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Examination of Flood Runoff Reproductivity for Different Rainfall Sources in Central Vietnam

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***Abstract*—**This paper presents the combination of different precipitation data sets and the distributed hydrological model, in order to examine the flood runoff reproductivity of scattered observation catchments. The precipitation data sets were obtained from observation using rain-gages, satellite based estimate (TRMM), and numerical weather prediction model (NWP), then were coupled with the super tank model. The case study was conducted in three basins (small, medium, and large size) located in Central Vietnam. Calculated hydrographs based on ground observation rainfall showed best fit to measured stream flow, while those obtained from TRMM and NWP showed high uncertainty of peak discharges. However, calculated hydrographs using the adjusted rainfield depicted a promising alternative for the application of TRMM and NWP in flood modeling for scattered observation catchments, especially for the extension of forecast lead time.

***Keywords*—**Flood forecast, rainfall-runoff model, satellite rainfall estimate, numerical weather prediction, quantitative precipitation forecasting.

I. INTRODUCTION

GROUND observation of precipitation has been considered the most reliable input for hydrological models. However, uncertainties are very much dependent on spatiotemporal resolution of rainfield. Flood modeling based on input precipitation from scattered rain-gages may not predict very well real hydrographs. It is because rain-gages provide measurement of rainfall at single points. Therefore, it is not able to represent for the whole basin, especially under the convective rainfall regime that precipitation is strongly uneven distributed. As a result, insufficient precipitation information always diminishes flood forecasting ability, Ngo, L. A., et al., [1]. Presently, global distributed precipitation data sets show increasing spatiotemporal resolution. Direction towards the use of these distributed data sets in flood modeling has been growing quickly. However, most of studies were restricted either at relatively coarse spatiotemporal resolution or regionally bounded. Evaluation of satellite rainfall estimate derived from Tropical Rainfall Measurement Mission (TRMM) in flood modeling has been mainly conducted on daily temporal resolution, for medium basin scale, Amanda, H. et al., [2], large basin scale, Piero, V., [3], and continental basin scale, Bruno, C., et al., [4], while the use of very short range quantitative precipitation forecast (QPF) in flood forecast was conducted for specific regions, Brazil, Bruno, W., et al., [5], Japan, Kardhana, H., Tatesawa, H., and Mano, A., [6], France, Younis, J., et al., [7]. For extension of forecast lead time, short range QPF was used for Upper Po River Basin, Italia, but the model reliability was not as expected, Jens, B., Ezio, T., [8].

This study purpose is to examine the flood runoff reproductivity of scattered observation catchments by using different precipitation data sets as inputs to the physically-based distributed hydrological model (so-called the super tank model). Input precipitation for the tank model includes ground observation from rain-gages, satellite estimate (TRMM), and numerical weather prediction model (NWP). The study results are a basis for application of satellite estimate and prediction rainfall data in flood forecasting in order to extend forecast lead time. A case study was conducted at three catchments located in Central Vietnam.

II. STUDY AREA, DATA, AND METHODOLOGY

A. Study area and event selection

Given the mentioned precipitation data sets are available at scales that are perhaps coarse both in time and space for hydrological modeling, basin scale effect on flood propagation behavior was considered. Basin selection includes small, medium, and large scales as following: (i) Upper Huong River basin of 190 km^2; (ii) Ve River basin of 750 km^2; and (iii) Upper Tra Khuc River basin of 2700 km^2. The locations of selected basins are illustrated in Fig. 1. These basins are located at upper parts of rivers where most of basin areas are covered by forest and upland crops. Soil types are classified into 4 major groups: (i) alluvium, (ii) intrusive magma, (iii) metamorphic, and (iv) continental sediments. Hydraulic conductivity of soil type for loam, clay-loam, and clay varies from 10^{-4} to 10^{-7} m/s. Distribution of land use and soil type was determined based upon master plan studies for comprehensive water resources and use of above mentioned river basins that was conducted by Institute of Water Resources and Planning of Vietnam – 2003.

The study selected the storm event which started on October 16th 00UTC and ended on October 19th 12UCT, 2007. The selected storm was considered a very severe one and influenced a large area including the three chosen basins. Peak 6-hour accumulative precipitation detected at the small basin approximate 200mm. Maximum discharges measured at

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the outlets of the basins are approximate 600 m^3/s, 1500 m^3/s, 4600 m^3/s.

B. Meteorological data

This study used hourly precipitation data obtained from relatively coarse observation rain-gages as showed in Fig. 1.

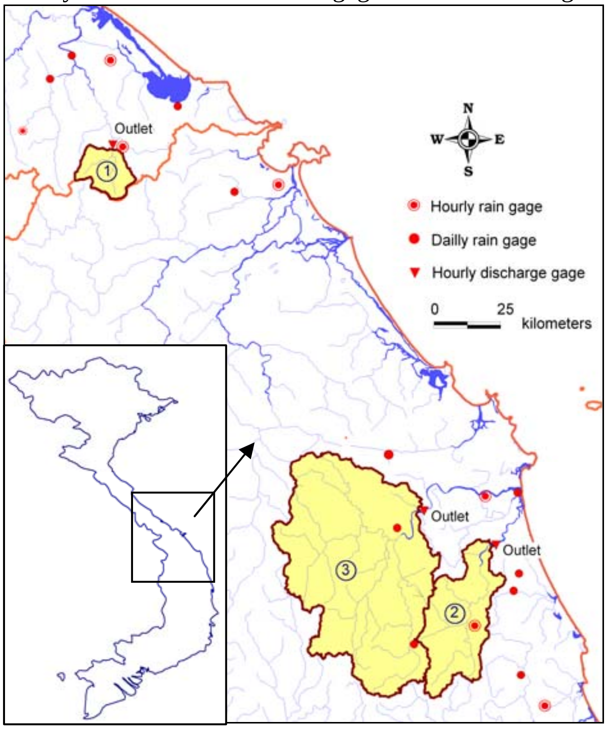

Fig. 1 Locations of study basins and existing hydro-meteorological observation network: (1) small sized basin, (2) medium sized basin, and (3) large sized basin.

Stream flow data at the outlets of basins was also available on hourly basis. The TRMM is currently providing estimate of near-real-time precipitation observation at quasi-global scale. Many types of product are available for research purposes. Accumulation of rainfall is estimated for various time intervals over grid cells of 0.25 x 0.25 degree. This study used the 3B42 version that estimates 3-hour accumulative rainfall amount based on the combination of micro wave sensor (TMI) sensor and precipitation radar (PR). It means the rainfall estimated by the microwave sensor then was adjusted with vertical cloud structure provided by the precipitation radar [11].

Forecast lead time and spatiotemporal resolution of NWP model have been getting remarkably improved. This study used short range forecast from the operational Global Spectral Model (GSM) run by Japanese Meteorological Agency (JMA), globally covered with spatial resolution of 1.25*1.25 degree. GSM produces 84-hour forecast, issued twice a day, at 00UTC and 12UTC. Precipitation data derived from the GSM is accumulated rainfall over a 6-hour period, 00-6UTC, 6-12UTC, 12-18UTC, and 18-24UTC.

It is clear that original resolutions of precipitation data sets are distinctly different, rain-gages represent single points, while satellite rainfall estimate and prediction model representing the averaged precipitation over a mesh that is defined as grid point value (GPV). For the evaluation, different temporal scales were aggregated up to 6-hourly basis, to be similar with temporal resolution of NWP model, and inverse distance weighting (IDW) method was used to downscale precipitation information to the same spatial resolution of basin grid cells.

C. Digital elevation data

To derive topography-based hydrologic parameters used in the hydrological model, this study used elevation information that was extracted from the Shuttle Radar Topographical Mission (SRTM) version 2 data products. This is a breakthrough in space-born elevation data at quasi-global scale. The SRTM used synthetic aperture radar technique to generate the land surface, offering 90-meter spatial resolution of elevation data. Vertical errors were reported less than 16 meters. Presently, SRTM has been considered as the best global elevation data set to others, for instance GTOPO30 [9], and GLOBE [10]. Given relatively large error of surface elevation, a couple of studies were conducted to verify inherent bias produced by the model. It was reported that SRTM usually produces voids for continental scale; however, meso scale basin sizes are not influenced, Ludwig, R., and Schneider, P., [11].

D. Description of hydrological model

The distributed hydrologic models tend to outperform lumped hydrologic models with respect to spatial variation consideration. As a result, distributed hydrologic models have been extensively developed and used in flood forecasting. TOPMODEL concept, Beven, [12] was introduced as a topography-based flood modeling technique. The model has been widely using because its simplicity; however, its application is limited to places where the assumptions of the model are valid. There are also many other distributed and physically-based models that were developed for different scales, for instance, distributed Large Basin Simulation Model, Bruno, W., et al., [5], TOPKAPI, Jens, B., et al., [8], BTOPMC, Takeuchi et al., [13] for hydrological simulation of large river basins.

In this study the semi-distributed and physically-based rainfall runoff model (the supper tank model) was used because the model simplicity. The tank model was originally developed by Kato, H., and Mano, A., [14]. The model was targeted to enhance river-depended features by using physically based parameters to simulate stream flow across a wide range of spatial and temporal scales; for a continental river scale, the Upper Chang Jiang River Basin, [14], and small-sized catchments, [6].

Model frame work is that the whole basin was divided into sub-basins that are represented by channel grids. The channel networks were defined based upon sub-basin of 270mx270m grid cells which was resampled three times larger than original spatial resolution of digital elevation model. Defined channel networks then were compared and corrected with digitized ones from contour-based maps owing to inherent error given by the digital elevation model. Flood propagation was calculated using averaged precipitation over a 6-hour period. In terms of flood forecast (using NWP), it was reported that model uncertainties and forecast lead time are in direct proportion [6]. Therefore, the 84-hour forecast lead time of prediction rainfall was reduced to 24-hour by updating the forecast on daily basis.

In view of hydrological process, the sub-basin represents a drainage area where precipitation throughfall reaches ground surface, partially infiltrates into ground, and the remaining turns into direct runoff. Eventually these are lumped into channels. The rainfall interception is the first component of the hydrologic model. It was estimated using Horton method, [15] that is showed in (1).

$$I = S + KET \,. \tag{1}$$

where, S = interception storage capacity (mm); K = ratio of evaporation surface over the projected area; E = evaporation rate during the storm (mm/hr); T= rainfall duration (hr). KE was determined equal to 0.2mm/hr and 0.1mm/hr for forestation and urban areas respectively, Hattori., et al., [16].

With respect to subsurface flow, the sub-basin comprises three linear cascade tanks that represent the uppermost soil layers. The thickness of each layer varies beyond soil types of sub-basins. Averaged depths that were used in the current study are 0.3 m, 0.6 m, 0.9 m for uppermost to lowermost layers respectively. Determination of infiltration rate and direct runoff were controlled by saturated hydraulic conductivity Ks of the top soil layer. The Ks was determined from field data and Nguyen, T.L., [17]. The distribution between excess flow and percolation is proportional with water content (λ) in the lower tank, showed in (2).

$$\lambda_i = \frac{H_i}{H_{i\max}} \tag{2}$$

where, λ_i = water content in tank; H_i = water depth in tank; H_{imax} denotes tank depth.

Excess flow from soil storage expressed from Darcy Law, showed in (3).

$$q_i = c.k_{si}.I.\frac{H_i}{H_{i\max}} = c.k_{si}.I.\lambda \tag{3}$$

where, q_i = excess saturated flow; c = deviation constant; I = slope of sub-basin. Subscript i denotes layer of soil; H_{imax} denotes tank depth.

Flood routing in streams and surface runoff used one dimensional kinematics wave approximation scheme (KWA) with manning equation for motion equation and assumption of rectangular river cross-section. KWA is solved by first order finite difference. Measured baseflow was used for the model initial condition. Distribution of roughness coefficient along rivers was defined as function of grain diameter by Strickler., [18].

$$n = 0.0131\, d^{1/6} \tag{4}$$

where, n = roughness coefficient; d = river bed grain diameter. The grain diameter is related with shear velocity with the average critical Shields' number as shown in (5) below.

$$\frac{u_{*c}^2}{\left(\frac{\sigma}{\rho} - 1\right) gd} = 0.5 \tag{5}$$

where, u_{*c} = shear velocity, σ = density of soil, ρ = density of water, and g = gravitational acceleration. The shear velocity is related with the bed slope I by the assumption of normal flow and broad cross section. It is expressed in (6).

$$u_{*c}^2 = ghI \tag{6}$$

where, h = water depth. By considering water depth of several meters and same order of drag friction by bottom undulation, substitute (5) and (6) into (4), Manning's roughness coefficient n is expressed as a function of the bed slope in (7).

$$n = \alpha I^{1/6} \tag{7}$$

where, α = parameter requires to be calibrated.

To evaluate model performance and uncertainty, the Nash Sutcliffe Index (NSI), and relative error (η) of peak discharge and time to peak were expressed in (8) and (9) below:

$$NSI = 1 - \frac{\sum (Q_{obs} - Q_{cal})^2}{\sum (Q_{obs} - Q_{obs\_mean})^2} \tag{8}$$

$$\eta = \frac{|Q_{cal} - Q_{obs}|}{Q_{obs}} \tag{9}$$

where, Q_{obs} = observed stream flow; Q_{obs_mean} = mean observed stream flow; Q_{cal} = calculated stream flow.

III. RESULTS AND DISCUSSION

The supper tank model has proven a wide range of application due to its simplicity and unempirical parameters that are independent from river characteristics. In this study, the tank model developed by Kardhana. H., et al., [6] was modified in accordance with the temporal resolution of the input precipitation (6-hour interval). Model parameters set-up was selected based on [6], and [14]. The interception storage capacity (S) was selected at the value of 0.025metre. The infiltration rate (I) has been controlled by the top soil saturated hydraulic conductivity Ks. The deviation constant coefficient (c) represents assumed deviation between estimation and actual interflow from the Darcy Law. This assumption follows the fundamental assumption on hydrologic of $Q=ciA$. The c coefficient tends to be the universal number, found at the value of 10. α coefficient was determined of 0.05, 0.1, and 0.15 for small sized basin, medium sized basin, and large sized basin respectively.

Fig. 2 illustrates the calculated hydrographs for the flood event on 16th October 2007 at the outlets of basins. These hydrographs were obtained by using deferent types of input precipitation from (i) rain-gages, (ii) satellite estimate, and (iii) prediction model for the tank model. The event duration was 84 hours. Time interval of model simulation was 6 hours. It is clearly seen in Fig. 2, simulated hydrographs based on rain-gages showed best agreement to the measured discharge, especially for medium and large basin scales (Fig. 2b and 2c). For small basin scale the simulated hydrograph remained uncertain (Fig. 2a), the true peak was missed, high relative error of peak discharge were observed (Table I). The more uncertainties were observed as actual rainfall estimated/predicted by TRMM/NWP algorithms was used as input for the tank model. Computed peak discharges were significantly underestimated, especially for those obtained from NWP. As depicted in the Table I, computed peak discharge using NWP severely underestimated to the actual peak discharge for the small basin (Fig. 2a). The trend of these uncertainties is getting less for larger basin scales, clearly observed in case NWP was used. However, calculated hydrographs depicted a very good agreement to the observed one in terms of time to peak discharges, especially for those obtained from NWP. The NWP-based hydrographs outperformed to TRMM-based hydrographs. It is clearly observed in Fig. 2c. The satellite rainfall estimate has produced three peaks instead of one as observed. This result was affirmed to [2] that flood prediction based on satellite rainfall estimate might miss true peaks.

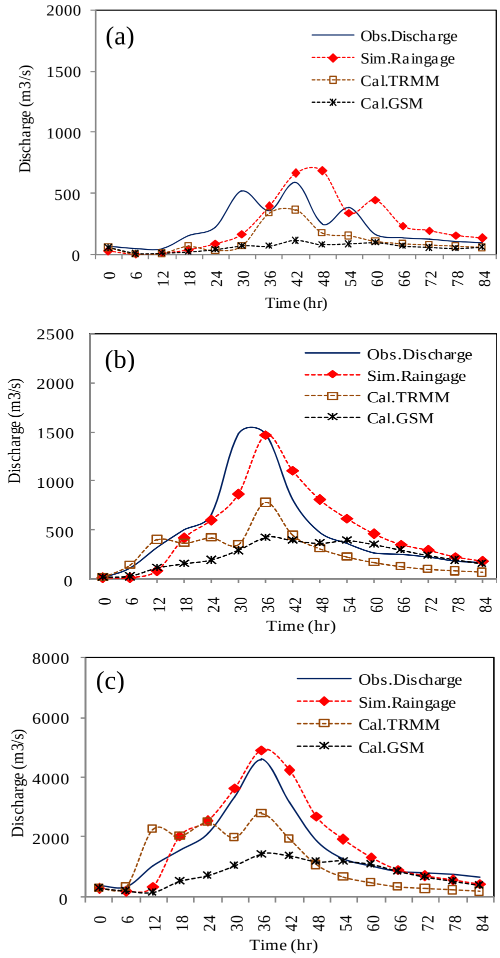

Fig. 2 Simulated v.s observed stream flow at outlets of catchments for the flood event on Oct.16th 2007 based on input precipitation from (i) rain-gages, (ii) actual satellite estimate, and (iii) actual prediction model with 24-hour forecast lead time. (a) small sized basin; (b) medium sized basin; and (c) large sized basin.

Given the inherent errors of TRMM-based and NWP-based rainfall estimates, use of these actual precipitation information as input for hydrological modeling at this stage results in unexpected uncertainties, especially in terms of peak discharges. For anticipation, this study also evaluated the model performance based on adjusted precipitation derived from TRMM based and NWP model. System bias was adjusted by using the amplification factors. Derivation of

TABLE I
MODEL PERFORMANCE INDICATORS AND RUNOFF ERROR STATISTICS FOR DIFFERENT BASIN SIZES USING INPUT PRECIPITATION FROM (I) RAIN-GAGES, (II) ACTUAL SATELLITE ESTIMATE, AND (III) ACTUAL PREDICTION MODEL WITH 24-HOUR FORECAST LEAD TIME. N/A MEANS NOT APPLICABLE

Catchment		Observation		Prediction
Size	Area (km^2)	Gage	TRMM	GSM
		Nash Sutcliffe Index (*NSI*)		
Small	190	0.65	N/A	N/A
Medium	750	0.84	N/A	N/A
Large	2,700	0.93	0.62	N/A
		Peak Error (%)		
Small	190	15.84	38.72	80.81
Medium	750	0.52	47.13	71.08
Large	2,700	7.03	38.93	68.61
		Time to Peak Error (%)		
Small	190	14.29	-	-
Medium	750	-	-	-
Large	2,700	-	-	-

amplification factors was determined from hyetographs depicted in Fig. 3a and 3b for TRMM and NWP models respectively. It was simply obtained by dividing the accumulative observation rainfall of the storm to those obtained from TRMM based and NWP models. As a result, the amplification factors were found of 1.56 and 2.05 for adjusted hyetographs of TRMM and NWP correspondingly.

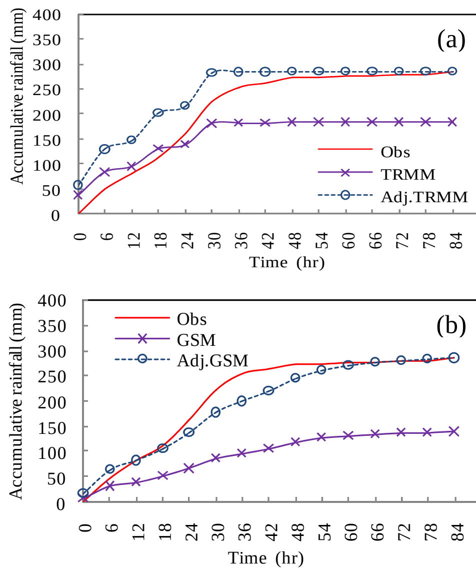

Fig. 3 Cumulative rainfall hyetographs for deriving bias adjustment. (a) satellite estimate, (b) prediction model.

Again, hydrographs were recalculated based on the adjusted rainfield. The adjusted hydrographs are plotted in Fig. 4, model performance indicators and statistical errors are presented in Table II, for three selected basins. The adjusted hydrographs showed better agreement with the measured hydrographs, in particular for those obtained from adjusted prediction rainfall model. It is clearly seen in Fig. 4a for the small basin scale; however, it is still underestimated to observed peak for medium and large basin scales. The prediction rainfall model tends to produce good time to peak. On the other hand, adjusted TRMM estimate seems improving the peaks, but not for hydrograph shapes.

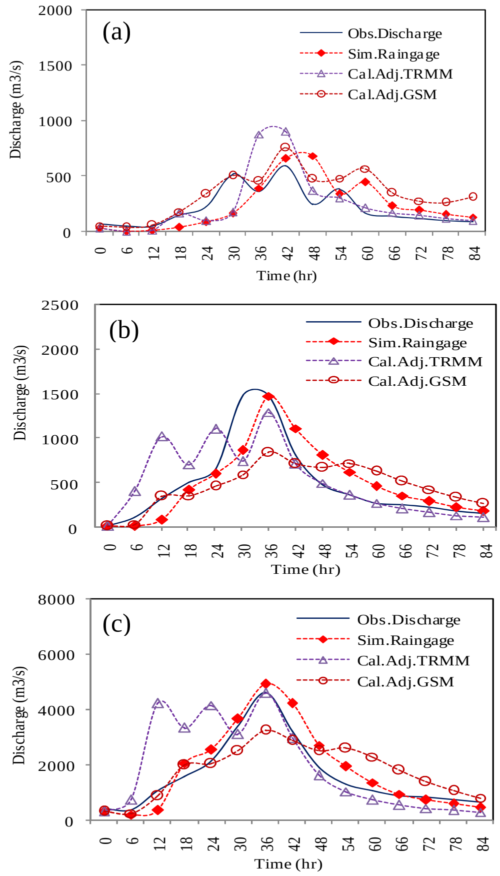

Fig. 4 Simulated v.s observed stream flow at outlets of catchments for the flood event on Oct.16th 2007 based on input precipitation from (i) rain-gages, (ii) adjusted satellite estimate, and (iii) adjusted prediction model with 24-hour forecast lead time. (a) small sized basin; (b) medium sized basin; and (c) large sized basin.

TABLE II
MODEL PERFORMANCE INDICATORS AND RUNOFF ERROR STATISTICS FOR DIFFERENT BASIN SIZES USING INPUT PRECIPITATION FROM (I) RAIN-GAGES, (II) ADJUSTED SATELLITE ESTIMATE, AND (III) ADJUSTED PREDICTION MODEL WITH 24-HOUR FORECAST LEAD TIME.

Catchment		Observation		Prediction
Size	Area (km^2)	Gage	TRMM	GSM
		Nash Sutcliffe Index (*NSI*)		
Small	190	0.65	0.63	0.78
Medium	750	0.84	0.74	0.66
Large	2,700	0.93	0.74	0.86
		Peak Error (%)		
Small	190	15.84	52.2	27.89
Medium	750	0.52	12.49	42.98
Large	2,700	7.03	0.44	29.44
		Time to Peak Error (%)		
Small	190	14.29	-	-
Medium	750	-	-	-
Large	2,700	-	-	-

IV. CONCLUSION

The work presented in this paper has revealed the flood runoff reproductivity of scattered observation basins by coupling different precipitation data sets with the super tank model. The tanks model again proved its advantage in flood modeling across various spatiotemporal scales. Though ground observation is scattered, calculated hydrographs based on input precipitation from rain-gages showed best fit to measured ones, especially for medium and large sized basins. High uncertainty of hydrographs was observed as actual TRMM and NWP rainfall estimates were used as input for the tank model. But, calculated hydrographs using the adjusted rainfield were significantly improved. Hydrographs using adjusted prediction rainfield outperformed to those obtained using satellite rainfall estimate. These results are encouraging for the application NWP rainfall estimates in flood forecast at scattered catchments, especially for the extension of forecast lead time.

However, the study results were limited for the case study; just a single flood event was selected. Further assessment is required to examine for more events. Especially, propose of proper adjustment models to TRMM and NWP based rainfall estimate is a focal point in near future research. In which, formulation of satellite rainfall error, Faisal, H., et al., [19] and Model Output Statistic (MOS), Glahn, H. R., et al., [20] will be considered. Analysis on the model uncertainty and forecast lead time will be included.

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