Journal of Hydroscience and Hydraulic Engineering
Vol. 18, No.1 May, 2000, 61-71

SYNTHETIC STORAGE ROUTING MODEL COUPLED WITH LOSS MECHANISMS

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SYNOPSIS

Flood runoff analysis by the storage function models normally requires an estimate of the effective rainfall as an input, which is computed by use of runoff coefficient or filtering of runoff-component separations. The present study proposes a new storage routing model that can accommodate a nonlinear relationship between the storage and discharge as well as loss mechanisms.

The model can produce a hydrograph from the observed rainfall instead of using the effective rainfall. The loss mechanisms take accounts of infiltration, evaporation and transpiration from a river basin. An unknown parameter of the loss component is identified at the same time as the other parameters involved in the storage function model. The proposed model has the advantage of the real-time flood forecasting, because the hydrologic data are directly processed.

The model developed in this study was applied to more than 70 flood records from the rivers in Hokkaido. The Newton-Raphson method was used to optimize the model parameters in which the sensitivity coefficients were theoretically derived and the technique of the lower triangular Cholesky factorization was employed to search the optimized values as fast as possible. The results clearly show that the proposed model appears to provide better reproduction of the hydrograph than the model using the hyetograph of effective rainfall patterns.

INTRODUCTION

Storage routing models are frequently used for flood runoff analysis in the following reasons: the models can accommodate a nonlinear relationship between the storage and discharge, their structures are relatively simple and hence the computation is easily carried out. In practical applications to runoff analysis, the storage routing models, however, require a cumbersome data processing in terms of estimating the effective rainfall. Normally, the effective rainfall is obtained by multiplying the observed rainfall by a runoff coefficient, which is again estimated by weighing out the share of direct flood runoff volumes from total runoff ones. It is often said that there is no concrete method for separating direct runoff and base flow components from the observed hydrograph. The direct runoff component significantly varies, depending on different separation methods for base flow, which subsequently affect the final results of runoff analysis.

Nagai *et al.* (9,10) examined the interdependence of the time of concentration, kinamatic wave and storage routing models. Nagai (11) also studied the relationship between a tank model and a storage routing model in which the pre-processed data calculated from the tank model were used as an effective rainfall input of the storage routing model. Recent studies by Tanaka *et al.* (14) and Baba and Hoshi (1) introduced the storage routing models coupled with loss mechanisms. These approaches need no calculation for an effective ration from the total rainfall and thus the observed rainfall can simply be used as input data of the model. It is also unnecessary to separate direct runoff and base flow components because the total runoff is simply used as output data for justifying the physical significance of model parameters.

The present study proposes a new storage routing model in which a nonlinear relationship between the storage and discharge as well as loss mechanisms can easily be incorporated into construction of a model. The model developed was applied to flood records from the Ishikari River basin and several rivers in Hokkaido. Optimized model parameters were processed to formulate the synthetic storage routing model.

OBJECTIVE OF STUDY

Effective rainfall is traditionally described as hydrologic ration in the observed rainfall that has a practical effect on discharge. The remained part is considered as hydrologic loss. This concept is helpful for obtaining better adaptation of the computed hydrograph to the observed one. Direct runoff is also processed by a separation method such as filtering. The observed discharge is largely divided into two hydrologic components such as the long-term base flow and short-term direct runoff. When conducting runoff analysis via use of storage routing models and the above pre-processed data, the optimized model parameters are significantly influenced by the selected methods of pre-processed rainfall and discharge data. Such a processing sometimes causes serious disagreement of the model to the actual hydrograph and uncertainty of the model parameters. For example, no matter what storage routing models may be selected on a real-time flood forecasting, it is almost impossible to carry out the effective rainfall separation in practice.

The objective of the present study is to develop the storage routing model that could directly deal with the observed rainfall and discharge data and to overcome the above-mentioned disadvantages. A subsequent discussion follows a formulation of model, application to historical flood datasets, verification of model, synthetic processing of parameters and practical utilization of model. Datasets used for this study are hourly records of rainfall and discharge obtained from Rank A rivers (national category) managed by Hokkaido Development Bureau and from Rank B rivers managed by Hokkaido Government. The discharges are calculated using the water level-discharge (*H-Q*) relationship at each station.

MODEL EQUATIONS

The storage routing model, which can express the nonlinearity of rainfall-runoff process as well as the hysteresis effect of storage-discharge relationship, produces an excellent agreement between the observed and calculated flood hydrographs (e.g. Civil Engineering Research Institute (2)). The equations of storage routing model are expressed as follows:

$$s_e = k_{1e} q_e^{\,p_1} + k_{2e} \frac{d}{dt}(q_e^{\,p_2}) \tag{1}$$

$$\frac{ds_e}{dt} = r_e - q_e \tag{2}$$

where s_e = storage from effective rainfall (mm); q_e = direct runoff depth (mm/h); r = observed rainfall (mm/h); r_e = effective rainfall (mm/h) ($r_e = f \cdot r$, f : runoff coefficient); and k_{1e}, k_{2e}, p_1, p_2 = model parameters.

Hoshi and Yamaoka (6) converted the kinematic wave equation, which is commonly used in a distributed-parameter model of rainfall-runoff system, into the nonlinear storage routing model and established the linkage between parameters for the two approaches. The synthesized parameters are expressed as

$$k_{1e} = 2.823(n/\sqrt{i})^{0.6} A^{0.24} \tag{3}$$

$$k_{2e} = 0.2835 k_{1e}^{2} \bar{r}_e^{-0.2648} \tag{4}$$

where n = equivalent roughness coefficient; i = average plain slope; and $\bar{r}_e$ = average effective rainfall intensity(mm/h).

Hoshi and Murakami (8) synthesized the parameters in Eqs. 3 and 4, using major flood records obtained in Hokkaido, in addition to hydrologic datasets analyzed by Nagai *et al.* (9). As a result, the value of $(n/\sqrt{i})^{0.6}$ in Eq. 3 had the mean of μ=1.564 and the variance of σ^2=0.430 (Civil Engineering Research Institute (2)). Substitution of the above statistics into Eq. 3 yields

$$k_{1e} = \begin{cases} 2.56A^{0.24} & (\mu - \sigma) \\ 4.42A^{0.24} & (\mu) \\ 6.27A^{0.24} & (\mu + \sigma) \end{cases} \tag{5}$$

A new model incorporating loss mechanisms can be developed by replacing effective rainfall (r_e) and direct runoff (q_e) by the total rainfall (r) and the observed discharge (q), respectively. Then, the new term of loss component is added to the continuity equation as explained below:

$$s = k_1 q^{p_1} + k_2 \frac{d}{dt}(q^{p_2}) \tag{6}$$

$$\frac{ds}{dt} = r - q - p \tag{7}$$

$$p = \alpha q \tag{8}$$

where s = storage given by the total rainfall (mm); p = loss depth (mm/h); and α = parameter.

It is of interest to compare the form of Eq. 7 with that of Eq. 2 that an adjustment involved in the continuity equation is made from the input side to the output one. The physical implication of loss mechanisms can be explained from unsaturated flow theory. Hatta *et al.* (3) transformed an unsaturated flow model including loss mechanisms into the storage routing model.

In general, the loss element appears to include evapotranspiration, infiltration, leaf storage in forest and so on. The loss term in Eq. 7 is structured in a simple linear relation to the discharge, but it could be expressed by a function of the storage. The difference of both equations is negligible as far as the relationship is linear. Baba and Hoshi (1) and Hirasawa *et al.* (4) showed that the storage routing model with the linear loss function in terms of discharge can satisfactorily reproduce the observed hydrograph. Therefore, this study uses the loss term proportional to the discharge. An initial loss of rainfall is considered to be included in the loss term of Eq. 8 and thus the pre-process of rainfall separation is completely removed.

ANALYSIS OF FLOOD DATA

Hydrologic datasets for flood analyses are obtained at gauging stations as listed in Table 1. Main data are collected in the 1975 and 1981 Floods in the Ishikari River basin. In particular, the 1981 Flood was a record-breaking event and caused disastrous damages to the whole region in the basin. The stations in the Toyohira River, which is a major tributary of the Ishikari River and runs through the City of Sapporo, are located at very steep slopes of mountainous reaches and have experienced many flash floods.

The proposed model has five parameters of k_1, k_2, p_1, p_2, and α in which p_1 and p_2 can be set fixed at 0.6 and 0.465, respectively, when Manning's law is used for the surface runoff as given by Hoshi and Yamaoka (6). Therefore, we have to optimize the remaining three parameters to adapt the model to the data. The

Table. 1 Hydrologic dataset for analysis

Rivers	Period of floods	Stations
Ishikari River	1981/8/3-5	Oku Ashibetsu Dam, Uryu #1 Dam, Uryu #2 Dam, Ohyubari Dam, Inou, Asahibashi, Nagayama, Nakaaibetsu, Akatsukibashi, Eoroshi, Nishikagura, Nishiikku, Nunobe, Sakuraoka, Rubeshibe, Ishikariohashi, Iwamizawaohashi, Tsukigataohashi, Naieohashi, Hashimotocyo, Moseushi, Osamunai, Nishikawamukai, Kiyohorobashi, Maruyama, Akabira, Uryubashi, Tadoshi, Horokanai, Ohobashi, Kariki, Ishiyama
Ishikari River	1975/8/22-25	Daisestu Dam, Hoheikyo Dam, Katsurazawa Dam, Kanayama Dam, Takadomari Dam, Nokanan Dam, Oyubari Dam, Toyama Dam
Mukawa	1992/8/9-10	Hobetsu
Wattsu River	1972-1986	Wattsu (13 records)
Toyohira River	1996/9/18	Johzankei
Toyohira River	1994-1996	Ananokawa (7 records), Okabarushi (7 records), Nonosawa (7 records)

Newton-Raphson method was used to optimize the model parameters in which the sensitivity coefficients were theoretically derived.

Typical application examples of rainfall-runoff analysis are shown from Fig. 1 to Fig. 4 in accordance with different sizes of drainage area. The results show that the proposed model appears to provide superior reproduction of flood hydrographs from small to large drainage areas. Hirasawa *et al.* (4) has compared the same model as presented herein with the one using pre-processed effective rainfall and proved that the former is in better agreement with the observed flood hydrograph than the latter.

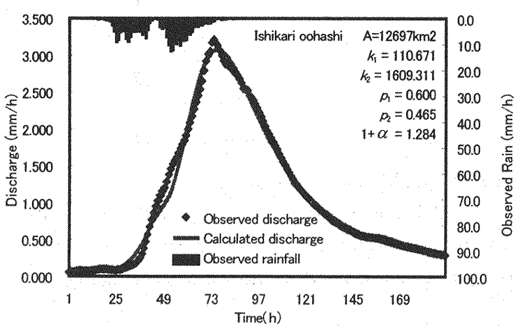

Fig. 1 Example in large-scale watershed.
Ishikari oohashi, Ishikari River, A=12,697km^2

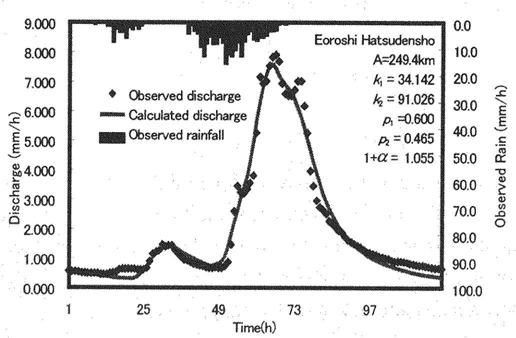

Fig. 2 Example in medium scale watershed.
Eoroshi, Chubetsu River, A=249.4km^2

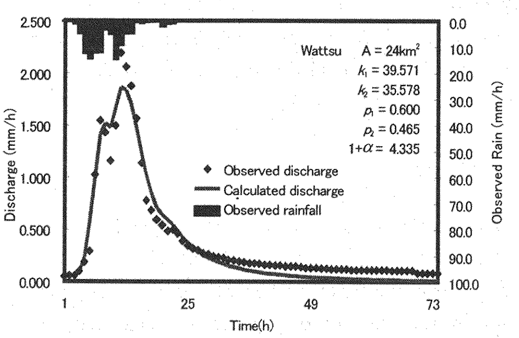

Fig. 3 Example in small-scale watershed.
Wattsu, Chitose River, A=24km^2

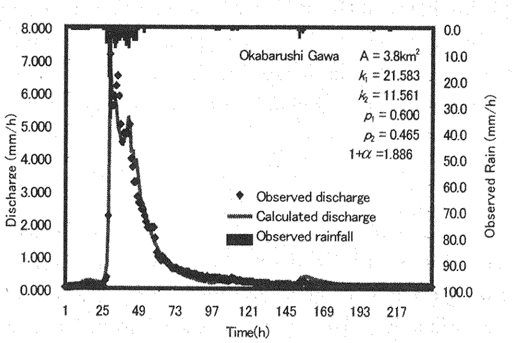

Fig. 4 Example in very small-scale watershed.
Okabarushi, Toyohira River, A=3.8km^2

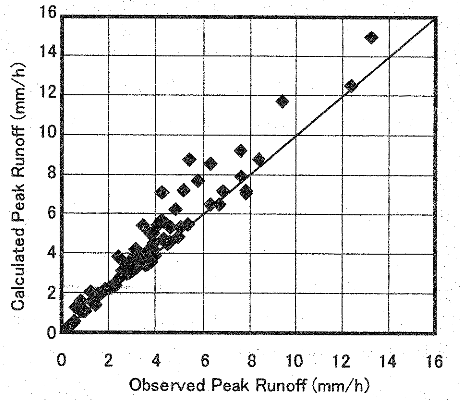

Fig. 5 Comparison between the calculated and observed flood peaks

Fig. 5 shows the difference between the calculated and observed peak values. For relatively bigger floods, the calculated flood peaks are larger than the observed ones in some cases, but this gives a safer design forecast. The reproduction of peak values is totally satisfactory.

SYNTHETIC MODEL PARAMETERS

In order to build the synthetic storage routing model, the optimized parameters of the model are statistically correlated with rainfall and geomorphologic characteristics of the basin. The relationship between parameter k_1 and drainage area A is synthesized as shown in Fig. 6 in which the regression line is obtained by using least-square approach and has the form of Eq. 9. The power value of A is held fixed at 0.24 in order to maintain the same objective implication as in Eq. 3.

$$k_1 = 11.62A^{0.24} \tag{9}$$

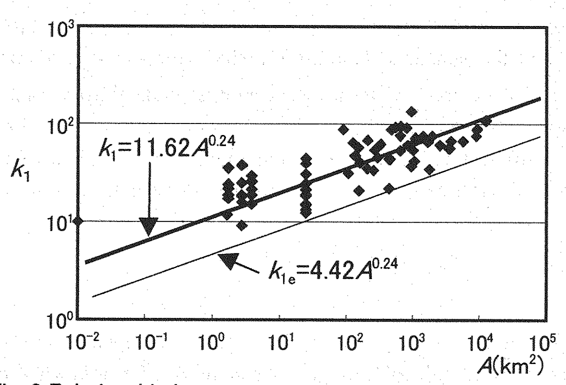

Fig. 6 Relationship between parameter k_1 and drainage area A

The relation of $k_{1e} = 4.42A^{0.24}$ as given in Eq. 5, when using effective rainfall and direct runoff, is also plotted in Fig. 6. It follows from the results in Fig. 6 that the coefficient of parameter k_1 with loss mechanisms is larger by 2 to 3 times than the one using effective rainfall and direct runoff. It is coincident in the present application that the runoff coefficient of pre-processed flood data approximately ranges from 1/3 to 1/2.

Furthermore, the degree of dispersion in terms of parameter k_1 in both models using effective rainfall and loss mechanisms is almost the same as explained in Eq. 5 and plotted in Fig. 6.

The relationship between parameters k_2 and k_1 is shown in Fig. 7. The regression line is determined by Eq. 10 in which the power value of k_1 is set fixed at 2 as the same implication of Eq. 4. When the power value of k_1 is not restricted, a corresponding regression equation is expressed as $k_2 = 0.1292 k_1^{1.709}$

$$k_2 = 0.0593 k_1^{2} \tag{10}$$

The parameter k_2 in Eq. 4 contains the parameter k_1 as well as the average effective rainfall intensity $\bar{r}_e$. For maintaining the same type of synthetic equations, the optimized parameters from the observation station with different flood records have been processed statistically. As an application example, a synthetic equation for parameter k_2 in the Wattsu River (see Table 1) is demonstrated by Eq. 11. The relationship between k_2 and k_1 involving the average rainfall intensity is shown in Fig. 8.

$$k_2 = 0.1706 k_1^{2} \bar{r}^{-0.8235} \tag{11}$$

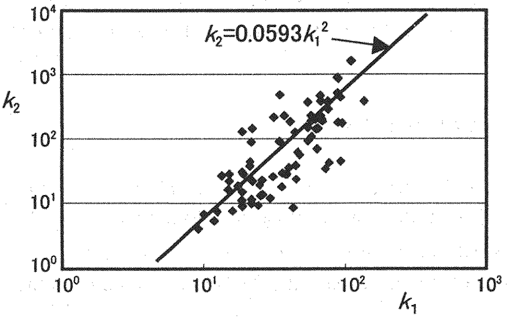

Fig. 7 Relationship between k_2 and k_1

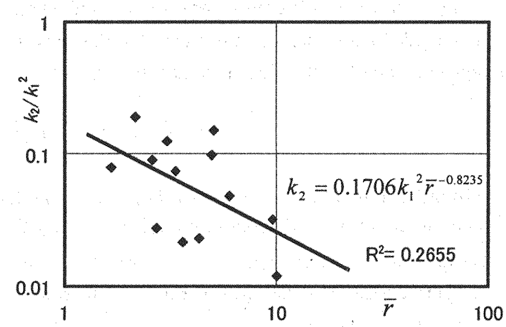

Fig. 8 Relationship between k_2 / k_1^2 and average rainfall intensity

It is worth noting that the parameter k_2 in Eq. 10, which includes k_1 only, is helpful for operational forecast because it is advisable to exclude unstable variables such as average rainfall intensity in real-time computations. On the other hand, the parameter k_2 in Eq. 11, which contains k_1 and rainfall intensity, is useful for design forecast because it can take account of the design event magnitude of hyetograph.

An attempt is made to examine the relationship between the loss parameter α, effective rainfall and direct runoff. Let f be the runoff coefficient defined by the ratio of total direct runoff volume to the total rainfall one. If β is defined as the ratio of direct runoff depth to the total runoff depth at each time step, Eq. 2 can be transformed into the following form:

$$\frac{ds_e}{dt} = fr - \beta q \tag{12}$$

The quantity of s in Eq. 7 is the storage yielded by the total rainfall input. Both sides of Eq. 7 multiplied by f should equal to the right-hand side of Eq. 12. As a result, the following relationship should be maintained between α, f and β:

$$\frac{1}{1+\alpha} = \frac{f}{\beta} \tag{13}$$

Equation 13 clearly shows that the loss parameter α is explicitly explained by the two coefficients of f and β which result from the computations of effective rainfall as well as direct runoff. In order to justify the relation of Eq. 13, the optimized value of $1/(1+\alpha)$ is plotted against f/β which was calculated from the effective rainfall and direct runoff. Such results are reported in Fig. 9. The coefficient β changes from time to time by definition. However, for the results shown in Fig. 9, the value of β was approximated by simply dividing the total direct runoff volume by the total runoff one in a flood hydrograph. The separation between the direct runoff and base flow components was made by the standard method as follows: the base flow portion is below the line connecting the rising point of flood with the second bending point in the recession limb of the hydrograph on a semi-logarithmic paper.

As shown in Fig. 9, most values with respect to loss parameter $1/(1+\alpha)$ are distributed within $\pm 20\%$ of the estimated values using the information of effective rainfall and direct runoff. It is therefore expected that the newly established model can reproduce the same result as the traditional method that needs pre-processing of data.

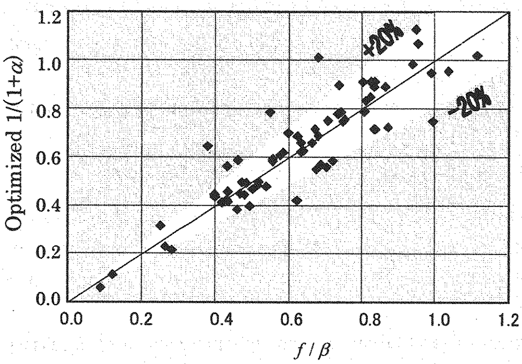

Fig. 9 Relationship between $1/(1+\alpha)$ and f/β

Suppose that the value of β is constant throughout the flood period. Then, Eq. 13 reduces to

$$\frac{1}{1+\alpha}=\frac{f}{\beta}\cong\frac{Q}{R} \tag{14}$$

where Q = total runoff depth (mm); and R = total rainfall amount (mm).

Equation 14 clearly indicates that the parameter α can easily be estimated from the observed hydrologic data without any pre-processing such as separation of rainfall or runoff. Furthermore, the estimate of this parameter together with the synthesized parameters k_1 and k_2 can be incorporated into the storage routing model to make optimization simultaneously. However, the results in Fig. 9 imply that the parameter α is not perfectly determined by Eq. 14. Therefore, the geological information is added to Eq. 14 to increase the accuracy of calibration. The factors, which may have an influence on runoff and loss mechanisms, are classified as follows:

Evapo-transpiration: Mainly dominated by vegetation, land cover and climatic conditions (temperature, humidity, wind and so on). Seasonal variations are comparatively large.

Infiltration: Mainly dominated by vegetation, land cover, geological condition and morphological condition. Seasonal variations are relatively small.

Other losses: Composition of storage in forests and consumptions by habitats, irrigation, industrial and public water use, diverted water flow or other interventions.

Among these factors, the conditions of land cover in the river basin, which are highly connected with all of the above classifications, have the most important impact on hydrologic conditions and loss mechanisms. Therefore, the new term is introduced in Eq. 14 to parameterize the conditions of land cover in the basin. The resulting calibration expression is given by

$$\begin{cases} \dfrac{1}{1+\alpha} = \phi_0 \dfrac{Q}{R} + E \\ E = \phi_A L_A + \phi_B L_B + \phi_C L_C + \phi_D L_D \end{cases} \tag{15}$$

where L_A, L_B, L_C and L_D = predictors corresponding to the percentage proportion rate of land covers classified from A to D as listed below, respectively; and $\phi_A, \phi_B, \phi_C, \phi_D$ = weighting coefficients for respective predictors. The coefficient ϕ_0 involved in Q/R is also introduced to compare the degree of contributions among the predictors. Equation 15 has no constant term because the sum of L_A, L_B, L_C and L_D has to become 1. Hokkaido Development Bureau (5) has issued the list of land cover codes in the Ishikari River basin. Based on this information, the conditions of land cover are classified into the following four groups:

A: Area of large loss = forest, bamboo grass (land cover code =1 to 108)
B: Area of small storage = cultivated land, cattle farm, grassland, natural bare ground, golf course (109 to 113, 124)
C: Area of small loss = residential area, urban area, airport, factory zone, developed yard (114, 119 to 122)
D: Area of large storage = rice field (115), open water (123)

The dataset used for the above classifications is collected from the third mesh data of land cover contained in the Ishikari River Landscape Information (5). The data are based on the survey of vegetations conducted by the Environment Agency in 1979 and from 1983 to 1986. The survey periods match with the time when flood data were analyzed.

In order to reflect the effect of land covers on loss mechanisms, it is necessary to eliminate the effect of seasonal fluctuations of evapo-transpiration and changes in meteorological conditions, which has much influence on loss mechanisms. For this reason, a large number of flood data should be selected in situations where floods occurred in the same period of time. As a result, 27 flood data at different stations in the Ishikari River basin were chosen in August 1981. The datasets of the above flood are large enough to synthesize the model parameters, but it is difficult to consider the effect of evapo-transpiration in the current study. The analysis in different seasons and under different meteorological conditions is remained for future studies.

Component regression analysis (Hoshi (7)) was applied to Eq.15 to orthogonalize correlated variates in a regression line. The multiple regression coefficients, standard errors and contribution coefficients are listed in Table 2. A multiple correlation coefficient is 0.911. The result indicates that the parameter α is determined mainly by the Q/R, secondarily by the proportion of urban area, but other classes of land cover are not significant. The land covers of rice field and open water have almost no effect on the parameter α. When comparing the regression coefficients between different land cover proportions, it is obvious that the proportion of urban area could most sensitively affect the loss parameter α. If the proportion of urban area increases, the parameter α will decrease. However, the standard error in terms of the urban area is also comparatively high at the same time.

Table. 2 Result of component regression analysis

Predictor	Regression coefficient	Standard error	Contribution coefficient (Standard partial regression coefficient)
Q/R	$\phi_0 = 0.9277$	0.1098	0.8959
L_A (forest etc.)	$\phi_A = 0.0633$	0.0670	0.0434
L_B (cultivated etc.)	$\phi_B = 0.0920$	0.2163	0.0395
L_C (urban etc.)	$\phi_C = 1.2451$	1.0281	0.1131
L_D (rice field etc.)	$\phi_D = -0.0264$	0.3228	-0.0101

Figure 10 depicts the comparison between the calibrated and optimized values of parameter α, using regression analysis of Eq. 15. Except for the two cases that α exceeds 1.3, the loss parameter α can be predicted by Eq. 15 with acceptable accuracy. When the model is used for the real-time flood forecasting, Q and R could be replaced by the accumulated values of discharge and rainfall, respectively up to the present time for the estimation of parameter α.

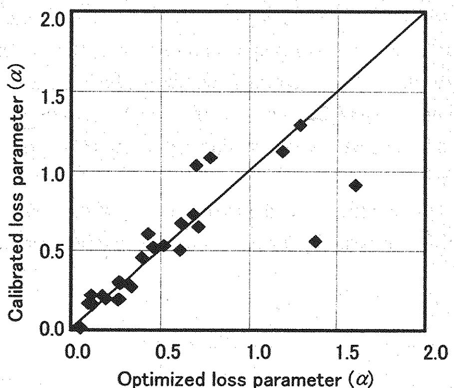

Fig. 10 Relationship between the calibrated and optimized loss parameters

DISCUSSION

The parameters of the storage routing model are highly variable according to whether the input to the model is the effective rainfall or the observed rainfall. As reported in Fig. 6, the storage routing model coupled with loss mechanisms yields the larger value of parameter k_1 than it does with the effective rainfall. Equation 1 was derived by converting the kinematic wave method to the storage routing model. When the surface flow satisfies Manning's friction law, the parameter k_1 is given by Eq. 3. This indicates that if the effective rainfall is given, the flood peak will become larger and the time to peak will be earlier with smaller friction factor $(n/\sqrt{i})^{0.6}$

On the other hand, for the case where the observed rainfall is an input to the proposed model, a portion of rainfalls is consumed to the loss depth, αq. To counterbalance with the same value of the direct runoff from effective rainfall, the parameter $(n/\sqrt{i})^{0.6}$ must be spuriously high in the proposed model. In the case where the model uses effective rainfall, the storage is determined by the effective rainfall only. However, the remained portion of rainfall, which is cut from the observed value, has a considerable impact on the storage through the process of evapo-transpiration, infiltration and other losses in real situations.

When the proposed storage routing model coupled with loss mechanisms is applied to flood runoff analysis, the total rainfall is distributed over the storage and loss simultaneously. The new model can remove the disadvantage of the traditional method in which the results of runoff analysis largely vary, depending on what separation methods are employed to obtain direct runoff and effective rainfall. Another merit of the proposed model is that the model parameters can simply be optimized without methodological bias and can be objectively evaluated as characteristic parameters that reflect river system's attribute. For example, Sasaki *et al.* (13) have illustrated a chronological change of the model parameters according to the urbanization of the Wattsu River catchment.

CONCLUSION

The present study has developed a new storage routing model that can accommodate a nonlinear relationship between the storage and discharge as well as loss mechanisms. Several loss elements involved in the rainfall-runoff system were parameterized by one parameter defined as α. The method is also presented for estimation of the parameter α from the observed hydrologic data and the land cover conditions. The proposed model can be extended for use of operational flood forecasts in which on-line estimations of parameter α can be performed. The model can also be improved by integrating the unsaturated flow model so that hysteresis effects of easy infiltration under dry conditions and tough infiltration under wet conditions can be incorporated in the model.

Saga *et al.* (12) introduced the loss mechanisms in a two-cascade storage routing model and found that the model provides an improved accuracy in hydrograph reproduction. When comparing the results from limited applications of the model by Saga *et al.* (12) and the model herein, both models reproduced almost the same flood peaks. It is easily understood that the simpler model with a single storage routing proposed by this study could practically be applied to runoff analysis with satisfactory accuracy, especially for river catchments with inadequate hydrologic information.

Further studies are needed to refine the equations for synthetic model parameters, which have been developed mainly in the Ishikari River basin, by increasing hydrologic information in many other river basins.

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APPENDIX - NOTATION

The following symbols are used in this paper:

A	=	drainage area (km^2);
f	=	runoff coefficient;
i	=	average plain slope;
k_1, k_2	=	storage coefficients using total rainfall;
k_{1e}, k_{2e}	=	storage coefficients using effective rainfall;
L_A, L_B, L_C, L_D	=	predictors corresponding to the percentage proportion of land covers;
n	=	roughness parameter;
p	=	loss depth (mm/h);
p_1, p_2	=	exponents in the storage routing model;
q	=	runoff depth (mm/h);
q_e	=	direct runoff depth (mm/h);
Q	=	accumulated runoff depth (mm);
r	=	observed rainfall (mm/h);
r_e	=	effective rainfall (mm/h);
$\bar{r}_e$	=	average effective rainfall intensity (mm/h);
R	=	accumulated rainfall (mm);
s	=	storage (mm);
s_e	=	storage using effective rainfall (mm);
α	=	loss coefficient;
β	=	ratio of the direct runoff to the total runoff observed; and
$\phi_A, \phi_B, \phi_C, \phi_D$	=	multiple regression coefficients involved in the respective predictors

(Received October 27, 1999 ; revised January 28, 2000)