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Flood Forecasting System Development for the Upper Ping River Basin

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ABSTRACT

A flood forecasting system for the upper Ping River basin located in Northern Thailand was developed as a flood mitigation measure. The system comprised the URBS model (a rainfall-runoff model) used for runoff estimation, the FLDWAV model (a hydrodynamic model) used for flood routing investigation, and a database system for data storage and data management to facilitate model application. URBS was used to simulate hydrographs at five runoff stations located along the main stream of the Ping River and at 10 stations on its tributaries. FLDWAV was used to route flood hydrographs along the Ping River between the most upstream station at P.20 and the most downstream station at P.73 (approximately 198 km in length). Flood hydrographs of ungauged catchments between P.20 and P.73 were estimated using URBS, then were input into FLDWAV. The flood forecasting system proved effective in accurately simulating flood hydrographs along the Ping River and its tributaries and can be applied for flood mitigation purposes in flood risk areas, such as the cities of Chiang Mai and Lamphun.

Keywords: flood forecasting system, URBS model, FLDWAV model, upper Ping River basin

INTRODUCTION

Flooding has been a common hazard in the upper Ping River basin during the last two decades, where it has caused economic losses, inundated farmlands and decreased crop productivity. For example, floods in August and September 2005 caused property damage of 1,000 million baht, more than 250,000 people were affected and at least five people lost their lives (Wood and Ziegler, 2007). The Royal Thai Government has allocated a significant budget to mitigate flood effects using structural measures, such as channel modification, bank protection and dikes. However problems still persist and are becoming exacerbated by deforestation and urbanization; furthermore, concerns on the impact of climate change also need to be addressed.

With the realization that structural measures alone are insufficient to address the problem, the Royal Thai Government has recently begun to consider non structural measures, such as flood forecasting, by developing flood forecasting system for many river basins. Flood forecasting is internationally accepted as one of the most effective non-structural flood mitigation measures, because when accurate forecasts are communicated effectively, people are empowered to prepare themselves to withstand a flood's damaging effects. As such, the reliability of flood forecasting systems to provide information to the public on accurate flood heights and the extent of

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flooding via the warning system is a crucial concern.

To forecast flooding accurately normally requires two model components, covering (a) the hydrological rainfall runoff processes on the catchment and (b) the hydraulic processes in the river channel and its flood plain. Hydrological models estimate flood discharges of various magnitudes coming from catchment areas, while hydraulic models determine the extent, depth and velocity of flood flows (O'Connor and Costa, 2004).

Conventional hydrological models were developed based on the hydrologic cycle. However, there are many components involved in the cycle that cannot be fully explained by any available models. All available models were developed for flood and flow estimation by considering only some significant hydrologic cycle components such as the SCS (USDA, 1972), NAM (Nielsen and Hansen, 1973), TANK (Sugawara, 1979), TOPMODEL (Beven and Kirkby, 1979), HEC-HMS (HEC, 2000), URBS (Carroll, 2004), SWAT (Neitsch *et al.*, 2005), and the IHACRES (Croke *et al.*, 2005). Among the hydrologic models developed so far, the URBS model has been applied successfully for real time flood forecasting in Australia and China (Mapiam and Sriwongsitanon, 2009), uses a simple and robust calculation scheme and has straightforward requirements for calibration of model parameters. As such, URBS was adopted for use as the hydrologic model in the upper Ping.

Hydraulic models used in flood forecasting are generally based on the Saint-Venant equations for one-dimensional flow that allow the flow rate and water level to be computed as functions of space and time, rather than of time alone as in the hydrologic models. Many models have been developed based on these equations such as CE-QUAL-RIV1 (Environmental Laboratory, 1995), FLDWAV (Fread and Lewis, 1998), MIKE 11 (DHI Water and Environment, 2002), HEC-RAS (Brunner, 2002). The USA Federal Emergency Management Agency (FEMA) has accepted FLDWAV model to be used for the purposes of the National Flood Insurance Program (NFIP). Taesombat and Sriwongsitanon (2006) concluded that FLDWAV is an effective model to investigate flood routing investigation in the upper Ping River, being as accurate as the MIKE 11-HD model, which is an accepted commercial model.

The objective of this study was to develop a flood forecasting system for the upper Ping River basin. The system is composed of three sub-systems: the URBS model system, the FLDWAV model system and the database system. This flood forecasting system for the upper Ping River basin would be used by the Royal Irrigation Department (RID), which has responsibility for flood mitigation in Thailand, to help mitigate flood effects in flood risk areas, such as the cities of Chiang Mai and Lamphun.

MATERIALS AND METHODS

Study area

The Ping River originates in Chiang Dao district north of Chiang Mai and flows downstream in the south to become the inflow for the Bhumiphol dam - a large dam with an active storage capacity of 9.7 billion m^3. The river drains mountainous areas with steep hills up to elevations of 1,500 to 2,000 m, and valleys at elevations of 330 to 500 m (Wood and Ziegler, 2007). The upper Ping River basin covers a catchment area of approximately 25,370 km^2 in the provinces of Chiang Mai and Lamphun, Northern Thailand. The terrain of the basin is undulating and rolling to steep in upland areas and flat along river floodplains. More than 70% of the basin cover is forest (Royal Forest Department, 2006).

Figure 1 shows the upper Ping River basin and the locations of rainfall and runoff stations used for the study.

Data collection

Rainfall data

The weather of the basin is mainly influenced by the southwest and northeast monsoons and atmospheric depressions from the South China Sea from July to September, resulting in abundant rainfall from May to October (Sharma *et al*., 2007). The average annual rainfall and runoff of the basin are 1,174 mm and 6,815 million m^3, respectively (Mapiam and Sriwongsitanon (2009).

In this study, daily rainfall data at 90 stations obtained since 1952 from the RID were entered into the database system to be used as the input data for the URBS model. The database system also contains hourly rainfall data obtained from 11 automatic rainfall stations belonging to the RID that started recording in November 2005; however only the daily rainfall data was used for the analysis as the events analysed predated the establishment of these gauges.

Runoff data

In the upper Ping River basin, there are 15 daily measured runoff stations and 12 automatic stations operated by the RID. Daily and hourly runoff data for both water level and discharge registered at these stations were entered into the database system. The rating curves at different water years necessary for interpreting the water level-to-discharge relationships were also collected and entered into the database system. As for the rainfall data, the automatic runoff stations started recording in November 2005, therefore the daily runoff data was used for the analysis. Figure 1 shows the locations of these runoff stations.

Cross section data

There were 140 cross-section data available along the Ping River between the stations P.20 and P.73, and 35 cross-section data along the Mae Kuang river between the Mae Kuang dam and its confluence with the Ping River. These cross-sections, surveyed in 2005 by the RID and the DWR, were used as the input data for the FLDWAV model. Table 1 presents details of cross-sections available at each river reach.

Flood forecasting system

There are three sub-systems in the flood forecasting system for the upper Ping River basin, URBS, FLDWAV, and the database. The concept and theory for each sub-system are described below.

URBS model system

The URBS model, developed by Carroll (2004), was chosen to simulate runoff hydrographs at gauged and ungauged catchments in the upper Ping River basin. URBS is a semi-distributed nonlinear rainfall-runoff routing model which can account for the spatial and temporal variations in rainfall (Malone, 1999; Malone *et al*., 2003). It has been applied successfully for real time flood forecasting in Australia by the Australian Bureau of Meteorology, and in China by the Chiangjiang (Yangtze) Water Resources Commission in China

Table 1 Details of cross section data.

River and location	Number of cross sections	River distance (km)
Ping riverPing River		
• P.20 station to Nong Saleak Weir (RID)	115	142.5
• The confluence of Mae Kuang and Ping river to P.73 (DWR)	25	57.3
Mae Kuang river		
• Mae Kuang dam to the confluence of the Ping River (DWR)	35	64

and in the Lower Mekong River Basin (see Jordan *et al*., 2004; Pengel *et al*., 2007). Mapiam and Sriwongsitanon (2009) applied this model for flood estimation on the gauged catchments in the upper Ping River basin and then formulated ungauged relationships to be applied on the ungauged catchments.

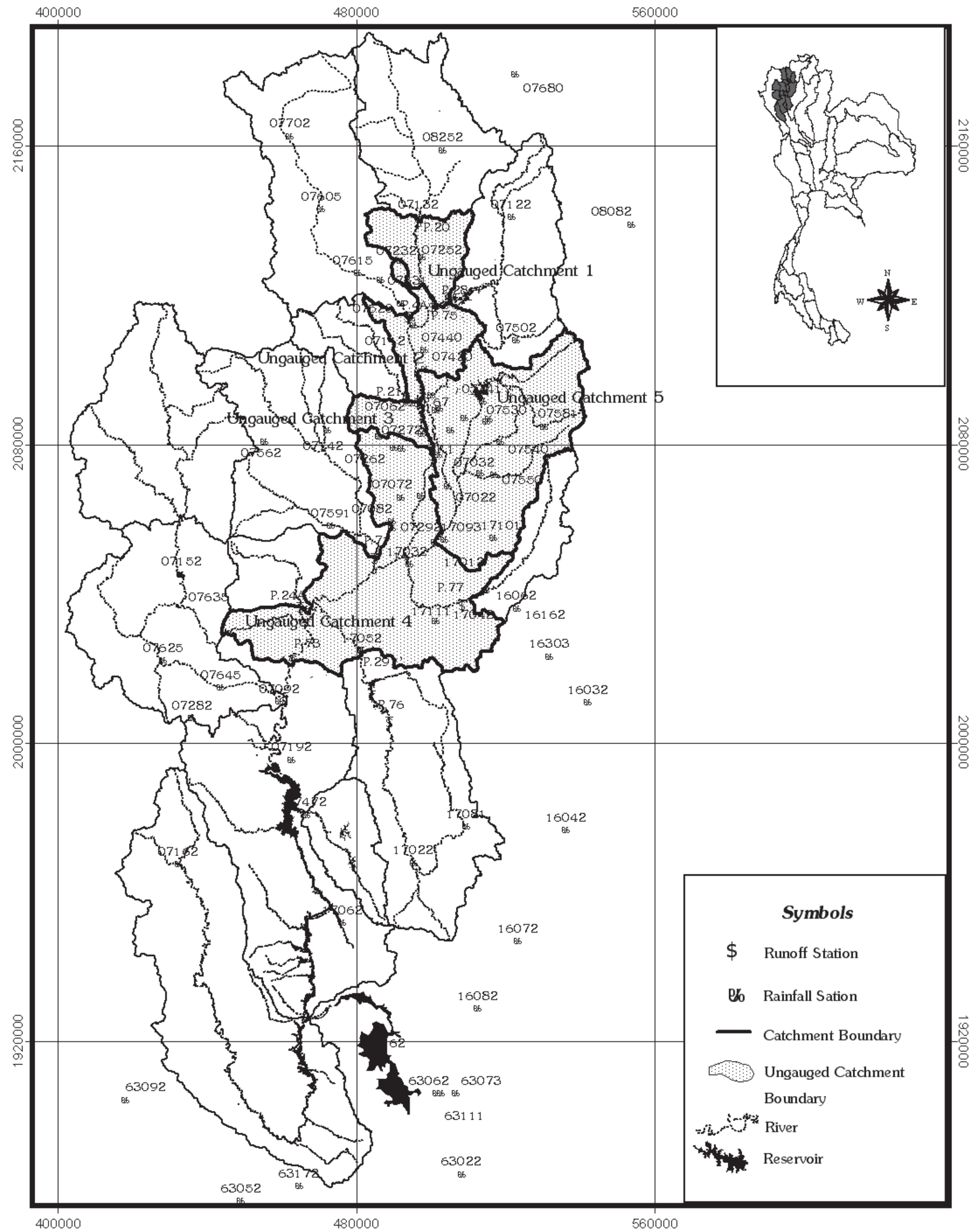

Figure 1 The upper Ping River basin and locations of rainfall and runoff stations.

The routing behavior on the catchment and in the channel can be described using either basic or split routing modules. The split module approach was selected for this study because it can provide better results than the basic module during model calibration (Pengel *et al*., 2007). In the split module, the rainfall excess is estimated by rainfall runoff–loss models. It is later routed through the catchment storage, located at the centroid of that sub-catchment, to the channel using the catchment routing relationship. Outflow of the catchment, which is the inflow of channel storage, is routed along a reach using a non-linear Muskingum method to the next downstream catchment. The catchment storage and channel routing storage in m^3 h/s are given in Equations 1 and 2, respectively:

$$S_{catch} = \beta\sqrt{AQ^m} \quad (1)$$

where, S_{catch} is the catchment storage (m^3 h/s), β is the catchment lag parameter, A is an area of sub-catchment (km^2), and is the catchment non-linearity parameter.

$$S_{chnl} = \alpha L\left(xQ_u + (1-x)Q_d\right) \quad (2)$$

where, S_{catch} is the channel storage (m^3 h/s), α is the channel lag parameter, L is the length of a reach (km), Q_u is the inflow at the upstream end of the reach (includes catchment inflow), Q_d is the outflow at downstream end of the reach (m^3/s), and x is the Muskingum translation parameter.

Excess rainfall was estimated using the initial loss-proportional runoff model (IL-PR) coupled with the spatial variability parameters loss model. In the IL-PR model, an initial loss (*il*, mm) is deducted from rainfall followed by the proportional loss (*pr*, mm) and then excess rainfall occurs. The URBS spatial infiltration model can be calculated using Equation 3. Excess rainfall for each time period (R_i) is calculated using Equation 4.

$$f_{eff} = f_u + \frac{F_t}{F_{\max}} \quad (3)$$

$$R_t = f_{eff} C_{imp} R_t^{tot} + \left(1 - f_{eff}\right) R_t^{per} \quad (4)$$

where, f_{eff} is the effective fraction of the area which is impervious, f_u is the fraction of area that is impervious, F_t is the cumulative infiltration into the pervious area after time t, $F_{\max}$ is the maximum infiltration capacity of the catchment. R_t^{tot} is the total rainfall depth at time t, C_{imp} is the impervious runoff coefficient (default is 1) and R_t^{per} is the pervious excess rainfall depth.

Since the model equations have been simplified, there are seven parameters necessary for the model application (α, m, x, β, IL, PR, and IF). However, the parameters m and x do not normally vary significantly from 0.8 and 0.3, respectively (Carroll, 2004; Jordan *et al*., 2004). Thus, both parameters were fixed at 0.8 and 0.3, respectively. As a result, only five parameters are necessary for further application. The parameters α and β are related to runoff routing behaviour and the parameters IL, PR, and IF are related to rainfall loss estimation.

For the URBS model application, there were six data files consisting of a Catchment Definition File (*.cat), Rainfall Definition File (*.rf), Gauging Station File (*.g), Inflow Definition file (*.i), Pluviograph File (*.r), and Batch File (*.bat) that needed to be prepared as the input data. A module was developed in the URBS model system to easily facilitate the preparation of those data files for 15 runoff stations in the upper Ping River basin, as well as the ungauged catchments between the stations P.20 and P.73 to support the application of the FLDWAV model.

FLDWAV model system

The FLDWAV model developed by the National Weather Service (NWS) (Fread and Lewis, 1998) was selected to simulate flood routing along the Ping River and its tributary, the Mae Kuang River. It has the capability to model flows through a single stream or interconnected waterways. The FLDWAV model, Version 1.0, was released in November 1998 to replace the NWS generalized flood routing models: DAMBRK, and DWOPER. FLDWAV allows the utilization of their combined capabilities as well as provides new hydraulic simulation features. This model is based on one-dimensional Saint-Venant equations of unsteady flow for conservation of mass and momentum, (Equations 5 and 6), coupled with an assortment of internal boundary conditions for simulating unsteady flows controlled by a wide range of hydraulic structures. FLDWAV solves these equations using an implicit weighted, four-point finite difference (Fread and Smith, 1978; Fread and Lewis, 1998 and 1993).

$$\frac{\partial Q}{\partial x}+\frac{\partial s_c(A+A_o)}{\partial t}-q_L = 0 \qquad (5)$$

$$\frac{\partial(s_m Q)}{\partial t}+\frac{\partial(\beta Q^2/A)}{\partial x}+gA\left(\frac{\partial h}{\partial x}+\overline{S}_f+S_e+S_i\right)+L+W_f B = 0 \qquad (6)$$

where, Q is the discharge, A is the wetted active cross-sectional area, A_o is the wetted inactive off-channel storage area, B is the channel flow width, S_c and S_m are depth-dependent sinuosity coefficients for mass and momentum, respectively, β is the momentum coefficient for non-uniform velocity, q is the lateral in/out flow, t is the time, x is the distance measured along the mean flow-path of the floodplain, g is the gravitational acceleration constant, h is the water surface elevation, L is the momentum effect of lateral flows ($L = -qv_x$ for lateral inflow, where v_x is the lateral inflow velocity in the x-direction, $L = -qQ/(2A)$ for seepage lateral outflows, $L = -qQ/A$ for bulk lateral outflows such as flows over levees), S_f is the boundary friction slope ($S_f = (Qn/(1.49AR^{2/3}))^2$, where n is the Manning roughness coefficient and R is the hydraulic radius), S_e is the slope due to local expansion-contraction, and W_f is the wind term.

For the FLDWAV model application, only one input data file needed to be prepared that contained flow and flood estimates, including inflows from the ungauged catchments along the Ping and Mae Kuang Rivers from the URBS model system. Preparing the input file can be time consuming. Therefore a module was developed under the FLDWAV model system to easily facilitate the preparation of the data file for flow and flood routing between the stations P.20 and P.73 along the Ping River and between Mae Kuang dam and the confluence between the Mae Kuang and Ping Rivers.

Database system

A database system was developed: (a) to manage the automatic and non-automatic rainfall and runoff data of the stations described in the previous sections; and (b) to facilitate the applications of the URBS and FLDWAV model system for flood forecasting system application. The database system is based on a relational database management system (RDMS) and provides access to stored data in a tabular format. The recorded data can be presented on an hourly or daily basis for both automatic and non-automatic stations, as well as in the form of monthly data for both station categories. Summaries of averages, maximum and minimum values of all data, and hyetographs of daily rainfall can all be presented in tabular or graphical format.

Model calibration and model verification

URBS model system

The URBS model system was used to simulate flood hydrographs at the 15 non-automatic stations in the upper Ping River basin. This was done to calibrate URBS by determining the most suitable model parameters at each station for the best fit between calculated and observed hydrographs. To implement the URBS model system for flood estimation, the catchments of the 15 runoff stations were divided into a number of sub-catchments, each having similar size and catchment characteristics. Table 2 shows the

Table 2 Details of data used for the model calibration and verification at the 15 runoff stations.

Station ID*	Catchment name	Catchment area (km^2)	Number of sub-catchments	Number of rainfall stations	Number of flood events
P.20	upper Ping River	1,339	25	2	5 (1994, 1995, 1996,2001,2003)
P.28	Nam Mae Ngat	1,267	27	3	5 (1967,1970,1971, 1973,1975)
P.75	Ping River section 3	3,090	6	3	3 (2001,2002,2003)
P.4A	Nam Mae Tang	1,939	30	3	5 (1994, 1995, 1996,2001,2003)
P.67	Ping River section 3	5,289	13	4	3 (2001,2002,2003)
P.21	Nam Mae Rim	510	5	3	4 (1994, 1996,2001,2003)
P.1	Ping River section 2	6,356	15	3	3 (2001,2002, 2003)
P.5	Nam Mae Kuang	1,777	15	4	3 (1980,1981,1982, 1992)
P.77	Nam Mae Kuang	544	5	2	2 (1999,2002)
P.71	Nam Mae Ngan	1,727	15	2	5 (1996,1999,2000, 2001, 2002)
P.29	Nam Mae Li	1,966	14	2	2 (1971,1973)
P.76	Nam Mae Li	1,543	11	2	2 (2001,2002)
P.24A	Nam Mae Klang	454	5	2	3 (1996,2000,2002)
P.73	Ping River section 3	13,353	32	8	3 (2001,2002,2003)
P.14	Nam Mae Jam	3,853	25	4	4 (1996,2000,2001, 2002)

Note: * locations are shown in Figure 1

Table 3 Data used for model calibration and verification at the five runoff stations to be used for ungauged application.

Station ID	River reach	Catchment Area (km^2)	Number of sub-catchments	Number of rainfall stations	Number of flood events	Ungauged catchment
P.75	P.20 to P.75	498	7	8	3 (2001, 2002,2003)	1
P.67	P.75 to P.67	322	6	8	3 (2001, 2002,2003)	2
P.1	P.67 to P.1	292	2	8	3 (2001, 2002,2003)	3
P.5	Mae Kuang dam to the Ping River confluence	1,222	10	6	3 (2001, 2002,2003)	5
P.73	P.1 to P.73	2,707	17	10	3 (2001, 2002,2003)	4

catchment area, sub-catchment number, number of rainfall stations and the number of flood events for each runoff station used for the URBS model calibration and verification. Daily areal rainfall for catchments of runoff stations were calculated using the Thiessen Polygon technique.

Following calibration and verification, URBS was then applied to estimate flood hydrographs for the ungauged catchments between the stations P.20 and P.73 as input data for the FLDWAV model. Ungauged areas were considered as catchments 1, 2, 3, 4 and 5 (Figure 1). Calibrated model parameters at neighbouring gauged stations at P.75, P.67, P.1, P.73, and P.5 were used as the model parameters for the ungauged catchments 1, 2, 3, 4, and 5, respectively. Flood hydrographs at these ungauged catchments was simulated using these model parameters as the input data for the FLDWAV model.

FLDWAV model system

Figure 2 shows the upper Ping River network and the Mae Kuang River network used for the FLDWAV model configuration. Ungauged hydrographs at the five catchments estimated using the URBS model system were divided and distributed along each river reach for use as the input data for the FLDWAV model system. Flood events in the rainy season in 2001, 2002, and 2003 were selected for model calibration and verification processes to find the most suitable model parameter (Manning's n) for each cross-section along the Ping and Mae Kuang Rivers. The best fit between calculated and observed hydrographs at the stations P.75, P.67 and P.1 along the Ping River were used to identify the most suitable Manning's n.

Evaluation of model performance

Statistical indicators

In the model calibration and verification, model performance was evaluated by a comparison between the model results and the observed data using three statistical indicators, the

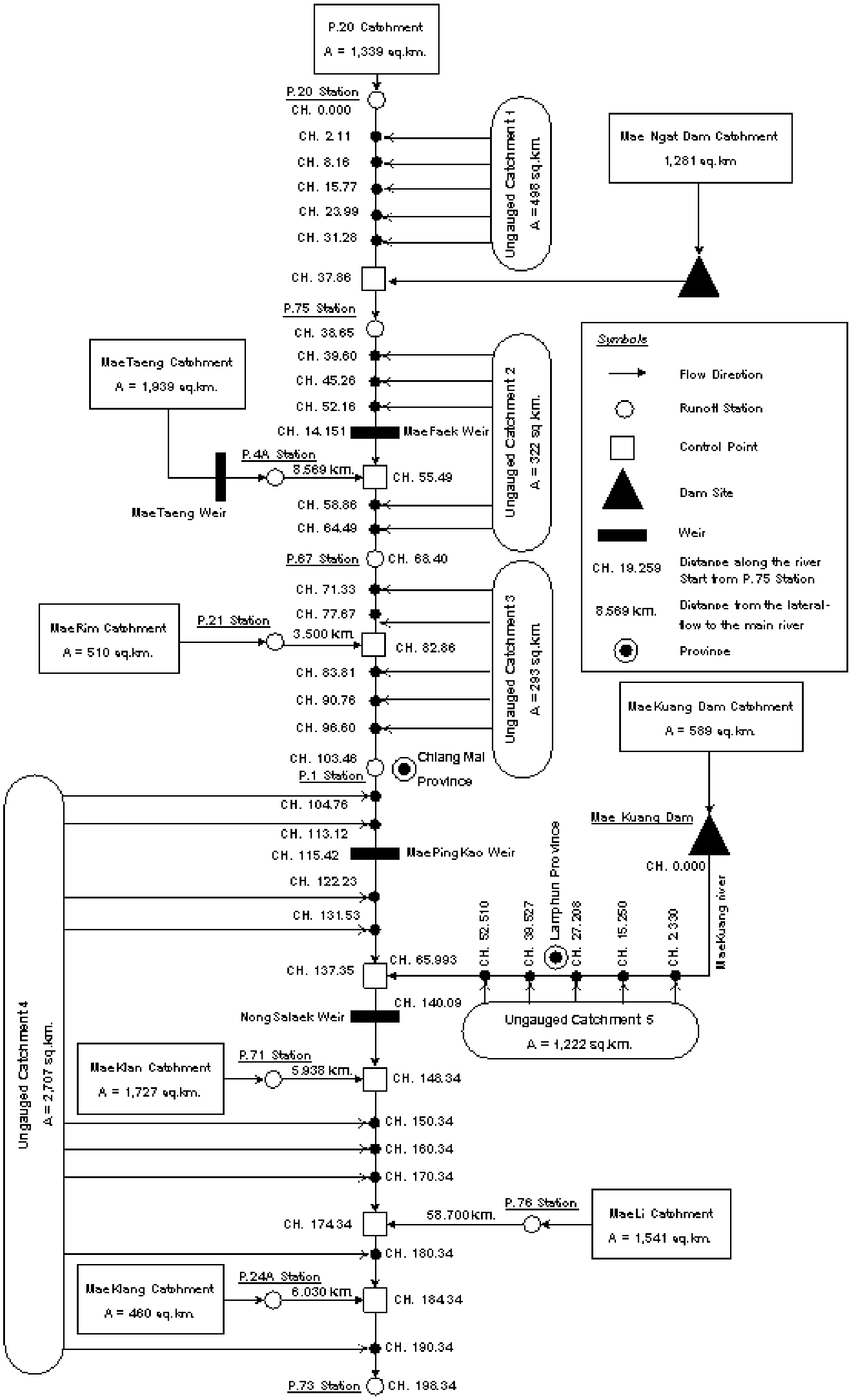

Figure 2 Schematic of the upper Ping River network between runoff stations P.20 and P.73.

correlation coefficient (r), efficiency index (EI) and root mean square error (RMSE) that can be calculated using Equations 7, 8 and 9, respectively. The best fit between the model results and observed data using these indicators occurs when r approaches 1, EI approaches 100% and RMSE approaches zero.

$$r = \frac{\sum_{i=1}^{N}\left(Q_{oi}-\overline{Q}_o\right)\times\left(Q_{ci}-\overline{Q}_c\right)}{\left[\sum_{i=1}^{N}\left(Q_{oi}-\overline{Q}_o\right)^2\times\sum_{i=1}^{N}\left(Q_{ci}-\overline{Q}_c\right)^2\right]^{0.5}} \quad (7)$$

$$EI = \frac{\sum_{i=1}^{N}\left(Q_{oi}-\overline{Q}_o\right)^2-\sum_{i=1}^{N}\left(Q_{oi}-\overline{Q}_{ci}\right)^2}{\sum_{i=1}^{N}\left(Q_{oi}-\overline{Q}_o\right)^2}\times 100\% \quad (8)$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[Q_{oi}-Q_{ci}\right]^2} \quad (9)$$

where, $\overline{Q}_o$ is the averaged observed data, $\overline{Q}_c$ is the average model results, Q_{oi} is the observed data at the time i, Q_{ci} is the model result at the time i, N is the number of data points.

RESULTS AND DISCUSSION

URBS model system

The model parameters at the 15 runoff stations providing the best fit between the calculated and observed hydrographs are presented in Table 4. Model results are mostly well matched to the observed data yielding acceptable values of the statistical indicators (r, EI, and RMSE), as shown. While some of the model results are not well matched to the observed data, this is quite normal in a situation where there is limited rain gauge rainfall data to represent the catchment rainfall.

Table 5 shows the model parameters calibrated at the five runoff stations used for estimating flood hydrographs at the five ungauged catchments between stations P.20 and P.73. The statistical values gained at these five stations are also presented in Table 5.

FLDWAV model system

Manning's n values determined by calibration and verification for channel and floodplain flows for the cross-sections between each river reach are presented in Table 6. The calculated hydrographs all showed good fits to the observed values at all four runoff stations along the Ping River, as demonstrated by the acceptable values obtained for the statistical indicators, r, EI and RMSE (also presented in Table 7). Table 8 summarizes model statistics for the combined URBS and FLDWAV and Figure 3 compares the hydrographs for simulated events against observed data. With these good statistical fits, it is clear that the URBS/FLDWAV modelling has good potential to be applied for flood forecasting of the upper Ping River basin.

CONCLUSIONS

A flood forecasting system for the Upper Ping River basin was developed. The system comprised three sub-systems: the URBS model system, the FLDWAV model system, and the database system. The URBS model system was developed to simulate flow and flood hydrographs at 15 stations in the upper Ping River basin, as well as to simulate flow and flood hydrographs of the ungauged catchments between stations P.20 and P.73 to support the application of the FLDWAV model system. The FLDWAV model system was developed to simulate flow and flood routing within the river reaches along the Ping River between P.20 and P.73, as well as along the Mae Kuang River, for the section downstream of the Mae Kuang dam to the confluence with the Ping River. The database system was developed to manage the automatic and non-automatic rainfall and runoff data and to facilitate the applications

Table 4 Model parameters and average statistical values of the 15 runoff stations.

Station ID	Model parameters					Range of statistical values (average value)		
	α	β	IL	PR	IF	r	EI (%)	RMSE (m^3/s)
P.20	0.30	9	0	0.21	550	0.79-0.93 (0.87)	52.48-81.20 (68.91)	11.44-29.63 (21.37)
P.28	0.35	8	0	0.22	400	0.84-0.95 (0.90)	50.96-83.27 (72.46)	18.56-51.74 (29.09)
P.75	0.5	8	0	0.12	700	0.98-0.99 (0.989)	93.53-98.48 (94.33)	4.39-7.12 (4.82)
P.4A	0.35	9	0	0.15	700	0.84-0.96 (0.91)	65.56-81.85 (74.64)	15.11-23.48 (18.94)
P.67	0.5	8	0	0.12	700	0.97-0.98 (0.974)	89.15-95.83 (95.93)	5.55-24.69 (14.23)
P.21	0.20	6	0	0.15	600	0.72-0.93 (0.87)	50.96-83.27 (72.46)	18.56-51.74 (29.09)
P.1	0.50	5	0	0.08	800	0.951-0.997 (0.976)	87.46-97.60 (93.03)	12.34-29.61 (20.65)
P.5	0.80	9	0	0.25	250	0.80-0.95 (0.87)	53.37-67.87 (62.07)	25.44-28.71 (26.51)
P.77	0.20	5	0	0.20	350	0.92-0.93 (0.92)	75.93-84.69 (80.31)	9.58-9.59 (9.58)
P.71	0.40	8	0	0.22	350	0.80-0.98 (0.88)	58.43-95.93 (74.71)	8.29-33.07 (19.97)
P.29	0.40	8	0	0.26	200	0.78-0.94 (0.86)	58.34-64.59 (61.46)	33.72-41.66 (37.69)
P.76	0.40	8	0	0.26	200	0.90-0.97 (0.94)	80.33-94.29 (87.31)	9.69-37.71 (23.70)
P.24A	0.20	5	0	0.25	280	0.81-0.96 (0.88)	58.03-91.48 (72.52)	6.17-13.71 (9.92)
P.73	0.45	9	0	0.25	250	0.90-0.98 (0.94)	76.41-94.90 (84.66)	76.61-108.6 (93.32)
P.14	0.2	5	0	0.11	500	0.80-0.93 (0.87)	50.87-79.58 (67.98)	24.84-45.11 (37.84)

Table 5 Model parameters and statistical values of the five runoff stations to be used for ungauged flood estimation.

Ungauged catchment (derived Station ID)	Model parameters					Range of statistical values (average value)		
	α	β	IL	PR	IF	r	EI (%)	RMSE (m^3/s)
UGC 1 (from P.75)	0.5	8	0	0.12	700	0.965-0.997 (0.984)	92.21-99.21 (96.22)	5.09-9.71 (6.89)
UGC 2 (from P.67)	0.5	8	0	0.12	700	0.973-0.999 (0.988)	93.60-99.43 (96.74)	9.02-18.17 (13.53)
UGC 3 (from P.1)	0.2	3	0	0.12	700	0.987-0.998 (0.991)	92.68-97.06 (95.41)	13.65-28.30 (19.20)
UGC 4 (from P.73)	0.45	9	0	0.55	130	0.907-0.966 (0.927)	77.73-91.84 (83.59)	96.91-105.5 (100.38)

Table 6 Calibrated Manning's n for channel and floodplain flows for cross-sections between P.20 and P.73.

River reach	Manning's n		
	Channel	Left flood plain	Right flood plain
P.20-P.75	0.035	0.45	0.45
P.75-P.67	0.030	0.55	0.55
P.67-P.1	0.033	0.55	0.55
P.1-P73	0.028	0.45	0.45

Table 7 Statistical values of the four runoff stations to be used for FLDWAV model calibration and verification.

Flood event	Runoff station ID	r	EI (%)	RMSE (m^3/s)
21 Jul 2001-30 Sep 2001	P.1	0.991	97.01	4.29
	P.75	0.918	92.21	9.71
	P.67	0.988	92.59	5.84
	P.73	0.984	82.49	28.06
12 Aug 2002 - 30 Oct 2002	P.1	0.987	96.32	4.13
	P.75	0.879	97.25	5.87
	P.67	0.973	94.99	4.81
	P.73	0.965	82.61	37.42
1 Sep 2003 - 30 Sep 2003	P.1	0.998	95.60	22.10
	P.75	0.965	99.21	5.09
	P.67	0.999	97.14	20.44
	P.73	0.997	67.97	128.39

of the URBS and FLDWAV model system for flood forecasting system application. These systems were proven to have the capacity required to provide the essential information of flood hydrographs at different locations in the upper Ping River basin to support a flood forecasting system for the basin as both the URBS and FLDWAV model systems could accurately simulate flood hydrographs close to the observed values at all four stations (P.75, P.67, P.1, and P.73) located along the Ping River.

Table 8 Comparison of statistical values of three flood events at each station using two model systems.

Runoff	URBS model systemFLDWAV model system					
station ID	r	EI	RMSE	r	EI	RMSE
	(%)	(m^3/s)				
P.1	0.976	93.03	20.65	0.989	96.31	10.17
P.75	0.989	94.33	4.82	0.984	96.22	6.89
P.67	0.974	95.93	14.23	0.980	94.91	10.37
P.73	0.942	84.66	93.32	0.925	77.69	64.62
Average	0.970	91.99	33.26	0.970	91.28	23.01

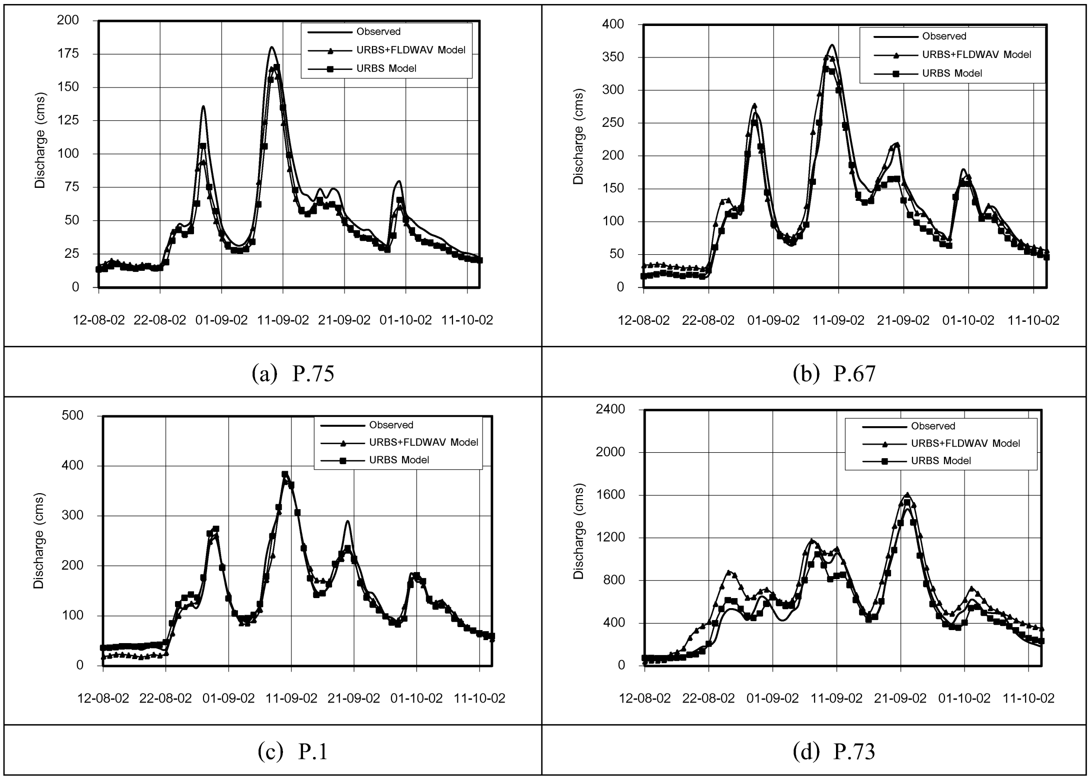

Figure 3 Comparison of calculated flood hydrographs in 2002 using the URBS and FLDWAV model systems and the observed hydrographs at each station along the Ping River.

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