The Decision Support Tool MINDS for Flood Management in the Upper Rhone River

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Abstract: *The Upper Rhone River is located in the Swiss Alps. Several hydropower schemes with large reservoirs were built in the catchment area, strongly influencing its hydrological regime. In past decades, several floods caused disasters in the catchment area. The MINERVE project aims to improve the flood protection safety, focusing on their prediction. Furthermore, the multi-reservoir system is optimally managed to limit or avoid damages during floods. A "Decision Support Tool" called MINDS has been developed for real-time decision making based on the hydrological forecasts. It proposes preventive measures as turbine and bottom outlet operations to the hydropower plants operators to provide an optimal storage capacity. The goal is to retain inflowing floods in reservoirs and to stop release during the peak flow. Such a reservoir management thus reduces the peak discharges in the Rhone River, thereby limiting the damages.*

Keywords: *Hydrological forecasts, hydropower operations, flood management*

1. INTRODUCTION

The catchment area of the Upper Rhone River is located in the Swiss Alps. It is characterized by high mountains, a surface of 5521 km^2 and elevations up to 4634 m a.s.l. Several hydropower schemes with large reservoirs are located in the catchment area, strongly influencing the hydrological regime of the river network.

During past decades, several flood events caused disasters in the catchment and showed the need of dealing with catastrophic inundations. The MINERVE project (Boillat 2009; García Hernández et al. 2009a) aims to improve the flood safety by reducing damages in this catchment area. The main objectives are to predict floods in advance for warning purposes and to optimally manage the multi-reservoir system to reduce or avoid damages during floods.

The hydrological forecast bases on the meteorological forecasts provided by MeteoSwiss and on a semi-distributed conceptual model, including all the hydraulic schemes. The hydrological forecasts are used to evaluate decisions concerning hydropower plants management for flood protection. A tool called MINDS (MINERVE Interactive Decision Support) has been developed for this purpose, as an improvement of a first deterministic management tool (Jordan, 2007). MINDS proposes preventive turbine and bottom outlet operations to the hydropower plants operators depending on discharge observations, hydrological forecasts and reservoir levels. The goal is to retain floods in reservoirs and to reduce their outflow during the flood peak. Appropriate operation regimes may reduce the peak discharges in the Rhone River and its tributaries, reducing or avoiding damages.

The model implemented in MINDS includes 21 reservoirs and 24 hydropower plants distributed in 10 independent groups (i.e. without any physical connections or interactions between them). The optimization of the preventive measures is done thanks to a Greedy or a SCE-UA algorithm. For the definition of the global function to optimise, different methods such as the mean risk have been used. Thereby, economical losses are minimized, taking into account the potential cost for the hydropower plants preventive measures and the expected damages caused by the flood. The parameters used for the optimization are the beginning and ending time of the turbine operations as well as the bottom outlet operations, respecting emergency rules and constraints of the system.

The simulation hydrological tool provides useful information regarding decision-making and the coordination of intervention measures if a catastrophic flood is expected. The hydrological outputs as well as the preventive measures serve as decision basis for the crisis task force.

2. MINERVE INTERACTIVE DECISION SUPPORT

2.1. Hydrological forecasts

The MINERVE system uses deterministic forecasts COSMO-2 and COSMO-7 as well as ensemble forecast COSMO-LEPS as inputs for the hydrological model. (García Hernández et al., 2009b).

The semi-distributed hydrological models Socont and GSM-Socont were developed within the frame of the project (Hamdi et al., 2005; Schäfli et al., 2005). The model was set-up with the hydrologic and hydraulic simulation tool Routing System II (García Hernández et al., 2007). This software was developed to simulate the formation and the propagation of unsteady free surface flows in a complex system. It allows hydrologic and hydraulic modelling by an object-oriented approach, according to the semi-distributed conceptual scheme. It takes into account special hydrological processes related to rain, evaporation, snow and ice melting as well as hydraulic process of valves, gates, water intakes, turbines or pumps.

An optimized software version provides ensemble flood predictions with all the available forecasts in real-time, coupling the observed measurements and the weather forecast information with the hydrological model (García Hernández et al., 2010). The hydrological forecast is updated whenever a new weather forecast is provided and real-time information is sent to the decision support system.

2.2. MINDS hydraulic model

The hydraulic model of the Upper Rhone River basin, as developed for the optimisation tool MINDS (MINERVE Interactive Decision Support), is a simplified approach to this complex catchment area (Fig. 1). It has been created for reservoirs management and real-time calculations. The model includes the most important reservoirs (RES) with their bottom outlets and spillways, the hydropower plants (HPP) with their turbines and pumps, as well as the main river network with the control points (CP).

Twelve of the 21 reservoirs are considered for water storage, including their level-volume relation. The other nine reservoirs have not enough storage volume to significantly affect the optimisation or to change the results. For that reason, they have been modelled as “punctual” reservoirs, working as elements which exclusively turbine, pump or derive flows according on their characteristics.

The hydropower plants are also included in the model. They connect two reservoirs, or a reservoir with a river network. If preventive measures are proposed, hydropower plants work at maximum capacity to limit the preventive measure time as much as possible. The main advantage of this assumption is that no added parameters are required. Preventive operations are generally realized with time restrictions and real operations should be near to this maximum. Nevertheless, decision maker could be test other final decision scenarios, such as proposing discharge values equal to the design discharges, checking the results in MINDS before applying them. The characteristics of the hydropower plants includes: the maximum discharge capacity, the hydraulic head, the plant efficiency and the current degree of discharge capacity (e.g. 0.8 if one of five equivalent turbine units is temporarily out of service).

Moreover, twelve control points (CP) on the river network are defined as locations with a potential for optimisation. Each CP is linked to its downstream neighbours, until the outlet of the entire basin at Porte du Scex. The critical discharge generating floods was individually defined for every CP. Once it is exceeded, a percentage of the total expected damage in the vicinity of the selected CP is considered. The expected damage increases following a power function (Section 2.3.1) depending on the maximum discharge expected at this CP for the entire forecast period. If the discharge reaches the assumed PMF (probable maximum flood), the expected damage is equivalent to the maximum damage as well. Thereafter, the damages are kept constant even if the discharge further increases. Furthermore, the CPs incorporate one additional characteristic: the possible breach opening ability (i.e. considering that certain CPs are source of damages and other CPs are “unbreakable”). Assuming that not all the breaches can be generated simultaneously, and that not all the CPs have the breach opening ability, a possible scenario has been created in advance with the collaboration of the survey authorities. This scenario provides a realistic breach opening ability at different CPs depending on the hydraulic and geotechnical characteristics expected to generate the biggest damages.

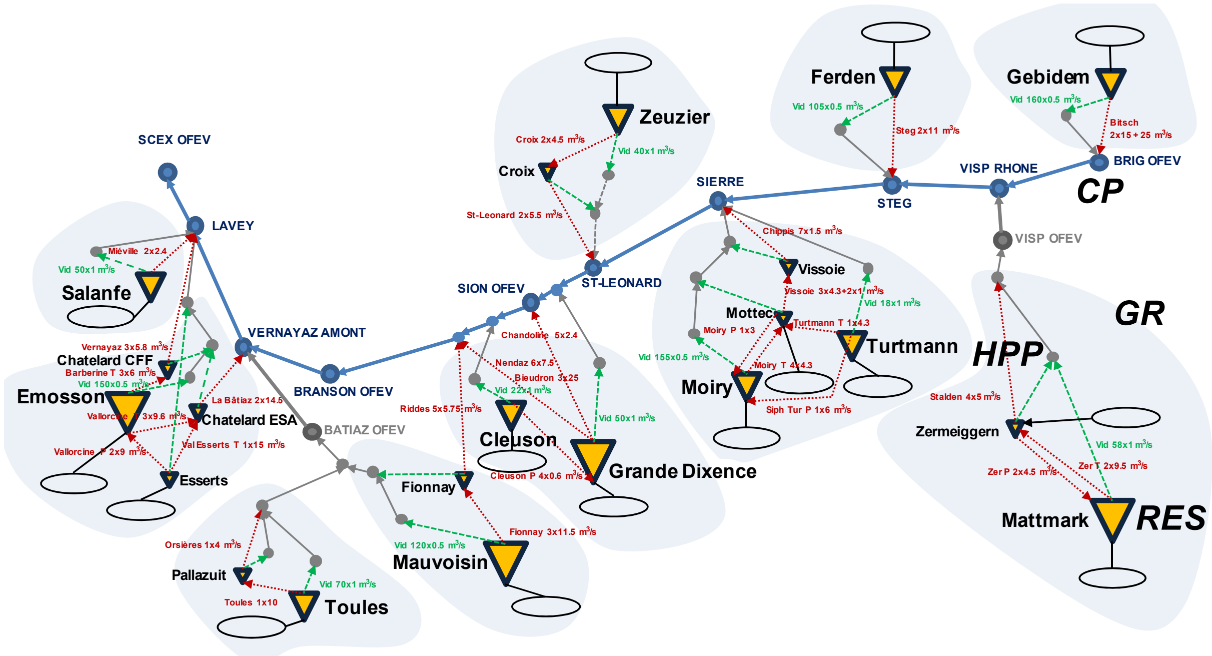

Figure 1 Scheme of the MINDS complex hydraulic model and its elements: the reservoirs RES (triangles), the bottom outlets and spillways (square dotted lines), the hydropower plants (round doted lines), the main river network (solid lines) and the control points CP (circles).

2.3. Optimisation system

The objective of the system is the minimisation of all expected damages and energy production costs in the Rhone River catchment area, upstream of a selected control point, which is usually identical with the control point located at the outlet of the entire basin, here Porte du Scex. Both, the expected damages and the energy costs are expressed as monetary values for comparison reasons.

Before starting with the optimisation computation, the expected damages in the catchment area due to the flood as well as the potential energy production costs of the hydropower plants resulting from preventive measures are investigated in a related section.

Once a control point CP at the downstream end of a considered area is selected, the objective function of the system is defined to minimise both, the expected damages and the energy losses upstream. The optimisation finds the optimal sequences of turbine, bottom outlet and pumping operations (start and end of each sequence) in the related hydropower plants. If no damage is expected, the system logically does not propose any preventive measures.

The energy production costs related to preventive measures simultaneously result in a maximisation of the reservoir volumes for the optimisation period. The reason is that preventive measures are done if they have an effect on the expected damages, and they are limited to the strictly necessary extend.

The inputs of the system are the hydrographs at the control points as well as the water inflows and initial levels of the reservoirs. The constraints are the usual ones for such cases, as the capacity of the turbines and pumps in the hydropower plants, the volume balance, the bottom outlet capacity, the emergency procedures and the reservoir spillway characteristics as well as the volume balance at the control points.

To solve the objective function, a *risk criteria analysis* (RCA) and an *Iterative Ranking Greedy Algorithm* (IRGA) are used. The RCA provides the mean risk function of the system based on damages and costs taking into account the weight of each member (i.e. particular forecast) of the probabilistic forecast. The IRGA allows the mathematical solving in series for all the investigated groups, searching the minimisation of the proposed function. Other functions based on the multi-attribute decision making theory have been also implemented on MINDS, among others: MinMax

Regret (Savage, 1951), TOPSIS (Hwang and Yoon, 1981) or an acceptable limited risk decided by the decision maker, but are not presented in this paper. Besides, the SCE-UA algorithm (Duan and al., 1994) has been also recently implemented for the objective function optimisation.

2.3.1. Expected damages and potential preventive measures costs

For the estimation of the expected damages (ED), the maximum discharge Q_{max} is computed in the investigated period at each individual control point (subscript *k*) CP_k. It is compared to the theoretical discharge for flooding ($Q_{fl,k}$) and to the probable maximum flood discharge $Q_{ex,k}$ at the same control point according to Eq. 1. If $Q_{max,k}$ exceeds $Q_{fl,k}$, an initial damage ($\delta^*ED_{max,k}$, $\delta \leq 1$) within the area affected the control point location is estimated. The maximum damage $ED_{max,k}$ occurs if $Q_{max,k} = Q_{ex,k}$. The total expected damages correspond to the sum of all the expected damages upstream of the selected CP location.

$$ED_k(a_{i_{set}}|f_j)=\begin{cases}0 & if\, Q_{max_k}(a_{i_{set}}|f_j)\leq Q_{fl_k}\\ \delta_k\cdot ED_{max_k}+(1-\delta_k)\cdot\left(\dfrac{Q_{max_k}(a_{i_{set}}|f_j)-Q_{fl_k}}{Q_{ex_k}-Q_{fl_k}}\right)^{1-\lambda_k}\cdot ED_{max_k} & if\, Q_{fl_k}<Q_{max_k}(a_{i_{set}}|f_j)<Q_{ex_k}\\ ED_{max_k} & if\, Q_{max_k}(a_{i_{set}}|f_j)\geq Q_{ex_k}\end{cases} \quad (1)$$

with a_{iset}: total set *i* of preventive measures in all the reservoirs; f_j : forecast *j*; δ: initial damage parameter, representing the percentage of initial damages compared to ED_{max} [-]; λ: exponent damage parameter [-]; Q_{max}: maximum discharge in the entire period studied [m^3/s]; Q_{fl}: flood discharge [m^3/s]; Q_{ex}: probably maximum discharge [m^3/s]; ED_{max}: maximum expected damages [Swiss Francs, CHF].

For the potential preventive measures costs (PPMC), the installed capacity (P) and the energy (E) are computed depending on the timely operating discharge sequences Q and head H of the hydropower plant *h*, HPP_h (Eqs. 2 and 3). If a reservoir is connected to several hydropower plants, the same preventive measure is provided for all of them.

The potential cost per reservoir *r* (RES_r) or group *g* (GR_g) are computed based on both the maximum energy selling prize (c_{max}) and the current estimated price ($c_{current}$) when preventive measures are realized (Eqs. 4 and 5). The current estimate price depends on time of day and on the week day, and is zero for bottom outlet operations.

$$P_{HPP_h}(a_{i_{RES_r}})=\rho\cdot g\cdot H_{HPP_h}\cdot Q_{a_{i_{RES_r}}}\cdot\eta_{HPP_h} \quad (2)$$

$$E_{HPP_h}(a_{i_{RES_r}})=\int_{t=t_a}^{t=t_b}\frac{P_{\mathrm{HPP_h}}(a_{i_{RES_r}})}{1000}\mathrm{dt} \quad (3)$$

$$PPMC_{\mathrm{RES_r}}(a_{i_{RES_r}})=\sum_{h=1}^{h=u}\int_{t=t_a}^{t=t_b}\frac{P_{\mathrm{HPP_h},\,\mathrm{HPP_h}\in RES_r}(a_{i_{RES_r}})}{1000}\cdot(\mathrm{c_{max}}-\mathrm{c_{current}})\mathrm{dt} \quad (4)$$

$$PPMC_{\mathrm{GR_g}}(a_{i_{GR_g}})=\sum_{r=1}^{r=h}PPMC_{\mathrm{RES_r},\,RES_r\in GR_g}(a_{i_{RES_r}}) \quad (5)$$

with ρ: water density [kg/m^3]; g: gravity, [m/s^2]; η: plant efficiency [-]; P_{HPPh}: installed power capacity [W]; E: energy [kWh]; PPMC: potential preventive measure costs [Swiss Francs, CHF]; $a_{i\ RESr}$: preventive measure *i* in the reservoir *r*; $a_{i\ GRg}$: set *i* of preventive measures in the reservoirs of the group *g*.

2.3.2. Risk calculation

Methods based on risk analysis are gaining importance as decision support tools in civil engineering applications (Faber and Stewart, 2003). The risk criteria analysis used in the present system is detailed hereafter.
The mean risk R_{ED} for the expected damages for a control point *k* (CP_k) is presented in Eq. 6. The risk of the total expected damages, upstream of the selected CP, are computed according to Eq. 7.

$$R_{ED_{CP_k}}(a_{i_{set}}) = \frac{1}{n} \cdot \sum_{j=1}^{j=n} \left(ED_{\mathrm{CP_k}}(a_{i_{set}} \mid f_j) \cdot P(f_j) \right) \tag{6}$$

$$R_{ED}(a_{i_{set}}) = \sum_{k=1}^{k=p} \left(\frac{1}{n} \cdot \sum_{j=1}^{j=n} \left(ED_{\mathrm{CP_k}}(a_{i_{set}} \mid f_j) \cdot P(f_j) \right) \right) \tag{7}$$

with n: total number of forecasts [-]; $P(f_j)$: occurrence probability of the forecast *j* [-]; p: total number of control points.

It is assumed that the potential preventive measure cost do not vary for different forecasts. Then, the risk for a reservoir *r* related to the energy losses of the preventive measures is presented in Eq. 8, for a group *g* in Eq. 9 and the total risk for all the groups summarized in Eq. 10.

$$R_{PPMC_{RES_r}}(a_{res_r}) = \frac{1}{n} \cdot \sum_{j=1}^{j=n} \left(PPMC_{RES_r}(a_{i_{RES_r}} \mid f_j) \cdot P(f_j) \right) = PPMC_{RES_r}(a_{i_{RES_r}}) \tag{8}$$

$$R_{PPMC_{\mathrm{GR_g}}}(a_{i_{GR_g}}) = \sum_{r=1}^{r=h} R_{PPMC_{\mathrm{RES_r}}, RES_r \in GR_g}(a_{i_{RES_r}}) \tag{9}$$

$$R_{PPMC}(a_{i_{set}}) = \sum_{g=1}^{g=s} PPMC_{GR_g}(a_{i_{GR_g}}) \tag{10}$$

with s: total number of groups.

Equation 11 shows the total mean risk R_{TOT} for a given total set of preventive measures ($a_{i\ set}$).

$$R_{TOT}(a_{i_{set}}) = R_{ED}(a_{i_{set}}) + R_{PPMC}(a_{i_{set}}) \tag{11}$$

2.3.3. Objective function

A coefficient for the risk of the preventive measures PPMC have been introduced to provide particular parameters useful for the end-users. The final risk R_{TOT} for a given combination of preventive measures ($a_{i\ set}$) is then (Eq. 12):

$$R_{TOT}(a_{i_{set}}) = R_{ED}(a_{i_{set}}) + \alpha \cdot R_{PPMC}(a_{i_{set}}) \tag{12}$$

with α: potential preventive measure cost coefficient [-].

Minimizing R_{TOT} of Eq. 12 results in the objective function of the system, f_{set}. It identifies the ideal preventive measures for the ensemble hydrological forecasts based on a mean risk assessment which depends on expected damages, potential costs and occurrence probability of the forecasts taken into account. Equation 13 shows the simplified minimum of Eq. 12, and Eq. 14 the extended form.

$$f_{set} = \min \left[R_{TOT}(a_{i_{set}}) \right] \tag{13}$$

$$f_{set} = \min \left[\sum_{k=1}^{k=p} \left(\frac{1}{n} \cdot \sum_{j=1}^{j=n} \left(ED_{\mathrm{CP_k}}(a_{i_{set}} \mid f_j) \cdot P(f_j) \right) \right) + \alpha \cdot \sum_{r=1}^{r=v} PPMC_{\mathrm{RES_r}}(a_{i_{set}}) \right] \tag{14}$$

with v: total number of reservoirs.

However, since calculation time increases considerably solving all preventive measures sequences at the same time (as confirmed with the SCE-UA algorithm), an *iterative ranking Greedy algorithm* procedure has been implemented in the process to solve the objective function (and the preventive measures) in different stages, reservoir by reservoir. This procedure (IRGA + RCA) decreases the calculation time for the real-time decision making task. In addition, it was shown that it does not affect the results concerning an optimal management of all elements in the considered Upper Rhone River basin (Jordan, 2007).

2.3.4. Iterative ranking Greedy algorithm

The IRGA allows the mathematical solving in series for all the hydropower plants. First of all, a hierarchy of priorities for the groups of the system is defined. Each optimisation stage represents, in the present case, the minimisation of the expected damages in the considered catchment as well as the minimization of potential costs as a result of preventive measures in the selected group. Thus, each optimisation stage is related to a group.

The hierarchy of the groups is given by their efficiency for storing water during a flood (Eqs. 15 and 16). Equation 15 provides the capacity of storage volume per reservoir. Equation 16 gives the final value of the relative storage volume (RSV) per group (summation of the individual values of its reservoirs). Finally, the groups are ranked from highest relative storage volume to smallest.

It is worth mentioning that the storage volume for this computation is taken into account from the moment when preventive measures in a hydropower plant finish (or from the initial time of the optimisation if there is no preventive operation), assuming that before the end of the preventive measures, releases does not influence the flood peak discharge.

$$RSV_{RES_x} = \frac{\int_{q_{RES_x}}^{t_f} (Q_{in_{RES_x}} - Q_{out_{RES_x}})dt}{\sum_{r=1}^{r=v} \int_{q_{RES_r}}^{t_f} (Q_{in_{RES_r}} - Q_{out_{RES_r}})dt} \quad (15)$$

$$RSV_{GR_w} = \sum_{r=1}^{r=h} RSV_{RES_r,\, RES_r \in GR_w} \quad (16)$$

with Q_{in}: water inflow; Q_{out}: water outflow; q : time when preventive measures stops, or zero if no operation was executed.

Then, a pre-defined ranking of the reservoirs of the group provides the order to optimise these reservoirs one by one. The global objective function (Eq. 14) becomes the objective function *x* (because it is related to the reservoir x) as presented in Eqs. 17 to 19.

$$f_x = \min\left[R_{TOT}(a_{i_{RES_x}})\right] \quad (17)$$

$$f_x = \min\left[\sum_{k=1}^{k=p}\left(\frac{1}{n}\cdot\sum_{j=1}^{j=n}\left(ED_{\mathrm{CP_k}}(a_{i_{set}} \mid f_j)\cdot P(f_j)\right)\right) + \alpha\cdot PPMC_{\mathrm{RES_x},\, RES_x \in GR_w}(a_{i_{RES_x}})\right] + \xi \quad (18)$$

$$\xi = \beta\cdot\sum_{r=1}^{r=v} PPMC_{\mathrm{RES_r},\, r\neq x} \quad (19)$$

with ξ : fixed cost of preventive measures for the not optimised hydropower plants.

The scheme shown in Fig. 2 summarises the detailed procedure. The optimisation is then obtained by a two-step exploration in the solutions space (with different density in the solutions exploration). It searches for the start and end of the preventive measures (turbine, pump and bottom outlet operations) for the ensemble of the forecasts in the hydropower plants linked to the optimised reservoir. First, the optimisation of the turbine and pump sequences is conducted. Afterwards, if flood damages still occur in the basin, the bottom outlet sequence is optimised.

The first exploration searches the sequence (start and end) of the preventive measures with a smaller density of potential solutions. The density is defined by the user, but pre-defined at four hours. Once this solution is found, a second exploration searches the optimal solution around the solution space of the first one. The calculation density is bigger in this case, normally the same than data coming from hydrographs and inflows (one hour in this system).

This optimisation is carried out for each reservoir of the system. If the preventive measures in the hydropower plants connected to the current reservoir are optimised, the operations of the hydropower plants of the other reservoirs are established in advance and kept invariable (ξ according to Eq. 19).

The optimization is performed several times by iteration until the optimum is found and the results do not vary anymore (expected damages in each sector and preventive measures costs in the reservoirs). In addition, the *iterative ranking Greedy algorithm* is re-computed before the next iteration and the hierarchy of the groups may be changed.

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→ For each iteration
      IRGA: Define priority ranking to optimise GR of the system
    → For each GR in the system (according to the rank order)
        → For each RES in GR (according to a pre-defined order)
              RCA: Resolution of the objective function x (Eq. 18)
          Next RES
      Next GR
      If ΔED & ΔPPMC = 0 (in two successive iterations) then
            Exit For (the optimisation finishes)
      End if
  Next iteration
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Figure 2 Scheme for the optimisation of the MINDS system

3. RESULTS

The optimisation of different past flood events with the presented decision-making tool has been realised. First results in resimulated past events (1993 and 2000 floods) provide a diminution of the flood peak higher than 10% thanks to the proposed preventive operations. Even with no perfect forecasts, the system is capable of presenting good results, especially because the inertia of all the hydrological system. Besides, coefficient α (for the PPMC) does not influence considerably the results for a range between one and two.

The results after an optimisation are presented in a clear and simplified way in order to be comprehensible for the end users, who partly do not belong to the scientific community. An overview of the possible losses before and after the optimisation is proposed for the whole basin. It follows a box plot representing the possible set of consequences and their associated occurrence probability.

Preventive measures include a certain risk which may generate monetary losses to the hydropower plants operators, who may then ask for economical compensations. The end user, i.e. the crisis task force, has to know precisely the probability that discharge thresholds are exceeded; where flood occur, when they occur, and the expected limitation of damages if applying preventive measures.

The control panel of MINDS provides the principal information necessary to decision makers during a flood situation displaying: optimum operation rules provided for every hydropower plant, flow hydrographs at the control points with and without preventive operation rules for the different forecasts, level variation in the reservoirs depending on operation rules and forecasts, and evaluation of associated risks related to the preventive measures scenarios.

4. CONCLUSIONS

The MINERVE system developed for the Upper Rhone River basin is currently operational. It allows simulating the discharge in the river network since it considers all hydraulic elements of the hydropower plants and dams, preventive turbine operations and water release for flood protection. The flood forecast system is the basis for the decision-making tool MINDS.

The decision support systems have become unavoidable for the optimization of complex reservoir networks with numerous objectives like hydropower generation or flood control. Further, flood management is always associated with uncertainty regarding meteorology, hydrology or a lack of knowledge. These uncertainties have to be appropriately addressed to develop a decision support tool being effective for flood management.

The program MINDS (MINERVE Interactive Decision Support) has been developed for preventive measures in reservoirs located in a catchment area based on probabilistic hydrological forecasts. It can be used by a crisis task force to limit flood damages. The strength of MINDS lies in its flexibility. If a certain river sector has a reduced flooding threshold and/or a turbine or a bottom outlet gate is out of service, the program recalculates the optimisation in real-time with the current characteristics of the system.

The preventive measures are proposed to the crisis task force of the Canton of Wallis, which decides whether or not to follow the preventive measures proposition and to impose them to the hydropower plants operators. Several conventions have been signed so far between the Canton of Wallis and the hydropower plants owners for possible economical compensations.

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