DECISION SUPPORT SYSTEM FOR THE SAANE RIVER BASIN

FLOOD MANAGEMENT BASED ON FLOW FORECAST

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ABSTRACT

The Saane River basin located in the Pre-Alps of Switzerland was subjected to several important floods in the recent past. During these events, a peak reduction induced by the multireservoirs system located in the catchment area was observed. In case of new high water, the potential damages are still important. For this reason, it is necessary to optimize the operation of the hydropower schemes based on a flood forecast.

In order to develop such a system, an analysis of the operation of the dams during past flood events has been achieved. Based on rainfall-runoff simulation, several scenarios have been defined to quantify the protective effect of the reservoirs. Finally, an innovative Decision Support System has been set up in order to help decision makers during future events.

Keywords : active flood management, Decision Support System (DSS), flow forecast

INTRODUCTION

During the last decade, flood risk management became a major concern in Switzerland. This is partly due to the obligation to establish hazard maps. In the Canton Fribourg, the local authorities have decided to be proactive in order to reduce future potential damages. In collaboration with the local hydro-electricity producer Groupe E, they set up an active flood management system of the Saane River basin. In the past, flood retention effects by dams have already been observed and analysed in this region (LCH, 2006). The first aim of the present study is to define the potential of discharge reduction due to preventive turbine operations based on hydro-meteorological forecasts. This analysis is based on historical flood events. The second goal consists in a design of an operational Decision Support System (DSS).

The Saane River basin is located in the swiss Pre-Alps (Fig. 1). It rises in the Sanetsch pass region in Wallis at an elevation of 2250 m a.s.l. The river flows northward through the canton Bern and westward in the canton Vaud. Then, it crosses the whole canton Fribourg from south to north. Finally, the Saane River flows into the Aare River downstream of the Lake Wohlen (canton Bern). The main characteristics of the catchment are summarized in Tab. 1.

The Saane River basin is mountainous, which has several incidences on the hydrological cycle. First of all, the pluviometry of the region is high: 1500 mm/year on average, but more than 2000 mm/year on the upper part. Secondly, a non-negligible fraction of the precipitation falls in a solid form. This has a strong influence on the hydrological regime of the river. Indeed, the snowpack stores large amounts of water during winter which can cause snowmelt floods if the temperature rises above 0°C. The natural discharge is characterised by high water during spring and low flow during winter. Nevertheless, the different hydropower plants located along the river change considerably its daily

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and annual regime. The average yearly discharge is 41.4 m^3/s in Fribourg and 53.6 m^3/s at the river outlet.

In the lower part of the basin, the Saane River flows through the City of Fribourg (Fig. 1). This town of 35'000 inhabitants is an important economical, administrative, historical and educational centre. The major part of the city is located on a hill overhanging the Saane river and therefore is not exposed to flood risk. Nevertheless, several areas are built in the valley floor along the Saane River. In addition, the waste water treatment plant of the city and an industrial zone are located close to the watercourse. In case of flood event, the economical and environmental damages can be very high. For the city of Fribourg, the potential damages reach tens of millions Euros.

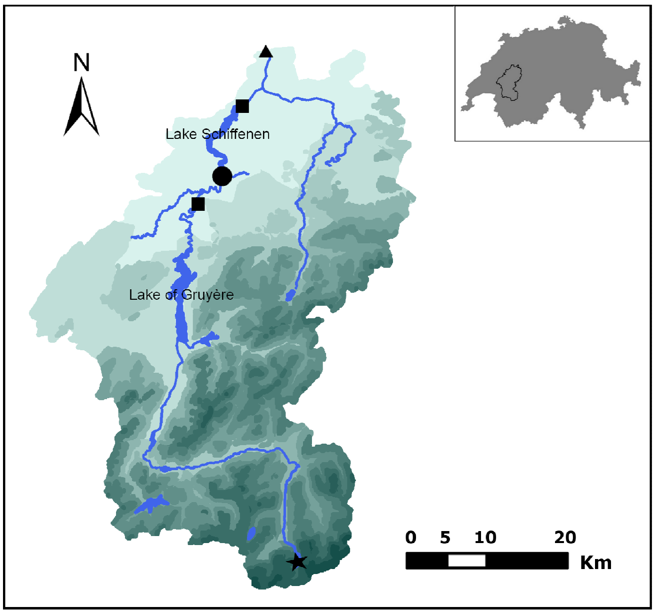

Fig. 1 The Saane River basin. The main hydropower plants are indicated by a square. The circle shows the city of Fribourg. The spring of the river is indicated by a star and the outlet by a triangle.

On a national scale, the Saane river is an important tributary of the Aare river (catchment area: 17'800 km^2, 43% of Switzerland). An optimal management of both rivers is required in order to prevent floods in the Swiss plateau located downstream. In particular, it is important to be able to avoid simultaneity of peak discharges at the confluence of the Aare and Saane Rivers.

Tab. 1 Main characteristics of the Saane River basin

Surface [km^2]	Glacier surface [%]	Mean elevation [m a.s.l.]	Min. elevation [m a.s.l.]	Max. elevation [m a.s.l.]
1861	0.21	1140	480	3242

Several hydropower plants are located along the stream (Fig. 1). The retention volumes and turbine capacities vary greatly from one scheme to the other. A sensitivity analysis of peak discharge and turbine capacity points out the relevant plants. In this study, we concentrate on the main artificial lakes: Gruyère and Schiffenen. The lake of Gruyère is located upstream of the city of Fribourg. This reservoir, with a volume 162 Mio m^3, is one of the largest in Switzerland. The turbine capacity is 75 m^3/s and the bottom outlet is limited at 100 m^3/s in this study. The Schiffenen lake (volume: 33 Mio m^3) is located in the lower part of the basin (downstream of Fribourg) and thus is used to regulate the discharge at the outlet of the watershed. The turbine capacity is 135 m^3/s. In case of emergency, the maximum operating flow could be used (186 m^3/s) instead of using bottom outlet.

HYDROLOGICAL AND HYDRAULIC MODEL

The hydrological model used in this study is a conceptual semi-distributed model named *RS 3.0*. It is based on the GSM-SOCONT concept (Schaefli et al. 2005) developed specifically for high mountainous catchment areas. The basic equations can be found in García Hernández et al. (2007).
First of all, the catchment has to be divided into sub-basins and then into 300 m elevation bands. This discretization enables to take into account the elevation-dependent processes. The general principle of the hydrological model is presented in Fig. 2. The first step of the computation consists in interpolating the meteorological variables (precipitation, temperature) as a function of the elevation and location of the elevation band. Afterwards, the different hydrological processes can be computed.

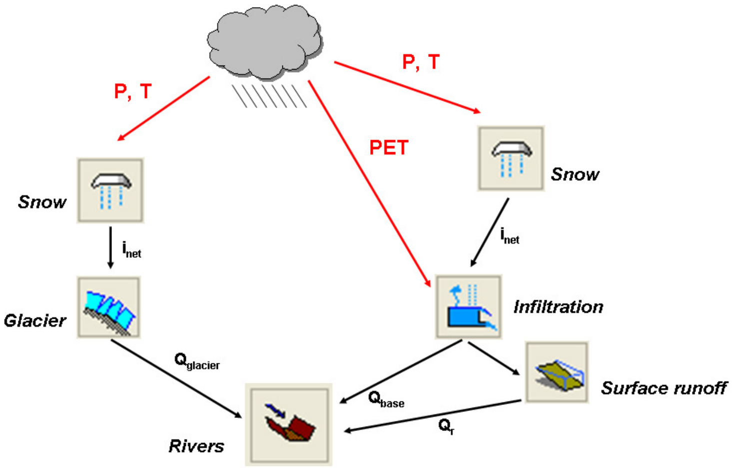

Fig. 2 Description of the hydrological modelling concept GSM-SOCONT (Schäfli et al., 2005). The input variables are the measured precipitation (P) and temperature (T). Based on this, the potential evapotranspiration (PET) is computed. On the left, the glacial part of the model is presented and on the right, the non-glacial part.

The model differentiates regions with and without glacier. When glaciers are present in the basin (Fig. 2, left part), the model is composed of a snow cover on top of the glacier. The snow model computes the evolution of the snowpack, its water content and the melt with the help of a degree-day equation. As long as the glacier is snow-covered, the ice is protected and will not melt. When the glacier is snow free, it begins to melt according to a degree-day model. Then, the water is transferred into a series of linear sub-glacial reservoirs. The model is also able to compute the global mass balance of the glacier and its long term evolution.
When the watershed is free of glacier (Fig. 2, right part), the model is slightly more complicated. The snow model is the same as before and computes the evolution of the snowpack. The melt water is then transferred to the soil. When there is no more snow on the ground, the precipitation is directly transferred to a non-linear soil infiltration model. This model is based on the GR3 equations and has been adapted for specific applications. The evapotranspiration and infiltration depend on the water content of the soil. The base discharge is computed by a series of reservoirs and varies principally with the soil saturation. The surface runoff is computed with the SWMM model, which solves the kinematic wave equation on an inclined plane. The main parameter of this model is the surface roughness.
Finally, the total discharge coming from glacierized and unglacierized bands is routed into a river channel.
The main strength of *RS 3.0* is to integrate easily hydraulic structures such as reservoir, turbine, spillway, bottom outlet or water intake in the simulation. In order to automate the turbine and bottom outlet operations, the company **e**-dric.ch has developed a specific algorithm. The general principle of this tool is to optimise preventive operations (turbine or bottom outlet) in order not to exceed a critical discharge downstream (Fig. 3). The operator defines a time horizon in the future (named prediction time) and threshold values (critical discharge, max. volume, etc.). Depending on the free volume in the reservoir and the forecasted inflow, the algorithm determines the best solution: do nothing,

operate the turbine or release water through the bottom outlet. Moreover, the model takes into account the electricity market price in order to turbine during periods of high demand. The aim is to maximise the economical income and avoid losing water.

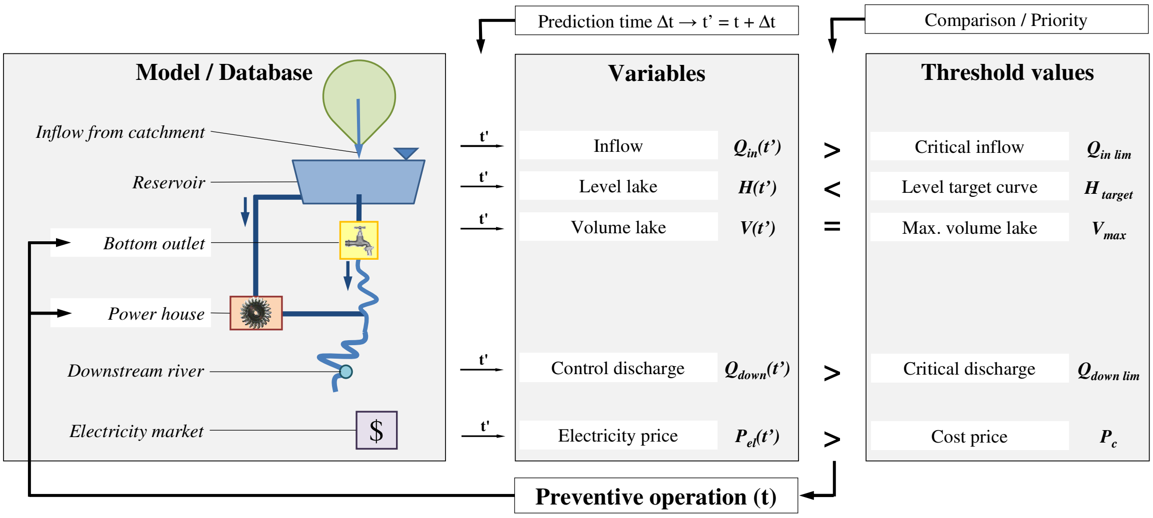

Fig. 3 Preventive operations optimisation process. Figure by courtesy of Martin Bieri.

The *RS 3.0* model has been applied successfully for several years in Switzerland (Jordan, 2007 and Jordan et al., 2010). Moreover, it is used operationally by the Groupe E as an inflow forecasting system since 2007. Consequently, the model has already been calibrated and validated in the Saane River basin. In this study, the operational calibration has been slightly modified in order to reproduce in detail the historical flood events.

DATA SOURCES

Hydrological modeling requires several data sets either as input data or as control data. The meteorological data come from different measuring networks. The Federal Office of Meteorology and Climatology (MeteoSwiss) has 7 automatic weather stations located in the Saane River basin and the surroundings. These stations measure the temperature and the precipitation at a 10 minutes time step. In addition, daily precipitation is also collected at 29 stations. These data are then disaggregated to hourly time step with the nearest stations. The Groupe E operates six weather stations in the catchment that measure temperature and/or precipitation at a 15 minutes time step.

The Federal Office of Environment (BAFU) has several gauging stations in the Saane River basin. The most relevant ones are located in Fribourg and Laupen (close to the basin outlet). These two measuring stations are used as reference to quantify the peak discharge reduction.

The Groupe E provides us the general characteristics, the rules of operation and the historical data of the different hydropower schemes. Finally, the electricity prices used in the optimisation process come from the European Energy Exchange (EEX).

HISTORICAL EVENTS AND SCENARIOS

The choice of historical events is not straightforward. The availability of meteorological and hydrological data is often a limiting factor. Moreover, initial reservoir levels and turbine operations are not always known precisely. Finally, two historical flood events have been chosen: August 2005 and August 2007. The return periods of these two events are 60 years and 30 years respectively and can be considered as the largest floods since the dams' construction (1944-1964). For each event, the following scenarios are computed.

The first scenario named *Reference* is supposed to reproduce the reservoir management observed during these events. No preventive operation is carried out and during the flood peak, the motto is "Business as usual". The turbine operations are optimised according to security rules and electricity prices but regardless of the downstream discharge. This scenario is compared with measured discharge in Fribourg and Laupen to validate the model. The model performances are globally very good. The main indicators are presented in Tab. 2.

Tab. 2 Performance indicators of the model in Fribourg and Laupen. The first one is the Nash–Sutcliffe model efficiency coefficient and the second one is the volume ratio between the simulated and measured discharge.

	August 2005		**August 2007**	
	Fribourg	Laupen	Fribourg	Laupen
Nash–Sutcliffe coefficient	0.81	0.84	0.65	0.78
$V_{simulated}/V_{measured}$	1.17	1.17	0.89	0.95

In the second scenario, all hydraulic structures are removed from the model. This scenario represents a hypothetical natural state of the river. By comparing it to the *Reference* scenario, one can determine the flow attenuation induced by dams. Indeed, the reservoirs will retain a non-negligible volume of water even if no preventive operation is done.

Finally, the third scenario considers preventive operations. For a given time horizon (Δt), we assume that the reservoir inflow is forecasted correctly. Consequently, the model will optimise the turbine and bottom outlet operations in order not to exceed a given discharge downstream. In addition, the algorithm will minimize the overflow and then, maximize the electricity production. The aim is to have filled dams at the end of the event. The general principle of reservoir management is presented in Fig. 4.

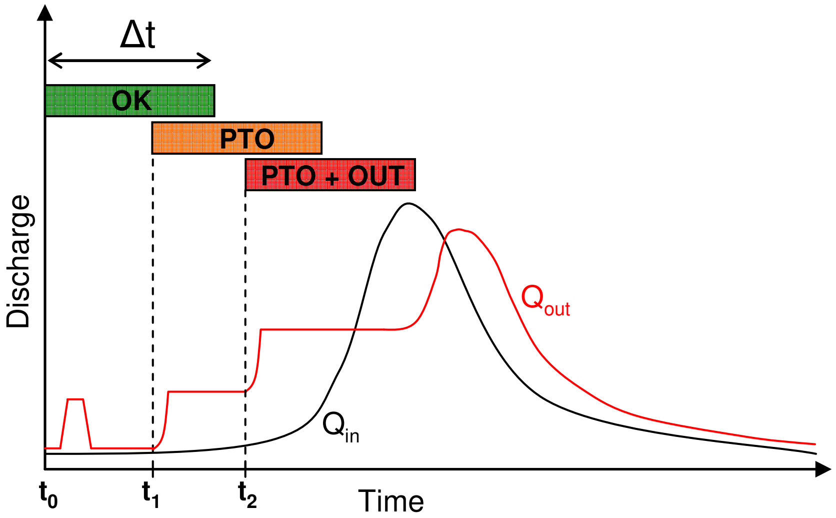

Fig. 4 Principle of reservoir management. OK is the normal production programme, PTO means preventive turbine operation and OUT is for bottom outlet. The curves represent the inflow (Q_{in}) and outflow (Q_{out}) of the reservoir.

In t_0, the situation is normal: the forecasted inflow is low and the free volume is enough. The normal production programme can be achieved. In t_1, the inflow becomes more important and if nothing is done, the lake will overflow. One decides to turbine more than programmed to lower the lake level. In t_2, the situation becomes critical: the forecasted inflow is very important. A water release by the bottom outlet is necessary. Finally, the downstream peak discharge (Q_{out}) is shifted in time and reduced in amplitude in comparison with the inflow. In this study, the situation is re-evaluated every hour; this enables a very precise flood management.

In this study, we consider a perfect forecast. In reality, the flow forecast is based on weather forecast. Consequently, the uncertainties are non-negligible and are limiting in the choice of the prediction time. From experience, it is known that flow forecast is reliable 36h in advance approximately. For this reason, the following prediction times are chosen for the turbine operations:

- 12h
- 24h
- 36h

In case of a false alarm, the economical loss induced by a water release through the bottom outlet is very high. It amounts to tens of thousands Euros per day. That is why the bottom outlet is only used as an emergency solution when the discharge is already increasing in the river. Consequently, the prediction time for the use of the bottom outlet is limited to 12h. In addition, the bottom outlet of the Schiffenen dam is not used because the turbine capacity is largely enough.

RESULTS AND DISCUSSION

The re-simulation of historical flood events is presented in Fig. 5 and Fig. 6. The comparison of different scenarios shows an important potential of discharge reduction.

In August 2005, the difference between the *Reference* scenario and the one without hydro-power plants is small. The peak flow is shifted in time but the amplitude is almost similar. With preventive operations, the flow attenuation is between 60 m^3/s (~9%) and 100 m^3/s (~16%) in Fribourg. The protective effect is much more important in Laupen: between 70 m^3/s (~8%) and 170 m^3/s (~19%). It is interesting to see that the scenario PTO 12h is also effective. This means that the decision can be taken relatively close to the flood peak. Thus, the uncertainties are smaller and the economical risk is more supportable.

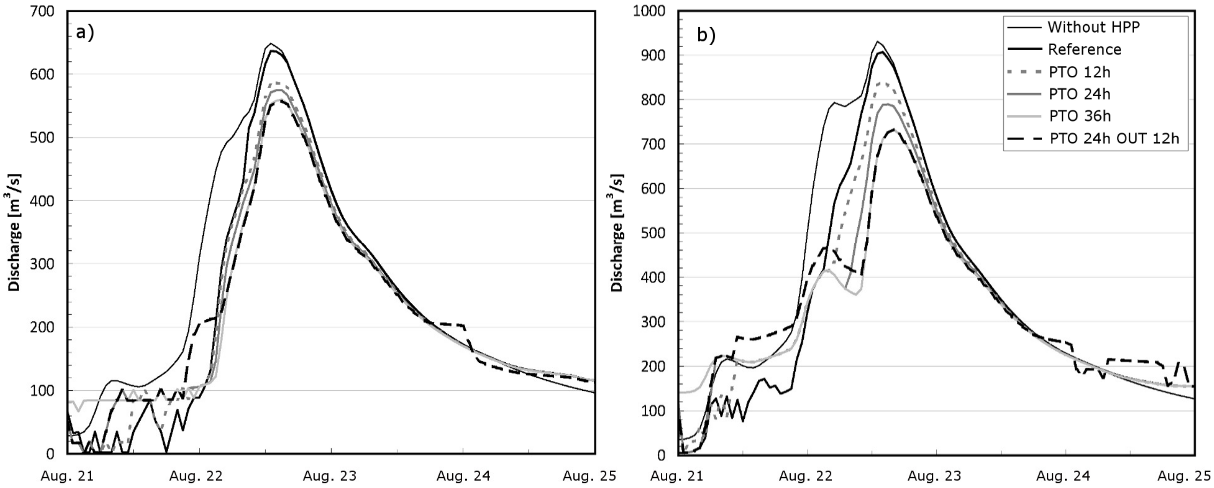

Fig. 5 Hydrograph of the Saane River in a) Fribourg and b) Laupen in August 2005. Flood peak reduction due to preventive turbine (PTO) and bottom outlet (OUT) operations for different lead time 12h, 24h, 36h are compared to reference case (Reference) and situation without hydro power plant (Without HPP)

Knowing that the river capacity is around 650 m^3/s in Fribourg, the preventive operations enable to avoid an overflow. In term of damages, the cost is much smaller if the capacity of the river is not exceeded. Moreover, it is interesting to know that the discharge in Laupen can be strongly reduced in case of critical situation in the Aare River basin.

In August 2007, the shape of the hydrograph is different: the flood occurs with a double peak. The preventive operations reduce strongly the first peak but are less effective on the second one. This effect is more visible in Fribourg than in Laupen. When the second peak arrives, the dams are almost full and the security rules are triggered. Consequently, the spillways are activated and the retention effect is limited. This also explains the difference between the *Reference* and the hydrograph without hydropower plants.

In Fribourg, the peak reduction ranges between 50 m^3/s (~8%) and 75 m^3/s (~13%) depending on the scenario. In Laupen, the flow attenuation is encompassed between 75 m^3/s (~9%) and 100 m^3/s (~12%).

In case of larger flood events, a peak discharge reduction is also visible. Nevertheless, that will depend greatly on the initial level of the different reservoirs. In these extreme cases, the key element is not necessarily the peak discharge but the total volume of the flood.

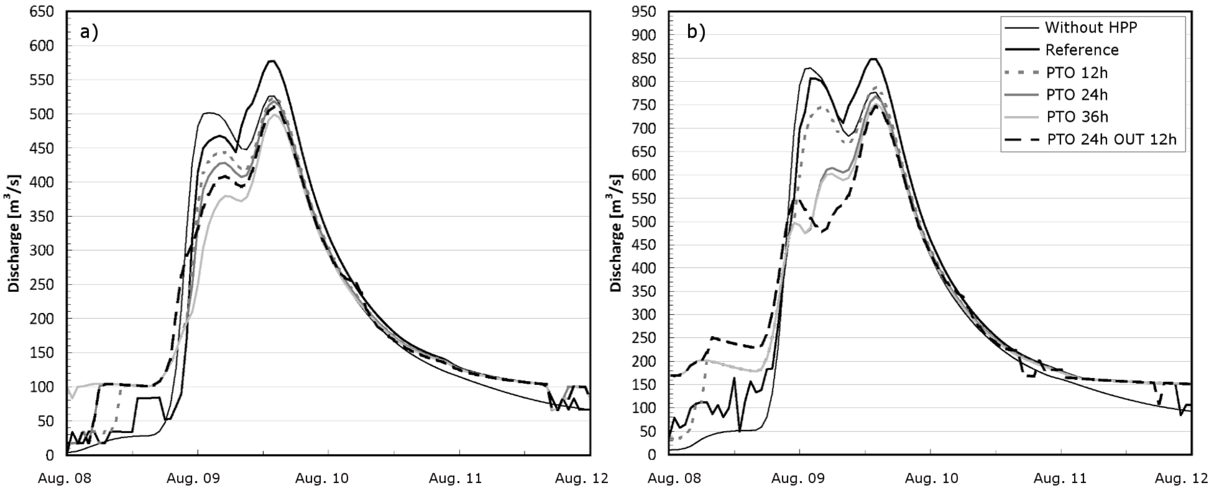

Fig. 6 Hydrograph of the Saane River in a) Fribourg and b) Laupen in August 2007. Flood peak reduction due to preventive turbine (PTO) and bottom outlet (OUT) operations for different lead time 12h, 24h, 36h are compared to reference case (Reference) and situation without hydro power plant (Without HPP)

For the electricity producer, preventive operations enable to reduce significantly the water overflow during the event. Depending on the scenario, the water loss can be reduced by 10% to 30%. The additional production reaches more than one thousand of megawatt-hour if the preventive operations are carried out 12h in advance. Therefore, the capital gain is non-negligible for the producer.

Based on previous results, an operational Decision Support System (DSS) has been set up. This tool is available on the web and is accessible to authorities and electricity producer.

Basically, the DSS contains two different parts. The first one is a map interface of the Saane River basin (Fig. 7) with the different hydrological and hydraulic elements. The user can click on these objects and quickly access information. The web technology is based on the Google Maps Application Programming Interface (API).

The available information on the website are measured and forecasted discharges, reservoir level evolution (in the past and in the future) and optimal preventive operations in order to minimize the downstream peak. The hydrological forecasts are based on the global ECMWF model, the regional COSMO2 and COSMO7 model.

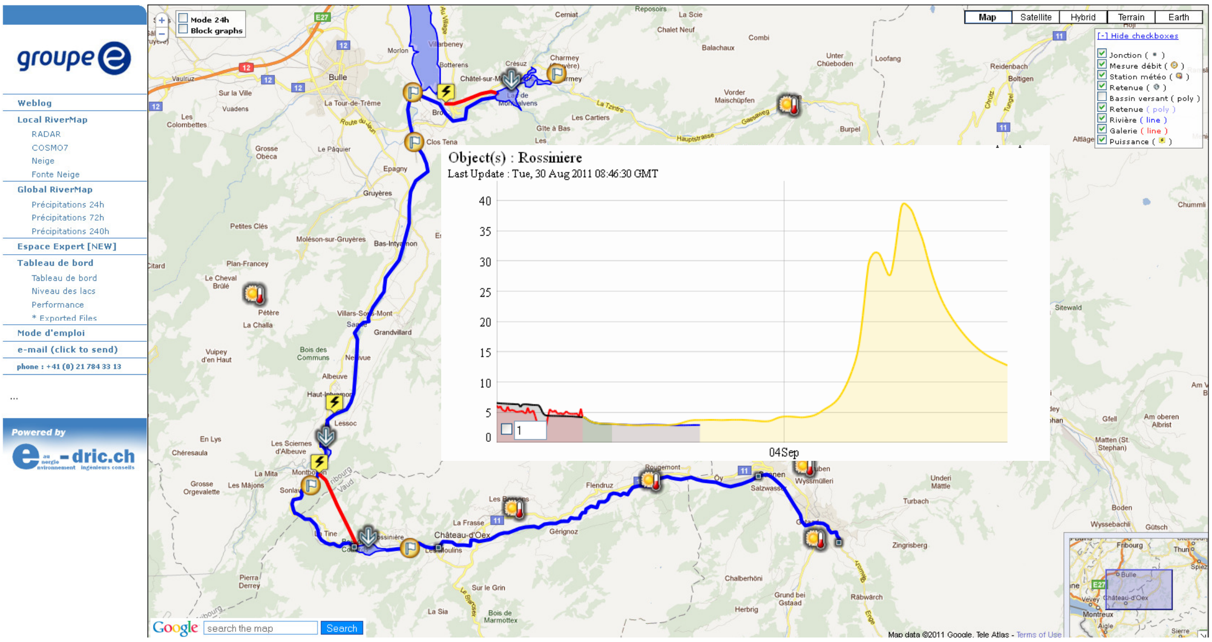

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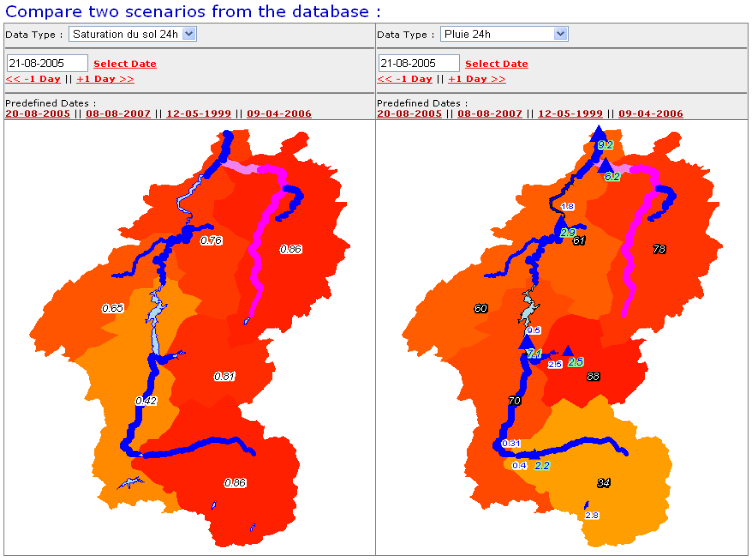
Fig. 7 Web interface of the Decision Support System.

The second unit of the DSS is a GIS database named *Expert Area* (see Fig. 8). The catchment is divided into six large zones that are coherent from a geographical and hydrological point of view. These entities enable to synthesize the hydro-meteorological information and give a global vision of the basin. Based on the simulation, the following maps are computed:

- Total precipitation for 24 hours and 48 hours
- Snow cover and snow melt
- Net rainfall
- Soil saturation
- Air temperature (altitude of the 0°C isotherm)
- River discharge and free volume in the reservoirs

The aim of these maps is really to highlight relevant hydro-meteorological processes leading to flood events. Based on these maps, the decision-makers must be able to understand which processes are critical: Is it a snowmelt flood? What is the spatial extent of precipitation? What is the initial state of the watershed (in term of soil saturation or snow cover)?



Compare two scenarios from the database :

Data Type : Saturation du sol 24h

21-08-2005 Select Date

<< -1 Day || +1 Day >>

Predefined Dates :
20-08-2005 || 08-08-2007 || 12-05-1999 || 09-04-2006

Data Type : Pluie 24h

21-08-2005 Select Date

<< -1 Day || +1 Day >>

Predefined Dates :
20-08-2005 || 08-08-2007 || 12-05-1999 || 09-04-2006

Fig. 8 User interface of the *Expert Area* in the DSS. Map of soil saturation [0-1] (on the left) and daily precipitation [in mm] (on the right) in August 2005.

The maps are computed in real-time for the recent past and the near future (based on hydrological forecast). Moreover, these maps are updated every hour. Thereby, the decision-makers have up-to-date information. When a new weather forecast is available or if the meteorological or hydrological conditions change suddenly, the preventive operations can be adapted or stopped very rapidly.

The database is incremented permanently since November 2010. Moreover, historical events have also been integrated since 2005. Therefore, it becomes possible to compare different situations and see the similarities. An automatic algorithm is currently developed by **e**-dric.ch to find the maximum likelihood between the current situation and similar events in the past.

CONCLUSION

An important peak reduction can be achieved by preventive turbine operations of the dams located in the Saane river catchment. This is true even if the decision is taken late (12h before the maximum discharge). The study also shows a win-win situation between the different partners. On one side, the local authorities reduce the potential flood damages. On the other side, the electricity producer maximizes the electricity production.

This study points out that an active flood management system is necessary. Therefore, an innovative DSS has been set up to provide relevant information for decision making The DSS is now operational and a practical use is currently experienced, which will probably lead to future evolutions of this system.

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