

A HYDROMETEOROLOGICAL FLOOD FORECASTING SYSTEM FOR THE RED AND CA RIVERS (CHINA, LAOS AND VIETNAM) PART I – INVESTIGATED AREAS AND MODEL SETUP

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ABSTRACT

As a result of two research projects conducted over the last six years, this paper describes the configuration a hydrometeorological flood forecasting system set up for the Red River (169 000 km² at the outlet) and the Ca River basins (23 830 km² at the outlet), across China and Vietnam, and Laos and Vietnam, respectively. The research objectives were to setup a hydrometeorological chain to forecast discharge flowing into reservoirs and at some control sections for flood control downstream, including the heavily populated Northern Delta and, for the Ca river, the Vinh area, both experiencing rapid development. The distributed hydrological model DIMOSHONG, which implements a modified Green-Ampt or an SCS-type soil moisture accounting scheme, is forced by Quantitative Precipitation Forecasts provided by the BOLAM and the MOLOCH meteorological models or by raingauge observations. The forecasting chain has an Extended Kalman Filtering updating module based on hydrometric measurements now available in real-time for two pilot stations installed in Ghenh Ga and Nam Dan, in the Red and Ca rivers, respectively. Several floods in the basins, including the August 1971 and October 2010 catastrophes which flooded the Red river and the Ca river regions, were simulated providing useful results in view of improving flood alert systems.

INTRODUCTION

Flood hazard mitigation measures have been traditionally mainly focused on structural defence systems, including river embankment, diversion, by-pass and reservoirs construction. Starting with the XIX century, non-structural measures based on flood alert systems, land planning, flood risk mapping and communication have been implemented in some areas and today are becoming an important alternative for

enhancing awareness of people about water-related hazards and for reducing flood risk. The effectiveness of flood alert systems is improving in the last decades as meteorological and hydrological forecast models become more accurate and raingauge and hydrometric observing systems providing data in real-time are installed in several basins worldwide. This is the case also of Vietnam, a country which is prone to water-related hazards triggered by monsoon and tropical typhoons rainfall.

In this paper, we give an overview of the set up of a hydro-meteorological system aiming at extending the lead time and improving the effectiveness of forecasting for a better control of reservoirs in the Red River and in the Ca river, draining from China and Laos to Vietnam (Figure 1). The system is based on three main components:

1. a quantitative precipitation forecast system provided by the BOLAM-MOLOCH Mesoscale Meteorological Model chain nested into the ECMWF (for Red River) and NOAA-GFS (Ca river) Global Circulation Model initial and boundary conditions;
2. a hydrological flood forecast with the DIMOSHONG (DIstributed hydrological Model for the Shong HONG) hydrological model;
3. a real time observation system of rainfall and river level, providing runoff data for the hydrological model updating with an Extended Kalman Filtering (EKF).

The investigated area and the first two components of the model setup are described in the following.

1 THE RED AND THE CA RIVERS IN VIETNAM

The Red River (Sông Hồng in Vietnamese) is an international basin located in China, Laos and Vietnam. With the area of about 169 000 km², it is the largest basin in Vietnam. Its source originates in China, flows to the southeast entering into Vietnam at Lao Cai, where the drained area is 41 000 km², and discharges into the Tonkin Gulf in the China Sea (East Sea). Three main tributaries in the Red River system in Vietnam's territory are called Lo (where rainfall reaching 4000 mm/year), Thao, and Da rivers (Figure 2). These three main tributaries join to form the Red River, upstream Hanoi, in Viet Tri. The Red river Delta is a very important area for the society, education, culture and also economics of Vietnam.

The climate of the basin is tropical to subtropical. It is dominated by the northeast monsoon in winter and the southwest monsoon in summer. The basin is located next to the sub-humid tropical region of South East Asia. Since the topography is divided into individual mountain ranges and climate regime is affected by many synoptic weather systems, rainfall in the basin varies strongly in space and time.

A forecasting system in the Red River basin has been developed and implemented by the Vietnamese National Flood Control Bureau. The warning time is the time lag of the basin in the Vietnamese territory. This time lag can be extended by means of Quantitative Precipitation Forecasts, issued some days in advance and obtained from the meteorological model chain mentioned above and described in the second section..

1.1 Rainfall data.

Annual precipitation ranges in the Vietnam's part of the Red River between 1600 to 2800 mm with mean annual 24 hours precipitation ranging from 140 mm in Sa Pa and Sin Ho to 300 mm in Bac Quang (see Fig. 1). Raingauge data are both from automatic and mechanical stations with hourly records and from climatological stations with 6 or

12 hours manual recording time. Readings are conducted at 1, 7, 13, and 19 local time, corresponding to UTC + 7 hours. In the Da river up to 23 raingauge data were available, 9 in the Thao river and 15 in the Lo river. In China data for only 7 raingauge stations were available for this study and this poses limitations on the accuracy of both the hydrological model simulations and the verification of the simulated rainfall fields.

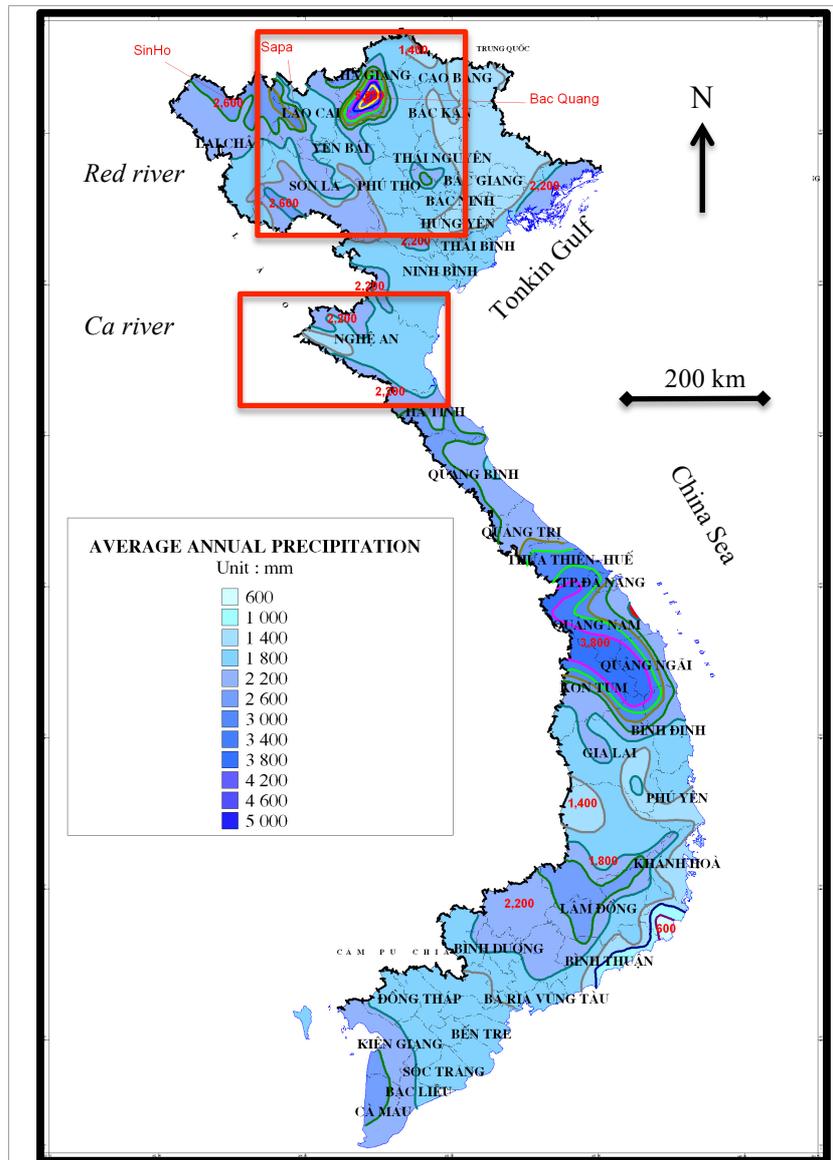


Figure 1. Location of the Red and the Ca rivers superimposed on the annual precipitation map of Vietnam.

1.2 Runoff data

Runoff data with 6 hours time steps were collected at 20 runoff stations for 5 major flood events occurred from 13 to 20 August 1971, from 13 to 20 August 1992, from 13 to 25 July 2000, from 10 to 19 August 2002 and from 19 to 25 July 2007. The most significant data are those of Vu Quang (draining 37 000 km²) in the Lo river, Yen Bai (48 000 km²) in the Thao river, Ta Bu (45 900 km²) in the Da river and Son Tay (144 000 km²) in the Red River downstream the junction of the three main tributaries, where the mean annual flow is 3 500 m³/s and the mean annual peak flow over the 1960-2004 period is 16 450 m³/s.

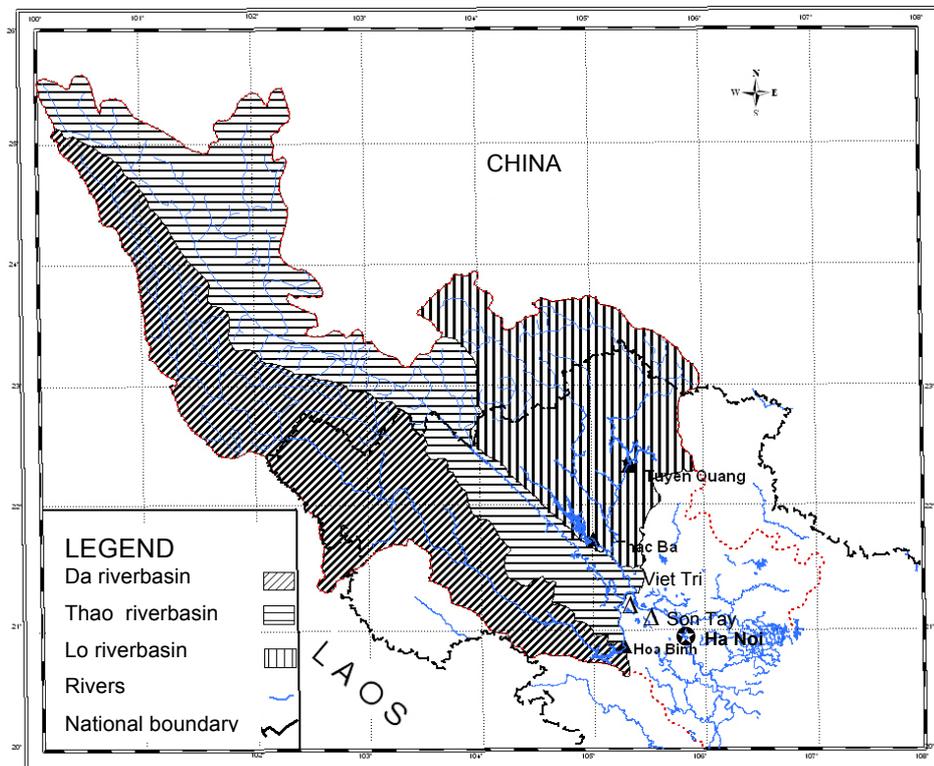


Figure 2. The Red River basin at the Viet Tri junction, and its three major tributaries, together with the Tuyen Quang, Thac Ba and Hoa Binh reservoirs.

1.3 Reservoirs

In the Red river system, there are 3 main reservoirs in operation now, others being built or planned in the Da and Lo rivers. The Hoa Binh reservoir (with $9.6 \cdot 10^9$ m³ storage, in operation since 1989) is in the Da river, the Thac Ba (with $2.49 \cdot 10^9$ m³ storage, in operation since 1971) and Tuyen Quang reservoirs (with $2.245 \cdot 10^9$ m³ storage, in operation since 2005) in the Lo river. The missions of these reservoirs are: the protection of the Ha Noi capital and the Red River Delta against all flood with 250 years return period at Son Tay (upstream of Hanoi), keep the water level at Hanoi less

than 13.4 m, generate hydropower and provide water for irrigation (Ngo et al., 2007; Castelletti et al., 2012). They are modifying the runoff and sediment transport regime (Ranzi et al., 2012) downstream, but have already been able to mitigate the intensity of major floods, after the catastrophic one of August 1971 which reached 34 300 m³/s in Son Tay. Because of their multiple purposes and their large storage capacity their effective operation would benefit from a warning of inflow some days in advance.

2 THE CA RIVER BASIN

Floods threaten frequently also the Ca river. Focusing in the recent past, in 2007 a series of five floods occurred in only one month period causing huge damage on both people and properties in the central districts of Nghe An province in the Ca River basin; also in October 2010 about 50 casualties and widespread inundation occurred in the same area. Ca river basin is on the northern part of Central Vietnam, with latitude ranging from 18°15' to 20°10'30" North and longitude ranging from 103°45'20" to 105°15'20" East (Figure 3). The main river originates from Muong Khut, Muong Lap in Laos at elevation of 1800-2000 m, flows down from the Northwestern to Southeast direction, enters into Nghe An province at Keng Du, flows still to the Eastern Sea at the Hoi estuary. This branch is properly named Ca river. The branch downstream of Ca river from Cho Trang to Hoi estuary, about 35 km long, should be named as Lam River rather than Ca River, and it is formed by Ca and La (originated from Ha Tinh) rivers. The natural area of the Ca River basin is 27 200 km² in total up to Hoi river mouth, of which 17 730 km² are in Vietnam and 9 470 km² in Laos. In some documents additional 2 650 km² are added to the Vietnamese part of the basin to account for wetlands, lagoons and little rivers in its downstream part which flow directly to the sea or through secondary branches of Ca river. With this addition the Vietnamese part of the basin is 20 460 km² and the total basin area is 29 850 km². The Ca river bed is very narrow, with steep slope in the upstream area, widens up in the middle basin (from Con Cuong to Anh Son), then joins the Hieu River on its left side. In the downstream area, the Ca River flows through the plain and finally joins the La River on the right side. The length of the main Ca river is 531 km in total, of which 361 km is in Vietnam and its mean elevation is 294 m a.s.l.

Hieu River is the largest tributary on the left side of the Ca River. The catchment area of the Hieu River is 5 340 km², its length is 228 km, originates from Pu Hoat Range in the Laos-Vietnam boundary, flows into the Ca River at Anh Son.

La River is the main tributary on the right side of the Ca River: it originates from the Giai mountainous area and enters into Ca river at Cho Trang. The catchment area of the La River is 3 210 km².

Mean annual precipitation in the basin ranges from 1100 mm in the upstream mountain area to 2400 mm close to the junction with the La river. Rainfall is concentrated in one rainy season from May to October when falls 80% to 85% of annual rainfall. Heaviest rainfall occurs in September when mean of maximum daily rainfall is up to 250 mm in the coastal area, and in 2010 a maximum value up to 800 mm was recorded in 24 hours. Land is covered mainly by forests (66%) and by agricultural crops (16%). In flat land, Gleysols, characteristics of lagoons, wetlands or areas with upper groundwater at low depth, are the least prone to infiltration due to frequent waterlogging conditions and to fine soil texture. In the mountain range, upstream

Acrisols, which are very common in tropical and subtropical areas, were considered less prone to infiltration than downstream ones, due to higher slopes. In the Laotian part of the basin also a small area of Leptosol is present, with low infiltration capacity due to their low depth.

In the Ca River basin, there are major reservoirs being operated or under construction such as Sao reservoir on the Sao River, Ban Mong reservoir on the Hieu River, Ban Ve reservoir and Khe Bo reservoir on the Ca River, and Thac Muoi reservoir on the Giang River. The operation of these reservoirs, which have a total storage capacity of $2.8 \times 10^9 \text{ m}^3$, an installed power generation capacity of 485 MW (excluding Song Sao) has to meet flood control with $411 \times 10^6 \text{ m}^3$ storage available, hydropower generation, water supply for irrigating 33 487 hectares, industrial, domestic and environmental demand (Vietnam Institute for Water Planning, 2004). Operation rules are set for single reservoirs, mainly for dam safety reasons, and no regulation practices are set for the overall reservoir system. For mitigation of damages caused by floods, as well as to take into account socio-economic and environmental effects of reservoirs operation, it is necessary to extend research on both medium range rainfall and runoff forecast and to set a comprehensive scientific basis for operation of the reservoir system (Hoang et al., 2012).

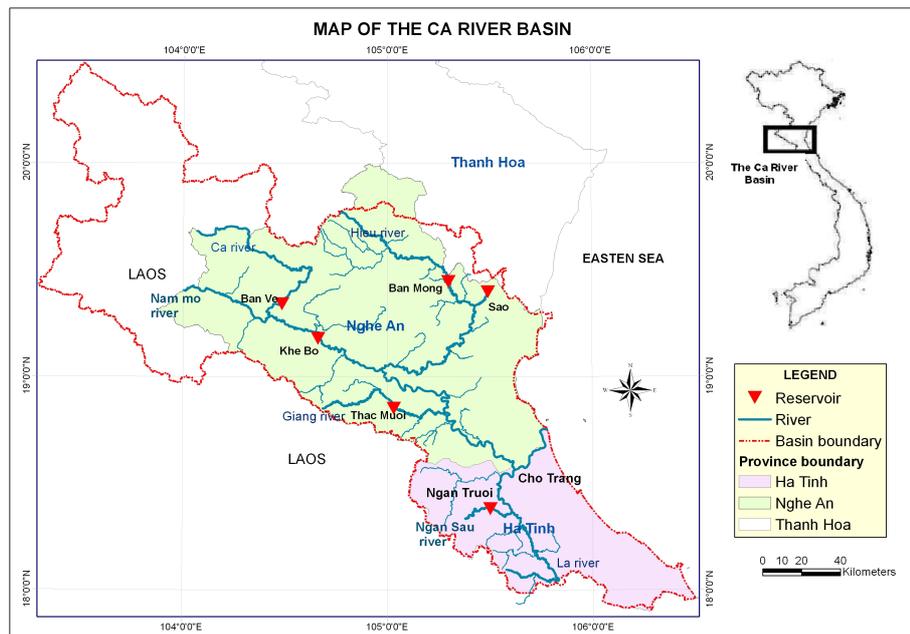


Figure 3. Map of the Ca river, in Vietnam, with the main river branches, reservoirs and administrative boundaries.

3 THE METEOROLOGICAL BOLAM-MOLOCH MODEL

3.1 The BOLAM hydrostatic mesoscale meteorological model

BOLAM is a mesoscale meteorological model based on hydrostatic primitive

equations and terrain-following coordinates. It was developed starting in the early 1990's at ISAC in Bologna. A detailed description of the dynamics and numerical schemes of the model can be found in Buzzi et al. (1994) and in subsequent papers. The model was continuously developed and updated over the last years and applied in Europe (Malguzzi et al., 2006), the Mediterranean, Africa, the Pacific Ocean and, within this project, in South-East Asia, in an area comprising China, Vietnam and Laos.

The initial and lateral boundary conditions from a Global Circulation Model (GCM in Figure 4) for the Red River study have been obtained from the ECMWF archives, by retrieving the 6-hourly analyses available at $0.5^\circ \times 0.5^\circ$ resolution. Snow cover, sea surface temperature, and soil temperature and wetness at four soil layers have been derived also from the ECMWF analyses. For the Ca river, the NOAA-GFS initial and boundary conditions were adopted. In order to provide the high resolution simulations with more suitable boundary data than those available from global models, a dynamical downscaling chain has been organized: global analysis data, after undergoing a pre-processing procedure, have been used as initial and boundary conditions for simulations at a relatively coarse spatial resolution (about 19 km), intermediate between the global analyses resolution and the inner grid resolution. The coarse model integrations are conventionally named "BOLAM-father" runs. Output data obtained from the BOLAM-father simulations have been used as initial and boundary conditions for simulations at high spatial resolution.

Such model simulations are conventionally indicated as the "BOLAM-son" runs (see the MMM in Figure 4).

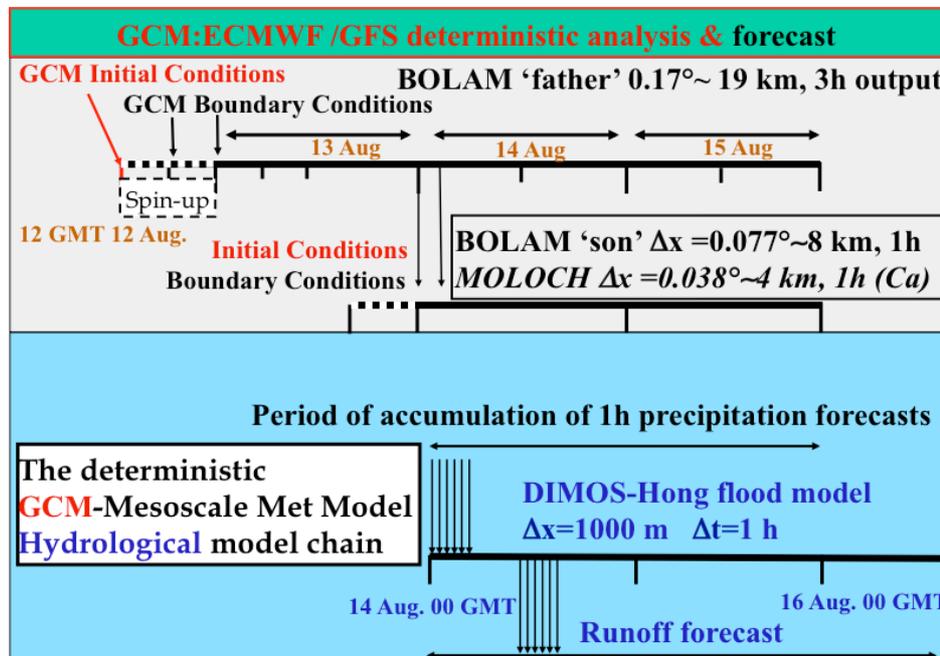


Figure 4. Scheme of the GCM (Global Circulation Model) – BOLAM/MOLOCH Mesoscale Meteorological Model – DIMOSHONG Hydrological model forecasting chain setup to forecast floods in the Vietnamese part of the Red and Ca rivers. Precipitation forcing to the hydrological model can be provided also by raingauge observations.

In the BOLAM-father configuration, the following parameters for the numerical solution have been used: rotated geographical system with the coordinate origin set at 21.3°N and 102.5°E; horizontal grid distance of 0.17° (about 19 km in both latitudinal and longitudinal directions); 38 hybrid levels in the vertical; basic time step of 150 s; output data storage every 3 hours; duration of each continuous run of 72 hours.

In the BOLAM-son configuration, the following parameters have been used: same rotated geographical system as for BOLAM-father; horizontal grid distance of 0.077° (about 8 km); 40 hybrid levels; time step of 72 s; output data storage every 1 hour; duration of each continuous run of 48 hours.

3.2 The MOLOCH non-hydrostatic mesoscale meteorological model

For the Ca river meteorological forecasting the high resolution meteorological forecasting was implemented using both the BOLAM 'son' configuration and the MOLOCH non-hydrostatic meteorological model at 4 km resolution (see Figure 2), also developed at CNR-ISAC. MOLOCH is a nonhydrostatic, convection-resolving model: this means that atmospheric convection equations are explicitly resolved by the numerical scheme instead of being parameterised, on the basis of already solved meteorological variables, as in BOLAM. It integrates the fully compressible set of equations with prognostic variables (pressure, temperature, specific humidity, horizontal and vertical velocity components, and five water species) represented on the lat-lon rotated, Arakawa C-grid (Malguzzi et al., 2006). Terrain following coordinates, relaxing smoothly to horizontal surfaces away from the earth surface, are employed. Model dynamics are integrated in time with an implicit scheme for the vertical propagation of sound waves, while explicit, time-split schemes are used for the remaining terms. Three-dimensional advection is computed using the eulerian WAF scheme. Horizontal second-order diffusion and divergence damping is included to prevent energy accumulation on the shorter space scales. The physical scheme consists of radiation (as for BOLAM), subgrid turbulence, microphysics, and soil water and energy balance. The turbulence scheme is based on an E-1 closure, where the Turbulent Kinetic Energy equation (including advection) is evaluated. Surface turbulent fluxes of momentum, specific humidity, and temperature are computed by the classical Monin-Obukhov theory with Businger/Holtslag functions in the unstable/stable case. The microphysical scheme is based on the parameterization proposed by Drofa and Malguzzi (2004) to take into account fast and slow processes of transformation of specific humidity and cloud quantities. The soil model is a four-layer model including vegetation.

4 THE HYDROLOGICAL DIMOSHONG MODEL

The output of meteorological simulations or raingauge-observed precipitation is then used as meteorological forcing to the distributed hydrological model implemented in this study called DIMOSHONG, standing for Distributed hydrological Model for the Shong HONG. The DIMOSHONG model is developed, for the Red River basin, from the DIMOSOP model (Ranzi et al., 2003). The topography was represented by the Digital Elevation Model resampled at 1 km resolution from the Global DEM GTOPO30, provided by the USGS-EROS, in a raster format, lat-long coordinate system. The river network is then determined through the Hortonian order. The other physical parameters are estimated from the landuse, geological maps took from USGS,

and Vietnam Atlas.

The model is basically built by four components (see Figure 5). The first is the soil model that aims at describing in a relatively simple mathematical scheme the complex physical processes that include the interception of rainfall by vegetation, the storage in surface ponds and the partitioning of the resulting rainfall volume into infiltration and runoff. This component of the model can be either of the ‘infiltration excess’ or of the ‘saturation excess’ type. For the ‘infiltration excess’ scheme a Green-Ampt Modified scheme was adopted, assuming that the wetting front propagates downward with a rate corresponding to an equivalent saturated conductivity decreasing with depth. Lateral subsurface interflow is assumed, in a Darcian framework, proportional to the lateral soil transmissivity and local topographic gradient (Ngo, 2008). The saturation excess model is developed according to the Soil Conservation Service-Curve Number method, but the soil columns are interconnected allowing for subsurface lateral flow propagation with a Darcian scheme, which is the second component of the model.

Infiltration excess or saturation excess surface runoff is then routed as overland flow with a linear reservoir model with time constant estimated from a kinematic wave equation.

The sum of overland flow and subsurface lateral interflow contribute to channel flow, which is propagated along the river network according to a Muskingum-Cunge scheme with celerity and diffusivity which can be estimated with a constant event-dependent value or changing dynamically during the flood development.

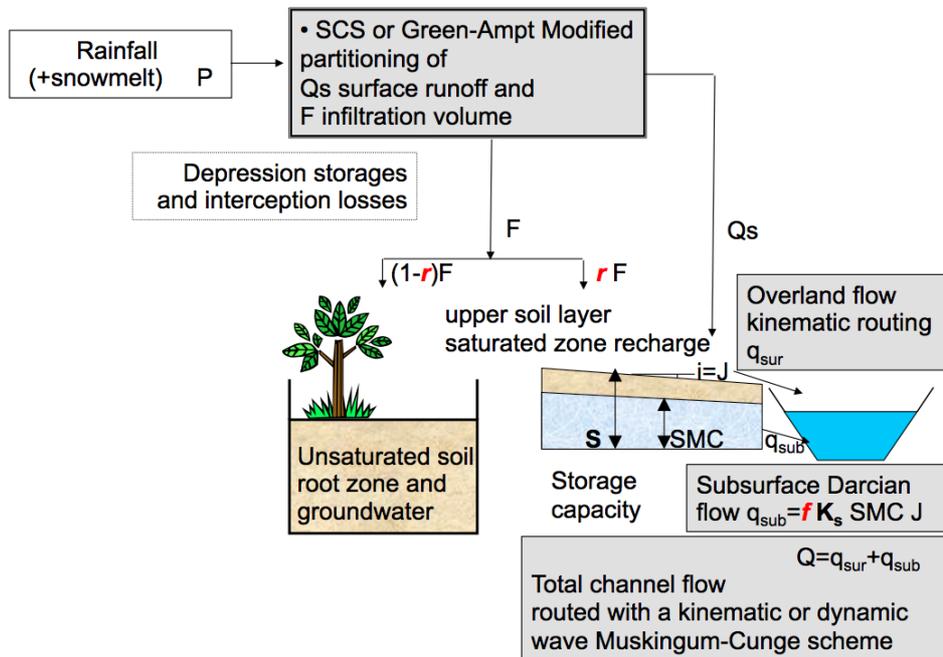


Figure 5. Scheme of the DIMOSHONG model. In evidence the four main components of the model: a) the rainfall partitioning scheme of rainfall, b) the overland flow, c) the subsurface Darcian interflow and d) the channel runoff routing.

5 CONCLUSIONS

In this first paper the meteorological and hydrological model's component of a flood forecasting systems for two basins in Vietnam was presented. The BOLAM-MOLOCH-DIMOSHONG model chain was designed with a spatial resolution of the meteorological model of 8 km and 4 km, respectively, for the Red and Ca rivers, taking into account their respective size. The hourly time resolution and 1 km spatial resolution of the hydrological model output is suitable for most applications, including warnings for reservoir operations and alert systems for the inhabited areas along the rivers.

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REFERENCES

- Buzzi, A., Fantini, M., Malguzzi, P. & Nerozzi, F. Validation of a limited area model in cases of Mediterranean cyclogenesis: Surface fields and precipitation scores, *Meteorol. Atmos. Phys.*, 1994, 53, 137–153.
- Castelletti, A., Pianosi, F., Quach, X. and Soncini-Sessa, R., Assessing water reservoirs management and development in Northern Vietnam, *Hydrol. Earth Syst. Sci.*, 2012, 16, 189–199.
- Drofa, O. V., and Malguzzi, P. Parameterisation of microphysical processes in a non-hydrostatic prediction model, *Proc. 14th International Conference on Clouds and Precipitation*, World Meteorological Organization, Bologna, Italy, 2004, 19–23 July.
- Hoang, T.T., Ranzi, R., Barontini, S., and Cat, V.M. Medium range rainfall and flood forecasting for reservoir system operation in the Ca river basin (Vietnam), *IAHR Asian-Pacific Division Congress, Korea*, 2012, 13 pp. (accepted).
- Malguzzi, P., Grossi, G., Buzzi, A., Ranzi, R. and Buizza, R.. The 1966 'century' flood in Italy: a meteorological and hydrological revisitation, *J. Geophys Res.*, 2006, 111, D24106, doi:10.1029/2006JD007111.
- Ngo, L. L., Madsen, H., and Rosbjerg, D.: Simulation and optimization modelling approach for operation of HoaBinh reservoir in Vietnam, *J. Hydrol.*, 2007, 269–281.
- Ngo L.A. Flood forecast in the Red river basin (China-Vietnam) using a hydro-meteorological modeling system. Ph.D Thesis, Politecnico di Milano, 2008, 170 pp.
- Ngo, L.A., Vu, M.C., Hoang, T.T., Buzzi, A., Drofa, O., Do, L.T., Barontini, S., & Ranzi, R. A hydrometeorological flood forecasting system for the reservoir control in the Red River, *Proc. of ICOLD-International Commission on Large Dams International Symposium "Dams & Sustainable Water Resources Development"* (on CD), Hanoi 23-25 May 2010, 11 pp.
- Ranzi, R., Bacchi, B. and Grossi G. Runoff measurements and hydrological modelling for the estimation of rainfall volumes in an alpine basin, *Quart. Journal Royal Meteorol. Soc.*, Vol. 129 Part B, n. 588, 2003, 653-672.
- Ranzi, R., Le, T.H. & Rulli, M.C. A RUSLE approach to model suspended sediment load in the Lo river (Vietnam): Effects of reservoirs and land use changes. *J. Hydrol.*, doi:10.1016/j.jhydrol.2011.12.009, 2012, Vol. 422-423, pp. 17-29.
- Vietnam Institute of Water Planning. The Ca River basin master plan. Ministry of Agriculture and Rural Development, 2004.