Rainfall-Runoff Models and Flood Mapping in a Catchment of the Upper Nan Basin,Thailand

Sombat Chuenchooklin[*1], Saharat Taweepong[2], Udomporn Pangnakorn[3]

[1,2]Water Resources Research Centre: WRRC, Faculty of Engineering, Naresuan University, Phitsanulok, Thailand

[3]Department of Agricultural Science, Naresuan University, Phitsanulok, Thailand

[*1]sombatc@nu.ac.th; [2]saharatt@hotmail.com; [3]udompornp@nu.ac.th

***Abstract*-The Pua Watershed is one of many small catchments in the Upper Nan River Basin, located in the upper portion of the Great Chao Phraya River Basin in Nan Province, Thailand. It was previously considered as an ungauged catchment due to the lack of observed hydrological data. It usually faces flood problems, affecting primarily farmland and residential areas. Two models from the Hydrologic Engineering Center (HEC) were applied: the Hydrologic Modeling System (HMS), and the River Analysis System model (RAS). HMS was used to synthesize daily flood hydrographs from existing daily rainfall data over its catchment, while RAS presents flood behaviors in the river reaches including existing cross-sectional profiles. The HMS model was calibrated in 2008 and validated in 2011 with observed daily rainfall and streamflow data collected at a gauge station in the catchment. Flood mapping on the topographic map in 2011 was delineated from the products by RAS. The simulated results from both the HMS and RAS models fit the observed data well, which can be applied to further efficient flood relief plans and management for any river basin.**

Keywords- Rainfall-runoff Models; HMS; RAS; Ungauged Catchment; Flood Mapping

I. INTRODUCTION

The Pua Watershed was selected as the area of study, situated in the Upper Nan River Basin in Nan, Thailand. The Nan River originated in this province and is comprised of many tributary streams, including Pua to produce inflow to the Sirikit dam in Uttaradit province as a huge reservoir, with a storage capacity of 9510x10^6 cubic meters (m^3). The Pua Watershed is one of several small catchments that directly produces streamflow to the Nan River in Pua district. The watershed includes 404 square kilometers (km^2) representing the Pua District and share area in the Upper Nan Basin (18.2%) and overall Nan River Basin (1.2%), shown in Fig. 1. The Pua River is a primary stream, producing streamflow all year, which is passed to all sorts of consumers and used primarily for agricultural areas within the nine local sub-districts in Pua district. Its stream length was approximately 56.3 kilometers (km) with an average channel slope of 1.9%. The typical problems of the Upper Nan Basin, including the Pua watershed, include the shortage of water for agriculture and domestic purposes during the dry season. Moreover, flash floods, including debris flow and mudslides, have occurred and caused flooding on agricultural lands, stream banks collapse, and sedimentary deposit in the water sources during heavy rainfall in the wet season [1, 2]. Therefore, the Integrated Water Resource Management (IWRM) [3] identified project development planning as bottom-up policy as participation in solving the flood problem was conducted in the Pua watershed, beginning in 2010. The learning processes involved in the collection of all local watercourse information, situations, and strengthening of the Local Sub-district Administrative Offices (LAO) and community leaders in order to perform their own water management were achieved [4]. The Pua watershed intersects nine sub-districts of Pua district: Phuka, Sakad, Silalang, Woranakhon, Satan, Pua, Ngang, Chaiwatana, and Chedichai. The Pua weir was constructed and bound between the plain and mountainous areas with upstream (u/s) drainage area of 149 km^2 and topographic coverage by forest and upland crops. Its u/s riverbed in the mountainous area was a very steep slope of 2.9%, and downstream of the weir in agricultural areas was a mild slope of 0.2%, as shown in Fig. 2. The major branch streams of the Pua river downstream (d/s) of the Pua weir were all ungauged catchments which were comprised of Kwang and Koon (tributary of Kwang) with a drainage area of 86 and 35 km^2 located u/s of Jao weir and Kang weir, respectively, shown in Fig. 3. Most land covering approximately 91.8% was covered by shifting cultivation of maize and upland rice, tropical rainforest, mixed deciduous forest, mixed orchard trees and shrubs, watercourses, and a residential area with 48.0%, 21.4%, 17.6%, 2.1%, 0.2%, and 2.5% of the total basin area, respectively. While the remaining areas were agricultural lands located at the foothill and lowland, including paddy fields, upland crops mixed with vegetables and cash crops (tobacco, corn, groundnuts, and soybeans), and orchards or fruit trees, representing 7.3%, 0.6%, and 0.3% of total area, respectively. The mean annual rainfall in the Pua watershed was 1891 mm, which produces a mean annual runoff of 578x10^6 m^3 to the outlet at the junction of the Nan river. Most of the streamflow is approximately 95% and 5% of the total runoff in the wet and dry seasons, respectively. The Pua and other tributary streams of the Nan river produce surface runoff to the Nan province and Sirikit dam, as shown in Fig. 1. The Royal Irrigation Department (RID) has continued responsibility for the Operation and Maintenance (O&M) of all Medium Scale Irrigation Project (MSIP) and Large Scale Irrigation Project (LSIP) systems, including the Pua weir after the completion of construction. However, Small Scale Irrigation Project (SSIP) and other water resource projects, including the Jao weir and the Kang weir, were transferred to the LAO for the operation and maintenance as well as extension works. There were a number of existing 626-watercourses in the Pua including MSIP and SSIP with potential for storage water of 4.8x10^6 m^3. The LAO have been affected by floods in the lowlands, beginning from the foothill to the outlet of the Pua. In order to be aware of flood behaviors and flood relief planning projects, the explanation

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of flood behaviors and flood prediction in an ungauged basin (PUB) was presented, using properly well-known freeware models. The application of the Hydrologic Modeling System (HMS) and the River Analysis System model (RAS) from the Hydrologic Engineering Center (HEC) of the United State Army Corps of Engineers (USACE) [5, 6] were applied to synthesize a flood hydrograph using existing rainfall data and presenting one dimensional unsteady flow behaviors in the Pua river via its cross-sectional profiles, respectively. The two models were incorporated to apply to any ungauged catchment with parameters smaller than the others [4]. The results from the RAS model incorporated with the flood mapping along the river reaches, which can be applied for further flood relief plan and management in the basin.

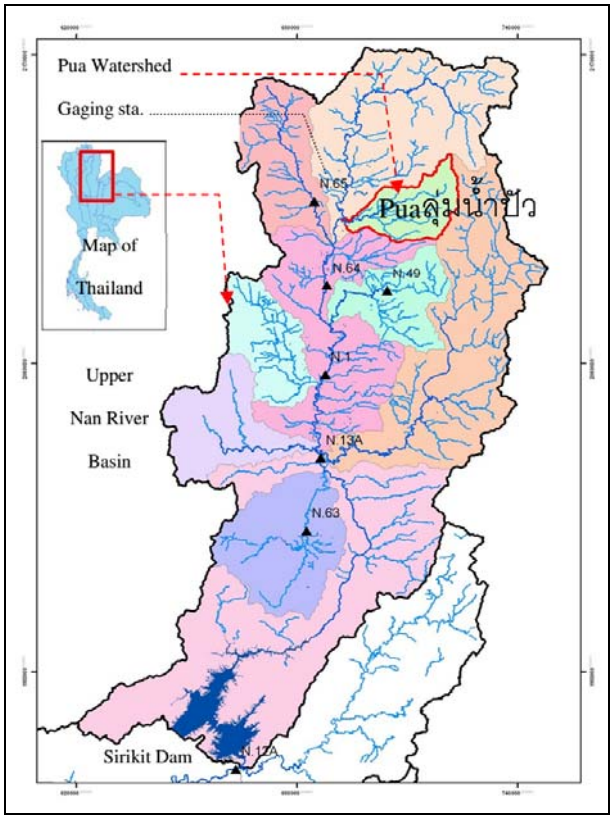

Fig. 1 Map of study area: Pua watershed in the Upper Nan River Basin and existing hydrological gaging stations upstream of the Sirikit Dam [4]

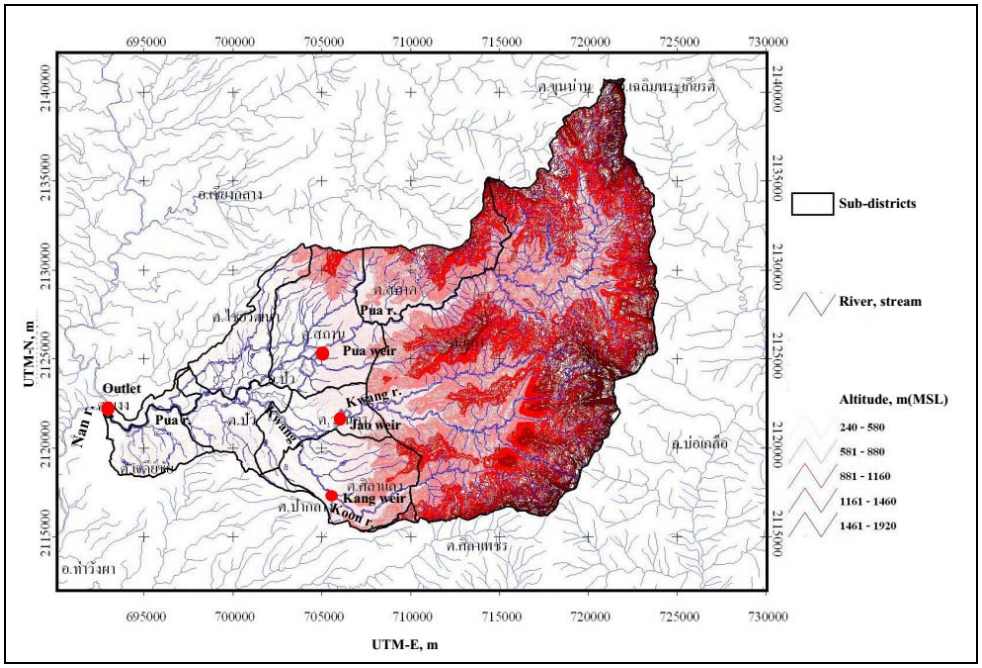

Fig. 2 Enlarged map of the study area, altitudes, stream networks, existing weirs, and sub-districts in the Pua watershed [4]

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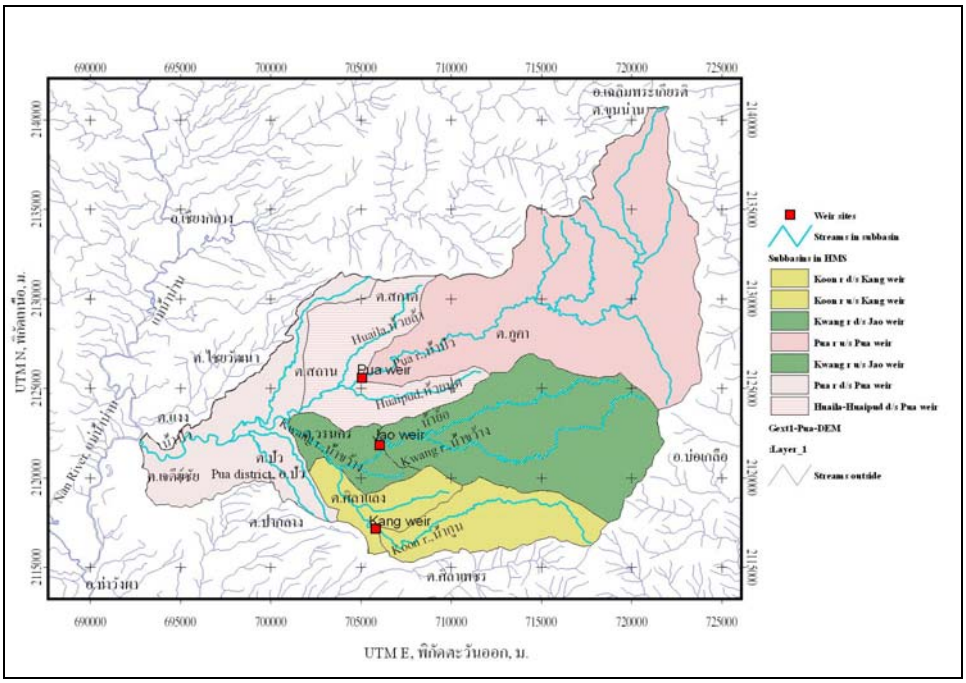

Fig. 3 Map of sub-basins in the Pua watershed to be used in the HMS and RAS models [4]

II. METHODOLOGY

First, the hydrologic modeling system, HMS [5] was applied to simulate the river flow hydrograph using input rainfall hyetograph as an ungauged catchment based on Snyder's synthetic hydrography. Predictions from the HMS were used as input data for the river analysis system, RAS [6], as a second procedure for the following simulation of water surface profiles and their behaviors including flood extents along the river reach and branch streams. All existing watercourses, including natural streams, ponds, and structures, included some cross-sectional profiles of the Pua river downstream of the Pua weir; these were investigated during the IWRM processes. The simple techniques with handheld global positioning systems (GPS) and existing topographic maps available from Google Map (maps.google.co.th), including the satellite-images [7, 8] were applied during site investigation in order to understand their own water resources systems and the situation downstream of the Pua weir to the outlet of the Pua, as shown in Fig. 3.

The existing daily rainfall data inside and outside of the study area was continuously recorded and reported by the Thai Meteorological Department (TMD) [9] with a standard rain gauge type (Pua 28042), Thawangpha (28073, outside of the basin), and Phuka National Park (28164) with the data recorded since 1942, 1968, and 1993, respectively. The Thiessen polygons were applied to an average rainfall in the basin from point observations to aerial rainfalls at stations 28042, 28073, and 28164, each with a polygon area of 39.5%, 2.5%, and 58.0% of the total area, respectively. In addition, another rain gauge station named Ban Nafang (090201) had been recorded by the Department of Water Resource (DWR) from 1977 to 2009. The daily water level and discharge observation data of the Pua river located 300 m u/s of the Pua weir at 19.21^{o}N and 100.95^{o}E [10] were used to verify the output from both models as well. The observation of flow crossing the Pua weir crest and diversion flow to the irrigation system was recorded by the RID during the irrigation supply scheduling in both wet and dry seasons. Most of the lateral streams of the Pua river were lacking in recorded data, and were considered to be ungauged catchments. Therefore, HMS was chosen for flood prediction in all six sub-basins including the Pua. First, the transposing unit hydrograph parameters for the Nan sub-basins in Thailand, as selected for regional study [11, 12] were calculated according to Equation (1), and the HMS model was applied based on Snyder's transformed model [11] and formulae shown in Equation (2). The calibration of hydrological parameters in the HMS were the peak coefficients (C_p), peak lags (t_p), and loss rates (infiltration). The basic equations of HMS are as follows:

$$t_p = C_t\,[LL_c / S^{0.5}]^b \quad \text{and} \quad Q_P/A = g t_p^{\,h} \tag{1}$$

$$t_p = 0.75 C_t\,(LL_c)^{0.3} \quad \text{and} \quad Q_P = 2.78 C_p A / t_{lR} \tag{2}$$

where L and L_c are the main channel length and midstream lengths in km, respectively; S is the channel slope; t_p and t_{lR} are basin lag and adjust the duration of rainfall in hours; Q_p is a peak discharge in m^3/s (cms); A is the catchment area in km^2; C_t and b are the basin coefficient and exponent with values of 3.2663 and 0.1900 [11], respectively; g and h are peak coefficient and exponent with 1.6160 and 1.6074 obtained during the regional study [11]; and C_p is peak coefficient values [5, 12].

The Pua sub-basin u/s of the Pua weir was considered to be a gauged basin during the period of research, therefore HMS was applied to determine the hydrological parameters. The process to optimize those parameters was achieved by comparing

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the simulated discharge (Q) to the observed data. The process of using the HMS is summarized and shown in Fig. 4.

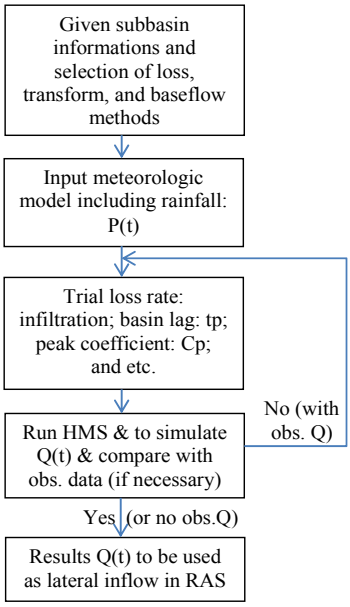

Fig. 4 Flow chart of the HMS model and trial of hydrological parameters in the sub-basins

The schematic of the Pua river and its system was presented in the HMS model, whereas Pua1, Kwang1, Kwang, Koon, HuaiLa-Pood, and Pua-Ngang consisted of six sub-basins. The runoffs from those sub-basins were flown via the streams name: Pua r1 (d/s the of Pua weir), Pua r2 (mid stream), Pua r3 (before the outlet), Namkwang1 (d/s of the Jao weir), Namkoon1 (d/s of the Kang weir). The junctions were named as follows: Bankaem (Koon to Kwang), Tonlang (Kwang to Pua), and Outlet (Pua to Nan river), shown in Fig. 5.

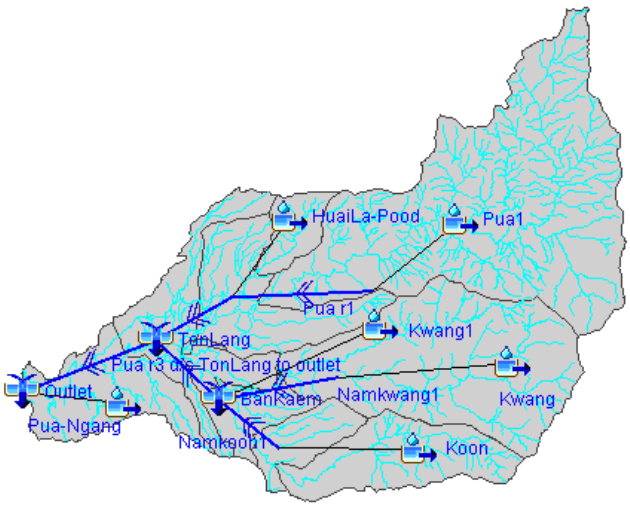

Fig. 5 Schematic of river networks in the Pua watershed and six catchments used in the HMS model

The calibration of HMS model parameters was achieved by optimization trial module using observed discharge at station 090201 (Nafang) in 2008, and then both simulated and observed data were fitted. The next step of the simulation utilized these hydrological parameters to compute the streamflow in the other years with new rainfall data, such as in 2011. For the other ungauged sub-basins, the hydrological effects were trials based on land use types. The results of streamflow from each sub-basin in 2011 which was produced from HMS will be used as the upstream (u/s) boundary condition of the river reach as uniform lateral inflows at each river station (RS) into the RAS model.

The RAS model is a mathematical model to simulate either 1-dimensional steady or unsteady flow profiles along the river reach using either friction slope based on Manning or the St. Venant with both continuity and momentum equations. For the existing simulation, the authors applied an unsteady flow model to those equations, as shown in Equations (3) and (4), respectively. The process of using the RAS model to compute water surface profiles along the river reaches at every river station (RS) was summarized and is shown in Fig. 6.

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$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}-q_l=0 \tag{3}$$

$$\frac{\partial Q}{\partial t}+\frac{\partial QV}{\partial x}+gA\left(\frac{\partial z}{\partial x}+S_f\right)=0 \tag{4}$$

where A is the flow area in each section; Q is u/s discharge in cms; q_l is lateral inflow per length of the channel in cms/m; t is considered time, x is the distance between each cross-sectional profile along the channel reach in m; V is the flow velocity in mps; z is water depth in m; and S_f is the friction slope based on the Manning equation.

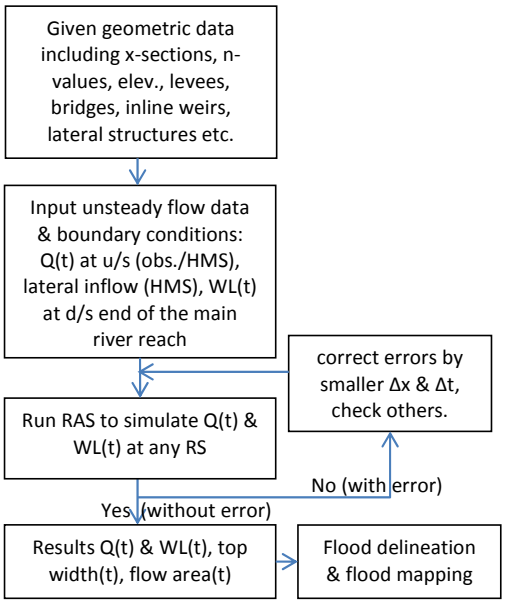

Fig. 6 Flow chart of RAS model to compute flow behaviors along the river reaches to be used in flood mapping

The geometric data module in RAS was done by providing all of the measured 19 cross-sectional profiles nearby each in-lined structure location; bridges and weirs were input to the model. The field surveyed results at both stream banks by handheld GPS and depth measuring in the mainstream by the placement of a tape meter at each structure. Moreover, the digital elevation models (DEM) data based on existing satellite-images were retrieved from the Geo-Informatics and Space Technology Development Agency (GISTDA) [7]. Aerial photo maps from the Land Development Department (LDD) [8] including Google Earth maps were used to specify ground surface elevations at both stream banks at the location of each RS. The reach of the Pua river with total length is approximately 18.3 km, beginning from the Pua weir at river station 18323 m (RS18323) and down to the outlet point (RS0) to the junction of the Nan River [13]. However, none of the riverbank and ground elevation data were located. Therefore, the authors applied the ground elevation data from existing Google Maps coupled with existing satellite-images [7]. All of the original cross-sectional profiles based on data from field surveys, including ground surface elevation versus distance from the left to the right banks, were used in the model. These were applied as a geometric model which automatically interpolated more stream cross-sectional profiles with a smaller step length (Δx) of 300 m, as shown in Fig. 6 with RS*. There was a major tributary stream (Kwang) which met the Pua river at RS 12517. There were two inline weirs cross-sectional profiles: RS17000 with a local weir (SSIP), and RS8526 with a Palan weir (SSIP). The two highway bridges at RS15500 (new route no. 1080) and RS1000 (old route no. 1080) were modeled. A former gauging station was located at RS13000 (N50) which belonged to RID from 1992 to 1994, but it had stopped recording since the completion of construction on the Pua weir in 1995. Moreover, every cross-sectional profile in the model contained Manning's roughness coefficient (n-values) at both floodplain on the riverbanks and in the main channel. The optional data was also considered, such as levee levelling at both riverbanks including bridges and other inline structures, i.e. weirs in a river reach. The simulation of preferable water profiles for this study was unsteady flow based on a daily basis at time increments (Δt). The upstream boundary condition in the model at RS18323 applied discharge across the Pua weir crest or streamflow from station 090201 (Nafang), but other lateral discharges were produced by HMS simulation results. The downstream boundary condition at RS0 applied either normal depth based on the average friction slope of water surface levels over a river reach, or river stage on the Nan river at the outlet point of the Pua river. However, there were no reported river stage observations nearby that location [4]. Therefore, the authors extrapolated by using the relationship between known water depths, riverbank level, and flow rate in the Nan river at N64 (Pha Kwang) with the location approximately 30 km downstream of the Pua outlet. The other four uniformed lateral inflows to the river reach were located at RS 16900, 13608, and 8626 in the HuaiLa-Pood, Kwang, and Pua-Ngang sub-basins, respectively. The systematic model of RAS is shown in Fig. 7, whereas Reach-1 was the Pua river. The lateral inflows to the Pua were Kwang, Koon, HuaiLa-Pood, and Pua-Ngang, based on simulation results from the HMS within the same year of the RAS. The simulation results from the models were calibrated and validated with field observation data

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from the midstream of the Pua river.

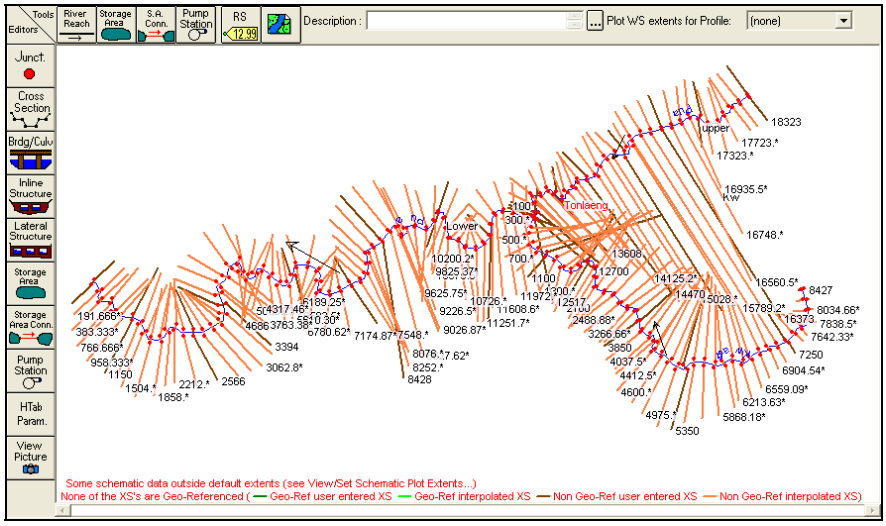

Fig. 7 Schematic models and plan view of the Pua River geometry with cross-sectional profiles every 300-m step length in RAS model

After the completion of RAS, the major productions at each river station (RS) from the simulation were river discharge at both river banks and main channel (Q), water surface elevation (WS), flow area, and top width. Therefore, the maximum flood mapping could be delineated by using the production of RAS with the maximum top width of each cross-sectional profile at each RS. Moreover, satellite-image during the flood period [7] might be used to validate the flood extent produced from the RAS.

III. RESULTS AND DISCUSSION

The result optimization trial of gauged hydrological parameters in 2008, i.e. C_p, t_p, and loss rate, including daily streamflow hydrograph in the Pua sub-basin (upstream of the Pua weir: Pua1*) were produced by the HMS model, based on input daily rainfall and compared to observed streamflow at station 090201 (Nafang), as shown in Table 1 (Row 1) and Fig. 8. The hydrological parameters of other sub-basins are also summarized in Table 1. The results of outflow from the Pua to the outlet and other junctions in the wet season of 2008 are shown in Fig. 9.

TABLE 1 HYDROLOGICAL PARAMETERS FOR EACH SUB-BASIN IN HEC-HMS IN PUA

Sub-basin	Area, km^2	L, km	L_c, km	S	t_p, hr	C_p	Initial loss, mm	Infiltration, mm/hr
Pua1*	149	38.0	19	0.0437	18	0.8	10	0.08
Kwang	86	22.8	12	0.0665	12	0.7	10	0.08
Koon	35	16.9	8.5	0.0847	9	0.6	10	0.08
Kwang1	33	7.7	3.8	0.0108	6	0.5	5	0.05
HuaiLa-Pood	43	8.1	4.0	0.1161	6	0.5	5	0.05
Pua-Ngang	58	13.5	6.8	0.0615	6	0.5	5	0.05

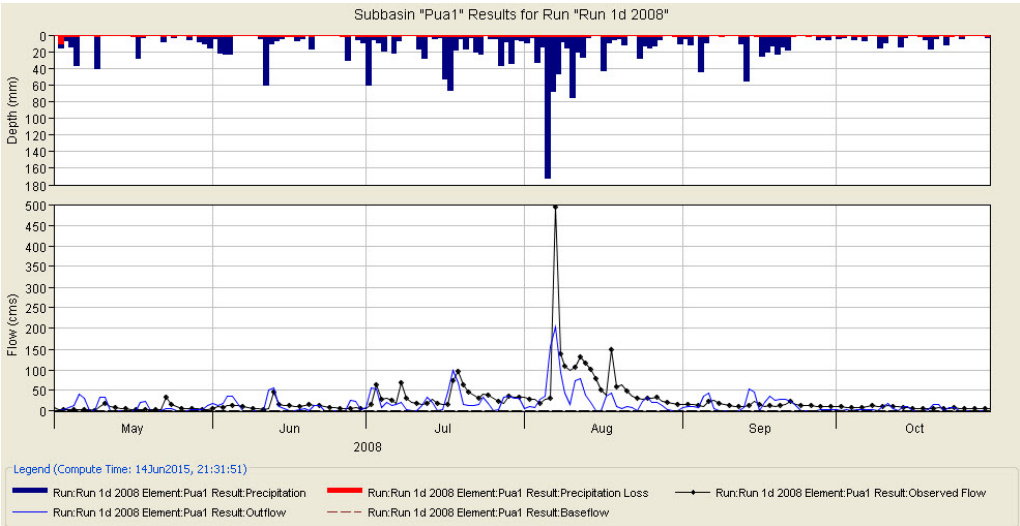

Fig. 8 Outflow hydrograph produced from HMS with daily rainfall in 2008 fitted to observed discharge at Pua weir as model calibration

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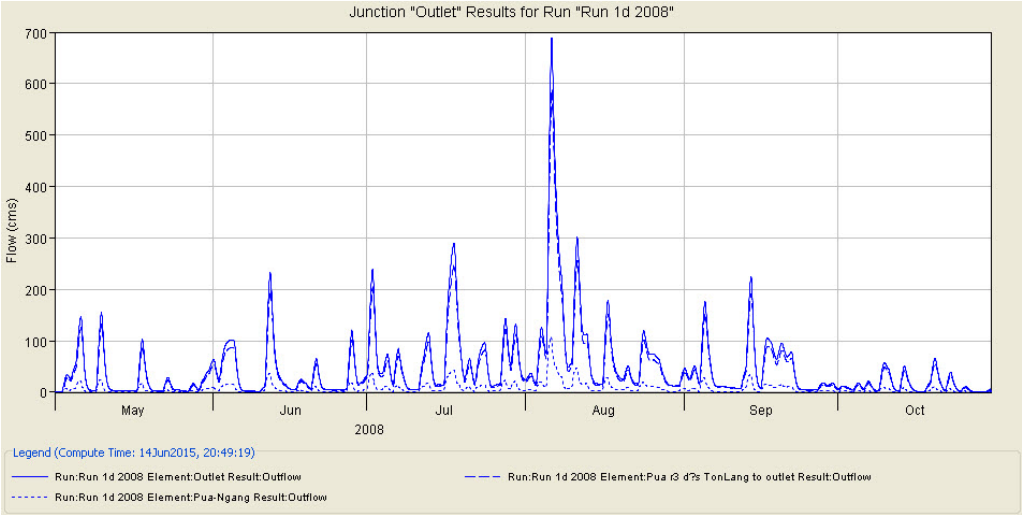

Fig. 9 Outflow hydrograph produced from HMS with daily rainfall in 2008 fitted to observed discharge at Pua weir

The HMS model was validated based on rainfall and water level data recorded hourly during the wet season of 2011 using automatic recorded data loggers at the Pua weir [4]. The water level was converted to calculate the discharge over the weir-crest using the ordinary weir equation [12]. The simulation results of the discharge were compared to observation, which fitted with those relationships as shown in Fig. 10.

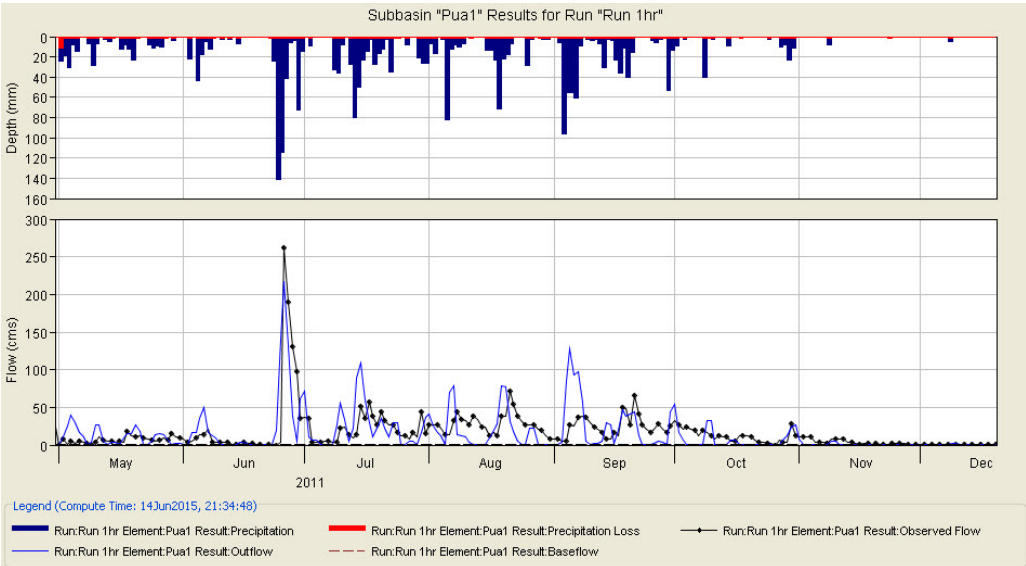

Fig. 10 Outflow hydrograph produced from HMS with daily rainfall in 2011 fitted to observed discharge at Pua weir as model verification

The RAS simulation 1-dimensional unsteady flow model of the daily discharge at the Pua weir during 24 June -13 October of 2011 was considered as the upstream boundary conditions at RS18323. The production of the discharge hydrograph in other sub-basins from the HMS model were applied in RAS as the boundary condition to lateral inflow to the Pua river at RS16373 and RS11427 and to the Kwang river at RS8427, RS5350, and RS3850, respectively shown in Fig. 7 and Fig. 11.

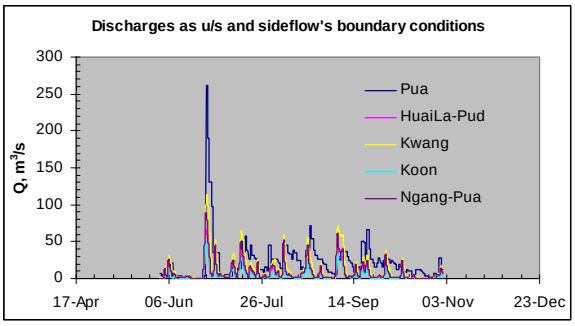

Fig. 11 Daily stream flow hydrohraph in the Pua river and its tributaries applied as u/s boundary conditions in 2011 using RAS

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The roughness coefficients (n-values) in the RAS geometric data module ranged from 0.030 and 0.035 for the main channel, and 0.08 to 0.10 for the floodplain of the Pua river and the Kwang river, respectively. However, there was no gauging station at the outlet of the Pua river to the Nan junction. Therefore, the observation of daily river stages at N64 at a location approximately 30 km downstream of the Pua in the Nan river, shown in Fig. 1, was used to extrapolate and generate the daily water level at the Pua outlet and used as the downstream (d/s) condition in the RAS model, shown in Fig. 12.

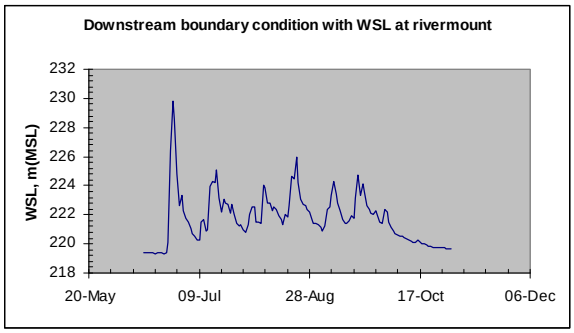

Fig. 12 Daily stage level in the Nan river at the outlet of the Pua river applied as downstage boundary conditions in 2011 using RAS

The maximum discharge in the Pua resulted in a maximum top width which was considered as flood delineation in 2011 with a plan view and water surface profile (WS) of maximum flood during 26-27 June 2011, as shown in Fig. 13 and Fig. 14. The WS downstream of the Pua weir at the outlet resulted as a consequence of the amount of rainfall, influenced by the backwater effect with the fluctuation WS in the Nan River during flood periods.

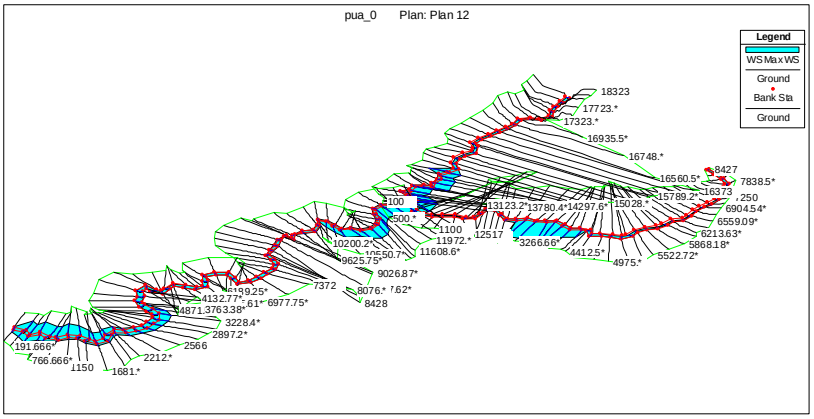

Fig. 13 Plan view of flood delineation with maximum flood on 26/06/2011 as an example result of RAS, to be presented as flood mapping as well

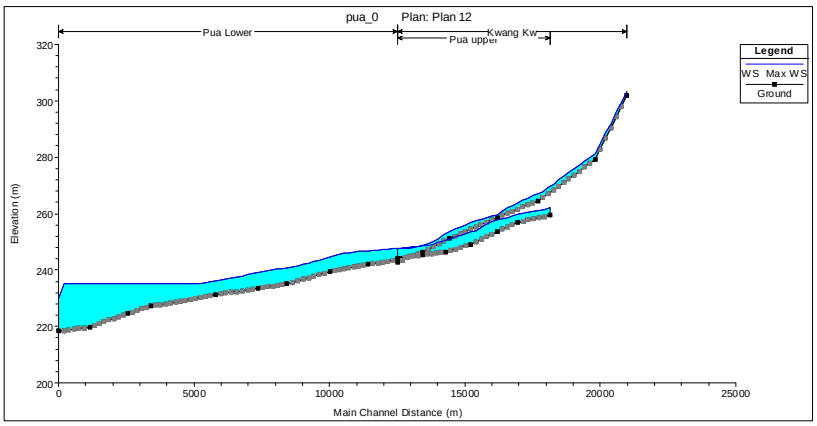

Fig. 14 Longitudinal profile of maximum water surface elevations on 26/06/2011 as an example RAS result in the Pua and Kwang rivers

The result of the maximum flood extent in 2011 from the RAS model was interpreted as an overlay of flood mapping using aerial topographic maps, shown in Fig. 15. The secondary data with the satellite-images during flooding on 29/06/2011, 16/07/2011, and 06/08/2011 in the Pua watershed [7] is shown in Fig. 16, and was used to verify the flood extent produced from the RAS. The relationship of both flood areas from the RAS (Fig. 15) and the result of satellite-image (Fig. 16) was fitted.

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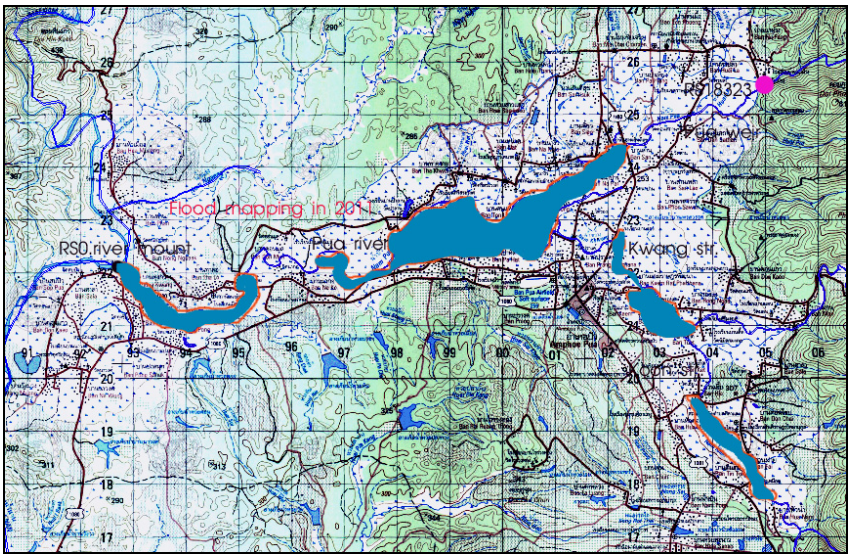

Fig. 15 Flood delineation and mapping in 2011 in the Pua and Kwang, drawn on the topographic map interpreted from the result of HEC-RAS

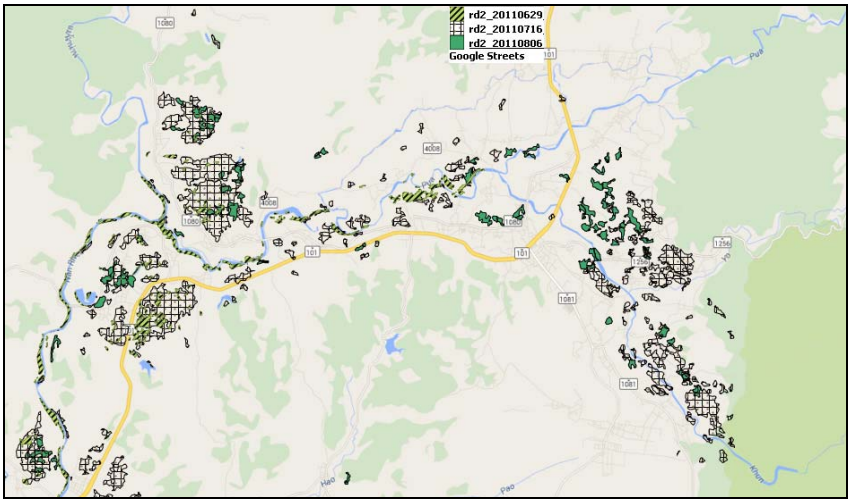

Fig. 16 Satellite-images during flood on 29/06/2011, 16/07/2011, and 06/08/2011 in the Pua watershed [7] including Pua and Thawangpha districts

IV. CONCLUSIONS

The results indicated that both of the Hydrological Modeling Systems from USACE, (HMS) and River Analysis System (RAS), were simple and capably applied to the Pua watershed. In summary, the results of HMS showed that the simulated hourly streamflow and observed data in 2011 were fitted and closely related, as shown in Fig. 10. The sensitivity of the HMS model simulation stemmed the difficulty in specifying the hydrological parameters using the optimization trial manager module. Moreover, improper distribution of rain gauges and missing rainfall data caused differences in the shape of the discharge hydrograph. The most sensitive variables to RAS were less cross-sectional profiles, and a longer time step in the model calculation. Therefore, some errors were reported and calculation was halted. The evidence showed that if applied to the very small time-step in the computation mode and with the use of more cross-sectional profiles by XS interpolation, the RAS model will run smooth and results were fitted to the observed data. Both models can be further applied to other PUB. Moreover, the ground surveyed by using measurement levelling or other precise DEM data with more accuracy than Google Earth and ASTER DEM [7], such as LIDAR, should be further investigated. The results produced by the RAS model would be better fitted to the observed data. Therefore, the flood mapping would be very useful for flood management in the watershed with a lack of hydrological data.

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Sombat Chuenchooklin is an Associate Professor at the Department of Civil Engineering, and Director of the Water Resources Research Centre (WRRC), Faculty of Engineering, Naresuan University, Phitsanulok province, Thailand since 1995. He used to work as an Irrigation Engineer in the Royal Irrigation Department before from 1978 to 1994. He earned his B.Eng. (Irrigation), M.Eng. (Water Resources), and Ph.D. (Water Resources) from Kasetsart University (Thailand), Asian Institute of Technology (Thailand), and Khon Kaen University (Thailand), respectively.

Saharat Taweepong was a Researcher of the Water Resources Research Centre (WRRC), Faculty of Engineering, Naresuan University too. He earned his B.Eng. (Geotech.), and M.Eng. (Water Resources) from Suranaree University of Technology (Thailand), and Khon Kaen University (Thailand), respectively.

Udomporn Pangnakorn is an Associate Professor at the Department of Agricultural Science, Faculty of Agriculture, Natural Resources and Environment, Naresuan University, Phitsanulok in the lower-northern part of Thailand since 1998. She earned her B.Sc. (Agr.), M.Sc. (Agr.), and Ph.D. (Entomology & Agronomy) from Khon Kaen University (Thailand), Kasetsart University (Thailand), The University of Queensland (Australia), respectively.

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