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## **MINERVE, a tool for flood prediction and management of the Rhone river catchment area**

Frédéric Jordan, Jean-Louis Boillat, Jérôme Dubois, Anton Schleiss

During the past 15 years, the Valais region has been hit by three major flood events. The Rhone River and some of its tributaries upstream of Lake Geneva flooded and caused severe damages leading to human deaths. In order to predict and reduce the risk of such natural disasters, a numerical model is under development, called MINERVE, using a deterministic and physically oriented approach. This model describes the rainfall runoff transformation on the different subcatchments of the Rhone river, the flood routing in the river channels as well as through the different hydraulic schemes built in the catchment. It was used for understanding the effect of the numerous hydropower schemes and their storage reservoirs on the reduction of the peak discharge at different places in the catchment area. The numerical simulations showed the significant routing effect of the reservoirs on the flood peak and revealed an important potential for the optimization of flood management using appropriate operation rules.

MINERVE is presently improved to become a flood forecasting tool. At first, the model is spatially extended in order to cover the whole Rhone catchment area upstream of Lake Geneva, which represents a surface of 5500 km<sup>2</sup>. Secondly, the size of the subcatchments is reduced for a better modeling of the water diversion by intakes, the natural runoff and the snowmelt. Thirdly, a regionalisation study of the hydrological parameters is completed. Finally, the full routing dynamic equations are implemented as well as floodplains and fuse plugs along the river embankments.

These additional functions allow to improve the performance of the model through a calibration and validation procedure, based on the comparison with historical data. The model will then be used as a tool for flood forecasting and flood management over the entire hydraulic network of the catchment area. Receiving the precipitation, wind and temperature forecast every 12 hours at various time scales up to three days, the simulation tool will be coupled with an expert system. This has the purpose to detect the risk areas and propose operation strategies for the hydropower schemes management as well as for the flood zones.

In order to increase the confidence of the flood forecast, the model will be connected in real time with rainfall measurement and discharge gauging stations. These data will be used to periodically reinitialize the numerical simulations. The runs will be started as soon as a high rainfall warning is transmitted by the swiss weather forecast service MeteoSuisse. With such a tool, the existing potential for the reduction of flood peaks might be fully exploited with the aim to improve the safety of the population and to protect infrastructures and agricultural zones on the catchment area.

Keywords: Flood Modeling, Flood Prediction, Flood Management

## 1 Introduction

Located in the centre of the Alps, the Canton of Valais is an important touristic region of Switzerland. Taking profit of the large available amount of water issued from alpine glaciers and snowfields melting during spring and summer, the Valais region is also a major electricity producer of the country. However, like most of alpine regions, the Valais is often hit by disastrous flood events on the Rhone river and its main tributaries. Recent events are the flood of August 1987 which hit the upstream part of the Rhone valley (*OFEE/SHGN, 1991*) and the one of September 1993 which mainly gave rise to an overtopping of the Saltina tributary and the deposition of 250'000 m<sup>3</sup> of sediments in the city of Brig. The total estimated cost of this flood event exceeded 500 mio CHF (*CRSFA, 1993*). The last major disaster in the Rhone valley occurred in October 2000 and caused severe damages at numerous places. The Rhone river spilled over its embankments in central Valais and tributaries deposited a very large amount of sediments in several villages. Saturated soils were also source of disastrous landslides in the Saas valley and the Simplon region (*Grebner & al., 2000; FOWG, 2002*). Following these events, river training works were conducted in order to provide local solutions, such as increase of hydraulic capacity or creation of sediment reservoirs. Furthermore, the 3<sup>rd</sup> Rhone river flood protection project was initiated and allowed the development of a global flood mitigation concept for the Rhone valley (*Arborino, 2000*).

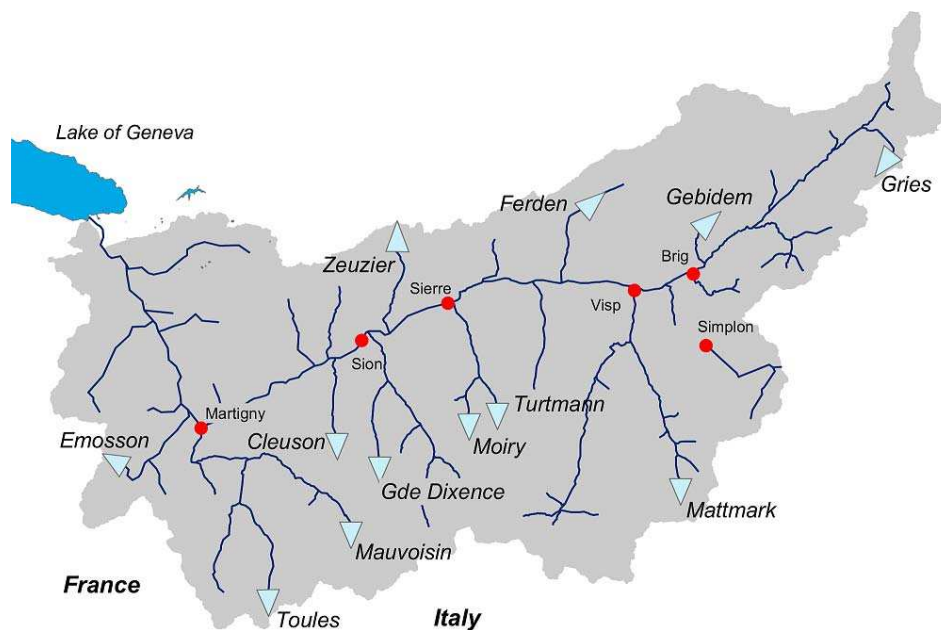
Beside technical measures, flood forecast and management is also able to provide durable solutions for the reduction of flood damages. In catchment areas equipped with numerous hydropower schemes and storage reservoirs, a major potential for peak discharge routing might exist (*Biedermann & al., 1996*). Moreover, the use of flood forecast can provide a powerful decision making tool for the management of flood alarms or people evacuation. In the best case, it should also be used for improving the management of storage reservoirs during flood events usually exclusively used for electricity production.

In detail, the aim of the MINERVE project is to provide such a decision making tool, using the weather forecast provided by the Swiss Weather Service MeteoSuisse, real-time measurements in discharge and rain gauging stations, and real-time operation data of the main hydropower schemes. The tool MINERVE will then compute a flood forecast and use it to generate solutions for the management of the hydropower storage reservoirs and the floodplains.

## 2 Preliminary analysis

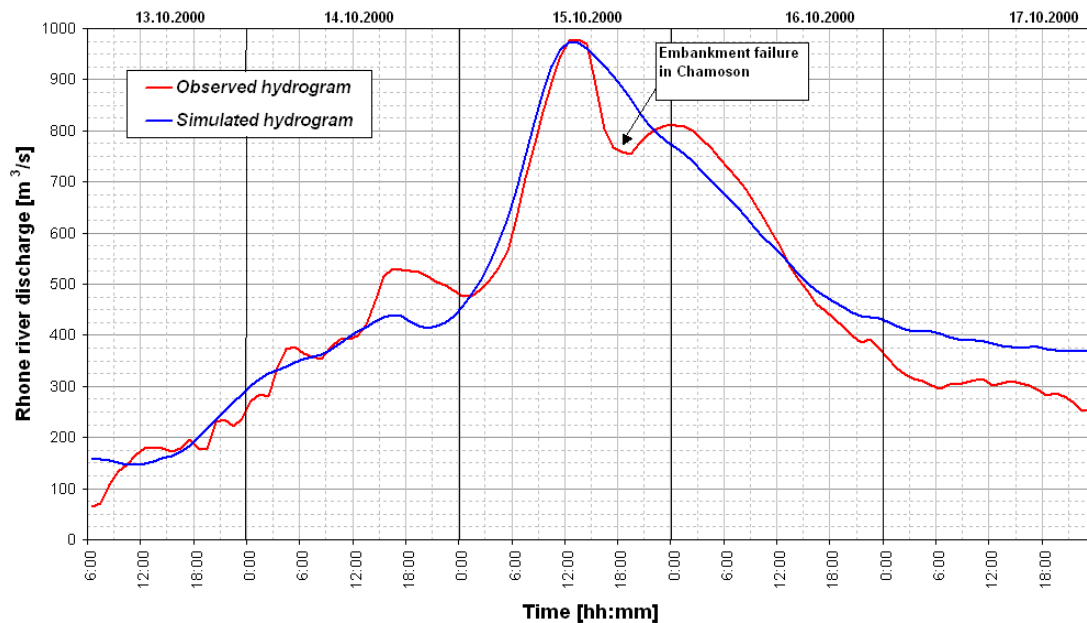
After the flood of September 1993, the need rose for original solutions in the flood management of the Rhone river during floods. A few years later, the Canton of Valais, in association with the Swiss Confederation (FOWG) supported the first part of the MINERVE project, with the aim to investigate the reduction potential of the flood peak discharge offered by the accumulation reservoirs in Valais (*Raboud & al., 2001; Boillat & al., 2002*).

In the Rhone valley upstream of Lake Geneva, numerous major hydropower schemes have been installed, with a total estimated storage volume of 1'203 Mio m<sup>3</sup> (Fig. 1). However, it is not evident to estimate the optimal contribution to the peak discharge reduction due to these reservoirs. A powerful numerical model containing a rainfall-runoff module as well as hydropower scheme operations is needed.



**Figure 1:** The Rhone catchment area upstream of Lake Geneva (5500 km<sup>2</sup>) with its hydrographic network and major storage powerplants with dams.

Using an appropriate numerical tool (*Dubois & al., 2000*), the three last flood events of 1987, 1993 and 2000 were simulated to calibrate and validate the model (Fig. 2). The observed rains were used as input, as well as the hydropower schemes operation data during these events (turbine, pump or water release discharges). The model was then run with the aim of highlighting the retention effect of the storage reservoirs for different initial filling rates.



**Figure 2:** Comparison between observed and simulated hydrograms in Martigny during the October 2000 flood event. The accidental embankment failure in Chamoson was not simulated.

The results showed the great importance of the peak discharge reduction effect due to the alpine reservoirs. As presented in Table 1, the peak discharges in several places along the Rhone river were reduced of about 10% to 20%, compared to the fictive situation without hydropower schemes. This effect is even more important when comparing tributary peak discharges such as the Vispa river upstream of Visp, where the peak discharge was reduced of almost 50%.

The observed operation of the alpine hydropower schemes reservoirs showed that its influence on flood control was very favourable even without special operation rules. However, an optimization of their use during floods should be studied, as well as a more systematical analysis of their influence for other meteorological situations.

**Table 1:** Comparison between observed (with reservoirs) and simulated (without retention effect of the reservoirs) discharges at different locations in the Rhone valley

		<i>Simulated flood event</i>		
		<i>1987</i>	<i>1993</i>	<i>2000</i>
<b>Brig</b>	<i>Natural simulated [m<sup>3</sup>/s]</i>	521	462	583
	<i>Observed [m<sup>3</sup>/s]</i>	495	460	560
	<i>Difference [m<sup>3</sup>/s]</i>	26	2	23
<b>Sion</b>	<i>Natural simulated [m<sup>3</sup>/s]</i>	1045	1054	1035
	<i>Observed [m<sup>3</sup>/s]</i>	775	830	910
	<i>Difference [m<sup>3</sup>/s]</i>	270	224	125
<b>Martigny</b>	<i>Natural simulated [m<sup>3</sup>/s]</i>	1029	1091	1080
	<i>Observed [m<sup>3</sup>/s]</i>	820	930	980
	<i>Difference [m<sup>3</sup>/s]</i>	209	161	100
<b>Visp</b>	<i>Natural simulated [m<sup>3</sup>/s]</i>	450	494	257
	<i>Observed [m<sup>3</sup>/s]</i>	278	330	196
	<i>Difference [m<sup>3</sup>/s]</i>	172	164	61

### 3 Flood forecast modeling

#### 3.1 Hydrological modeling

Modeling the 5500 km<sup>2</sup> catchment area of the Rhone valley upstream lake of Geneva is a challenging problem. The different meteorological behaviors of the subcatchments, their heterogeneous surface conditions, the large variation of elevations going from 400 to 4600 [m a.s.l.] and the presence of numerous hydropower schemes with water diversion and storage reservoirs required the development of a new conceptual hydrological model. Based on four basic modules, it is able to simulate the hydrological behavior of surfaces covered by glaciers as well as the effect of snow melt, soil infiltration and runoff. Flow routing in rivers is also modelled in the Rhone river and its major tributaries (Fig. 1).

Taking into account modeling limits such as the minimum surface of the subcatchment area and the presence of water intakes, the catchment area has been subdivided into 239 subcatchments having about 23 km<sup>2</sup> average surface. These basic modeling units are subdivided in elevation bands of 500 meters containing the four mentioned hydrological modules. The sum of the discharges

produced by each elevation band gives the discharge at the outlet of the subcatchment at every computation time step.

The actual model is running in continuous simulation mode. The definitive values of the parameters will be defined after calibration of numerous test basins and applied in a regionalized manner to the remaining subcatchments. The model state variables such as snowpack and soil-reservoir will be adjusted at the beginning of each computation run in order to fit the previous measured values.

### 3.2 Weather forecast

The weather forecast provided by MeteoSuisse is the first input of the simulation model. The meteorological model is able to offer, every 12 hours, forecasts at a maximum time period of 72 hours divided in 1 hours time steps. The values of the parameters are given in each node of a 7 by 7 km<sup>2</sup> horizontal raster and in elevation layers every 100 meters. The parameters required by the MINERVE model are rain intensities, equivalent snow intensities, air temperatures, snowfall limit and snow cover surfaces.

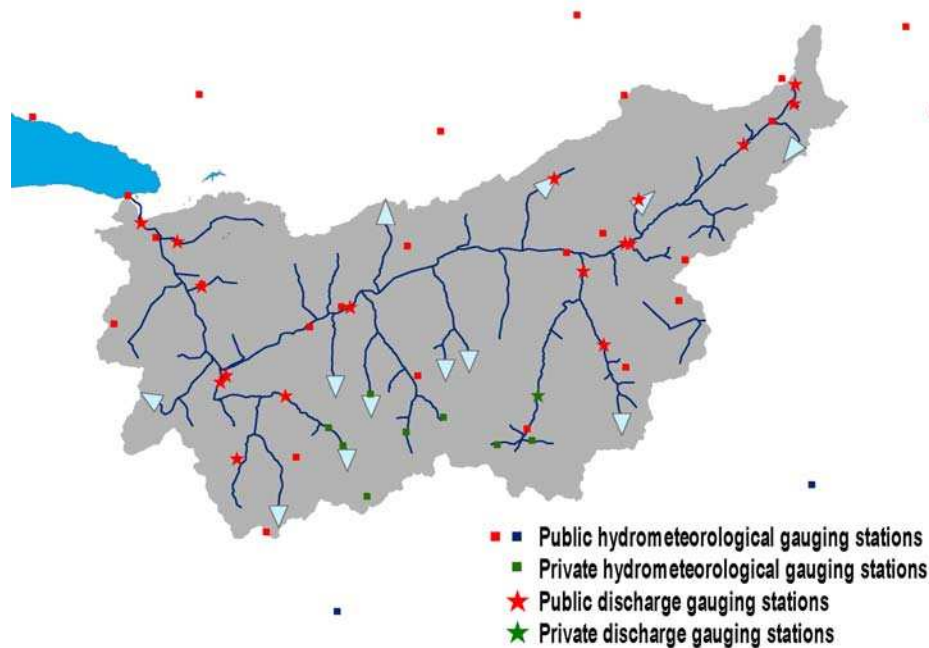
These values will then be converted in order to supply the hydrological models. In a first development stage, the spatial rainfall distribution provided by the meteorological model will be converted by simple approximation formulas in average values for the subcatchments.

### 3.3 Real-time data

The weather forecast cannot provide satisfactory results for such a large surface of the catchment, as it is the case for small to medium sized ones (*Koussis, 2003*). The MINERVE project has therefore to make use of a large number of rain and discharge gauging stations. The selected measurement network will be connected in real-time to the model server and used as second input of the hydrological model. Measured rain intensity and air temperature will be used as "historical" values and the discharges will serve as target data for the adjustment of the model state variables. Fig. 3 shows the existing real-time measurement stations network in the Rhone valley, operated by local communities, Swiss Confederation as well as by hydroelectric companies.

Of greatest interest are also another type of real-time operation data related to the hydropower schemes. These are the state variables of the hydropower schemes, such as reservoir water levels, openings of the water intakes, time sequences of turbines, pumps or water release operations. These data are

essential in order to adjust the water balance in the reservoirs and in the discharge gauging stations downstream.



**Figure 3:** Real-time measurement network on the Rhone catchment area upstream of Lake Geneva including public and private hydrometeorological and discharge gauging stations.

## 4 Expert system

### 4.1 Hydropower schemes modeling

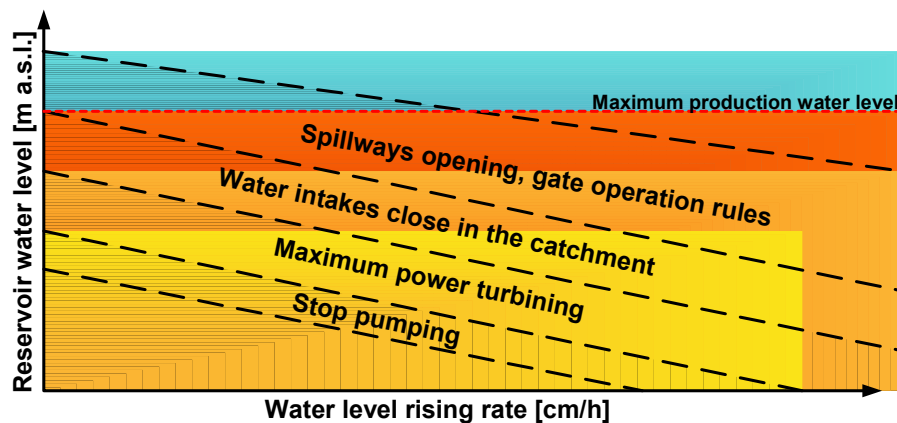
The reservoirs of hydropower schemes can be implemented in the hydrological model by their main hydraulic functions, which are water intake, storage and release discharge as a function of time and reservoir level. These particular behaviors can be managed without major approximations when choosing an adequate hydrological modeling scale. That means, no artificial structure should be located in the middle of a hydrological unit and each water intake, reservoir or water release should correspond to a node of the hydrological network. Each hydraulic structure (water intake, flood control gate, spillway, power station) is modelled separately, except when water intakes are located close to each other. In order to ensure an adequate adjustment of the hydrological model state variables (i.e. calibration of the model), a realistic modeling of the hydropower schemes is needed, due to the fact that relative small errors on the reservoir water levels may cause larger errors on the discharges in the downstream river



sections. This also constitutes a major reason for the real-time acquisition of the hydropower scheme operation data.

## 4.2 Emergency policies

The main purpose of the MINERVE project is to forecast the flood evolution during strong precipitations periods. The artificial alpine reservoirs can be filled during such flood events. For this reason, it is of greatest importance to take into account the real reservoir operation rules during emergency situations, which give relationships between water level, water level rising rate, operation of pumps, turbines as well as spillways (Fig. 4). The procedures are different for each hydropower scheme and represent rigid constraints for the expert system.



**Figure 4:** Typical emergency rules for a complex hydropower scheme

Despite the rigidity of such operation rules, there is still a need for reservoir management optimization during floods. As major events often occur during the autumn season, when the alpine reservoirs have normally filling rates higher than 95%, it is wise not to wait until the last moment, when emergency rules come into play, before managing preventive turbinning. The problem then lies on a true risk management analysis, including a strong economic component.

It may also be of greatest interest to encourage water diversion by pumping from a valley to another, in order to optimize the retention capacity of the reservoirs.

## 4.3 Optimization strategy

The optimization analysis reveals complex, due to the presence of numerous and varied hydropower schemes using water diversion, pumping of water between different subcatchment areas and multiple reservoirs, rigid operation rules during emergency situations and costs of preventive actions, all related to the

hydrometeorological uncertainties. Providing realistic analytic solutions will not be possible, and the use of evolutionary algorithms as optimization techniques will certainly require a huge computational time, caused by the numerous model variables.

A reasonable time consuming method for finding near-optimal solutions of reservoir and hydropower plant management rest on a case to case reasoning. At first, a systematic analysis of the behavior of every hydropower scheme during a flood event will be engaged. Then, a combined analysis focused on the interactions between the different hydropower schemes will be undertaken, with the aim to propose basic management strategies and near-optimal operation solutions. At third, some basic realistic hydrometeorological scenarios will be developed in order to adjust the proposed management strategies.

Finally, the predefined hydrometeorological scenarios will be allocated as a function of the hydrometeorological and flood forecasts, whereas objective functions for the optimization of the system will be defined. A predefined near-optimal watershed management strategy will so be proposed and optimized, taking into account uncertainties and real-time data for spillway openings and preventive reservoir emptying.

## **5 Outlook**

The focused multi-disciplinary problem challenges numerous difficulties. Appart from scientific considerations, technical limitations exist which are related to the real-time connection between different communication systems. Furthermore, maintenance of the database and of the control panel will require a continous support. Finally, the management solutions related to preventive water releases from storage reservoirs face political and economical objections caused by the strong competitive environment between private electricity producers. However, since the project MINERVE should create a win-win situation also for the energy producers, these oppositions can be overcome.

## **6 Acknowledgements**

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