A HYDROMETEOROLOGICAL FLOOD FORECASTING SYSTEM FOR THE RED AND CA RIVERS (CHINA, LAOS AND VIETNAM) PART II – APPLICATION AND RESULTS

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ABSTRACT

Applications and results of the hydrometeorological flood forecasting chain which has been setup for the Red River and the Ca River are briefly presented here. Five major floods occurred in the Red river in the 1971-2007 period and several floods occurred in the Ca river from 2006 to 2011, including the October 2010 disaster, were simulated with the BOLAM-MOLOCH-DIMOSHONG forecasting chain. The use of runoff observations at fourteen hydrometric stations in the Lo river, a major branch of the Red river, enabled the distributed model updating with an Extended Kalman Filtering, showing an improvement of flood forecasts compared to the results obtained with the rainfall-runoff model without hydrometric observations. Perspectives for improving the forecasting chain and for an operational implementation including surface observations and meteorological corrections using weather-types classification are discussed.

INTRODUCTION

In this paper, which follows the description of the investigated areas and the setup of the hydrometeorological flood forecasting chain (Ranzi et al., 2012), a quantitative evaluation of results obtained in flood forecasting on the Red River, flowing from China to North Vietnam, using the BOLAM meteorological and the DIMOSHONG hydrological model are presented in the first section. In the second section results on the Ca River, flowing from Laos to the provinces of Nghe Anh and Ha Tinh in Vietnam, for which the non-hydrostatic MOLOCH model is nested into BOLAM are presented, together with hydrological simulations of the October 2010 flood. This episode was characterized by 800 mm of rainfall accumulated in a single day in Chu Le, which caused about 50 casualties, and about 100 000 houses inundated.

1 METEOROLOGICAL AND HYDROLOGICAL FORECASTS IN THE RED RIVER

1.1 Verification of precipitation forecasts

Precipitation forecasts for five major floods occurred in August 1971, August 1996, July 2000, August 2002 and July 2007 in the Red river were simulated with a BOLAM "Son" model, a 8 km resolution model grid nested into a BOLAM "Father", with 19 km resolution grid. Initial and boundary conditions were provided by the ECMWF model, as described in Ranzi et al. (2012). Precipitation forecasts were compared at the event scale (Figure 1) and at the daily scale (Figure 2) with raingauge observations, interpolated on a 1 km grid with a nearest-neighbour algorithm. The comparison was conducted by spatial averaging rainfall on the Vietnamese part only, where the available raingauge data density was close to 1/1000 km^2, of the Lo at Vu Quang, Thao at Phu Tho and Da at Hoa Binh basins, and the Red River at Son Tay. As shown in Figure 1, the coefficient of determination of simulated vs. observed rainfall at the event scale, in each of the investigated areas, ranges from 0.06 only, in the Lo River, to 0.87 in the Da River. However, the BOLAM model at high resolution overestimated observed precipitation by 42%, on average. Figure 2 shows that the time pattern of modelled daily precipitation reproduces quite satisfactorily the observations, especially for the 1971 flood, both at low and high model resolution, and for the 1996 and 2007 events.

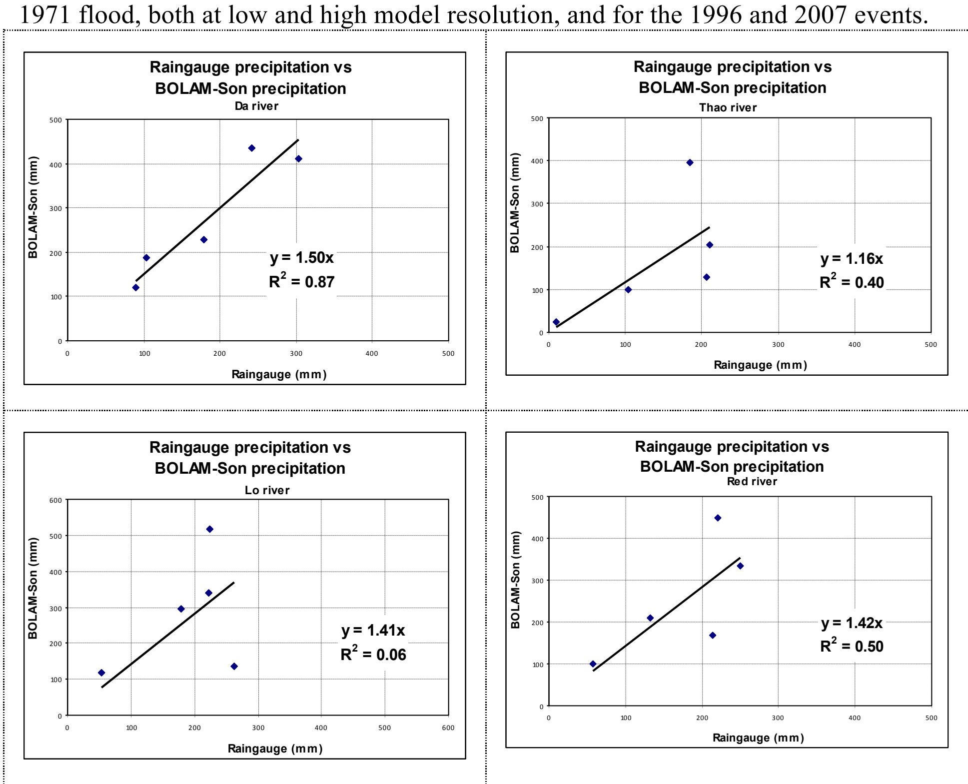

Figure 1. Comparison of the observed vs. simulated total precipitation averaged over the three major sub-basins and the Red River for the five flood events selected (1971, 1996, 2000, 2002 and 2007). The results of BOLAM with high resolution are adopted.

The overestimation of observed precipitation by the model in 2002, instead, is quite significant. Although the BOLAM model was already verified to be capable of reproducing tropical cyclones quite satisfactorily, in comparison with other mesoscale models (Nagata et al., 2003), reasons of the bias of the BOLAM model are possibly due to the earlier scheme adopted for microphysics and convection: the new version applied to the Ca river performed better.

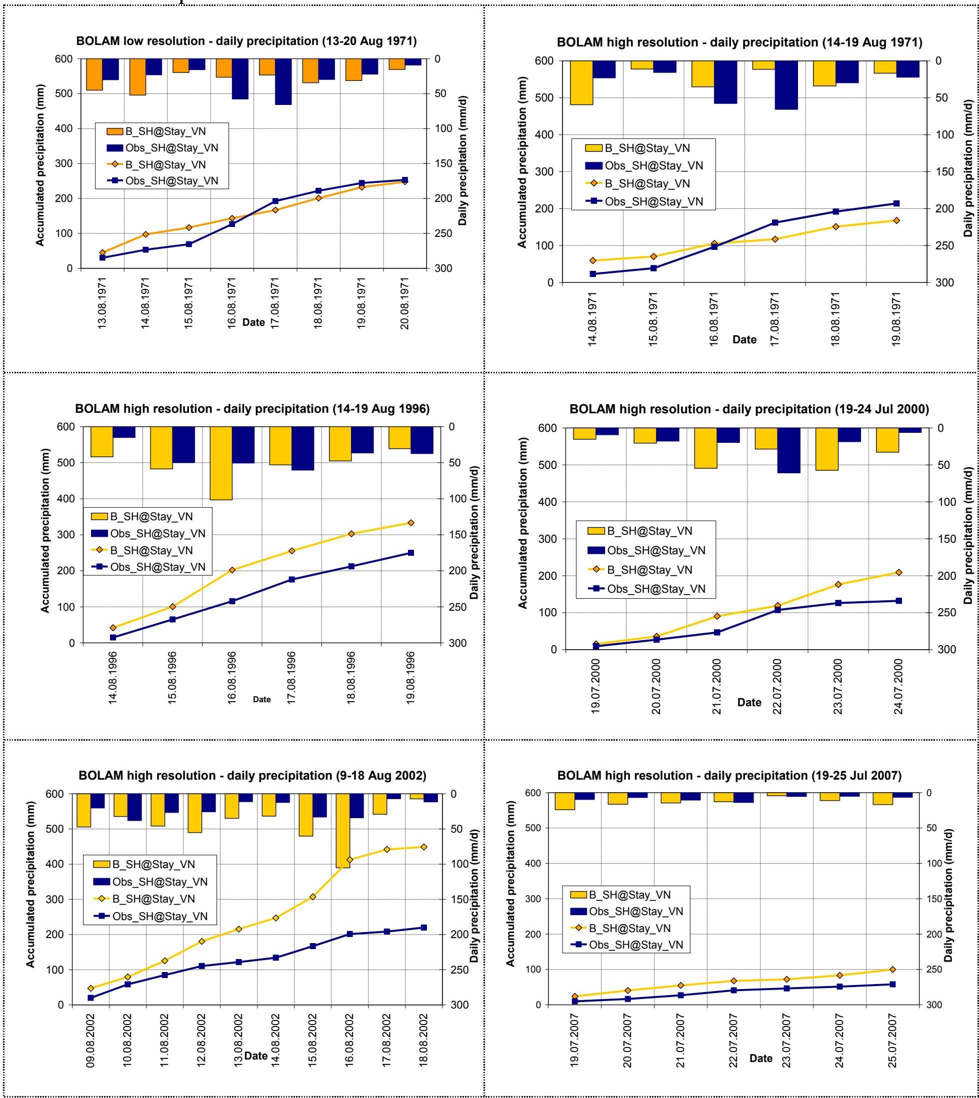

Figure 2. Comparison of the observed (Obs_SH@Stay_VN) vs. BOLAM (B_SH@Stay_VN) simulated total daily and accumulated precipitation averaged over the Red River (SôngHồng) at Son Tay for the five flood events selected (1971, 1996, 2000, 2002 and 2007). The Bolam-high resolution results are shown, with the exception of the top left panel where the BOLAM-Low resolution results are shown.

1.2 Runoff observations and forecasts with an Extended Kalman Filtering

Hydrological simulations with any model are affected by several sources of errors, mainly due to inadequate rainfall forcing, processes conceptualisation and parameters adopted. For this reason runoff observations are fundamental to correct the model's state or parameter variables on the basis of simulated and observed output. For the model's adaptation to be effective runoff data must be easily accessible with a time delay much shorter that the response time of the basin. If this happens we can say that the data are available in "real-time". In the perspective of the hydrological model's adaptation to runoff observations, two surveys were conducted by staff members of the Water Resources University and the University of Brescia in December 2007 in the Lo basin and in October 2009 in the Ca basin to identify existing hydrometric stations suitable for the installation of automatic monitoring instruments with data transmission systems. The installation of two ultrasonic hydrometers manufactured by CAE was completed in 2008 and 2012, in Ghenh Ga and Nam Dan, respectively in the Lo and Da basins (see Figure 3). Because of the availability of hydrometric data in real-time in Ghenh Ga since 2008, an adaptive hydrological forecasting system was setup first on the Lo basin. The theory for adapting hydrological models to observations has been developed starting with the 70s (Todini et al., 1976; O' Connel and Clarke, 1981). It is based, in principle, on either modelling forecast errors in a stochastic and statistical approach or in updating model's state and parameter values. Montanari and Grossi (2008), among others, provided recent advances on the error modelling framework. Moradkhani et al. (2005) discuss and provide novel techniques for the second class of model updating, based on ensemble Kalman filtering (EnKF). Early theory of model's updating was mainly based on the assumption of linearity of hydrological systems and often use "classical" Kalman filtering method. Because of the non-linearity of most hydrological processes, including infiltration, runoff formation and propagation, the Extended Kalman Filtering (EKF) method should be, in principle, more suitable for hydrological models.

Figure 3. Surveys conducted by the University of Brescia (Roberto Ranzi) and Water Resources University staff (Vũ Minh Cát, Hoang Thanh Tung, Le Van Chin, Nguyễn Hoàng Sơn and Tran Kim Chau) for the installation of a tipping-bucket raingauge and ultrasonic hydrometer installed by the CAE company (Bologna, Italy) in a well (left) in the Ghenh Ga station on the Lo river. On the right image the ultrasonic hydrometer ready for the installation on the Nam Dan bridge, in the Ca river basin. On the right Mr. Nguyen Xuan Tien the Vice-Director of the Central Northern Provinces Flood Forecasting Centre, responsible for flood forecasting on the Ca river.

Extended Kalman Filter relies on linearization using first order approximation of Taylor series of the state-space model (1), which can be non-linear, and can be used when the non-linearity of the system is weak. In the state-space non-linear model

$$\mathbf{x}_{t+1} = F_t(\mathbf{x}_t) + G_t(\mathrm{x}_t)\mathbf{w}_t \tag{1}$$

$$\mathbf{y}_t = H_t(\mathbf{x}_t) + \mathbf{v}_t \tag{2}$$

(1) is the state-update equation and (2) is the observation equation. In this system $\boldsymbol{x}_t$ is an n-sized state vector (e.g. water volume in the surface streams and channel), $\boldsymbol{w}_t$ the error vector, $\mathbf{y}_t$ is the measurement vector (e.g. runoff at some hydrometric station) and $\mathbf{v}_t$ is the observation error vector. $\mathbf{G}_t(\mathbf{x}_t)$ is a non-constant, state-dependent weighting matrix. Both $\boldsymbol{w}_t$ and $\boldsymbol{v}_t$ are assumed to be independent zero-mean white Gaussian noise processes.

In summary, the filtering algorithm is applied in the following way: given the error covariance matrix **P**, it is projected with equation (3). Then the Kalman gain **K** is computed from equation (4). The measurements enable to estimate $\mathbf{v}_{t+1}$ to update the state with equation (5) and the error covariance with (6).

$$P_{t+1|t} = F_t^{'} P_{t|t} F_t^{'T} + G_t^{'} Q_t G_t^{'T} \tag{3}$$

$$K_{t+1} = P_{t+1|t} H_t^{'T} [H_t^{'} P_{t+1|t} H_t^{'T} + R_t]^{-1} \tag{4}$$

$$\hat{x}_{t+1|t+1} = \hat{x}_{t|t+1} + K_{t+1} v_{t+1} \tag{5}$$

$$P_{t+1|t+1} = (I - K_{t+1} H_t^{'}) P_{t+1|t} \tag{6}$$

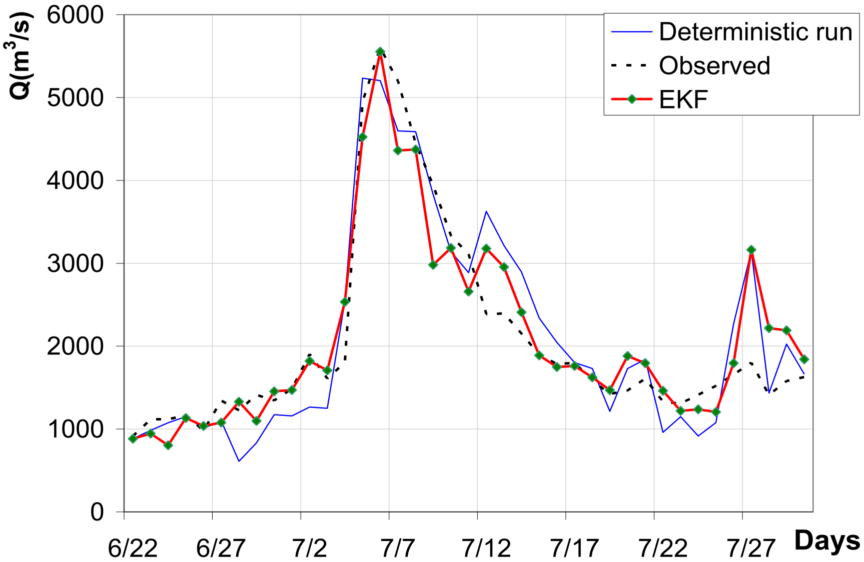

Figure 4. Comparison of deterministic and Extended Kalman Filtered forecasts with DIMOSHONG vs. observations at the Tuyen Quang station during the 2009 flood.

As we observed a power-law type of relationship between simulated storage in surface water and observed runoff at hydrometric stations, Nguyen (2011) explored the potential of EKF for flood forecasting in the Lo River using the DIMOSHONG distributed model. While the theory of Kalman filtering, with linear or non-linear models, is well defined for state-space models with a limited number of state variables, more difficult is model updating for distributed hydrological models as the state variables, including surface runoff and subsurface soil moisture, can easily become several thousands, considering the variability in each computational grid cell. In principle each observed variable, as runoff at one gauging station, provides information useful to update one state variable. In our application to the Lo River runoff observed at each of 14 streamgauges was used to update the surface water storage spatially averaged in the river network upstream the measurement stations. The updated storage is then distributed over each cell with a multiplicative correction. In computing runoff the water stored in the Tuyen Quang and Thac Ba reservoirs, which influence simulations in Chiem Hoa, Tyuen Quang and Vu Quang, was taken into account.

As shown in Table 1 and, for example, in Figure 4 the application of the EKF is capable of improving, on average, the model's performances quantified in terms of Nash-Sutcliffe efficiency, RMSE, peak error timing and percentage error. However, as the EKF can lead to unstable results when the nonlinearity in the system is strong, in some cases the model's performances are better without the application of EKF.

	Chiem Hoa (16 500 km^2)		Ham Yen (11 900 km^2)		Tuyen Quang (29 600 km^2)		Vu Quang (37 000 km^2)	
2006 Event	*CAL*	*EKF*	*CAL*	*EKF*	*CAL*	*EKF*	*CAL*	*EKF*
Nash Efficiency	0.77	*0.87*	*0.74*	0.65	0.90	*0.92*	*0.82*	0.80
Mean flow (m^3/s)	1356	1295	777	700	2354	2180	2544	2440
RMSE (m^3/s)	342	*237*	*287*	305	500	*434*	*743*	746
Time error (days)	1.00	*0.00*	1.00	1.00	0.00	0.00	0.00	0.00
Peak error (%)	12.28	*7.33*	*1.07*	9.63	21.05	*4.13*	26.46	*11.93*
2008 Event	*CAL*	*EKF*	*CAL*	*EKF*	*CAL*	*EKF*	*CAL*	*EKF*
Nash Efficiency	0.91	*0.92*	0.51	0.51	0.72	*0.85*	0.57	*0.73*
Mean flow (m^3/s)	1073	1085	1165	1355	2325	2595	2709	2924
RMSE (m^3/s)	186	*176*	*662*	769	714	*565*	965	*759*
Time error (days)	1.00	1.00	5.00	*0.00*	5.00	*2.00*	4.00	*1.00*
Peak error (%)	7.46	*6.57*	*8.27*	29.58	17.19	*1.82*	11.18	*9.63*
2009 Event	*CAL*	*EKF*	*CAL*	*EKF*	*CAL*	*EKF*	*CAL*	*EKF*
Nash Efficiency	0.88	*0.89*	*0.58*	0.54	*0.86*	0.85	0.72	*0.74*
Mean flow (m^3/s)	1041	1043	949	1056	2092	2102	2394	2356
RMSE (m^3/s)	198	*190*	*533*	555	*479*	431	743	*664*
Time error (days)	0.00	0.00	0.00	0.00	1.00	*0.00*	1.00	1.00
Peak error (%)	7.99	*7.70*	*50.35*	63.91	6.54	*0.83*	33.98	*29.77*

Table 1 DIMOSHONG model performance in simulating daily runoff at four stations in the Lo River basin in standard calibration mode (CAL), using observed rainfall as meteorological forcing, and after the application of the Extended Kalman Filtering (EKF). In *italics* the best results in the CAL vs. EKF comparison.

2 METEOROLOGICAL AND HYDROLOGICAL FORECASTS IN THE CA RIVER

2.1 Verification of precipitation forecasts

The accuracy of the BOLAM-MOLOCH precipitation forecasting chain was evaluated by simulating, at the National Center of Hydro-Meteorological Forecasting (NCHMF) based in Ha Noi, 31 precipitation events occurred from 2008 to the end of 2010. Some additional events occurred in 2011, including the September 2011 flood, have been simulated using BOLAM only. The versions of the BOLAM and MOLOCH models delivered by ISAC-CNR in November 2010 were used for the simulations. In computing performance statistics, interpolated forecast precipitation is compared to point measurements at seven raingauge stations in the Ca River, so the representativeness of point values influences the statistics. In an overall assessment of the 31 events, the mean error and correlation coefficient obtained by comparing forecast and observed precipitation accumulated in 24-hours indicates that the BOLAM-MOLOCH chain (in practice, the MOLOCH model) tends to underestimate observed rainfall by a factor ranging from -60% to 0, and the linear correlation coefficient is on average 0.55 ranging from 0.2 to 0.8, depending on the site.

Focusing on the heaviest flood event occurred from 14th to 18th October 2010, meteorological model error statistics improve. Between 16 and 17 October, both model forecasts agree very well with the observations, in terms of intensity and location: precipitation exceeding 200 mm in 24h is centred around Vinh, in the lower part of the Ca-Lam River basin and in the La River basin branch (see Figure 5, top panels).

The comparison among the fields of precipitation, accumulated over the 120 hour period between 12 UTC of 13 October to 12 UTC of 18 October 2010 (shown in Figure 5, bottom panels), allows to draw a general qualitative evaluation of the models performance in forecasting this severe weather episode. Extremely high amounts of rainfall insisted over a large portion of the Viet Nam territory, both along the coast and over the mountain chain, extending from north of the Ca River region to the city of Hue. Precipitation in excess of 500 mm affected a wide area of Central Vietnam.

BOLAM provides a satisfactory prediction in the region extending south of the Ca riverbasin, slightly underestimating the total rainfall amount, although forecasting more than 400 mm of precipitation. However, forecast heavy rainfall affects only marginally the Ca River, being characterized by a rapid decrease with latitude in proximity of Vinh. Thus the flood magnitude in the target basin is slightly underestimated.

The MOLOCH forecast precipitation fields is affected by a general underestimation in the wide scale region, but the prediction is reliable in the Ca riverbasin, both in intensity and location, with an underestimation, however in the La River area, south of Vinh. Overall, the spatial distribution of model precipitation appears in good agreement with the observations and the most intense rainfall is correctly predicted over the mountains. Over the Ca River basin, MOLOCH is apparently able to provide a much better forecast with respect to BOLAM, displaying some maxima along the coast north of Vinh and a wide area of precipitation, whose accumulated amount is around 200 mm.

As in the central provinces rainfall can occur because of a complex combination of weather types, including typhoons and tropical low pressure, Inter-Tropical Convergency Zone, high pressure in the Pacific Ocean, a lookup table of weather conformations producing medium and heavy rains in the Ca River Basin has been proposed by Hoang et al. (2012) to correct, when appropriate, model's predictions.

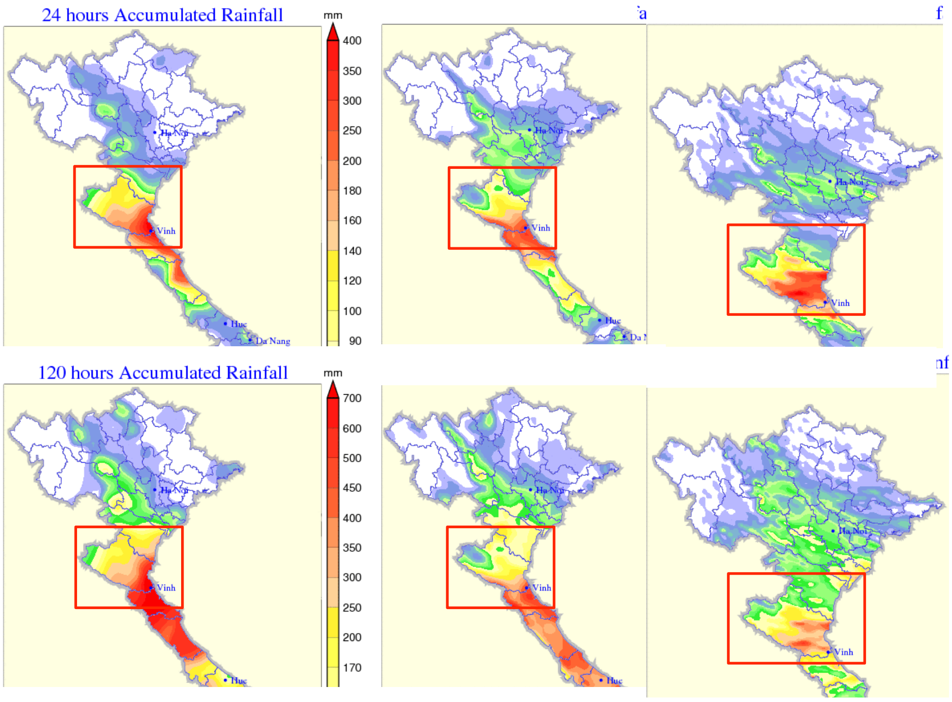

Figure 5. Comparison of the raingauge-observed (top left panel) vs. simulated total 24-hours accumulated precipitation at 12 UTC (19 Local Time) of October 17 2010 with the BOLAM model (top central panel) and MOLOCH model (top right panel) during the period of heaviest precipitation in the October 2010 flood on the Ca River (in the red box). In the bottom panels observed 120-hours accumulated precipitation until 18 October at 12 UTC, BOLAM-predicted (center) and MOLOCH (right).

2.2 Runoff observations and forecasts

The October 2010 and September 2011 floods were simulated with a complete BOLAM-MOLOCH-DIMOSHONG hydrometeorological flood forecasting chain. The highest water level at Nam Dan, located just upstream the junction with the La River, was 7.44 m on 19/10/2010, 7 a.m. between the level II and level III warning which is set to 7.9 m. But in the La River water level at Linh Cảm station reached 7.28 m, over the level III warning set at 6.5 m: it was the fourth highest level recorded since 1975.

The flood forecasts by the DIMOSHONG model with forecast lead time, Δt_f, of 48 hours from the forecast time, t_f, were tested in two case: (1) without forecast rainfall and (2) with rainfall forecast from the BOLAM model.

In the first case at the time of the forecast only observed rainfall is adopted for the meteorological forcing of the hydrological model. In the second case, at the time of the forecast t_f, the observed rainfall is used until t_f, and for the successive 48 hours the rainfall forecast from BOLAM is used as input to the DIMOSHONG model.

The experience in forecasting with DIMOSHONG for some floods such as the October 2010 and the September 2011, with case (1) and case (2) was done in this research. The result of the forecasting experience indicates that, in case (2), the calculated runoff hydrographs better match with observed runoff than in case (1). In the upstream stations as Nghĩa Khánh (Figure 6) and Muong Xen (near the Viet Nam – Laos border), DIMOSHONG using rainfall from BOLAM model shows much more suitable results, also because observed rainfall does not cover the catchment area in Laos. For downstream stations the forecast experiment is not very representative yet because the effect of reservoirs is not taken into account in the present stage of the research project. It is planned to be implemented in the future.

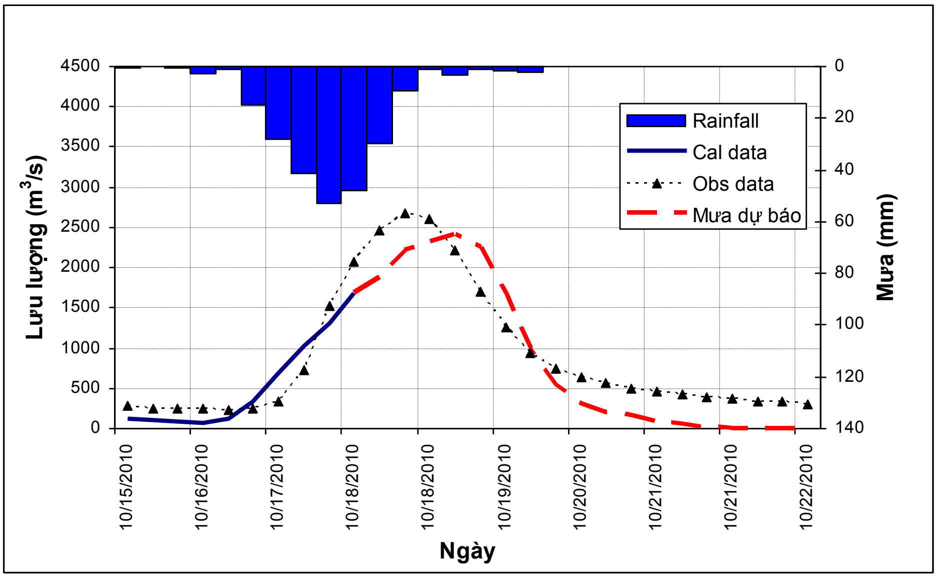

Figure 6. Flood forecast for the Ca River basin at the Nghĩa Khánh station (area 4020 km^2 in the Hieu river) with the observed precipitation until the forecast time t_f at 01 hours on 18th October 2010 hours and BOLAM-predicted rainfall thereafter for the forecast lead time Δt_f of 48 hours. The hydrograph is simulated with the DIMOSHONG model.

3 CONCLUSIONS

A hydrometeorological flood forecasting system, complete with two mesoscale meteorological models BOLAM and MOLOCH coupled wit the distributed hydrological model DIMOSHONG, was tested for both the Red River and Ca River in Vietnam. The BOLAM hydrostatic meteorological model simulations of five floods occurred in the Red River show quite a satisfactory capability of forecasting rainfall up to three days in advance, with good timing but some overestimation of rainfall amount. Improvements have been achieved with the new version of the model and with the non-hydrostatic MOLOCH model applied to the Ca River. In this case some underestimation of precipitation was observed, confirming that precipitation is a difficult variable to be predicted in tropical areas, because of the combination of different weather types and of the widespread presence of convective instability. The results show, however, the usefulness of meteorological modelling for precipitation estimation in the upstream part of both basins, in China and Laos, in case a lack of raingauge information occurs. Flood hydrographs simulated by the DIMOSHONG model, especially when surface observations are used for model adaptation with the Ensemble Kalman Filtering, are fairly well reproduced when observed precipitation is used and when the mesoscale model is accurate enough in the rainfall prediction as for the 1971 or 2010 flood. The tests conducted so far encourage the joint effort for a further improvement of the flood forecasting system, considering the regulation of reservoirs and using real-time hydrometric data. The results achieved indicate that the BOLAM-MOLOCH-DIMOSHONG model chain can provide information useful to assist medium term flood forecasting for the Red and Ca Rivers, thus enabling flood hazard mitigation measures, as the operation of reservoirs, or the issue of alerts for towns along the rivers.

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