RESEARCH ARTICLE
doi: 10.2306/scienceasia1513-1874.2009.35.049

ScienceAsia 35 (2009): **49–56**

Estimation of the URBS model parameters for flood estimation of ungauged catchments in the upper Ping river basin, Thailand

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Received 3 Jul 2008
Accepted 27 Feb 2009

ABSTRACT: Flood hydrographs are usually estimated from models on gauged catchments. Flood estimation on ungauged catchments requires relationships between model parameters and catchment characteristics. In this study, both the URBS model and Nedbor-Afstromings model (NAM) were shown to be successful in simulating flood behaviour in the upper Ping river basin, Northern Thailand. To formulate the relationships for applying to ungauged catchments, we chose the URBS model as it requires only 4 parameters whereas the NAM requires 6. The relationships between the URBS model parameters calibrated from 11 runoff stations and the corresponding catchment characteristics were adopted to estimate the URBS model parameters at 4 runoff stations in the target area as if the catchments were ungauged. The results of flood estimation obtained from the ungauged catchment approach were then compared with that gained from the gauged catchment approach. The results revealed that the proposed relationships between the URBS model parameters and catchment characteristics can be confidently applied for flood estimation of the ungauged catchments within the catchment area of the 11 stations used in the formulation process.

KEYWORDS: hydrologic model, Nedbor-Afstromings model, calibration, model verification

INTRODUCTION

Flood forecasting is a non-structural measure useful for mitigating the economic and social damage of flooding, especially with regard to human life. To be able to estimate flooding correctly, a hydrologic model is a crucial tool. Conventional hydrologic models were developed based on simulating the hydrologic cycle. However, there are many components involved in the cycle such as interception, infiltration, depression storage, evaporation, subsurface flow, groundwater flow, overland flow, and channel flow [1,2], most of which cannot be measured directly. Different techniques have been developed to estimate such unmeasurable hydrological components. Empirical formulas have been developed to estimate interception [3], infiltration [4], channel flow [5], and overland flow [6]. Lowdermilk [7], Hursh [8], and Hursh and Brater [9] concluded that subsurface water is a significant hydrological component in flood hydrographs by observation in humid regions. Keulegan [10] introduced the kinematic wave approach for overland flow. The Soil Conservation Service [11] have developed the SCS curve-number approach to evaluate rainfall loss rate. Various models [12–14] have been developed for runoff estimation by considering only the most significant hydrologic cycle components. More complicated models normally require more input data and are difficult to apply, especially for catchments with insufficient or no hydrologic data (known as ungauged catchments). This study aims to select a simple model for flood hydrographs assessment at runoff stations in the upper Ping river basin located in Northern Thailand and to formulate relationships between model parameters and catchment characteristics for use on ungauged catchments. The URBS model, which has been applied successfully for real time flood forecasting in Australia and China [15–18], and the NAM model, which has been accepted worldwide, were chosen for model comparison.

STUDY AREA

The Ping river basin is situated in Northern Thailand and has an area of around 34 856 km^2 across the provinces of Chiang Mai, Lamphun, Kamphaeng Phet, Tak, and Nakhon Sawan. The Ping river, the main river of the Ping River Basin, is 740 km in length and originates in Chiang Dao District in the north of

Chiang Mai. The Ping flows downstream to the south and joins the Wang and Nan Rivers at Tak and Nakhon Sawan provinces, respectively, to become the Chao Phraya river whose catchment covers one third of the country. There are 3 large reservoirs situated in the Ping river basin: the Bhumiphol, Mae Kuang, and Mae Ngat reservoirs with a capacity of approximately 13462, 263, and 265 million m^3, respectively. The Bhumiphol dam, located in Doi Tao district in Chiang Mai province, separates the Ping river basin into the upper and lower Ping river basins.

The upper Ping river basin (17°14′30″–19°47′52″ N, 98°4′30″–99°22′30″ E), which was chosen as the study area, has a catchment area of approximately 25 370 km^2 in the provinces of Lam Phun and Chiang Mai. The terrain of the basin is undulating and rolling. The upper Ping river basin can be separated into 14 sub-basins (Fig. 1). The average annual runoff and rainfall are around 6815 million m^3 and 1174.1 mm, respectively. There are 80 rainfall stations and 44 runoff stations in the upper Ping river basin and its surroundings, but only 19 rainfall stations and 15 runoff stations have sufficient data available for this study. These stations (shown in Fig. 1) are non-automatic stations with only daily data available.

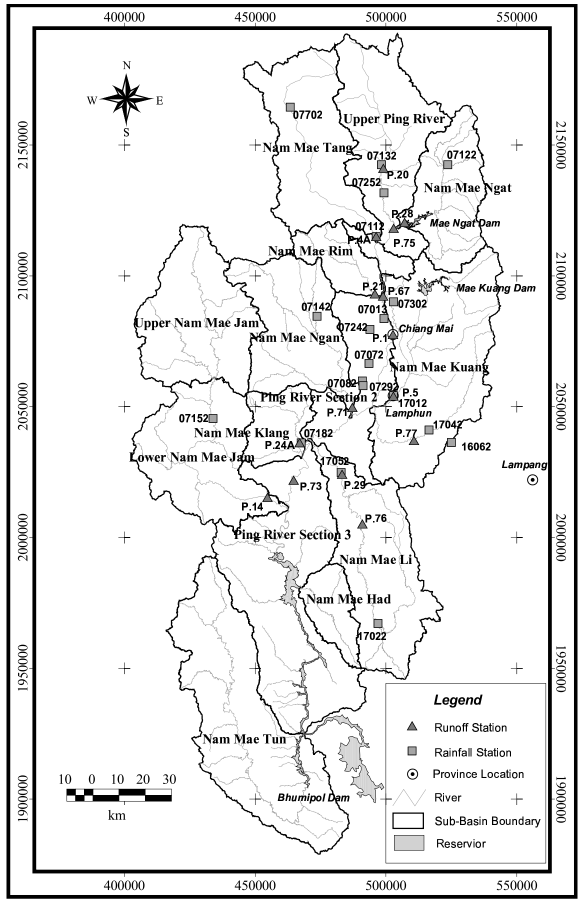

Fig. 1 The upper Ping river basin and locations of rainfall and runoff stations.

URBS HYDROLOGICAL MODEL

The URBS model[19] is a distributed nonlinear rainfall runoff routing model which can account for the spatial and temporal variation in rainfall[15,16]. It has been applied successfully for real time flood forecasting in a range of catchments from small to very large basins in Australia[18]. In the URBS model, the routing behaviour in catchment and channel can be described using either basic or split routing modules. The split module, which is similar to the Watershed Bounded Network Model[20], was selected for this study because it gives better results than the basic module during model calibration[18].

The hypothesis used in the split module is that the rainfall excess, estimated by rainfall runoff-loss models, is routed through the catchment storage, located at the centroid of that sub-catchment, to the channel using the catchment routing relationship. Thereafter, outflow of the catchment, which is the inflow of the channel storage, is routed along a reach to the next downstream catchment using a nonlinear Muskingum method. The catchment storage (in m^3 h/s) is given by

$$S_{\mathrm{catch}} = \left\{ \frac{\beta\sqrt{A}(1+F)^2}{(1+U)^2} \right\} Q^m \qquad (1)$$

where Q, β, A, U, F, and m are the outflow discharge (m^3/s), catchment lag parameter, area of sub-catchment (km^2), fraction of sub-catchment urbanized, fraction of sub-catchment forested, and catchment nonlinearity parameter, respectively. The channel storage (in m^3 h/s) is given by

$$S_{\mathrm{chnl}} = \alpha f \frac{nL}{\sqrt{S_{\mathrm{c}}}} (xQ_{\mathrm{u}} + (1-x)Q_{\mathrm{d}})^{n_1} \qquad (2)$$

where α, f, L, S_{c}, Q_{u}, Q_{d}, x, n_1, and n are the channel lag parameter, reach length factor, length of reach (km), channel slope, inflow at upstream end of reach (includes catchment inflow), outflow at downstream end of the channel reach, Muskingum translation parameter, Muskingum nonlinearity parameter (exponent), and Manning's n or channel roughness, respectively. In this study, (1) and (2) were simplified by setting $F = U = 0$, and $n_1 = f = n/\sqrt{S_{\mathrm{c}}} = 1$. This leaves

$$S_{\mathrm{catch}} = \beta\sqrt{A}Q^m, \qquad (3)$$

$$S_{\mathrm{chnl}} = \alpha L(xQ_{\mathrm{u}} + (1-x)Q_{\mathrm{d}}). \quad (4)$$

Excess rainfall estimation is crucial for rainfall-runoff modelling[21]. For the URBS model, excess rainfall can be assessed using either an event-based or a continuous-loss approach. Event-based loss modelling is suitable for single and short-term flood estimation, while continuous modelling is appropriate for long term flow simulation. Here, short-term flood estimation was investigated so an event-based approach was used.

There are several methods for event based loss estimation. In this study, the initial loss - proportional runoff (IL-PR) model coupled with the spatial variability parameters loss model were chosen. The assumption of IL-PR model is that an initial loss IL (in mm) will be deducted from rainfall followed by the proportional loss PR (in mm) and then excess rainfall will occur. Spatial variability is accounted for using the following equations. The effective fraction of the area which is impervious is given by

$$f_{\mathrm{eff}} = f_{\mathrm{u}} + \frac{F_t}{F_{\max}}, \quad (5)$$

where f_{u} is the fraction of the area that is impervious, F_t is the cumulative infiltration into the pervious area after time t, and $F_{\max}$ is the maximum infiltration capacity of the catchment. Note that infiltration is the process by which water on the ground surface enters the soil. Excess rainfall (R_t) can be calculated from

$$R_t = f_{\mathrm{eff}} C_{\mathrm{imp}} R_t^{\mathrm{tot}} + (1 - f_{\mathrm{eff}}) R_t^{\mathrm{per}} \quad (6)$$

where R_t^{tot} is the total rainfall depth at time t, C_{imp} is the impervious runoff coefficient (the default is 1), and R_t^{per} is the pervious excess rainfall depth.

As the URBS model equations have been simplified, there are only 7 model parameters necessary for the model application: the channel lag parameter (α), the catchment nonlinearity parameter (m), the Muskingum translation parameter (x), the catchment lag parameter (β), the initial loss (IL), the proportional amount of runoff (PR), and the maximum infiltration rate (IF). The first four parameters are related to runoff routing behaviour and the last three are related to rainfall loss estimation. In general, the values of m and x do not normally vary significantly from 0.8 and 0.3, respectively[17,19], and so these values were used in this study. The remaining five model parameters are determined during the calibration process. When applying the model, each gauged basin needs to be divided into at least 5 sub-catchments[19]. Each sub-catchment should have a similar size and also similar catchment characteristics.

NAM HYDROLOGICAL MODEL

The Nedbor-Afstromings model (NAM)[22] is a type of precipitation-runoff model which uses semi-empirical equations to describe the behaviour of the land phase of the hydrologic cycle. Catchments are represented by four storage layers (snow, surface, lower zone, and groundwater). Flow storage approximations are provided in the NAM manual[13]. The following 8 parameters are needed: the maximum water content in surface storage ($U_{\max}$), the maximum water content in root zone storage ($L_{\max}$), the overland flow runoff coefficient (CQOF), the root zone threshold value for overland flow (TOF), the time constant for routing overland flow (CK_1), the time constant for routing interflow (CK_2), the root zone threshold value for groundwater recharge (TG), and the time constant for routing baseflow (CKBF). For model calibration, only 6 of the parameters need to be determined since one can set $U_{\max} = 0.1 L_{\max}$ and $\mathrm{CK}_1 = \mathrm{CK}_2$.

METHODS

Method for comparing the URBS and NAM models

Model calibration and verification were carried out to decide upon the most suitable set of control parameters for each model and each runoff station. Goodness of fit between the observed and calculated discharges was evaluated using the correlation coefficient (r)[23], root mean square error (RMSE)[24], and the efficiency index or Nash-Sutcliffe criterion (EI)[25,26]:

$$r = \frac{\sum_{i=1}^{N} (Q_{mi} - \bar{Q}_m)(Q_{ci} - \bar{Q}_c)}{\sqrt{\left(\sum_{i=1}^{N} (Q_{mi} - \bar{Q}_m)^2\right)\left(\sum_{i=1}^{N} (Q_{ci} - \bar{Q}_c)^2\right)}} \quad (7)$$

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{N} (Q_{mi} - Q_{ci})^2}{N}} \quad (8)$$

$$\mathrm{EI} = 1 - \frac{\sum_{i=1}^{N} (Q_{mi} - Q_{ci})^2}{\sum_{i=1}^{N} (Q_{mi} - \bar{Q}_m)^2} \quad (9)$$

where, Q_{mi} and Q_{ci} are, respectively, the daily observed and calculated discharge at time i, and $\bar{Q}_m$ and $\bar{Q}_c$ are the corresponding average values. N is the number of data points. The best fit between the calculated and observed discharges using these parameters occurs when r approaches 1, RMSE approaches zero, and EI approaches 100 percent.

Method for model application for the ungauged catchments

Runoff stations P.20, P.4A, P.28, P.21, and P.71 were used for model selection (Table 1). Model parameters for gauged catchment were obtained by finding the best fit between the observed and calculated discharges at a particular runoff station. Unfortunately, most of the catchments are ungauged in the upper Ping river basin. To apply the selected hydrologic model to the ungauged catchments, relationships between model parameters and catchment characteristics, which were measured from topographical maps, need to be obtained.

After comparing the results from the URBS and NAM models the simpler and more effective model was selected to investigate the ungauged relationships. It was then used to find model parameters suitable for another 6 runoff stations (P.1, P.77, P.24A, P.29, P.76, and P.73). Model parameters of the first 11 runoff stations shown in Table 1 and their catchment characteristics were used to formulate the best relationships for the ungauged catchments. The effectiveness of the relationships were tested by using them to calculate the model parameters of the last 4 runoff stations (P.5, P.14, P.75, and P.67). The model parameters estimated using the gauged catchment approach (obtained by the best fit between the observed and calculated hydrograph) at the 4 runoff stations were also carried out to compare with the parameters obtained from the ungauged relationships. The results of flood estimation at the last 4 runoff stations calculated using the ungauged and gauged catchment approaches were later compared to the observed flood hydrograph to show the performance of the ungauged catchment approach.

Table 1 Catchment area (A), sub-catchment number (SCN), number of rainfall stations (N_{rs}), and number of flood events (N_{fe}) for the runoff stations used whose data was used for the hydrograph simulations.

Runoff Station ID (Catchment name)	A (km^2)	SCN	N_{rs}	N_{fe}
P.20 (Upper Ping River)	1339	25	2	5
P.4A (Nam Mae Tang)	1939	30	3	5
P.28 (Nam Mae Ngat)	1267	27	3	5
P.21 (Nam Mae Rim)	510	5	3	4
P.71 (Nam Mae Ngan)	1727	15	2	5
P.1 (Ping River section 2)	1112	15	4	6
P.77 (Nam Mae Kuang)	544	5	1	2
P.24A (Nam Mae Klang)	454	5	2	4
P.29 (Nam Mae Li)	1966	14	2	2
P.76 (Nam Mae Li)	1543	11	2	2
P.73 (Ping River section 3)	2242	14	8	3
P.5 (Nam Mae Kuang)	1777	15	5	3
P.14 (Nam Mae Jam)	3853	25	4	3
P.75 (Ping River section 3)	771	6	3	3
P.67 (Ping River section 3)	498	13	4	3

RESULTS AND DISCUSSION

URBS and NAM calibrations and verifications

Applications of the URBS and the NAM models on particular runoff stations and flood events were undertaken by adjusting model parameters to achieve the best fit between the observed and the simulated flood hydrographs for both the calibration and verification processes. The simulation results showed that both models can simulate flood hydrographs close to the observed hydrographs for most flood events as shown by the acceptable average statistical values for model parameters in Fig. 2. Examples of the model application results for the three calibrated runoff stations are shown in Figs. 3–5. Both models cannot simulate flood hydrographs accurately for a few flood events. This is most likely to be due to inaccuracy of daily rainfall data, which is the most significant input data for model estimation, and only few rainfall stations are located within the catchment areas of some of the runoff stations.

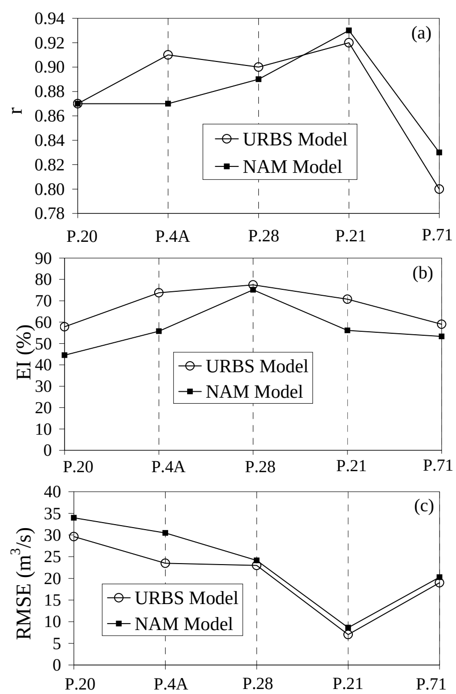

Fig. 2 Statistical measures of the similarity between simulated and observed hydrographs using URBS and NAM.

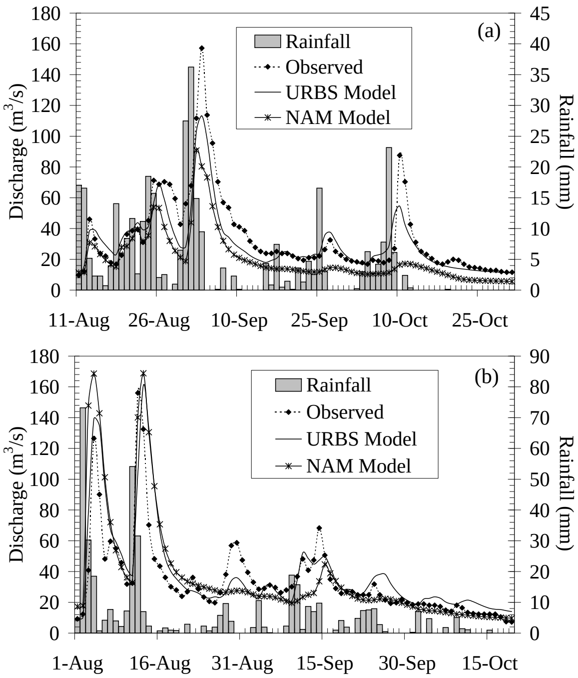

Fig. 3 Observed and calculated flood hydrographs at the runoff station P.20 in (a) 1996 (b) 2001.

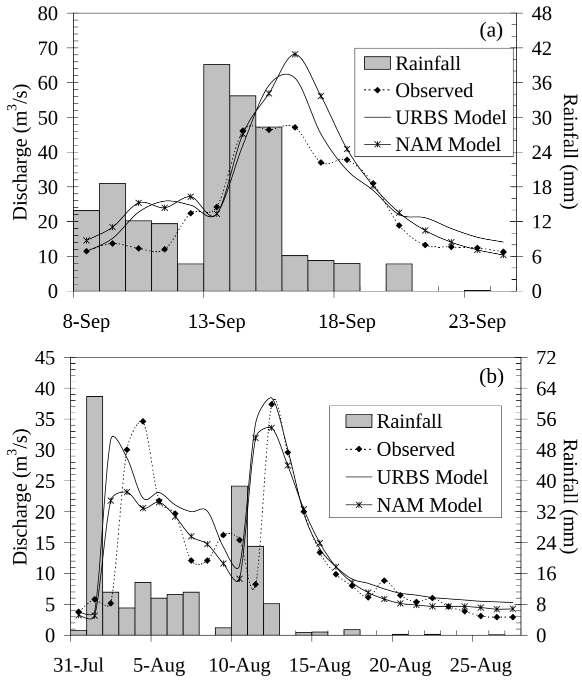

Fig. 5 Observed and calculated flood hydrographs at the runoff station P.21 in (a) 1994 (b) 2001.

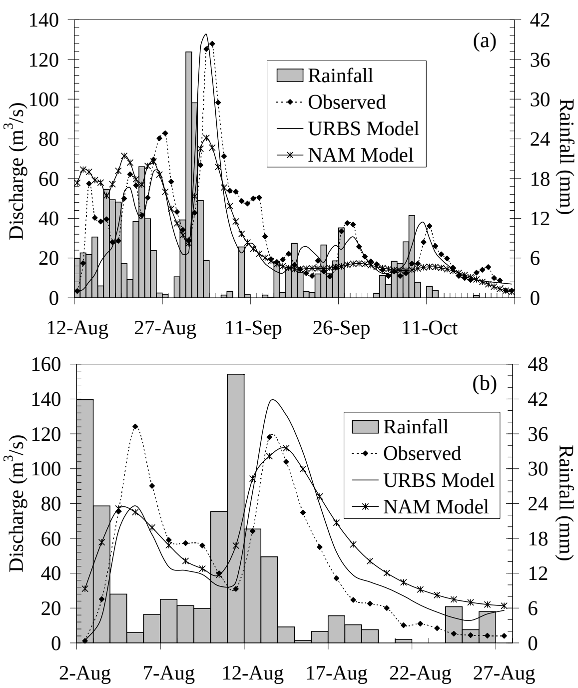

Fig. 4 Observed and calculated flood hydrographs at the runoff station P.4A in (a) 1996 (b) 2001.

Table 2 shows that there are 5 parameters necessary to be calibrated for the URBS applications. However, the parameter IL (the initial loss) was set to be zero to give the best fit between the observed and calculated flood hydrographs. This is because the model was used to simulate large flood events that occur in the wet season after some previous flood events, whereby soil moisture is expected to be saturated. This brings the number of parameters to four compared with six parameters that need to be calibrated for the NAM. As fewer model parameters are needed and slightly better flood hydrograph results were obtained using the URBS model, this model was chosen for formulating the relationships that could be applied to the ungauged catchments.

Generalised URBS model parameters and catchment characteristics

Having chosen the URBS model, the model was calibrated using 6 further runoff stations, and the combined results for the 11 stations are given in Table 3. The catchment characteristics of each runoff station comprising the catchment area (A), main channel length (L), main channel length from the centroid (L_c), channel slope (S), and the percentage of land use consisting of agricultural (Ag) and forest areas (F), are also given.

To apply the URBS model to ungauged catchments, expressions for α, β, PR, and IF in terms

Table 2 Results of the URBS and the NAM model applications.

Runoff Stations	Control parameters gained from model calibration and verification processes										
	URBS model					NAM model					
	α	β	IL	PR	IF	$L_{\max}$	CQOF	TOF	CK_1	TG	CKBF
P.20	0.30	9	0	0.21	550	350	0.5	0.4	26	0.4	1500
P.4A	0.35	9	0	0.15	700	520	0.5	0.3	48	0.1	1000
P.28	0.35	8	0	0.22	400	330	0.5	0.1	42	0.9	2000
P.21	0.20	6	0	0.15	600	450	0.6	0.6	30	0.7	5000
P.71	0.40	8	0	0.22	350	480	0.5	0.1	40	0.9	3000

Table 3 Model parameters and catchment characteristics of the 11 runoff stations used in ungauged relationship formulation.

Runoff	Control parameters of the URBS model					Catchment characteristic parameters					
Station	α	β	IL	PR	IF	A (km^2)	L (km)	L_c (km)	S	Ag (%)	F (%)
P.20	0.30	9	0	0.21	550	1355	85.0	44.0	0.00942	17.3	81.9
P.4A	0.35	9	0	0.15	700	1902	148.1	69.0	0.00411	13.9	85.5
P.28	0.35	8	0	0.22	400	1261	81.4	37.1	0.00699	19.6	78.1
P.21	0.20	6	0	0.15	600	515	47.3	26.6	0.01213	35.3	63.1
P.71	0.40	8	0	0.22	350	1771	112.4	53.4	0.00666	18.9	78.8
P.1	0.30	7	0	0.17	500	1322	97.9	45.0	0.00058	31.2	61.5
P.77	0.20	5	0	0.20	350	547	72.1	26.3	0.00625	12.3	86.0
P.24A	0.20	5	0	0.25	280	460	41.9	24.7	0.03510	23.0	75.9
P.29	0.40	8	0	0.26	200	1970	179.0	60.0	0.00271	12.7	84.8
P.76	0.40	8	0	0.26	200	1541	144.4	47.8	0.00277	14.9	82.2
P.73	0.45	9	0	0.25	250	2284	96.1	44.2	0.00038	34.4	55.5

of the proposed catchment characteristics comprising A, L, L_c, and S need to be obtained. This was done by applying both multiple linear regression analysis (MLRA) and multiple power regression analysis (MPRA). Higher correlation coefficients were obtained when using MPRA for expressions for α and β and MLRA for PR and IF (Table 4). Hence the relations we used were

$$\alpha = 0.006(A^{0.784}L^{0.179}L_c^{-0.608}S^{0.041}) \quad (10)$$
$$\beta = 0.484(A^{0.484}L^{-0.199}L_c^{0.102}S^{0.035}) \quad (11)$$

$$PR = 0.176 + 0.0001A + 0.002L - 0.006L_c + 3.498S \quad (12)$$

$$IF = 386.94 - 0.329A - 7.037L + 28.623L_c - 10024S \quad (13)$$

Using MLRA and MPRA, equations for the four model parameters in terms of the 4 primary catchment characteristics plus Ag and F were also obtained. However, the resulting increases in r were not substantial (Table 4), and since Ag and F are more difficult to measure, these equations in terms of the 6 characteristics were not used.

Table 4 Correlation coefficients obtained using MLRA and MPRA for the relationships between the model parameters and catchment characteristics.

Model	4 characteristics[a]		6 characteristics[b]	
Parameter	MLRA	MPRA	MLRA	MPRA
α	0.97	0.98	0.97	0.99
β	0.91	0.95	0.95	0.96
IL	0.95	0.79	0.97	0.80
PR	0.94	0.75	0.96	0.82

[a] A, L, L_c, S
[b] A, L, L_c, S, Ag, F

Verification of the proposed relationships for flood estimation in ungauged catchment

Flood hydrographs at the 4 runoff stations (P.5, P.14, P.75, and P.67) gained from the ungauged and gauged catchment approaches were compared with the observed data (Tables 5–7, Figs. 6 and 7).

From the high values of r and EI for stations P.75 and P.67 (Table 7), and the fact that the estimated flood hydrographs attained from both approaches at these

Table 5 Catchment characteristics for the 4 runoff stations.

Runoff	Catchment characteristic parameters			
Station	A (km^2)	L (km)	L_c (km)	S
P.5	1777	97.9	49.1	0.00392
P.14	3853	194.2	99.6	0.00437
P.75	771	64.1	29.4	0.00088
P.67	498	35.4	16.3	0.00148

Table 6 Estimated URBS model parameters obtained from gauged and ungauged catchment approaches.

Runoff	Gauged catchment				Ungauged catchment			
Station	α	β	PR	IF	α	β	PR	IF
P.5	0.80	9	0.25	250	0.38	9	0.20	481
P.14	0.20	5	0.11	500	0.52	12	0.23	560
P.75	0.30	7	0.17	500	0.22	5	0.18	430
P.67	0.30	7	0.17	500	0.24	6	0.16	520

two stations are very close, it can be concluded that the ungauged relationships can be confidently applied for flood estimation for the ungauged catchments at these two locations. At stations P.5 and P.14, the values of r and EI attained from the ungauged approach are less than those from the gauged approach while the RMSE of the ungauged approach are higher than that of the gauged approach. Hence the ungauged approach cannot simulate flood hydrographs at these stations as well as the gauged approach.

It should be noted that the catchment area of stations P.75 and P.67 are the sub-catchments of station P.1, which is one of the 11 stations used to formulate the ungauged relationships. On the other hand, the stations P.5 and P.14 are in independent catchments which have not been used in the formulation process of the ungauged relationships. From the results, it could be concluded that the ungauged relationships can be confidently applied for flood estimation purpose only for the ungauged catchments that lie within the catchment area of the stations which are involved in formulating the ungauged relationships. More

Table 7 Comparison of gauged (G) and ungauged (U) approaches to flood events used in verification process.

Runoff	r		EI (%)		RMSE (m^3/s)	
Station	G	U	G	U	G	U
P.5	0.85	0.75	64.98	47.98	26.76	31.74
P.14	0.86	0.70	67.33	36.98	36.13	54.24
P.75	0.98	0.96	93.16	89.35	12.39	14.66
P.67	0.96	0.96	91.68	90.33	26.96	29.73

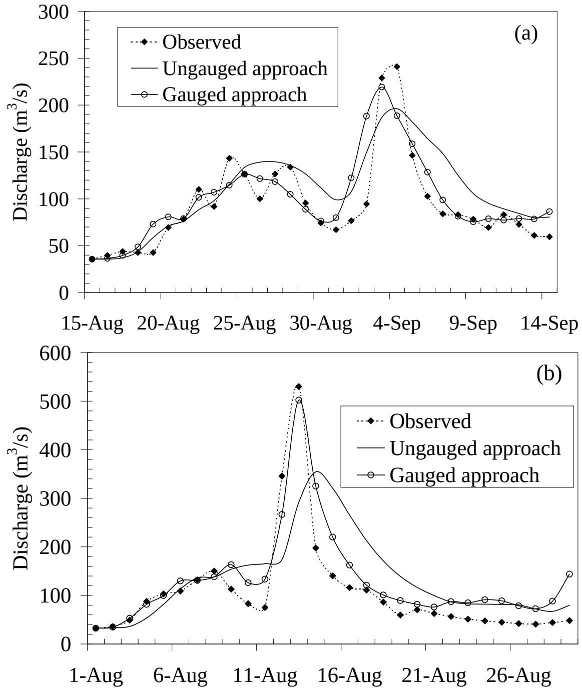

Fig. 6 Observed and calculated flood hydrographs at the runoff station P.14 in (a) 1996 (b) 2001.

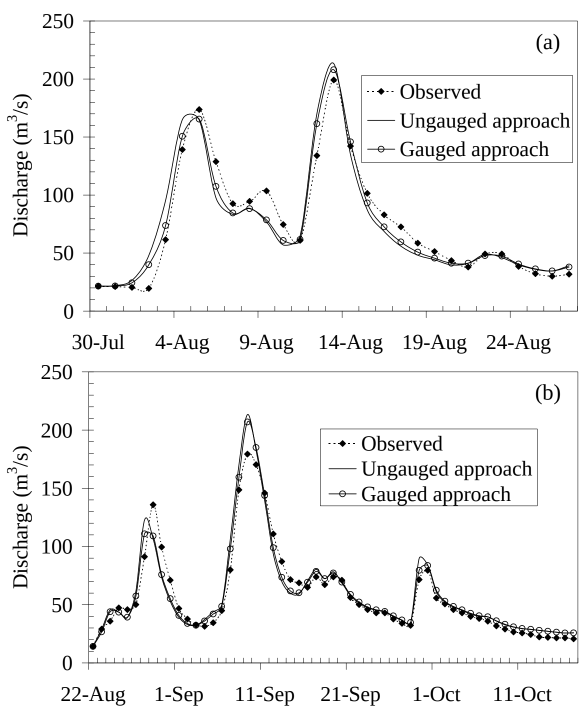

Fig. 7 Observed and calculated flood hydrographs at the runoff station P.75 in (a) 2001 (b) 2002.

caution is needed when these relationships are applied for general ungauged catchments located outside the basins of the 11 stations used in the formulation process of the ungauged relationships. The form of the ungauged relationships possibly varies depending on the catchment and flood characteristics, which are used in formulating the relationships.

The methods used in formulating the ungauged relationships proposed in this study should be performed in other catchments in river basins in Thailand to find out the efficiency of the proposed method that would be a helpful tool for flood estimation of the ungauged catchments in Thailand.

Acknowledgements: The authors gratefully acknowledge the Thailand Research Fund through the Royal Golden Jubilee PhD programme (Grant No. PHD/0118/2547) and Kasetsart University Research and Development Institute for financially supporting this research. We wish to thank Mr. Terry Malone (Australian Bureau of Meteorology, Queensland) for many helpful suggestions on applying the URBS model. We also thank the Royal Irrigation Department, the Department of Water Resources, Thai Meteorological Department for providing the hydrological data used in this study. Finally the authors wish to thank Dr. Michael Waters for correcting the manuscript.

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