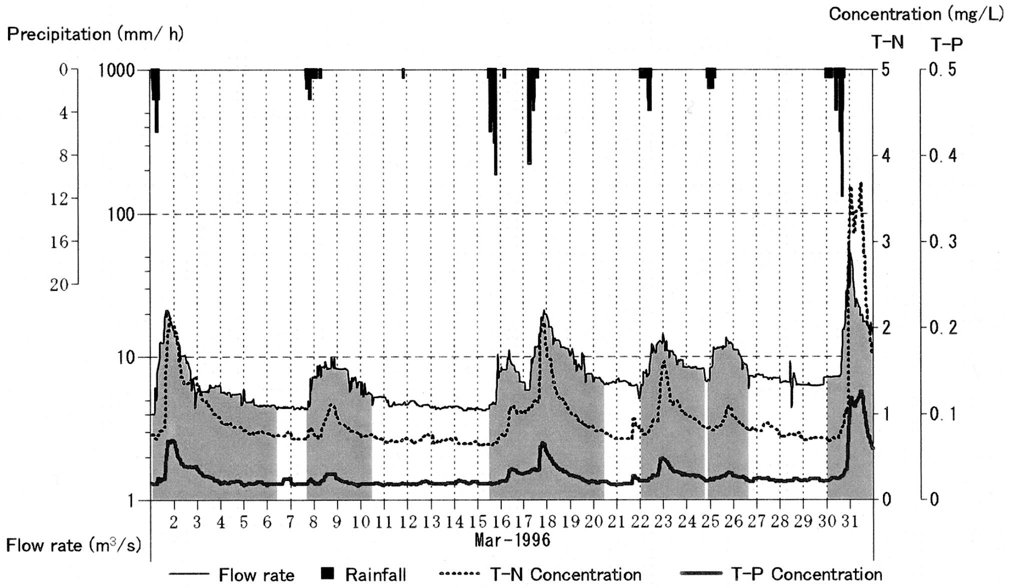

Fig. 5. Rainfall and outflow discharge at the Hosokawa Point

the Meiji point. Table 3 shows the correlation coefficients with estimated figures and measured values (integration by unit-hour of data of flow rate and water quality) based on the model of coefficient and logarithm taken from the regression equations of each model. However, the correlation coefficient tended to decrease in equation $\Sigma L - \Sigma R$, compared with other models. This phenomenon was ascribed to the fact that such relations were represented by the storm runoff loading record at a single observatory station both at the Hosokawa and the Meiji points which have wide drainage basins.

Table 4 shows a comparison between estimated figures and measured values of storm runoff loading during rainfall using each model. The duration of the period for the calculation of the storm runoff loading was equal to the identification period of coefficients both for the Hosokawa and the Meiji points. The highest frequency obtained, compared with the measured values, was based on equation $\Sigma L - \Sigma Q$ for both the Hosokawa and the Meiji points. Equations LQ and $\Sigma L - \Sigma R$ were slightly less accurate than the above equation. The values tended to be underestimated in the range from 0.6 to 0.9 times and 0.60 to 0.65 times of actual measurements, respectively. Figs. 6 and 7 show the relationship between the measured flow rate and the load of river and that between the total precipitation and total runoff loading of one rainfall in plots drawn on linear graphs with the addition of the logarithmic linear format indicated in Table 4. In the equations LQ and $\Sigma L - \Sigma R$, there were significant differences in the relationship between estimated figures and measured values under a high flow rate and heavy rainfall. As a result, it is assumed that the accuracy of the loading estimation using models could have been significantly affected. To address such problems related to the

Table 3. Regression equations and correlation coefficients

Site	Model	$L = aQ^b$		$\Sigma L = a(\Sigma Q)^b$		$\Sigma L = a(\Sigma R)^b$	
		Regression equation	Correlation coefficient	Regression equation	Correlation coefficient	Regression equation	Correlation coefficient
Hosokawa Point	T–N	a: 1.012×10^{-4} b:1.262	0.945	a: 1.248×10^{-4} b: 1.235	0.973	a: 0.790 b: 0.864	0.785
	T–P	a: 1.346×10^{-6} b: 1.385	0.924	a: $2.969\ 10^{-6}$ b: 1.284	0.964	a: 2.51×10^{-2} b: 0.910	0.799
Meiji Point	T–N	a:1.635×10^{-3} b:0.961	0.880	a: 7.791×10^{-4} b: 1.078	0.960	a: 1.042 b: 0.815	0.723
	T–P	a: 0.921×10^{-4} b: 0.911	0.866	a: 3.643×10^{-5} b: 1.057	0.956	a: 4.063×10^{-2} b: 0.815	0.734

Table 4. Comparison between estimated figures and measured values of storm runoff loading (linear regression)

Unit: kg/km^2, %

Estimation method / Gauging Point		Measured values (A)	$L = aQ^b$		$\Sigma L = a(\Sigma Q)^b$		$\Sigma L = a(\Sigma R)^b$	
			Estimation (B)	B/A×100	Estimation (C)	C/A×100	Estimation (D)	D/A×100
Hosokawa	T–N	3,236	2,473	76	3,077	95	1,996	62
Point	T–P	116	102	88	110	95	73	63
Meiji	T–N	2,068	1,326	64	1,957	95	1,359	66
Point	T–P	86	49	57	75	87	54	62

identification of coefficients, the results of the estimation made on coefficients ‘a’ and ‘b,’ obtained by the least squares method of non-linear regression (Gauss and Newton method) are shown in Table 5. Estimated storm runoff loading by the models generally increased, leading to a decrease of significant differences with the measured values on the negative side. Although slight differences were noted on the positive side at the Hosokawa point, the accuracy of the loading calculation results obtained by equations *LQ* and $\Sigma L - \Sigma R$ improved considerably as a whole.

Where the total runoff loading is obtained for a wide range of data including those of large-scale floods described above, it was noted that the logarithmic linear format of equations *LQ* and $\Sigma L - \Sigma R$ tended to cause differences under a high flow rate, suggesting that storm runoff loading could be roughly determined under a high flow rate, even if high correlation coefficients obtained were calculated by linear regression using observation data under a low flow rate.

Meanwhile, although such problems did not occur in the non-linear regression, it was reported that inaccurate regression equations can be obtained by data combinations which lead to unstable regression[3]. Therefore, it is difficult to determine the suitability of both methods based on only the results obtained this time, and it is necessary to consider the effects of the method of determining coefficients ‘a’ and ‘b’ of the models on the accuracy of estimation of the storm runoff loading.

Comparisons were made between the estimated figures and measured values based on the number of measured data (unit-hour). However, it would be possible to estimate the storm runoff loading by equations (1) – (3) for the models with a considerably high accuracy if data that could properly determine the coefficients and the identification method could be used. Equation (3) for the

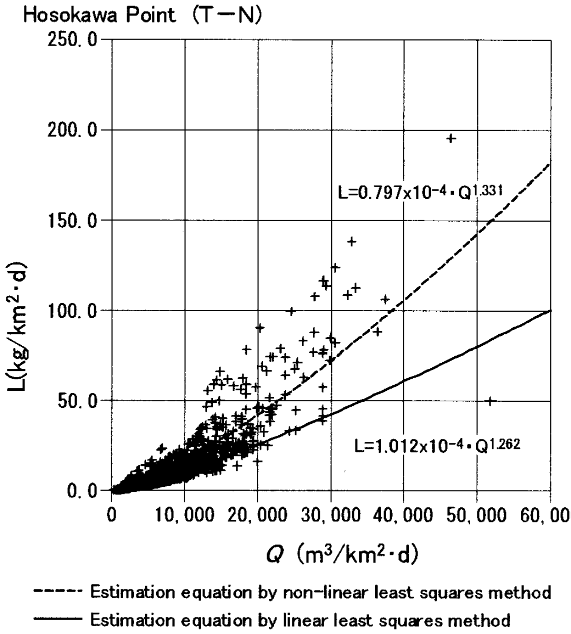

Fig. 6. Relationship between stream flow and storm runoff loading

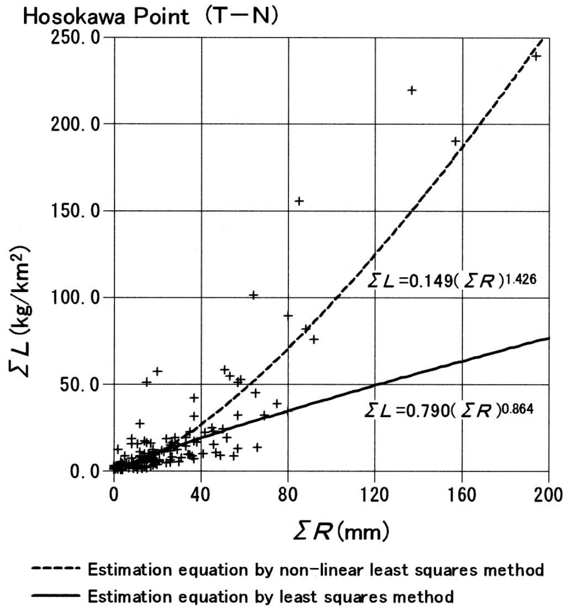

Fig. 7. Relationship between one rainfall cumulative outflow discharge and cumulative storm runoff loading

Table 5. Comparison between estimated figures and measured values of storm runoff loading (non-linear regression)

Unit: kg/km^2, %

Gauging Point \ Estimation method		Measured values (A)	$L = aQ^b$		$\Sigma L = a(\Sigma R)^b$	
			Estimation (B)	B/A×100	Estimation (D)	D/A×100
Hosokawa Point	T–N	3,236	3,403	105	3,489	108
	T–P	116	119	103	146	126
Meiji Point	T–N	2,068	1,922	93	1,848	89
	T–P	86	66	76	67	78

model enables to calculate the load of past discharge if precipitation data are available. For drainage basins of small streams, the applicability was verified by Kunimatsu et al.$^{5)}$. This method could be effective to estimate the load even if highly accurate flow rate data or continuous observation data of large river drainage basins are not available.

Examination of hydrological factors that can affect the storm runoff loading calculation

1) Basic concept of correlation between storm runoff loading and hydrological factors

Hydrological factors related to storm runoff loading are considered with equations (2) and (3) for the models that represent response results of drainage basins to the input of precipitation. Since these models are input as the volume of runoff from a given rainfall and total precipitation as descriptive variables of such models, the average rainfall intensity of the given rainfall, R_t (mm/h); intensity of the preceding rainfall, $R_t(-1)$ (mm/h); storm runoff of the preceding rainfall, $Q(-1)$ (m^3); amount of the preceding rainfall, $R(-1)$ (mm); and preceding dry weather period, D (h) are considered here as hydrological factors. The relationship between these factors and storm runoff loading was obtained by the analysis of the residual value of estimated figures deduced from measured values in each model. That is, the examination was made by analyzing the relationship between the distribution of the residual value and individual factors to determine whether any variables other than those that cannot be described only by ΣR or ΣQ as descriptive variables, were included or not in the variations of the load ΣL.

Here, estimation by the regression equation is as follows:

$$\log(\Sigma\hat{L}) = \log a + b(\Sigma\log Q).$$

The residual value, e, becomes $e = \log\left(\frac{\Sigma L}{\Sigma\hat{L}}\right)$ at

$$e = \log(\Sigma L) - \log(\Sigma\hat{L}).$$

Similarly, the residual value of $\Sigma L = a \cdot (\Sigma R)^b$ becomes $e = \log\left(\frac{\Sigma R}{\Sigma\hat{R}}\right)$.

Figs. 8–12 show the scatter diagrams of the residual values of hydrological factors and ΣL when a correlation was observed at the Hosokawa and the Meiji points.

2) Equation $\Sigma L - \Sigma Q$

At the Hosokawa point, there was a slightly positive correlation between the residual value and R_t unlike for the other factors, suggesting that discharge loading increased as the average intensity of rainfall increased even when rainfall storm runoff loadings were similar. At the Meiji point, the residual value and $Q(-1)$, D showed a slightly negative correlation. Storm runoff loading tended to decrease when storm runoff of the preceding rainfall and the duration of the preceding dry weather period increased even when rainfall discharge loadings were similar.

3) Equation $\Sigma L - \Sigma R$

At the Hosokawa and the Meiji points, there was a slightly negative correlation between the residual value and D. The storm runoff loading tended to decrease with the increase of the duration of the preceding dry weather period even when rainfall discharge loadings were similar. It can be considered that the water retention capacity of the drainage basins increased while runoff decreased when the duration of the preceding dry weather period increased at the Hosokawa and the Meiji points which are widely covered by mountainous areas, even when the rainfall runoff was similar.

Conclusion

Analyses were carried out on hydrological factors that can affect storm runoff loading during rainfall, to compare estimated figures and measured values using

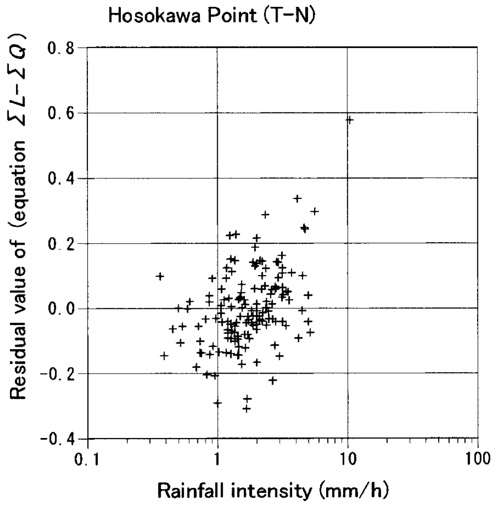

Fig. 8. Relationship between rainfall intensity and residual value

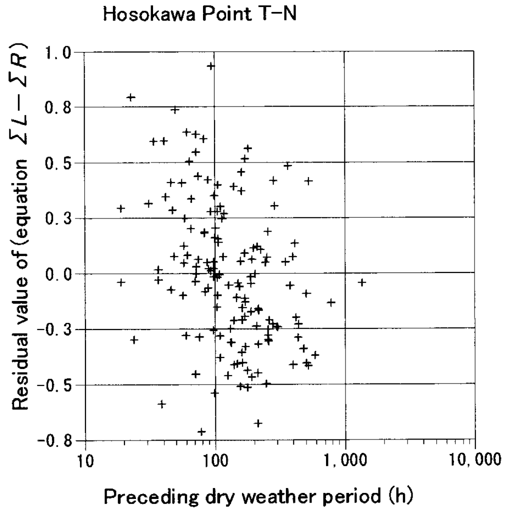

Fig. 9. Relationship between preceding dry weather period and residual value

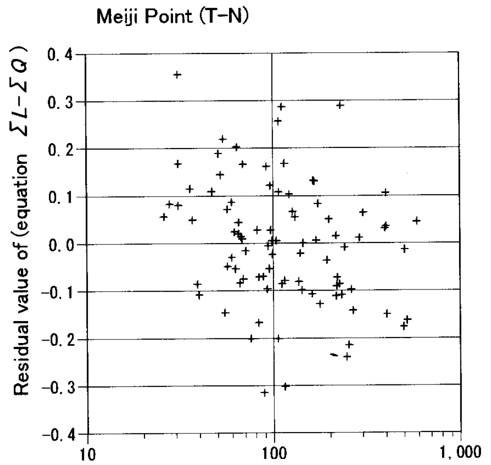

Fig. 10. Relationship between preceding dry weather period and residual value

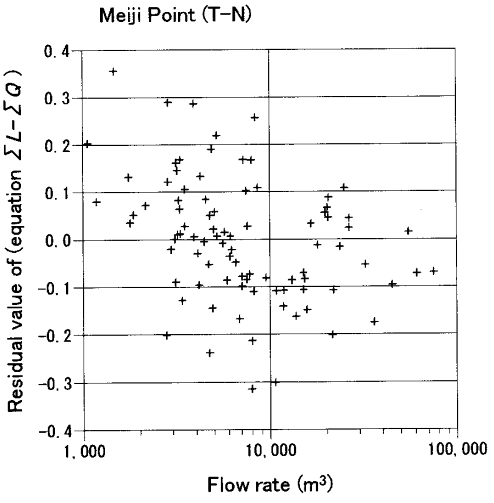

Fig. 11. Relationship between preceding rainfall runoff and residual value

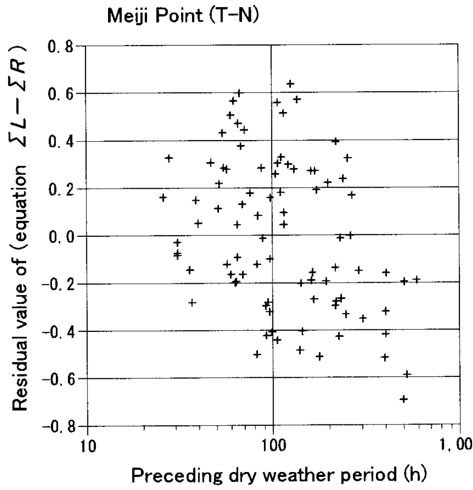

Fig. 12. Relationship between preceding dry weather period and residual value

existing simple models, based on the flow rate and precipitation (unit-hour), and water quality data obtained at the Hosokawa and the Meiji points in the Yahagi River drainage basin. The results of the analyses are as follows.

1) For storm runoff loading during rainfall, estimated figures and measured values were compared in all the models. Values nearly equal to the measured values were obtained by using equation $\Sigma L - \Sigma Q$ when storm runoff loading was calculated by using the coefficients 'a' and 'b' identified by the least squares of linear regression. On the other hand, differences from the measured values tended to increase during large-scale floods if the calculations were made using equations LQ and $\Sigma L - \Sigma R$. It was considered that the estimation accuracy of these models in which differences from the measured values increased

could be improved if runoff loadings were calculated using the coefficients ‘a’ and ‘b’ identified by non-linear regression (Gauss and Newton method). These findings indicated that methods of determining model coefficients can affect the accuracy of the estimation of storm runoff loading even when the quantity and quality of the measurement data obtained were similar.

2) When equation $\Sigma L - \Sigma Q$ was used, there was a negative correlation among the residual values, storm runoff of the preceding rainfall, and dry weather period (at the Meiji point) while there was a positive correlation with the average intensity of rainfall (at the Hosokawa point).
3) When equation $\Sigma L - \Sigma R$ was used, there was a negative correlation between the residual values and the preceding dry weather period both at the Hosokawa and the Meiji points, and storm runoff loading tended to decrease when the duration of the preceding dry weather period increased, even when the total rainfall (runoff) was equal. These findings were attributed to the fact that the volume of runoff decreased, as the storm water retention capacity increased in drainage basins, and storm runoff loading decreased when mountainous areas predominated at the observation points.

Such studies should be further conducted for acquiring a larger number of evaluation data related to storm runoff loading during rainfall to promote water quality preservation in drainage basins through the control and management of runoff loading.

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