Calibrating a Water Yield Model for Development of Hydrologic Parameters of Ungauged Small Watersheds in the Mountainous Terrain of the Tropical Monsoon Region

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Abstract

The present environmental conditions of watersheds of the mountainous terrain of the tropical monsoon region, particularly in Central Java, Indonesia, are degrading. Most of them lie in small ungauged watersheds. Soil and water conservation measures are needed. An innovative method for predicting water yield model parameters for small ungauged watersheds has been created in order to provide a tool for ameliorating the situation and especially in order to conserve water resources. A water yield model of five parameters was calibrated on eight small watersheds. The first five watersheds, denoted as the calibration watersheds, were used to develop the regression equations for predicting the model parameters. The other three watersheds were used in testing the calibrated model. The development parameters for ungauged watersheds were applied by relating the model parameters to topographic, land-use, and geomorphologic characteristics of the watershed. The relationships were tested by comparing observed and simulated runoff records from the three test watersheds. The results show that the water yield can be satisfactorily applied to ungauged basins.

Introduction

In order to ameliorate the environmental degradation in Indonesia, particularly in ungauged watersheds in Java, the Indonesian goverment has implemented many rehabilitation programmes meant to conserve soil and water resources by such means as reforestation and soil conservation measures, but the rate of degradation still exceeds that of the programmes. A simple hydrological calculation is still needed for predicting water yield in these ungauged watersheds.

A monthly water yield model developed by van der Beken and Byloos (1977) was modified to study water yield from eight small watersheds in the mountainous terrain of the tropical monsoon region of Central Java, Indonesia. The objective of this study was to develop a reliable method for estimating five parameters of the model for small ungauged watersheds in the region. Equations for predicting parameters were developed for a set of gauged watersheds and tested on a second independent set of ungauged watersheds by tailoring the relationships between the five parameter-models to measurable watershed characteristics. This testing gave a reliable check on the accuracy of prediction.

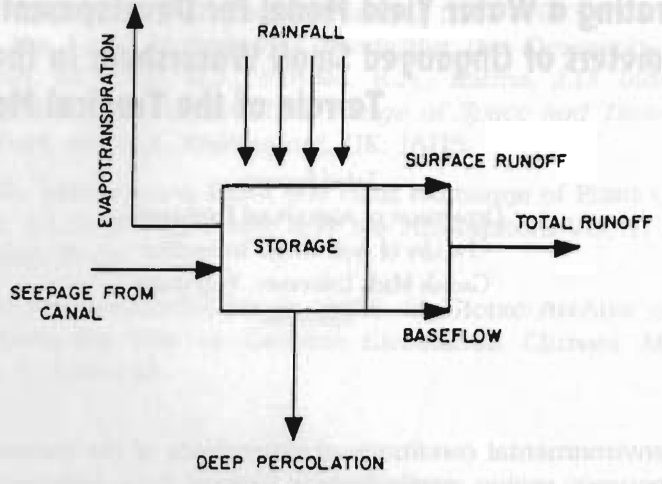

Figure 1: The Model

The Model

A water balance approach was used, with rainfall and evapotranspiration being the inputs to the model. These inputs are operated on by a series of equations that relate to the different hydrologic processes, such as infiltration, evapotranspiration, surface runoff, percolation, and groundwater return. Figure 1 shows the configuration of the model. P is natural rainfall, ETa is natural evapotranspiration, QT is total runoff, Qo is surface runoff, Qb is base flow, Lc is seepage from canals, Lp is deep percolation, Qbi and Qbo are underflow input and output from another basin, respectively, and S is storage. The governing model equation can be expressed as:

$$\Delta S = N - QT - NR + Qbi - Qbo \quad (1)$$

where,

ΔS is the change in storage, N is effective rainfall, QT is total streamflow, and NR is natural recharge.

The model assumes that the rest of the watershed is considered to be non-contributory with respect to base flow. This area can in practice be checked by comparing the base flow of a given watershed with the estimated recharge. However, since the area of watersheds is considered to be small, Qbi and Qbo can be neglected, and the equation becomes:

$$\Delta S = N - QT - NR \quad (2)$$

a. *Evapotranspiration, ETa*

The storage at the beginning of a month has a value of *S*. Actual evapotranspiration, *Eta*, is assumed to occur at a rate equal to or less than the known potential evapotranspiration rate, *Eto*, which can be predicted through a climatological approach. Therefore,

$$ETa = ETo\,[1 - \exp(-a1 * S)] \quad (3)$$

where,
a1 is a parameter (*a1* >= 0).

The underlying hypothesis of Eq. (3) is that *ETa* = *ETo* until the soil moisture content drops to the wilting point. For the same value of S, a^1 should decrease when the soil texture is more sandy.

b. *Effective rainfall, N*

Effective rainfall is the rainfall minus actual evapotranspiration. When ETa exceeds P, the storage in the next month is depleted by the effective rainfall: *N* = *P* - *ETa*. On the other hand, if *ETa* is less than *P*, part of *N* fills the storage reservoir and the other part goes to the river directly.

c. *Streamflow, QT*

The streamflow has two components: (1) base flow and (2) immediate runoff. The former depends upon the storage and the latter on the effective rainfall. Therefore,

$$QT = a^2 * S + a^3 * N \quad (4)$$

where,
$0 <= a^2 <= 1$; and $0 <= a^3 <= 1$.

The value of a^2 will increase when the soil texture is more sandy, while *a3* will increase with the degree of urbanisation and the average watershed slope.

d. *Natural recharge, NR*

Natural recharge contains (1) deep percolation of natural rainfall, *Lp*, and (2) seepage from canals, *Lc*. Mathematically, it can be written:

$$NR = Lp - Lc \quad (5)$$

The deep percolation of natural rainfall can be evaluated as a linear function of the water storage, S. If S = 0, Lp must be zero. Then,

$$Lp = a4 * S \quad (6)$$

The canal seepage remains more or less constant:

$$Lc = a5 \quad (7)$$

Therefore,

$$NR = * a^4 * S - a^5 \quad (8)$$

Where,

a^4 is a parameter relating to deep percolation and a^5 relates to canal loss.

e. Optimisation parameter

(i) Initial parameters

An initial estimate of *a1* can be obtained as follows. For sandy soil ETa/ETo may be taken as 0.75. If the average groundwater level in a given region is one metre above the riverbed and the effective porosity of the sandy layer amounts to 15 per cent, then the average active water storage becomes 150mm. Substitution of these values into Eq. (3) gives an initial estimate of $a1 = 0.01$. If N is negligible, which is true in the dry season, the following equation can be used for making an initial estimate of a^2 and a^3.

$$QT = a^2 * S \quad (9)$$

This then leads to the exponential base flow formula,

$$QT = QTo \exp [- a2 (t - to)] \quad (10)$$

and, therefore

$$S = Qdt = \frac{Qto}{a2} \quad (11)$$

in which QTo is QT at time t = to (initial value). An initial estimate of *a2* to be 0.27 is recommended.

The parameter *a3* is analogous to the rational runoff coefficient. It represents the percentage of N that immediately becomes QT. Therefore, *a3* is related to the percentage of impermeable surface. It is suggested that *a2* and *a3* are interrelated in accordance with the following equation:

$$a2 < \frac{a3}{1 - a3} \quad (12)$$

This condition may not hold in the initial estimate of *a2* and *a3* but can be assumed for the initial stage of the optimization process.

An initial estimate of *a4* can be made from an estimate of the average deep percolation of natural rainfall, Lp. If the groundwater recharge is uniformly distributed over the whole watershed,

$$\overline{Lp} = \frac{Qg}{A} \qquad (13)$$

where
Qg is groundwater, A = area of watershed. Therefore,

$$a4 = \frac{\overline{Lp}}{S} \qquad (14)$$

An initial estimate of *a4* to be 0.03 can be considered reasonable, and *a5* can be estimated by determining the long-term averages of N, QT, and Lp. A value of *a5* = 3mm is recommended.

For the initial storage, at the beginning of the period of computation, S is normally unknown. It can be estimated by correlation with the long-term average discharge volumes. As an initial estimate, it may be assumed that Si = 2 S*, where S* is the average water storage.

(ii) Optimisation method

The five initial values of the model parameters can be stated from gauged watersheds. These initial parameters can then be used in a pattern-search procedure for automatic optimisation of the model parameters. In this study, the optimum values were obtained by minimising the sum of the squares of differences between observed and simulated monthly discharge. For watersheds with no records, alternate methods for estimating the five model parameters had to be found. A relationship between the five-parameter model and measurable watershed characteristics was presupposed.

Results

Five small, gauged watersheds were used for optimising the parameter model of this study. Optimum parameters were regressed on the measurable watershed characteristics, namely, the average slope of watershed (S), the gradient of the main river (G), the percentage of forest area to total area of watershed (AF), the percentage of rice field area to total area of watershed (AR), the percentage of upland or rainfed area to the total area of watershed (AU), and the percentage of settlement area to the total area of watershed (AS). The relationships were tested by comparing observed and simulated runoff records from three watersheds that were not contained in the five calibrated watersheds. Three years of monthly data were used in this study.

Table 1 shows the characteristics of the watershed studied. A first group of five gauged watersheds, denoted as the calibration watersheds, was used to develop the regression equations for predicting the model parameters. The result of the regression analysis was a prediction equation for each of the five model parameters. These equations are:

a1 =	- 0.0262	- 0.0194 S	- 0.0055 G	- 0.0229 AF	-0.0090 AR	-0.1110 AU	-0.0023 AS	(15),
a2 =	- 0.5637	- 0.3589 S	- 0.1852 G	- 0.2966 AF	-0.6701 AR	-0.3445 AU	-0.0672 AS	(16),
a3 =	+ 1.4244	- 0.3715 S	- 0.3572 G	- 1.0807 AF	+0.2723 AR	-1.3867 AU	-0.9663 AS	(17),
a4 =	- 1.7086	- 0.4100 S	+ 0.5377 G	+1.7489 AF	+1.7931 AR	+1.7520 AU	+2.0823 AS	(18), and
a5 =	+0.7666	- 3.1007 S	+ 5.6446 G	+5.1660 AF	+9.3965 AR	+3.4369 AU	+11.5243 AS	(19).

Table 1 Watersheds Studied

No	Watershed	A (ha)	S (%)	G (%)	AR (%)	AF (%)	AU (%)	AS (%)
1.	Duren	163	24	6.3	13	28	37	22
2.	Wader	202	40	19.0	17	47	23	13
3.	Wungu	203	46	18.5	27	6	63	4
4.	Plawatan	261	24	5.0	4	40	46	10
5.	Padas	3485	34	0.6	13	12	59	16
6.	Ngunut I	596	18	3.0	21	7	27	27
7.	Ngunut II	186	9	7.0	12	0	46	42
8.	Tapan	184	41	12.2	5	59	30	5

Notes: A : watershed area; S : average slope of watershed; G : gradient of main river; AF : percentage of forest area to total area of watershed; AR: percentage of rice field area to total area of watershed ; AJ: percentage of rainfed area to total area of watershed ; AS : percentage of settlement area to total area of watershed

On the basis of these equations, a typical result of model performance arrived at by comparing observation and simulated water yield for the gauged watershed of Duren and the ungauged watershed of Tapan is shown in Figures 2 and 3, respectively. An evaluation of the accuracy of the model on the basis of four statistical measures is presented in Table 2. These measures indicate that the water yields were simulated well by the model.

Table 2 Parameter Values and Statistical Measures for Each Watershed Studied

No	Watershed	*a1*	*a2*	*a3*	*a4*	*a5*	SE	CD	CC	MB
1.	Duren	0.006	0.30	0.10	0.40	10	0.82	0.73	0.88	0.15
2.	Wader	0.002	0.15	0.33	0.10	7	0.96	0.76	0.88	0.09
3.	Wungu	0.005	0.05	0.33	0.40	6	1.78	0.64	0.83	0.06
4.	Plawatan	0.005	0.30	0.33	0.06	6	1.45	0.86	0.93	0.03
5.	Padas	0.010	0.03	0.08	0.01	5	3.60	0.72	0.87	0.05
6.	Ngunut I	0.001	0.06	0.08	0.01	6	0.13	0.55	0.79	0.12
7.	Ngunut II	0.001	0.08	0.01	0.90	10	0.39	0.60	0.86	0.18
8.	Tapan	0.001	0.065	0.04	0.001	5	0.33	0.57	0.82	0.03

Notes: SE : standard error; CD : Coefficient determination; CC : coefficient correlation; MB : mass balance

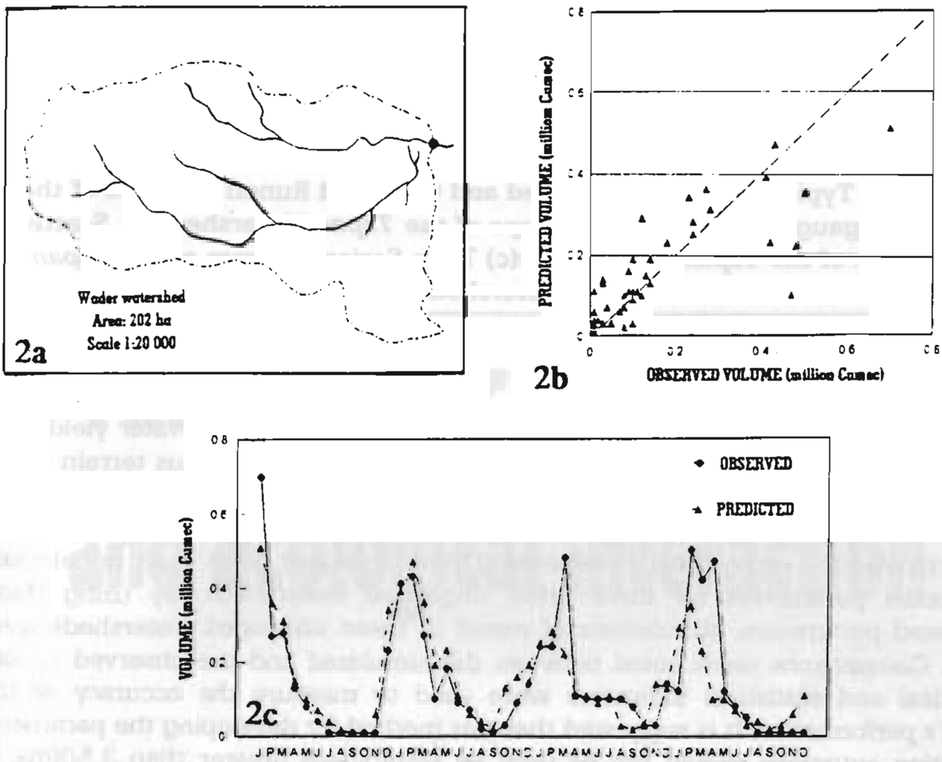

Figure 2: Typical Result of Predicted and Observed Runoff Volumes of the *Wader* Gauged Watershed (a) Shape of the *Wader* Watershed, (b) Scatter Diagram for the *Wader* watershed, (c) Time Series Diagram of *Wader* Watershed

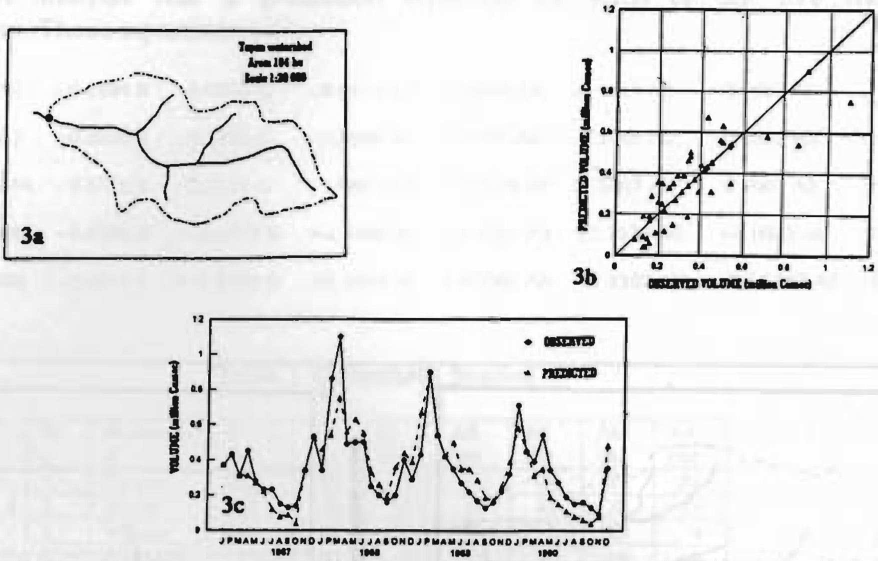

Figure 3 Typical Result of Predicted and Observed Runoff Volumes of the *Tapan* Ungauged Watershed (a) Shape of the *Tapan* Watershed, (b) Scatter Diagram of the *Tapan* Watershed, (c) Time Series Diagram of the *Tapan* Watershed

Conclusion

The optimum parameters for a five-parameter model of monthly water yield have been obtained on five, small gauged watersheds in the mountainous terrain of the tropical monsoon region in Central Java, Indonesia. These optimum parameters were then regressed on measurable watershed characteristics. Prediction equations were derived for each model parameter. These equations were used to calculate the model parameters for three other ungauged watersheds. By using these calculated parameters, simulations of runoff in these ungauged watersheds were made. Comparisons were noted between the simulated and the observed runoff. Graphical and statistical indicators were used to measure the accuracy of the model's performance. It is suggested that this method for developing the parameter prediction equations should not be used on watersheds greater than 3,500ha in area.

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Reference

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