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Hydrologic Models with Radar Precipitation Data Input

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ABSTRACT

This study is intended to assess performance of radar quantitative precipitation estimate (QPE) input from Doppler Meteorology radar with two hydrologic models. Principal interest is not only streamflow outputs accuracy but also time require to run model simulations. The latter is crucial to determine whether it is feasible to run the models in near-real-time for decision assistance to water management officials along Lower Chi and Lower Mun rivers. This study has been intended with a goal of accuracy assessing in near-real-time inflows from numerous sideflows of the Upper Chi and Upper Mun rivers. These inflows are problematic to reservoir operations in rare event of a heavy widespread rainfall into sideflow basins. The radar quantitative precipitation estimates (QPE) are obtained from WSR-8500S radar type of the Bureau of Royal Rainmaking and Agricultural Aviation at Pimai site, A.Pimai, Nakhon Ratchasima province in the Northeast of Thailand, which used a reflectivity-rain intensity (Z-R) ; $Z=294R^{1.33}$ relationship tailored for the 10-14 August 2001 rain event. The results of hydrologic models performance with this QPE input found that both two hydrologic models, Vflo ™ model and HEC-HMS model can give hydrographs output trend as similar to the hydrograph record, it indicated high performance of radar input.

Key words: radar, precipitation, radar rainfall, hydrologic model, Chi, Mun

INTRODUCTION

Managing water resources, protecting lives and property from flood damage, and flood warning systems can benefit from customized and timely hydrologic prediction. Knowing how much runoff is occurring at any location in a watershed requires integration of distributed hydrologic prediction models, multi-sensor estimates of precipitation from radar, satellite and gage, and information system for hydrologic model information dissemination. The overall goal of fully-distributed, physics-based hydrologic models are to provide high accurate runoff estimation for management of water from watersheds up to river basin scale. The advantage of physics-based models is that they can be set up with minimal historical data and still generate meaningful results. Representing the factors that control runoff in a spatially variable manner makes more accurate predictions possible. This paper presents the level of accuracy of radar rainfall with two models, two case studies and two issues representative of a range of watershed conditions and climate. Additionally, runoff from hydrologic model can be determined for flood return period.

The purpose of Vflo and HEC-HMS are to simulate the flow of water across the terrain represented by geographical maps such as digital elevation, soils, and land use/cover. Precipitation

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inputs consists of rainfall rate maps at time intervals, as 1 hour, from radar or multi-sensor inputs. The radar data obtained from WSR-8500S radar type of the Bureau of Royal Rainmaking and Agricultural Aviation at Pimai site, A.Pimai, Nakhon Ratchasima province in the Northeast of Thailand. Vieux (2001 a,b) describes the use of NEXRAD radar in hydrology modeling within a GIS framework. When radar is supplemented with satellite, rain gauge networks, multi-sensor input results that can overcome terrain blockages and other anomalies. The main use of the software is for simulating hydrologic response of basins or regions experiencing severe storms and heavy rain. The subject matter of this paper is organized with a description of how accuracy of radar rainfall, distributed hydrologic modeling approaches; and then preliminary results that demonstrate application of Vflo and HEC-HMS to watersheds under diverse conditions and regions.

MATERIALS AND METHODS

Methodology

The methodology for this research were:

1. Data collection including of radar reflectivity from radar images, rainfall from automatic rain gages, cloud top temperature from satellite images, rain event records, DEM data, digital soil map and land use map.
2. Analysis of rain event record with satellite images and radar images to locate area of rainfall in study areas.
3. Analysis of the reflectivity from radar images, thereafter check a quality control of radar data and constructed the relation between the reflectivity data and rainfall from automatic rain gages.
4. Constructed and prepared data input of Vflo™ model and HEC-HMS model in GIS format.
5. Calibrated and verified model by using rain event 10-14 August 2001.
6. Compared hydrograph output from hydrologic models with hydrograph record.
7. Determined return period of peak discharge.

Description of data and study areas

Radar rainfall data

The WMO (1994) described in HEC-HMS Manual; Version 3 (US Army Corps of Engineers, Hydrologic Engineering Center, 1981,2000) guided to hydrological practices that rainfall depth estimating from weather radar can permit observation of location and movement of areas of precipitation. Certain types of radar equipment can yield estimates of rainfall rates over areas within range of the radar. Weather Surveillance Radar Doppler units (WSR-8500S) of the Bureau of Royal Rainmaking and Agricultural Aviation at Pimai site, A.Pimai, Nakhon Ratchasima province in the Northeast of Thailand provides coverage of a 240-km-radius circular area. This WSR-8500 radar transmits s-band signal that is reflected when it encounters a raindrop or another obstacle in the atmosphere and power of the reflected signal, which is commonly expressed in term of reflectivity. The simple model to estimate rainfall from reflectivity is a Z-R relationship, and the most commonly-used of these is $Z = a R^b$, in which Z= reflectivity factor; R= rainfall intensity; and a and b = empirical coefficients. Thus, as a product of weather radar, rainfall for cells of a grid that is centered about a radar unit can be estimated. This estimate is mean average precipitation (MAP) for that cell and does not necessarily suggest rain depth at any particular point in the cell. The principal of weather radar can be illustrated in Figure 1(a), Figure 1(b) shows the watershed like grid system superimposed. Data from a radar unit will provide an estimate of rainfall in each cell of the grid. Commonly these radar rainfall estimates are presented in graphical format, as illustrated in Figure 1(c), with color codes for various intensity ranges.

Study areas

Hourly radar reflectivity obtained from rain events which occurred in Northeast region of Thailand, during March 2001 to December 2002 for long rainfall - reflectivity record from the Bureau of Royal Rainmaking and Agricultural Aviation at Pimai site, A.Pimai, Nakhon Ratchasima province which corresponds to 2.5 km of CAPPI radar products and ground surface rainfall from automatic rain gauges. At Pimai site operates a S-band polarmetric radar that transmits radiation with a wavelength of 10.7 cm and produces a beam width of 1.2 degrees, maximum range is 480 km, as illustrated in Table 1. This study assumes that there is no bias caused by bright band effect and different observation altitude in 2.5 km. CAPPI data that lie within 200 km. from the radar, reflectivity values that are less than 10 dBZ and greater than 55 dBZ are excluded from the analysis. Rainfall data were obtained from 50 automatic tipping bucket rainfall stations that are located in 200 km of S-band polarmetric. Table 2 and Figure 2 represent a rain gauge network which can be divided into Upper Chi and Upper Mun basins which applied to study areas that shows in Figure 3. Study areas were the Upper Chi and the Upper Mun basins. An unregulated headwater

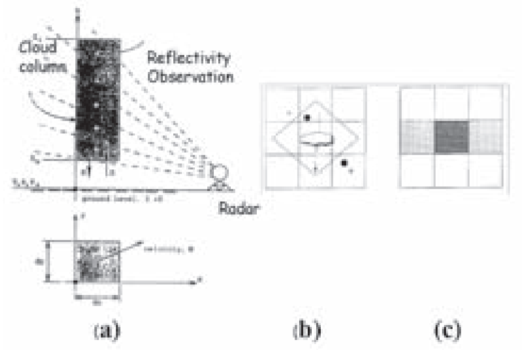

Figure 1 Weather radar providing rainfall observations on a grid.

Table 1 The characteristic of radar at Pimai site.

Details of radar	Characteristics
Type of radar	Doppler weather surveillance radar model DWSR-8500 S , S band
Wave length : cm	10.7
Beam width : degree	1.2
Pulse length : microsecond	0.8
Resolution of record data	1 degree × 1 degree × 1 km
Maximum transmission power : Kw	850
Maximum Range : km	480
Sequence of elevation angles	Operation A : 0.8, 1.7, 2.5
	Operation B : 3.4, 4.2, 5.1, 6, 7.4,9.2, 11.6, 14.8, 18.4, 22

Table 2 Details of automatic rain gauge network.

Range of radar (km.)	Automatic rain gauge in		Total (stations)
	Mun basin (stations)	Chi basin (stations)	
0-50	8	-	8
50-100	22	9	31
100-150	4	6	10
150-200	-	1	1

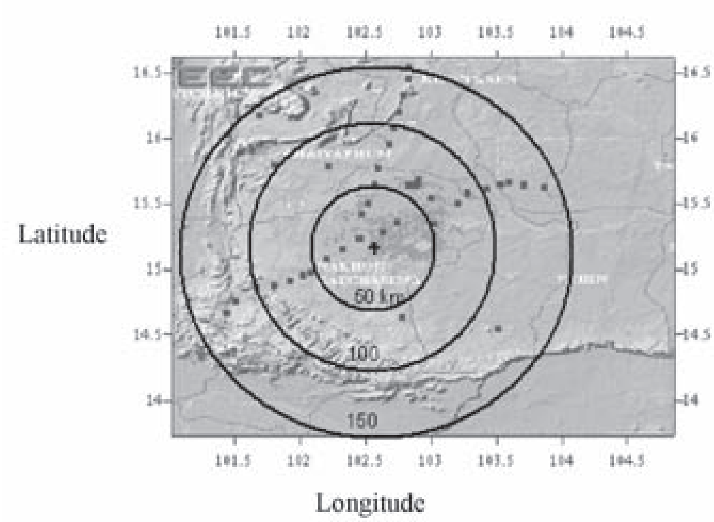

Figure 2 Rain gauge network.

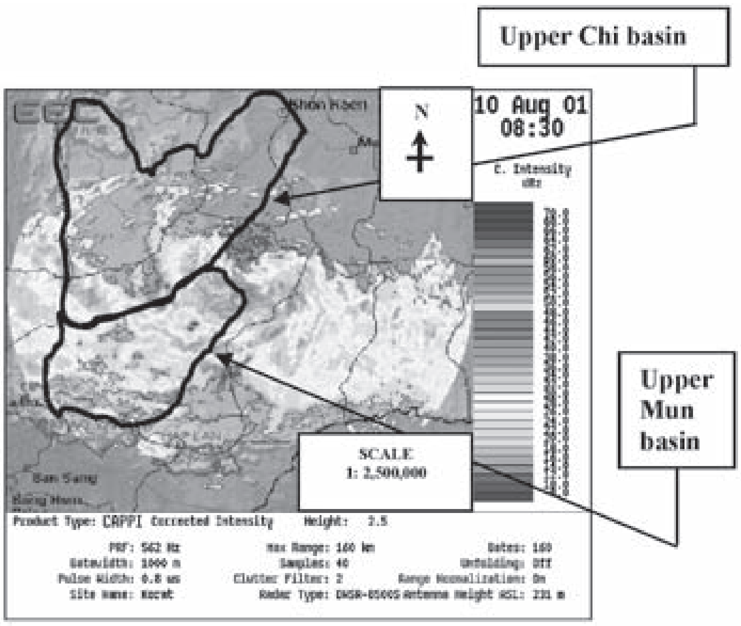

Figure 3 Study area.

basin flowing from 100-200 metre (mean sea level) and 0.0017 (1:600) slope, an 200-250 metre (mean sea level) and 0.0022 (1:450) slope for the Upper Chi and Upper Mun areas, respectively. The area of the Upper Chi basin is 2,906 square kilometers and Upper Mun basins is 454 square kilometers.

Z-R Relationship

The principal of relationship between radar reflectivity and ground surface rainfall diagram is shown in Figure 4. This study assumes that the raindrops fall absolutely vertical from the atmosphere to the rain gage and radar reflectivity

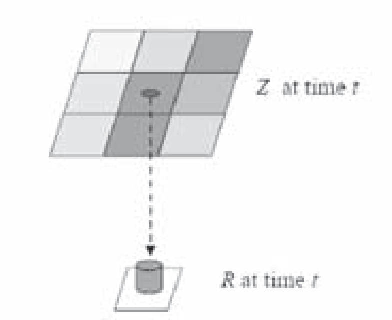

Figure 4 The traditional Z-R matching method : TMM.

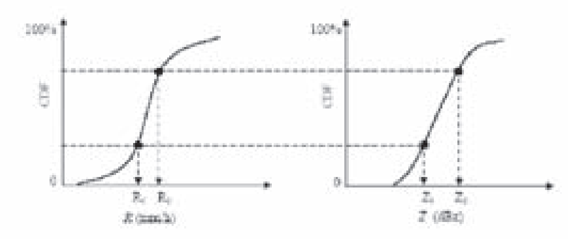

Figure 5 The relation of cumulative density function of Z-R matching method

(*Z*) at time, *t* is related with ground rainfall intensity (*R*) at time, *t* too. And the probability of cumulative density function between radar reflectivity and ground surface rainfall is matched as Figure 5, this means that the radar reflectivity has the same probability of occurrence as the gauge measured rain intensity (Atlas *et al.*, 1990; Rosenfeld *et al.*, 1993). radar reflectivity data obtained from the Royal Rainmaking Research center at A.Pimai, Nakhon Ratchasima Province and ground surface rainfall from automatic rain gauge was investigated (Compliew,S. and Khuanyuen, B. 2003, 2004). The rainfall data was collected from August, 2001 to October, 2002. The results showed that the relation was in power equation form $Z=294R^{1.33}$, then the equation was compared with the value in the literature. It was found that the relation was in 95 % confident limit of relation recommended by most authors and the mean areal correlation was 0.50-0.86 when compared with rainfall event and this relation can be used for rainfall forecasting in the Upper Chi basin and Upper Mun basin the Northeast of Thailand. The results of using this equation can be compared (Figure 6) and data precision influence on relation of radar reflectivity and ground rainfall shown in Figure 6 and the results of using this equation can be compared in Figure 7 and data precision influence on rainfall intensity shown in Table 3.

Hydrologic modeling

Overview of hydrologic modeling approach

A model capable of using wealth of information content available in digital datasets derived from remote sensing and GIS offers potential for improved predictability. Practical application of the unit hydrograph methods through the development of HEC-1 and HEC-HMS have been advanced by the US Army Corps of Engineers, Hydrologic Engineering Center (1981, 2000). These techniques often assume basin averaged or sub-basin averaged parameters and inputs giving rise to the lumped model. Lumped models can be less responsive to very intense, but short-lived rainfalls, because the accumulate depth may be small and only over a limited area of the watershed.

One of the most significant errors in estimating hydrologic response of a basin is precipitation input. When rain gauges sparsely arranged in or near a watershed were sole means of gauging the input, severe stream flow estimation errors often result. Before advent of radar and satellite remote sensing of atmosphere, there was little motivation for development of better hydrologic models. Given high-resolution spatial and temporal resolution of precipitation intensities, advanced hydrologic modeling techniques hold some promise in better hydrologic prediction. With

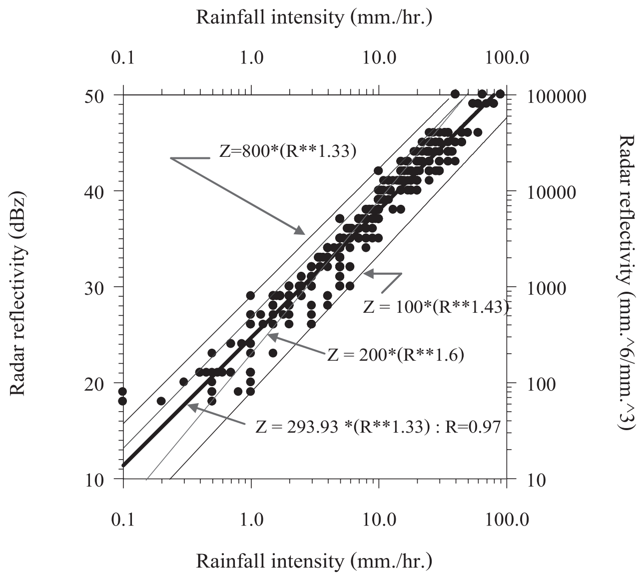

Figure 6 The relation of averaged radar reflectivity and averaged rainfall intensity (Z-R) in Northeast of Thailand.

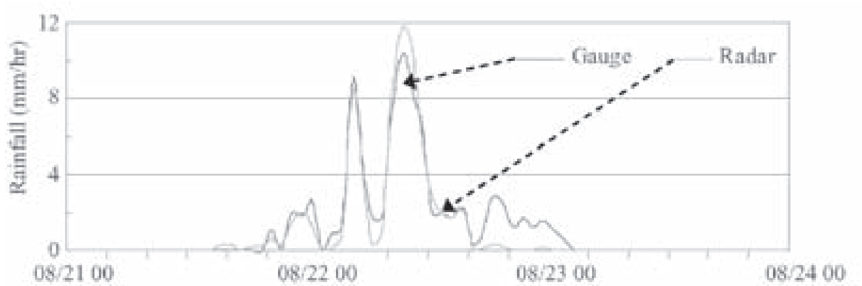

Figure 7 Compared the average radar rainfall and average gauge rainfall in the upper Chi Basin.

detailed precipitation input widely available, there is more motivation to formulate a better hydrologic model.

Vflo ™ model formulation

The mathematical analogy for governing equations is kinematic wave analogy (KWA).The KWA has most applicability where principle gradient is land surface slope. Thus in almost all watershed except for very flat areas, the KWA may be used. As such, this analogy may be used wherever backwater effects are not important. The simplified momentum equation and continuity equation comprise the KWA. The one-dimensional continuity for overland flow resulting from rainfall excess is expressed by :

$$\frac{\partial h}{\partial t} + \frac{\partial (uh)}{\partial x} = R - I \qquad \ldots(1)$$

Where R is rainfall intensity; I is infiltration rate; h is flow depth ; and u is overland flow velocity. In the KWA, it equates bed slope with friction gradient.

Table 3 Data precision influence on rainfall intensity in Northeast of Thailand.

Reflectivity (dBZ)	Rainfall intensity (mm/hr)	Rainfall intensity (in/hr)
10	0.08	0.00
15	0.19	0.01
20	0.44	0.02
25	1.07	0.04
30	2.51	0.10
35	5.97	0.23
40	14.18	0.56
45	33.69	1.33
50	80.08	3.15
55	190.30	7.49
60	452.25	17.79

RESULTS

The distributed-parameter hydrologic models Vflo and HEC-HMS are being tested in the case of heavy rainfall over Upper Chi and Mun basins in the Northeast of Thailand. The heavy rain was produced by Tropical Storm, 10-11 August 2001. The test areas are Upper Chi and Mun basins, an unregulated headwater basin flowing from 100-200 metre from mean sea level and 0.0017 (1:600) slope, an 200-250 metre from mean sea level and 0.0022 (1:450) slope, for both areas, respectively. Area of the Upper Chi basin is 2,906 square kilometers and Upper Mun basin is 454 square kilometers.

Data inputs and parameters

Precipitation input: Hourly precipitation input to Vflo ^{TM} is from WSR-8500S radar deployed by the Royal Rainmaking at A.Pimai, Nakhon Ratchasima Province. Depending on application and size of the hydrologic prediction area, several different radar products should be used. Real-time data feeds from individual radars should be setup to download and process rainfall rate for input to the model.

Flow direction: The flow direction map was derived from topography map. The 8-directions in this map define connectivity of overland and channel finite elements. The resolution of data sets does not matter, except that all data sets must have the same resolution and geographic projection. To obtain the highest quality flow direction map, a stream network delineated from a Digital Elevation Model (DEM) should be burned in. Several methods exists such as those described in Moore *et al*. (1991) to bias the flow direction map towards stream network. This technique is advantageous in relatively flat areas, such as coastal plains or plateaus.

Slope: This map defines slope for channel and overland flow in Manning equation. The HYDRO-1K data set is a useful source of slope information worldwide, and is available online http://edcdaac.usgs.gov/gtopo30/hydro. The slope was converted from degrees to percent slope. At this point the slope map represents overland slope (i.e. non-channel cells). The slopes of channel cells are burned into overland slope for final slope map. Slope values in Vflo^{TM} are generated as non-percentage values, but are displayed as percentage.

Infiltration: The infiltration map is essentially saturated hydraulic conductivity and should be derived from any soil map with requisite property information. The depth from surface to 5-cm, was chosen. Initial infiltration values for each soil class should be estimated for conditions expected in the watershed. Planned development will account for temporal changes in soil moisture using Green and Ampt. equations.

Roughness: The hydraulic roughness map may be derived from 30-meter Landsat data (Landsat ETM+band 4,3,2 RGB which was acquired on 14 May 2001). The data set should be resampled the model resolution using a bilinear or other interpolation technique. This map controls both channel and overland flow roughness values. In this study, the average hydraulic roughness for Upper Chi and the Upper Mun basins are 0.035 and 0.038, respectively.

Channels: Channels are parameterized with maps defining channel width, channel side slope, and channel bed slope. This may be entered from field surveys or estimated from gauging station information. Extending channel parameters from several measured locations to all stream reaches may require generalization using geomorphic relationships, by stream order, or other scheme.

Shapefiles: The shapefiles in the same projection should be viewed as overlays along with finite element connections. Point, polyline, and polygon shapefiles should be used. Shapefiles that extend beyond the Vflo^{TM} domain do not need to be clipped to the domain. Mapped features orient the user and allow detailed editing of the drainage network by visual comparison.

Calibrotion and verrification

This study used calibration adjustment using a physically-based approach and verification, a physical-based model calibration scheme adjust parameters within realistic ranges. Volume is adjusted by varying hydraulic conductivity, timing and peak discharge are controlled by hydraulic roughness map and channel hydraulics and statistical criteria 2 indexes were selected for calibration and verification : correlation coefficient (r) and efficiency index (EI).

$$r = \frac{\sum_{i=1}^{N}\left(Q_i - \overline{Q}\right)\bullet\left(F_i - \overline{F}\right)}{\sqrt{\left[\sum_{i=1}^{N}\left(Q_i - \overline{Q}\right)^2 \bullet \sum_{i=1}^{N}\left(F_i - \overline{F}\right)^2\right]}} \quad \ldots(2)$$

$$EI(\%) = \left|\frac{\sum_{i=1}^{N}\left(Q_i - \overline{Q}\right)^2 - \sum_{i=1}^{N}\left(Q_i - F_i\right)^2}{\sum_{i=1}^{N}\left(Q_i - \overline{Q}\right)^2}\right| \times 100 \quad \ldots(3)$$

$$\overline{Q} = \frac{1}{N_i}\sum_{i=1}^{N} Q_1 \quad \ldots(4)$$

Where Q_i is observed discharge, $\overline{Q}$ is the average of observed discharge, F_i is simulated discharge, $\overline{F}$ is the average of simulated discharge and N is the number of data. A higher value of EI indicates good agreement between observed discharge and simulated discharge.

Reconstructing events from archive radar rainfall, stream and rain gauges provides important information regarding expected accurate forecast during actual events (Sun *et al.*, 2000). The operational model was developed by adjusting overland and channel hydraulic roughness parameter maps to minimize rising limb differences for several storm events. The calibrated model is continuing to be validated operationally. While, there is only one day validation event reported here (10 August 2001) and four days verification event reported (10-14 August 2001), it showed excellent agreement both Upper Chi and Upper Mun basins. Table 4 presented performance of areal radar precipitation input and basin rainfall average from automatic rain gages with hydrologic models, simulated discharge can be compared the forecast accuracy for two basins. On average, a value of efficiency index (EI) with radar rainfall for both models is close to 80% which indicated that radar precipitation input can be estimated

Table 4 Discharge values for validation events.

Event	Upper Chi basin						Upper Mun basin					
	Vflo model			HEC-HMS			Vflo model			HEC-HMS		
10-14 August 2001	r	EI (%)	% Q_{peak}	r	EI (%)	% Q_{peak}	r	EI (%)	% Q_{peak}	r	EI (%)	% Q_{peak}
Radar rainfall	0.79	77.86	19.70	0.81	79.81	17.69	0.79	75.45	14.32	0.80	76.53	15.25
Gage rainfall	0.74	72.25	21.02	0.77	70.23	23.05	0.68	73.01	25.27	0.67	70.35	21.32

hydrograph near observed discharge at Upper Chi and Upper Mun basins, whereas difference of peak discharge for two basins, is not more than 20% and the coefficient of correlation is close to 0.80, whereas the rain gage rainfall gave the value lower than 0.75 and a value of efficiency index (EI) is near 70% and difference of peak discharge is more than 20% which indicated that the radar rainfall gave the results closer to the observed hydrograph than using gage rainfall. Using radar rainfall in hydrologic models gave the peak of runoff to be underestimated value when compared with observed runoff.

Figure 8 shows an example of a hydrograph between observed discharge and simulated discharge from two models at runoff stations in the Upper Chi basins.

DISCUSSION

Radar systems provide high-resolution precipitation measurements that are useful for hydrologic applications. Radar measurement characteristics have important consequences on predictability of watersheds. Operational system simulation experiments provide guidance on design of quantitative precipitation estimated for distributed hydrologic modeling. Event reconstruction with WSR-8500S radar shows that radar rainfall is capable of producing accurate and site-specific forecast with distributed hydrologic model. In this study, Only HEC-HMS model can

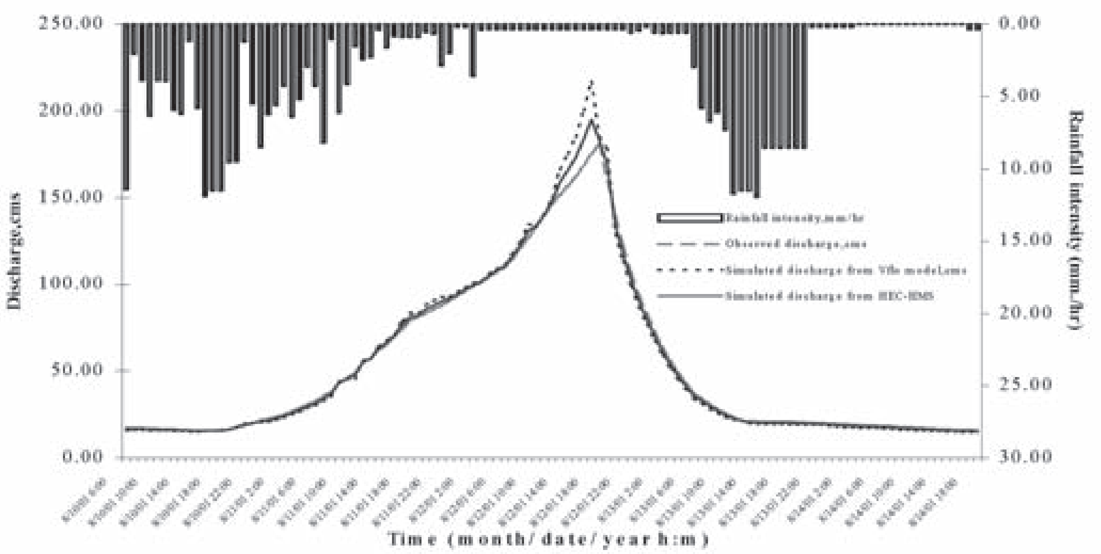

Figure 8 The relationship between rainfall intensity and discharge in the Upper Chi basin.

be applied and simulated the hydrograph output close to hydrograph record. However, quality control of radar data is the important consideration, radar estimated precipitation should be compared or corrected to correlate with field observations. Radar measures only movement of water in the atmosphere, not the volume of water falling on watershed. Ideally average rainfall would combine radar and rain gage networks.

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LITERATURE CITED

Atlas, D., Rosenfeld, D. and D. B. Wolff. 1990. Climatologically tuned reflectivity-rain rate relations and links to area-time integrals. **J. Appl. Meteorol.** 29: 1120-1135.

Compliew, S. and B. Khuanyuen. 2003. The relation of radar reflectivity and ground rainfall in the Northeast of Thailand. **Agricultural Engineering 4th Proceedings**, KU Home, Kasetsart University, Bangkok, Thailand.

Compliew, S. and B. Khuanyuen 2004. The effect of radar range on radar rainfall estimation. **APHW 3rd ProceedingÀ**, Suntec City, Singapore.

Rosenfeld, D., D.B. Wolff and D. Atlas. 1993. General probability –matched relations between radar reflectivity and rain rate. **J. Appl. Meteorol.**32: 50-72.

Sun, X., R.G. Mein, T.D. Keenan and J.F. Elliott. 2000. Flood estimation using radar and raingage data. **J. Hydrol.** 239: 4-18.

US Army Corps of Engineers, Hydrologic Engineering Center. 1981,2000. **Manual of HEC-HMS ; Version 3**.

Vieux, B.E. 2001a. *Distributed Hydrologic* Modeling Using GIS. **Kluwer Academic Publishers**.

Vieux, B.E. 2001b. Radar Rainfall Applications in Hydrology. Chapter 11 *In* P.B. Bedient and W.C. Huber. **Hydrology and Floodplain Analysis,** Addison-Wesley Publishing Co., Reading, Massachusetts, 3rd Edition.