Development of an Event Rainfall-Runoff Model in Small Watersheds

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ABSTRACT : A linear reservoir rainfall-runoff system was developed as a rainfall-runoff event simulation model. It was achieved from large modification of runoff function method. There are six parameters in the model. Hydrologic losses consist of some quantity of initial loss and some ratio of rainfall intensity followed by initial loss. The model has analytical routing equations. Hooke and Jeeves algorithm was used for model calibration. Parameters were estimated for flood events from '84 to '89 at Seomyeon and Munmak stream gauges, and the trends of major parameters were analyzed. Using the trends, verifications were performed for the flood event in September 1990. Because antecedent rainfalls affect initial loss, future researches are required on such effects. The estimation method of major parameters should also be studied for real-time forecasting.

1. Introduction

A rainfall-runoff event simulation model was proposed in this paper. It is major characteristics of the rainfall-runoff model that the model has analytical routing equations, it is composed of linear reservoirs through parallel and serial combinations, and is a lumped parameter model. We focused on the simplicity of the model structures and efficiency in simulations because it should constitute a sub-component of a multi-reservoir operation model (Lee, 1993).

As the model is achieved from large modification of Japanese runoff function method, it was compared with runoff function method for a flood event in the model building procedure. It is also compared with Japanese storage function method in an application result.

Before taking up the main subject, it is required to illustrate the term, "small watersheds" used in this paper. Ponce (1989) classified watersheds on the basis of characteristics of rainfall and runoff. According to his proposal, the following characteristics describe a small catchment: (1) rainfall can be assumed to be uniformly distributed in time and space; (2) storm duration usually exceeds con-

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centration time; (3) overland flow primarily forms runoff and channel storage processes are negligible. A mid-size catchment is defined by the following characteristics: (1) a rainfall intensity varies within the storm duration; (2) runoff can be assumed to be governed by overland flow and channel flow, but channel storage processes are negligible.

For large catchments, rainfall is likely to vary spatially as well as in time. Another important feature of large catchments that depart them from mid-size catchments is their substantial capability for channel storage.

This work used watersheds whose areas cover 1,000 km^2 or so. Thus rainfall varies spatially and temporarily, but channel storage is not likely to be important as the watersheds located in mountainous region. According to the definition by Ponce, those watershed characteristics pass the limit of those of mid-size catchments. However, the rainfall-runoff model was developed so that it may be applied to tributaries of the Han River basin whose area is about 26,200 km^2. Each tributary occupies small portion of the whole Han River basin. Thus, although the watershed used in this work is likely to be classified into a large size catchment, the term of "small watershed" used in this paper has opposite meaning against the large Han River basin.

2. Development of a Rainfall-Runoff Model

There are lots of rainfall-runoff models around the world. American and Japanese models served as a good reference to the establishment of rainfall-runoff relationship for this research. First of all, the concept of soil zones became basis to build model structures on which American rainfall-runoff models are based. Famous SWM-Ⅳ and many revised versions divide a soil mass into three layers: upper zone, lower zone, and deep groundwater storage zone. The upper and lower zones account for overland flow, infiltration, interflow, and outflow to groundwater storage, and they represent rapid rainfall-runoff relations. The deep groundwater storage zone supplies baseflow to stream channels. It represents water storage phenomena on the deep portions of the bulk of a soil mass, and delayed runoff processes. Japanese tank model also expresses soil zone concepts with several hypothetical tanks.

Conceptual reservoir theory made another fundamental notion in the development of this rainfall-runoff model. Japanese storage function method and runoff function method also use linear or nonlinear reservoirs. However, they are event simulation models and do not use soil zone concepts.

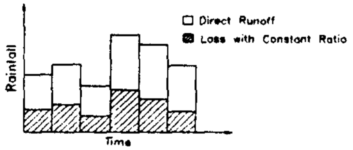
2.1 Hydrologic Abstractions

A catchment has abstractive capability that acts to reduce total rainfall into effective rainfall. The difference between total rainfall and effective rainfall is the hydrologic abstraction. Thus, it is an important process to be treated in rainfall-runoff relations. There are many kinds of methods to compute hydrologic abstractions: infiltration formulas, Soil Conservation Service method, constant loss rate (mm/hr), constant loss ratio (dimensionless), etc. Infiltration indexes, for example Φ-index method, assume that infiltration rate is constant throughout the storm duration and can be classified into constant loss rate method. On the other hand, loss ratio means areal proportion contributing hydrologic loss.

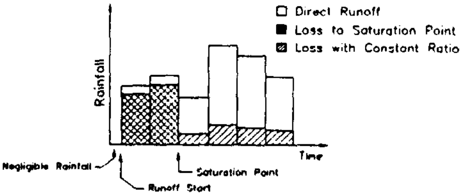
Engineers have used infiltration formulas such as Horton, Plilip, Holtan, and Green-Ampt, etc. However, they require iterations to determine future infiltration rates. Constant loss rate method is a typical one that constantly infiltrates throughout the storm duration. While it is very simple, it can hardly be related with soil zone concepts. Japanese models have frequently used constant loss ratio. They assume that hydrologic loss occurs in some region with a constant proportion to the total area, then the rainfall precipitated into the other region contribute to runoff. Detailed descriptions of Japanese models are as follows.

Runoff function method divide rainfall intensity into two portions with constant ratio and each proportion contributes to loss or runoff (see Fig. 1(a)). Storage function method uses initial runoff ratio and saturation runoff ratio. When rainfall starts, runoff occurs just in the runoff region whose area amounts f_1A (f_1: initial runoff ratio, A: catchment area). Therefore, precipitation loses at the ratio of $(1-f_1)$ in rainfall intensity (mm/hr). When cumulative rainfall exceeds saturation amount, R_{sa}, an infiltration region as well as a runoff region contribute to runoff with a constant ratio, f_{sa}. Thus, loss occurs with the ratio of $(1-f_{sa})$ in rainfall intensity (see Fig. 1(b)).

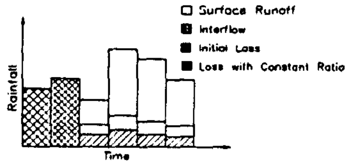
This work also used constant loss ratio to simplify the model structures. In addition, we divide rainfall intensity with another parameter of runoff ratio, which represents interflow proportion in rainfall. That is, after a cumulative rainfall exceed some amount of initial loss, they contribute to



(a) Runoff Function Method



(b) Storage Function Method



(c) This Research

Fig. 1. Hydrologic Losses and Contribution of Rainfall Intensity

three components: one is surface runoff, another interflow, and the other become loss (see Fig. 1 (c)).

2.2 Linear Reservoir Rainfall-Runoff System

Total runoff is generally assumed to be composed of direct runoff and groundwater flow. Direct runoff also is divided into surface runoff and interflow. If one significantly treats all the three constituents, model structures become very complex. However, this work has focus on a simulation model of flood events. Thus, simplification was performed in the determination of model structure.

SWM-Ⅳ is a continuous simulation model and its structure is widely accepted by many revised versions of American runoff simulation models. It calculates total runoff with three runoff components. Japanese tank model can simulate continuous rainfall-runoff relations with a standard tank system that has four tanks in series and simulates three runoff components (Sugawara et al., 1984). Lower two tanks simulate groundwater flows and it has very similar structure to SWM-Ⅳ that simulate groundwater flow with lower and deep groundwater zones. Those models have complex structure because they should account groundwater component as major one in total runoff.

While USGS model can continuously simulate runoff, its main purposes are estimation of peak runoff and runoff volume. Thus groundwater component is accounted by simple input data (Viessmann et al., 1989) and surface runoff takes major runoff computation (Dawdy et al., 1972). By simple arrangement of two or three tanks, tank model can be applicable to flood events, too. HEC-1 calculates only two runoff components, direct runoff and baseflow. The baseflow is calculated by recession curve from start of a flood event to some point whose discharge amounts to 5-15 % of peak discharge. After that point, new recession curve starts with the discharge at that point.

It is very difficult for us to estimate the volume of groundwater runoff in a flood hydrograph but we can guess indirectly the amount through related research results. For example, the "time constant" is a good reference, used in tank model. Its definition is the time that is needed to deplete some amount of storage in a simple tank, discharging out continuously and constantly with initial rate. Each tank has the following values in a standard tank system: first tank has the time constant of one or several days, second tank ten days, third tank several months, and the last fourth several years.

The previous review gives a direction in the determination of rainfall-runoff structure that the groundwater flow does not have significant meaning in a flood event simulation and can be treated simply. As flood events have very short duration of 3~5 days in Korea, the contribution of groundwater is far smaller. Therefore, it does not give large errors to express groundwater contribution only with recession curves. Although groundwater component occupies somewhat larger portion in the latter part of a flood hydrograph in reality, its effect can be included into the interflow component to simplify the model structure. From the above discussions, we determined runoff components to be simulated with the three elememts: surface runoff, interflow implying some groundwater, base flow by recession curves. Followings are detailed descriptions of the model.

When rainfall exceeds interception and surface storage, it infiltrates into the ground and fills voids of a soil mass. That volume is very significant and plays a major role in hydrologic loss at the early period of a rainfall event. This work used a parameter IL (initial loss) to express the above complex loss processes in the early stage (see Fig. 2). The model assumes that runoff does not occur till exceeding point of initial loss. Once cumulative rainfall becomes greater than initial loss, the proportion of F1 in rainfall intensity contributes to surface runoff. That amount is routed through two identical linear reservoirs with storage coefficient K1.

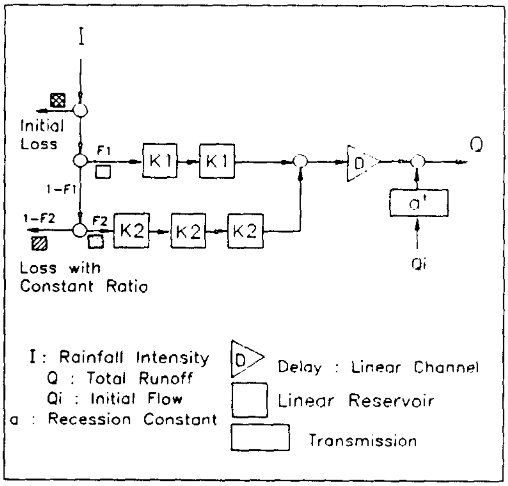


Fig. 2. Conceptualization of Linear Reservoir Rainfall-Runoff System

Interflow is modeled by two parameters. First, the remaining portion in rainfall intensity, subtracted by surface runoff component, is divided into two parts, the proportion of F2 × (1-F1) and (1-F2) × (1-F1). The former will result in interflow and the latter will make another hydrologic loss that includes evapotranspiration at upper zone and percolated water into deep groundwater zone. Interflow component is routed through three identical linear reservoirs with storage coefficient K2. After surface runoff and interflow are routed and made into one, delaying effect is added to it with linear channel. LAG is the parameter of linear channel that has the unit of hours. Through the above routing procedure, three components make the total runoff at a catchment outlet: surface runoff, interflow, baseflow by recession curves.

Singh and McCann (Singh, 1988) have studied on the determination for the number of linear reservoirs in a rainfall-runoff modeling. Estimating parameters with the method of moments, they proposed that it is difficult to improve model accuracy with the use of linear reservoirs more than three. They explained the reason that higher moments are sensitive to errors in effective rainfall and direct runoff.

2.3 Derivation of Rainfall-Runoff Equations

Performing convolution integral between two rainfall components and their unit hydrographs from two or three identical linear reservoirs, we can derive routing equations for surface runoff and interflow. First, each instantaneous unit hydrograph (IUH) should be derived, and then unit hydrographs are made from IUHs. Finally, routing equations can be written in terms of unit hydrographs.

2.3.1 Derivation of IUH

Catchment responses can be mathematically expressed by the following storage equation for a linear reservoir and continuity equation.

$$S = Kq \tag{1}$$

$$i - q = dS/dt \tag{2}$$

where $i(t)$ = rainfall input; $q(t)$ = runoff; $S(t)$ = storage; t = time; and K is a parameter. We assume that K is dependent on rainfall intensity and can vary on time, but we use constant value of K for a specific flood event. Eliminating S in Eqs. (1) and (2), the following equation is derived.

$$i - q = K\, dq/dt \tag{3}$$

Taking Laplace transformation of Eg. (3), we obtain:

$$(Ks+1)\, Q(s) = I(s) \tag{4}$$

By the inverse Laplace transformation with initial condition, $q(0)=0$, the IUH, u_1, for a single linear reservoir is derived as follows:

$$u_1(t) = u(t) = L^{-1}\{1/(Ks+1)\} = (1/K)\, L^{-1}\{1/(s+1/K)\} = 1/K\ e^{-t/K}\ (t \geq 0) \tag{5}$$

When two or three linear reservoirs are serially combined, the IUHs, u_2 or u_3 can also be derived as follows:

$$u_2(t) = u(t) * u_1(t) = 1/K\ (t/K)\ e^{-t/K} \tag{6}$$

$$u_3(t) = u(t) * u_2(t) = 1/K\ (t/K)^2 (1/2)\ e^{-t/K} \tag{7}$$

where the symbol, $*$ denotes a convolution integral.

2.3.2 Routing Equations

As hourly rainfall data are generally available in a hydrologic measurement system, routing equations were derived upon hourly base. One hour unit hydrograph(UH), which is the impulse response function of a cascade of two identical linear reservoirs with parameter K1, can be derived from Eq. (6) as:

$$U_2(t)=\int_{t-1}^{t}(\tau/K1^2)\exp[-\tau/K1]\,d\tau$$
$$=[(t-1)/K1+1]e^{-(t-1)/K1}-[t/K1+1]e^{-t/K1} \tag{8}$$

Putting dU_2/dt to zero, we obtain the following expression for the time to peak (T_p):

$$T_p=e^{1/K1}/(e^{1/K1}-1) \tag{9}$$

Using an hourly integer index, i instead of the continuous variable, t in Eq. (8), and redefining t as a discrete time variable, we can get the following equation for discrete convolution integral between $U_2(i)$ and effective rainfall P_i ($i=1, 2, \cdots\cdots$):

$$q_2(t)=\sum_{i=1}^{t}P_{t-i+1}\{[(i-1)/K1+1]e^{-(i-1)/K1}-[i/K1+1]\,e^{-i/K1}\} \tag{10}$$

After cumulative rainfall exceeds initial loss IL, surface runoff occurs from rainfall amount P(i) that is formed from rainfall intensity r (cm/hr) multiplied by surface runoff ratio F1. If we define $q_2(t)$ as the surface runoff function from unit area, we can derive the routing equation for surface runoff from total area:

$$Q_2(t)=2.7778\ F1\ A\sum_{i=1}^{t}r_{t-i+1}\{[(i-1)/K1+1]e^{-(i-1)/K1}-[i/K1+1]\,e^{-i/K1}\} \tag{11}$$

Interflow component is routed through three identical linear reservoirs with parameter K2. To account that component, we derived one hour UH from Eq. (7) as follows:

$$U_3(t)=\int_{t-1}^{t}(\tau^2/2K2^3)\exp[-\tau/K2]\,d\tau$$
$$=(1/2)[\{t^2/K2^2+2(1/K2-1/K2^2)t+1/K2^2-2/K2+2\}e^{-(t-1)/K2}-\{t^2/K2^2+2t/K2+2\}e^{-t/K2}] \tag{12}$$

Similarly to the routing equation for surface runoff, we can obtain the following equations for interflow from total area.

$$q_3(t)=\sum_{i=1}^{t} P_{t-i+1}(1/2)[\{i^2/K2^2+2(1/K2-1/K2^2)i+1/K2^2-2/K2+2\}\ e^{-(i-1)/K2}$$
$$-\{i^2/K2^2+2i/K2+2\}e^{-i/K2}] \tag{13}$$

$$Q_3(t)=1.3889(1-F1)F2\ A\sum_{i=1}^{t} r_{t-i+1}[\{i^2/K2^2+2(1/K2-1/K2^2)i+1/K2^2-2/K2+2\}\ e^{-(i-1)/K2}$$
$$-\{i^2/K2^2+2i/K2+2\}e^{-i/K2}] \tag{14}$$

Baseflow component is treated only by a recession equation. This work used the following equation (An improvement, 1985).

$$Q_b(t)=Q_i\times 0.9747^t \tag{15}$$

where Q_i represents initial stream discharge and $Q_b(t)$ is baseflow at time t. It is derived from the runoff analysis for Tanyang, Chungju, and Yoju gauging stations.

Now, we can describe the total runoff $Q_T(t)$, which is made of three quantities: (1) surface runoff; (2) interflow; and (3) groundwater flow. After delaying effect is imbedded into surface and interflow components with the hourly parameter LAG, total runoff, $Q_T(t)$, is made up of the above three constituents:

$$Q_T(t)=Q_b(t)+Q_2(t\text{-}LAG)+Q_3(t\text{-}LAG) \tag{16}$$

In conclusion, the rainfall-runoff system have 6 parameters; (1) initial loss IL, (2) the ratio of surface runoff component in rainfall intensity F1, (3) the ratio of interflow component (1-F1)×F2, (4) time to peak T_P in the UH of surface runoff, (5) the parameter $\alpha(=1/K2)$ in the linear reservoirs for interflow routing, and (6) time delay LAG. T_P is expressed in terms of storage coefficient K1 as in Eq. (9).

2.4 Parameter Estimation

We can use two types of parameter estimation methods for model calibration. One is a simple trial and error method and the other is an automatic calibration method by a nonlinear programming. Brazil (1988) compared various parameter estimation methods that use optimization technique and stated following results. Although it is more efficient to apply an optimization technique relying on derivatives, the results may not converge a (local) optimum point. On the contrary, a direct search method can almost always find an optimum solution even if the procedures consume more time than the method using derivatives.

From the above reason, this work also used Hook and Jeeves method (Cuester and Mize, 1973) in parameter estimation procedure that is a kind of direct search method. The objective function used is as follows:

$$\mathrm{Min}\sum_{i=1}^{n}(Q_{ob}(i)-Q_c(i))^2W(i) \tag{17}$$

$$W(i)=(Q_{ob}(i)+Q_{av})/(2Q_{av}) \tag{18}$$

where Q_{av} is the average value of observed discharges, Q_{ob} observed discharge, Q_c computed value. The type of objective function is the same as that of HEC-1 (Hoggan, 1989). Among the 6 parameters, time delay parameter LAG was assumed to have discrete values by hours. As it is not difficult to decide time delay values, for example, 1, 2, 3, etc., only the other 5 parameters were taken as unknown variables to be decided excluding the parameter LAG in calibration procedures.

2.5 Model Building Procedures and Sensitivity Analyses for Parameters

Including base flow, we first tried to simulate runoff only with surface runoff component through serially combined two linear reservoirs. That structure is very similar to Japanese runoff function method. Parameters, T_p and F1, are related to the first structure. T_p means time to peak in the UH of surface runoff component. Changing the values of T_p, we can adjust the gradient of the rising limb of a computed hydrograph. F1 denotes runoff ratio by which we can change the runoff volume.

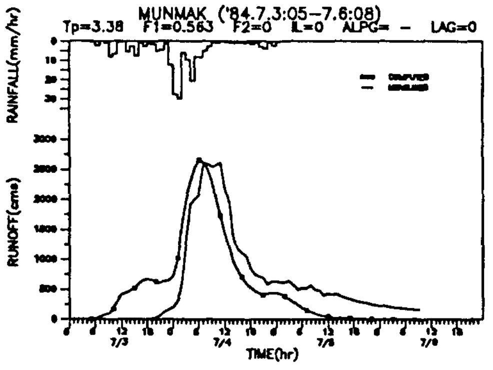


Fig. 3. Model Building 1: Runoff Function Method

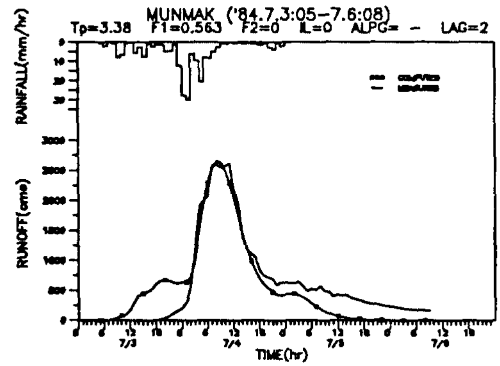


Fig. 4. Model Building 2: LAG Imbedding

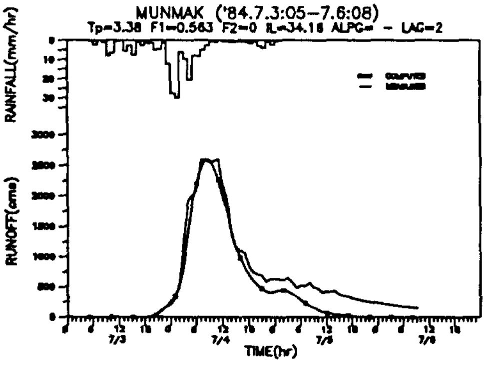


Fig. 5. Model Building 3: Introduction of the Initial Loss

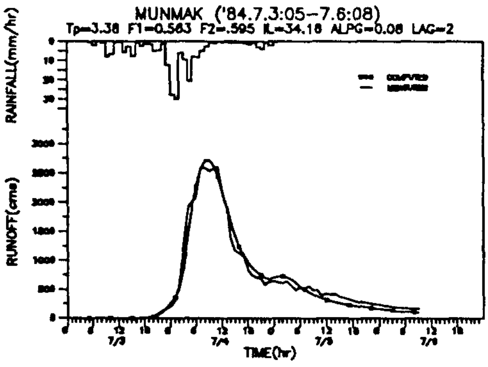


Fig. 6. Model Building 4: Completion of the Model Building by Addition of an Interflow Component

We used a flood event data in July 1984 at Munmak gauging station and tried to produce small gap between observed peak value and simulated one. Fig. 3 shows the results, where the computed hydrograph has still larger values in the early stage of the flood event but has smaller values in the falling limb. Secondly, we imbedded a time delay parameter LAG in the simulated hydrograph by 2 hours in order to accord the center of computed hydrograph with that of observed one (see Fig. 4). Subsequently, we introduce a parameter of initial loss IL to the model structure so that we might exclude the excessive runoff in the early stage of the flood event (see Fig. 5). Finally, we added an interflow component by the amount of (1-F1)×F2 in rainfall intensity to overcome the large discrepancy in the falling limb of hydrographs. Fig. 6 shows the final result.

Another flood event was selected to analyze the role of assumed three runoff components and corresponding rainfall series. Fig. 7 shows the three components and a simulated total runoff hydrograph. Fig. 8 shows rainfall components that contribute to hydrologic losses and runoffs. From Fig. 7, we can see that surface runoff takes major portion in the flood hydrograph. As it goes to the end of a flood hydrograph, the interflow component plays a main role in the total runoff. The baseflow, its initial value is 5 m^3/s, is so small compared to the total runoff that it cannot be distin-

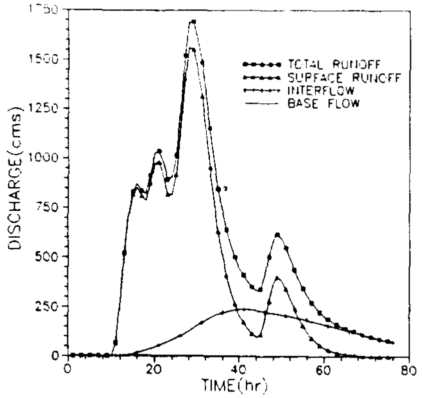


Fig. 7. Runoff Components of a Simulated Hydrograph

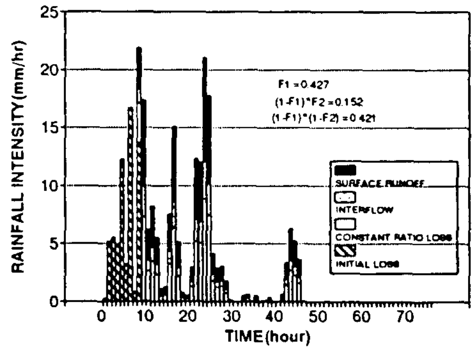


Fig. 8. Contribution of Rainfall to Runoff Components

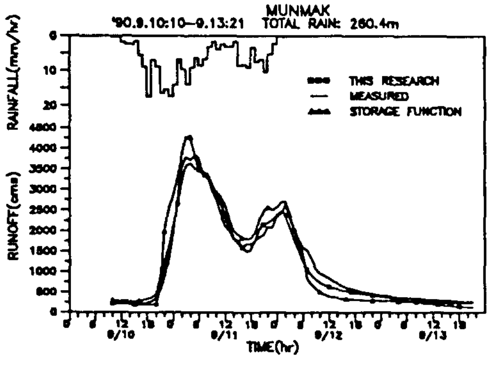


Fig. 9. A Comparison with Storage Function Method

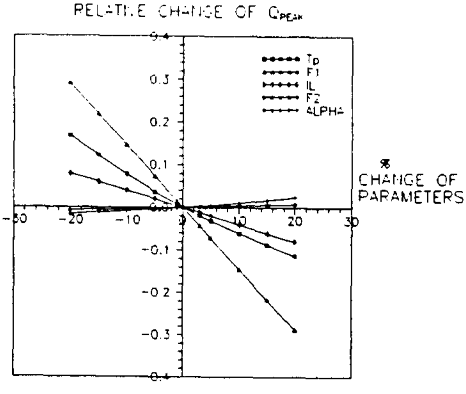


Fig. 10. A sensitivity Analysis for Peak Discharges

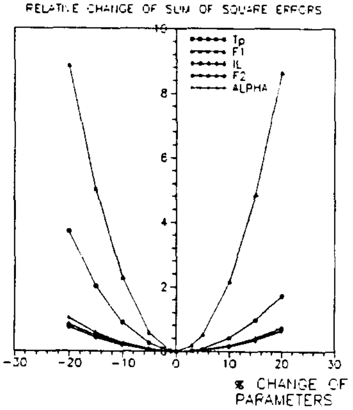


Fig. 11. A Sensitivity Analysis for Sum of Square Errors

guished from the time coordinate axis.

We can find that all the rainfall loses until 8 hours in the early stage of the rainfall event (see Fig. 8). Once the cumulative rainfall exceeds initial loss, IL, rainfall begins to contribute to runoff.

In this case, the surface runoff component occupies 42.7 % in the rainfall intensity, interflow component 15.2 %, and constant ratio loss 42.1 %.

We compared an application result of the model with Japanese storage function method (see Fig. 9). We used the flood data on September 1990 at Munmak gauging station. While unknown variable was stage in the storage function method (An improvement, 1991), this work simulated discharges. The computed stage data were transformed into discharge to be shown in Fig. 9. Storage function method applies an initial runoff ratio until a cumulative rainfall reaches a saturation point. Therefore, initial hydrograph has slightly larger values than the observed hydrograph. On the contrary, as this work produces runoff only by a recession curve in the early stage of a flood event, somewhat smaller values were simulated. Storage function method has larger peak value by 500m^3/s than observed one, but this research shows smaller peak value by 250 m^3/s. This work represents more reasonable results for the steep rising limb and for the late falling limb.

Excluding the parameter, LAG, we performed sensitivity analysis for the other 5 parameters. We used flood data on July 1987 at Seomyeon gauging station. Fig. 10 represents the parameter sensitivities for peak discharges. The results show that peak discharges are more sensitive to T_P, F1, and IL than the others. Fig. 11 shows the results of sensitivity analysis for sum of square errors that it is more sensitive to F1 and T_P. The sensitivity analysis gave the result that T_P and F1 are the most important parameters of the rainfall-runoff model developed in this study.

3. Application

3.1 Study Area and Data Used

We applied the rainfall-runoff model to tributaries of the Han River. The Seom River is a tributary of the South Han River and Hongcheon River is that of the North Han River. Each tributary has a stream gauge, named as Munmak and Seomyeon. Telemetry data were collected over the study area for the purpose of model calibration and verification. From 1975 to 1986, only major flood event data were collected, and continuous hourly data were gathered from 1987 to 1990. However, the number of telemetry rainfall stations has been increased: 38 stations have been operated during the period of 1975-1983; 54 stations during the period of 1984-1986; 71 stations during the period of 1987-1988; 78 stations during the period of 1989-1990. Therefore, it is very difficult to use hourly rainfall data consistently in the rainfall-runoff modeling. With the rainfall network before 1983, there are so many data available but we should use a sparse network. With the recent rainfall network, we can use only small data. Then we used rainfall data from telemetry network after 1984.

Fig. 12 shows the two watersheds, measurement stations, and Thiessen polygon. The watershed boundaries are found from 1:50,000 topographical map. After digitizing the boundaries on Auto CAD systems, we estimated areas and constructed Thiessen polygons. Seomyeon basin covers 1326.8 km^2 and that of Munmak basin is 1348.8 km^2.

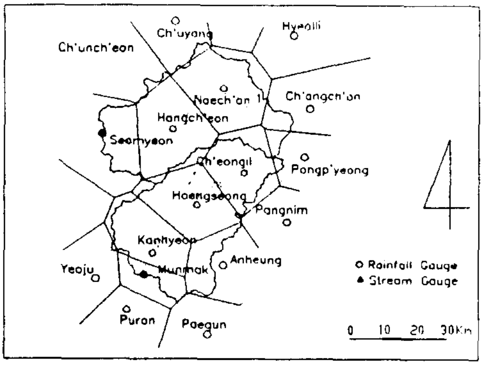


Fig. 12. Thissen Polygons and Telemetry Gauges in 1984

3.2 Model Calibration

Stage-discharge relations were collected and used for the model application (see Table 1). Two equations were used for Seomyeon station and three equations for Munmak station. The equation for Seomyeon in 1991 has a range of application, $H \geq 1.5$ m. Therefore, the equation for 1985 was used for the range of $H < 1.5$ m. It is the reason why the equation in 1985 could hardly be used alone in the application that it was made only with low discharges less than 1,000m^3/s and seemed to give large errors in higher water level. For example, while the equation in 1985 gives 14,107 m^3/s for the highest stage, 7.14 m, on the flood in 1984, we can get 8,832 m^3/s from the equation of 1991.

Only big flood events were selected for the application, which have the total rainfalls greater than 140 mm. Four events fall under the above criteria for Seomyeon station and three events come within the range for Munmak station. Calibration results are shown in Figs. 13-16.

Parameter estimation procedure did not suffer any problem with the flood event in July 1984 (see

Figs. 13 and 14). However, various problems occurred in the parameter estimation procedure for the big flood event in September 1990. When Seomyeon watershed recorded average areal rainfall of 478.6 mm in the flood event, the highest stage was converted into discharge of 9,000 m^3/s. It seems

Table 1. Stage-discharge Relations (H: Stage, [m]; Q: Discharge,[m^3/s])

Gauge	Division	Equation	Reference	Flood Events
Seomyeon	$H > 1.5$	$Q = 259.11\ H^2 - 680.94\ H + 484.4$	KICT (1994)	'84/7,'84/9,
	$H < 1.5$	$Q = 25.75\ H^{3.208}$	HRFCC (1985)	'87,'90
	no	$Q = 25.75\ H^{3.208}$	HRFCC (1985)	'89
Munmak	no	$Q = 296.20\ H^2 - 804.67\ H + 539.94$	HRFCC (1985)	'84/7, '84/9
	no	$Q = 26.968\ H^{3.1068}$	KICT (1994)	'87
	$0.92<H<6.33, H=h+1$	$Q = 48.8663(H-0.09)^{2.3790}$	KICT (1994)	'90

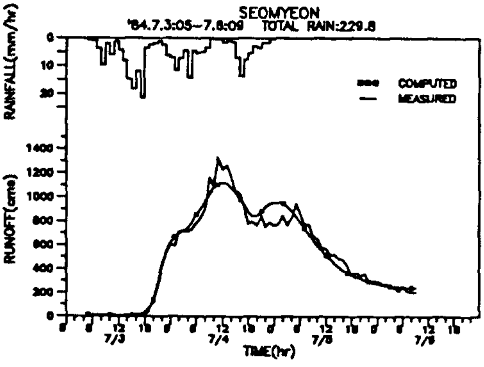


Fig. 13. Hydrographs in Model Calibration for Seomyeon Station (July 1984)

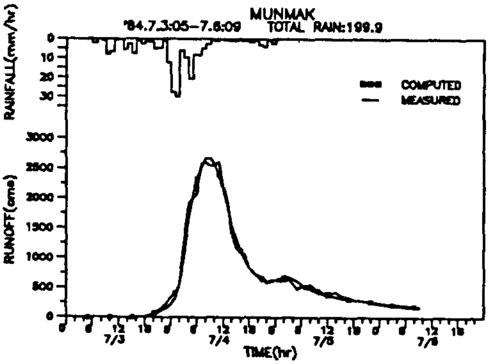


Fig. 14. Hydrographs in Model Calibration for Munmak station (July 1984)

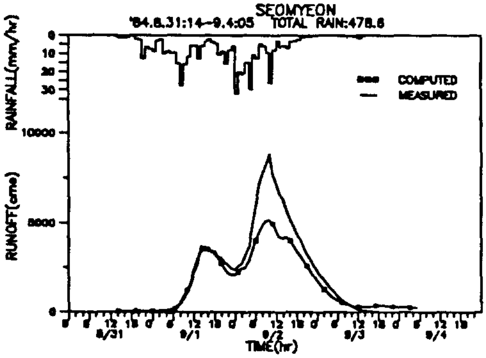


Fig. 15. Hydrographs in Model Calibration for Seomyeon Station (September 1984)

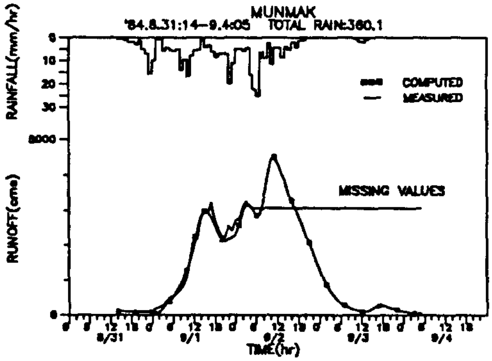


Fig. 16. Hydrographs in Model Calibration for Munmak Station (September 1984)

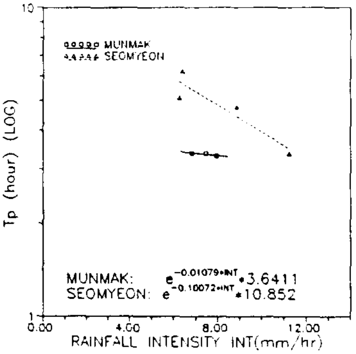


Fig. 17. Relations between Peak Times of UH for Surface Runoff and Values of Rainfall Intensity

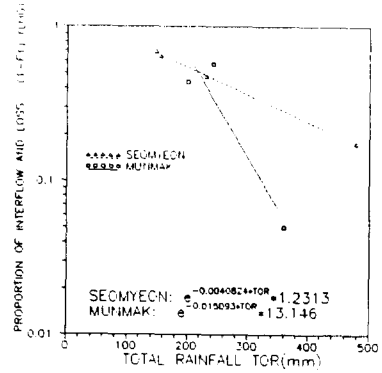


Fig. 18. Relations between Ratios of Loss and Interflow Components and Total Amounts of Rainfall

to be too large, being compared with 12,000 m^3/s of the maximum inflow to Soyanggang Dam whose area is about two times larger than Seomyeon watershed. The uncertainty in converted discharge seems to be inherent in inaccuracy of stage-discharge relation or measurement errors of rainfall. It also was illogical that the surface runoff ratio F1 had the value greater than 1 in the parameter estimation. Thus, we estimated only T_P and IL, after fixing F2 and α as the averaged value from the other three flood events and letting F1 have the value that gave the same loss amount as 14.9 mm that was the amount of total loss with constant ratio in the flood event in September 1990.

Munmak station recorded partial missing data for the flood event in September 1990. Therefore, F2 and were fixed as the averaged values of the estimated parameters from the other flood events. Parameter F1 also converged to the value greater than 1. Thus, F1 was subjectively determined by 0.95. Above the value 0.95, the weighted sums of square residuals, Eq. (18), had the similar values in a search procedures. Two cases of model calibration for the Seomyeon station and one case for Munmak can be found elsewhere (Lee, 1993). All the estimated parameters are summarized in Table 2.

Table 2. Estimated Parameters

	Year/ Month	Total Rainfall(mm)	T_P (hr)	F1	IL (mm)	F2	α $=1/K2$	Rainfall Intensity : T_P	Total Rainfa -ll : 1-F1	LAG (hr)
Munmak	'84/7	199.9	3.38	0.563	34.2	0.595	0.080	7.47 : 3.38	199.9 : 0.437	2
	'84/9	360.0	3.31	0.950	41.7	0.431*	0.094*	7.95 : 3.31	360.0 : 0.05	2
	'87/7	242.3	3.38	0.427	62.8	0.266	0.108	6.82 : 3.38	242.3 : 0.573	2
	'90/9	260.4	2.54	0.738	22.5	1.000	0.106	11.32 : 2.54	260.4 : 0.262	2
Seomyeon	'84/7	229.8	6.23	0.523	55.0	1.000	0.030	6.39 : 6.23	229.8 : 0.477	3
	'84/9	478.6	3.37	0.825※	48.5	0.803※	0.043※	11.22 : 3.37	478.6 : 0.175	3
	'87/7	147.0	4.77	0.313	40.9	0.616	0.083	8.87 : 4.77	147.0 : 0.687	3
	'89/7	155.7	5.11	0.354	53.8	0.792	0.015	6.28 : 5.11	155.7 : 0.646	3
	'90/9	415.0	2.15	0.758	103.	0.803※	0.043※	12.50 : 2.15	415.0 : 0.242	3

* Averaged value of estimated parameters excluding that of the flood in 1990.

※ Fixed value that equalizes the loss by constant ratio to that of the flood in 1990.

As the parameters in Table 2 had different values for every flood event, we tried to analyze the relationship between major parameters and rainfall characteristics in order to find useful information for forecasting problem. Only T_P and F1 were used to be related with rainfall characteristics because of their importance from sensitivity analysis. We used two variables, a total rainfall and a rainfall intensity among the rainfall characteristics. The rainfall intensity has a special meaning in this analysis. It does not mean an averaged value for the whole rainfall event but a partially averaged value with the period from excess point of IL to peak discharge point. The followings are the reason why we specially define the term, rainfall intensity: (1) a flood hydrograph are mainly composed by the rainfall exceeding initial loss; (2) rainfall precipitated until time to peak contribute to almost all of the runoff; (3) if we give importance on the rainfall after time to peak, it is difficult to determine end point of rainfall because of intermittence.

After analyzing the significance of four combinations between two rainfall characteristics, total rainfall and rainfall intensity, and two parameters, T_P and F1, we found some trends in two combinations, rainfall intensity versus T_P and total rainfall versus F1. Fig. 17 shows the relations between values of rainfall intensity and T_P with calibrated data. Even if Munmak station recorded somewhat large flood event in September 1984, whose average areal rainfall amounted to 360.1 mm, its rainfall intensity records 7.95 mm/hr at most. Therefore, all the values of intensity are located within the range of 7-8 mm/hr for Munmak station. Seomyeon on the other hand has a big flood event in September 1984 that recorded 478.6 mm in total rainfall and 11.22 mm/hr in rainfall intensity. From the results, it seems that other flood events are liable to come under the range of rainfall intensity, 6-11 mm/hr, in Seomyeon station. Fig. 18 shows the relation found between total rainfall and (1-F1), the proportion of interflow and constant ratio loss.

3.3 Verification

Using the fitting equations between values of T_P and rainfall intensity, and between values of (1-F1) and total rainfall, the model was verified for a flood event in September 1990 (see Figs. 19 and 20). In the case of Seomyeon, following three values are first fixed by averaged values estimated with three flood event except the flood in September 1990: IL=48.5; F2=0.803; and $\alpha=0.043$. With the values of a rainfall intensity and a total rainfall, T_P and F1 were estimated by the fitting equations as 3.081 and 0.774, respectively. Total average areal rainfall recorded 415.0 mm in Seomyeon catchment and we can see observed hydrograph with missing values in Fig. 19. Fig. 19 shows that the simulated hydrograph rises more fast than the observed hydrograph in spite of initial loss, 48.5 mm.

Fitting equations also gave parameters T_P and F1 for the flood event in September 1990 at Munmak station: $T_P=3.14$; and F1=0.742. The other variables fixed with the values; IL=41.7 mm; F2=0.431; $\alpha=0.094$ (see Table 2). Fig. 20 shows the result that excess initial loss generates large errors in rising limb and constant ratio loss gives some errors in falling limb.

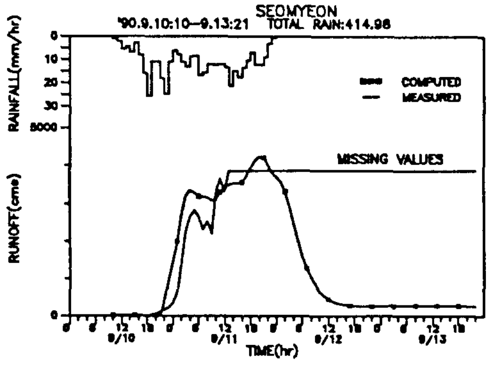


Fig. 19. Hydrographs in Model verification for Seomyeon Station (September 1990)

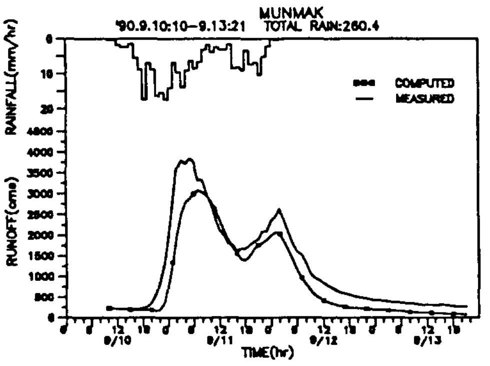


Fig. 20. Hydrographs in Model Verification for Munmak Stat (September 1990)

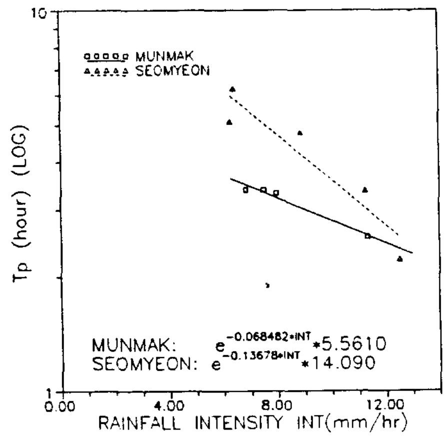


Fig. 21. Modified Relations between Peak Times of UH for Surface Runoff and Values of Rainfall Intensity

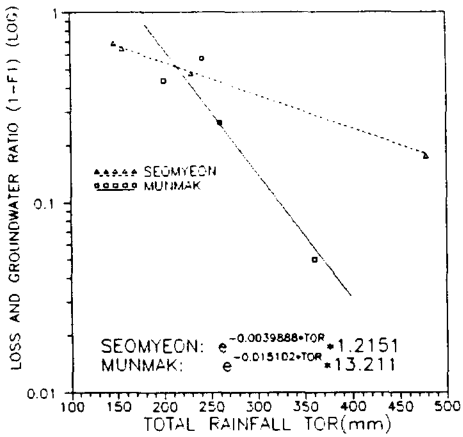


Fig. 22. Modified Relations between Ratios of Loss and Interflow Component and Total Amounts of Rainfall

In the case of real-time forecasting, we have difficulties in estimating T_P and F1. Even if T_P can be expressed by a rainfall intensity or F1 by a total amount of rainfall, we cannot know the future values of a rainfall intensity and a total amount of rainfall. Then, we have difficulties in determining what value we can use. In order to give practical availability to fitting equations of T_P and F1, we should develop a decision algorithm for the rainfall intensity and the total amount of rainfall through the analysis of various rainfall events. In spite of the above defect, we can tolerate the errors induced by an uncertainty of parameters, as the model developed is a submodel of the combined forecasting and control model for the Han River-Reservoir system (Lee, 1993). We estimated parameters for a big flood event in September 1990 and added the values, T_P and F1, to the fitting equations (see Figs. 21 and 22).

4. Conclusions

We have developed a rainfall–runoff event simulation model. It is composed of linear reservoirs through parallel and serial combinations. The model has analytical routing equations and can be classified into a lumped parameter model. From sensitivity analysis, we found that rainfall intensity T_P and surface runoff proportion F1 are major parameters that largely affect simulation results. After model building, we performed procedures of calibration, in which we used major flood data from 1984 to 1989. From a few sets of parameters estimated, we derived the relationships between values of T_P and rainfall intensity, and between values of (1–F1) and amounts of total rainfall. Then, we verified the model for a flood event in September 1990 using the derived equations.

We used a nonlinear programming algorithm, Hook and Jeeves method, in parameter estimation, which renders the model calibration procedure very simple. As the model has analytical routing equations, we can analyze some characteristics of catchment runoff. For example, we can utilize time to peak, T_P, and delay parameter, LAG, to simply acquire peak timing of a runoff hydrograph.

Two major limitations are as follows. When the model is applied to real–time simulation, major parameters, T_P and F1, are still unknown variables to be estimated. Although we found some relations between the parameters and rainfall characteristics, rainfall intensity and amounts of total rainfall, we should study on an algorithm to decide the values rainfall intensity and the amounts of total rainfall for a real–time application. The model has not included an algorithm for antecedent moisture accounting. Neglecting an effect from antecedent moisture, we fixed a parameter IL, initial loss, in verification procedures. It gave large errors in the rising limb of a flood hydrograph. Thus, we should work out a way to account soil moisture that may strengthen practical usefulness of the model.

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