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Flood Investigation in the Upper Ping River Basin Using Mathematical Models

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ABSTRACT

The objective of this study was to evaluate the performance of two public domain models - the IHACRES (rainfall-runoff model) and the FLDWAV (hydrodynamic model) - using the upper Ping River basin as the study area. Rainfall, runoff and meteorological data on a daily basis were used for model calibration and verification. IHACRES was used to estimate ungauged flows for three sub-catchments along the study reach between stations P.75 and P.73 of the Ping River, which were used subsequently as input data for FLDWAV. The IHACRES model parameters used for ungauged flood estimation of the three sub-catchments were calibrated at their neighboring gauging stations - P.20, P.76 and P.77. IHACRES was able to produce flood hydrographs close to the observed values at these three stations. The calibrated IHACRES model parameters were later used for flood estimation for three ungauged catchments and three selected flood events in 2001, 2003 and 2004, which were used subsequently as input data for FLDWAV. For the three selected flood events, FLDWAV was effective in estimating flood hydrographs that were also close to the observed values at all three stations - P.67, P.1 and P.73 - located along the Ping River. Even though they may not be as easy to use as some commercial models, these two public domain models are quite flexible and can be used in many circumstances and produce reasonable results that are as accurate as other commercial and non-commercial models.

Key words: IHACRES model, FLDWAV model, upper Ping River basin

INTRODUCTION

Flood is a natural phenomenon that occurs when excessive catchment runoff causes a river to overflow its banks. Floodwater can spread to agricultural, residential, industrial and commercial areas and can cause economic and social damage and threaten human life. Engineers and researchers have been trying to understand the physical characteristics and to simulate flood hydrographs to be able to mitigate flooding and its effects. The correct simulation of flood hydrographs normally requires two model components - a hydrologic and a hydraulic model. The hydrologic model can estimate flood discharges of various magnitudes, while the hydraulic model can determine the extent, depth and velocity of flooding (O'Connor and Costa, 2004). These two types of models can be further developed to increase the accuracy of flood estimates.

Conventional hydrologic models were developed based on imitating the hydrologic cycle. However, there are many components involved in

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the cycle such as interception, infiltration, depression storage, evaporation, subsurface flow, groundwater flow, overland flow and channel flow that cannot be fully explained by any available models (Mapium and Sriwongsitanon, 2009). Therefore, models have been developed to explain only important components in the hydrologic cycle and so can be applied only to suitable areas of interest. There are examples of models that have been developed for runoff estimation that consider only some of the significant hydrologic cycle components, such as SCS (USDA, 1972), NAM (Nielsen and Hansen, 1973), TANK (Sugawara, 1974), TOPMODEL (Beven and Kirkby, 1979), HEC-HMS (HEC, 2000), SWAT (Neitsch *et al*., 2005), and IHACRES (Croke *et al*., 2005a). Among the models that have been developed so far, the IHACRES model has been accepted because of its structural simplicity to reduce the parameter uncertainty inherent in hydrologic models, while at the same time attempting to represent more details of the internal processes than is typical for a distributed model (Croke *et al*., 2005b). It has been successfully applied worldwide to investigate the hydrologic response, in Australia (Carlile *et al*., 2004), Thailand (Croke *et al*., 2003), USA (Evans, 2003), UK (Littlewood *et al*., 1997), and South Africa (Dye and Croke, 2003).

Hydraulic models on the other hand can be used to estimate the flow rate and water level at important locations in the channel system. This type of model is usually based on partial differential equations (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 (Chow *et al*., 1988). There are several hydraulic models that have been developed such as CE-QUAL-RIV1 (Environmental Laboratory, 1995), FLDWAV (Fread and Lewis, 1998), MIKE 11 (DHI, 2002), HEC-RAS (Brunner, 2002). The FLDWAV model has proven to be an effective model to investigate flood routing in the upper Ping River as has MIKE 11-HD, which is an accepted commercial model (Taesombat and Sriwongsitanon, 2006). Moreover, the FLDWAV model has been implemented on major rivers in complex river systems, not only in the USA, such as the Mississippi River (Ming and Sylvestre, 2001), the Red River, Minnesota (Buan, 2003) and the Susquehanna River (Sylvestre and Sylvestre, 2002), but also in China in the Yangtze delta area (Xu and Zhang, 2002) which has complicated river networks associated with the city of Shanghai.

In this study, the two public domain models, IHACRES and FLDWAV were selected to calculate flood hydrographs at ungauged locations and flood properties (flow rate and water level) at important locations, respectively, in the upper Ping River basin. The study river reach was between the gauging stations P.75 and P.73. Section 2 describes study area and data collection used in this study. Section 3 and Section 4 present the theory and concept of the IHACRES and FLDWAV models, respectively. Section 4 also presents the methodology for estimating flood hydrographs and flood properties. Section 5 describes the methodology used for model calibration and model verification. Section 6 presents an evaluation of the model performance. Conclusions from the study are presented in the Section 7.

MATERIALS AND METHODS

Study area

The study area was in the upper Ping River basin, which covers a catchment area of around 25□370 km^2 in the provinces of Chiang Mai and Lamphun, northern Thailand. The Ping River originates in Chiang Dao District, north of Chiang Mai and flows to the south where it enters the Bhumibol Dam - a large dam with an active storage capacity of 9.7 billion m^3. The average annual rainfall and runoff of the basin are around 1174 mm and 6815 million m^3, respectively. The upper Ping River basin is covered mostly by mountain ranges and forests. It is one of the main tributaries of the Chao Phraya River, which encompasses around one third of the country's area. The upper Ping River basin is one of the main water supplies for the people living in the basin and downstream. However, the forest area has declined continuously to around 72% of the basin area (Royal Forest Department, 2006). Figure 1 shows the upper Ping River basin and the location of rainfall, runoff and meteorological stations used for the analysis.

Data collection

Rainfall data

Daily rainfall data at 37 stations collected by the Royal Irrigation Department (RID), the Department of Water Resources (DWR) and the Thai Meteorological Department (TMD) were used in this study. The rainfall data were used as

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

the input data for the rainfall-runoff model (IHACRES) to simulate flow hydrographs for the ungauged catchments within the range of stations between P.75 and P.73. Figure 1 shows the locations of the 37 rainfall stations used in the study.

Runoff data

The study used daily runoff data at 10 stations, including flow release from the Mae Kuang Dam (MK-Re), which is located on the Mae Kuang River and has an active storage capacity of 263 billion m^3. These stations are operated by the RID. Runoff data at the upstream locations (P.75, P.4A, P.21, P.71, P.76, P.24A and MK-Re) were used as the input data for the hydrodynamic model (FLDWAV) and runoff data at the downstream locations (P.73) were used for calibration proposes. Rating curves (the stage and discharge relationships) were used at P.73, downstream, as the input data for the FLDWAV. The runoff stations at P.20, P.76 and P.77 were also used for model calibration and verification of the IHACRES model. Figure 1 shows the locations of 11 runoff stations used in the study.

Meteorological data

Daily temperature data at two meteorological stations, located at Chiang Mai (CM-Met) and Lamphun (LP-Met), were used as the input data for the IHACRES model. The stations are operated by the TMD. Figure 1 shows the locations of the two stations used in the study.

Cross section data

The study also used data from 165 cross sections located along the Ping River between the upstream and downstream stations (P.75-P.73), and along the Kuang River between the Mae Kuang Dam and the confluence of Mae Kuang and Ping Rivers. The data was used as inputs for the FLDWAV model. The data were collected by the RID and the DWR. Table 1 summarizes the cross-sections between locations, which were collected at different times by these two government agencies.

IHACRES model

IHACRES stands for "identification of unit hydrographs and component flows from rainfall, evaporation and streamflow data". It is a catchment-scale rainfall-runoff model and 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. The updated version added a non-linear loss module and alternative model calibration techniques (Croke *et al.*, 2003) to the previous version. Figure 2 shows the model structure, which comprises modules of non-linear and linear relationships. The

Table 1 Details of cross section data.

River and location	Number of cross sections	River distance (km)
Ping River		
• P.75 station to Nong Saleak Weir (RID, 2005)	99	103
• The confluence of Mae Kuang and Ping river to P.73 (DWR, 2005)	31	60
Mae Kuang River		
• Mae Kuang Dam to the confluence of Mae Kuang and Ping river (DWR, 2005)	35	67

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

Non-linear module

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

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

where, r_k is the observed rainfall in mm, 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 p are 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 given as shown in Equation 3.

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

where, t_k is the observed temperature in degrees Celsius, τ_w is the drying rate at reference temperature in degrees Celsius, f is the temperature modulation in degrees Celsius^{-1}, and t_r is the reference temperature in degrees Celsius, which can be identified by using local average air temperature. The parameter f relates to seasonal variation in 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, while t_r correlates to the average air temperature.

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

Linear module

In this 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. For many applications, it has been recommended to use the two components 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, for a time step k, combines quick flow ($x_k^{(q)}$) and slow flow ($x_k^{(s)}$) to yield runoff (x_k) as presented in Equations 4,5 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 quick flow, and α_s, β_s for slow flow. Dynamic response characteristics (DRCs) unit hydrographs for quick flow and slow flow are calculated as shown in Equations 7 and 8, respectively.

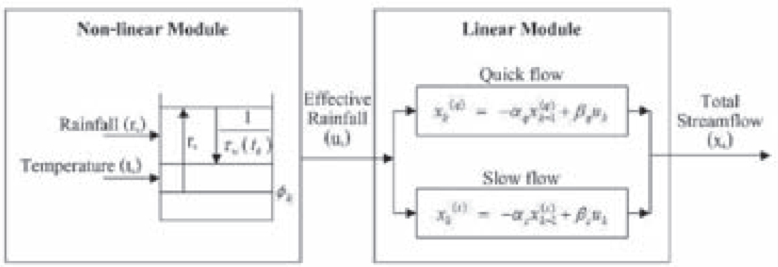

Figure 2 IHACRES model structure (Evans and Jakeman, 1998).

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

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

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. The parameter τ_q is recommended to be less than the time step (Δ). The relative volume of quick flow and slow flow can be calculated by 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 quick flow to the total flow ($1–V_s$).

FLDWAV model

FLDWAV is a hydrodynamic public domain model, developed by the National Weather Service (NWS) (Fread and Lewis, 1998). It is a generalized flood routing model with 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 two NWS generalized flood-routing models, DAMBRK and DWOPER. It allows the utilization of the combined capabilities of the two flood-routing models, as well as providing new hydraulic simulation features. The Federal Emergency Management Agency (FEMA) has accepted this model for use in the National Flood Insurance Program (NFIP). The model is based on one-dimensional Saint-Venant equations of unsteady flow coupled with an assortment of internal boundary conditions for simulating unsteady flows controlled by a wide spectrum of hydraulic structures. A set of model equations can be solved by a weighted four-point implicit finite-difference. The Saint-Venant equations of the conservation of mass and momentum equations with additional terms of the expansion/contraction effect (Fread and Smith, 1978), channel sinuosity (DeLong, 1986 and 1989), and non-Newtonian flow (Fread and Lewis, 1988; Fread and Lewis,1993) are shown in Equations 10 and 11, respectively.

$$\frac{\partial Q}{\partial x} + \frac{\partial s_c(A+A_o)}{\partial t} - q_L = 0 \quad (10)$$

$$\frac{\partial (s_m Q)}{\partial t} + \frac{\partial (\beta Q^2 / A)}{\partial x} + gA\left(\frac{\partial h}{\partial x} + \overline{S_f} + S_e + S_i\right) + L + W_f B = 0 \quad (11)$$

where Q is the discharge, A is the wetted active cross-sectional area, A_o is the wetted inactive off-channel (dead) storage area associated with topographical embankments or tributaries, B is the channel flow width, s_c and s_m are depth-dependent sinuosity coefficients for mass and momentum, respectively that account for meander river, β is the momentum coefficient for non-uniform velocity, q is the lateral flow (inflow is positive, outflow is negative), t is 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 (large eddy loss), and W_f is the wind term.

Model calibration and model verification

IHACRES model

The IHACRES model was used to estimate flow hydrographs for the ungauged catchments within stations P.75 and P.73 to be used subsequently as the input data for the FLDWAV model. In this study, ungauged catchments were separated into three areas called the ungauged catchments 1, 2, and 3, which had catchment areas of around 873, 2325, and 1973 km^2, respectively, as shown in Figure 1. Since these areas are ungauged, model parameters cannot be determined using the calibration and verification processes. In this study, calibrated model parameters at neighboring gauged stations P.20, P.76, and P.77 - which cover areas of around 1355, 1541, and 547 km^2, respectively - were used to define model parameters for these ungauged catchments. Flood hydrographs at these three stations between August to November in 2001 and 2002 were used for model calibration and in 2003 and 2004 were used for model verification. Table 2 shows rainfall and meteorological stations used for model calibration and verification at the three runoff stations. Daily temperatures registered at each meteorological station and area rainfall data were used as the input data for the IHACRES model. Daily areal rainfall data for each runoff station and each flood event were calculated by the Thiessen polygon technique (Thiessen and Alter, 1911).

Once the calibrated model parameters at stations P.20, P.77 and P.76 had been acquired, their parameters were then applied to the ungauged catchments 1, 2 and 3, respectively. The flow hydrographs at these three ungauged catchments were then calculated for the flood periods in 2001 (1-31 August), 2003 (1-30 September), and 2004 (1-30 September) to be used as the input data for the FLDWAV model in the model calibration and model verification, respectively. Table 3 shows the rainfall and meteorological stations as well as the catchment area of each ungauged catchment used for the application of the IHACRES model. Flood hydrographs simulated at these ungauged catchments were later used as the input data for the FLDWAV model.

FLDWAV model

The FLDWAV model usually can be calibrated using unsteady flow characteristics to evaluate the suitable roughness coefficient (Manning's n) for both the channel and floodplain of each cross-section. For the upper Ping River

Table 2 Rainfall and meteorological stations used for model calibration and verification.

Runoff station	Meteorological station	Rainfall station
P.20	CM-Met	07122, 07132, 07702, 030205, 060406
P.76	LP-Met	17022, 17062, 17081
P.77	LP-Met	07032, 07052, 17042

Table 3 Rainfall and meteorological stations used for estimating the hydrographs at three ungauged catchments.

Ungauged catcment	Covering area (km^2)	Meteorological station	Rainfall station
1	Ping River between P.75 and P.1 (873)	CM-Met	07013, 07042, 07052, 07062, 07112, 07142, 07242, 07262, 07341, 07391, 07502, 060601, 060602
2	Mae Kuang River between Mae Kuang Dam and Ping River confluence (2,325)	LP-Met	07013, 07032, 07042, 07052, 07341, 07391, 16072, 16162, 17012, 17032, 17042, 17052, 17093
3	Ping River between P.1 and P.73 (1,973)	CM-Met	07013, 07082, 07092, 07142, 07182, 07192, 07242, 07262, 07292, 07391, 07472, 17012, 17022, 17032, 17052, 17081, 17093, 060801, 061006

network between stations P.75 and P.73 as shown in Figure 3, a flood event was selected in 2001 (1-31 August) to be used for model calibration. The maximum flow rate of this event at P.1 was around 450 m^3/s which exceeded its channel capacity (350 m^3/s). The suitable Manning's n for both the channel and floodplain of each cross-section between stations P.75 and P.73 were chosen by trial and error to obtain the best fit between calculated and observed flood hydrographs at stations P.67 P.1 and P.73. In the model verification procedure, selected values of Manning's n for each cross section were applied in the other two flood events in 2003 (1-30 September), and 2004 (1-30 September). The maximum flow rates of these two events at P.1 were around 414 and 400 m^3/s, respectively, which also exceeded its channel capacity. Input data for the FLDWAV model used for routing floodwater from P.75 to P.73 (Figure 3) were as follows:

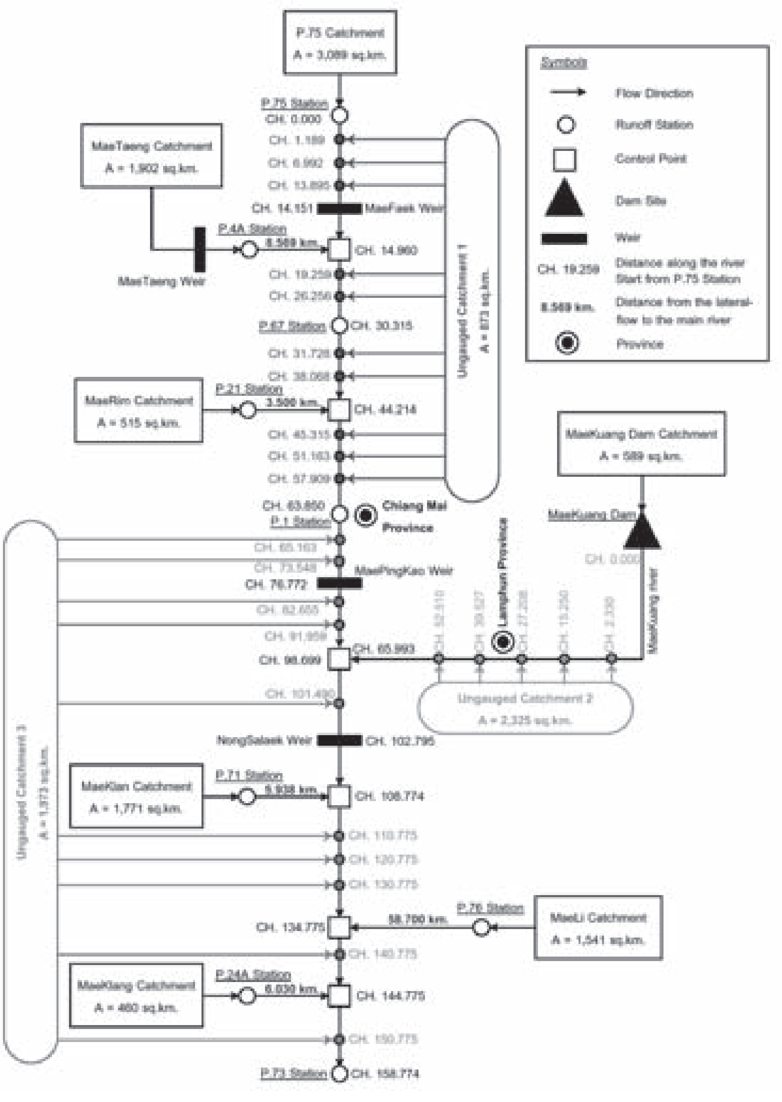

Figure 3 Schematic diagram of the upper Ping River network between P.75 and P.73.

1) Daily runoff data at all upstream locations of the river network comprising P.75, P.4A, P.21, P. 71, P.24A, and flow release from Mae Kunag Dam,

2) Local flows at three ungauged catchments calculated using IHACRES,

3) Observed rating curves at P.73 observed in 2001, 2003, and 2004.

Evaluation of model performance

Statistical indicators

To evaluate the model performance, the model results were compared to the observed data using three statistical indicators - correlation coefficient (r), efficiency index (EI) and root mean square error (RMSE) - as shown in Equations 12, 13 and 14, respectively. The best fit between the model results and observed data using these indicators occur when the correlation coefficient (r) approaches 1, the efficiency index (EI) approaches 100% and the root mean square error approaches zero.

$$r = \frac{\sum_{i=1}^{N}\left(Q_{oi}-\bar{Q}_o\right)\times\left(Q_{ci}-\bar{Q}_c\right)}{\left[\sum_{i=1}^{N}\left(Q_{oi}-\bar{Q}_o\right)^2\times\sum_{i=1}^{N}\left(Q_{ci}-\bar{Q}_c\right)^2\right]^{0.5}} \quad (12)$$

$$EI = \frac{\sum_{i=1}^{N}\left(Q_{oi}-\bar{Q}_o\right)^2-\sum_{i=1}^{N}\left(Q_{oi}-Q_{ci}\right)^2}{\sum_{i=1}^{N}\left(Q_{oi}-\bar{Q}_o\right)^2}\times 100\% \quad (13)$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[Q_{oi}-Q_{ci}\right]^2} \quad (14)$$

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

RESULTS AND DISCUSSION

IHACRES model

The suitable model parameters at stations P.20, P.76 and P.77 are presented in Table 4. By applying these parameters, the values of statistical indicators comparing the calculated and observed hydrographs for these runoff stations are presented in Table 5. Table 5 shows that the r values are between 0.75 and 0.93 with an average of 0.85, the EI values are between 81% and 94% with an average of 88%, and RMSE are between 0.8 and 13.1 m^3/s with an average of 7.0 m^3/s. These values are within the acceptable ranges and so at stations P.20, P.77, and P.76 can be applied therefore to

Table 4 IHACRES model parameters for the stations P.20, P.76 and P.77.

Runoff Station	Area (km^2)	Non-linear module			Linear module		
		c	τ_w	f	τ_s	τ_q	v_s
P.20	1,355	0.012584	5	11	24.23	1.13	0.766
P.76	1,541	0.007422	37	16	63.10	3.05	0.540
P.77	547	0.001939	15	1	28.31	1.39	0.287

Table 5 Values of statistical indicators evaluated at three stations for four flood periods.

Flood Period	P.20			P.76			P.77		
	r	EI (%)	RMSE (m^3/s)	r	EI (%)	RMSE (m^3/s)	r	EI (%)	RMSE (m^3/s)
2001	0.80	87	9.1	0.87	88	6.5	0.89	87	3.4
2002	0.78	90	7.9	0.91	92	13.1	0.83	82	4.9
2003	0.75	81	11.3	0.93	94	6.2	0.89	89	0.8
2004	0.83	91	9.7	0.80	90	9.9	0.90	88	1.5

the ungauged catchments 1, 2, and 3, respectively. Figures 4, 5 and 6 show the comparison between calculated and observed hydrographs at these three stations.

During the calibration and verification processes, the parameters in the non-linear module (c, τ_w and f) were found to have significant direct effects on volume and the peak of flow hydrograph. The parameters in the linear module (τ_s, τ_q and v_s) had an effect on the peak of flow hydrograph, but not on its volume. The parameter τ_q, τ_s and v_s had indirect effects on peak flow.

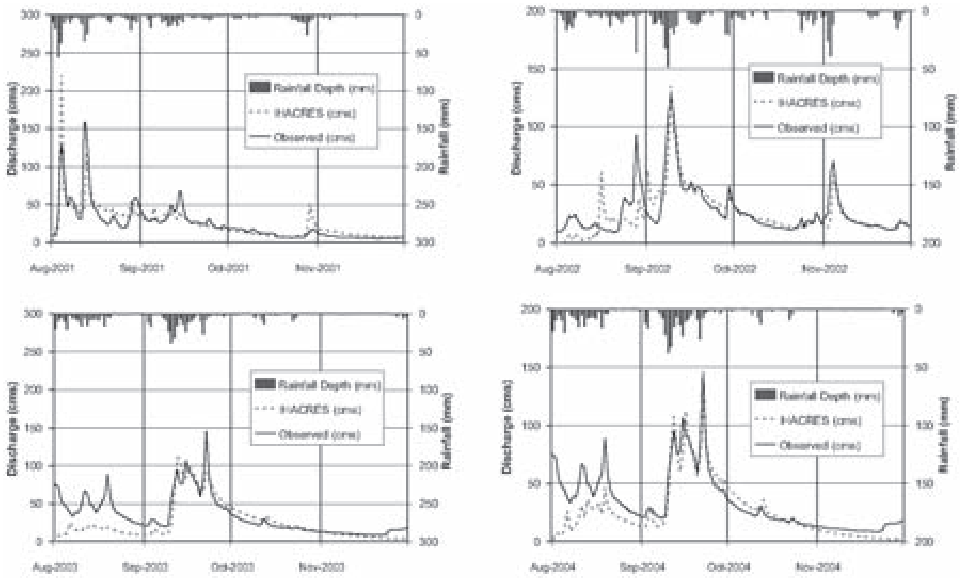

Figure 4 Comparison of calculated and observed flood hydrographs at P.20.

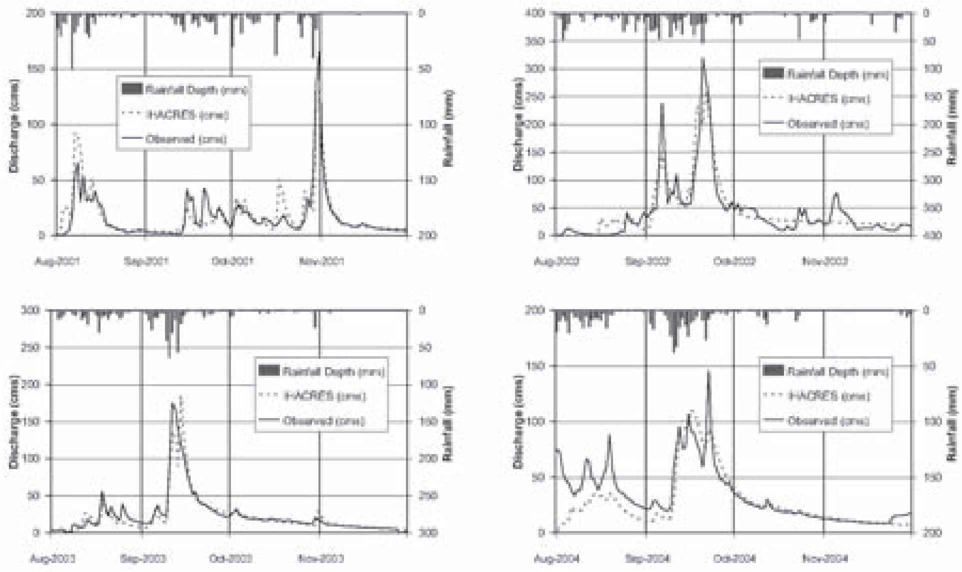

Figure 5 Comparison of calculated and observed flood hydrographs at P.76.

FLDWAV model

The suitable Manning's n values for the channel and floodplain flows of the Ping River were 0.035 and 0.070, respectively. Increasing Manning's n values reduced the flow magnitude and increased the travel time. Using these values provided the best fit between observed and calculated flood hydrographs for all three flood events at the runoff stations P.67, P.1 and P.73 located along the Ping River from upstream to downstream. Table 6 presents the statistical values resulting from the model calibration and verification of these flood events. The r values were between 0.91 and 0.99 with an average of 0.97, the EI values were between 97 and 99% with an average of 99% and RMSE were between 4.0 and 33.8 m^3/s with an average of 15.7 m^3/s. These values were also within the acceptable range. The Manning's n values applied in the model were therefore applicable in other situations. Figures 7, 8 and 9 show the comparison between calculated and observed hydrographs at these three stations for each flood event.

CONCLUSIONS

This research has proved that the two public domain models - IHACRES and FLDWAV – can be effectively used for flood estimation and flood routing along the river reach, respectively. The main data required for these two models comprised: rainfall, runoff, temperature on a daily basis and channel cross-sections, which are normally required for the same categories of the

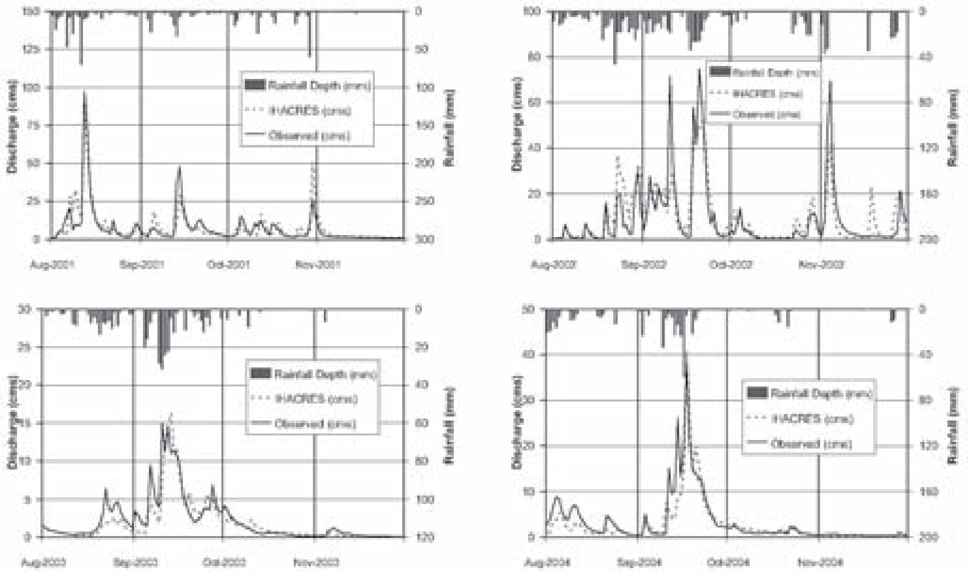

Figure 6 Comparison of calculated and observed flood hydrographs at P.77.

Table 6 Statistical indicators used to evaluate the FLDWAV model performance.

Flood Period	P.67			P.1			P.73		
	R	EI (%)	RMSE (m^3/s)	R	EI (%)	RMSE (m^3/s)	r	EI (%)	RMSE (m^3/s)
2001	0.97	99	6.9	0.97	99	9.7	0.93	99	33.8
2003	0.99	99	6.0	0.99	99	4.0	0.91	99	29.6
2004	0.97	99	8.1	0.97	96	24.2	0.98	99	17.9

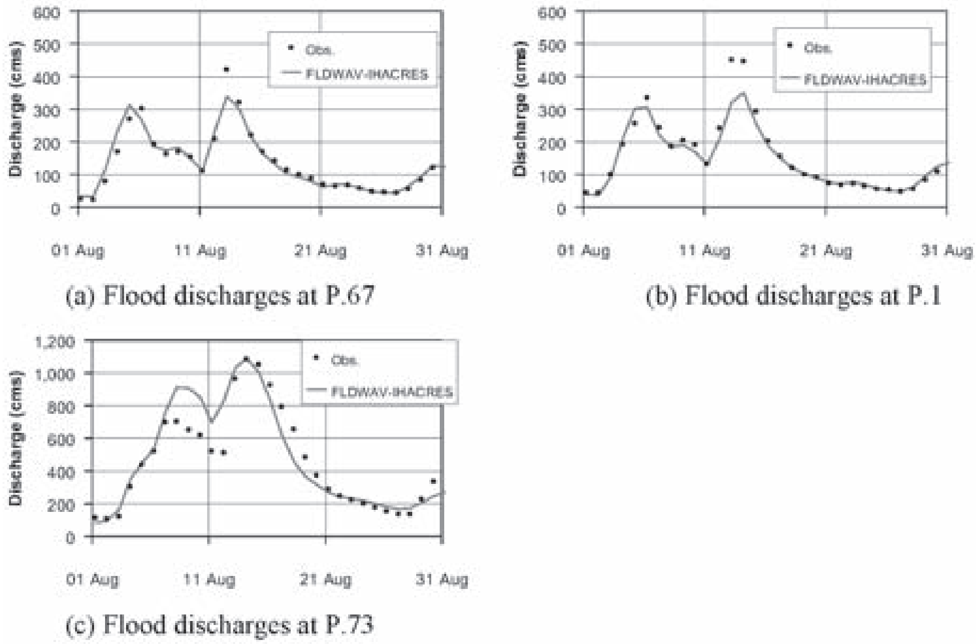

Figure 7 Comparison of calculated and observed flood hydrographs in 2001.

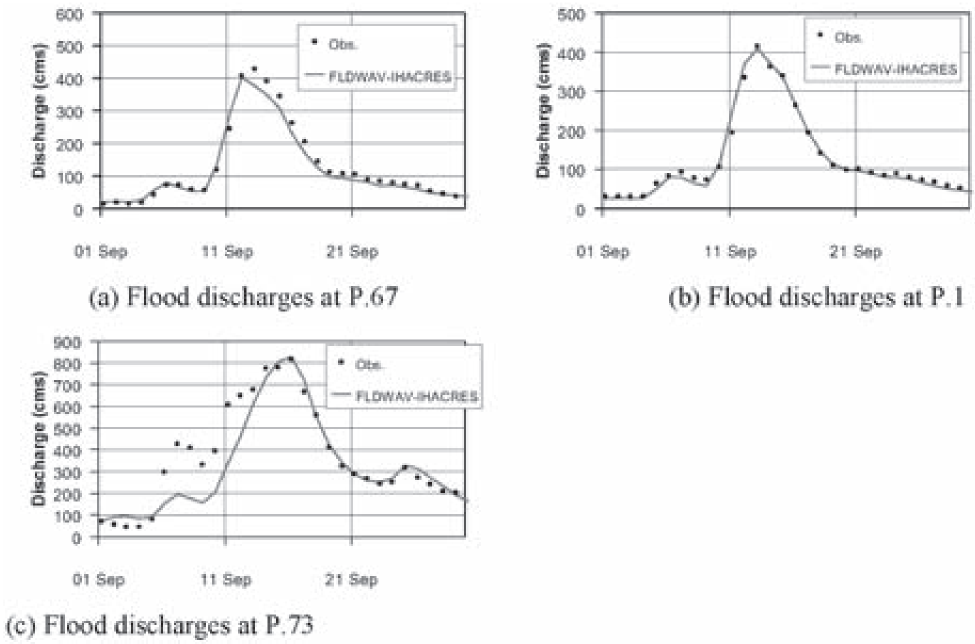

Figure 8 Comparison of calculated and observed flood hydrographs in 2003.

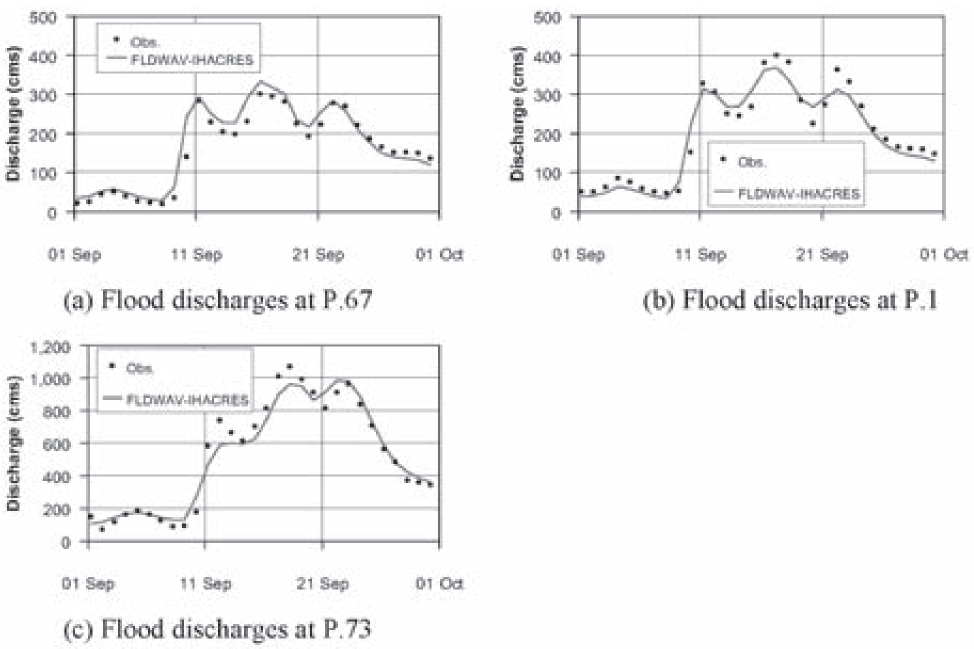

Figure 9 Comparison of calculated and observed flood hydrographs in 2004.

models. In the IHACRES application, it was shown that the parameters in the non-linear module (c, τ_w and f) had significant direct effects on the volume and the peak of flow hydrograph, while the parameters in the linear module (τ_s, τ_q and ν_s) had an effect on the peak of flow hydrograph, but not on its volume. For the FLDWAV model, only the channel roughness coefficient (Manning's n) needed to be calibrated. An increase in the Manning's n value resulted in a reduction in the flow magnitude and an increase in the travel time. The performance of these two models applied to the Upper Ping River basin proved to be within acceptable ranges. The models were quite user-friendly and not difficult to use. Taking into account that no charge is involved to access the models, IHACRES and FLDWAV are obviously worthwhile models to be considered as alternatives to other available commercial models, especially those that have a high cost.

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