# Towards an Operational Flood Forecasting System Taking into Account Hydro-Power Plants Operations

*Aurélien Claude[1], Isabella Zin[1], Charles Obled[1], Alain Gautheron[2], Christian Perret[3]*
*(1) Laboratoire d'étude des Transferts en Hydrologie et Environnement, Grenoble, France*
*(2) DDT de l'Isère - Service de Prévision des Crues Alpes du Nord,Grenoble, France*
*(3) EDF - Division Technique Générale, Grenoble, France*

## Abstract

*The operational flood forecasting service for French Northern Alps (called Service de Prévision des Crues des Alpes du Nord) needs to develop and implement an integrated flood forecasting system for the alpine Isere River basin at Grenoble (5720 km²). This basin has a rain and snowmelt dominated regime. Consequently, most parts of the basin are harnessed for hydropower. Within this framework, the semi-distributed Routing System II model (Dubois et al., 2007) has been implemented on a sub-basin of 909 km² where flows are intensively influenced by this power system. Firstly, the human-induced natural flows regime modification has been examined: natural discharges have been reconstructed and compared to the observed ones. This allowed understanding the impact of waterworks operations on runoff at basin scale especially during floods. Secondly, the hydrological model construction at daily time step is described. Model parameters were first calibrated and validated for pseudo-natural hydrological conditions, i.e. based on reconstructed natural discharges, without taking into account the hydro-electric waterworks. Next, different representations of the later were tested leading to model architectures with various degrees of refinement that allow for a consistent representation of water imports and exports of the basin. Our first conclusions are that waterworks must be represented essentially the main reservoirs, while a certain degree of aggregation remains acceptable for scattered water intakes. Finally, because of the high uncertainty in the meteorological forcing fields (precipitations and temperatures) due to a sparse measurement network and to the mountainous context, a sensitivity analysis is suggested according to the accuracy of the input precipitation and to a further division of each sub-basin into elevation bands.*

*Keywords: operational flood forecasting, snowmelt, waterworks, hydrological modelling*

## Introduction

The operational flood forecasting service of French Northern Alps (called Service de Prévision des Crues des Alpes du Nord) needs to implement an integrated flood forecasting system for the alpine Isere River basin in Grenoble (5720 km²; Fig. 1). His present system is based on Discharge-Discharge relationships allowing forecasting Isere River floods in Grenoble with about 7 hours lead-time. To enhance the forecasting performances, it becomes necessary to take into account the hydro-meteorology of the upstream basin and then to develop a Rainfall-Runoff method.

Because of the snowmelt flows provided during spring, the Alpine catchments are often harnessed for hydropower (e.g. Marnezy, 2008). Indeed, reservoirs are able to store those flows to produce electricity during the next winter. Thus the influence of existing hydropower multi-reservoir systems on the river flows can be significant (e.g. Vivian, 1994; Jordan et al., 2007; Fig.2). Several studies have considered their representation in a hydrological model, either though a lumped (e.g. Payan, 2008), a semi-distributed (e.g. Jordan, 2007) or a fully distributed (e.g. Verbunt et al., 2005) approach. These studies showed that their taking into account improve significantly the flows simulation at the catchment outlet.

## Isere river sub-catchment in Moutiers

### General conditions

The study area, located in the Northern French Alps, will be restricted here to the North-East part of the Isere River basin: the Isere River sub-basin in Moutiers (grey area in Fig. 1 and basin in Fig. 3). The length of the Isere River is 63 km, and this watershed has a surface of 909 km², with an altitude range between 468m and 3840m and a median of 2200m. The hydroelectric waterworks existing on this basin consists of two main accumulation reservoirs, one compensation reservoir, 49 water intakes, 2 reservoir intakes, 9 hydropower stations and more than 60 km of gallery and penstock.

About one third of the basin territory is covered with forest. Valley bottoms are mostly agricultural land (between Malgovert and Moutiers) or urbanized areas. The slopes are on average around 50%. Most frequently the soils of the valley bottoms consist of recent alluvial sediments alternately with lime and acidified textures often sandy gravel to silty sand. At high elevation, soils are composed of shale (calcareous or not), micaschist and flysch.

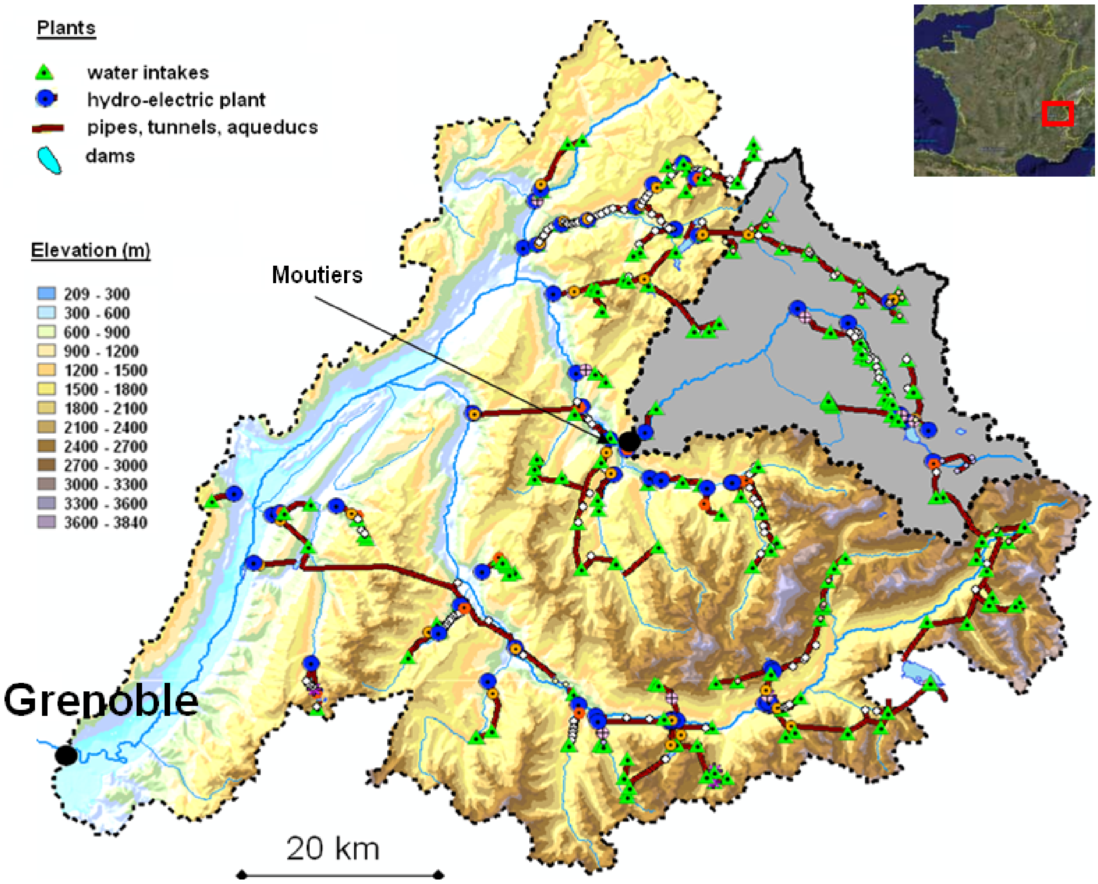

Figure 1: Location of Isere River basin in Grenoble (in Moutiers in grey)

### Climatic and hydrological conditions: a snow influenced regime

The high elevations of this basin give it a snow dominated hydrological regime with a low flow period in winter due to the solid precipitation and a high flow period in spring and early summer due to the both snow and ice melt (4% of glacier cover) (Fig 2, left part). The observed flows at the outlet of the basin are slightly lower since 1994 and this finding is consistent with the trend observed in the precipitation (Fig 2, right part).

In such an alpine environment, many parts of the basin are harnessed for hydropower (see their location in Fig 1 and Fig.3). This is reflected by the presence of many hydraulic structures (dams, water intakes, etc...) that allows storage, import and export modifying the natural hydrological cycle of the basin (red and black graphs in Fig 2). At the intra-annual time scale, results show that influenced flows are less variable than natural flows throughout the year; with reduced discharges during the spring snowmelt period to fill reservoirs, but conversely sustained winter low flows to meet the high demand for electricity. Then it appears necessary to analyse in more detail how the natural flow regime is modified before starting any basin hydrological modelling and to verify that the model selected is able to reproduce the observed flows.

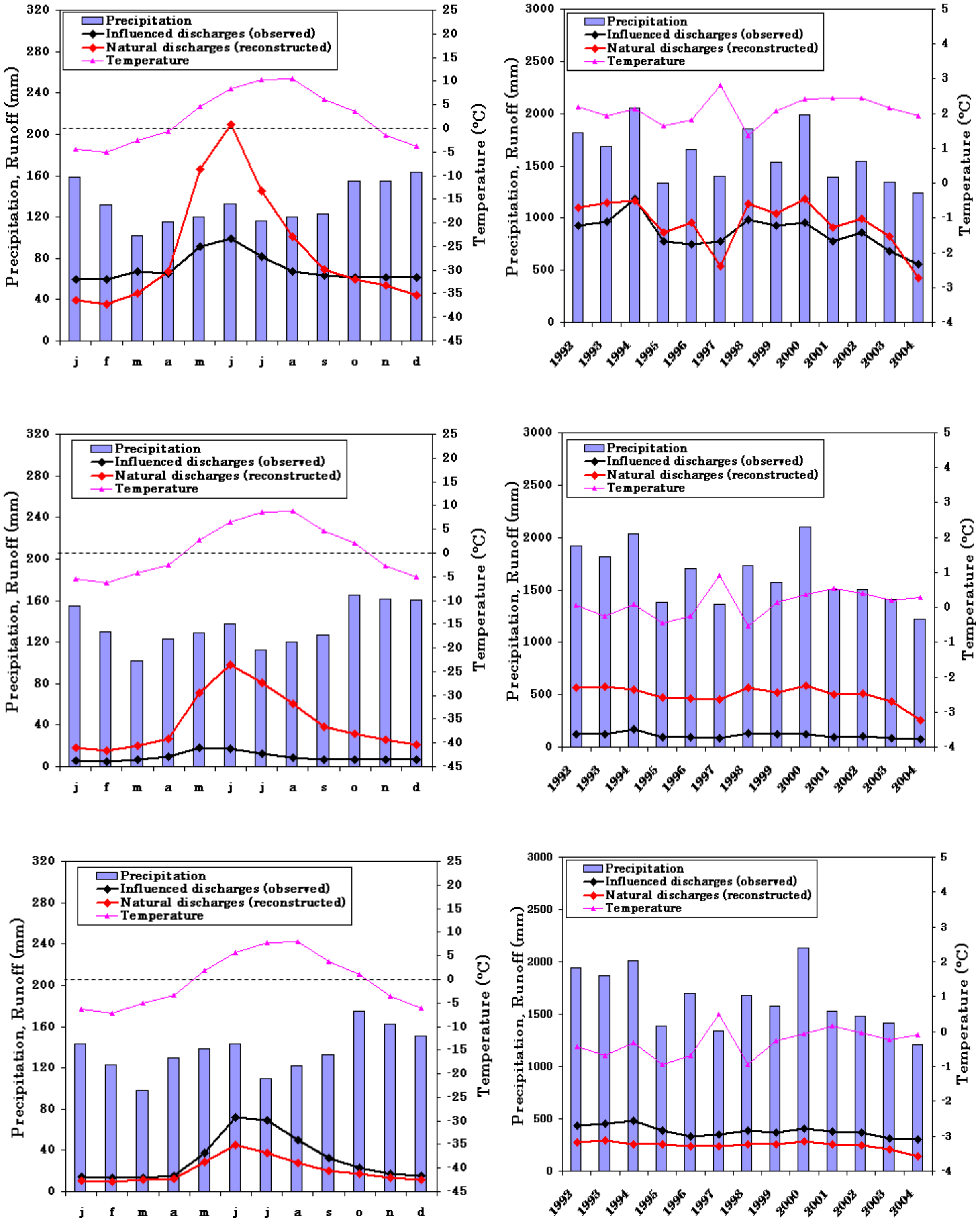

Figure 2: Intra-annual (left) and inter-annual (right) hydro-meteorological regime of Isere River basin in Moutiers (upper), Malgovert Amont (middle) and in the Tignes dam input (bottom)
(see Fig.3 for the location ; hydrological years)

## Analysis of the human-induced natural flow regime modification

The human-induced modification of the natural flow regime has been: natural discharges have been reconstructed and compared to the observed influenced discharges. The following analysis helped to understand the overall impact of the hydro-electric waterworks operations on the discharges, and to evaluate their weight first at the intra-annual monthly scale and finally during flood events.

### Description of the different import, export and storage capacities affecting the basin

These transfers are described here from upstream to downstream. Firstly the basin receives flows from a neighbouring valley in the South-East (all water intakes close to the blue arrow in Fig.3) used to increase the inputs of Tignes reservoir. Then the water level of the dam is used to run two large power plants. One, called “Les Brévières”, is located just at the bottom of the Tignes dam. Its turbinated flows, once released in the Isere riverbed downstream, are diverted again to another power station located just downstream of the stream gauge of Malgovert Amont (this plant is called “Malgovert”). Concurrently the basin exports water in two ways in its North-West part: one to Roselend reservoir and another to a plant downstream of this dam.

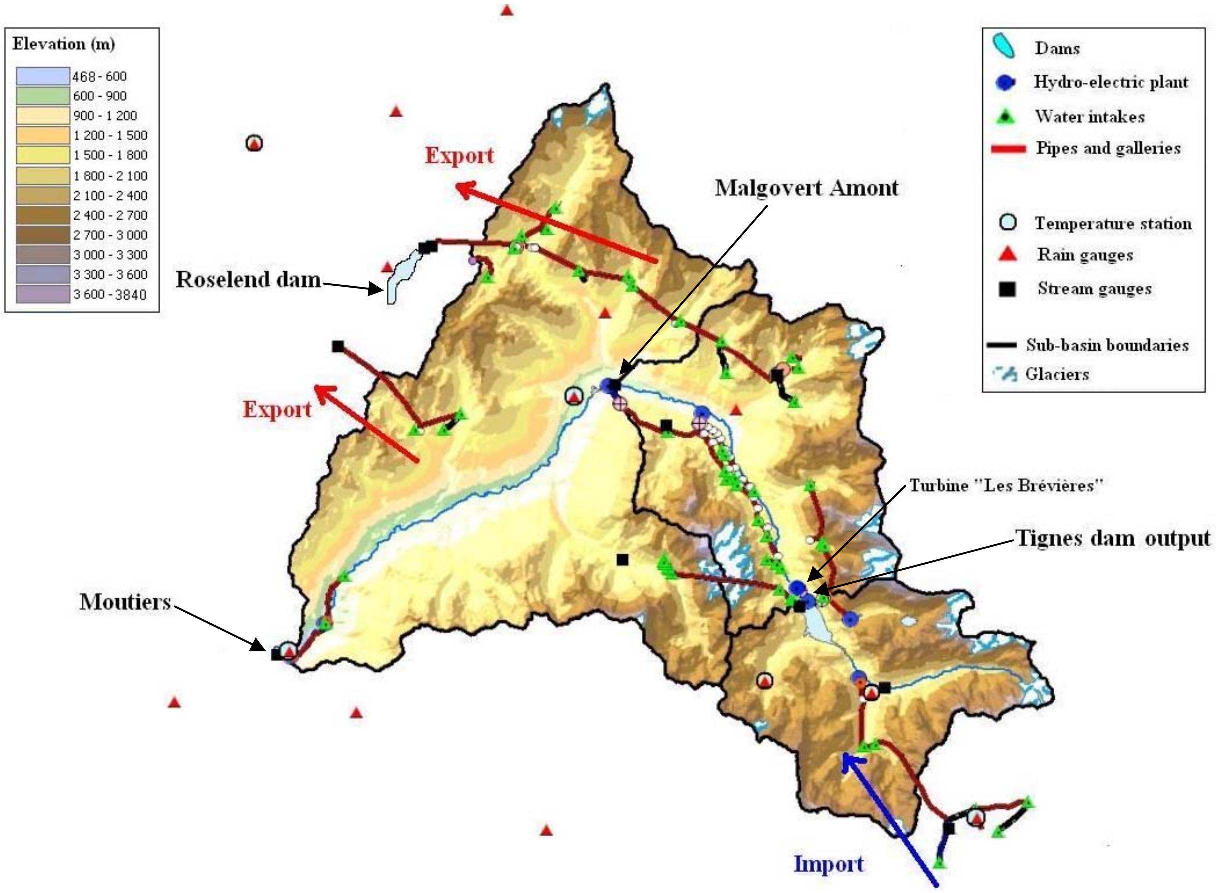

Figure 3: Hydro-electric plants and measurement network of the Isere River basin in Moutiers

### Available dataset

The different available data have been provided by EDF, one of the largest European companies in charge of water and energy related resources. These include the daily observed streamflows, daily turbinated discharges at 7 power stations, the daily levels and volumes of reservoirs, both the Level-Discharge and Level-Volume relationships for each dam and flooding reports for some hydro-electric plants.

### Natural flow reconstruction

The method adopted to reconstruct natural flows on a daily basis is as follows (Fig.4):

- When considering an intermediated sub-basin, input first the natural flow of the upstream headwater;
- Then add the difference observed between the output and input discharges of sub-basin;
- Next subtract all extra-basin imports (in red);
- And add all extra-basin exports (blue);
- Finally add all variations of storage.

Thus the natural flows of the Isere River at the Tignes dam outlet, at Malgovert Amont and Moutiers were reconstructed (Fig.3).

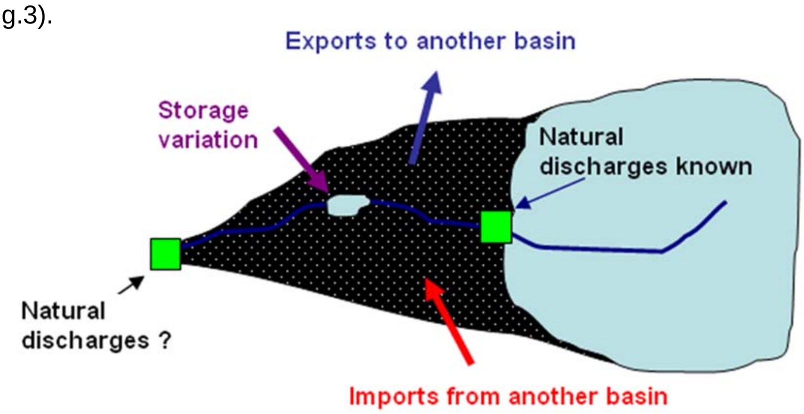

Figure 4: Scheme of natural discharges reconstruction
(Reconstructed natural Q = natural input + observed (output – input) + export – import + storage variation)

### Intra-annual water balance

The natural reconstructed flows at these three strategic points were then compared to the observed discharges at the same points. At the intra-annual scale, one can observe that during the snowmelt, half of the flows are stored in Tignes dam (dark pink part in Fig 5) and the other half is exported to another neighbouring sub-basin (to the Roselend dam, North-West part of the basin). This storage allows producing electricity in winter and thus sustaining the low flow period (release in blue in Fig.5).

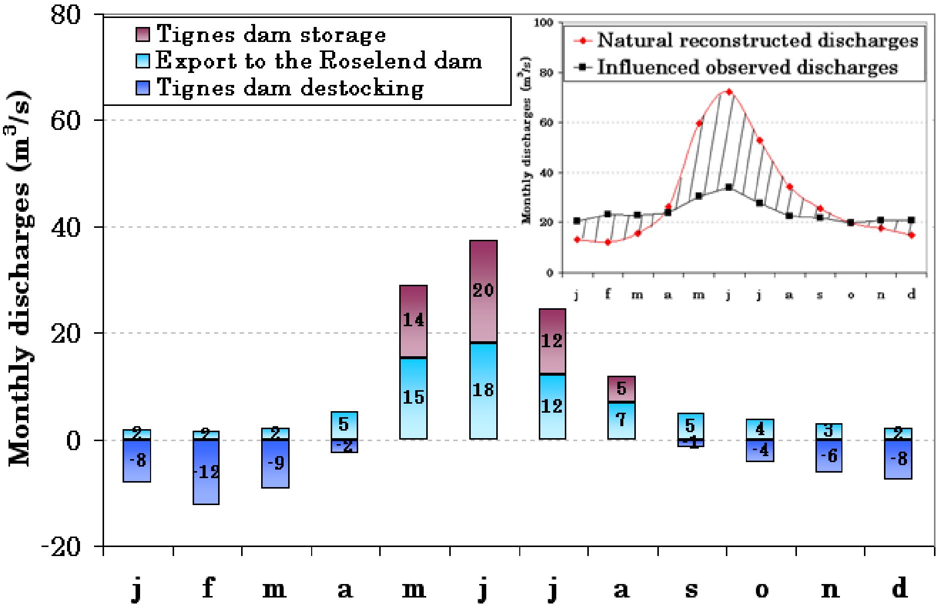

Figure 5: Explanation of the difference between the influenced and reconstructed natural discharges of Isere River basin in Moutiers **in the intra-annual mean balance** (1992-2006)

### Flooding period water balance

Some flood events were selected (Fig. 6). During flood time, the observed flows appear significantly lower than the expected natural flows (left part in Fig.6). This difference is in general caused for two thirds by the detentions storage in Tignes reservoir, equivalent to about one fourth of the natural flow (see dark pink colour in the right part of Fig.6) and for the last third, the difference represents the export to the Roselend reservoir, equivalent to one sixth of the natural flow (light blue colour in the right part in Fig.6). At the watershed outlet in Moutiers, another rather robust relationship appears both for snowmelt floods and rain floods, where observed flood flows are approximately equal to two thirds of natural flows.

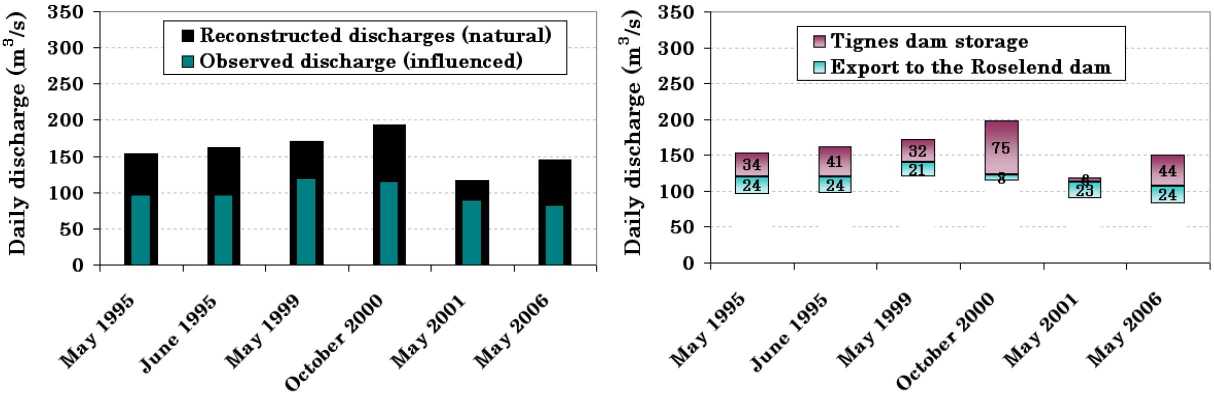

Figure 6: Explanation of the difference between the influenced and reconstructed natural discharges of Isere River basin in Moutiers **during floods**

A rather little storage was observed at Tignes dam for the May 2001 flood because the precipitation event has mostly affected the North-East part of the basin (right picture of the first row in Fig.7; EDF-Gottardi, 2009), where warm temperatures (right pictures of the both second and third row in Fig.7) caused liquid precipitations and therefore a significant export to Roselend reservoir. Regarding the October 2000 flood, a considerable storage in the Tignes reservoir can be noted (dark pink area in right part of the Fig.6 and middle pictures in Fig.8). This is explained by a typical regional meteorological circulation (called “East return”) that brings a lot of precipitation in the upper valley of the Isere River (middle picture of the first row in Fig.7). But only a very little export to Roselend was recorded while apparently indicated as consequent by the estimated precipitations and the both minimum and maximum temperatures (middle pictures in Fig.7). Three hypotheses are then issued: a clogging of water intakes which would stop the flow diversion to Roselend, an activation of a bypass system located just before the stream gauge which led to a flow measurement non-accounting or a bad estimation of the meteorology in this area.

Finally when the event is generalised (as in the case of other floods including May 1999, left pictures in Fig.7) with temperatures sufficiently positive to generate flows, the same type of functioning is observed: about 24 $m^3/s$ are exported to Roselend dam and between 30 and 40 $m^3/s$ are stored in Tignes dam (left pictures in Fig. 8).

So during floods, several conclusions could be drawn about operations of the hydro-electric waterworks:

- The storage in the Tignes dam can represent about one fourth of the natural flood at the outlet;
- The export to Roselend is done up to the capacity of water intakes (about $24m^3/s$);
- Only two-thirds of total natural flow is observed at the outlet of the basin;
- Diverted discharges of all water intakes do not depend on the event (no special management during floods), except those related to the South-East import which receive surplus that cannot be diverted to another dam (Mont-Cenis). Thus it becomes difficult to anticipate them but the modelling of these intakes is necessarily required to represent all inputs in Tignes dam.

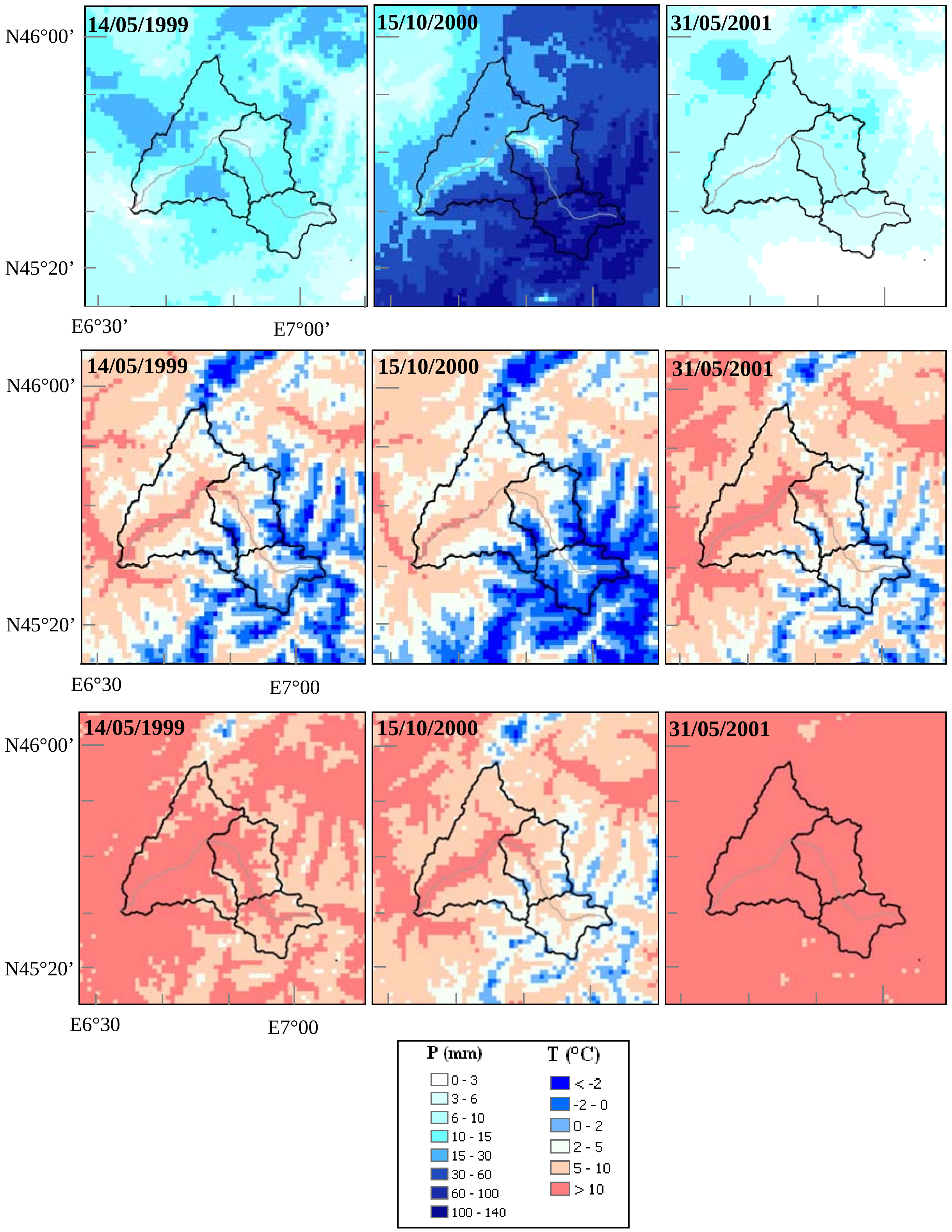

Figure 7: Spatial estimated values (EDF-Gottardi, 2009): **precipitation** (upper)**,** ***minimum*** (middle) and ***maximum*** (bottom) **temperature** for the Isere River basin in Moutiers

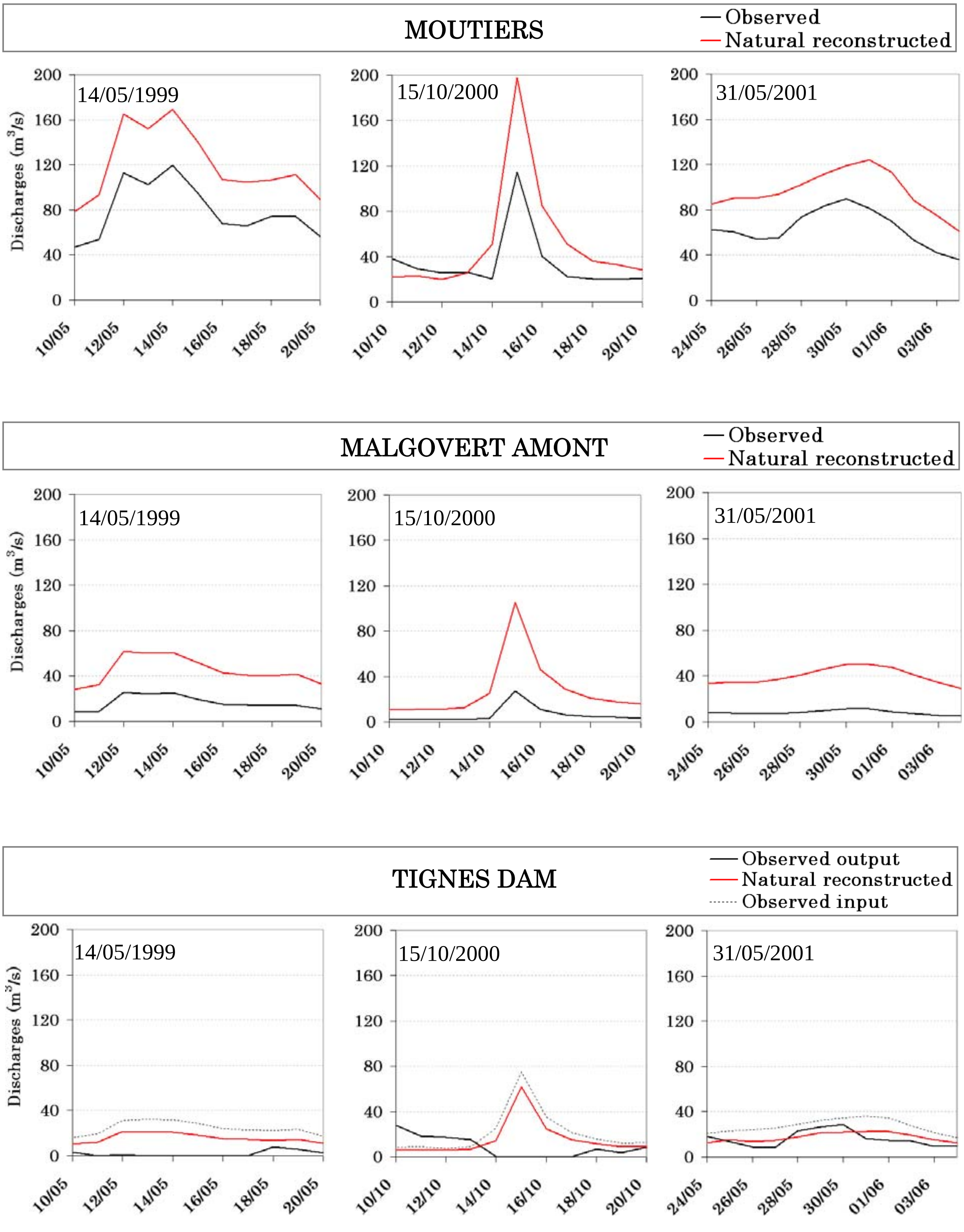

Figure 8: Reconstructed natural and observed discharges in Isere River in **Moutiers** (first row), **Malgovert Amont** (second row) and **Tignes dam** output (third row) for three flood days (from left to right : May 1999, October 2000 and May 2001)

## Hydrological modelling

The analysis of natural flow modification highlighted the role of the different waterworks during floods, suggesting how they have to be taken into account within the hydrological modelling. It was necessary to check that the model adequately reproduces the different imports, exports and storages affecting the basin and the peak flow at the outlet of the basin.

### Available data

The available data have been provided by EDF and MeteoFrance, the French national meteorological service. These include the daily observations of precipitation at 13 stations, of temperature at 8 stations, of discharges at 11 gauging stations (Fig.3) and flow features of water intakes (capacity, instream flows, etc.).

### Modelling tool: Routing System 2 (RS2)

The semi-distributed Routing System 2 developed at EPFL-Lausanne (Dubois et al., 2007) is operational in the Valais Swiss canton. Various model applications in Swiss Alpine catchments have shown that RS2 is capable of simulating all relevant hydrological processes observed in mountainous basins (Schäfli, 2005; Jordan, 2007). It allows representing both snow and ice melt by a degree-day method and the hydro-electric works operations. The model inputs are sub-basin spatial average values: precipitation (P), temperature (T) and potential evapo-transpiration (PET). The first two were estimated by the Shepard method embedded in RS2: the evaluation of a variable Xs from n stations localized at i=1,2,…,n is obtained by weighting the value of each station according to the inverse square distance between station i and the calculation point s (virtual station) located in general at the gravity centre of the sub-catchment. The altitudinal gradient was fixed for temperature (-0.5°C/100meters), but none was considered for the precipitation. The ETP was estimated by the Oudin's method (Oudin, 2004) that takes into account only the average temperature of the sub-basin and the extraterrestrial radiation incoming into the basin. The modelled outputs for each sub-basin are: snow depth (above a glacier or not), both melting and liquid rain, filling rate of the ground reservoir, real evapo-transpiration, base flow, runoff flow, and finally total flow at the outlet. There are 8 parameters to calibrate for each sub-basin: the degree-day factors (for snow localized above a glacier or not and glacier melt), the release coefficients of linear reservoir (snow and glacier), capacity and release coefficient of infiltration reservoir and Strickler coefficient for the surface runoff sub-model.

### Taking into account the hydro-electric works

Different representations of the hydro-power plants were tested leading to model architectures with various degrees of refinement that allow for a consistent representation of basin water imports-exports:

- A1 model: no hydro-electric work is considered and only the stream gauge at the outlet (Moutiers) is used to calibrate the model, thus only one sub-basin (left part in Fig.9);
- A2 model: only the storage variation of the Tignes dam is taken into account in the modelling and an intermediate stream gauge (Malgovert Amont) is used in complement of Moutiers, so the basin is split into 3 sub-basins (right part in Fig.9). As it is difficult to predict turbinated discharges of the Tignes dam output (which depend essentially on both the demand and the market of electricity), here it is introduced directly into the model from the available time series of Tignes dam outputs;
- A3 model: all hydro-electric works are represented: Tignes reservoir variations and water intakes and three control points are used: Moutiers, Malgovert Amont and the Tignes dam input (Fig.10). The Tignes dam outputs forcing is kept. The water intakes are characterised by the intake capacity Qc and the minimum discharge Qr to be reserved before any diversion. Then the diverted discharge is modelled through a simple linear relationship between the input discharge Qi and the intake capacity Qc: the diversion begins when Qi exceeds Qr and linearly increases with Qi up to Qc. To make modelling easier, the different intakes whose diverted flows join the same hydro-power plant were aggregated into a single equivalent water intake (total of 8), which lead to only 12 sub-basins.

### RS2 parameters calibration

For each model, two different set of runs were performed: one assuming that the catchment fully natural and for A2 and A3 models a run including the more or less refined description of the waterworks. In the first runs (natural catchment), parameters were calibrated and validated for pseudo-natural hydrological conditions, i.e. based on reconstructed natural discharges. Next, in the second runs, the hydro-electric works are taken into account, but using the previous parameters calibrated in natural conditions and the simulated discharges will now be compared to the observed influenced ones.

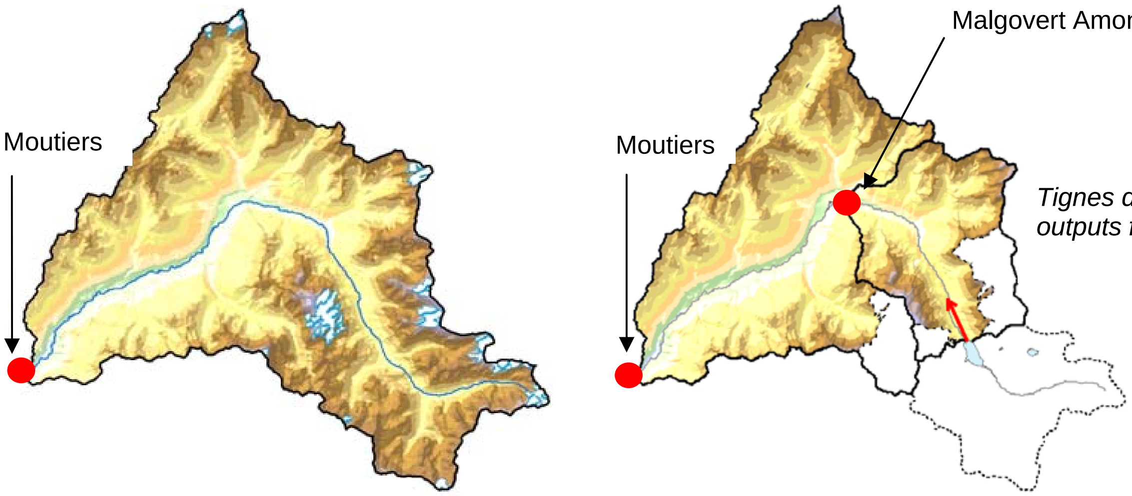

Figure 9: A1 and A2 models used to modelling the Isere River basin in Moutiers

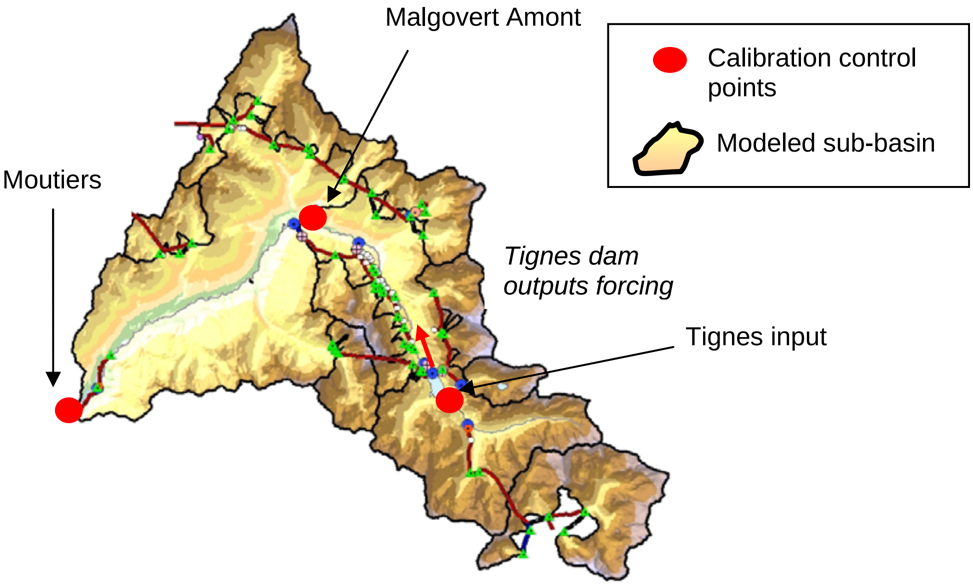

Figure 10: A3 model used to modelling the Isere River basin in Moutiers

Calibration was performed from 1st August 1999 to 31st July 2003, period during which the hydro-meteorology remained around normal (Fig.2) except for the wet year 2000 over which transfer parameters were calibrated to fit the timing of the October 2000 flood. The hydrological years of the validation period (1997; 1998 and 2003; 2004; 2005) were rather dry, except for 1998 where we assessed the ability of the calibrated model to reproduce the May 1999 flood.

The calibration was performed manually following a specific protocol (Verbunt et al., 2003; Verbunt et al., 2005; Jordan, 2007): the calibration of the snowmelt degree-day factors was realized only during the snowmelt periods (trying to fit the slope and the peak of the hydrograph) and the ice-melt degree-day factors during the end of this period corresponding to glacier melt. In the model, the capacity of the soil reservoirs and their release coefficients were calibrated according to the flows amplitude, giving special attention to the dynamics of the basin to fully reproduce the flood. Finally the release coefficients for snow and ice melt, and the Strickler coefficient were calibrated to fit the flood peaks. The criteria for assessing the quality of model simulations are 2 types (the optimal parameter combination must satisfy all these criteria):

- Numerical criteria: Nash (Nash et al., 1970), Volume bias (ratio simulated/observed discharges), classified flows, correlation between observed and simulated discharges;
- Visual criteria: flood hydrographs reproduction, low flows period level and melt period dynamics.

## Results

### Calibration (without waterworks)

A general and expected observation was made at this stage: the simulated flows are systematically underestimated relative to reconstructed flows (Fig.11 to 13). This is certainly due to the fact that most rain gauges are located in valley bottom and consequently the measurement network doesn't allow estimating representative precipitations for the entire basin. One solution would be to allow for a precipitation correction factor or to include a vertical precipitation gradient. But its estimation can be troublesome in mountain areas (Ranzi et al. 2003; Gottardi 2009). So for this study it was preferred not to consider any.

Nevertheless, the calibration period during which no waterworks were considered (into the three models) allowed the evaluation of the model sensibility to basin separation into several sub-basins. It showed logically that the more the spatial heterogeneity of precipitation and temperature are taken into account, the better the model simulations are. This is reflected into the correlation coefficients between reconstructed and simulated natural discharges that increase from 0.70 for A1 model to 0.82 for A2 model (Fig.11). The A2 model produces a better flows dynamics (especially at the beginning and the end of the melt period) because the consideration of high sub-basin (upstream of Tignes) and low sub-basin (downstream of Malgovert) allows generating both early and late snowmelt, therefore a better reproduction of flood periods (see red and blue hydrographs in Fig.12 and 13). The A3 model doesn't generate better correlation between reconstructed and simulated natural discharges (see the R² from A2 to A3 in Fig.11) because the calibration couldn't be further optimized due to the lack of measured control points downstream of each sub-basin (Fig.10). However this model simulates a better dynamics for snowmelt period (see its beginning and its end with blue and black hydrographs in Fig.12 and 13).

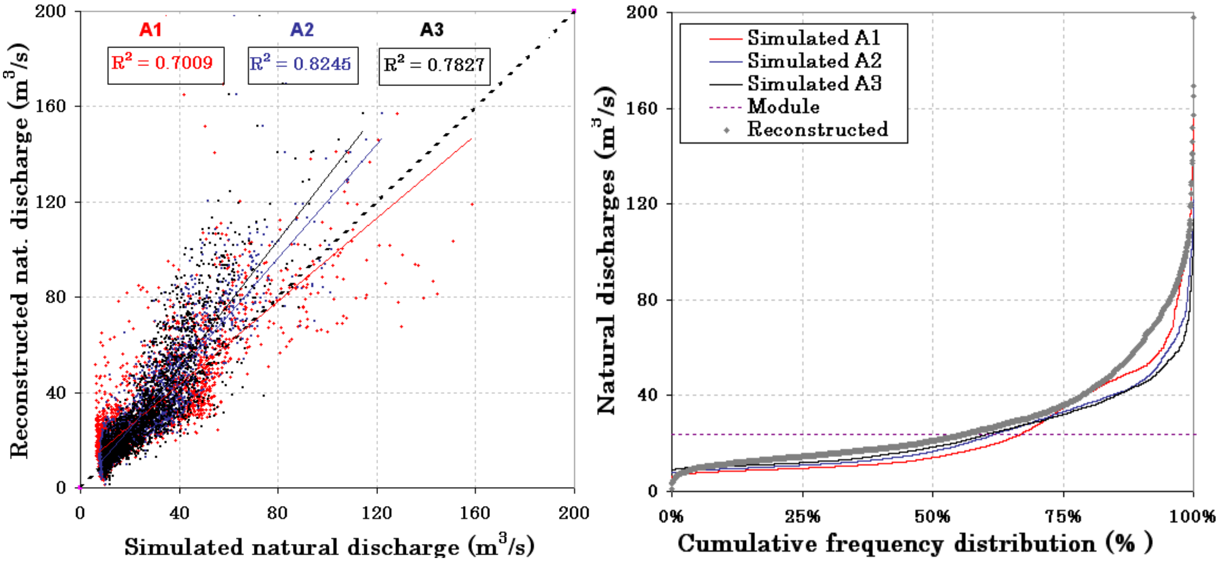

Figure 11: Correlation between the both reconstructed and simulated natural discharges for the three A1-A2-A3 models (left) and classified discharges analysis (right) (for the Isere River in Moutiers)

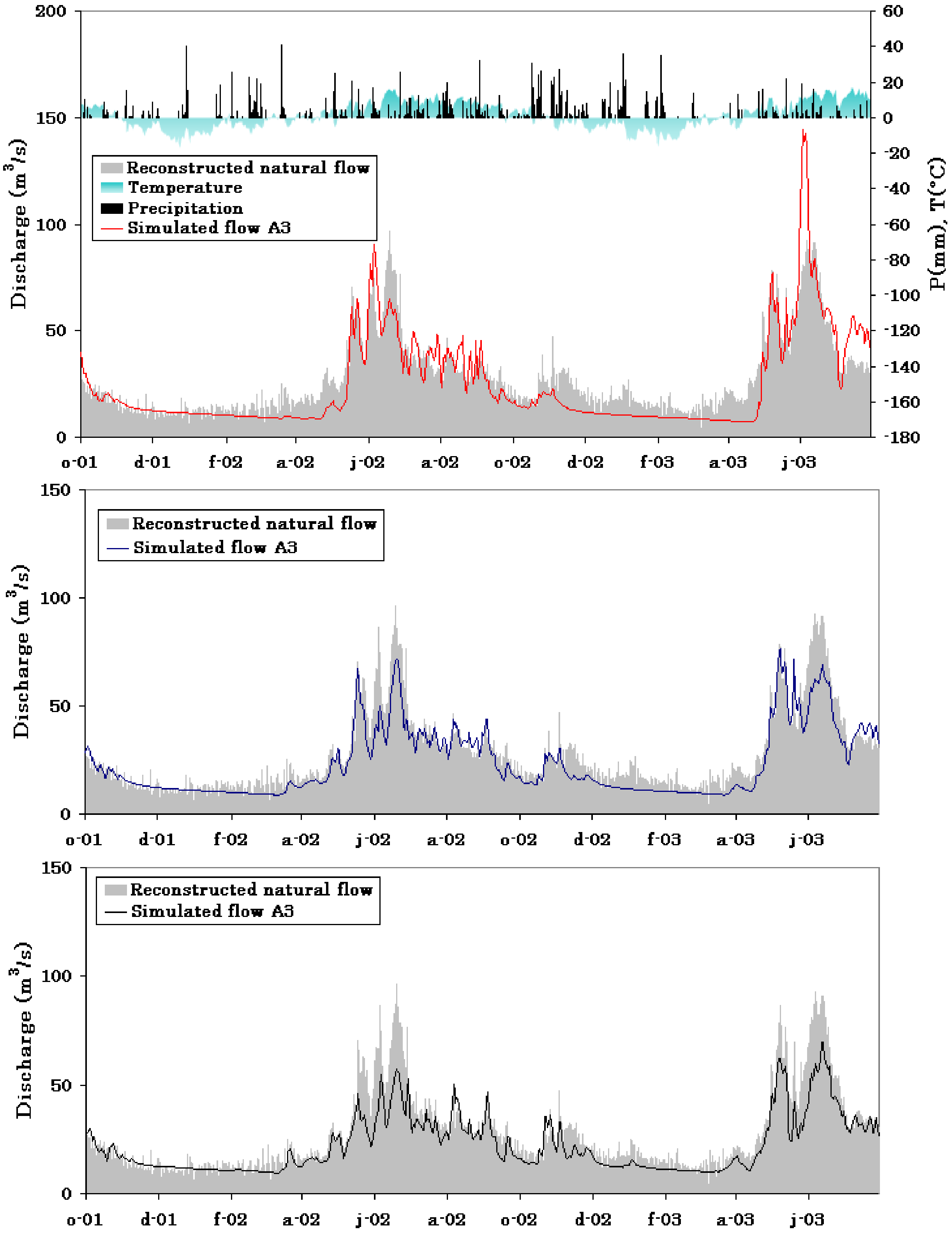

Figure 12: Result of simulations for the years 2001 and 2002 (from 08-01-2001 to 07-31-2003) and for the three model architectures without taking into account hydro-electric works (for the Isere River in **Moutiers**)

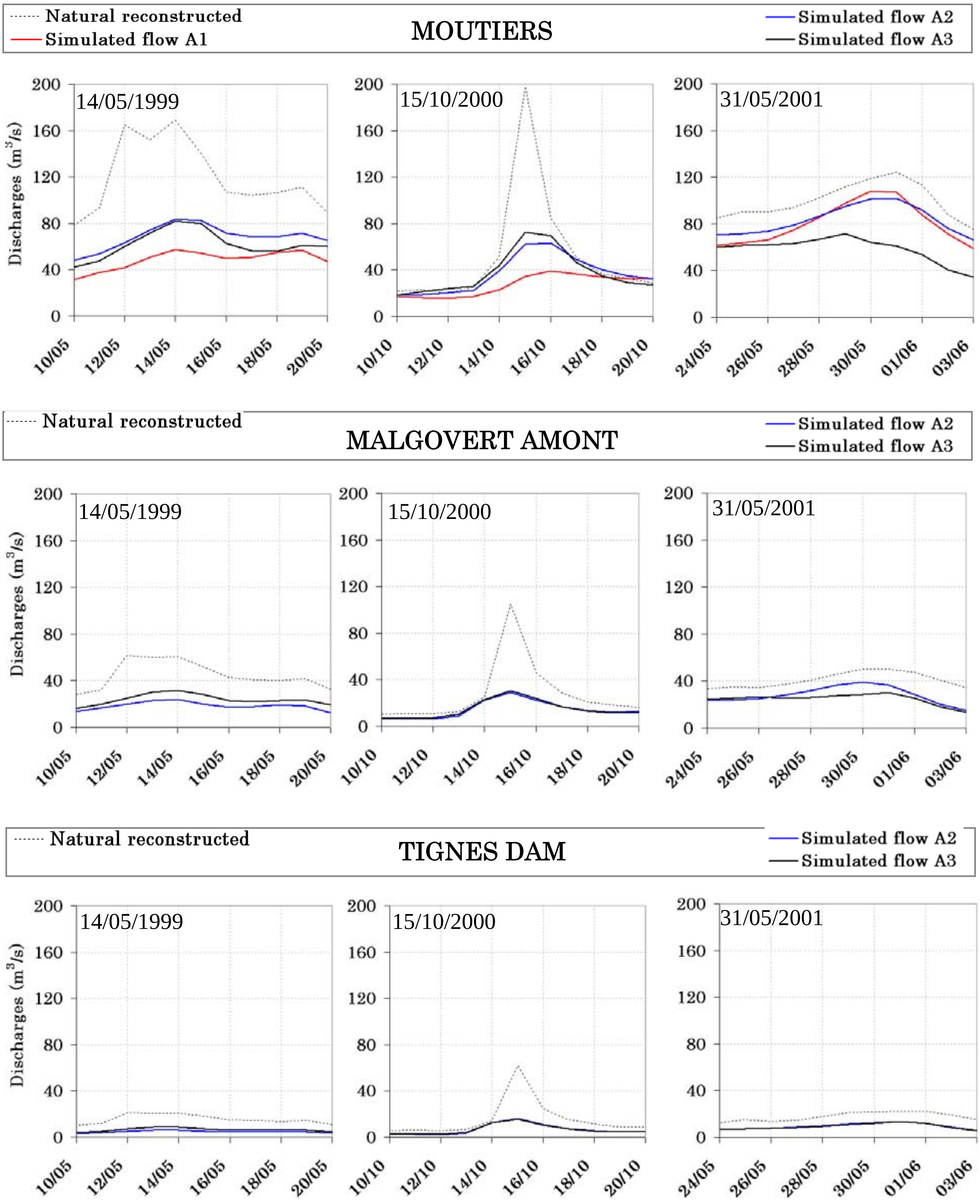

Figure 13: Reconstructed and simulated natural discharges in Isere River in **Moutiers** (upper), **Malgovert Amont** (middle) and **Tignes** (bottom) for three flood days (form left to right : May 1999, October 2000 and May 2001)

***Validation (with waterworks)***

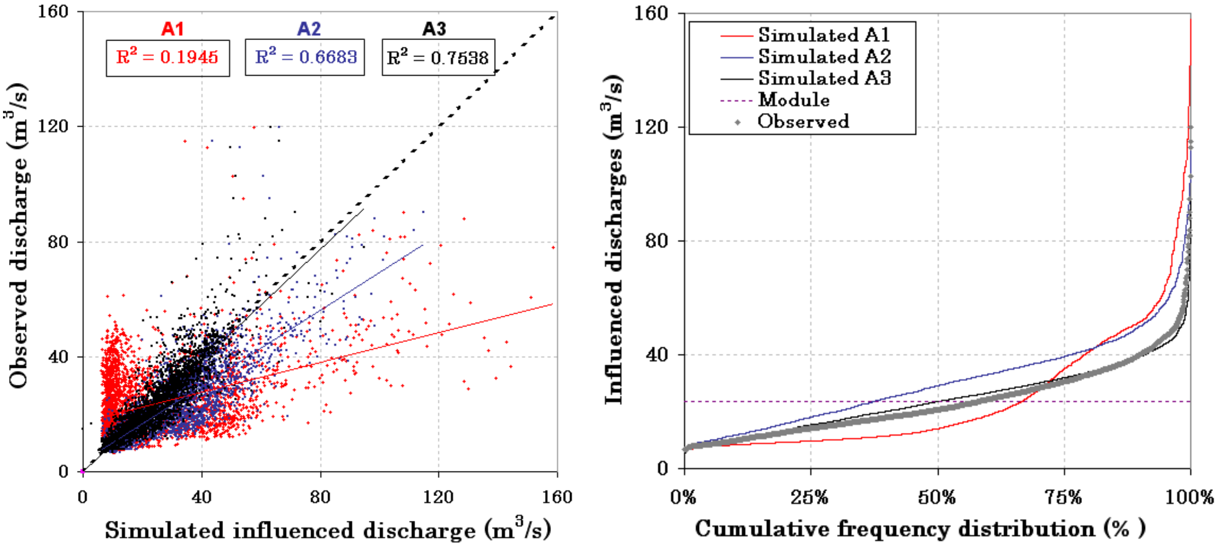

Figure 14: Correlation between the observed and simulated influenced discharges for the three A1-A2-A3 models (at left) and classified discharges analysis (at right) (Isere River in Moutiers)

Then in the second set of runs, the waterworks influences were taken into account into the model, keeping the same parameter calibration as the first runs (pseudo-natural conditions). The correlations between observed and simulated influenced discharges show the evolution of the simulations quality from A1 to A3 (left part in Fig.14).The mean annual Nash and Volume criteria for the whole simulation period (1997-2006) and for the three models were calculated. The Nash criterion logically increases with the degree of refinement of hydro-power works representation (Fig.15). The inclusion of Tignes dam storage variations into the model generates a significant increase of the Nash. These variations actually allow taking into account the Tignes dam release during the winter and also the spring snowmelt storage (red and blue hydrographs in Fig.16). Nevertheless, even if the volumes of storage and release are compensated annually, the simulated discharges are still overestimated (blue curve in Fig.14; Volume criteria is stable from A1 to A2 in Fig.15). Taking into account the export to the Roselend outside reservoir, the Nash criterion moves from 0.3 to 0.7 becoming acceptable and the Volume criterion comes very close to 1 (1.04). The discharge overestimation during the snowmelt period disappeared (difference between the blue and black hydrographs in Fig.16). Moreover, the model A3 seems to produce a better spatio-temporal structure during floods compared to the A1 and A2 models (Fig.17).

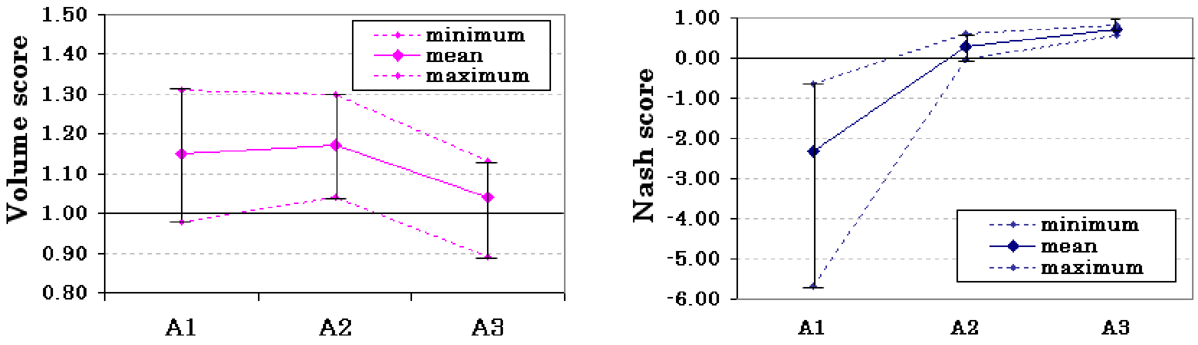

Figure 15: Mean annual criteria of Volume and Nash results for all the simulation period (1997-2006) and for the three architectures (for the Isere River in **Moutiers**)

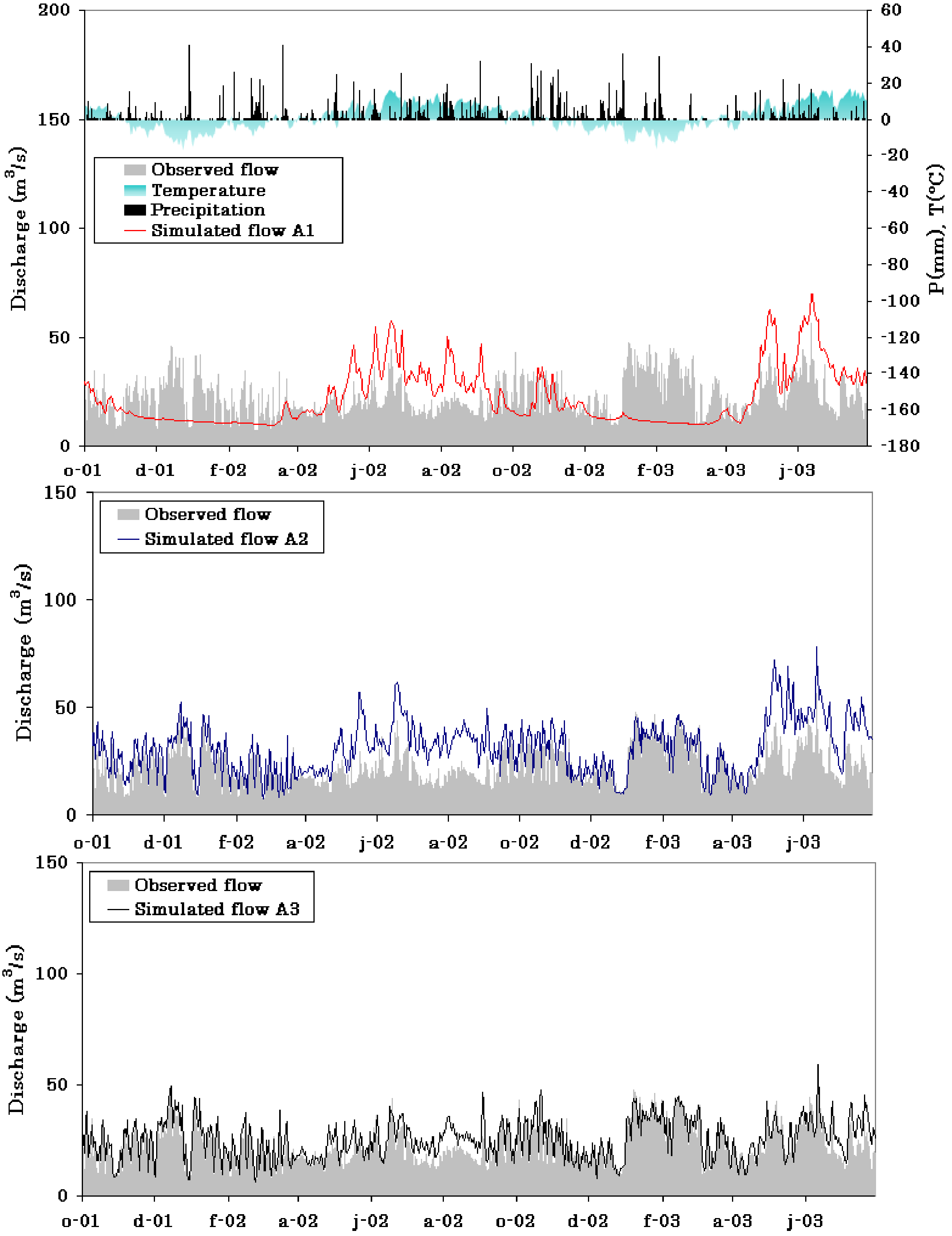

Figure 16: Result of simulations from 08-01-2001 to 07-31-2003 for the Isere River in Moutiers and for the three model architectures (**A1**: without any hydro-electric; **A2**: with Tignes dam storage variations; **A3**: with Tignes dam storage variations and export to Roselend)

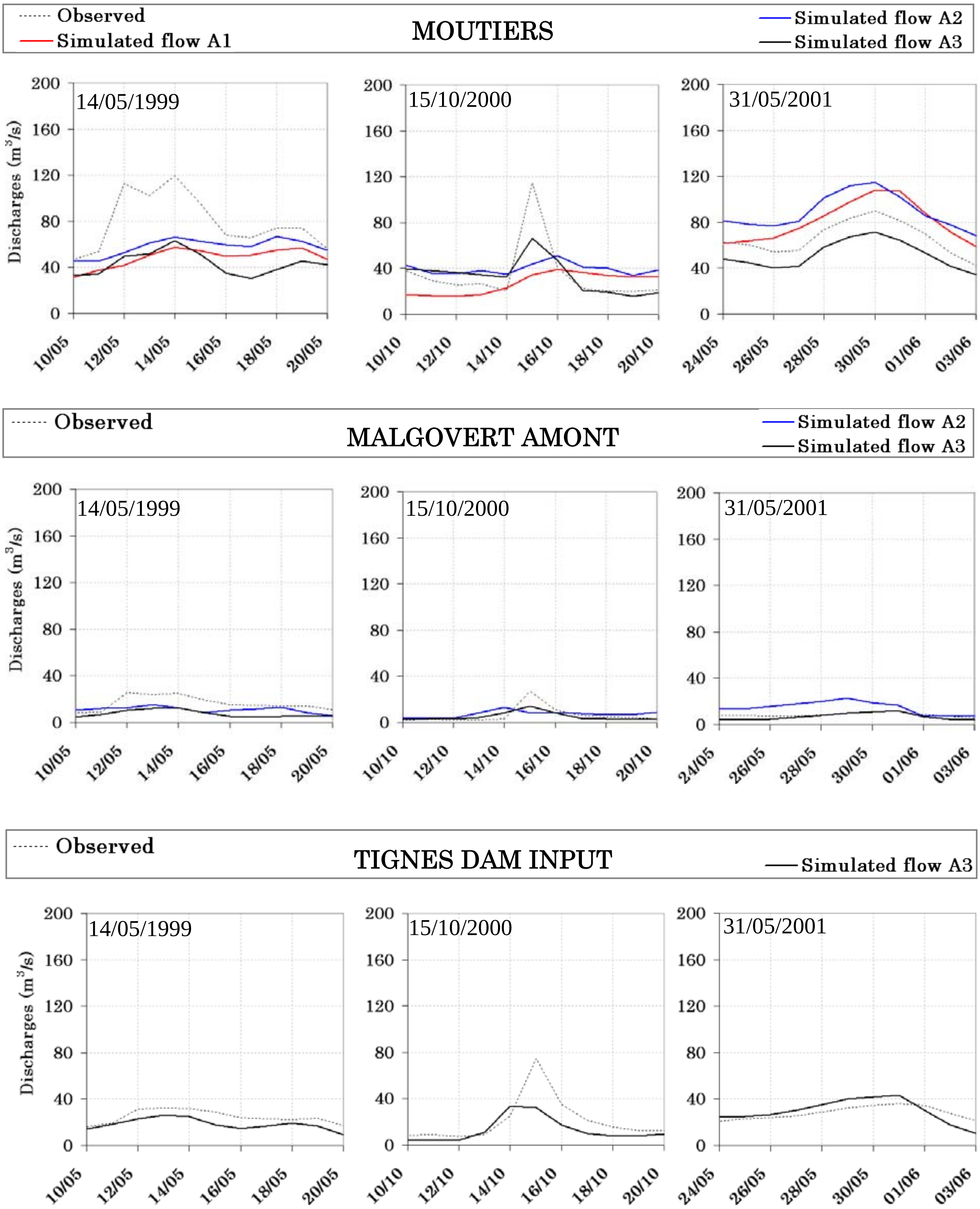

Figure 17: Observed and simulated discharges in Isere River in **Moutiers** (upper), **Malgovert Amont** (middle) and **Tignes dam output** (bottom) for three flood days (May 1999, Oct. 2000 and May 2001) and for three model architectures with different representations of hydro-electric works

## Discussion and conclusions

The analysis of natural flow modification helped to understand the impact of hydro-electric waterworks operations, firstly at the inter-annual scale and finally during individual floods. On the one hand one fourth of the snowmelt spring flows are stored on average in the Tignes reservoir and later turbinated by the hydro-plants during winter to meet the electricity demand. On the other hand, another one fourth of these flows is exported to the Roselend reservoir. Therefore, the Isere River flows in the Tignes outputs tend to exceed the natural flows because of the 3 imports into the dam. However at Malgovert they become in deficit because of the export to the Roselend reservoir and of the diversion immediately downstream from the Brevières plant to that of Malgovert. During floods, when the event is generalised with temperatures sufficiently positive to generate flow, the same type of operation is seen: about one sixth of the natural (reconstructed) flow of the Isere River at the Moutiers outlet is exported to the Roselend dam and about one fourth is stored in Tignes dam (depending on the event intensity).

So this analysis has highlighted the role of the different waterworks during floods, suggesting how they have to be taken into account within the hydrological modelling. A rather simple approach was developed to represent the snowmelt and the hydro-power operations. It allowed evaluating which model has the better architecture to reproduce the observed meteorological variability according to the available data. In this operational context of flood forecasting, it seems therefore necessary to privilege the A3 model that is not overall optimal but simulates better flood periods. The impact of waterworks on the simulated flows was assessed and allowed thus to reproduce the influenced observed flows of Isere River basin in Moutiers, with its hydraulic complex network that involves imports, exports and storages.

In perspective, several uncertainty sources were identified to explain the flood discharges underestimation: the precipitations estimation for which no altitudinal gradient was introduced, and the absence of account for the basin elevation (sub-basin separation, but not into in elevation band). This will be the subject of the next steps of the study currently in progress.

## Acknowledgements

The “Laboratoire de Constructions Hydrauliques” at EPFL-Lausanne has kindly provided the RS2 simulation package. MeteoFrance provided part of the available hydro-meteorological data used. EDF provided hydro-meteorological data, discharges data, waterworks characteristics and for some periods logs of their operations. This study is financed by a PhD grant from the “Service de Prévision des Crues” at DDT38. We greatly thank all of them.

## References

***Dubois, J. et al., 2007.*** *Modélisation des écoulements dans les systèmes hydrauliques: Routing System II, Communication 32, 70 p., ISSN 1661-1179.*

***Gottardi, F., 2009.*** *Estimation statistique et ré-analyse des précipitations en montagne. Utilisation d'ébauches par types de temps et assimilation de données d'enneigement. Application aux grands massifs montagneux français, PhD Thesis, EDF-DTG, INPG-LTHE, 249 p.*

***Jordan, F., 2007.*** *Modèle de prévision et de gestion des crues, optimisation des opérations des aménagements hydroélectriques à accumulation pour la réduction des débits de crue, PhD Thesis, EPFL-Lausanne, 267 p.*

***Jordan, F., 2007.*** *Real time decision-making during floods: application to the Upper Rhone River in Switzerland, Proceedings of the 32nd Congress of IAHR, Special session 10 (SS10-29-0), 10p.*

***Marnezy, A., 2008.*** *Les barrages alpins. De l’énergie hydraulique à la neige de culture, Journal of Alpine Research, Dossiers 96-1, p.92-102*

***Nash, J.E. and Sutcliffe J.V., 1970.*** *River flow forecasting through conceptual models, Part I, Discussion of principles, Journal of Hydrology, 10(3), pp. 282-290, doi: 10.1016/0022-1694(70)90255-6.*

.

**Oudin, L., 2004.** *Recherche d'un modèle d'évapotranspiration potentielle pertinent comme entrée d'un modèle pluie-débit global, PhD Thesis, ENGREF (Paris)- Cemagref (Antony), 495 pp.*

**Payan, J.-L. and al., 2008.** *How can man-made water reservoirs be accounted for in a lumped rainfall-runoff model? Water Resources Research, 44, W03420, 11 p., doi: 10.1029/2007WR005971.*

**Ranzi, R. and al., 2003.** *Runoff measurements and hydrological modelling for the estimation of rainfall volumes in an Alpine basin, Royal Meteorological Society, 129, pp. 653-672, doi:10.1256/qj.02.60.*

**Ritter, J., 1959.** *L'aménagement hydro-électrique du bassin de l'Isère, Annales de Géographie, Vol. 68, No. 365, p.34-53.*

**Schäfli, B. and Gupta, H.V., 2007.** *Do Nash values have value? Hydrological Processes, 21(15), pp. 2075 – 2080, doi: 10.1002/hyp.6825.*

**Schäfli, B. and al., 2005.** *A conceptual glacio-hydrological model for high mountainous catchments, Hydrology and Earth System Science, 95–109, SRef-ID: 1607-7938/hess/2005-9-95.*

**Verbunt, M. and al., 2003.** *The hydrological role of snow and glaciers in alpine river basins and their distributed modeling, Journal of Hydrology, 282, p.36-55, doi: 10.1016/S0022-1694(03)00251-8.*

**Verbunt, M. and al., 2005.** *The hydrologic impact of land cover changes and hydropower stations in the Alpine Rhine basin, Ecological modelling, 187, p.71-84, doi: 10.1016/j.ecolmodel.2005.01.027.*

**Vivian, H., 1994.** *L'hydrologie artificialisée de l'Isère en Amont de Grenoble. Essai de quantification des impacts des aménagements, Revue RGA, n°2, p.97-112.*

**Vivian, H. and Pupier, N., 1996.** *Crues et aménagements hydroélectriques. L'exemple des crues de l'Isère et du Drac à Grenoble, Hommes et Terres du Nord, p.13-19.*