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Coupling hydrological models and wheather forecast for improved real-time management of water resources

A. Salvetti [a] [b], F. Pianosi[b], E. Weber[b], R. Soncini Sessa[b]

[a] *Dipartimento del Territorio, Ufficio dei Corsi d'Acqua, CH-6500, Bellinzona, Switzerland (andrea.salvetti@ti.ch)*

[b] *Politecnico di Milano, Dipartimento di Elettronica e Informazione, I-20123, Milano, Italy (pianosi@elet.polimi.it, weber@elet.polimi.it, soncini@elet.polimi.it)*

Abstract: The use of Stochastic Dynamic Programming for designing optimal regulation policies for water reservoirs networks is well established in the literature. However, the calculation of the optimal solution for many real problems is prohibitively time-consuming and this has motivated approximations, particulary in the description of the reservoirs inflow process. Furthermore the variability of climatic forcing and the continuous adaptation in the management of water resources required by economic iusses represent a challenge for developing adapting real-time optimizazion procedures. In this paper a real time control approach is proposed and applied to the case study of the multiprupose regulated lake Lugano, Switzerland. The lake operation problem is first solved at planning level (off-line), using ciclostationary long-term statistics of the inflow, and is then refined on-line using inflow forecast from a dynamical, non-linear, heteroscedastic model, that provides both the expected value and the standard deviation of the inflow forecast. The model is forced by all the hydrometeorological information available in real time, both rainfall and runoff measured at previous time steps. The effectiveness of the model in terms of the reservoir regulation is evaluated through simulation and comparison with the results provided by conventional homoscedastic inflow models and with a "perfect" forecast. Simulation results show that real-time control can significantely improve the system performances, especially for the purpose of flood control. The improvements are more significant by increasing the forecasting horizon.

Keywords: real-time control; reservoir operation; anticipatory management.

1 INTRODUCTION

Operational water managers are often informed too late about upcoming extreme events to take prompt actions and mitigate their effect. Real-time control (RTC) is an effective tool to enhance the manager's ability to respond to extreme events and ultimately improve water system mangement. In real-time control, the decision to be taken at each time is computed by solving an optimal control problem over a finite horizon starting from the current time step and updating the model of the system with all the available hydrometeorological information (both measurement and forecast). The optimal decision so obtained is implemented for the current time step and, at the following one, the entire procedure is repeated over a translated horizon (receding horizon principle) so that any new information can be included as soon as it becomes available.
Real time control is an anticipatory and adaptive management scheme. It is anticipatory since it allows for assimilation of weather and hydrological forecast that can be used to expand the forecasting horizon and react to forthcoming events in advance. It is adaptive because updating of the system model can include not only hydro-meterological forecast but also information on changed system conditions, like variations in the water users' demand or in the energy price (relevant for

hydropower), etc.
In this paper, real-time control is used to improve the operation of a regulated lake. Application of RTC to reservoir optimization is not straightforward as it must take into account two important features of reservoir systems [Soncini-Sessa et al., 2007]. Firstly, as reservoir managers must find a balance between the predicted costs over the short run and the long term costs, performances of RTC strongly depends on the proper definition of a penalty function over the final state of the receding horizon, which account for long-term cost. Secondly, in multipurpose reservoirs the management must seek for a compromise between the conflicting water uses. Given the inherentely multi-objective nature of the decision-making problem, the set of Pareto-optimal management policies is the solution to the optimal control problem, while the choice of one policy in this set is the result of a non-technical, subjective process of analysis of the Pareto frontier by the manager or negotiations among the stakeholders [Oliveira and Loucks, 1997].
Both issues cannot be resolved at real-time level, as current forecasting ability does not allow one to extend the forecasting horizon beyond several days, and the analysis of Pareto-frontier to choose a compromise management cannot be repeated at each decision time step. In this paper we propose and apply a two-level strategy. First, a set of Pareto-optimal policies is derived using historical time series of reservoir inflows, and discussion among stakeholders is promoted to single out the best compromise policy (planning level). At the management level, this best policy is refined using real-time control. The proposed procedure is applied to the case study lake Lugano, Switzerland.
The paper is organized as follows. In the next section, the case study area is described. Then, results of the planning phase are reported. Finally, the method adopted for real-time control (named POLFC, Bertsekas [1976]) is discussed and simulation results are reported. Comments and topics for futher research concludes the paper.

2 Case Study Description

The Lake of Lugano is a international lake, since its catchment (615 km^2) is divided between Switzerland (368 km^2, around 60%) and Italy (247 km^2, around 40%). It is an important resource for the territory, both from a socio-economic and an environmental perspective. In particular, the tourist sector related to the lake plays a not negligible role for the income of the whole region.
The catchment has a typical Prealpine pattern, characterized by quite steeply sloping mountain sides in the Northern part of the basin and by more gentle hills in the Central and Southern part. The average elevation of the catchment is about 1000 m a.s.l., a maximum elevation of 2150 m a.s.l. The pluviometric regime in the catchment is typical of sublittoral Alpine zones, characterized by high precipitation, about 1800 mm/year, not uniformly distributed during the year. As a consequence, the trajectory of the (median) inflow to the lake has an absolute minimum in winter and two peaks in autumn and late spring.
The hydrologic regime of the most tributaries is defined as Southern Nivo-Pluvial and Pluvial Regime, which are all characterized by a torrential runoff regime and a quite short time response (6-12 hours); therefore, floods caused by intense precipitations over the whole basin are fast and sudden. The regulation of the lake started in 1963, with the goal of reducing flood events in Lugano and, parallely, to stabilize the outflow from the lake, in order to increase the energy production of a hydropower plant constructed 1933 in the Italian territory.
Among the upstream Stakeholders there are the shoreline inhabitants, who own property that could be damaged by water during lake *floods* or whose activities could be negatively influenced by the effects induced by high lake levels. All the tourist operators are also shoreline Stakeholders, because they use the lake environment as a tourist attraction. The most important centre is Lugano (56'889 inhab.), in Switzerland. Just as in the upstream area, downstream inhabitants who own property that could be damaged by floods in the Tresa river or whose activities could be influenced by the effects induced by the variations of river flow are counted among the Stakeholders. Among the downstream Stakeholders the most important is ENEL, an italian hydropower company.

3 Planning the management of the lake

The interests to be considered in the lake operation were grouped into sectors, and a sector hierarchy was determined, and the indicators associated to its leaf criteria were defined by interviewing the Stakeholders representatives. It was decided to consider four design indicators relative to the sectors: *Upstream Flooding*, *Upstream Environment*, *Hydropower production* and *Upstream Tourism*. Based on the identified hierarchy of evaluation criteria, a single design indicator for each sector was identified that is a measure of the overall satisfaction of the sector and that is expressed by a separable functional.

As for the upstream flooding sector, the indicator *Average annual flooded area* was choosed.The sector *Upstream tourism* is described by means of a unique indicator, that defines the unsatisfaction of the sector as a function of the measured lake level at each time step t. For the *Upstream environment* sector the design indicator also considers an *Unsatisfunction Range* for the environmental quality of the lake as a whole. This time-variant range was identified by considering the intersection of the ranges defined for the single environmental indicators (erosion of the reed beds and reproduction of Cyprinids): inside this range the Unsatisfaction is equal to 1, outside this range is zero. The step-cost for the *Hydropower* sector was finally defined as the revenue obtained by the hydropower production.

To derive a set of Pareto-optimal management policies, a multi-objective optimal control problem was solved, using the above four indicators as objective functions. The lake dynamics is given by a mass-balance equation and the reservoir inflow is considered as a stochastic process. Two alternative inflow models were tested: an AR(0) model, where the inflow is assumed to be a white noise and an AR(1) model, which allows for lag-one autocorrelation. In both cases, the inflow is described by a log-normal distribution with periodic mean and standard deviation estimated over historical time series. The multi-objective problem is solved by the weighting method, which consists of solving a sequence of single-objective problems where the objective function is defined by a convex combination of all objectives. At each step a different combination of weights is used and the relevant single-objective problem is solved by *Stochastic Dynamic Programming*, using the *Successive Approximations Algorithm* (SAA) [White, 1963; Bertsekas, 1976; Soncini-Sessa et al., 2007]. By comparing the Pareto Frontier obtained with the two approaches it is possible

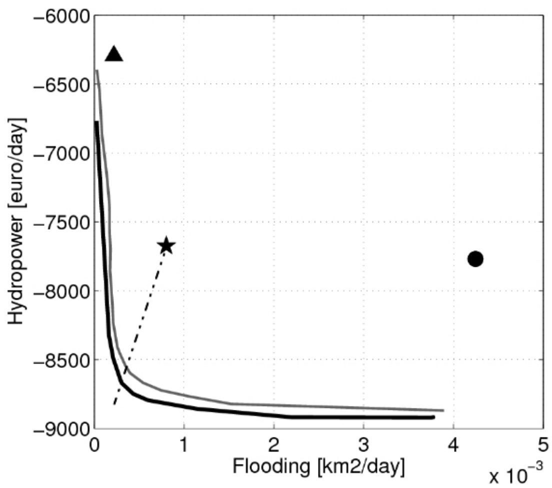

Figure 1: Projection of the 4D-Pareto Frontier for the design indicators J^{Hydro} and J^{Flood} with both the AR(0) and the AR(1) models. Circle = natural regime, Star = prescribed regime, Triangle = historical regime.

to quantify the basic trade-off between the complexity of a model and its predictive accuracy in

terms of design policies.
By analysing the different 2D projections of the Pareto Frontier and by considering only the upstream sectors it can be concluded that they are not conflictual. Figure 1 shows the Frontier for the two objectives J^{Hydro} and J^{Flood}, which are the most conflictual. The point corresponding to the *natural regime* has a quite low performance for the *Upstream Flooding* sector, as expected since this was the main reason for the construction of the dam. The *historical regime* was, on the contrary, trying to minimize J^{Flood} and the hydropower requirements were almost neglected, by causing a significant lost to energy production revenue compared to the performance it would be obtained by strictly applying the Regulation Licence.
For the *Upstream Flooding* sector the same performance are obtained both with the AR(0) and AR(1) model (also the utopia points are almost coincident for this objective), on the contrary for ENEL a reduction of the global revenue is obtained moving to the more complex AR(1) inflow model. It can be concluded that the information added to the system by considering the inflow measured the day before seems to be useless and even counterproductive for the hydropower production. A detailed analysis of the release trajectories obtained with the different models was carried out, in order to explain this surprising behavior [Salvetti, 2010].
Although on average, during several years the performance of the two models are almost identical, a disagreement between the daily hydropower production is usually observed during very long low flow periods or during the final part of a recession limb after a flood event, when the lake is close to its minimum level. When the inflow is continuously decreasing, the AR(1) model is in average more 'optimistic' than the AR(0), and water volume is lost in terms of hydropower production if the release is lower than the minimum volume usable from the turbines.
Since the Pareto-efficient solutions obtained only by considering J^{Hydro} and J^{Flood} have a very low performances for the *Environment* sector, a satisfactory compromise among the stakeholders could be identified by investigating the efficient solutions in a three-dimensional Pareto space. During a pre-negotiation procedure among the stakeholders, they decided to explore the region on the 3D-Pareto frontier, around the line connecting the point of the actual prescribed regime with the utopia points; based on these conclusions, one efficient AR(0) alternative was selected. In the following section the a priori policy refers to this selected point.

4 REAL TIME CONTROL

The a priori policy designed at the planning level is not directly implemented but rather it is refined at the management level by means of Real Time Control. This includes: (1) updating the system model based on real-time meteo-hydrological information and (2) solving the optimal control problem over a receding horizon. The two topics are discussed in the following paragraphs.

4.1 The inflow forecasting model

When formulating the real time optimal control problem, the model of the system is updated with all information collected up to the current decision time step. In the application presented in this paper, the lake dynamics is left unchanged, while the description of the reservoir inflow is updated at each step using measurements of past inflow and precipitation. Unlike most RTC applications, where hydrological models are used to generate a deterministic trajectory of the reservoir inflows, in our approach the inflow is regarded as a stochastic process also in real-time optimization. The difference between planning and management level is that in the former the inflow process is described by its unconditional probability distribution function (pdf), while in the latter the pdf conditional on available data is used.
In this study, the conditional inflow pdf is derived from a deterministic model by simply adding the deterministic inflow forecast with its error, which is described by a probability density function. The lumped, semi-conceptual LOGARMAX model described in Pianosi and Raso [2008] is used to compute the inflow forecast as a function of past observed inflows and precipitation. The model is calibrated using time series of observed precipitation and inflow over the period 1984-2000. Since the model is unbiased, forecasting errors are symmetrically distributed around zero and they can be described by a zero mean Gaussian distribution. Time series of errors over the calibration data set were used to estimate the error standard deviation.

Three different modelling approaches are compared: constant standard deviation model, periodic model, and dynamical model, which correspond to assuming the forecasting error be, respectively, a stationary, cyclostationary or heteroscedastic stochastic process. In the dynamical approach, the standard deviation is linearly related to past model errors and precipiation, thus accounting for heteroscedasticy and increased unpredictability during flood events [Pianosi and Raso, 2008].

4.2 The Real Time Control Scheme

The real-time optimization works as follows. At each time t, a stochastic optimal control problem over the finite horizon $[t, t+h]$ is formulated (on-line problem). For each time τ in the finite horizon $[t, t+h]$, the pdf $\phi_\tau(\cdot)$ of the disturbance is provided by the inflow forecasting model described in the previous section, which uses the hydro-meteorological information I_t available at time t. The on-line problem is solved and the resulting release decision for time t is applied. At time $t+1$, a new problem is formulated over the horizon $[t+1, t+1+h]$ with new pdfs for the disturbances, based on I_{t+1} (*receding horizon principle*). In our application, the information vector I_t includes the inflow and precipitation measurements up to time t.
The problem statement is

$$\min_{m_t(\cdot),\ldots,m_{t+h-1}(\cdot)} \quad \mathop{E}_{q_{t+1},\cdots q_{t+h}} \left[\sum_{\tau=t}^{t+h-1} \sum_{i=1}^{q} w_i g_\tau^i(x_\tau, u_\tau, q_{\tau+1}) + \breve{g}_{t+h}(x_{t+h}) \right] \tag{1a}$$

subject to

$$x_{\tau+1} = f_\tau(x_\tau, u_\tau, q_{\tau+1}), \qquad x_t \text{ given} \tag{1b}$$

$$q_{\tau+1} \sim \phi_\tau(\cdot|I_t) \tag{1c}$$

$$u_\tau = m_\tau(x_\tau) \tag{1d}$$

where x_t is the system state (reservoir storage), u_t is the decision (reservoir release), q_{t+1} is the disturbance (reservoir inflow), $g_t^i(\cdot)$ is the cost paid by the i-th water user in the time interval from t to $t+1$, according to the definition introduced in section 3 for the different sectors, $g_{t+h}(\cdot)$ is the penalty over the final state and $E[\cdot]$ denotes expectation.
Multiple costs are aggregated in (1a) using the same aggregation weights w_i that generated the a priori policy in off-line optimization, so that real-time control realizes the tradeoff that was agreed upon at the planning level. The penalty function $g_{t+h}(\cdot)$ is set to the optimal cost-to-go function computed when designing the a priori policy via Stochastic Dynamic Programming (see Bertsekas [1976] for details). This guarantees that the long-run costs are properly accounted for in the real time control.
Equation (1b) is the state transition function (the lake mass balance equation in our case), while $\phi_\tau(\cdot|I_t)$ in (1c) is the pdf of the disturbance (inflow) conditional on information I_t. Given the stochastic nature of the problem, minimization in (1a) is taken with respect to the sequence of control laws (or decision rules) providing the decision as a function of the state, see (1d), rather than the sequence of decision values.
This real time control scheme is referred to by Bertsekas [1976] as *Partial Open-Loop Feedback Control* (POLFC) and it can be solved via SDP.

4.3 Simulations results

The real-time control scheme was simulated over the year 2002, which is characterized by two extraordinary and independent flood events in May and November. Several simulation experiments were performed considering different models for forecasting the lake inflow and different lengths of the receding horizon. In all cases, the storage trajectories obtained with the a priori (off-line) and a posteriori (on-line) policy differ significantly only in the late spring and in autumn (the periods when most of the flooding events occur). By the end of November the a priori and a posteriori trajectories converge: the shortness of the control horizon h causes the real-time control scheme to generate only local perturbations of the system trajectories with respect to the a priori ones. Therefore, the performances of the different policies can be compared by simply comparing the average the step-costs paied over the simulation horizon, while the long-term performances from the end of the simulation horizon onwards are the same.

Receding horizon h=1 day. Let us first consider the results relevant to the case when 24 hours inflow forecast is used ($h = 1$) in the real-time control scheme. Table 1 reports the average value of the flooded area, the energy production, and the environmental cost over the year 2002, with the off-line policy and the real-time control fed by the inflow forecast from the LOGARMAX model with heteroschedastic, constant and periodic variance introduced in Sec. 4.1. The acronym MOD1 refers to the proper structure of the inflow model, MOD2 refers to a improper model structure which uses also a perfect precipitation forecast.
A global index I of the system performances can be obtained by linearly combining the three indicators with the coefficient values that were used for deriving the aggregate objective function of the on-line stochastic optimal control problem. As a matter of comparison, the results obtained by using the real-time control scheme with the perfect forecast are also reported (last row in the table).
It can be noticed that the on-line policies based on the different models, as aspected, performs better than the a priori policy with respect to flooding control; for energy production and environment protection the results with the off-line policies are not always dominated by the on-line ones. The results obtained with the perfect forecast represents the upper bound of the sector performances, which could be obtained if a perfect knowledge of the inflow process would be available.

Table 1: Indicator values with off-line and on-line policy (with different inflow models) over the period 1.3.2002-31.12.2002 with receding horizon = 1 day

control scheme	inflow forecast	i_{Flood} [km^2/day]	$i_{Flood}N$ [km^2]	i_{Hydro} [$Euro$/day]	i_{Env} -	I -
off-line	a priori	$8.6 \cdot 10^{-3}$	2.63	$1.107 \cdot 10^4$	$6.29 \cdot 10^{-2}$	$7.737 \cdot 10^{-1}$
POLFC						
MOD1	*heterosched.*	$7.7 \cdot 10^{-3}$	2.36	$1.094 \cdot 10^4$	$6.29 \cdot 10^{-2}$	$6.927 \cdot 10^{-1}$
	stat.	$7.3 \cdot 10^{-3}$	2.25	$1.096 \cdot 10^4$	$6.99 \cdot 10^{-2}$	$6.567 \cdot 10^{-1}$
	ciclostat.	$7.7 \cdot 10^{-3}$	2.35	$1.110 \cdot 10^4$	$7.34 \cdot 10^{-2}$	$6.927 \cdot 10^{-1}$
MOD2	*heterosched.*	$7.0 \cdot 10^{-3}$	2.13	$1.104 \cdot 10^4$	$5.59 \cdot 10^{-2}$	$6.297 \cdot 10^{-1}$
	stat.	$6.4 \cdot 10^{-3}$	1.97	$1.118 \cdot 10^4$	$4.90 \cdot 10^{-2}$	$5.757 \cdot 10^{-1}$
	ciclostat.	$6.7 \cdot 10^{-3}$	2.04	$1.120 \cdot 10^4$	$5.94 \cdot 10^{-2}$	$6.027 \cdot 10^{-1}$
	perfect	$5.9 \cdot 10^{-3}$	1.79	$1.123 \cdot 10^4$	$3.85 \cdot 10^{-2}$	$5.307 \cdot 10^{-1}$

In general, two issues are influencing the controller: on the one hand, the need for flooding control, which leads to increase the release; on the other hand, the need for saving water in the view of hydropower production (Hydropower objective), which leads to not release more water than the maximum capacity of the hydropower power plant. The on-line controllers favour the flood protection objective during the rising limb of the flood since the inflow forecast is more accurate than the a priori one; during the recession phase more water can be saved for hydropower generation.

4.4 Different lengths of the horizon

In order to understand the interplay between the length of the receding horizon and the time constant of the lake, the real-time control was simulated with increasing receding horizon ($h = 2$ and $h = 3$ days). The result for the Flooding sector are reported in Tab. 2. It is interesting to note that the improvement obtained by extending the receding horizon from $h = 1$ to $h = 2$ are almost negligible for all the three objectives. A further increase is obtained by enlarging the horizon ($h = 3$). With a perfect 3 days a-head inflow forecast it is possible to efficiently cope with the extraordinary flood of November 2002 and, in parallel, to modulate all over the year the

release according to the energy demand downstream. On the contrary, small flood events can be successfully managed also with a shorter receding horizon.
The simulation experiments with the heteroscedastic variance MOD1 and MOD2 show that the dynamic description of the error variance with increased receding horizon is able to further reduce the flooding costs compared to the a-priori policy but also to the same model with ciclostationary or stationary variance. As the Hydropower sector is concerned, a clear improvement of the performances obtained with the a-priori policy is not obtained and for the Environment sector the use of a heteroscedastic model of the error variance with $h = 3$ performs even better than the real-time control with perfect forecast.
The effectiveness of the inflow forecast with heteroscedastic variance is clear if a longer receding horizon (of length $h > 1$) is used in the real-time control scheme. This result can be explained

Table 2: Indicator value for the *Flooding Sector* with off-line and on-line policy with different inflow models and different length of the receding horizon over the period 1.3.2002-31.12.2002.

control scheme	inflow forecast	i_{Flood} $[10^{-3} km^2/day]$ $([km^2])$		
OFF-LINE	a priori	8.6 (2.64)		
		receding horizon		
		$h = 1$	$h = 2$	$h = 3$
POLFC				
MOD1	heterosch.	7.7 (2.36)	5.6 (1.73)	3.5 (1.06)
	ciclostat.	7.7 (2.35)	6.6 (2.01)	5.3 (1.62)
	stat.	7.3 (2.25)	6.5 (2.00)	5.8 (1.77)
MOD2	heterosch.	7.0 (2.13)	5.1 (1.55)	3.6 (1.11)
	perfect	5.9 (1.79)	5.5 (1.68)	3.8 (1.17)

by observing that the heteroscedastic model of the variance assumes that the residual absolute value is computed with a dynamical linear model (Eq. 2b), as function of past precipitation values and forecasting errors; more precisely the adopted model is a simple ARX(1,1) model defined as follows:

$$\sigma_t = \sqrt{2\pi}/2 \cdot E[|\varepsilon_{t+1}|] \tag{2a}$$

The following linear model was used to estimate the absolute value of the error

$$E[|\varepsilon_{t+1}|] = \alpha + \beta_1 |\varepsilon_t| + \gamma_1 p_t \tag{2b}$$

Since the concentration time is much shorter than 24 hours (the time resolution of the model) during very sudden flood events the error ε_t the day before the event is still small and also the precipitation is negligible or even null, and the estimated value of $E[|\varepsilon_{t+1}|]$ will be small too. By sudden event the underestimation of the error variance at the beginning of the event is crucial for the lake regulation and in this case the model with stationary variance of the inflow forecast yields a better overall performance. This phenomenon is less relevant if the precipitation event is more distributed in time and the lake level increases slower, as the November 2002 event, since the initial underestimation of the error variance can by easily compensated during the following days, when the heteroschedastic model performs better then all other models. Similar considerations can explain the results obtained with a stationary and ciclostationary model of the variance (see Tab. 1) with a receding horizon $h = 1$.
The real-time control scheme with the proper inflow forecast model (without rainfall forecast, MOD1) and heteroscedastic variance leads to an improvement of the system performances with respect to the off-line policy, from the flooding standpoint. However, the above evaluation concerns the global performance. If the whole trajectory of the step-costs $g_t^{Flood}(\cdot)$ is analyzed, it emerges that there exist single events where the a priori policy performs better than the a posteriori policy. For example, if we analyse the behaviour of the two policies during the Spring 2002 event

the off-line policy performs better than the on-line policy with heteroscedastic variance. The opposite behaviour can be observed during the fall event of 2002. The first case is a very impulsive Spring event and the proper heteroscedastic model with time-step equal to 24 hours is not able to cope with this flood and to anticipate the level increase (remember that the concentration time of the different watersheds draining into the lake is much shorter than 24 hours), the second event, although extraordinary in its magnitude, was casued by several consecutive days of medium rainfall intensity. The lake level increased slower and with the heteroschedastic model over the whole flood period the overall costs of the flood sector can be reduced with respect to the a priori policy. The model MOD2, feed with a perfect rainfall forecast and therefore not applicable for on-line optimization, further improve the overall performance as expected.

5 CONCLUSIONS AND FUTURE RESEARCH

In this study a cascade of an off-line optimal policy and an on-line policy based on the POLFC scheme is suggested for the design of an efficient management policy for a multipurpose reservoir, the Lake Lugano. The experiments were driven with different inflow forecasting models, with particular attention to a heteroscedastic approach for the modelling of the error variance.
Preliminary results discussed in the previous sections indicate that the on-line design of the management policy with the heteroscedastic error allows for an improvement of the system performances and especially for the purpose of flood control already with a one-step ahead horizon; this improvement is more significant for two- and three-step ahead RTC experiments.
However, conclusions are still preliminary since simulations refer only to year 2002, when a significant flood event happened. The choice of the period was conditioned by data availability and unfortunatly precipitation forecasts were available only for the sub-period 2004-2008, characterized by very dry regime and no flood event. Therefore, rainfall forecast of the high resolution MeteoSwiss COSMO-7 wheater forecast model have been used only for the validation of the heteroscedastic inflow forecasting LOGARMAX model but not for the real-time policy design. A precise quantification of the advantage provided by rainfall forecast in RTC still remains an open issue for future analysis.
A second research direction will address the use of probabilistic precipitation forecast (COSMO-LEPS *Limited Area Ensemble Prediction System*) for the assessment of the inflow forecasting uncertainty. COSMO-LEPS provides daily 5-steps ahead probabilistic forecasts at a very high resolution (horizontal mesh-size of 10 km) based on a 16-member ensemble for central and southern Europe and this will allow to further extend the receding horizon h of the POLFC experiments. Finally, the on-line design approach will be further extended to a subdaily basis, in order to benefit for the increased performances of the inflow forecast with 6 hours time resolution.

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