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# A Study on Computation Methods of Monthly Runoff by Water Balance Method

# 물수지 개념을 이용한 월유출량 산정방법에 관한 연구

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## Abstract

Hydrologists have tried to develop monthly runoff simulation models which are important factor in water resources planning. One of the models called Kajiyama formula is widely used for monthly runoff simulation in Korea. In recent work by Xiong and Guo (1999), they suggested Two-parameter monthly water balance model to simulate the runoff and showed that the model can be used for the water resources planning program and the climate impact studies. However, they estimated two parameters of transformation of time scale, c and of the field capacity, *SC* by the trial and error method. Therefore, the purpose of this study is to suggest the estimation methodologies of c and *SC*, and compare Kajiyama formula with a Two-parameter monthly water balance model to simulate the runoff in Han river and IHP representative basins in Korea. The c is estimated by using the relationship of actual and potential evaporations, and *SC* is estimated from association with *CN*. We show that the estimated c and *SC* can be used as the initial or optimal values in the model.

*keywords* : Kajiyama formula, water balance, runoff simulation, field capacity, *CN*

## 요 지

수자원 기술자들은 수자원 계획에 있어서 중요한 월유출 모의 모형을 개발하여 왔으며, 우리 나라에서는 가지야마 모형을 대표적인 월유출 모형으로 이용하고 있다. 최근 Xiong과 Guo (1999)는 2-변수 월 물수지 방정식 모형을 제안하였고, 수자원 계획과 기상학적인 영향을 분석하기 위하여 제안한 모형을 이용할 수 있음을 보였다. 그러나 그들은 시간변환 변수 c와 저수지 포장 용수량 변수 *SC*를 시행착오에 의하여 추정하였다. 따라서, 본 연구의 목적은 2-변수 모형의 변수인 c와 *SC*를 추정하는 방법론을 제안하고, 2-변수 월 물수지 방정식 모형과 가지야마 모형을 한강 유역과 IHP 대표유역에 적용하여 비교 검토하고자 한다. c는 실제 증발산량과 잠재 증발산량 사이의

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관계에 의하여 추정하였고, $SC$는 $CN$ 값과의 관계를 사용하여 추정하였으며, 추정된 모형변수 c와 SC는 2-변수 월 물수지 방정식 모형을 위하여 초기치 혹은 최적치로 이용할 수 있음을 보이고자 한다.
**핵심용어** : 가지야마 모형, 물수지, 유출모의, 저수지 포장 용수량, 유출곡선지수

## 1. Introduction

Water balance models were developed in the 1940's by Thornthwaite (1948) and later revised by Thornthwaite and Mather (1955). These models are essentially bookkeeping procedures which estimate the balance between the income of water from precipitation and snowmelt and the outflow of water by evapotranspiration, streamflow, and groundwater recharge. Generally, the monthly water balance model is applied in three fields, i.e., the reconstruction of hydrologic characteristics of a watershed for climatic impacts, the evaluation of seasonal and geographical patterns of water supply, and irrigation demand (Xu and Singh, 1998).

Early monthly runoff models related to climate were developed by Meyer (1947) and Thornthwaite (1948) (Alley, 1984) and the developed models are for annual and monthly timescales, respectively. Thornthwaite method is a simple water balance model which was developed originally for the Delaware river basin, USA.

Palmer (1965) used a monthly water balance model to develop the index of meteorological drought. Thomas (1981) and Thomas et al.(1983) suggested that the state variables simulated in a water balance may be useful in themselves. Gleick (1987) developed a monthly water balance model specifically for climate impact assessment and addressed the advantages for water balance type models in practice. Mimikou et al.(1991) developed a monthly timescale runoff model to study the effects of climate change on the mountainous watersheds in Greece.

Kim (1984) simplified the water balance for river runoff by the relationship of rainfall, evapotranspiration, and variation of soil water content. He was done regression analysis with the variables of watershed rainfall, the measured evaporation, and runoff of previous month for investigating the effects of variables on monthly runoff. KRIHS (1987) developed a model called KRIHS by using water balance analysis of the watershed for the estimation of monthly runoff.

The monthly water balance models have been developed in last 50 years and is becoming more complicated for more physical based analysis and various applications. However, the simple models can still be efficient and useful in runoff simulation, just like the conceptual hydrological model is still of great use in flood forecasting despite the emergency of the physical based models (Woolhiser, 1996). Therefore, one of our aims is to apply the simple models of Kajiyama and Two-parameter monthly water balance model to the Han river and IHP representative basins in Korea.

## 2. Kajiyama Formula

In practice, we may need monthly, seasonal or annual runoff volumes for the determination of a reservoir capacity and the analysis of a reservoir operation. However, it is difficult to obtain a long term runoff from the rainfall-runoff relationship because there are many factors having an effect on runoff.

Since the length of runoff record is not enough and the measuring site is also limited in Korea, the appropriate method is needed for the determination of availability of water resources which is required in carrying out water resources development and the design of hydrologic structures at a site. If a proper relationship between rainfall and runoff depth can be established the runoff depth may be obtained from monthly or annual rainfall. Thus, the Kajiyama formula is widely used for the calculation of monthly runoff depth at an ungaged site in Korea. The formula is given by

$$R=\sqrt{P^2+(138.6f+10.2)^2}-138.6f+EP \qquad (1)$$

where $R$ represents runoff depth in mm, $P$ monthly rainfall, $f$ runoff coefficient in a watershed, and $EP$ the coefficient for monthly rainfall depth. The coefficients of $f$ and $EP$ are given according to watershed characteristics and monthly rainfalls (Yoon, 1998).

## 3. Two-Parameter Monthly Water Balance Model

This section describes a simple Two-parameter monthly water balance model(TPM) suggested by Xiong and Guo (1999) and a modified TPM for the estimations of two parameters

### (1) Model construction

Ol'dekop (1911) (in Brutsaert, 1992) suggested the following Eq.(2) to calculate the actual annual evapotranspiration.

$$E(t)=EP(t)\times \tanh[P(t)/EP(t)] \qquad (2)$$

where $E(t)$ is the actual annual evapotranspiration, $EP(t)$ the annual pan evaporation, $P(t)$ the annual rainfall, and tanh[ · ] the hyperbolic tangent function. After many numerical experiences, Xiong and Guo (1999) suggested that Eq.(2) can be used to calculate the actual monthly evapotranspiration if its right side is multiplied with a new coefficient.

$$E(t)=c\times EP(t)\times \tanh[P(t)/EP(t)] \qquad (3)$$

where $E(t)$ is the actual monthly evaportranspiration, $EP(t)$ the monthly pan evaporation, $P(t)$ the monthly rainfall, and c the new coefficient which is the first model parameter. This parameter $c$ is used to take an account of the effect of the change of time scale, i.e., from year to month.

The runoff $Q(t)$ is also assumed as a hyperbolic tangent function of the soil water content S, which is given by

$$Q(t)=S(t)\times \tanh[S(t)/SC] \qquad (4)$$

where $Q(t)$ is the monthly runoff, $S(t)$ the water content in soil, and $SC$ the field capacity of catchments. Thus, $SC$ is the second parameter used in TPM

### (2) Numerical computation of the model

The quantity of soil water will be $[S(t-1)+P(t)-E(t)]$ after the loss of evapotranspiration $E(t)$, with $S(t-1)$ which represents the water content at the end of the (t-1)th month and at the beginning of the tth month. The Eq.(4) is then used to calculate the tth monthly runoff $Q(t)$ as follows:

$$Q(t)=[S(t-1)+P(t)-E(t)]\times \tanh\{[S(t-1)+P(t)-E(t)]/SC\} \qquad (5)$$

Finally, the water content at the end of the tth month, i.e. $S(t)$ is calculated according to the water balance

$$S(t)=S(t-1)+P(t)-E(t)-Q(t) \qquad (6)$$

The determination of an initial value of soil water content, $S(0)$, affects the monthly runoff, $Q(t)$, especially for less observations. The $S(t)$ has similar quantity in same time scale in hydrological cycle. Say, the same month in each year represents similar soil water content. Thus, $S(0)$ can be determined in TPM as follows:

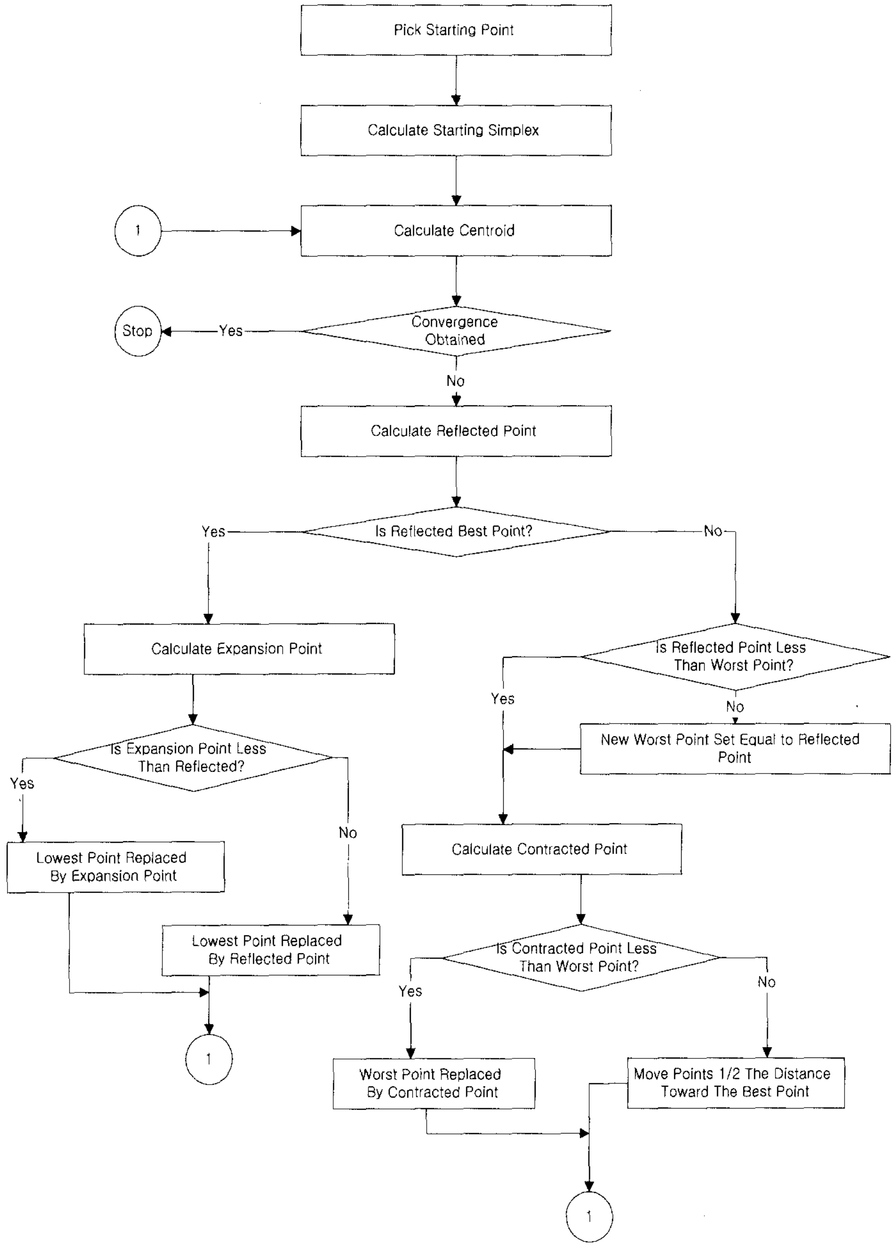


**Fig 1. Process of simplex method**

$$S(0) \approx \sum_{j=1}^{m} S(j \times 12)/m \qquad (m = N/12) \qquad (7)$$

where $N$ is the period.

The optimum values of the proposed two parameters of the model can be obtained by automatic optimization with Simplex method (Fig. 1). However, Xiong and Guo (1999) did not describe for the initial values of two parameters and they estimated those by the trial and error method. If the initial values can be obtained we may compute water balance in more reasonable sense especially for an ungaged site. The following section demonstrates how two parameters could be estimated.

### (3) The parameter estimation

If the runoff observations exist the optimum values of the model parameters can be estimated by comparison between the observed and simulated runoffs. However, it may be difficult to determine the parameters if there is no observations and thus we may estimate them by using the meteorologic, topographic and geologic characteristics. This study suggests the estimation of two parameters in TPM

A common method in practice for the conversion of the pan evaporation to actual evaporation is to use the reduction factor $k$, i.e., $E(t) = k \times EP(t)$ and Eq.(3) can be written as follows:

$$E(t) = c \times EP(t) \times \tanh\left[\frac{P(t)}{EP(t)}\right] = k \times EP(t)$$

Then the parameter c is given by

$$c = \frac{k}{\tanh\left[\frac{P(t)}{EP(t)}\right]} \quad (8)$$

Therefore, if $k$ is known the parameter c can be estimated with monthly rainfall and pan evaporation and the following table represents the values of $k$ (Yoon, 1998).

| month | 5,6,7,8 | 3,4,9,10 | 11,12,1,2 |
|---|---|---|---|
| $k$ | 0.8 | 0.7 | 0.6 |

The $SC$ is defined as the moisture content of soil after gravity drainage is complete(or field capacity). The parameter, $SC$, is the variable which includes the spatial meaning and it may have a similar value in a watershed (Xiong and Guo, 1999). Therefore we consider the field capacity is related to $CN$ which has associations with the soil type and land use, and the parameter $SC$ has a linear relationship with $CN$ of AMC-II condition as follows:

$$SC = (a_1 \times CN) + a_2 \quad (9)$$

where a1 and a2 are the constants.

## 4. Application

### (1) Data used and TPM

The study areas are the Han river and IHP representative basins in Korea. The data sets used are the monthly rainfalls, runoffs and pan evaporations at the basins (Table 1). ChungMi and HoengSung sites in Table 1 are used for the comparative purposes between TPM and Kajiyama formula using the suggested methodologies in a section 3 for parameter estimation and thus the two sites are excluded in this section.

The parameters of c and SC are estimated by the method of Xiong and Guo (1999) and the results by TPM are in Table 2. Xiong and Guo (1999) verified the mentioned parameters in seventy watersheds in China. Here the mean values by Xiong and Guo (1999) are used as the initial values for parameter estimations and the observations are obtained from the Ministry of Construction and Transportation (1987-1997) and KICT (1989). The observed and simulated monthly runoffs for WiChun and PyungChang sites are compared in Figs. 2 and 3. As shown in Table 1, the analyzed points have short records and we did not classify the calibration and verification periods.

The root mean square error (RMSE) is used as an error criterion between the observed and simulated runoffs and the efficiency criterion, $R^2$ by Nash and Sutcliffe (1970) is used for the model efficiency. The rating curve should be constructed for stage data in each sites but, in reality, it is not constructed properly for the sites and it is difficult to estimate runoff data. Although the rating curve is applied to flood and low flow seasons, most of rating curves are not constructed carefully for low flow data and thus the runoff estimation is less accurate in low flow seasons than flood. In our simulation, the results for KanHyun and YoungWol sites are not satisfactory and it may be due to relatively large watershed area. However, $R^2$ is relatively high for KyungAhn, HongChun, and JuChun sites(Table 2).

### (2) Determination of $c$ and $SC$

The parameters at ChungMi and HoengSung sites are estimaed for the comparative purposes between TPM and Kajiyama formula. The parameter $c$ is estimated by Eqn.(8) and the results for two sites are represented in Tables 3 and 4. In Tables 3 and 4, the values of c are 1.004 in ChungMi and 1.283 in HeongSung and we applied these values to TPM. The estimated parameter, $c$ may be used as its optimal or initial value for the runoff simulation by TPM. The $SC$ in Table 2 is used for the relationship with $CN$ which is represented in Table 5 (Ministry of Construction, Korea, 1991, Minstry of Construction and Transportation, 1983). The regression is determined by Eq.(9) and gives the following Eqn.(10)

**Table 1. Subbasins, data period, and watershed areas for study area.**

| Subbasin | | Period | Area ($km^2$) |
|---|---|---|---|
| IHP representative basins | PyungChang(BangLim) | 1985-1991 | 519.7 |
| | WiChun(MuSung) | 1993-1997 | 472.5 |
| | BoChun(SanGye) | 1994-1997 | 346.5 |
| Hanriver basins | KyungAhn | 1985-1988 | 264.3 |
| | HongChun | 1963-1972 | 874.3 |
| | KanHyun | 1979-1983 | 1173.7 |
| | JuChun | 1973-1975 | 528.8 |
| | YoungWol | 1982-1986 | 2450.6 |
| | ChungMi | 1985-1987 | 523.8 |
| | HoengSung | 1986-1989 | 439.0 |

**Table 2. The estimated parameters, *RMSE*, and $R^2$**

| Subbasin | $c$ | $SC$ (mm) | $RMSE$ (mm) | $R^2$ (%) |
|---|---|---|---|---|
| PyungChang | 0.594 | 1200 | 71.98 | 66.88 |
| WiChun | 1.080 | 1100 | 33.63 | 65.36 |
| BoChun | 1.170 | 700 | 28.68 | 61.28 |
| KyungAhn | 0.563 | 600 | 39.44 | 90.41 |
| HongChun | 0.901 | 1300 | 52.10 | 83.18 |
| KanHyun | 0.631 | 1000 | 40.10 | 59.28 |
| JuChun | 0.377 | 1200 | 46.81 | 75.84 |
| YoungWol | 1.078 | 1400 | 31.51 | 33.33 |

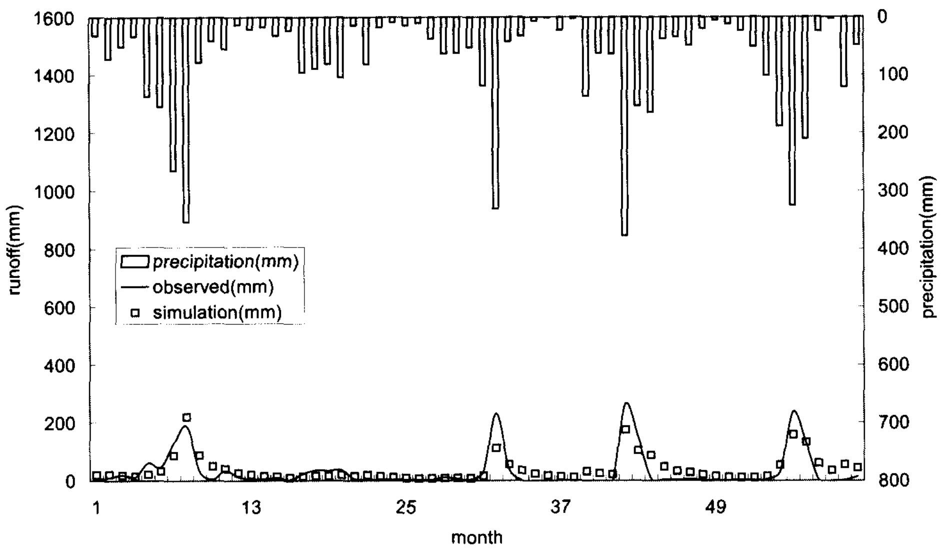


Fig 2. The observed and simulated monthly runoff hydrographs at the WiChun site(1993~1997)

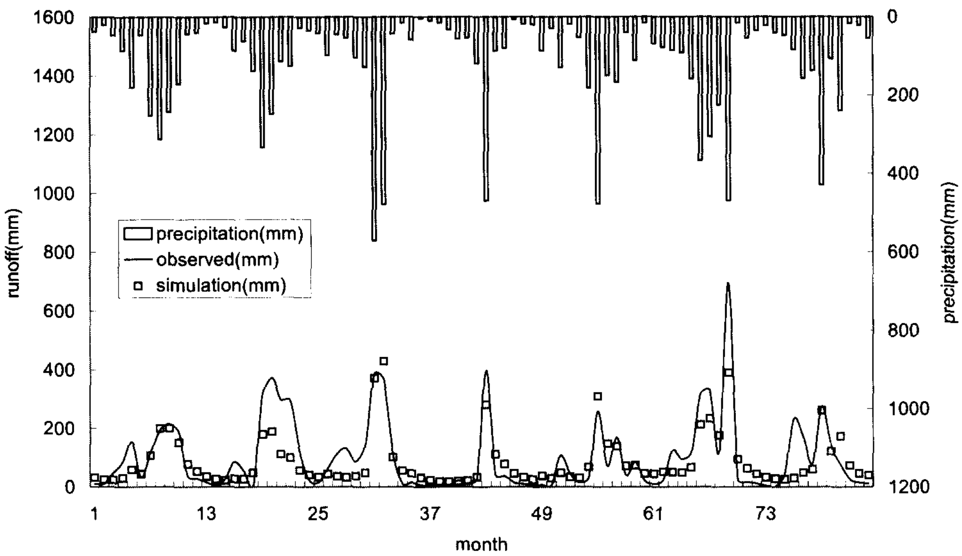


Fig 3. The observed and simulated monthly runoff hydrographs at the PyungChang site(1985~1991)

Table 3. The estimated $c$ for ChungMi site in Han river basin.

| | month / year | Jan. | Feb. | Mar. | Apr. | May | Jun. | Jul. | Aug. | Sep. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Precipitation | 1985 | 31.2 | 15.8 | 40.4 | 43.2 | 175.4 | 58.3 | 201.9 | 248.0 | 177.1 | 194.3 | 66.5 | 41.4 |
| | 1986 | 11.0 | 9.3 | 16.6 | 42.0 | 67.1 | 143.1 | 316.9 | 257.1 | 121.8 | 78.4 | 26.0 | 50.3 |
| | 1987 | 55.7 | 42.4 | 41.1 | 47.3 | 101.4 | 107.7 | 612.2 | 558.3 | 32.5 | 18.8 | 55.9 | 5.5 |
| | Mean | 32.6 | 22.5 | 32.7 | 44.2 | 114.6 | 103.0 | 377.0 | 360.5 | 110.5 | 97.2 | 49.5 | 32.4 |
| Evaporation | 1985 | 18.30 | 18.90 | 58.20 | 94.50 | 112.30 | 124.20 | 107.2 | 104.6 | 62.5 | 50.8 | 25.0 | 29.6 |
| | 1986 | 26.6 | 34.1 | 69.2 | 129.4 | 146.7 | 129.5 | 100.9 | 103.7 | 84.9 | 52.9 | 37.3 | 25.3 |
| | 1987 | 30.2 | 42.9 | 71.4 | 108.9 | 143.6 | 170.8 | 91.6 | 93.0 | 106.2 | 70.1 | 29.9 | 27.2 |
| | Mean | 25.0 | 32.0 | 66.3 | 110.9 | 134.2 | 141.5 | 99.9 | 100.4 | 84.5 | 57.9 | 30.7 | 27.4 |
| | $c$ | 0.696 | 0.989 | 1.532 | 1.850 | 1.154 | 1.286 | 0.800 | 0.801 | 0.811 | 0.751 | 0.650 | 0.724 |

Table 4. The estimated $c$ for HoengSung site in Han river basin.

| | month / year | Jan. | Feb. | Mar. | Apr. | May | Jun. | Jul. | Aug. | Sep. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Precipitation | 1986 | 23.8 | 71.9 | 29.2 | 93.4 | 55.4 | 101.6 | 345.9 | 245.4 | 124.00 | 82.1 | 31.1 | 40.0 |
| | 1987 | 43.3 | 51.6 | 32.8 | 39.4 | 110.1 | 110.5 | 490.3 | 572.9 | 43.2 | 20.8 | 57.4 | 3.7 |
| | 1988 | 8.5 | 7.9 | 34.7 | 51.9 | 45.0 | 103.5 | 498.5 | 78.1 | 79.1 | 5.4 | 16.1 | 19.8 |
| | 1989 | 86.4 | 25.6 | 121.3 | 9.3 | 45.3 | 115.9 | 343.1 | 141.5 | 96.0 | 11.5 | 79.7 | 11.4 |
| | Mean | 40.5 | 39.3 | 54.5 | 48.5 | 63.9 | 107.9 | 419.4 | 259.5 | 85.6 | 29.9 | 46.1 | 18.7 |
| Evaporation | 1986 | 38.3 | 46.2 | 78.4 | 148.6 | 174.3 | 152.1 | 118.3 | 126.9 | 108.2 | 67.8 | 45.0 | 31.7 |
| | 1987 | 36.3 | 40.1 | 73.0 | 115.7 | 158.2 | 180.5 | 111.0 | 97.0 | 116.8 | 89.6 | 52.1 | 38.3 |
| | 1988 | 39.9 | 52.0 | 80.8 | 140.6 | 164.6 | 173.2 | 107.1 | 175.3 | 124.0 | 97.3 | 63.0 | 37.4 |
| | 1989 | 28.9 | 43.3 | 78.5 | 156.3 | 189.5 | 166.8 | 137.9 | 151.1 | 109.4 | 85.2 | 42.6 | 32.4 |
| | Mean | 35.9 | 45.4 | 77.7 | 140.3 | 171.7 | 168.2 | 118.6 | 137.6 | 114.6 | 85.0 | 50.7 | 35.0 |
| | $c$ | 0.740 | 0.859 | 1.157 | 2.105 | 2.246 | 1.414 | 0.801 | 0.838 | 1.106 | 2.068 | 0.832 | 1.225 |

Table 5. The estimated $SC$ (shaded) in association with $CN$

| Subcathcments | $SC$ | $CN$ |
|---|---|---|
| Pyungchang | 1200 | 65.0 |
| WiChun | 1100 | 65.8 |
| BoChun | 700 | 77.8 |
| KyungAhn | 600 | 73.5 |
| HongChun | 1300 | 54.0 |
| KanHyun | 1000 | 63.5 |
| JuChun | 1200 | 48.5 |
| YoungWol | 1400 | 41.3 |
| ChungMi | 1400 | 45.0 |
| HoengSung | 1000 | 64.2 |

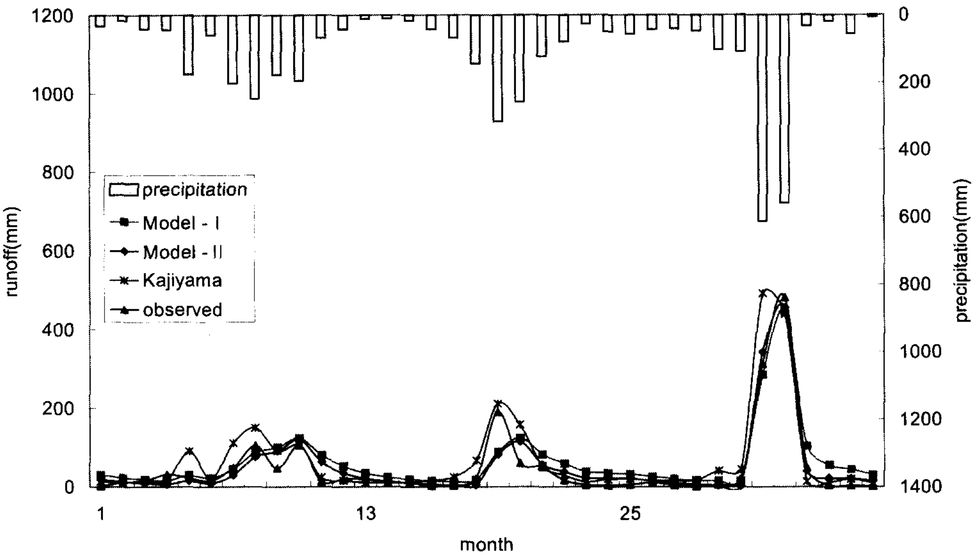


Fig 4. The observed and simulated monthly runoff hydrographs at the ChungMi site(1985～1987)

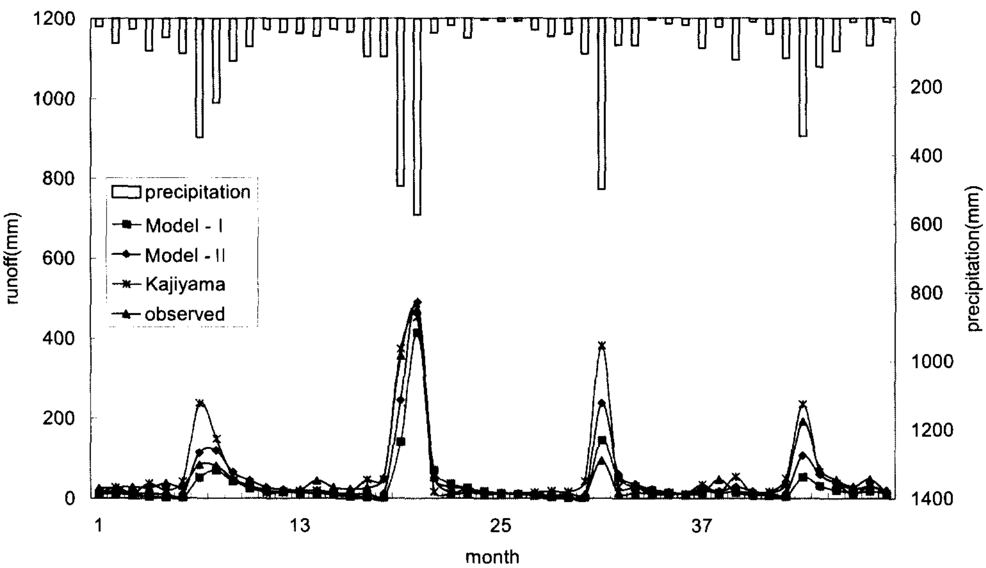


Fig 5. The observed and simulated monthly runoff hydrographs at the HoengSung site(1986～1989)

$$SC = (-19.808 \times CN) + 2274.1 \quad (10)$$

Eq.(10) is the linear regression equation for $SC$ of eight sites in Table 2 and $CN$ in watersheds of eight sites. And we estimate $SC$ values for ChungMi and HoengSung sites by using Eq.(10) (Table 5).

The parameter $SC$ is estimated using Eq.(10) for ChungMi and HoengSung sites (shaded cells in Table 5). Also, the estimated $SC$ could be used as its optimal or initial value. Say, this study simulates the runoff with two type models; one is to use the estimated parameters as the optimal values (Model I) and another as the initial values (Model II).

### (3) Comparative study of the models

First, the parameters are estimated by using Eqs.(8) and (10) and the results for the

ChungMi and HoengSung sites are rearranged in Table 6. Based on the parameters of Table 6, the runoffs are simulated by using Model I, and Model II, and Kajiyama formula is also simulated by Eq.(1). The results are compared with the observations (Figs. 4 and 5).

This describes that the estimated parameters can be used as the optimal values for the runoff simulation by TPM.

The Model I, Model II, and Kajiyama formula can be compared by the RMSE and $R^2$ in Table 6. The RMSE are 34.38mm in Model I, 27.11mm in Model II, and 42.48mm in Kajiyama formula for ChungMi site, and 43.40mm in Model I, 33.61mm in Model II, and 50.50mm in Kajiyama formula for HoengSung site. The $R^2$ are 86.79%, 91.78%, and 79.82% in Model I, Model II, and Kajiyama formula for ChungMi site. Also, for HoengSung site, $R^2$ are 72.81%, 83.70%, and 63.06% in Model I, Model II, and Kajiyama formula.

For the total runoff depth, the observation is 1731.90mm and the simulated results are 2280.98mm in Model I, 1837.10mm in Model II, and 2438.40mm in Kajiyama for ChungMi site. And also, for HoengSung site, the observation is 2322.32mm and the simulated total runoff depths are 1540.72mm in Model I, 2236.04mm in Model II, and 2856.24mm in Kajiyama formula.

The Model I and Model II are better optimized than the Kajiyama formula and the Model II is the best one from Table 6. Therefore, the Model II may be used for monthly runoff simulation in practice and it has more reasonable physical soundness than the Kajiyama formula which is widely used in Korea. Also, the TPM by Xiong and Guo (1999) was used for the gaging station but, if we use the estimated parameters suggested in this study the model could be used for the ungaged sites.

## 5. Conclusions

The TPM was suggested by Xiong and Guo

**Table 6. The estimates of c & $SC$ and $RMSE$ & $R^2$ for the simulated runoff at ChungMi and HoengSung sites in Han river basin.**

| Subcatchment | | $c$ | $SC$ | $RMSE$ | $R^2$ | Total runoff depth (mm) |
|---|---|---|---|---|---|---|
| ChungMi | Observed | - | - | - | - | 1731.90 |
| | Model I | 1.004 | 1400.0 | 34.38 | 86.79 | 2280.98 |
| | Model II | 1.247 | 699.6 | 27.11 | 91.78 | 1837.10 |
| | Kajiyama | - | - | 42.48 | 79.82 | 2438.40 |
| HoengSung | Observed | - | - | - | - | 2322.32 |
| | Model I | 1.283 | 1200.0 | 43.40 | 72.81 | 1540.72 |
| | Model II | 1.012 | 779.5 | 33.61 | 83.70 | 2236.04 |
| | Kajiyama | - | - | 50.50 | 63.06 | 2856.24 |

(1999) and we modified the original model for the estimations of parameters. The modified model which we suggested in this study has proved to be quite efficient in simulating the monthly runoff with the simple structure and two parameters. The modified model could be also used at the ungaged site because the parameters can be estimated by using the meteorological and geological conditions and the parameter optimization by using observations is not required in the modified model. Especially, the modified model gave better results than the Kajiyama formula which is widely used in Korea and thus it may be used for the monthly runoff simulation study.

However, we may consider more exact relationship of regional properties for the transformation of potential evapotranspiration into actual evapotranspiration to apply TPM to ungaged sites. Also, the equation for a parameter estimation of SC might be improved by obtaining more exact antecedent soil moisture condition and by performing the analysis for many sites.

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