FLOOD FORECAST AND FLOOD MANAGEMENT MODEL

OPTIMIZATION OF THE OPERATION OF STORAGE POWER PLANTS FOR FLOOD ROUTING

Frédéric Jordan [1], Javier Garcia Hernandez[2], Jean-Louis Boillat [3] and Anton Schleiss [4]

ABSTRACT

A new model for flood prediction and management of the Rhone river basin is presented. This 5500 km^2 mountainous catchment area contains 10 major hydropower plants with their accumulation reservoirs. Based on a deterministic weather forecast, a new conceptual semi-distributed hydrological model provides a 72 hours lead time discharge forecast for the river network. It also provides the necessary input data for computing the optimal operation of the hydropower plants. The model takes into account snowmelt, glacier melt, soil infiltration, evapotranspiration as well as flood routing in rivers and reservoirs. It also uses the real-time weather and discharge measurements in order to adjust the hydrological forecast. The hydrological model was able to produce high quality discharge forecasts without real-time update and provides promising results with its transformation to an adaptative model. Another challenge presented in this study is the optimization of the operation of the existing hydropower plants during floods. The optimal operation is highly efficient for the reduction of the damages during such flood events. The first results highlighted its significant influence on flood peak reduction. The observed reduction of the peak discharge due to the alpine reservoirs was about 10% at the catchment outlet for the major flood events of 1993 and 2000 and the maximum reduction could have reached 25% with optimal operation of the hydropower plants during the same flood events.

Keywords: Flood, Hydrological Prediction, Optimization, Reservoir Routing, Decision Making

INTRODUCTION

Discharge prediction is an important information for the real-time management of river basins as well as storage reservoirs (Andrade-Leal et al., 2002; Bürgi, 2002; Jasper et al., 2002; Boillat, 2005). Typical applications are flood forecast in large river basins for emergency planning (Homagk et al., 1998; Koussis et al., 2003) and inflow forecast for optimized reservoir operations (Turcotte et al., 2004;). Different technologies exist for predicting discharge, which fit the numerous scales and morphologies considered.

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The management of multireservoir systems can be based on inflow forecasts. Assessing optimal operations is not trivial and necessits an appropriate strategy. The numerous variables controlling the sequences of water releases have to be optimized. Moreover, multiobjective optimization is to be considered (Labadie, 2004). Methods such as linear programming (Kumar et al., 2001), non-linear programming (Barros et al., 2003) or evolutionnary algorithms (Strafaci, 2001) are often used when a discharge forecast is available.

In this study, a new conceptual semi-distributed hydrological model is presented. This model takes into account snowmelt, glacier melt, infiltration, surface runoff and flood routing in rivers (Hamdi et al., 2005). Hydropower plants with their water intakes, aqueducs, reservoirs, pump stations, powerhouses as well as gated spillways are also accounted for (Dubois, 2005). Such semi-distributed models need a robust calibration procedure in order to avoid the dissimulation of hydrological errors. The numerous hydrological parameters have to be chosen according to the related region in a typical range of values. Moreover, the influence of the existing hydropower plants has to be considered. For this reason, multiple control points are used for the model calibration.

The presence of multireservoir systems in the catchment area offers a possibility to regulate floods by routing. In this case, preventive turbine or gate operation can be used for reserving storage volume in reservoirs during the flood peak. The high number and layout of the existing hydropower schemes creates a strong non-linearity in the system. For this reason, a deterministic optimization method was developed to assess the preventive turbine or gate operations (Jordan et al., 2005a). This model takes into account the influence of preventive operations on the electricity production and the potential damages at multiple control points in the river network. A simulation-optimization procedure was developed, which rapidly provides the optimal preventive operations. This procedure uses inflow forecasts in reservoirs and discharge forecasts at the control points as input. These data are introduced in a rule-based optimization model which result is the release schedule for each hydropower plant (HPP) connected to a large reservoir. This solution is checked by simulation before acceptance and application.

An application of the model is presented for the Rhone river basin upstream of Lake Geneva. This 5520 km^2 and mountainous catchment area contains 10 major hydropower plants with large dams and reservoirs. During the last flood events which occurred in 1987, 1993 and 2000, the flood routing in reservoirs contributed to the reduction of the peak discharge in the Rhone river of 10% to 15%. However, optimal preventive turbine and gate operations could have reduced the peak discharge by 25% to 30%.

HYDROLOGICAL MODELLING

In catchment areas with complex morphology, numerous hydrological processes may occur. In mountaineous regions, the presence of glaciers and snow has a strong influence on the hydrological response of the catchment area. Snowmelt and glacier melt have to be considered, as well as infiltration and surface runoff. The melt processes are temperature-driven. For this reason, the altitude of the sub-catchments is an important parameter. Moreover, typical deep valleys in such regions are characterized by variable and local precipitations. An appropriate model discretization which allows taking into account the spatial distribution of the precipitations during floods is needed.

A conceptual semi-distributed hydrological model was developed, which takes into account these morphological and meteorological characteristics (Hamdi et al. 2005). It is based on a previous version developed by Schäfli et al. (2005) for a daily time step. The general framework of the model can be described as follows: every sub-catchment is subdivided into elevation bands in order to account for temperature-driven processes. The elevation bands can be either glacier or non-glacier areas. The modelling concept is presented in Fig. 1 with the example of a sub-catchment composed of one non-glacier and one glacier elevation bands.

Every non-glacier elevation band is composed of a snowpack model and of soil infiltration and runoff model with serial connection. Based on temperature (T) and precipitation (P), the snowpack model simulates the time evolution of the snow pack (accumulation and melt) and produces an equivalent precipitation (P_{eq}) used as input for the soil infiltration and runoff model. This model also takes into account the potential evapo-transpiration (ETP). The resulting discharge (Q_s) is transferred to the sub-catchment outlet. Every glacier elevation band is composed of four different models a four-reservoir model. A snowpack model creates an equivalent precipitation (P_{eq}) which is transferred to a linear reservoir (R_N) and finally to the catchment outlet (Q_{NGL}). The glacier melt model creates a glacier melt discharge only when the simulated snowpack is zero (H_n=0). The glacier melt discharge (P_{eqGL}) is then transferred into a linear reservoir (R_{GL}) and the resulting discharge (Q_{GL}) to the catchment outlet. The final discharge at the sub-catchment outlet (Q_{tot}) is the sum ot these three contributions.

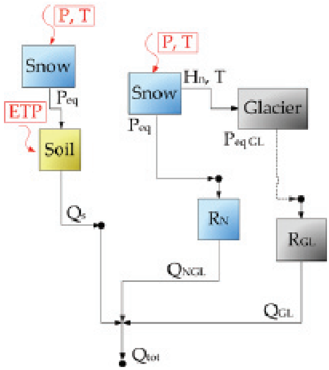

Fig1: Description of the hydrological modelling concept. Example of a sub-catchment with one non-glacier and one glacier elevation band.

The snowpack model is composed of two reservoirs (Fig. 2). The inputs of the model are the temperature (T) and the precipitation (P). At first, the precipitation is decomposed in solid precipitation (N) and liquid precipitation (P*) depending on the temperature (Equ. 1 to 3).

$$P^* = \alpha \cdot P \tag{1}$$

where P* = liquid precipitation in mm/h; α = separation factor; P = precipitation in mm/h.

$$N = (1-\alpha) \cdot P \tag{2}$$

where N = solid precipitation in mm/h.

$$\begin{cases} \alpha = 0 & \text{if } T < T_{cp1} \\ \alpha = (T - T_{cp1})/(T_{cp2} - T_{cp1}) & \text{if } T_{cp1} < T < T_{cp2} \\ \alpha = 1 & \text{if } T > T_{cp2} \end{cases} \tag{3}$$

where T = temperature in °C; T_{cp1} = low critical liquid precipitation temperature in °C; T_{cp2} = high critical liquid precipitation temperature in °C.
When the observed temperature is lower than T_{cp1}, there is only solid precipitation, and when it is higher than T_{cp2}, there is only liquid precipitation. When the observed temperature is in the range between the critical values, both solid and liquid precipitations occur. The solid

precipitation (N) is used as input for the snow pack reservoir, which content varies depending on precipitation, snowmelt or freeze. The snowmelt is calculated as follows:

$$\begin{cases} M_N = A_n \cdot (1 + b_p \cdot P^*) \cdot (T - T_{cr}) & \text{if } T > T_{cr} \\ M_N = A_n \cdot (T - T_{cr}) & \text{if } T < T_{cr} \end{cases} \tag{4}$$

$$\begin{cases} dH_N = (N - M_N) \cdot dt \\ M_N \leq N + H_N / dt \\ M_N \geq -W_N / dt \end{cases} \tag{5}$$

where M_N = snowmelt or freeze in mm/h; A_n = degree-day coefficient in mm/h/°C; b_p = coefficient in h/mm; T_{cr} = critical snowmelt temperature in °C; H_N = height of snow in m; W_N = water content in mm; t = time step in h.
The equivalent precipitation is produced by the water content reservoir (Equations 6 to 8):

$$\theta = W_N / H_N \tag{6}$$

$$\begin{cases} P_{eq} = P^* + W_N/dt & \text{if } H_N = 0 \\ P_{eq} = 0 & \text{if } H_N > 0 \text{ and } \theta \leq \theta_{cr} \\ P_{eq} = \frac{1}{K_f} \cdot (\theta - \theta_{cr}) \cdot H_N & \text{if } H_N > 0 \text{ and } \theta > \theta_{cr} \end{cases} \tag{7}$$

$$dW_N = (P^* + M_N - P_{eq}) \cdot dt \tag{8}$$

where θ = relative water content in the snow pack; θ_{cr} = critical relative water content in the snow pack; K_f = melt coefficient in h.

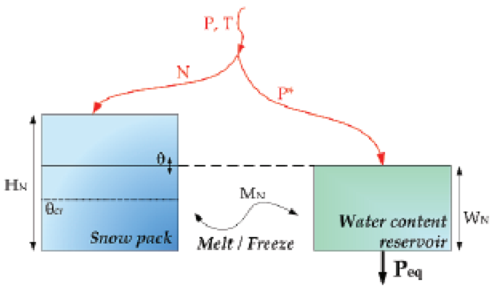

Fig2: Description of the snowpack model with its two reservoirs.

The glacier melt depends on the temperature and on the presence of snow over ice. The total glacier discharge depends on storage processes in the linear reservoirs R_N and R_{GL}. The snowmelt linear reservoir is described as follows:

$$dH_{NGL}/dt = P_{eq} - K_N \cdot H_{NGL} \tag{9}$$

where H_{NGL} = level in snow linear reservoir in mm; K_N = snow linear reservoir coefficient in 1/h (inertia of the glacier melt).
The outflow from the snow linear reservoir Q_{NGL} is:

$$Q_{NGL} = K_N \cdot H_{NGL} \tag{10}$$

The glacier melt Q_{GL} only happens when no snow is present over the glacier and when the temperature is higher than the critical glacier melt temperature. It is defined in Equations 11 to 13:

$$\begin{cases} P_{eqGL} = 0 & \text{if } \mathrm{T} \leq \mathrm{T_{cr}} \text{ or } H_N > 0 \\ P_{eqGL} = A_{GL} \cdot (T - T_{cr}) & \text{if } \mathrm{T} > \mathrm{T_{cr}} \text{ and } H_N = 0 \end{cases} \tag{11}$$

$$dH_{GL} / dt = P_{eqGL} - K_{GL} \cdot H_{GL} \tag{12}$$

$$Q_{GL} = K_{GL} \cdot H_{GL} \tag{13}$$

where P_{eqGL} = glacier melt in mm/h; A_{GL} = degree-day glacier melt coefficient in mm/h/°C; H_{GL} = level of glacier linear reservoir in mm; K_{GL} = glacier linear reservoir coefficient in 1/h (inertia of the snowmelt over glacier);
The infiltration reservoir is computed as follows:

$$\begin{cases} i_{\inf} = P_{eq} \cdot (1\text{-}(h/h_{\max})^2) & \text{if } h < h_{\max} \\ i_{\inf} = 0 & \text{if } h \geq h_{\max} \end{cases} \tag{14}$$

$$\begin{cases} ETR = ETP \cdot (h/h_{\max})^{1/2} & \text{if } h < h_{\max} \\ ETR = ETP & \text{if } h \geq h_{\max} \end{cases} \tag{15}$$

$$Q_{base} = k \cdot h \cdot S \tag{16}$$

$$\partial h / \partial t = i_{\inf} - ETR - Q_{base} / S \tag{17}$$

where ETP = potential evapo-transpiration in mm/h; i_{inf} = infiltrated intensity in mm/h; h = level in infiltration reservoir in m; h_{max} = capacity of the infiltration reservoir in m; ETR = real evapo-transpiration in mm/h; Q_{base} = base discharge in m^3/s; k = release coefficient in 1/s; S = surface in m^2.
The surface runoff resulting from the excess equivalent rainfall is estimated with a non-linear transfer reservoir (Equations 18 to 21).

$$i_{net} = P_{eq} - i_{\inf} \tag{18}$$

$$\begin{cases} dh_r / dt = i_{net} - i_r \\ h_r > 0 \end{cases} \tag{19}$$

$$i_r = K_s \cdot J_0 \cdot h_r^{5/3} \cdot B / S \tag{20}$$

$$Q_r = i_r \cdot S \tag{21}$$

where i_{net} = inflow runoff intensity in mm/h; h_r = level of runoff in m; i_r = outflow runoff intensity in mm/h; K_s = Strickler coefficient in $m^{1/3}$/s; J_0 = average slope of the plan; B = width of the plan in m.

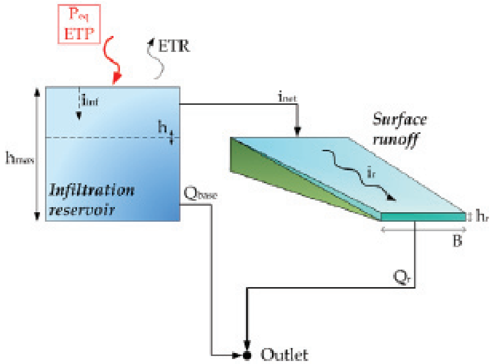

Fig3: Description of the infiltration and runoff model

MODELLING THE HYDROPOWER PLANTS

The hydropower plants are implemented in the hy-drological model. The object-oriented programming used in Routing System II (Dubois, 2005) allows to connect the different hydrological and hydraulic ob-jects automatically. The sub-catchment model is an object containing the different elevation bands. The water intakes are implemented downstream of their sub-catchment areas and connected to river reaches or junctions. Reservoirs, powerhouses or spillways are implemented easily as well (Figure 4).
In order to optimize the preventive operations on the HPP, it is necessary to compute and evaluate multiple operation schemes. The use of a numerical model computing at each time step all the hydrological parameters is inappropriate due to the time necessary to perform this task. For this reason, a simplified method was developed to calculate the optimal operation, presented in detail in (Jordan & al., 2005b).

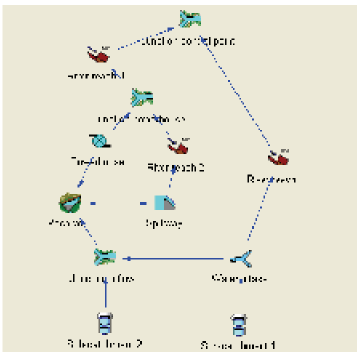

Fig4: Exemple of modelling a catchment area using *Routing System II*.

This method uses the predicted inflows in the reservoirs and water intakes and the predicted hydrographs at the multiple control points in the river network. The preventive operations are

obtained by optimizing of the routing effect of each reservoir. The influence of the HPP on the reduction of the peak discharge is estimated with the use of transfer functions. The optimization of operations is performed by computing cost functions associated to flood damages in a rule-based framework. The result of this procedure is the optimal turbine and gate operation schedule for each HPP.
The operation schedule obtained is finally introduced in the simulation model for validation.

MODEL CALIBRATION

Every sub-catchment area is described by numerous parameters which need to be calibrated. The calibration parameters for one glacier elevation band are A_n, A_{GL}, K_N, K_{GL}. The other parameters (b_p=0.0125, θ_{cr}=0.1, T_{cp1}=0°C, T_{cp2}=0°C, T_{cr}=2°C) are supposed constant. The calibration parameters for a non glacier elevation band are A_n, h_{max}, k, K_s. The number of parameters to adjust is very high when a sub-catchment contains multiple elevation bands. The calibration values are then supposed similar for every elevation band in a sub-catchment.

The calibration procedure follows simple rules according to the separation of the multiple contributions. As presented in Fig. 5 with the example of the Gletsch basin upstream of Brig, the different processes contribute to the total discharge at differ-ent periods. The snowmelt is produced during spring from may to June, after the constitution of snowpack during the winter season. The glacier melt is pro-duced in summer since July, when no more snow is present on the glacier elevation bands. At the same period, heavy precipitations may occur and produce floods due to the surface runoff process. The base flow is only produced by infiltration of snowmelt or liquid precipitations.

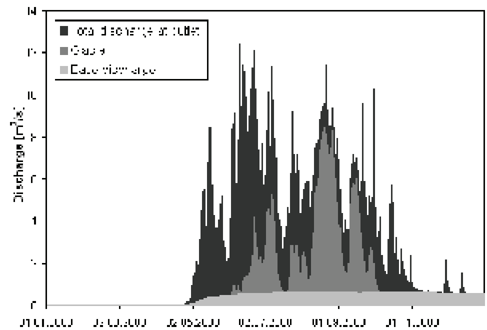

Fig5: Glesch basin. Contribution of the glacier elevation bands (gray) and the base flow (light gray) to the total discharge (dark gray). The discharge which is not produced by glacier melt and base flow is due to snowmelt (may to june) and surface runoff (july to november).

The calibration procedure follows the hydrological processes, which allows separating the different contributions. In fact, the parameters to be calibrated can be considered in a sequence following the annual hydrological cycle. The Nash indicator is used for the evaluation of the performance of the model (Nash and Sutcliffe, 1970). Concretely, the simulation period begins in October, which allows the snow pack to build-up during the autumn and winter seasons. The snow degree-day parameter A_n, which influences the total discharge from February to June, is first calibrated. The optimum value of this parameter is obtained, because there is no coupling with any other calibration parameter. The same justification can be applied to the next parameters to be calibrated: A_{GL}, K_{GL} and K_N. The soil infiltration parameters, which control the separation between base flow and runoff, are then calibrated. Finally the K_s coefficient, which only influences the flood events is adjusted. A result of this calibration procedure is presented in Fig. 6 for the Gletsch basin, where the annual hydrological cycle is well represented. The snowmelt period occurs from February to early June, before the first glacier melt period until middle of July. A second and third glacier melt periods occur until early October (year 2000). Finally, the flood of October 2000 is produced by surface runoff. The Nash indicator is 0.87 and the bias 0.98 during this simulation period.

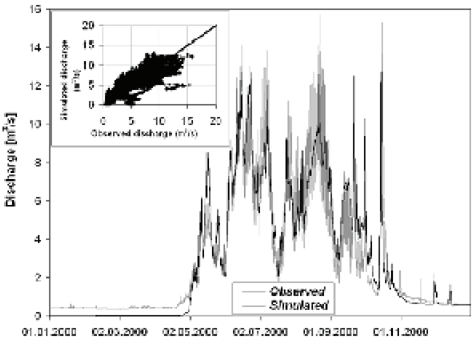

Fig6: Performance of the calibration procedure. Gletsch basin, simulated period 01.10.2000-31.12.2000, Nash=0.87, biais=0.98.

PERFORMANCE OF PREVENTIVE OPERATION BASED ON FLOOD FORECAST

The flood forecast allows representing the predicted hydrological situation for the next 72 hours. When damages due to river overtopping are supposed, flood management by preventive turbine or gate operations might be useful in order to mitigate the predicted damages. A rule-based deterministic optimization model was developed for the decision support during flood events. Using the hydrological forecast and the operation state of the existing HPP, this tool provides optimal operation schedules (Jordan et al., 2005a ; Jordan, 2007).

An application of the optimization model is presented for the flood of October 2000. The weather forecast is the one which was really available at this time. The presented flood forecast starts on the 13th of October 2000 and ends on the 15th of October 2000 at 23h00 (Fig. 7). The hydrological parameters issued from calibration are not changed. The initial conditions are set to the existing ones at the start date of the flood event. The initial state of the HPP is set to the real ones. As a result, the peak discharge without influence of reservoirs reaches 1423 m^3/s and occurs at hour 65. With optimal operation of the existing HPP, the peak discharge can be reduced at 1227 m^3/s. In fact, only 4 HPP need to operate and release water in order to store the maximum inflow. Based on the hydrological forecast, the 6 other HPP have sufficient available storage volume during the flood event. To assess the performance of the scheduled scheme we calculated the target hydrograph (lower limit). In this case, we suppose that all the reservoirs have a sufficient storage volume to store the incoming flood and that they do not need to release water during the flood event. Their damping effect is thus maximal and the flood obtained downstream corresponds to the minimal value of the flood hydrograph. As illustrated in Fig. 7, the hydrograph obtained with the scheduled scheme is very close to this target hydrograph.

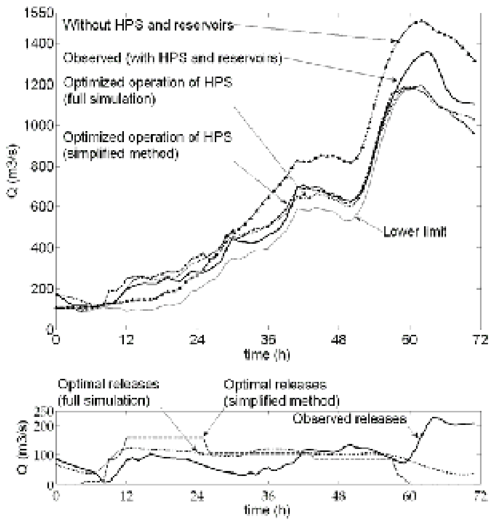

Fig7: Example of optimal operations based on the 72 hours flood forecast of the 13th of October 2000.

The example presented in this paper shows that the use of real forecasts allows to make appropriate decisions for the management of the reservoirs during floods.

CONCLUSION

A model for flood prediction and management of the upper Rhone river is presented. The semi-distributed conceptual hydrological model provides a hydrological forecast at numerous control points in the catchment area. This deterministic forecast is based on the weather forecast provided by the Swiss Weather Service. A model for the optimization of the preventive water releases by turbine or gate operation of the existing hydropower plants in the catchment area uses this hydrological forecast as input. The model provides the operation schedule and the modified predicted hydrographs.

The performance of the hydrological model was tested by continuous simulation over annual periods and the model revealed robust. However, the deterministic optimization of the turbine or gate operations is associated with a high level of uncertainty. Indeed, water can be lost or damages can occur by inappropriate operation. The deterministic optimization approach described here provides good information, but en efficient control of the system is necessary. The comparison between forecasts and field observations is important, as well as the update of the last forecast.

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