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Integrated representation of hydropower facilities in an operational flood warning system for a mountainous watershed

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Abstract. An integrated flood forecasting system adapted to mountain basins is under construction at the flood forecasting service of the French Northern Alps (SPCAN), whose jurisdiction area covers the whole Isère River basin (12000km²). Most parts of this area are harnessed for hydropower production, thus modifying flows at all the main sections of the stream network. A semi-distributed conceptual modeling approach was chosen for predicting warning levels at daily time step. Before giving results on the strategic warning point of Montmélian, simulations on two representative sub-basins of about 1000 km² are detailed. The first sub-basin includes the large Sautet dam, on the Drac River. The second, on the Isère River, includes the large dam of Tignes and is characterized by multiple diversions. The influence of hydroelectric facilities was analyzed for reconstituting natural flows. Then, a two-steps modeling strategy was deployed: firstly, natural reconstituted flows were simulated; next, the effect of hydroelectric works was introduced, considering the operating status of the main reservoirs and of the water intakes, the latter being aggregated together as a unique equivalent device. While keeping a reasonable level of model complexity, the developed tool provides accurate simulations of observed flood events and is planned to be further used in real-time.

1 Introduction

The operational flood forecasting service of the French Northern Alps (named SPCAN) is joined to the regional Environment Agency (DREAL) Auvergne-RhôneAlpes and as a part of the national Vigicrues network is currently developing an integrated flood forecasting system for its mountain area of jurisdiction (see Figure 1). The application of such a forecasting system is focused on the Isère River basin, whose area is of about 12 000 km². As other Alpine basins, this is intensively harnessed for hydropower [1,2,3]. A number of hydraulic devices operated by Electricité de France (EDF) are listed on the zone of interest: 132 dams, 120 hydropower plants, about 400 water intakes and many km of penstocks, all contributing to the gross installed hydropower capacity of 7.6 GW in the French Alps (total of 22 GW in France). Indeed, the flow regime of the whole Isère River system is strongly influenced: snowmelt and rain induced runoff is stored in large reservoirs during springtime and summertime, then released in wintertime following hydropower needs. One can also observe water transfers to and from reservoirs located in neighbor valleys or basins (e.g. Figure 2).

It is worth noting that regulation of hydraulic devices modify not only the hydrological regime, but also any single hydrograph, even during flood events [4,5,6]. It is therefore crucial to take hydraulic operations into account within the framework of flood forecasting. Another peculiarity than one needs to have in mind is that in the zone of interest there is no specific objective for large dam operators concerning downstream flood mitigation, contrary to what is practiced in other countries such as Switzerland [5,6]. Indeed, in parallel to their duty of optimization of energy production, the two main objectives of EDF during flood events are (i) ensuring the safety of the installation while (ii) not aggravating flood hydrographs immediately downstream. Therefore, during a given flood event, the following operating mode is usually observed for large reservoir dams: the water level is raised to ensure the spillways loading, then these are opened so that the outflow equals the inflow, making the dam as 'transparent'. Spillways are in general dimensioned to be able to evacuate 1000 to 10000-year floods according to the type of dam.

Within this specific context, SPCAN is in charge of providing two types of information at different strategic sections of the stream network: (i) every day, an estimation of the risk level for flood occurring over the next 24 hours and (ii) during a flood event, a deterministic forecasting of the expected peak flow in the coming hours. Flood risk is associated to warning levels, which are defined by different colors (green, yellow, orange and red), relative to different flow threshold exceedances and gradually moving from no particular risk (green) to a major risk (red). As an example, Table 1 shows the thresholds for the stream gauge of

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Montmélian, on the Isère River, whose flows allow to anticipate of a few hours the ones at Grenoble (the most important target section for forecasts in terms of vulnerability).

Threshold	**Flow** [m^3/s]	**Return period** [years]
1: green to yellow	400-450	2
2: yellow to orange	800-900	10
3: orange to red	1100-1200	30

Table 1: Warning levels and their associated approximate return periods for the stream gauge of Montmélian.

To estimate the threshold exceedances and thus the corresponding warning levels, SPCAN relied up to now on statistical abacus, based on flow observations over the last 24 hours and precipitation forecasts for the next 24 hours. This approach doesn't allow obtaining robust results, nor consider the effects of hydropower facilities operations on flows. For enhancing the performances, an integrated hydro-meteorological system, taking account for hydraulic operations, is under development.

An important point in such a forecasting system is how the hydraulic devices are represented within the hydrological model. Several studies have been proposed in the literature, either through lumped [7], semi-distributed [6,8] or fully distributed [3,4] approaches. Whatever the chosen architecture was, all showed significant improvements on flow simulations at the basin outlet when hydraulic operations were considered. For warning purposes, the developed hydro-meteorological system is run by SPCAN at daily time step and allows issuing a bulletin valid for the next 24 hours. At this time step, a semi-distributed architecture has proved to be able to simulate hydropower facilities effects as accurately as a fully distributed one. It was then chosen for its flexibility, as it allows forecasts even if a part of the information about some hydraulic devices is missing. Furthermore, the operating status of the principal dams (and thus their outflow) is simulated on the basis of statistically-derived formulations, function of the reservoir levels and the observed inflows. To show the relevance of the previous choices, detailed analysis of simulations obtained on two representative sub-basins of the whole study area are given: the Drac River basin at the Sautet dam and the Isère River basin at Moûtiers (see Figures 1 and 2).

Section 2 describes the two case study basins, as well as their respective networks of hydraulic devices. Available data for hydrological modeling are also presented. In section 3, the hydrological model and the modeling strategy are presented. Section 4 summarizes and discusses simulation results. Finally, section 5 gives conclusions and perspectives stemming from this work.

2 Study area and available datasets

2.1 Study area

The area considered by SPCAN is the whole Isère River basin (12 000 km²), located in French Northern Alps (see Figure 1). The Isère River successively flows across the French Alpine departments of Savoie, Isère, Drôme and Hautes-Alpes for reaching a total length of 286 km, before flowing into the Rhône River. The mean annual flow at the confluence is 330 m^3/s. Two main tributaries intersect the left bank of the Isère River: from North to South, the Arc River and the Drac River. The Isère River and its tributaries have all a snow and rain dominated regime. The basin is equipped with several big reservoirs and many hydropower plants (HPP) of different types: high, mean, low head and pumping hydropower stations. The hydroelectric production is operated thanks to a complex hydraulic network which transfers and diverts water through artificial galleries and channels towards plants, before to release it back to the stream. The most important devices in terms of hydraulic capacity or reservoir volume are plotted in Figure 1.

For the present study purposes, the whole Isère River basin and two sub-basins will be considered: the Drac River basin at the Sautet dam and the Isère River basin at Moûtiers.

2.1.1 Basin of the Drac River at the Sautet dam

As shown in Figure 2a, the Drac River starts in Southeastern zone of the basin. The considered outlet is taken downstream from the large dam of Le Sautet. This study basin is boarded by high relief, except in its southern part, which makes it at the same time confined but also responsive to storms coming from the Mediterranean Sea. Its surface is of 986 km², with a median elevation of 1740m (min 765m and max 3669m). The average precipitation amount is of 1250 mm/year (40% of which is snowfall). Soil cover is predominantly sandy-loam with sporadic clay. Approximately 1.2% of the surface area is covered by glaciers and 22% by forests.

Floods are typically associated with storm patterns originating from the Mediterranean Sea. The 8th of October 1993 and the 29th of May 2008 events are typical major floods associated to such a southern circulation. These two events generated 50-year flood inflows into the dam (mean daily flow peaks of 340 and 360 m^3/s, respectively). In both cases, the total flood volume was estimated to about 31 Mm^3, which is equivalent to 30% of the Sautet reservoir capacity (Effective volume of 95 Mm^3).

The Drac River basin was chosen as it allows testing the statistical representation of its reservoir operating procedure, which significantly impacts downstream flows. The Sautet hydraulic system characteristics are summarized in Table 2. In a nutshell, water released by the Sautet dam is directly slogged by the Sautet hydropower plant which has a flow capacity of 100 m^3/s. The release of water stored by the dam reservoir is made by a spillway of total capacity of 1395 m^3/s.

2.1.2 Basin of the Isère River at Moûtiers

The second considered sub-basin, presented in Figure 2b, is the Isère River basin at Moûtiers.

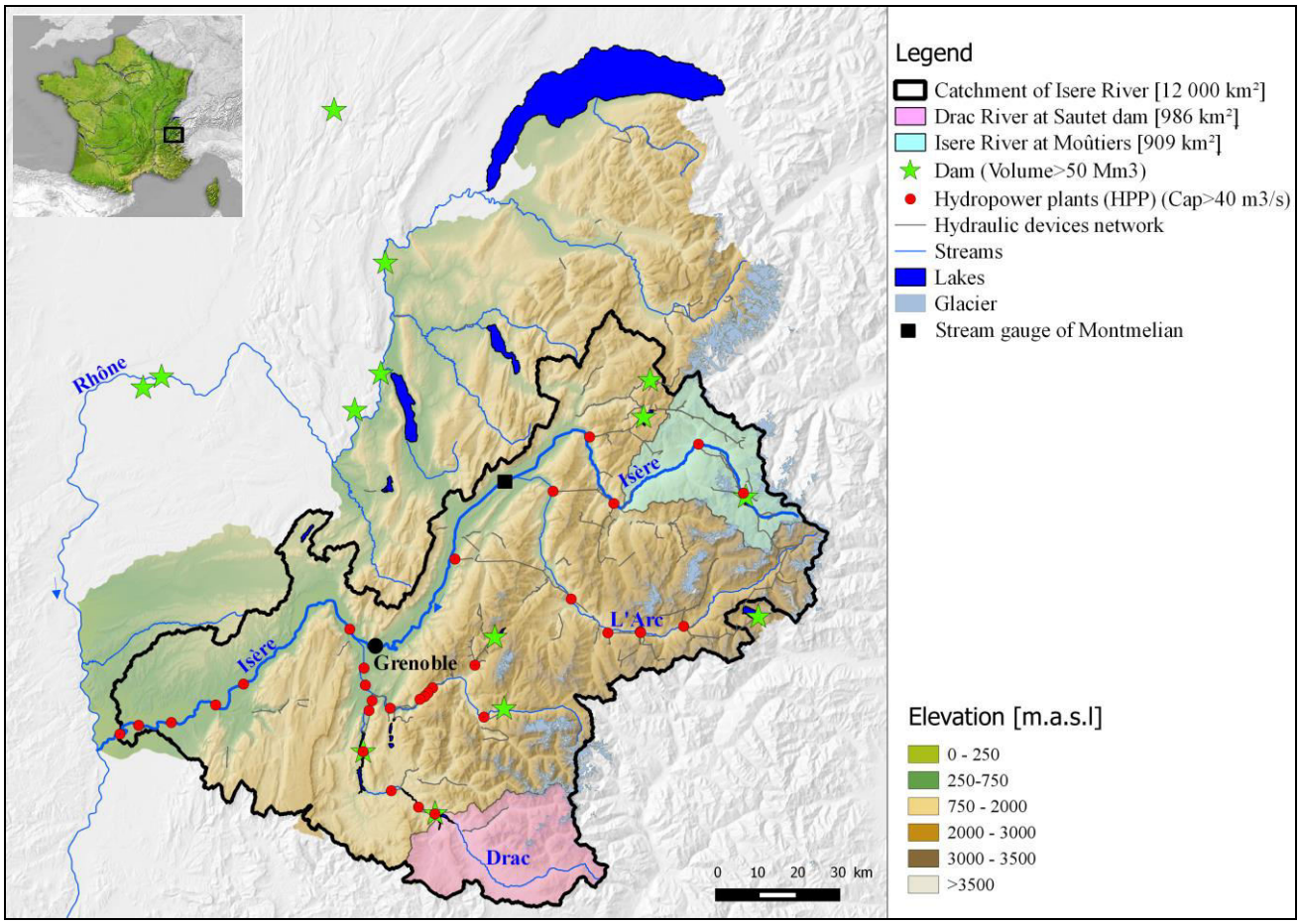


Figure 1. Territory of jurisdiction of the SPCAN and location of the Isère River basin and the two studied basins.

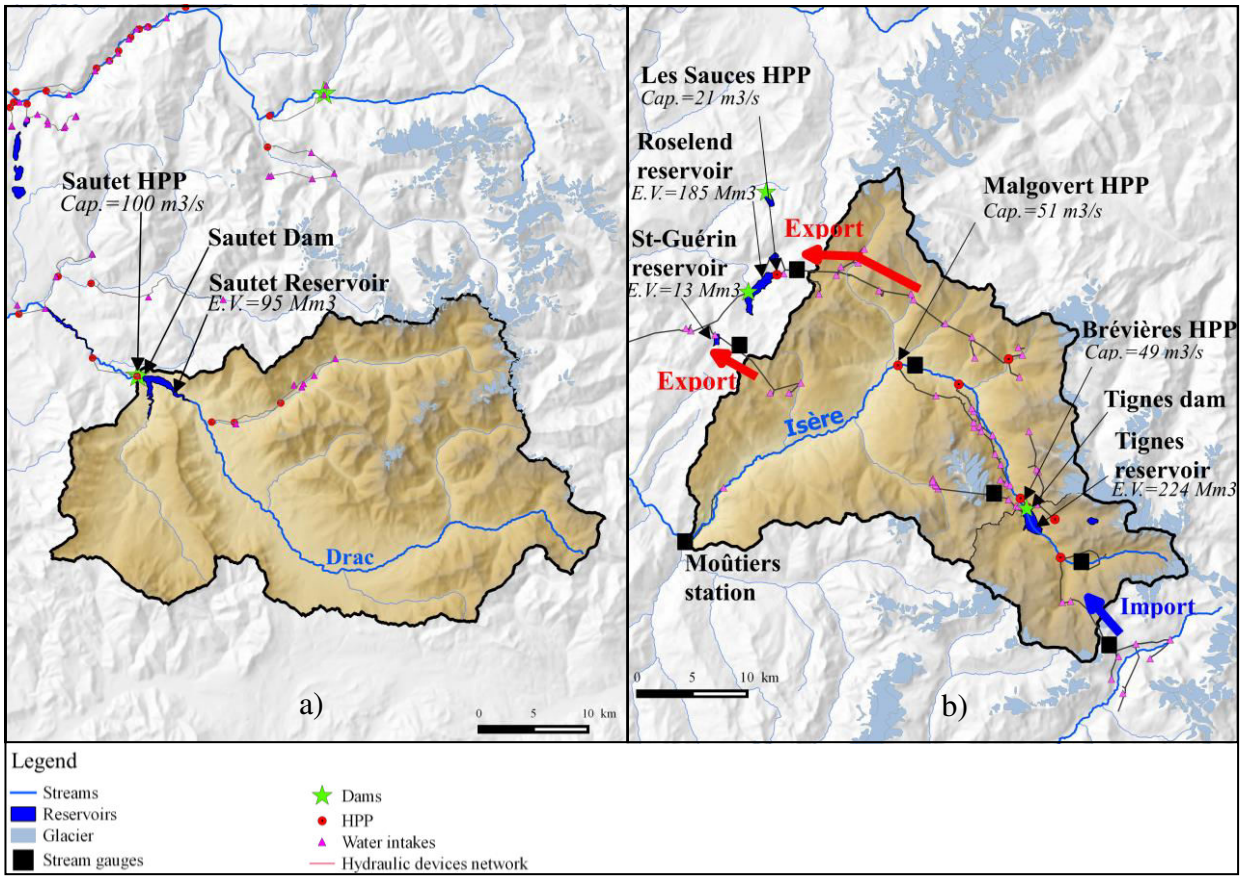


Figure 2. Studied basins: the Drac River at the Sautet dam (a) and te Isère River at Moûtiers (b) (E.V.: Effective Volume).

The Isere basin at Moûtiers is located in the north-eastern part of the stuy area and is bordered by a series of high mountains which give it an isolated situation. The basin area is 909 km², with an altitude range between 468m and 3840m. Despite a median elevation of 2200m, shading effects from prevailing winds explain relatively low annual precipitation amount (1220 mm/year, with 54% of snowfall). The length of the upper Isère River is 63 km down to Moûtiers. About 3.5% of the surface area is covered by glaciers and 14% is covered by forests. Soil cover is composed of schists and sandstones.

Floods are generated by two typical weather situations. The more intense is East return flow, the air mass of which is continuously alimented by the Mediterranean Sea. Penetrating by the south-eastern zone of the basin it sometimes leads to abundant amounts of rainfall. East return is often observed in spring and autumn, what can induce critical situations as reservoirs are typically filled and cannot be used to mitigate floods. As an example, the 15th of October 2000 event generated 100-year floods in some Swiss neighboring basins. The second patterns is the steady oceanic flow, which is more frequent but less strong than East return. An example of precipitation event associated to such a pattern is the 14th of May 1999 event, which generated a 120 m^3/s daily flow at Moûtiers. Although more intense in terms of precipitation, the 15th of October 2000 event produced the same daily flood flow at Moûtiers (equivalent to a daily volume of 10.5 Mm^3) thanks to a partial but significant water storage in the Tignes reservoir (Effective volume of 224 Mm^3; 75 m^3/s, equivalent to 6.5 Mm^3, were stored during the event).

Components facilities		Drained Area [km²]	Q cap. [m^3/s]	Mean obs. Q [m^3/s]
Sautet reservoir	Natural condition	986	-	31
	Sautet turbine	986	100	31
	Spillway	986	1395	-

2a) Drac River at Le Sautet Dam

Components facilities		Drained Area [km²]	Q cap. [m^3/s]	Mean obs. Q [m^3/s]
Import	Maurienne	100	19	1
Tignes reservoir	Natural part	171	-	9
	Left import	35	7	1
	Right import	33	8	2
	Brevieres turbine	339	50	11
	Spillway	339	510	-
Export	To Roselend	134	26	6
	To Saint-Guérin	28	6	1

2b) Isère River at Moûtiers

Table 2: Area, device capacity (or potential diverted flow) and observed mean daily flow diverted by the hydropower system for the two study basins.

Two water exports are performed on the North-West part of the basin: one towards the Saint-Guerin reservoir and another towards the Roselend reservoir, via the Sauces hydropower plant (see Figure 2b). These two exports are realized by a rather complex network of water intakes located on the main mountain streams (see Figure 2b and Table 2). They represent a drained surface of 162 km² (18% of the total area), with a potential maximum flow capacity of 35 m^3/s. Indeed, only a part of the basin natural flows are observed at the Moûtiers outlet. This second application study basin has thus been chosen so as to test different representations of the water intakes (fully distributed and semi-distributed, considering a single equivalent intake for each intake group).

2.2 Available datasets

2.2.1 Meteorological data

MeteoFrance provides hourly observations of precipitation and temperature at 42 stations distributed on the whole Isère River basin. A main problem is the lack of data at high elevation. For instance, for the whole Isère River basin there is almost no data available over 2000m (i.e. on 30% of the total basin area), as shown on Figure 3. This imply a real difficulty to estimate the basin spatial averaged precipitation and its phase (rainfall or snow).

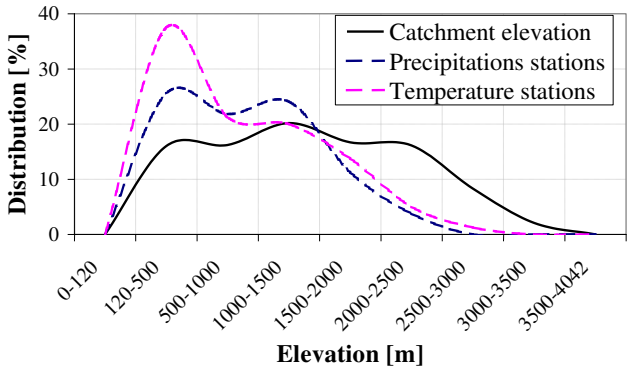


Figure 3. Hypsometric curve of the whole Isère River basin and altitudinal distribution of the meteorological stations.

Therefore, it was decided to use as input for the modelling the SAFRAN reanalyses elaborated by MeteoFrance [9, 10]. These are gridded at a resolution of 8x8 km² at daily time step.

2.2.2 Hydrological data

Flow data were provided by EDF and SPCAN. These include hourly values at 35 gauging stations and daily values of diverted and slogged flows in correspondence of the main hydroelectric devices (HPP, water intakes). Natural reconstituted flows (QNR) have been calculated at strategic points (i.e. in correspondence of a stream gauge or a reservoir input), following [8]: a simple water balance between all the input and output flows (natural and man-induced) was applied at daily time step, which is the time step at which operation data were generally available (and which also insure that flow propagation time between different hydraulic devices is negligible)..

For the Drac River basin, a single strategic point was selected: the entrance of the Sautet dam. For the Isère River basin at Moûtiers, three strategic points were selected: the entrance of the Tignes dam, the entrance of the Malgovert hydropower plant and Moûtiers.

Finally, given the meteorological and the hydrological dataset availability, a 14-years long hydro-meteorological

archive was constituted from 1997 to 2010, which is the reference period for simulation.

2.2.3 Hydroelectric network data

Besides daily flow values in correspondence of hydroelectric works, EDF provided instantaneous daily measurements of reservoir levels and the corresponding volumes (at 0h00 UTC), as well as the characteristics of the facilities (flow capacity, level-flow of the spillways and level-volume relationships for each reservoir), operating instructions and flooding reports (including meteorological event descriptions, initial conditions of hydroworks, operation procedures, encountered difficulties). Moreover, a dataset of operating abacus for determining the operating status (usual, alert and flood) of the reservoirs was established from documents graciously provided by USOH (Unity of Hydraulic Facilities Security, DREAL Auvergne-RhôneAlpes). All these valuable documents helped to understand the operation of facilities and writing the statistical formulation of

2.2.4 Elevation and land cover data

Elevation data were obtained from the French National Geographic Institute (IGN) with a resolution of 25x25m² on the whole SPCAN territory. These data allowed to define the basins boundaries and their hypsometric curves, as well as to divide them into several altitudinal bands for the semi-distributed hydrological modeling (see section 3). Land cover data, including glaciers covers, were taken from the 2006 Corine Land Cover database established at 100x100m² by the European Agency of Environment.

3 Modeling strategy

3.1 Hydrological model description

The chosen hydrological modeling tool is CEMANEIGE-GR4J, developed by Irstea [11, 12]. It is a conceptual rainfall-runoff model that allows representing hydrologic processes such as snowmelt (by a degree-day factor approach), as well as surface and underground flows (based on two linear reservoirs, one for runoff production and another for flows routing) at daily time step. The CEMANEIGE snow module makes a discretization of the basin area into 300m elevation bands. The total amount of liquid water generated by rainfall and snowmelt over each band is aggregated at the basin scale and transformed by the production module of GR4J into evaporation, storage, runoff and percolation. The resulting outflow (sum of the last two) is routed to the outlet with two different unit hydrographs: one for quickflow and another for baseflow.

To model glacial melt, a glacier module has been added, also based on a degree-day factor approach, and derived from the Glacial SnowMelt model developed at EPFL-Lausanne [13] and already operational in the Swiss Valais canton.

In addition, some changes have been necessary to adapt CEMANEIGE-GR4J to the SPCAN context. These improvements concerns mainly the precipitation input and its extrapolation over the elevation bands: two weighting coefficients were added for correcting the total precipitation and the snowfall amount, respectively [14].

3.2 Model set-up

Input values spatially averaged over the 5 elevation bands are needed for the simulation: precipitation (P), temperature (T) and potential evapo-transpiration (PET). Concerning precipitation, basin averaged P is estimated from the SAFRAN distributed data at each time step. Then, CEMANEIGE simulates precipitation values for each elevation band according to a altitudinal correction factor. Similarly, a daily linear altitude gradient is applied in CEMANEIGE to the basin averaged T in order to estimate temperature values for each elevation band. Finally, daily PET is estimated for each elevation band on the basis of temperature and incoming potential solar radiation, according to [15].

After a sensitivity analysis, 6 parameters were retained for calibration: the two weighting coefficients for precipitation, the snowmelt degree-day factor, the maximum production store capacity, the maximum routing store capacity and the base time of quickflow unit hydrograph. 8 other parameters were a priori fixed: the extrapolation coefficient for precipitation with altitude, a weighting coefficient of the snowpack thermal status, the ice melt degree-day factor, two threshold temperatures for snow and glacial melt, an ice melt release coefficient, a coefficient of minimal melt, and the groundwater exchange coefficient.

To develop the flood warning system on the whole Isère River basin, the following 3-steps strategy has been pursued:

- Step 0: the total basin area is split into several sub-basins, according to the catchment topography, the hydraulic devices network and the strategic warning points (see section 3.2.1);
- Step 1: CEMANEIGE-GR4J is calibrated and validated at each sub-basin scale in order to simulate natural reconstituted flows QNR (see section 3.2.2);
- Step 2: the effect of hydraulic operations is added and the model is validated against observed flows Q. At the end of this step, flood warning levels at strategic points are issued (see section 3.2.3).

3.2.1 Splitting the study area into several sub-basins

By considering the stream gauges location and the most significant dams and diversion, the study area is firstly split into several sub-basins with rather comparable sizes, whose outlets are ‘strategic’ nodes that are represented within de model. In order to identify the facilities that have to be represented, the next rules were followed:

- A reservoir is systematically ignored if its effective volume capacity is smaller than 1 Mm^3 (which corresponds to a daily flow of 11 m^3/s in the very exceptional case where the volume of the reservoir is full), or if its daily flow variations are never greater than a few m^3/s or 5% of natural inflow;
- Run-of-river diversions are not considered;
- Diversions are systematically ignored if their maximum flow capacity is lower than $10m^3/s$ (which gives a mean actual diverted flow of some m^3/s), or if the diverted flows are never greater than 5% of the total inflow of the fed reservoir.

Application of such rules leads to consider the following strategic nodes for our application study basins (see also Figure 4):
- *for the Drac River basin at the Sautet dam*: the outlet of the Sautet reservoir. This basin is thus not split into several sub-basins, but taken as a whole.
- *for the Isère River at Moûtiers:* the outlet of the Tignes reservoir, the outlet of the Sauces water intakes group and the basin outlet at Moûtiers. This basin is thus split into 3 sub-basins whose simulated outflows are directly aggregated at Moûtiers, as their propagation time towards the basin outlet is lower than 24 hours (which is the simulation time-step).

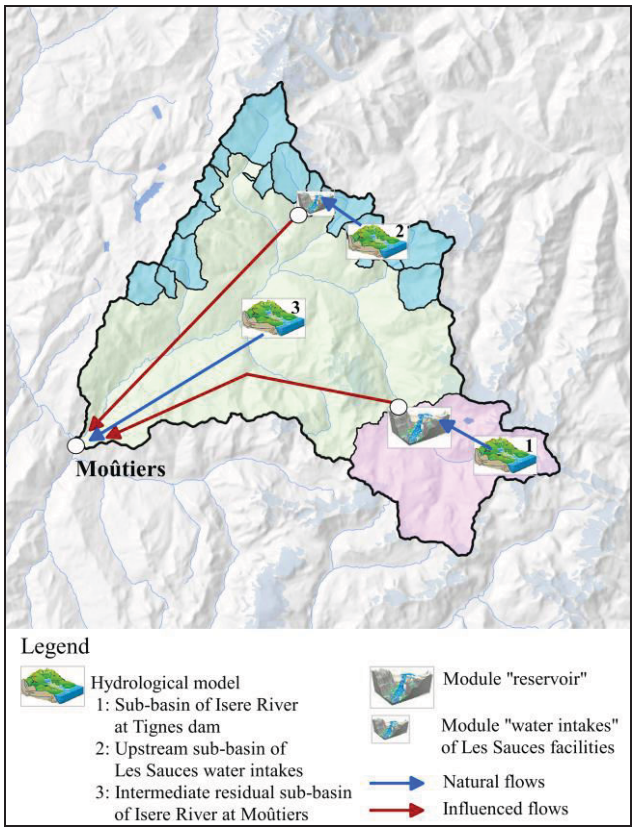


Figure 4. Modeling scheme for the Isère River at Moûtiers.

3.2.2 Modeling the natural outflow of each sub-basin

As a second step, the natural outflows of each sub-basin are simulated, after calibration of the corresponding models against QNR. Automatic calibration was made, based on a genetic algorithm [16] nd optimization criteria such as Nash and Sutcliffe efficiency [17], Volume Bias (ratio of simulated versus observed flow) and correlation between observed and simulated flows,. When necessary, further manual adjustments were in order to obtain more accurate hydrographs, especially for flood hydrographs. The calibration and validation phases cover the period 01/09/1997-31/08/2004 and 01/09/2004-31/08/2010, respectively.

3.2.3 Calculation of the hydraulic facilities outflow and issue of the warning levels

This last step consists in the simulation of man-made outflows at each considered strategic node (dams and diversions), then in the calculation of total outflows at warning points. Two types of modules have been developed for the mathematical formulation of the outflows in correspondence of reservoirs and water intakes, respectively (see the two following sections). A third module allows converting total outflows at warning points into warning levels (see section 3.2.3.3). In order to evaluate the model, the number of Hits, Missed and False Alarms (FA) were counted.

3.2.3.1 Reservoir module

Generally, each reservoir has an operating abacus which reflects the potential risk related to the dam security at all times. An example of such an abacus is shown in Figure 5: two different thresholds allow passing from usual status to alert status and from alert status to flood status. As its name indicates it, the operating abacus defines the operations that have to be executed for ensuring the spillways loading, according to the reservoir level and the observed or predicted inflow. Thus, it gives the target outflow to achieve.

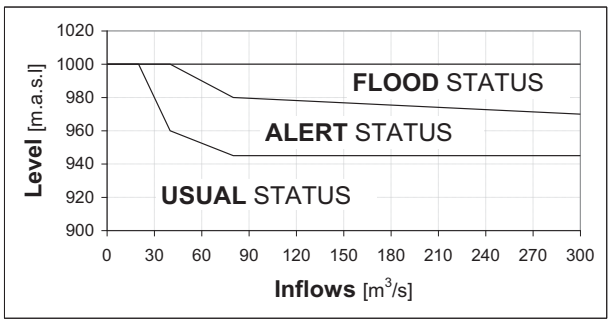


Figure 5: Example of operating abacus of a reservoir.

In the reservoir module, the outflow is calculated function of the current operation status of the considered reservoir.

First, potential overflow is defined and calculated as:

$$PotOUT(t) = QIN(t) - QRU(t) \quad (1)$$

Where
$PotOUT(t)$ $[m^3/s]$ is the mean daily potential overflow at a given time step t;
$QIN(t)$ $[m^3/s]$ is the mean daily inflow to the reservoir;
$QRU(t)$ $[m^3/s]$ is the free volume available in the reservoir expressed as mean daily flow.

For each reservoir, two different thresholds on PotOUT(t) have to be determined in order to characterize alert and flood status. These have been calibrated by maximizing the number of Hits and minimizing the number of False Alarms against observed flows.

Then, for each reservoir a formulation depending on its status was determined to estimate the actual outflow.

During current status periods (that represents more than 99% of the days over 1997-2010), outflows are determined by the hydroelectric production. The estimation of daily slogged flows is complicated, as it does not rely on inflows, but on others external conditions: temperature, energy demand, energy market prices, etc. Nonetheless, slogging follows intra-weekly cycles: the energy consumption is higher from Monday to Friday and in business days than during week-ends and holidays. In addition, the energy demand depends on air temperature for supplying heating or air conditioning systems. Indeed, a seasonal cycle is also observed. As a result, different values of slogged outflows were proposed for each considered reservoir, depending on the week of the year and the day of the week (Monday to Friday and Saturday-Sunday): a total of 52x2 values per year were considered, identical from an year to another. Depending on the considered dam, the median or the 90% quantile of these 104 values was selected as optimal slogged flow in usual conditions.

During alert and flood periods, the reservoir outflows are less complicated to estimate, because they are dependent on operating modes issued from the operating abacus. Firstly, the reservoir storage variation (expressed in terms of mean daily flow) is calculated by calibration against storage variations registered during observed past operations on pre-flood and flood events:

$$QVAR\_STOCK(t) = a*QRU(t) + b \qquad (2)$$

Where :
QVAR_STOCK(t) *[m³/s]* is the daily storage variation of the reservoir;
a *[-]* and b *[m³/s]* are the coefficients of the linear regression of *QVAR_STOCK*(t) from *QRU*(t), calibrated on observed daily storage variations.

Then, outflows are calculated:

$$QOUT(t) = QIN(t) - QVAR\_STOCK(t) \qquad (3)$$

$$QOUT(t) = QIN(t) - a*QRU(t) + b \qquad (4)$$

Where :
QOUT(t) *[m³/s]* is the mean daily reservoir outflow at time step t.

To consider uncertainties related to QOUT(t), additional minimal and maximal values ($QOUT_{MIN}$ and $QOUT_{MAX}$) were also proposed, corresponding to the instream flow and the maximum slogging capacity of the hydropower plant fed by the reservoir outflow, respectively. As an example, Figure 6 illustrates the outflow calculation chart for the Sautet dam.

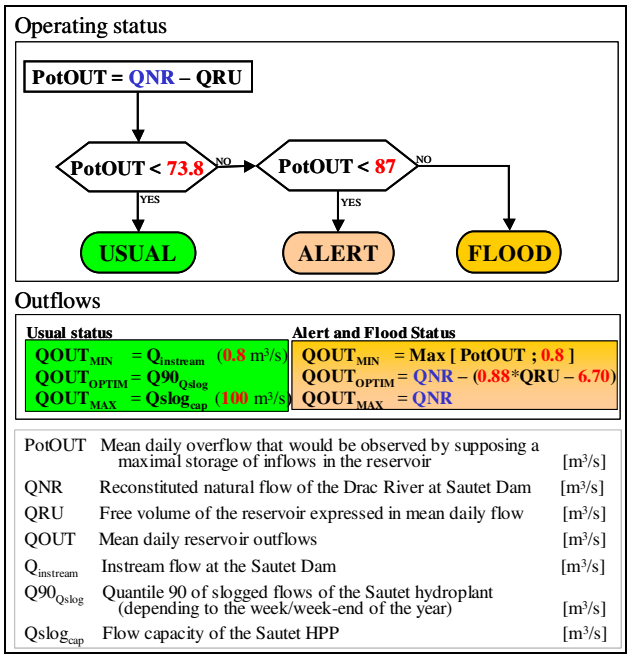


Figure 6: Calculation of the Sautet dam outflows

3.2.3.2 Water intake module

Water intakes located in the study area are mainly open or free-level intakes, in which the water supply levels are uncontrolled. Sometimes, a weir can be used to ensure a constant supply to the intake, but no active control is generally made for maintaining the diverted flows *QD(t)* within given conditions. Thus, these are function of the streamflow *QIN(t)*: every intake is characterized by its equipment flow (or maximum capacity) *Qequip* and the instream flow *Qinstream* that has to be guaranteed after any diversion. The diverted flow *QD(t)* is estimated according to a simple linear relationship: the diversion begins when *QIN(t)* exceeds *Qinstream* and linearly increases with *QIN(t)* up to *Qequip* (see Figure 7).

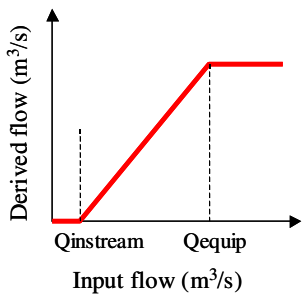


Figure 7 – QD(t)-QIN(t) relationship scheme, with activation / saturation thresholds on Qinstream / Qequip respectively.

A simplified representation of water intakes was tested, by aggregating into a single equivalent water intake those for which the diverted flows join the same hydropower plant (or the same reservoir). It was thus necessary to represent the aggregated intakes into a single function. Of course, the flow derived by the equivalent intake is the sum of the flow derived by every individual intake, and the equivalent intake cannot produce derived flows greater than the sum of the intake capacities. But

the equivalence relationship is not intuitive: the activation and the saturation thresholds for generating diverted flow *QD(t)j* by each intake *j* depend on their geometrical characteristics (represented by the equipment flows *Qequip_j* and the instream flows *Qinstream_j*) and their respective inflows *QIN(t)j*, therefore on the basin area they drain if one assume that meteorological input and the runoff coefficient are both spatially uniform on the upstream area of the aggregated water intakes. As a result, and contrary to what happens for every individual intake, for the equivalent intake the relation *QD(j)-QIN(j)* is not linear around the thresholds of activation and saturation, as it is shown, as an example, in Figure 8.

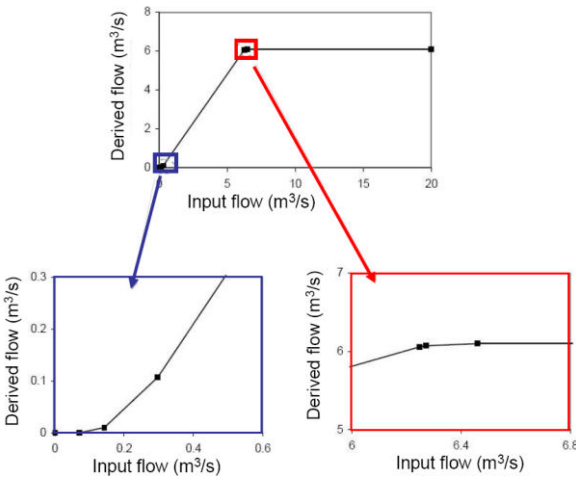


Figure 8 – QD(t)-QIN(t) relationship for equivalent intakes.

In order to validate the water intakes aggregation approach, the Isère River basin at Moûtiers was investigated. A comparison was made between two simulations accounting respectively for individual and equivalent representations of the existing 17 water intakes exporting flows to the Roselend and St Guérin reservoirs (see Figure 2b) (total drained area by these intakes of 162 km² and total export capacity of 32 m^3/s).

3.2.3.3 Warning point module

The reservoir and the equivalent water intakes modules were applied to simulate outflows from all the dams and the equivalent water intakes of the Isère River basin. In order to estimate the total streamflow at each gauged station (considered as critical nodes), a new warning point module was developed, allowing to add the hydraulic devices outflows to natural streamflow calculated on intermediate sub-basins that are not harnessed for hydropower.

To detect any threshold exceedance and issue the associated warning level, one needs to determine the expected maximum daily flow. This is estimated from mean daily flow thanks to a weighting coefficient, which is adjusted for each gauging station by linear regression applied on past observed flood events. Warning results obtained for the two study sub-basins, as well as at Montmélian, which is a strategic warning point upstream from Grenoble, as already said, are presented in section 4.

4 Results and discussion

4.1 Hydrological model calibration

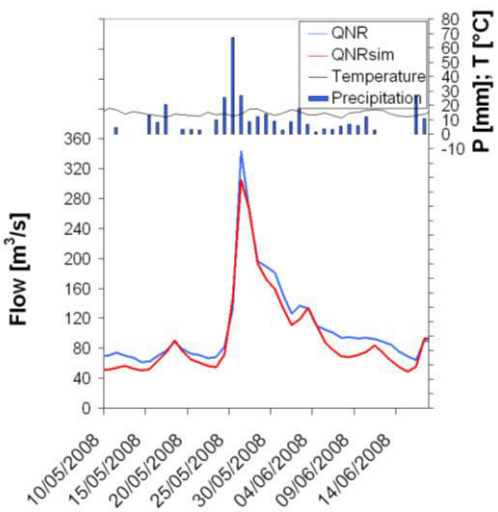
For the two studied sub-basins, three hydrological models were calibrated according to the availability of QNR at the outlet: the Drac River sub-basin at the Sautet dam, the Isère River sub-basin at Tignes and the Isère River intermediate sub-basin between Tignes and Moûtiers. Parameters calibrated for the latter were used as a first guess to calibrate the models of both the upstream sub-basin of Les Sauces equivalent water intake and the intermediate residual sub-basin (respectively named 2 and 3 in Figure 4).

As shown in Table 3, calibration results are satisfactory: the average Volume Bias is lower than 5%, both in the calibration and the validation periods, and Nash values are globally greater than 0.80, except for the Tignes dam sub-basin. This results reflects the difficulty of reproducing flows for small hydrological entities, essentially due to uncertainties on meteorological forcing.

Sub-basin / basin	Nash		Volume	
	Cal.	Val.	Cal.	Val.
Drac River at Sautet Dam	0,87	0,80	1,00	1,00
Isere River at Tignes Dam	0,74	0,77	0,97	1,01
Intermediate Isere River at Moûtiers	0,83	0,79	0,96	1,05
Isere River at Moûtiers	0,84	0,86	0,97	1,03

Table 3: Calibration and validation results.

Floods are globally reproduced with high accuracy, with the exception of the Drac River sub-basin, where an underestimation of the peak flows is generally observed. The models calibration seems to be very consistent, with good results even in the validation period: Figures 9 and 10 illustrate two examples in the calibration and the validation periods, respectively (26th Oct. 1999 and 29th May 2008 for the Drac River sub-basin, 15th of Oct. 2000 and 29th May 2008 for the Moûtiers basin). Both overestimations and underestimations of the flood peak reflect the uncertainty on meteorological input.



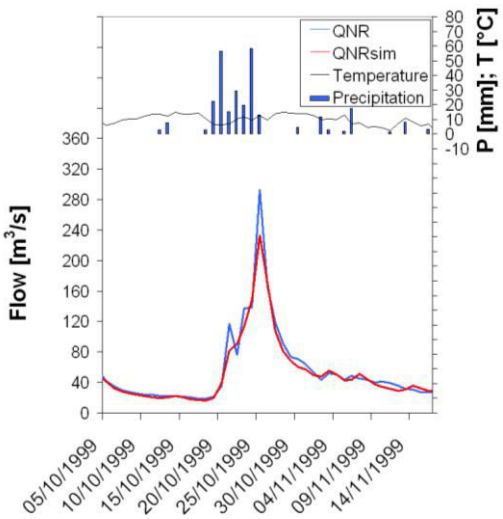


Figure 9: QNR simulation of the Drac River at the Sautet dam for October 1999 (top) and May 2008 (bottom) floods.

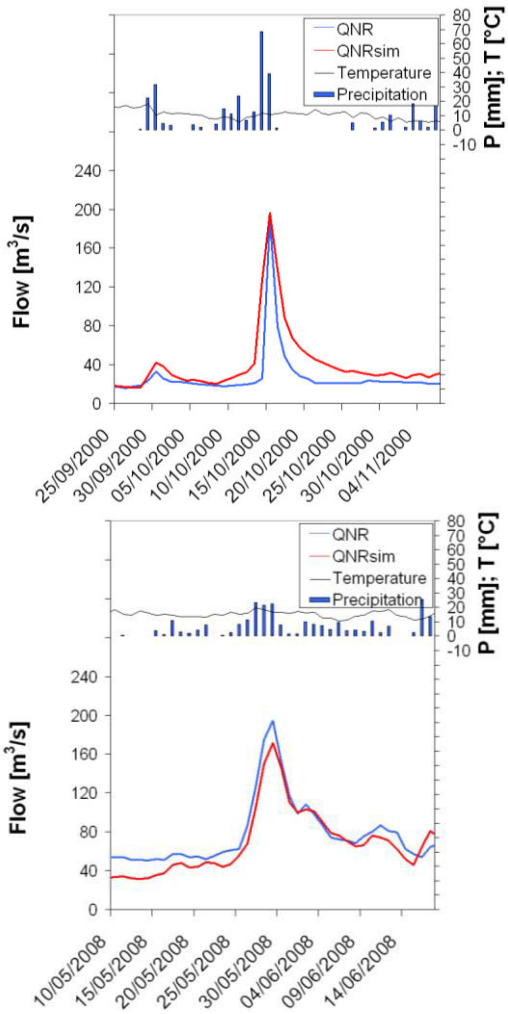


Figure 10: QNR simulation of Isère River at Moûtiers for October 2000 (top) and May 2008 (bottom) floods.

4.2 Reservoir modeling: outflow simulation at the Sautet Dam

Counts results obtained after calibration of the thresholds that determine the operating status (usual, alert, flood) are summarized in Table 4.

Status	Detection type	Count	
		PotOUT =	
		QNR-QRU	**QNRsim**-QRU
Alert	Hits (/2)	2	0
	Missed (/2)	0	2
	False Alarms (/4352)	9	3
Flood	Hits (/11)	10	9
	Missed (/11)	1	2
	False Alarms (/4352)	1	12
Alert or Flood	Hits (/13)	12	11
	Missed (/13)	1	2
	False Alarms (/4352)	10	13

Table 4: Number of Hits, Missed and False Alarms for the operating status estimation of Le Sautet reservoir (1997-2010).

When *PotOUT(t)* is calculated with observed QNR (meaning that we know what the inflow in the Sautet dam is), only 1/11 floods (1/13 if the alert status is also counted) is missed. With simulated inflow, the two observed alert status are missed (due to underestimation of peak flows, cf. results from the previous section).

When both alert and flood status are considered, 1 False Alarm per year is observed in average (13 FA over the whole 1997-2010 period), which is satisfactory.

The calibrated threshold values for the estimation of which is the operating status are given in Table 5. In theory, the threshold values of *PotOUT(t)* for alert and flood status should be greater than the slogging capacity (here, 100 m3/s – cf. Figure 6). In reality, according to the obtained results, this is not the case.

Threshold on PotOUT	Usual to Alert	73,8	m^3/s
	Alert to Flood	87	m^3/s

Table 5: Calibrated threshold values for the estimation of the operating status of Le Sautet Reservoir.

Three supposed reasons can be argued. The first is directly related to chosen simulation time step, because a daily time step (longer than the concentration time of the basin) tends to mix both usual and unusual operating status. It also smooths the instantaneous flow peak, which is used for deciding which the operating status is. This hypothesis is particularly critical when floods are straddle across two different time steps. The second reason is based on the fact that dam operators may maximize the production just before the flood passing. This means that in reality the reservoir can be already in unusual operating status (alert or flood) with a smaller value of *PotOUT(t)* than expected. The third hypothesis is due to possible anticipations of forecasted floods, in order to plan an additional safety margin for the dam.

Figure 11 shows the comparison between simulated and observed outflows from the Sautet dam. At the top of the figure, inflow is known (model is forced with observed QNR). At the bottom, inflow is simulated by the hydrological model. Two main results can be deduced. Firstly, the uncertainty on outflow estimations is largely greater at usual operating status than in flood or alert status. Significant simulation errors for usual status days reflect the difficulty in simulating actual slogged flows. Secondly, outflows are accurately reproduced in alert and flood status days, with an almost perfect

estimations of outflow when inflow is known (top of Figure 11). Once again, this validate our estimation of PotOUT threshold values for alert and flood operating status determining. In addition, estimation errors due to False Alarms days remains acceptable (inferior to 15 m^3/s). When inflow is simulated (Figure 11 at the bottom), outflow estimations are obtained with little less reliability. The graph shows overestimated outflows for some unusual status days due initially an overestimation of inflow by the hydrological model.

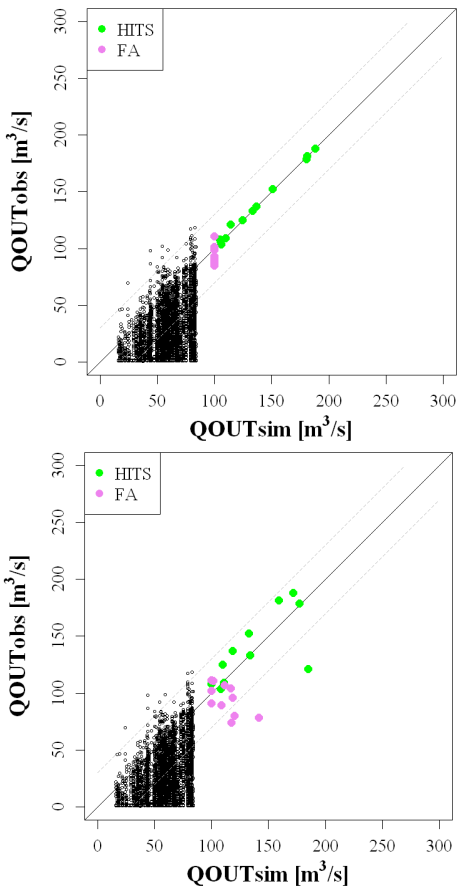


Figure 11: Comparison between simulated and observed outflows from the Sautet dam with known inflow (the observed QNR – top of the figure) and by simulating inflow with the hydrological model (bottom). Black dots represent flows in usual status, colored dots represent flows in flood or alert status.

Figure 12 presents results obtained for two specific floods, namely the 26th October 1999 and the 29th May 2008, already analyzed at the calibration step. At the top of each graph *PotOUT(t)* values plotted as grey area and *PotOUT(t)* threshold that detect the passing from usual status to alert is plotted as dotted line. For the two floods, an initial low level allowed storing an important part of inflows, and then to reduce considerably the outflow.

It is worth noting that the Sautet reservoir kept an usual operating status during the 8th October 1999 event, which is correctly estimated by the model (except for October 26th, when the model generates a False Alarm, with a significant overestimation of outflow). During the second considered event, inflow completely filled the Sautet reservoir in two days (from May 25th to May 26th). Then, 9 consecutive days of flood status were observed: the model perfectly reproduced the situation and allowed obtaining a very coherent simulated of flood dynamics, with a peak outflow of 188 m^3/s the 29th of May.

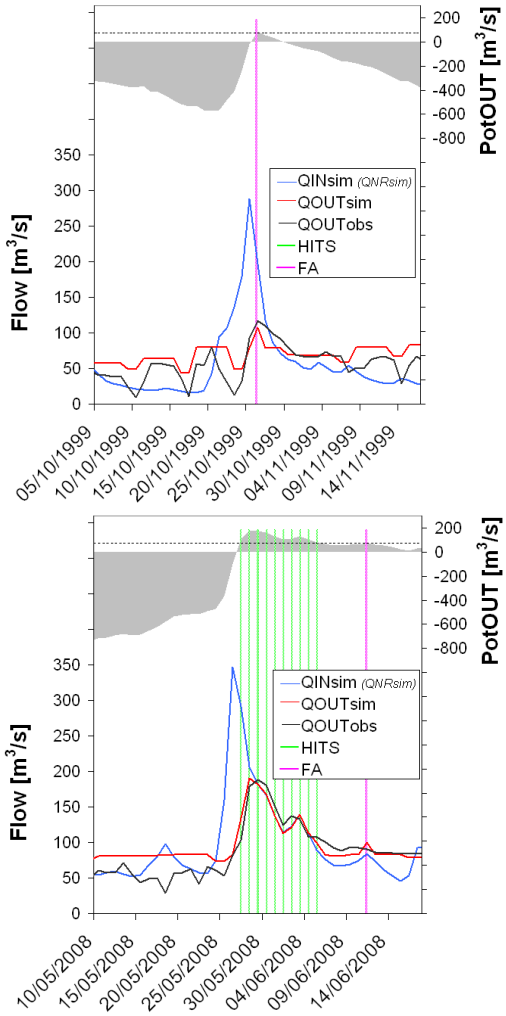


Figure 12: Outflow simulation of Le Sautet Dam (on the Drac River) for October 1999 (top) and May 2008 (bottom) floods.

4.3 Equivalent water intake: flows simulation of the Isère River at Moûtiers

Results are presented in Figure 13.

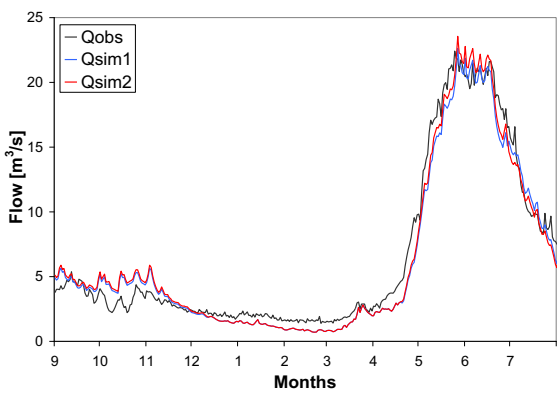


Figure 13: Simulation of diverted flows to Les Sauces plant: comparison between two water intakes representations, individual (Sim1) and equivalent (Sim2).

At the inter-annual scale, the simulated diverted flows show almost no difference between the two tested configurations (individual or equivalent water intakes) and are very closed to observed diverted flows.

In both configurations, Nash and Volume Bias values are of about 0.83 and 0.99, respectively, which is undeniably satisfactory. Similar performances were obtained during flood events.

Anyway, using the equivalent water intake approach allows to reduce significantly the modeling complexity of the upstream sub-basins of water intakes; for Isère River at Moûtiers this means moving from 19 to 3 sub-basins (cf Figure 4). So we decide to retain this method for the modeling of the whole Isère basin.

In addition, the reservoir module was applied to simulate the outflow of the Tignes dam. Total streamflows were then simulated at Moûtiers as the sum of the Sauce equivalent intake outflows, plus Tignes simulated outflows, plus streamflows simulated on intermediate residual sub-basin. Results are highly satisfactory. As an example, Figure 14 gives an illustration of the obtained simulations for October 15th 2000 and May 29th 2008 events.

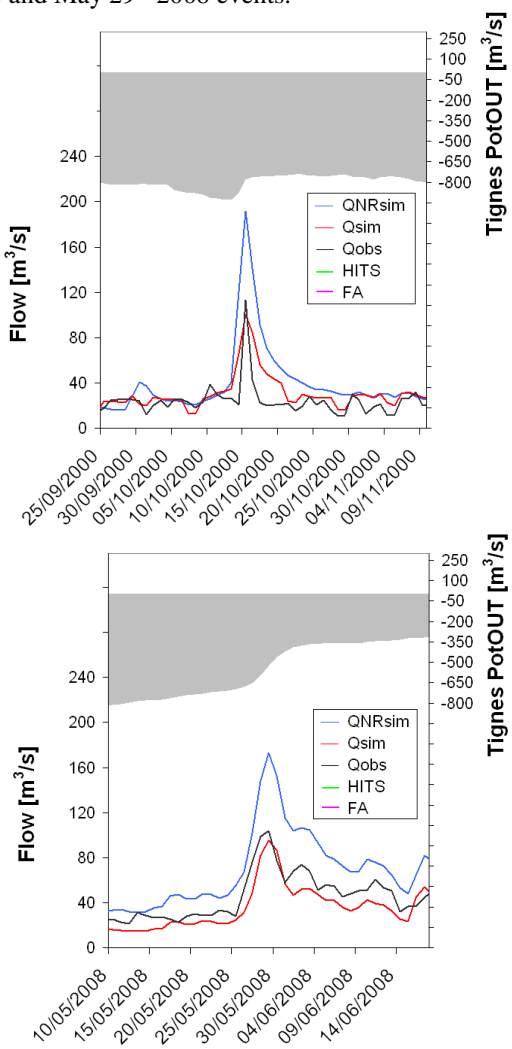


Figure 14: Flows simulation for the Isère River at Moûtiers: 15th of Oct. 2000 (top) and the 29th of May 2008 (bottom).

4.4 Flood warning at reference gauging stations

Hits, Missed and FA were counted on simulations obtained first with observed QNR as dam inflows and then with simulated dam inflows (lack of data for QNR reconstitution at the whole basin scale explain the small number of 10 considered events in the first case).

Results show Hit rate scores from 80% to more than 90%, while generating only an average rate of four False Alarms per year (cf. Table 6).

Stream gauge	Detection type	Count		
		Vigilance status		
		Yellow	Orange	Red
Montmelian (QNR as dam inflow)	Hits (/10)	8	0	0
	Missed (/10)	2	0	0
	False Alarms (/2196)	25	0	0
Montmelian (simulated dam inflow)	Hits (/27)	25	0	0
	Missed (/27)	2	0	0
	False Alarms (/3403)	32	0	0

Table 6: Hits, Missed and False Alarms results for the warning station of Montmélian calculated on 1998-2010.

However, uncertainties are concatenated within the flow forecasting chain and make flow simulations the less and less reliable from upstream to downstream of the whole Isère basin. The main source of uncertainty seems to be due to input meteorological forcing (P, T). Correctly taking account for hydrological processes related to these two variables (notably, orographic effects) is essential in mountain basins. Second, the chosen daily time step tends to smooth the hydrological response of the basin. In addition, with regard to small upstream reservoirs, the use of a daily time step is not adapted for making robust detection of flood status. Third, QNR reconstitutions can also be highly uncertain, notably because flow propagation times between different hydraulic devices are not considered. This impacts model calibration, with an increasing effect with basin size. Finally, facilities may be operated unexpectedly during given flood events. Turbines may be stopped to empty penstocks or reservoirs, intensive runoff can clog water intakes, heating can be operated on streamflow in order to release sediments from reservoirs, etc. These particular events cannot be statistically predicted, nevertheless it was decided to consider them in the warning module by suggesting different scenarii to the SPCAN operators.

5 Conclusions and forthcoming works

This study presents a flood forecasting system that meets the SPCAN objective of flood warning at daily time step, up to 24 hours ahead. The proposed tool takes account of the complex characteristics of its jurisdictional territory (mountain area, hydroelectric devices), with high rates of Hits and very low rate of False Alarms in different strategic points. It can now be implemented in real-time. Conclusions from the presented results include the following:

- The CEMANEIGE-GR4J model seems to be adapted to the study context and its calibration on QNR allows reproducing adequately floods on different sub-basins;

- The consideration of the operational status of large dams provides evidence for increased accuracy in the prediction of their outflows. The proposed statistical method for warning thresholds identification generates successfully detections;
- A simplified method of water intakes representation within the model was validated and allowed reduce the complexity of the model architecture of the entire basin, without degrading the results on streamflow simulation;
- Uncertainty related to the meteorological input is significant and can greatly impact the simulation results;
- Hydroelectric facilities data are mandatory to run the warning tool in real-time and to obtain consistent predictions. This necessitates an imperative cooperation between SPCAN and EDF.

This study is obviously only a first step in the development of the warning system. Future objective will consist on the use of meteorological forecasts in order to obtain a forecasted indicator of warning degree with a horizon of a few days. The GRP model [18] is a good candidate for taking over GR4J for an hydrologic ensemble prediction approach. New uncertainties will have to be taken into account and processed to facilitate decision making by the operators pool. Moreover, the daily time step was here selected as first approach because it allowed to implement a simple and robust tool. But it will be necessary to get more detailed monitoring of flood events in order to (i) be able to forecast hourly flood peaks, (ii) adapt the model to the response time of smaller sub-basins and reservoirs and (iii) allow SPCAN to improve the crises management. An evolution towards the 6-hours or the 1-hour time step is planned.

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