DEVELOPMENT OF SHORT-TERM FLOOD FORECAST MODEL - A CASE STUDY FOR CENTRAL VIETNAM

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This paper presents the development of a short-term flood forecast model by coupling the relatively high resolution (0.5°) global numerical weather prediction model (NWP) with the distributed rainfall runoff model. The case study was conducted for a medium sized basin (the Ve River) located in Central Vietnam. Model output statistic (MOS) was applied to improve quantitative precipitation forecast (QPF) derived from the NWP model. Separate regression equations for single storm events and continuous storm events were formulated based on training data of the wet season, 2008. Results of 24-hour lead time flood forecast using MOS-derived QPF were comparable to those obtained using raingages. Model validation demonstrated that the short-term flood forecast model is encouraging for the further extension of flood forecast lead time at global-scale applicability.

Key Words: Flood forecast, quantitative precipitation forecast, rainfall-runoff model, model output statistic.

1. INTRODUCTION

Recently, numerical weather prediction model has been providing (NWP) increasing spatiotemporal resolution forecast of climatic parameters. Direction towards the use of quantitative precipitation forecast (QPF) obtained from NWP models to predict river flow has been growing quickly, for instance, Regional Scale Model, Bruno et al.¹⁾, Mesoscale Model, Kardhana, Tatesawa, and Mano.²⁾, and limited area model, Younis et al.³⁾. Results from these studies depicted the usefulness of NWP in flood forecasting. However, there has been existing limitation that these studies were restricted either at relatively short-term forecast or regionally bounded. It means that greater lead times of flood forecast are required for improvement, Jens et al.⁴⁾. The use of ensemble flood forecasting demonstrated an added value for medium-term flood forecast systems in many European countries, but more case studies are needed, Cloke, and Pappenberger.⁵⁾. In addition, applicability of forecast models should be expected in larger scales, especially in developing countries where globally covered NWP models are available and its benefit is maximized.

This paper presents the development of a

short-term flood forecast model by coupling QPF derived from Global Spectral Model (GSM), operational at Japan Meteorological Agency (JMA), with the physically-based distributed hydrological model (so-called the tank model). The short-term flood forecast is followed the convention defined in *Kardhana, and Mano.*⁶⁰, for a time period generally from few hours to a couple of days in advance. The case study was conducted for a medium sized basin located in Central Vietnam. The expected outputs with sufficient forecast lead time are considered substantial usefulness in terms of river management, reservoir operation, especially for flood disaster mitigation and evacuation.

2. STUDY AREA AND METHODOLOGY

(1) Study area

The Central Vietnam experiences flooding disaster almost every year. Facing to the East Sea, the region is often hit by tropical typhoons associated with extremely intense rainfall in wet seasons that usually begins in early September and lasts until late December. Major characteristics of rivers in the study area are generally short and steep; flood plain areas are relatively narrow. As a result, flood is powerful and short in response. The basin selected in this study is the Ve River (Fig.1) with the basin area of 750 km². Average basin elevation is about 350m above the mean sea level. Upstream parts of the basin are covered by forest and upland crops; urban areas are distributed further downstream of the river. Soil types are classified into 4 major groups: (a) alluvium, (b) intrusive magma, (c) metamorphic, and (d) continental sediments. Hydraulic conductivity of soil types for loam, clay-loam, and clay varies from 10^{-4} to 10^{-7} m/s. Distribution of land use and soil type was taken the master plan study of comprehensive water resources and use in the Ve River Basin that was conducted by Institute of Water Resources and Planning of Vietnam – 2003.



Fig.1 Location of study basin and hydro-meteorological observation system

(2) Digital elevation data

To determine topography-based hydrologic parameters required for the hydrological model, this study used elevation information that was extracted from the Shuttle Radar Topographical Mission (SRTM) version 2 data product. 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 and GLOBE (1km spatial resolution). Assessment on inherent bias produced by the SRTM model was conducted by Ludwig et al.⁷⁾. It was reported that SRTM usually produces voids for continental scale, however, meso scale basin sizes are not influenced.

(3) Meteorological data

Globally covered NWP models are operational at, for example, the European Centre for Medium-Range Weather Forecasts (ECMRWF), National Centers for Environmental Prediction of the US (NCEP), and Japan Meteorological Agency (JMA). This study used short range QPF and other atmospheric parameters from the Global Spectral Model (GSM) that is operational at JMA, globally covered with spatial resolution of 0.5° since November 21st, 2007. The GSM produces 84-hour forecast, issued 4 times per day, at 00UTC, 06UTC, 12UTC, and 18UTC. Precipitation data derived from the GSM is accumulated rainfall over a 6-hour interval, 00-6UTC, 6-12UTC, 12-18UTC, and 18-24UTC.

Before November 21^{st} , 2007 spatial resolution of the GSM was very coarse (1.25^o) to the requirement of hydrological models. It means available archived data used for analysis in this study is relatively short. In fact it is just 4 months during the wet season, 2008.

Observed hourly rainfall and discharge data were collected in the same period from 3 raingages and a stream flow gauge across the study area (Fig.1). Original temporal resolution was aggregated in 6-hour interval, the same with temporal scale from the GSM.

This study addressed a convention that precipitation obtained from raingages was considered as reference rainfall (truth) for the comparison. Inverse distance weighting (IDW) method was used to downscale precipitation information and related atmospheric parameters either from a point representation (raingage) or grid point value representation (NWP) to required area averaged basis.

(4) Brief description of distributed 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. In this study the semi-distributed and physically-based rainfall runoff model (or so called the tank model) was used to generate flow in channels. The tank model was originally developed by Kato and *Mano*.⁸⁾, and then further improved by *Kardhana*, Tatesawa, and Mano.²⁾, with consideration to simulate river flows across a wide range of spatial and temporal scales; for a continental river scale, the Upper Chang Jiang River Basin, and small-sized catchment, the Shichikashuku Dam basin in Japan. Moreover, model parameters are minimized and nearly free from calibration requirement that is a great benefit for flood modeling, especially for ungauged catchments.

In this study, overall 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-cell size that 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 area averaged precipitation in a 6-hour interval. It is clear that flood forecast models always include uncertainties either induced from hydrological model or resulted from rainfall prediction model. It was reported that forecast model uncertainties are proportional to forecast lead time⁶⁾. The more forecast lead time, the more uncertainties are expected from the forecast model. As a result, the original 84-hour forecast lead time of present QPF was reduced to 24-hour by using update of forecast on daily basis.

With respect to 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. Interception was calculated based on Horton⁹⁾. In terms of 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 topsoil, middle layer, and the lowermost layer 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 Nguyen¹⁰. The distribution between excess flow and percolation is proportional with water content (λ_i) in the lower tank, as Eq.(1).

$$\lambda_i = \frac{H_i}{H_{i\max}} \tag{1}$$

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

Excess flow from soil storage expressed from Darcy Law, as Eq.(2).

$$q_i = ck_{si}I\frac{H_i}{H_{i\max}} = ck_{si}I\lambda_i$$
⁽²⁾

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 based flow was used for the model initial condition.

Evaluation of model performance, the Nash

Sutcliffe Index (*NSI*), and relative error (η) of peak discharge and time to peak were expressed in Eq.(3) and Eq.(4).

$$NSI = 1 - \frac{\sum (Q_{obs} - Q_{cal})^2}{\sum (Q_{obs} - Q_{obs_mean})^2}$$
(3)

$$\eta = \frac{\left|Q_{cal} - Q_{obs}\right|}{Q_{obs}} \tag{4}$$

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

(5) MOS and equation development

The Model Output Statistic (MOS) approach proposed by *Glahn et al.*¹¹⁾ has been widely used in atmospheric research to improve the forecasted parameters from the NWP model. In this study, the multiple linear regression was used to develop MOS equations for QPF. The MOS equation takes a form of:

$$R_{mos} = a_o + a_1 R_{dmo} + a_2 X_2 + \dots + a_n X_n$$
 (5)

where, R_{mos} = model output statistic QPF; R_{dmo} = direct model output QPF; $X_{2,n}$ = independent NWP parameters; a_0 = regression constant; $a_{1,n}$ = regression coefficients; n = number of independent parameters.

At quasi global scale, the GSM product provides forecast of 104 parameters at different pressure levels, from 10hPa to the earth surface. Preliminary selection of predictors that have strong influence on rainfall mechanism, was based on consideration that orographic rainfall is predominant the Central Vietnam. Mountain ridge of approximate 1500 meter height lies on the border between Laos and Vietnam induced orographic effect on rainfall mechanism in the region. Intense rainfall is mainly distributed on the windward side of the mountain ridge (to the Eastern) and less rainfall is distributed on the leeward side (to the Western). Therefore, accumulation of precipitation over 6-hour interval at surface and momentum parameters of pressure levels of 700hPa and 850hPa were selected in regression analysis. The momentum predictors include meridional and zonal wind velocity and pressure vertical velocity (Table 1).

Table 1 Selected parameters in MOS equation development

Parameters	Layer (hPa)
Total precipitation	Surface
Meridional wind velocity	700, 850
Zonal wind velocity	700, 850
Pressure vertical velocity	700, 850

The training data used for the MOS equations

development was selected over period of September-December, 2008. There were 8 single storm events with average duration of 3 to 4 days and a continuous event of 4 storms lasting in 11 days (from 17th to 27th November) occurred in this period. Accordingly, different MOS equations were proposed for single storms and continuous storms.

Screening predictors was usually incorporated in the MOS equations development to select a good set of predictors. In this study, the most practical technique is so call "stepwise regression" or forward selection was used¹².

3. RESULTS AND DISCUSSION

(1) Flood reproduction

Flood reproduction based on input rainfall data from raingages was conducted to validate the model parameters. Rainfall from selected raingages was downscaled to the same spatial resolution of basin grid cells. Hourly temporal resolution was aggregated in a 6-hour interval. The interception storage capacity (S) was selected at the value of 0.025m^{2} . The infiltration rate (I) has been controlled by the top soil saturated hydraulic conductivity Ks. c is a dimensionless modification coefficient on the saturated hydraulic conductivity (k_{si}) that represents the assumed deviation between estimation and actual interflow from the Darcy law given the nature of soil structure. The c coefficient tends to be the universal number, found at the optimal value of $10^{2(6)8)}$. α coefficient was used to determine the distribution of roughness coefficient⁸⁾ $(n=\alpha I^{1/6})$, where I is bed slope) in river. The α coefficient was determined with the value of 0.15 for this study basin.

Reproduction of river flows, for instance, single storm event (October 10-13, 2008) and continuous storm event (November 17-27, 2008) were illustrated in Fig.2a and Fig.2b. Reproduced hydrographs show good agreements with measured river flows. However, reproduced time to peak was uncertain; early arrival for single storm event, but late arrival for the beginning of continuous storm events. It could be explained due to the effect of relatively coarse ground observation precipitation on flood propagation behavior.

(2) Flood forecast based on direct model output (DMO)

The next step, direct precipitation information derived from NWP output (R_{dmo}) was coupled with the tank model to forecast river flows. The flood forecasts were conducted also for the same events that have been reproduced. Forecasted river flows were compared to those obtained from using

raingages and measured discharge (Fig.2a and Fig.2b). Nash Sutcliffe Index (NSI), and relative error (η) are presented in Table 2.

It was observed that the DMO provided better forecast for continuous storm events than single storm event. Forecasted river flows using DMO for the continuous events were able to compare with those obtained using raingages. However. significant underestimates of the forecasted peak discharge of 42% and 64% were detected for single event and the beginning of continuous events respectively. Overestimation was detected at falling limb (Fig.2a). Time to peak was also observed early arrival for the single event and late arrival for the beginning of continuous events.

 Table 2 Model performance index and runoff error for flood

 reproduction and direct NWP output derived flood forecast



Fig.2 Time series of observed discharge (Q_obs), reproduced discharge based on raingages (Q_rep), and forecasted discharge based on direct model output (Q_dmo) for: (a) the single flood event on 2008 October $10^{th}-13^{th}$, and (b) the continuous flood events on 2008 November $17^{th}-27^{th}$.

(3) Flood forecast based on model output statistic (MOS)

The MOS equations were developed to improve model direct output QPF. Multiple linear regression equations were formulated for single storm event and continuous storm event basis. Screening technique using stepwise regression was applied to reduce insignificant correlation predictors. As a result the Eq.(5) was reduced to Eq.(6).

$$R_{mos} = a_o + a_1 R_{dmo} + a_2 P_{V700} + a_3 P_{V850}$$
(6)

where: P_{V700} and P_{V850} are presure vertical velocity of forecasted layer 700 hPa and 850 hPa respectively. The regression constants and regression coefficients for single storm events (7 storm events were selected for training data; the last storm event then was used for model validation) and continuous storm events are presented in Table 3.

 Table 3 Regression constants and regression coefficients used in MOS equations

Type of storm event	a _o	a ₁	a ₂	a ₃
Single	-3.37	1.31	0.00	-7.95
Continuous	9.84	0.58	-13.42	10.97

Comparison of total DMO derived QPF and MOS derived QPF with those obtained from raingages were conducted (Fig.3). While, DMO tends to underestimate rainfall for single storm events, slight overestimation of rainfall for continuous storm events was detected. QPF based on MOS equations has explained good agreement with those obtained from raingages.



Fig.3 Comparison of total forecasted rainfall derived from DMO and MOS with observed raingage: (a) single storm events, and (b) continuous storm events.

The MOS derived QPF then was coupled with the tank model to forecast river flows. Significant improvement of the forecasted river flows was observed at the single storm event (Fig.4a), while little enhancement was found at continuous storm events (Fig.4b). NSI has increased from 0.63 (Table 2) to 0.76 (Table 4) for single event.

Relative error has reduced remarkably; from 46.84% to 26.03%. Forecasted hydrographs are comparable with those obtained using raingages, except for the falling limb of the hydrograph for single flood event. The model overestimated the river flows to those attained using raingages and actual observation.

 Table 4 Model performance index and runoff error for flood

 reproduction and MOS derived flood forecast



Fig.4 Time series of observed discharge (Q_obs), reproduced discharge based on raingages (Q_rep), and forecasted discharge based on model output statistic (Q_mos) for: (a) the single flood event on 2008 October $10^{th}-13^{th}$, and (b) the continuous flood events on 2008 November $17^{th}-27^{th}$.

(4) Model validation

The flood forecast model using MOS derived QPF then was validated for the last flood event (single storm event type), December $25^{\text{th}} - 29^{\text{th}}$, 2008. Forecasted hydrographs using QPF derived from DMO and MOS are showed in Fig.5. Validated model statistic is shown in Table 5.

The validation depicted substantial improvement (40%) in terms of model performance (NSI rises from 0.51 to 0.85). Flood propagation behavior

showed very good agreement with observed one. On the other hand, forecasted time to peak was still ahead to the actual observed peak discharge.

Table 5 Model performance index and runoff error statistic forDMO and MOS derived flood forecast

River flow		Validated event					
			N	SI		η	
Q_dmo			0	.51		37.22	
Q_mos		0	.85		39.71		
	1000	[O aha		
scharge (m3/s)	800	-	Q_obs < Q_dmo Q_mos				
	600	-	Ø				
	400	-		\sim			
D	200	- \$		Q V Q Q V Q V	e fe g		
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		0 24	84 Time	2 e (hr)	96	120	

Fig.5 Validation of forecasted river flow for the flood event, December $25^{\text{th}} - 29^{\text{th}}$, 2008.

4. CONCLUSION

Development of the short-term flood forecast model based on coupled approach between the NWP model and the tank model has been proposed in a medium sized basin located in Central Vietnam. Key findings are summarized as following:

- (1) Using direct the short range QPF derived from the NWP model to forecast river flow was found good agreement with observed discharge during continuous storm events, while uncertainties were found for single storm event.
- (2) Separate MOS equations for single storm events and continuous storm events have been formulated, in order to improve the QPF. As a result, flood forecast using the QPF obtained from MOS equations significantly outperformed those using from DMO. It is comparable to those obtained using raingages.
- (3) Though model validation was just conducted for the single storm event type, it demonstrated very high potential for further development of the current model to be an operational flood forecast model.

In the future study, it is planned to focus on: (a) Further development of the MOS model, (b) extension of forecast lead time and uncertainty analysis, (c) Analysis of basin scale effect on flood propagation behavior.

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