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강우-유출에 대한 선형저수지 모형의 매개변수 연구

Parameters Study of Linear Reservoir Models for Rainfall-Runoff Response

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Abstract

In this study, a various rainfall-runoff modelling approaches have been applied to the runoff response of flood hydrograph in three experimental watershed of the western part of korea. Mathematical models of runoff response also have been studied including linear system theory based on modelling techniques. Eight models were operated at the five water level gauging stations and the parameters of each model were computed by the Rosenbrock's hill climbing method to minimize the objective function. For the parameter verification of the models, a different complex rainfall-runoff event was selected in the same of the three river basins and derived IUH of the each model could be calibrated. Furthermore multiple regressions of the logarithmic transformation method between model parameters and catchment characteristics were studied in the selected five stations.

Keywords: Rainfall-runoff, Flood runoff, Linear reservoirs model, IUH

요 지

서해안의 3개 실험유역을 선정, 강우-유출 현상 중 홍수수문곡선을 모의하기 위하여 선형저수지 모형을 적용하고 모형의 매개변수를 유역특성과 상관시켜 회귀분석을 실시하였다. 분석을 위하여 총 8개 모형이 이용되었으며 3개 유역, 5개 수위관측지점에서 시험·적용하였다. 선정된 모형의 매개변수 최적화는 선형계획기법의 일종인 Rosenbrock방법을 이용하였고 유도된 모형의 매개변수는 또 다른 강우-유출 사상에 모의하여 검정하였다. 그리고 검정된 모형 중 Nash모형은 저수지 수(N)와 저류상수(k), 그리고 선형저수지 모형의 경우 저류상수(k)를 유역특성치인 유역의 크기, 경사도 및 하천길이와 상관시켜 회귀분석을 실시하였으며 이 결과는 무계측 유역의 순간단위도(IUH)를 유도하는데 이용할 수 있을 것이다.

핵심용어 : 강우-유출, 홍수유출, 선형저수지, 순간단위도(IUH)

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1. Introduction

This paper was written to apply a linear reservoir model for the rainfall-runoff response of flood discharge in a given experimental watershed. The rainfall-runoff model is a popular tool for analyzing hydrological system. This method has been called parametric or deterministic hydrology. Mathematical models have been an important tool in the study of hydrology fields. These are used for scientific study of watershed runoff process, engineering problem solving, and forecasting or predicting hydrologic phenomena.

Until now in Korea, these models have not been applied to derive for a design flood hydrograph in the practical purpose at a given catchment area.

In this study, many inflow models have applied to the runoff response of catchment to meteorological input(rainfall). Most of existing dams in Korea(Agri. Develop. Cor., 1973), the design flood runoff have been estimated by Japanese tank model or classical unit or synthetic hydrograph method designed by Agricultural Development Corporation(1975). For the practical design purpose, estimation of flood discharges using a linear reservoir model have been studied in the Nonsan river basin by Suh et al.(1987).

2. Outlines of three experimental river basins

Ansung river : This river basin consists of 41% agricultural, 43% forest and 16% other area. The catchment area of the Ansung river is 1,670 km^2, river length is about 66.4km, estuarine reservoir, named A-san reservoir, located at the mouth of river was constructed during the period of 1971-1976, and the length of sea dike is 2,564m. In the A-san estuarine reservoir, irrigation water has been supplied to about 14,000ha on paddy field and 350,000 m^3/day for municipal water has planned. For the study of inflow modelling of this river, two stations on the river are selected namely Yu-chen and Hae-hwa as shown in Fig. 1.

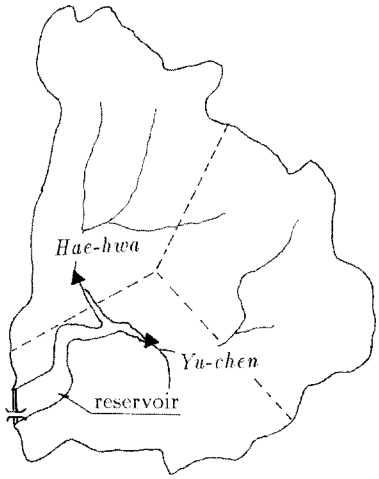


Fig. 1. Schematic map of Ansung river basin

Mankyung · Dongjin rivers : In these river basins, a flat plane was much developed compared with other river. The percentage of low level area below 100m in elevation is about 81% and 64% of agricultural area in the each river basin. Saemankeum sea dike is constructing the mouth of two rivers and the scale of this project considered for the multipurpose land reclamation. This project has been designed about 15-years ago but until now the detail items of land utilization have not been completed. The total development area is estimate about 22,350ha and the length of sea dike is 32.3km which longer than Zyder zee dike in Holland. Selected two stations in the Mankyung and Dongjin river are Dae-chen for the Mankyung and Sin-tae-in for the Dongjin river basin as shown in Fig. 2.

Youngsan river : This river is located the end of south-western part of the Korean peninsula and the mouth of this river also closed by sea dike for construction of

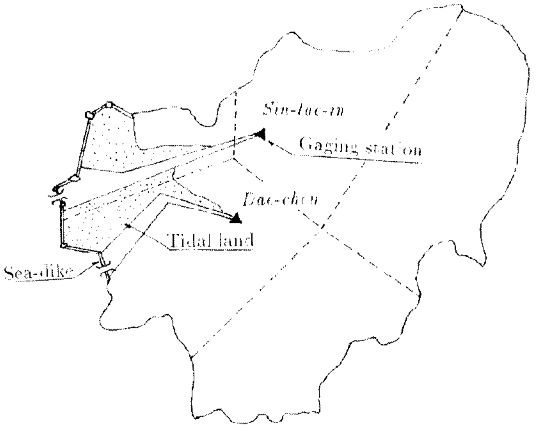


Fig. 2. Schematic map of Mankyung and Dongjin river basins

freshening reservoir on May of 1981. Reclaimed area of this project is estimated 4,690ha in tidal land and 20,700ha of upland for the irrigation water supply. The catchment area of main Youngsan river is 3,470 km^2 and river length is 115km. Youngsan estuarine reservoir was well mixed with freshwater due to much inflow, so that the salinity of freshwater layer has been observed 1,000ppm after operating the tidal gate during one year. Selected station for the river flow modelling is Na-ju as shown in Fig. 3.

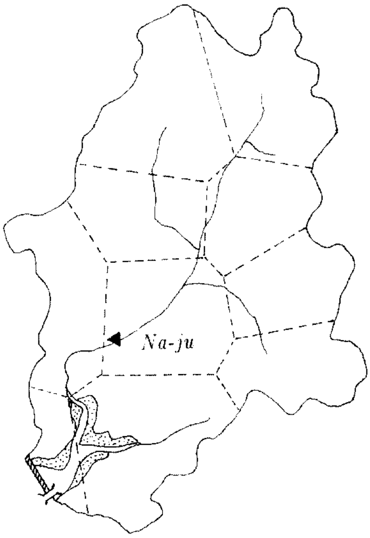


Fig. 3. Schematic map of Youngsan river basin

3. Impulse Function of Linear Reservoir Models

The main characteristic of a hydrology system is that it converts an input(rainfall) into an output(discharge from the catchment). We also considered that in broad lines we are dealing with three elements in lumped system i.e., input, the system operation, and output (USDA, 1973). If we denote the impulse response of the system on an impulse $x(t)$ by $y(t)$, written as

$$x(t) \quad \rightarrow \quad y(t) \tag{1}$$

and a system operation is represented as

$$\begin{aligned} Impulse\ x(t) &\rightarrow [System\ Operation] \\ &\rightarrow Impulse\ response\ y(t) \end{aligned} \tag{2}$$

then for a time-invariant system it follows that

$$x(t-\tau) \quad \rightarrow \quad y(t-\tau) \tag{3}$$

also for a linear, time-invariant system it follows further that considered constant C

Table 1. Characteristics of the selected river basins

River name	*Ansung*		*Mankyung · Dongjin*		*Youngsan*
Station	*Yu-chen*	*Hae-hwa*	*Dae-chen*	*Sin tae in*	*Na-ju*
Catchment area(Km^2)	491.7	367.3	856.9	221.9	2053.0
Main river length(km)	40.0	34.5	43.5	26.5	69.0
Slope of river ×(10^{-3})	2.2370	3.0769	2.0000	4.2918	1.8181

$$C \times x(t-\tau) \rightarrow C \times y(t-\tau) \tag{4}$$

The impulse response of a linear, time-invariant system on an instantaneous input(impulse) at $t=0$, is represented by the IUH(Instantaneous Unit Hydrograph) denoted as u(0,t) of which each of the elements u(0,t) for $t=1,2,3,\cdots\cdot\infty$, corresponds to a fixed ordinate in a hydrograph. A sequence of instantineous inputs can be represented by a smooth distribution described by the function $x(\tau)$, where τ denoted the time elapse since the reference time t=0. The input $x(\tau)*d\tau$ at $t=\tau$ will result in a response of the linear system u(0, t) equal to

$$u(0,\ t-\tau)*x(\tau)\,d\tau \tag{5}$$

which is simply the result of the response function u(0,t) shifted over a distance τ. The output(or response) of Eqn. (7) is only the result of the partial input $x(\tau)\,d\tau$ and consequently represents only a fraction of the total response, written as

$$dy(t) = u(0, t-\tau)\, x(\tau)\, d\tau \tag{6}$$

and usually, it is most convenient to put the start of the input at t=0, so that

$$y(t) = \int_{\tau=0}^{\tau=t} u(0, t-\tau)\, x(\tau)\, d\tau \tag{7}$$

4. Description of Applied Models

J-model : J-model is based on the ground water runoff to equidistant parallel ditches or drains, following an instantaneous recharge P_i of effective precipitation as shown in Fig. 4. Krayenhoff Van de Leur(1973) derived the instantaneous unit hydrograph(IUH) of flow to the drainage channels, expressed by

$$U(0,t) = \frac{8}{\pi^2} \cdot \frac{1}{j} \cdot \sum_{n=1,3,5,\cdots}^{\infty} \cdot e^{-(n^2 \cdot t/j)} \tag{8}$$

where j is the reservoir coefficient and n is the number of reservoir. Using the convolution integral and S-curve theory in the unit hydrograph(Suh, 1992), the distribution unit hydrograph(DUH) is founded in time intervals of D hours.

$$DUH(1) = 1 - j \cdot \frac{\pi^2}{12} - j \cdot \frac{8}{\pi^2} \cdot \sum_{n\ 1,3,5,\cdots}^{\infty} \frac{1}{n^4} \cdot e^{n^2/j} \tag{9}$$

and for the time of i th ordinate with i>1 then

$$DUH(i) = j \cdot \frac{8}{\pi^2} \cdot \sum_{n\ 1,3,5,\cdots}^{\infty} \frac{1}{n^4} \cdot (e^{n^2/j} - 1)^2 \cdot e^{-n^2 \cdot i/j} \tag{10}$$

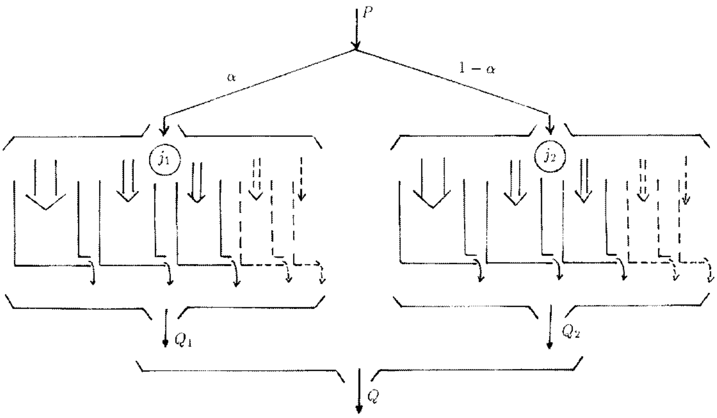


Fig. 4. J-model of Linear Reservoirs Response

The J-model consists of two of the described diffusion type hydrographs, which are used parallel so that the input P is distributed by a factor α and $(1-\alpha)$ over both branches which are characterized by respectively j_1 and j_2.

Parallel Linear Reservoirs(PLR) model : The main characteristics of a hydrological system is that it converts an input into an output as mentioned above. Unit impulse response function can be derive for the convolution integral from the system analysis and the linear storage or reservoir is a fictitious reservoir whose volume S is proportional to the outflow Q which denoted catchment response, unit volume of first reservoir can be expressed by

$$IUH = U(0, t) = Q(t) = \frac{1}{k} \cdot e^{-t/k} \qquad (11)$$

also using the S curve theory, Single Linear Reservoir(SLR)(Fig. 5.) can be expressed

$$\begin{aligned} DUH(SLR) &= \int_{t-1}^{t} U(D, t)dt = \int_{t-1}^{t} (1-e^{-t/k})dt \\ &= k e^{-t/k} - (k-1) \quad ; \text{ for } t=1 \end{aligned} \qquad (12)$$

$$\begin{aligned} DUH(SLR) &= \int_{t-1}^{t} e^{-t/k} (e^{-1/k}-1)\, dt \\ &= k e^{-t/k}(e^{1/k}-1)^2; \text{ for } t=2,3,4,\cdot\cdot\cdot \end{aligned} \qquad (13)$$

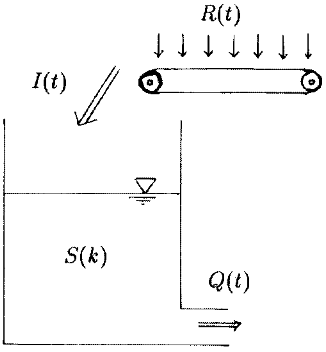


Fig. 5. Single Linear Reservoir model (SLR-model)

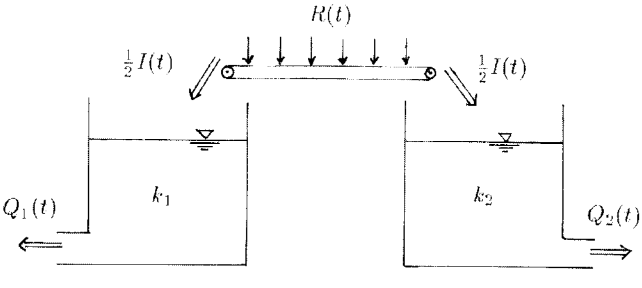
and for the Two-Parallel Linear Reservoirs (2 PLR, in Fig. 6.) model is as defined

$$\begin{aligned} DUH(2-PLR) &= \frac{1}{2}[k_1 e^{-t/k_1} - (k_1-1)] \\ &+ \frac{1}{2}[k_2 e^{-t/k_2} - (k_2-1)] \quad t=1 \end{aligned} \qquad (14)$$

$$\begin{aligned} &= \frac{1}{2} k_1 e^{-t/k_1}(e^{1/k_1}-1)^2 \\ &+ \frac{1}{2} k_2 e^{-t/k_2}(e^{1/k_2}-1)^2 \quad t=2,3,4,\cdot\cdot\cdot \end{aligned} \qquad (15)$$

also for the N-Parallel Linear Reservoir model(in Fig. 7.) of equally distributed rain can be expressed as the following equation.

$$DUH(N-PLR) = \sum_{i=1}^{N} \cdot \frac{1}{N}[k_i e^{-t/k_i} - (k_i-1)] \quad ; \; t=1 \qquad (16)$$



$Q(t) = Q_1(t) + Q_2(t)$

Fig. 6. Conceptual 2-PLR model

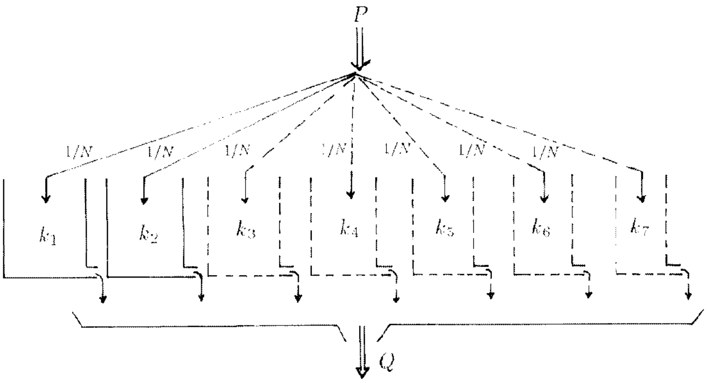


Fig. 7. N-Parallel Linear Reservoir model

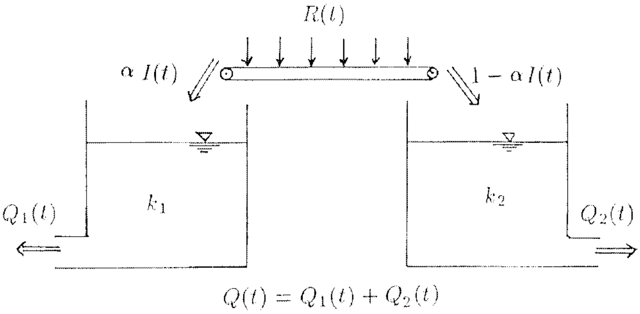


Fig. 8. Conceptual 2-PLRu model

$$= \sum_{i=1}^{N} \cdot \frac{1}{N}\left[k_i e^{t/k_i} \cdot (e^{-t/k_i}-1)^2\right] \; ; \; t=2,3,4,\cdots \tag{17}$$

Especially, for the 2 Parallel Linear Reservoirs model which is unequally distributed rainfall (2-PLR$_u$) as shown in Fig. 8., by a factor α, on input and output the parameters appear in the following sequence, k_1, k_2 and α instead of 0.5 in 2 PLR model.

$$\begin{aligned} DUH(2-PLR_u) &= (\alpha)[k_1 e^{-t/k_1}-(k_1-1)] \\ &\quad + (1-\alpha)[k_2 e^{t/k_2}-(k_2-1)] \; ; \; t=1 \end{aligned} \tag{18}$$

$$\begin{aligned} DUH(2-PLR_u) &= (\alpha)[k_1 e^{-t/k_1}-(e^{1/k_1}-1)^2] \\ &\quad + (1-\alpha)k_2[k_2 e^{-t/k_2}-(e^{-t/k_2}-1)^2] ; t=2,3,4,\cdots \end{aligned} \tag{19}$$

Nash model : Nash model(1957) is also a linear reservoir model but is a sequence of cascade reservoirs. This model is very well known in the world and then the expression of governing equation is omitted.

5. Simulation Procedure

Eight models were adapted for the optimal parameter computation in the rainfall-runoff response. Computer program for the parameter optimization brought from the irrigation and drainage paper in FAO(1975). Initial starting parameters for the modelling procedure were decided by storage function of the reservoir k which derived from the master recession curve of observed flood hydrograph as followed in Eq. (20). This approach largely reduces computer running time, but it does not allow an optimization for the channel delay time (LAG). The channel delay time may, however, be introduced by shifting the IUH one or more time intervals along the time axes. Values for the channel delay time for each model should be specified by the use as an integer value before the start of optimization. As the best values for LAG are easily found from the rainfall-runoff data or from a few trial runs, the channel delay times are not considered as true parameter values. Most of simulation runs were taken as four or five times by comparing of the objective function. The objective function, F value estimated as follows :

$$F = \Sigma(observed\ value - computed\ value)^2$$

$$k = \frac{t}{\ln \frac{Q_1}{Q_2}} \tag{20}$$

where Q_1 and Q_2 is initial and ending discharge during the time interval of t on a master recession curve bring the observed hydrograph

6. Modelling Results and Discussion

All of 8 model parameters which applied to 5 selected water level gauging stations at upstream in the estuarine reservoir were automatically estimated including the optimum LAG values. As the results in Table 2, the most fitted one was Nash-model in the every stations. In the result of PLR-model runs, the derived final parameters were represented nearly same values in the whole cases (SLR, 2-PLR, 3-PLR, 4 PLR, 5-PLR, 2 PLR$_u$). These means that each selected catchment area can be represented a homogeneous condition of hydrological response but the parameters of 2 PLR$_u$ in the Dae chen station calculated the different values.

Fig. 9. was shown an example presentation of modelling result by displayed a hydrograph of 4 PLR model at the Hae hwa station in Ansung river.

7. Parameter Verification for Each Models

Through the described previously in optimization procedure, parameters and DUH of the each model were generated as a response function of catchment characteristics. In order to verify DUH and parameters of the each model, a different complex rainfall-runoff event must be applied to the derived IUH of the each model. Therefore the other of rainfall-runoff events are selected at the each station and derived parameters are calibrated for each model verification.

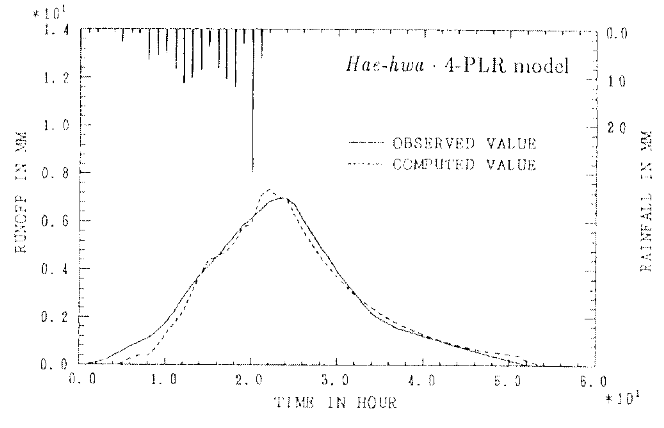


Fig. 9. An Example Presentation of Modelling Result

Table 2. Ending presentation of parameter optimization

Station	Models	Starting parameters	Fitted LAG(t)	Final parameters	Depth of IUH(cm)	F	RMS
Na ju	SLR	14.87	5	14.356	0.9975	5.742	0.00235
	2 PLR	14.87, 36.68	5	14.353, 14.354	0.9776	5.742	0.00235
	3 PLR	14.5, 14.5, 14.5	5	14.354, 14.354, 14.354	0.9766	5.742	0.00235
	4 PLR	14.5, 14.5, 14.5, 14.5	5	14.356, 14.354, 14.354, 14.354	0.9776	5.742	0.00235
	5 PLR	14.5, 14.5, 14.5, 14.5, 14.5	5	14.364, 14.351, 14.353, 14.351, 14.353	0.9776	5.742	0.00235
	2 PLRu	14.0, 14.0, 0.5	5	14.355, 14.353, 0.509	0.9776	5.742	0.00235
	J model	14.0, 14.0, 0.5	7	16.130, 16.135, 0.361	0.9685	11.67	0.00335
	Nash	2.648, 6.131	0	2.251, 7.675	0.9943	1.195	0.00107
Dae chen	SLR	10.3	4	9.377	0.9816	3.060	0.00328
	2 PLR	10.3, 10.9	4	9.376, 9.376	0.9817	3.060	0.00328
	3 PLR	9.5, 9.5, 9.5	4	9.377, 9.374, 9.377	0.9817	3.060	0.00328
	4 PLR	9.5, 9.5, 9.5, 9.5	4	9.371, 9.378, 9.380, 9.374	0.9817	3.060	0.00328
	5 PLR	9.5, 9.5, 9.5, 9.5, 9.5	4	9.375, 9.382, 9.374, 9.372, 9.376	0.9817	3.060	0.00328
	2 PLRu	9.0, 9.0, 0.5	5	0.028, 8.738, 0.036	0.9842	2.831	0.00316
	J model	9.5, 9.5, 0.5	6	10.330, 10.330, 0.471	0.9737	10.37	0.00605
	Nash	1.829, 4.989	3	1.606, 5.859	0.9947	1.140	0.00200
Sin tae in	SLR	7.1	9	5.678	0.9981	14.53	0.00467
	2 PLR	7.1, 51.34	9	5.678, 5.678	0.9981	14.53	0.00467
	3 PLR	5.6, 5.6, 5.6	9	5.678, 5.678, 5.678	0.9981	14.53	0.00467
	4 PLR	5.6, 5.6, 5.6, 5.6	9	5.886, 5.593, 5.612, 5.626	0.9981	14.53	0.00467
	5 PLR	5.6, 5.6, 5.6, 5.6, 5.6	9	5.997, 5.607, 5.602, 5.598, 5.598	0.9980	14.53	0.00467
	2 PLRu	5.6, 5.6, 0.5	9	5.686, 5.670, 0.473	0.9981	14.53	0.00467
	J model	5.6, 5.6, 0.5	10	7.220, 5.250, 0.507	0.9957	26.66	0.00633
	Nash	2.029, 5.737	2	1.671, 6.834	0.9993	1.894	0.00271
Hae hwa	SLR	10.02	1	9.422	0.9958	7.581	0.00278
	2 PLR	10.02, 19.14	1	9.422, 9.422	0.9958	7.581	0.00278
	3 PLR	9.5, 9.5, 9.5	1	9.426, 9.425, 9.413	0.9958	7.582	0.00278
	4 PLR	9.5, 9.5, 9.5, 9.5	1	9.459, 9.408, 9.401, 9.421	0.9958	7.582	0.00278
	5 PLR	9.5, 9.5, 9.5, 9.5, 9.5	1	9.443, 9.424, 9.403, 9.419, 9.419	0.9958	7.582	0.00278
	2 PLRu	9.5, 9.5, 0.5	1	9.422, 9.420, 0.501	0.9958	7.582	0.00278
	J model	9.5, 9.5, 0.5	2	10.908, 10.906, 0.489	0.9919	18.68	0.00436
	Nash	1.279, 6.683	0	1.385, 7.433	0.9984	5.022	0.00226
Yu chen	SLR	14.85	3	10.680	0.9672	5.943	0.00427
	2 PLR	14.85, 27.05	3	10.680, 10.680	0.9672	5.943	0.00427
	3 PLR	10.5, 10.5, 10.5	3	10.680, 10.680, 10.680	0.9672	5.943	0.00427
	4 PLR	10.5, 10.5, 10.5, 10.5	3	10.683, 10.683, 10.672, 10.679	0.9672	5.943	0.00427
	5 PLR	10.5, 10.5, 10.5, 10.5, 10.5	3	10.682, 10.680, 10.672, 10.684,10.673	0.9672	5.943	0.00427
	2 PLRu	10.5, 10.5, 0.5	3	10.681, 10.677, 0.454	0.9672	5.943	0.00427
	J model	10.5, 10.5, 0.5	4	13.220, 13.219, 0.445	0.9446	17.40	0.00731
	Nash	2.412, 4.711	0	2.020, 5.862	0.9906	0.514	0.00126

As shown in Table 2, the parameters of SLR model was calibrated for verification only as the representative values among the linear reservoir models because the storage function k was shown the same values in the whole of the PLR-models.

Fig. 10 was shown an example result of parameter verification for 2 PLR_u model by

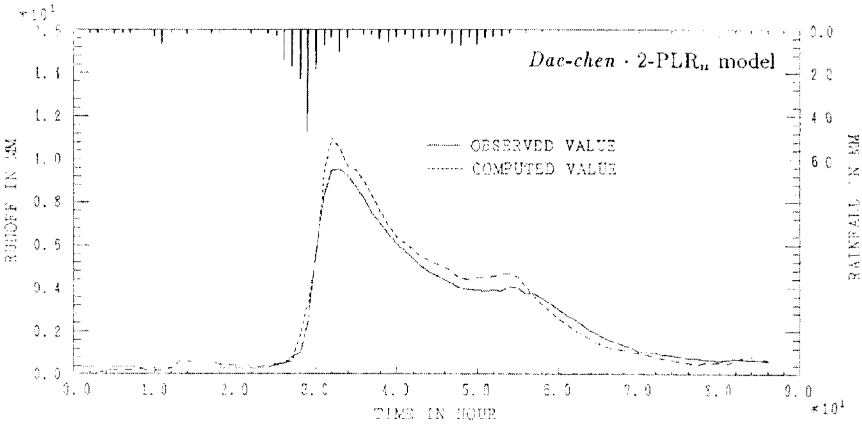


Fig. 10. An Example Result for Parameter Verification

Table 3. Verification of DUH for the selected models

Models	*Na ju*	*Dae-chen*	*Sin tae in*	*Hae hwa*	*Yu-chen*
SLR	0.0028290	0.0019024	0.0027733	0.0026410	0.0042373
Nash	0.0024552	0.0025803	0.0029822	0.0027062	0.0050757
J model	0.0035742	0.0027226	0.0029344	0.0029496	0.0047474

displayed hydrograph at the Dae chen station in Mankyung river basin.

As results of in Table 3, the calibrated root mean square, RMS, $\sqrt{\Sigma(\textit{observed value} - \textit{computed value})^2/n}$, value in Nash model was shown the minimum value at the Na ju station but the case of other stations, the values of PLR model were represented a minimum value.

8. Correlation Between Model Parameters and Catchment Characteristics

Regressions with logarithmic transformations are common in hydrologic data analysis and these techniques are essentially a method of simulation. Their main value are in prediction rather than in the investigation of causal linkages. Once the decision has been made to use a regression method, it is necessary to decide what type of reservoir model will be used. Therefore in this study, the multiple regression method between model parameters and catchment characteristics was done of the sampled five stations. The selected variables are the drainage area(A, km^2), main channel length(L, km), main channel slope(S, in part per thousand) between two points that are 10% and 85% of the channel distance along the river from a gaging station to the watershed division.

The linear reservoirs and Nash model's parameters were chosen to correlate with catchment characteristics. The series of N reservoirs in Nash model were correlated with the channel length(km) and the storage coefficient k of the conceptual reservoir in Nash and linear reservoir model also was correlated with above mentioned three values.

$$N = 0.4466\, L^{0.3704} \tag{21}$$

$$k_{(Nash)} = 0.2014\, A^{-0.1183}\, L^{0.9802}\, S^{0.6689} \tag{22}$$

$$k_{(PLR)} = 0.2739 A^{-0.7329}\, L^{2.3115}\, S^{-0.3660} \tag{23}$$

9. Conclusions

The study on this paper has highlighted the basic theory and operation method of conceptual rainfall-runoff model which involved in finding the optimum values for the parameters of linear reservoir models in a given experimental river basin.

The linear reservoir models have well played an important role in modelling test of catchment response and estimation of flood hydrograph concerning river inflow with flood forecasting. All of the selected drainage basins of the three rivers can be proved homogeneous condition in catchment behaviour of the runoff system by the parameter derivation in PLR models. These mean that the computed final parameters of the those models were represented almost same values in every run even though unequal distributed rainfall model(2-PLRu).

Throughout these entire studies, it is apparent that the most fitted model of expressing the relation between rainfall-runoff data in the selected basins is the Nash and PLR models due to comparison of the computed results. It was also catchment characteristics correlated in logarithmic regression equation even though that the parameters are limited in linear reservoir series N and storage coefficient k.

It is possible that if more data of the rainfall runoff response were collected in the various drainage basins, further much work required on usefulness of representation values which are obtaining optimum parameter ones of rainfall-runoff models.

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