FLOOD FORECASTING IN THE UPPER RHONE RIVER FOR THE MANAGEMENT OF MULTIRESERVOIR SYSTEMS

Frédéric Jordan, Jean-Louis Boillat , Javier García Hernández, Anton J. Schleiss

Laboratory of Hydraulic Constructions, Ecole Polytechnique Fédérale Lausanne,
Station 18, CH-1015 Lausanne, Switzerland
E-mail : fred.jordan@e-dric.ch

Abstract: A semi-distributed hydrological model was developed for the upper Rhone River basin in Switzerland to provide 72 h lead time discharge forecasts with the aim to optimize a multireservoir system during floods. The model takes into account the hydraulic influence of the existing hydropower schemes as well as the different hydrological processes such as snow melt, glacier melt, soil infiltration and surface runoff.
The performance of the model is presented and correlated with the spatial distribution of the hydrological processes. Moreover, the assimilation of the meteorological forecasts provided from the MAP D-PHASE framework is presented and its performance for decision-making is assessed.
Special focus is put on the spatial and temporal scales of the meteorological and hydrological processes. The influence of the uncertainty of quantitative precipitation and temperature forecasts on the predicted discharges of basins with small to average surfaces up to several thousands km^2 is discussed.

Keywords: *Flood forecasting, meteorological forecasting, multireservoir system, decision-making tool*

1. GENERAL DESCRIPTION OF THE MINERVE PROJECT

The Upper Rhone River basin is located in the canton Wallis, in Switzerland. Its catchment area is characterized by high mountains with large glaciers, on a surface of 5521 km^2 and elevations varying from 400 to 4634 m a.s.l. Moreover, numerous hydropower schemes with large reservoirs are located in the catchment area, which influence strongly the hydrological regime of the system (Figure 1).

During the last two decades, the Upper Rhone River basin has been hit by three flood events causing important damages. In order to improve the flood safety for the local population and reduce the risk of damages, a flood forecasting system called MINERVE was developed. Its purpose is to predict floods three days in advance by taking advantage of the existing accumulation reservoirs to reduce the peak flows, thanks to preventive gate or turbine operations. Appropriate operations allow decreasing the peak discharges in the Rhone River and its main tributaries, thus reducing significantly the damages as well (Jordan et al., 2005a).

A semi-distributed hydrological model of the river basin was developed using the *Routing System II* software, developed by HydroCosmos and the Laboratory of Hydraulic Constructions of the Ecole Polytechnique Federale in Lausanne (Dubois, 2005). The object-oriented programming features allow the modelling of snow-melt, glacier melt, soil infiltration, run off as well as flood routing in rivers and hydropower schemes operations. The MINERVE model includes 239 sub-catchments divided into 500 m elevation bands, for a total of 1050 sub-catchments (Figure 1). The elevation bands are considered in order to accurately describe the temperature-driven processes such as snow and glacier melt. The input data of the 1050 sub-catchments are precipitation and temperature. For the calibration and validation of the model, only measured data were used, but for operational flood forecast, a new data assimilation procedure was developed, in order to allow the operational use of the flood forecasting system.

For the computation of flood prediction, the numerical meteorological forecasts provided by MeteoSwiss have to be assimilated. These are provided by MeteoSwiss every 12 hours from the aLMo model (Kaufman et al., 2003), with variables as precipitation and temperature. The lead time considered is 72 hours at an hourly time rate. Numerous other variables, such as snow cover, snowfall limit, relative humidity and wind velocity could be obtained by the meteorological model, but were not all considered in this work. The spatial resolution of the meteorological prediction is based on a 7 x 7 km^2 grid (Figure 1) and the vertical resolution is about 100 m. As presented in Figure 1, 513 grid points of the aLMo model are considered, which cover the whole Rhone River basin.

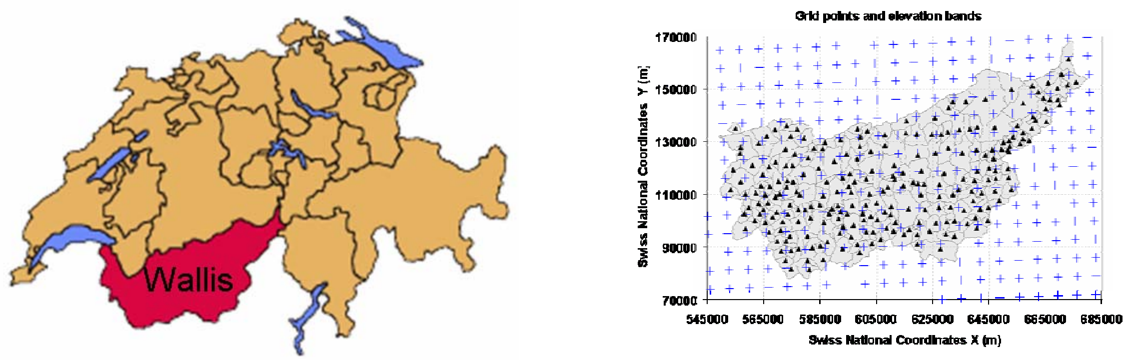

Figure 1: Left: Particular location of the Upper Rhone River basin (Wallis) in the southern part of Switzerland. Right: Upper Rhone River basin divided into 239 sub-catchments, with superimposed aLMo grid.

2. METEOROLOGICAL FORECASTING

2.1 Temperature

The temperature has to be predicted for every elevation band in each sub-catchment. The available temperature outputs from the aLMo model are given for every 513 grid points at 2 m and 30 m relative elevations above the DEM of aLMo; at fixed elevations and at fixed atmospheric pressure levels. So, three-dimensional analysis is required. Extrapolation methods based on a unique grid point and interpolation methods combining 4 grid points, all of them with constant (-0.0065 °C/m) or variable altimetric temperature gradient have been compared (García Hernández, 2006). Besides, temperature values at the grid points corresponding to elevations located under the digital elevation model (DEM) of aLMo are not valid and were eliminated.

In the selected method, the 4 nearest grid points are used and transformed as temperature estimation at the height of the elevation band using a linear regression or constant gradient with temperature at 2 m elevation, depending on the height of the snow cover calculated in the aLMo model.

2.2 Precipitation

Rainfall prediction from the aLMo model is provided at every 513 points directly at ground elevation (DEM of aLMo). Deterministic methods used for the assimilation of the predicted rainfall by every sub-catchment of the hydrological model have been analysed, assuming a constant altimetric gradient of the precipitation.

Four different methods using different numbers of grid points for the interpolation (5 to 13) were tested (García Hernández, 2006). The weight associated to each grid point depends on the relative distance between the grid point and the sub-catchment gravity center. The performances of the tested methods are quite similar. Anyway, method with 6 interpolated grid points, weighted in function of the inverse square distance was finally chosen according to its performance.

After the assimilation, in order to evaluate the uncertainties related to the precipitation forecasts, the predicted volumes over the entire Rhone River catchment area were analyzed. The precipitation intensities were averaged over 12 hours periods and compared to the measured rainfall volume over the same area. This evaluation was done for 23 forecasts during 4 flood events. This method does not take into account the spatial offsets of the rainfall fields, but provides an average value of the prediction error. The results indicate an increase of the bias and standard deviation with lead time.

As an example, Figure 2 illustrates the precipitation forecasts during the flood event of October 2000. The high variability of the forecasts during the high precipitation period (14^{th}-15^{th} of October) can clearly be seen. Nevertheless, the beginning and the end of the flood event was in general well predicted. Similar results were obtained for the three other studied flood periods.

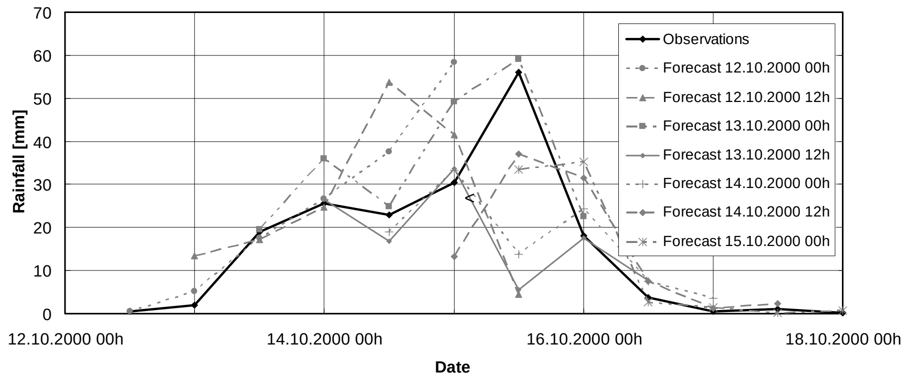

Figure 2: Mean predicted rainfall volumes over 12 hours periods on the Upper Rhone River catchment area for 7 different forecasts, comparison with mean observed volumes.

3. FLOOD FORECASTING

The results obtained with the predicted rainfalls for the flood forecasts at the outlet of the catchment area are in the following compared. The quality of the flood forecasts computed by the rainfall-runoff model is highly dependant on the rainfall and temperature predictions. The response time of 24 hours of the catchment area is shorter than the available 72 h lead time of a flood forecast, and errors in the rainfall predictions cannot be corrected by the assimilation of the discharge observations for periods longer than 12 hours (Jordan, 2007).

Figure 3 shows the predicted hydrographs at the outlet of the catchment area during the October 2000 flood event, obtained by assimilation of the meteorological forecasts. Over-estimation or under-estimation of the discharges depends of the forecast.

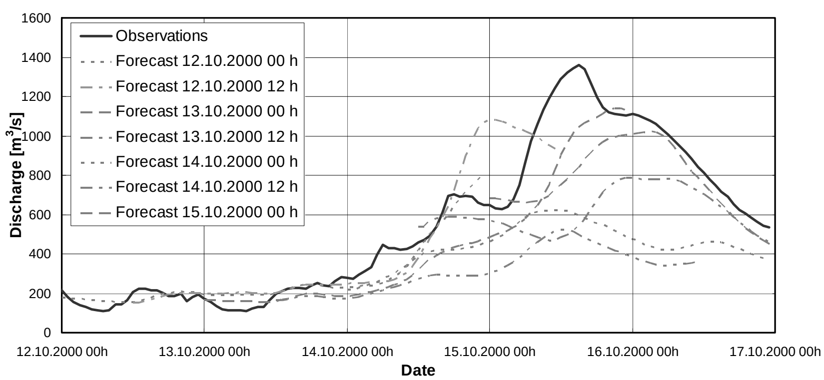

Figure 3: Right: Predicted and observed flood hydrographs at the Upper Rhone River catchment outlet for the October 2000 flood event.

After evaluation of the four analyzed flood events, no significant trend of over-estimation or under-estimation of the forecasts was obtained (García Hernández, 2006). For this reason, until now it is difficult to estimate the validity of a flood forecast by expert knowledge in this catchment area. However, associated to the 24 h response time of the catchment area, it allows a reliable 24 hours flood forecast in the catchment area. Besides, the performance of the model allows correctly representing all hydrological cycles, as well as the observed floods. Moreover, a new procedure for real-time data assimilation was developed in the model, in order to automatically adjust the initial conditions before starting a new hydrological forecast.

5. DECISION-MAKING OPTIMISATION TOOL

A new decision-making tool was developed to optimize the preventive operations of the existing hydropower plants with large reservoirs in order to limit the flood damages in the basin. This tool uses the hydrological forecast, especially the inflow forecasts in the reservoirs and the hydrographs at the numerous control points on the river network. It takes into account the mentioned data in order to provide an operational decision about any necessary preventive turbine or gate operations. It also allows the decision maker to have an idea on the cost of the decisions and of the non-decisions, as well as of the cost of an inappropriate decision due to an error in the flood forecast. The new algorithm was validated against full simulation and against another optimization evolutionary algorithm called MOO, developed in the LENI-EPFL. The decision-making tool is able to provide am excellent efficiency without excessive computation time, and to forward these results automatically into the simulation model for validation.

The operational performance of the flood prediction and management model was evaluated by simulation of two major flood events occurred in the Rhone river basin in September 1993 and October 2000 (Figure 4), as well as by a first operational use in September 2006. The obtained results indicate that if the decisions relative to the operations of the 10 major considered hydropower plants had been in accordance with the new decision tool, the decision would have been similar to a posteriori optimal solution. The application of the model to the Rhone River catchment area demonstrates the possibility to widely increase the protection effect due to the existing reservoirs. In fact, the observed reduction of the peak flow at the Rhone basin outlet was 12% in 1993 and 10% in 2000.

By using the new model, the reduction would have reached 26% in 1993 and 21% in 2000. In this case, important damages could have been avoided in the Rhone valley.

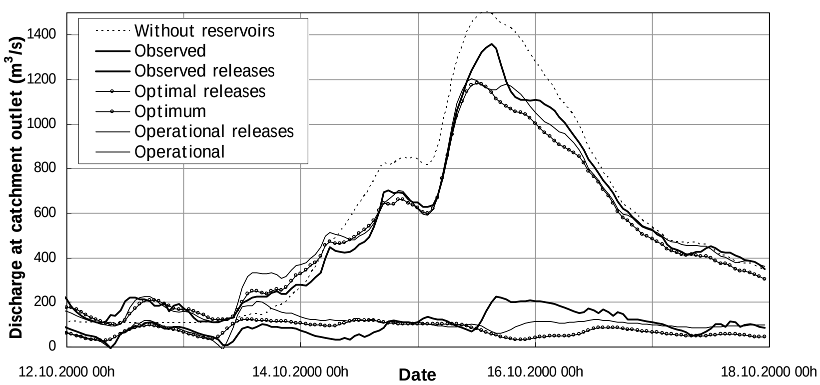

Figure 4: Flood hydrographs during the October 2000 event. The hydrographs without reservoirs, without preventive turbine operations and with optimized turbine operations are compared.

Although the system is now operational and convincing, it would be more profitable to explore the possibilities of dealing with uncertainty in the whole information path of the system. As a main goal, the use of probabilistic meteorological forecasts can also be of interest, since it could help the decision-maker to obtain a first evaluation of the uncertainty associated to a flood forecast and the objective risks.

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