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Estimation of the IHACRES Model Parameters for Flood Estimation of Ungauged Catchments in the Upper Ping River Basin

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ABSTRACT

The estimation of model parameters for ungauged catchments usually involves formulating relationships between model parameters and catchment characteristics from neighboring gauged catchments. This study examined the effectiveness of the IHACRES rainfall-runoff model for flood estimation in the upper Ping River basin (UPRB). As a first step, the model was calibrated for nine subcatchments in the basin. Relationships among catchment attributes (catchment area, drainage, slope and elongation) and six model parameters at nine runoff stations were derived using a multiple regression. A sensitivity analysis of the six IHACRES parameters at the P.4A station was carried out to determine the effect these parameters had on flood hydrograph characteristics. Regression relationships were then applied to estimate the model parameters at two independent runoff stations as if these catchments were ungauged and compared with model results if the parameters were chosen to give a best fit with recorded data. The results showed that the suggested relationships can be reasonably applied for flood estimation of the ungauged catchments within the UPRB.

Keywords: IHACRES model, ungauged catchment, upper Ping River basin

INTRODUCTION

Hydrological models are commonly used for flow and flood estimation to serve several purposes in water resources projects. There are many hydrological models which can be divided into the two categories of empirical and conceptual models (Carcano *et al*., 2008). An empirical model is based on a mathematical linkage between an input and output series (for example, rainfall and runoff data) considering the catchment as a lumped unit, with no physical characteristics of the basin. Examples of this type of model include: classical autoregressive moving average (ARMA) models, initially developed by Box and Jenkins (1976) and all extensions; transfer function models (Hipel and McLeod, 1994); and artificial neural networks (ANNs) described by Cybenko (1989). On the other hand, conceptual models describe relevant components of hydrological behavior through simplified conceptualizations of the physical transportation processes associated with the hydrological cycle. Various models have been developed under this concept, for example, the Soil Conservation Service (SCS) developed by USDA (1972), NAM (Nielsen and Hansen, 1973), TANK (Sugawara, 1974), HEC-HMS (Hydrologic Engineering Center (HEC), 2000), SWAT (Neitsch *et al*., 2005), TOPMODEL (Beven and Kirkby, 1979; Beven *et al*., 1995) and IHACRES (Croke

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et al., 2003). The IHACRES model which has been used in the present study is a conceptual rainfall-runoff model consisting of two modules: a non-linear loss module to transform the measured rainfall to effective rainfall, and a linear routing module to compute a linear combination of antecedent streamflow values and effective rainfall. Despite its relatively recent development, IHACRES has been widely and quickly accepted in the hydrological modeling community because of its structural simplicity that reduces parameter uncertainty, while at the same time attempting to represent more details of the internal processes than is typical for a distributed model (Croke *et al*., 2005). It has been successfully applied to investigate the hydrological response for various catchments worldwide such as in Australia (Carlile *et al*., 2004), Thailand (Croke *et al*., 2003; Taesombat and Sriwongsitanon, 2010), the USA (Evans, 2003), the UK (Littlewood *et al*., 1997) and South Africa (Dye and Croke, 2003).

In applying hydrological models, model parameters need to be evaluated, normally through calibration and validation procedures on gauged catchments. For ungauged catchments, model parameters have to be estimated, usually by formulating relationships between model parameters and catchment characteristics on nearby gauged catchments. For instance, Post and Jakeman (1996) found that some parameters of the IHACRES model could be successfully related to catchment characteristics in sixteen small catchments in the Maroondah region of Victoria, Australia. Sefton and Howarth (1998) also successfully derived relationships between parameters of the IHACRES model in terms of the physical catchment characteristics in 60 catchments in England and Wales using multiple regression techniques. Mapiam and Sriwongsitanon (2009) revealed that relationships between the URBS model parameters and catchment characteristics can be confidently applied for flood estimation of ungauged catchments within the catchment area of the 11 stations in the upper Ping River basin (UPRB), Northern Thailand.

The present study investigated the relationships between the IHACRES model parameters and catchment characteristics for gauged catchments in the UPRB in order to allow IHACRES to estimate flooding in nearby ungauged catchments also within the UPRB. First, IHACRES was applied on 11 runoff stations: 9 for calibration and 2 for validation to determine the model's ability in flood estimation and to derive relationships between model parameters and catchment characteristics. The sensitivity of model parameters was also checked at the P.4A station to develop an understanding of how the model parameters affect the peak and volume of a flood hydrograph.

MATERIALS AND METHODS

Study area

The UPRB covers a catchment of around 25,370 km^2 in the provinces of Chiang Mai and Lamphun in northern Thailand. The Royal Forest Department reported that the forest area in the UPRB had declined from nearly 100% historically to 72% of the total area by 2006. The basin is mostly mountainous and is one of the main tributaries of the Chao Phraya River which covers around one third of Thailand. The Ping River originates in Chiang Dao district in the north of Chiang Mai province and flows southward into the Bhumibol dam, a large reservoir with an active storage capacity of 9.7 billion m^3. The average annual rainfall and runoff of the basin are 1,174 mm and 6.8 billion m^3, respectively. Figure 1 shows a map of the UPRB.

Data collection

Runoff data

Data between 1988 and 2006 were available for the study from 18 runoff stations in the UPRB operated by the Royal Irrigation Department (RID). However, some of these stations were unsuitable for the study for the following reasons:

1) P.56A station can be affected by backwater from the Mae Ngat reservoir so data from this station could be unreliable, especially during flood events.

2) Stations P.75, P.67, P.1 and P.73 located along the Ping River and downstream of the Mae Ngat and Mar Kuang reservoirs were not used, as reservoir operations would be expected to affect flood behavior at these stations.

3) Stations P.79 and P.80 only commenced operation in 2001, so insufficient data were available for use in this study.

After eliminating these unsuitable stations, daily runoff data were available from a network of 11 stations throughout the UPRB, as shown in Figure 1 and Table 1.

Rainfall data

Daily rainfall data selected from a network of 62 stations operated by the RID, the Department of Water Resources (DWR), and the Thai Meteorological Department (TMD) were used in the study. Areal rainfall estimation was carried out using the thin plate spline (TPS) technique which provides more accurate results of rainfall estimation than the isohyetal technique and particularly the Thiessen polygon technique (Taesombat and Sriwongsitanon, 2009). The areal daily rainfall data were used as the input data for IHACRES to simulate flood hydrographs for 11gauged catchments within the UPRB. Figure 1 shows the locations of the 62 rainfall stations used in the study. These rainfall stations provided data covering the period between 1988 and 2006 that was used as runoff data for the IHACRES application.

Meteorological data

Daily temperature data at three meteorological stations, located in Chiang Mai (CM-Met), Lamphun (LP-Met), and the Bhumibol dam site (BB-Met), were used to provide input data for IHACRES. These stations are operated by the TMD. Figure 1 shows the locations of these three stations used in the study. All of meteorological stations were able to provide data covering the period between 1988 and 2006 for use as runoff data in the model.

Table 1 Analysis of 11 runoff stations.

Runoff station	Area (km^2)	Runoff data period of records	Number of rainfall stations	Mean annual runoff (mm)	Mean annual rainfall (mm)	Runoff/Rainfall (%)
P.4A	1,902	1988–2006	9	187	1,142	16.4
P.14	3,853	1988–2006	10	258	1,128	22.8
P.20	1,355	1988–2006	6	277	1,023	27.1
P.21	515	1988–2006	5	690	1,029	67.1
P.24A	460	1988–2006	5	290	1,043	27.8
P.42	315	1988–2001	3	103	862	12.0
P.64	336	1990–2006	2	434	1,056	41.1
P.65	240	1992–2006	2	508	1,162	43.7
P.71	1,771	1996–2006	12	161	1,088	14.8
P.76	1,541	2000–2006	4	130	828	15.7
P.77	547	1999–2006	4	146	922	15.8

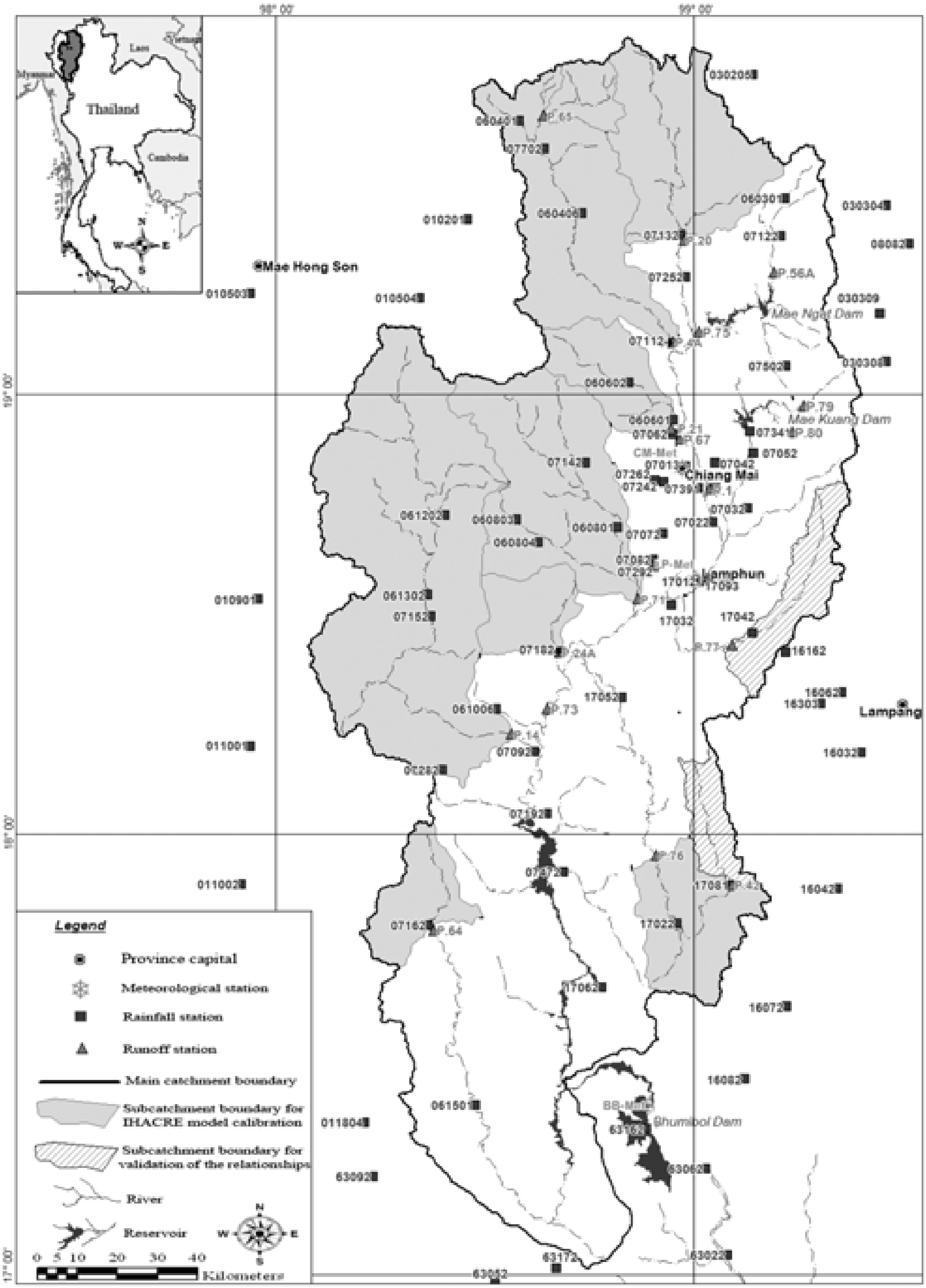

Figure 1 Location of upper Ping River basin and rainfall, runoff and meteorological stations. Meteorological stations were located at Chiang Mai (CM-Met), Lamphun (LP-Met), and Bhumibol dam site (BB-Met).

Catchment characteristics

IHACRES considers four attributes of catchment morphology. First, catchment size (A) is determined based on the catchment area (square kilometers). Catchment shape is described by the catchment elongation (EG), defined as the ratio of the diameter of a circle with the same area as the catchment to the catchment length (Schumm, 1956). The slope of the catchment (S) is defined by the angle formed by the catchment maximum vertical relief and channel length. Catchment drainage density (D) is defined by Horton (1932) as the total length of streams in kilometers per square kilometer. Table 2 presents the four catchment attributes which were derived for each of the 11 subcatchments in the UPRB.

The IHACRES model

IHACRES is an acronym for 'Identification of unit Hydrographs And Component flows from Rainfall, Evaporation, and Streamflow data'. It is a catchment-scale rainfall-runoff model that aims to characterize the dynamic relationship between rainfall and runoff. The first version of the model (Version 1.0) was developed in 1994 by the Institute of Hydrology (IH), Wallingford, UK (Littlewood and Jakeman, 1994). The model was later updated to Version 2.1 by the Centre for Resource and Environmental Studies (CRES), Australian National University, Australia by adding a non-linear loss module and alternative model calibration techniques (Croke *et al*., 2003). Figure 2 shows the model structure, which

Table 2 Derived catchment attributes for 11 subcatchments in the upper Ping River basin.

Station	Area (km^2)	Drainage (km/km^2)	Slope (%)	Elongation
P.4A	1,902	0.40	7.84	0.06
P.14	3,853	0.43	8.13	0.04
P.20	1,355	0.33	8.01	0.09
P.21	515	0.38	7.23	0.13
P.24A	460	0.42	9.83	0.13
P.42	315	0.33	4.23	0.19
P.64	336	0.77	4.90	0.08
P.65	240	0.44	6.41	0.16
P.71	1,771	0.43	6.88	0.06
P.76	1,541	0.25	4.12	0.12
P.77	547	0.32	6.32	0.15

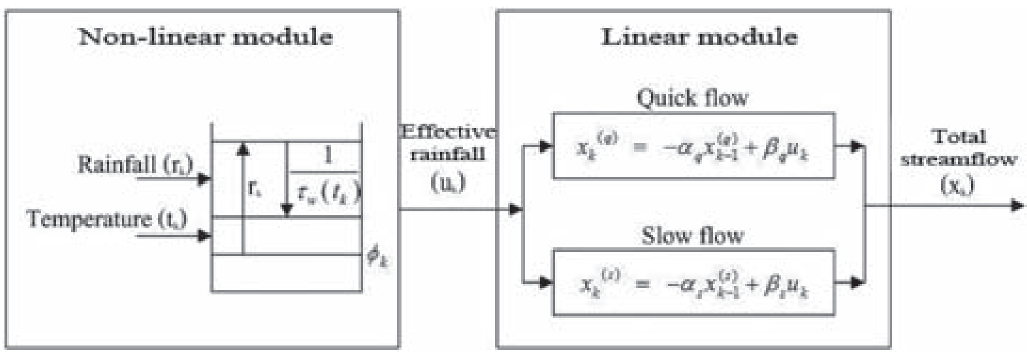

Figure 2 IHACRES model structure (Evans and Jakeman, 1998).

comprises the modules of the non-linear and linear relationships. The non-linear module represents a transformation of rainfall and temperature into effective rainfall, while the linear module converts the effective rainfall into runoff.

In the non-linear module, Equation 1 shows the non-linear representation of the effective rainfall (u_k) in mm proposed by Ye *et al*. (1997):

$$u_k = \left[c(\phi_k - l)\right]^p r_k \quad (1)$$

where, r_k is the observed rainfall in mm on day k, c is the mass balance, l is the soil moisture index threshold for producing flows and p is the non-linear response term. The parameters l and are p typically only necessary for ephemeral catchments (Carcano *et al*., 2008). Soil moisture (ϕ_k) is described by Equation 2:

$$\phi_k = r_k + \left(1 - \frac{1}{\tau_k}\right)\phi_{k-1} \quad (2)$$

where, τ_k is the drying rate as determined by Equation 3:

$$\tau_k = \tau_w e^{(0.062 f(t_r - t_k))} \quad (3)$$

where, t_k is the observed temperature (°C), τ_w is the drying rate at reference temperature (°C), f is the temperature modulation (°C^{-1}) and t_r is the reference temperature (°C), which is set to the local average air temperature. The parameter f relates to seasonal variation of evapotranspiration, which is mainly affected by climate, land use and land cover. The parameter τ_w affects the variation of soil drainage and infiltration rates.

IHACRES Version 2.1 is a more general version than the original Version 1.0. However, users can switch from Version 2.1 to Version 1.0 by setting the parameters l and p to be zero and one, respectively, and then the soil moisture index $s_k = c\phi_k$ as in the original version.

In the linear module, the effective rainfall is converted into runoff using a linear relationship. There are two components in the flow routing—quick flow and slow flow. These two components can be connected either in parallel or in series. It has been recommended in most applications to use the two components connected in parallel, except for semi-arid regions or in ephemeral streams, where one component is usually sufficient (Ye *et al*., 1997). The parallel configuration of these two stores at time step k—quick flow ($x_k^{(q)}$) and slow flow ($x_k^{(s)}$)—are combined to yield the runoff (x_k) as presented in Equation 4 supported by Equations 5 and 6:

$$x_k = x_k^{(q)} + x_k^{(s)} \quad (4)$$

$$x_k^{(q)} = -\alpha_q x_{k-1}^{(q)} + \beta_q u_k \quad (5)$$

$$x_k^{(s)} = -\alpha_s x_{k-1}^{(s)} + \beta_s u_k \quad (6)$$

where, parameters α_q, β_q are time constants for the quick flow and α_s, β_s are time constants for the slow flow. Dynamic response characteristics (DRCs) unit hydrographs for the quick flow and slow flow are calculated as shown in Equations 7 and 8, respectively.

$$\tau_q = \frac{-\Delta}{\ln(-\alpha_q)} \quad (7)$$

$$\tau_s = \frac{-\Delta}{\ln(-\alpha_s)} \quad (8)$$

where, Δ is the time step, τ_q and τ_s are the recession time constants for quick flow and slow flow in days, respectively. Evans and Jakeman (1998) recommend that the parameter τ_q be less than the time step. The relative volume of quick flow and slow flow can be calculated using Equation 9:

$$V_q = 1 - V_s = \frac{\beta_q}{1+\alpha_q} = 1 - \frac{\beta_s}{1+\alpha_s} \quad (9)$$

where, V_q is the proportion of the quick flow to the total flow ($1-V_s$) and V_s is the relative volume of slow flow.

Model calibration

To calibrate the model, firstly, the entire period of record for each catchment was divided into three-year periods, each of which overlapped the previous period by one year. In this way, model parameters were exposed to some inter-annual variability, while ensuring that the hydrological response of the catchment did not change dramatically within the calibration period. The outcome of the calibration of each period was used to determine suitable values of each model parameter for the years 1988–2006 for each subcatchment.

Sensitivity analysis for the IHACRES model

The purpose of the sensitivity analysis was to understand how the hydrograph outputs produced by the IHACRES model are affected by the six significant model parameters of c, τ_w, f, τ_s, τ_q and V_s. If trends are evident that signify how changing parameter values affects the characteristics of the hydrograph for the UPRB, a better understanding of how IHACRES represents catchment rainfall-runoff processes on the UPRB can be developed.

Sensitivity analysis of the hydrograph to changes of parameters was carried out by running the model with a range of values for each parameter independently, while other parameters remained constant at the P.4A station. As parameter values were changed, increases or decreases in the flood peak and flood volume were noted.

Relationships between model parameters and catchment attributes

To date, generalized relationships between IHACRES parameters and physical catchment attributes have yet to be developed. Yet, having such relationships would greatly enhance more widespread use of the model (Sefton and Howarth, 1998). The relationships between calibrated model parameters and catchment attributes should ideally contain independent variables, be statistically significant and physically sensible, whilst yielding good estimates of model parameters that can be shown to allow the model to reliably simulate observed discharge.

To determine if such relationships can be developed for IHACRES, linear and non linear multiple regression analysis were applied to determine a set of equations suitable for estimating all six model parameters based on the catchment attributes for the nine sub-catchments used in the calibration. Catchments of stations P.42 and P.77 were excluded from the determination of the multiple regression relationships as these catchments were used to validate the equations. Based on the equations, each parameter was compared against the parameters obtained from the normal calibration in order to test the reliability of the equations that had been formulated in the multiple regression analysis.

RESULTS AND DISCUSSION

Calibration of IHACRES model

A comparison between the outcomes of the calibration of discharge as derived from the predictions of the IHACRES model during the years 1988–2005 and the actual observations is illustrated by the correlation coefficient (r), efficiency index (EI) and root mean square error ($RMSE$) as shown in Figure 3. An example of the model calibration results for the P.4A runoff station is shown in Figure 4.

Sensitivity analysis of IHACRES model

By varying values of each parameter individually while keeping other parameters constant for the catchment of the P.4A station, sensitivity analysis was performed to determine their effects on the flood peaks and flood volumes of the hydrograph. The month of September 2003 was selected for the calibration of IHACRES. Over this period, the best fit parameters as determined in the calibration phase were c = 0.005579, $\tau_w = 2$, $f = 2$, $\tau_s = 12.361$, $\tau_q = 1.945$ and $V_s = 0.081$. The results associated with the sensitivity of flood peaks and flood volumes to changes in the six parameters are shown in Tables 3 and 4 and in Figure 5.

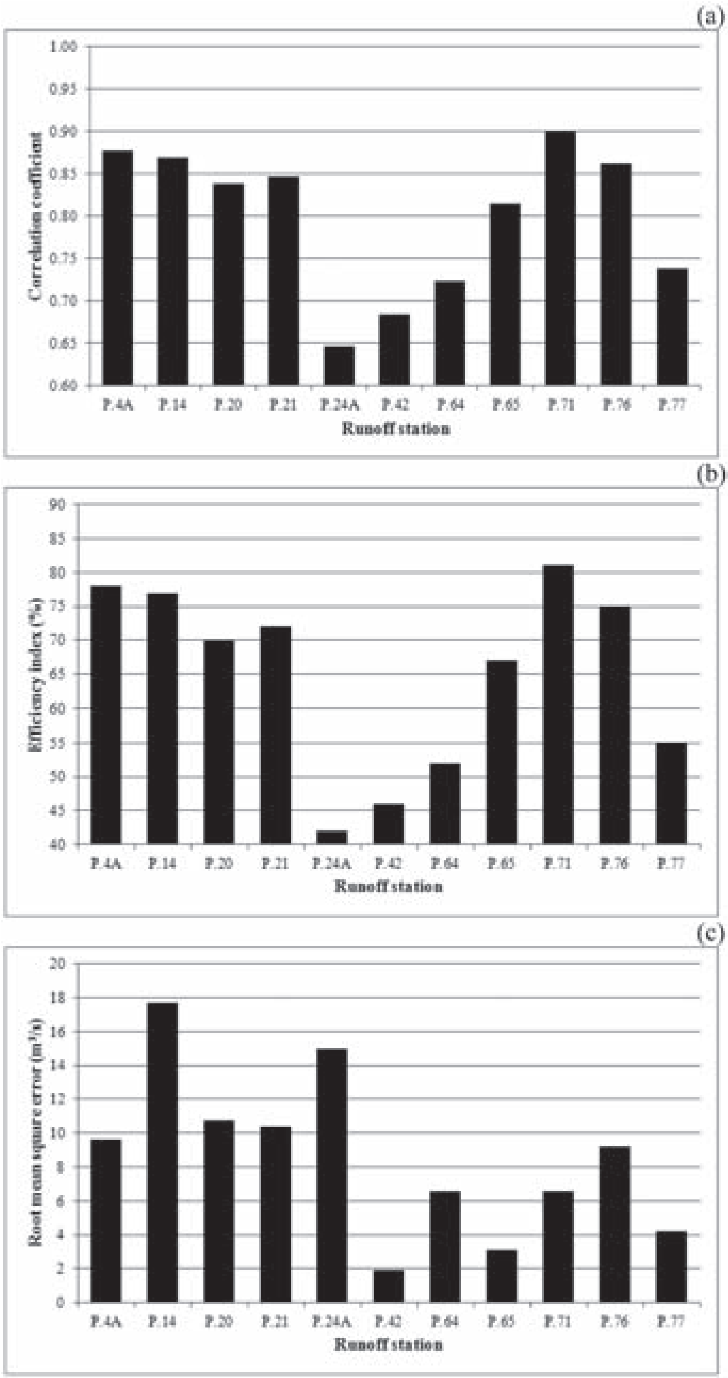

Figure 3 Statistical indicators for the calibration and validation results: (a) Correlation coefficient; (b) Efficiency index; (c) Root mean square error.

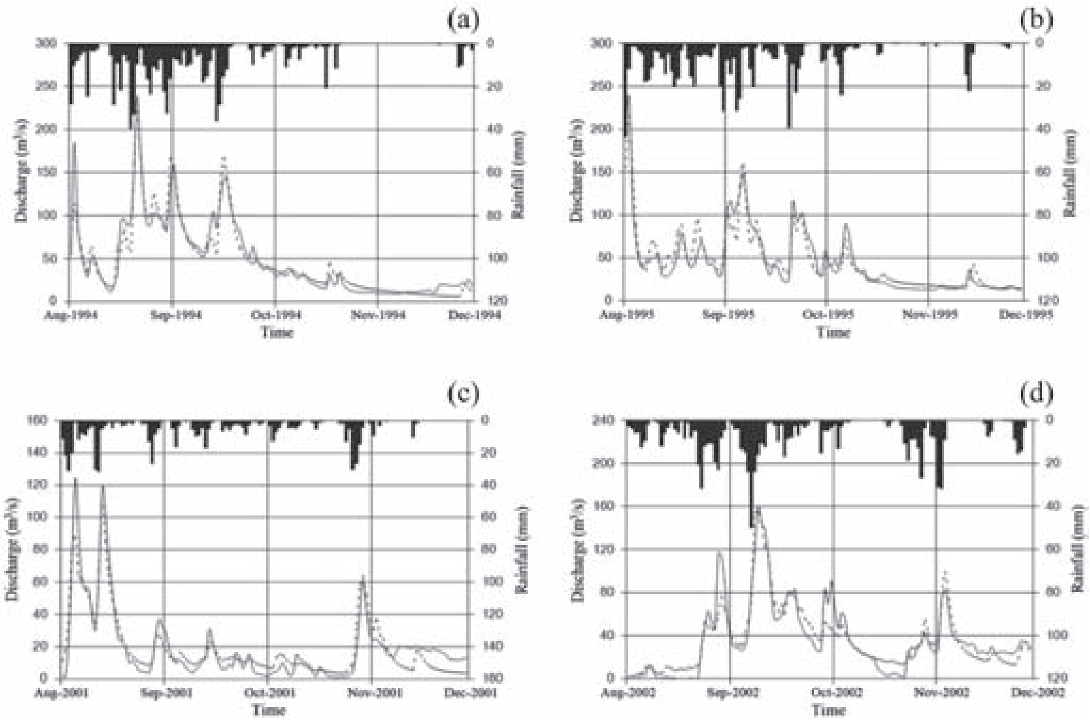

Figure 4 Calibration results for the station P.4A: (a) Year 1994; (b) Year 1995; (c) Year 2001; (d) Year 2002. ■ Rainfall —— Observed - - - IHACRES

Table 3 Sensitivity results of non-linear module of the IHACRES model parameters at station P.4A.

Change parameter	c		Change parameter	τ_w		Change parameter	f	
	Peak (%)	Volume (%)		Peak (%)	Volume (%)		Peak (%)	Volume (%)
0.003	-46.2	-46.2	1	-42.6	-40.0	1	3.5	4.2
0.004	-28.3	-28.3	3	36.2	32.0	3	-3.6	-4.1
0.006	7.6	7.6	4	65.4	59.8	4	-7.4	-8.3
0.007	25.5	25.5	5	89.6	84.9	5	-11.3	-12.5
0.008	43.4	43.4	6	110.3	108.1	6	-15.4	-16.6
0.009	61.3	61.3	7	128.7	130.0	7	-19.4	-20.5
0.010	79.3	79.3	8	145.3	150.6	8	-23.6	-24.1
0.011	97.2	97.2	9	160.6	170.2	9	-27.7	-21.2

c = mass balance; τ_w = drying rate at reference temperature (°C); f = temperature modulation (°C^{-1}).

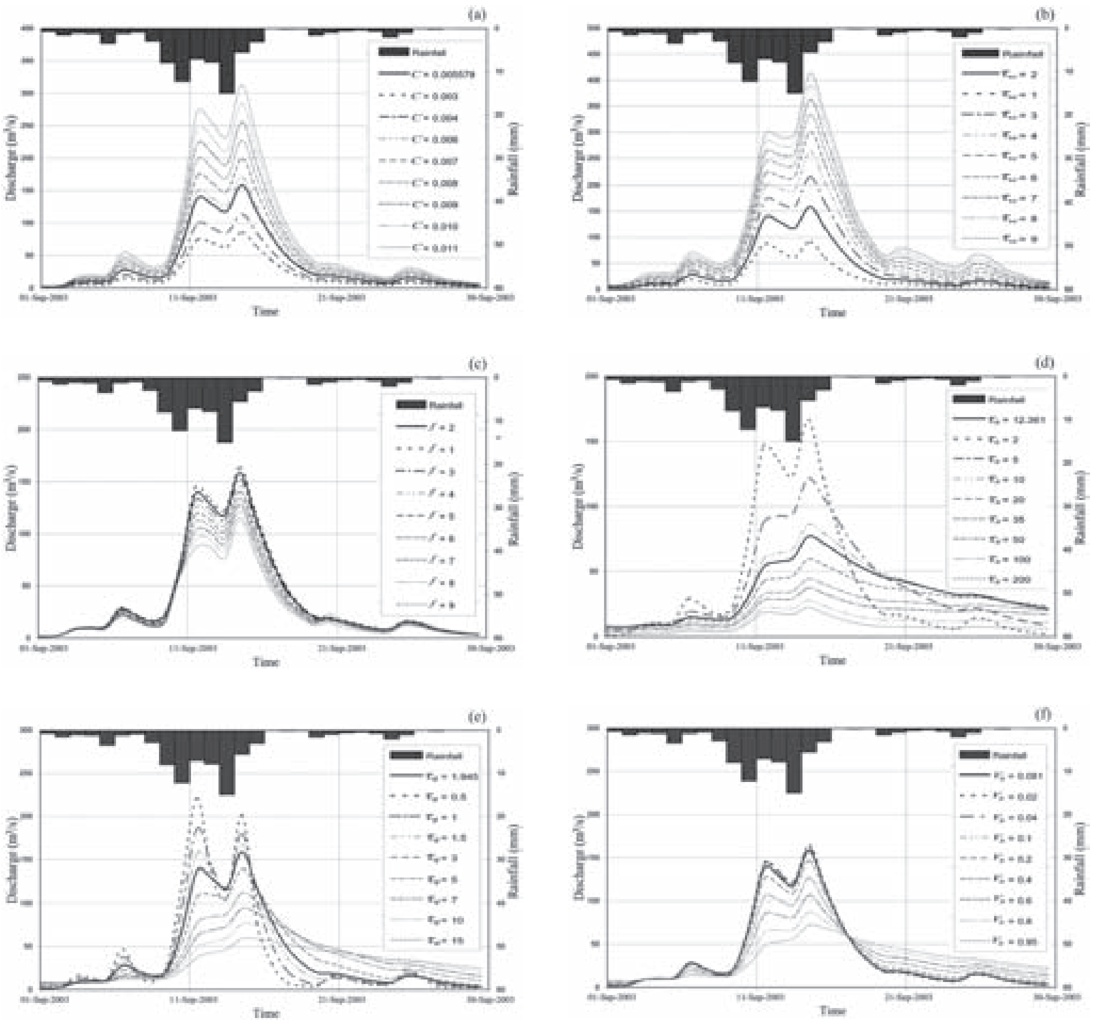

Figure 5 Sensitivity results for IHACRES model parameters at station P.4A.
(a) mass balance = c; (b) drying rate at reference temperature (°C) = τ_w; (c) temperature modulation (°C^{-1}) = f; (d) recession time constant for slow flow in days = τ_s; (e) recession time constant for quick flow in days = τ_q;(f) relative volume of slow flow = V_s.

With regard to the sensitivity characteristics of parameters, the parameters in the non-linear module (c, τ_w and f) were found to have significant effects on the volume and peak of the flow hydrograph. The parameters in the linear module (τ_s, τ_q and v_s) also affected the peak, shape and volume of the hydrograph (see Table 4).

Multiple regression analysis using IHACRES parameters and catchment attributes

Multiple regression analysis was used to determine equations relating the six IHACRES model parameters to the catchment attributes. It was found that non-linear multiple regression gave higher correlation coefficients than linear regression. Most regression relationships had satisfactory values of correlation coefficient ranging from 0.6 to 0.85 as shown in Table 5 which showed that the parameter *c*, (the mass balance) had significant relationships only with catchment size (*A*) and catchment shape (*EG*), while the other five parameters showed good correlation with all four catchment attributes.

Validation of relationships between model parameters and catchment attributes

The relationships between the model parameters and catchment attributes were validated by applying them to estimate the model parameters for the nine calibration subcatchments. Comparisons of parameter values derived from the regression relationships and from the normal calibration are shown in Figure 6. The estimation of parameters based on the proposed equations gave a satisfactory result when compared to the results from the normal calibration. Next, these equations were validated on the two sub-catchments, P.42 and P.77. After this procedure, the parameters obtained from the regression equations for P.42 and P.77 were used in IHACRES to estimate the discharge time series as if these two sub-catchments were ungauged. The calculated discharges were then compared with the earlier estimates based on the parameters derived from the normal calibration (gauged approach).

Table 4 Sensitivity results of linear module of the IHACRES model parameters at station P.4A.

Change parameter	τ_s		Change parameter	τ_q		Change parameter	V_s	
	Peak (%)	Volume (%)		Peak (%)	Volume (%)		Peak (%)	Volume (%)
2	116.4	21.7	0.5	39.8	0.3	0.02	3.8	1.2
5	57.7	18.3	1.0	17.3	0.2	0.04	2.6	0.8
10	11.7	6.0	1.5	5.8	0.2	0.10	-1.2	-0.4
20	-22.9	-16.5	3.0	-12.0	-0.6	0.20	-7.5	-2.4
35	-42.5	-36.6	5.0	-29.2	-2.9	0.40	-20.0	-6.4
50	-51.7	-48.1	7.0	-40.7	-6.8	0.60	-32.6	-10.5
100	-63.9	-65.2	10.0	-51.9	-13.5	0.80	-45.2	-14.5
200	-70.8	-75.7	15.0	-62.7	-24.0	0.95	-54.6	-17.5

τ_s = recession time constant for slow flow in days; τ_q = recession time constant for quick flow in days; V_s = relative volume of slow flow.

Table 5 Equations derived from the relationship between model parameters and catchment attributes.

Relationship equation	*r*	Range of model parameter
$1/c = 14.628 \times A^{0.236}\, EG^{-0.733}$	0.85	0.003–0.011
$f = 5.256 \times A^{1.515}\, D^{2.908}\, S^{0.684}\, EG^{3.52}$	0.64	1–9
$\tau_w = 5.047 \times A^{3.703}\, D^{7.133}\, S^{-0.503}\, EG^{6.458}$	0.66	1–9
$\tau_q = 0.078 \times A^{3.505}\, D^{6.518}\, S^{0.615}\, EG^{6.685}$	0.80	0.5–15
$\tau_s = 6.729 \times A^{0.208}\, D^{0.717}\, S^{0.813}\, EG^{0.173}$	0.78	2–200
$1/V_s = 2.043 \times A^{-0.207}\, D^{-0.667}\, S^{-0.242}\, EG^{-0.418}$	0.71	0.02–0.95

r = Correlation coefficient.

c = mass balance; τ_w = drying rate at reference temperature (°C); *f* = temperature modulation (°C^{-1}); τ_q = recession time constant for quick flow in days; τ_s = recession time = constant for slow flow in days; V_s = the relative volume of slow flow; A = catchment area (km^2); D = Catchment drainage density (km/km^2); S= Catchment slope (%); EG = catchment elongation.

An example of the comparison between the gauged and ungauged approaches at runoff station P.77 is presented in Figure 7. The values of *r*, *EI*, and *RMSE*, which compared these two types of hydrographs at these two stations are presented in Table 6 and considered satisfactory. The ungauged approach provided a slightly lower value of *r* and *EI* and a slightly higher *RMSE* than those of the gauged approach, which was to be expected because the proposed relationships do not estimate the model parameters as accurately as actual readings from a gauged catchment can.

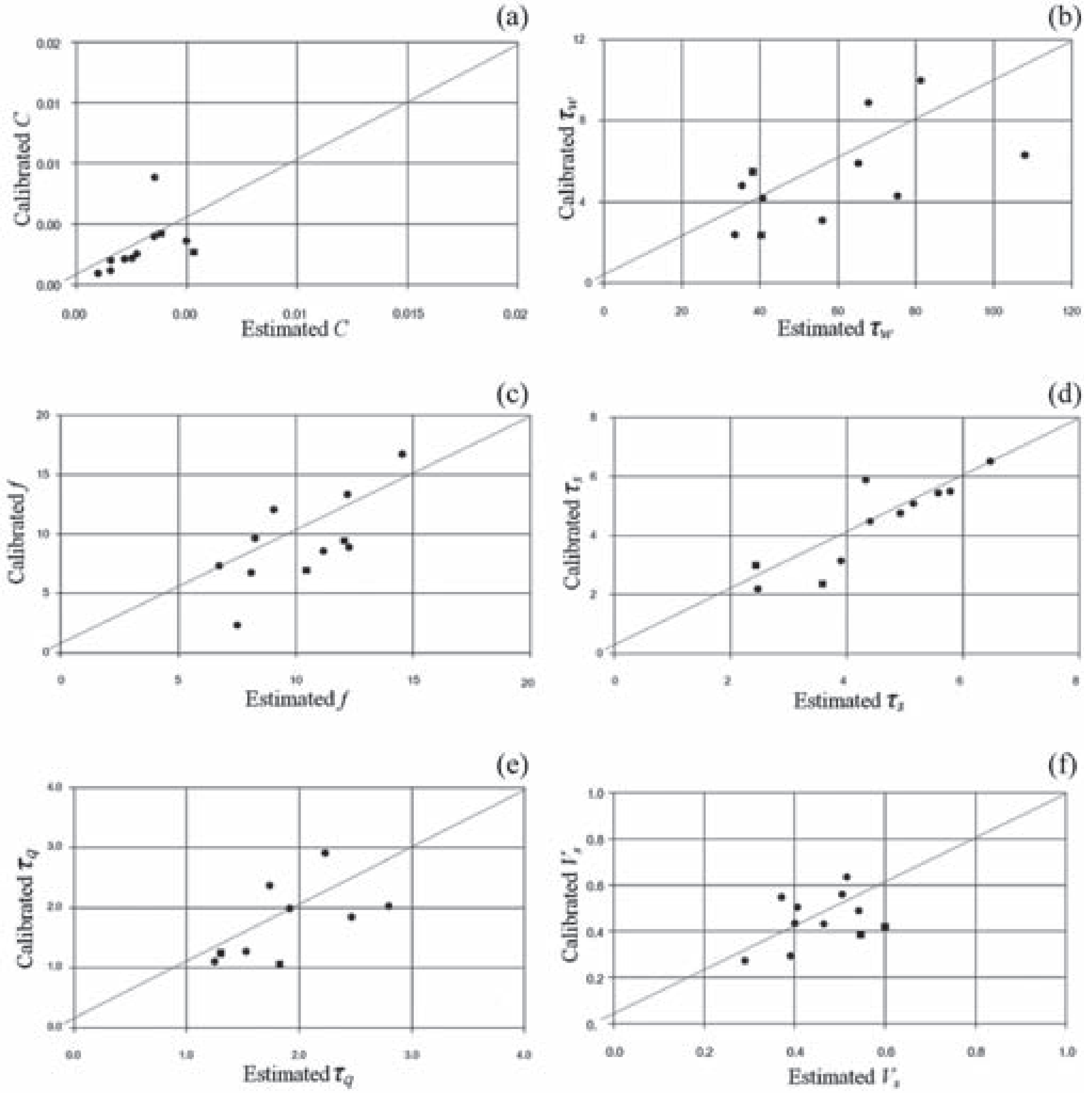

Figure 6 Scatter plot showing the relationship between model results where the model parameters were determined directly as best fit cases (calibration) and were estimated by regression cases (estimated) for nine calibration and two validation catchments:
(a) Mass balance = c; (b) drying rate at reference temperature (°C) = τ_w; (c) temperature modulation (°C^{-1}) = f; (d) recession time constant for slow flow in days = τ_s; (e) recession time constant for quick flow in days = τ_q; (f) relative volume of slow flow = V_s .
● Calibration catchment ■ Validation catchment

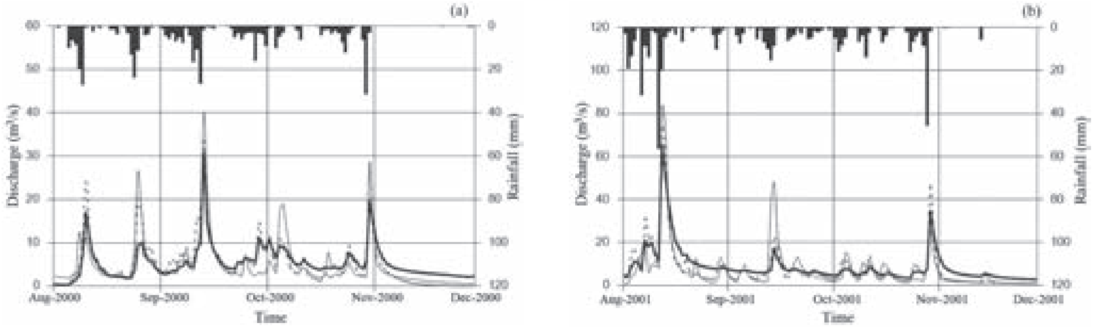

Figure 7 Observed and calculated flood hydrographs at runoff station P.77: (a) Aug-2000 and Nov-2000; and (b) Aug-2001 and Nov-2001.
Rainfall —— Observed - - - - Gauged approach ▬▬ Ungauged approach

Table 6 Statistical indicators for the validated stations.

Runoff station	Year	*r*		*EI* (%)		*RMSE* (cm)	
		Gauged	Ungauged	Gauged	Ungauged	Gauged	Ungauged
P.42	2000	0.65	0.63	57.7	52.3	1.8	2.3
	2001	0.83	0.82	68.2	66.6	2.9	3.0
P.77	2000	0.86	0.82	73.8	65.3	3.0	3.5
	2001	0.88	0.85	77.0	69.2	5.5	6.4

r = correlation coefficient; *EI* = efficiency index; *RMSE* = root mean square error.
Gauged = Gauged approach; Ungauged = Ungauged approach.

CONCLUSION

The study showed that IHACRES can be used quite reliably for estimating flood hydrographs at different stations in the UPRB. Since most of the selected hydrographs used in this study recorded floods whose flows overtopped the riverbank (such as the flood in 2003 at station P.4A), it can be expected that this rainfall-runoff model is suitable to be applied for flow and flood estimation in other river basins in Thailand. The sensitivity analysis carried out at one station in the basin helped to understand the effect of each model parameter on the characteristics of the hydrograph. This procedure has produced guidelines for the model's application. To make the model useful for a number of ungauged catchments in the UPRB, the relationships between model parameters and catchment attributes were derived using multiple regression techniques. The proposed relationships proved to be practical for estimating model parameters in the ungauged basins. It should be noted that the proposed relationships can only be applied to the basins surrounding the one in which the relationships were formulated. The methodology carried out in this research paper can be used as a guideline in formulating the relationships between model parameters and catchment attributes in other river basins in Thailand where many areas are still ungauged.

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LITERATURE CITED

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