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A procedure for the quantitative assessment of water resources management under climate change and the design of adaptation measures

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Abstract: The pressure on water resources has tremendously increased in the last decades and water stress is expected to further augment in many part of the world due to multiple social, economic and climatic factors. Climate change (CC) will play a key role in determining water availability especially in those countries where other drivers like population growth or economic conditions are rather stable. A huge research effort is undergoing to better understand how CC may affect the hydrological cycle. In this paper, we propose and apply a procedure on the basin of lake Como, Italy, to assess the impact of CC on water-related activities. Traditionally, this is done combining model-based approaches (e.g. downscaling of GCM outputs coupled with hydrological models to obtain future discharge scenarios) and qualitative evaluations (e.g. visual inspection of simulated discharges). In the proposed procedure, quantitative assessment is extended from hydrological variables to the impact on human activities via simulation of the entire water system and evaluation of the impacts on flooding, agriculture, ecosystems, etc. through performance indicators. As this procedure allows for a quantitative, transparent evaluation of different management policies under CC scenarios, it also opens the way to a rigorous design of adaptation measures taking into considerations future discharge scenarios on the one hand and Stakeholders' needs on the other.

Keywords: climate change, water resources management, reservoir optimization

1 INTRODUCTION

A great effort has been devoted by the scientific community to the examination of historical climate trends and regional level projections of future climate change (CC), as well as CC potential effects on the water cycle at the basin scale. However, the impact of simulated discharge scenarios on water-related activities is usually analyzed with much less accuracy and qualitative assessment prevails over quantitative approach. Recently a new research effort is being paid to extend quantitative assessment from hydrological variables to the very impact on human activity, at least for hydropower production (see Schaefli et al. [2007] and references therein).
Quantitative assessment is essential to plan effective adaptation measures to CC at regional and local level, since it provides the knowledge base to support decision-making in a rational and reproducible way. This is of fundamental importance also to increase public awareness and promote Stakeholders' participation; as stated by EEA [2009], "until now no reports on the impacts of CC on the water resources of the European Alps have included specific Stakeholder-oriented information on strategies to adapt to these impacts" (p. 18, sec. 1.2).
The goal of the present study is to develop a procedure for the quantitative assessment of the CC impacts on water-related activities.

The conceptual workflow of traditional approaches to CC assessment at the basin scale is depicted in Figure 1a. Data analysis and mathematical modelling are used to downscale Global Climate

Models (GCMs) outputs, thus obtaining future climatic scenarios at the regional scale, and to derive future discharge scenarios via simulation of hydrological models. The evaluation of simulated discharge scenarios is then committed to experts, who provide a qualitative assessment, for instance by analyzing the future duration curve or the average monthly/weekly discharges.
The quantitative procedure here proposed requires adding to the above two-steps procedure, the following phases: simulation of the water system management under future discharge scenarios and evaluation of the impacts on water-related activities (i.e. flooding, agriculture, hydropower generation, etc.) by means of performance indicators (Figure 1b). Both tasks are not trivial as they require a deep knowledge of the system functioning in all its aspects, from engineering to social and economic issues.
Simulating the system management requires modelling the behaviour of the reservoir managers. In this study, we formulate the decision-making problem faced by the human regulators as an optimal control problem. We use multi-objective optimization techniques to derive Pareto-optimal management policies, thus obtaining an upper-bound of system performances that may be achieved by a fully rational decision-maker.
The definition of performance indicators is even more challenging a task, especially when not strictly economic issues are concerned (e.g. evaluation of changed hydrological regime on the riparian ecosystems) or when the relation between water availability and economic outcome is complicated (for instance some irrigation districts in Northern Italy can resort to multiple surface and underground water sources at different costs, so that the economic impact of a water shortage is highly variable and difficult to estimate). Defining and validating indicators usually requires a long and complex process of knowledge elicitation from experts and Stakeholders' representatives [Soncini-Sessa et al., 2007], so that one can guarantee that the analysis will account for the true expectations and needs of the water users.
Besides allowing for a transparent and reproducible evaluation of the potential impact of CC, the proposed approach also constitutes a first step towards the assessment of potential adaptation measures within a quantitative, objective-as-possible, framework: it opens the way to a rigorous design of adaptation measures taking into consideration the future discharge scenarios, on the one hand, and the Stakeholders' needs, on the other (Figure 1c).

The proposed procedure will be applied to the real world case study of the Como basin (Italy), including lake Como, a multipurpose regulated lake mainly operated for irrigation, and several upstream hydropower reservoirs.
The paper is organized as follows. In the next section, the case study is briefly introduced. Section 3 illustrates the modelling tools used to apply the procedure in Figure 1b to the case study. Simulation results are reported and commented in Section 4. Limits of the proposed approach and topics for further research conclude the paper.

2 THE LAKE COMO CASE STUDY

Lake Como is a regulated lake in Northern Italy; its storage is about 254 Mm^3 and it is fed by a 3500 km^2 catchment. The catchment, situated for the most part on the Italian Alps, is characterized by the classical alpine hydrological regime with scarce inflows in winter and summer and high in autumn and late spring. The regulation of the lake aims to attenuate flooding along the lake shores, especially in Como city, and to supply downstream users (5 irrigation districts and 9 run-of-river power plants) through a wide network of canals. The lake catchment area is in its turn covered by a dense network of smaller artificial lakes operated for hydropower production. The overall storage of hydropower reservoirs is of 510 Mm^3, more than twice the storage of the lake [OLL, 2005].
Despite the environmental, social and economic relevance of this huge water resources system and its potentially low resilience to CC [EEA, 2009], few studies have addressed the problem of the rigorous quantification of CC impact on water-related activities in this region. CC may impact this complex water system in multiple ways. The average inflow to the lakes is expected to decrease, due to reduced snow melt in late spring and increased evaporation in summer. The subsequent reduced water availability may lead to water stress situations, possibly accrued by increased water demand from the downstream irrigated areas due to the temperature raise. Also, side effects

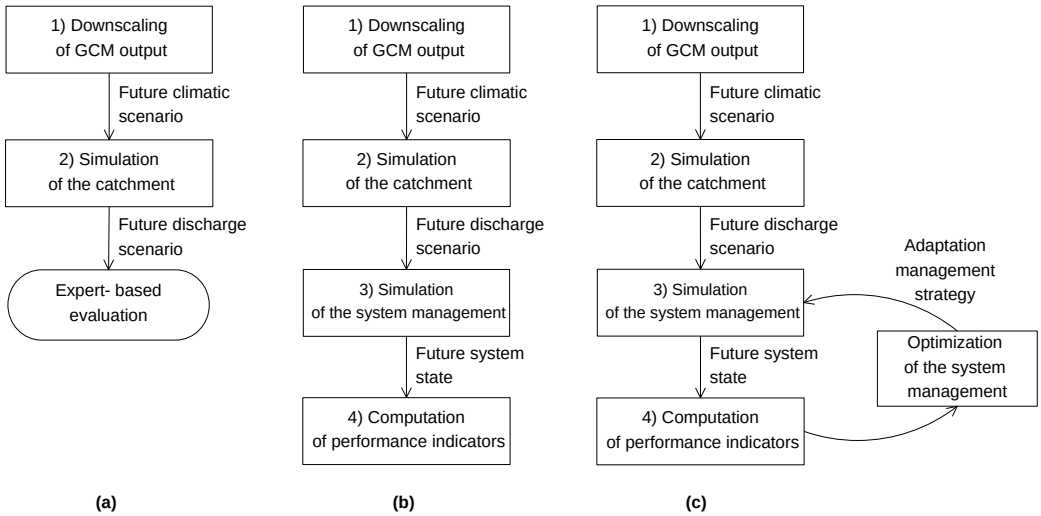

Figure 1: Procedures for assessing climate change impacts on water resources (a,b) and planning adaptation strategy (c).

can be expected from increased frequency and intensity of flood events, since large alpine lakes are also used for flood control in the effluent rivers, with potentially augmented conflict among upstream and downstream water users.

3 MODELLING TOOLS

The analysis of potential CC impacts on water-related activities in the lake Como catchment requires an integrated simulation tool to reproduce the behaviour of the system under future climatic scenarios, according to the pattern of Figure 1b,c. For the sake of simplicity, in the case study here presented, the alpine hydropower reservoirs are described by one single equivalent reservoir whose capacity is the sum of the total capacity of the actual reservoirs, and the different water users downstream of the lake are lumped into one equivalent downstream user, whose benefit/cost is related to the total water amount that is diverted from the lake effluent (river Adda) to the main irrigation canals. The modelling time step is one day, that is the decision time step currently adopted by the lake manager.
Application of the procedure shown in Figure 1b requires four modelling steps: (1) downscaling future weather scenarios (precipitation and temperature); (2) modelling the catchment response to climatic input; (3) modelling the operation of lake Como and the equivalent hydropower reservoir; (4) computing the performance indicators for the hydropower producers and the equivalent downstream user.

3.1 Downscaling procedure

The climate of the Alps is strongly influenced by local phenomena (orographic forcing, rain-shadowing, etc.). In such cases, Regional Climate Models (RCMs) provide more realistic climatic forecast at the regional scale with respect to GCMs, since the mismatch of scale between the resolution of the climate models and the scale of interest for regional impacts is lower [Mearns et al., 2003; Fowler et al., 2007; Frei et al., 2006]. The climatic time series considered in this study were derived as part of a larger multimodel ensemble in the frame of the European project PRUDENCE (see http://prudence.dmi.dk/ and [Christensen and Christensen, 2007]). Each time serie is the result of the simulation of a different RCM using the emission scenario A2 [IPCC, 2000] and the GCM HadAM3H [Pope et al., 2000] as driving data. The time series of daily precipitation and mean temperature over the control period 1961-1990 were used as backcast and time series of the same variables over the years 2071-2100 as forecast.

Even if RCMs provide good estimate of the climate at the regional scale, some biases from the local climate of interest may still exist. In this study, RCMs' output were corrected via the statistical downscaling method known as quantile-quantile mapping transformation. For a given variable, the cumulative density function (cdf) of the backcast is first matched with the cdf of the observations, thus generating a correction function depending on the quantile. The correction function is then used to unbias the variable from the forecast quantile by quantile. This method has been used in many hydrological impact studies, using a correction function at either annual or seasonal level [Reichle and Koster, 2004; Déqué, 2007; Boé et al., 2007; Dettinger et al., 2004; Wood et al., 2002].
One major limitation of this technique (as of any statistical downscaling method) is that the goodness of the correction strongly depends on the quality of the available observations. To mitigate such effect, the control period was split into two sub-periods that were used for calibration and validation respectively. Both an annual and seasonal correction function was derived over the calibration period for both temperature and precipitation, and the one producing the smaller mismatch between downscaled and observed data over the validation sub-period was adopted. This is an annual correction function for the precipitation time series, and a seasonal correction function for the temperature time series.

3.2 Hydrological model

The catchment response to climatic input is simulated through a lumped model developed by the authors for the lake Como system. The model is composed of three sub-models (Figure 2).

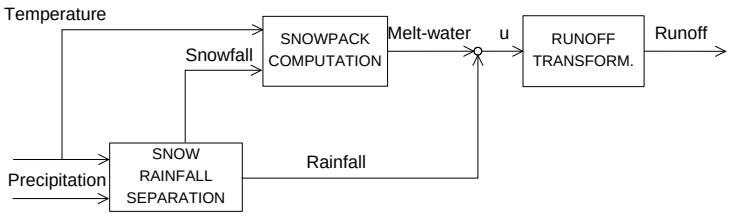

Figure 2: Hydrological model structure. Three sub-models are cosidered: "Snow-Rainfall separation", "Snowpack computation" and "Runoff transformation".

The "Snow-Rainfall separation" sub-model splits the precipitation input into snowfall and rainfall. For the hydropower reservoir catchment, the total amount of precipitation is regarded as snowfall if the average temperature is below zero and viceversa. For the much wider lake Como catchment, snowfall is computed as a fraction of the total precipitation through a proportionality coefficient that accounts for the catchment's area situated above the freezing level.
The "Snowpack computation" sub-model reproduces the seasonal processes of accumulation and snow melt, based on a degree-day approach. The model equations are discussed in details in Guariso et al. [1986].
The "Runoff transformation" sub-model simulates the runoff process as a consequence of both melt-water and rainfall. A lag-1, linear model was used,

$$q_{t+1} = \phi(q_t + \bar{q}) + \varphi(m_t + r_t) \tag{1}$$

where q_{t+1} is the catchment outflow in the time interval $[t, t+1)$ (24 hours), m_t is the snowmelt, r_t is the rainfall, $\bar{q}$ is the baseflow and ϕ and φ are constant parameters.
The model parameters were calibrated using historical time series of daily precipitation, temperature and catchment outflow over the time horizon 1967-1978. The coefficient of determination (defined as one minus the ratio between the model error variance and the measured output variance) equals 0.73 over the calibration data set and 0.67 over the validation data set (1979-1984) for the hydropower reservoir catchment, 0.67 and 0.65 for the lake Como catchment.

3.3 Reservoir model and performance indicators

Multiple and conflicting concerns co-exist in the lake Como basin. The reservoirs located in the upper catchment of lake Como are managed for hydropower production, while the main aim of the lake regulation is to supply downstream users and especially the irrigation-fed agricultural districts downstream of the lake. However, the lake operation must also consider multiple other concerns like flood control, recreational activities and ecosystem conservation. In previous research projects [Castelletti et al., 2006, 2007], a set of indicators was developed together with the Stakeholders' representatives to capture all these issues.
Performance indicators provide the basis for the optimization of the system management. At present, the regulation of lake Como is committed to the river basin organization, while hydropower reservoirs are operated by different power companies. This has brought to an age-old conflict between the alpine hydropower producers and the downstream lake users (especially farmers). Recently, Amodeo et al. [2007] used Stochastic Dynamic Programming to design joint management policies of the hydropower equivalent reservoir and lake Como by solving a two-objective optimization problem including hydropower production and irrigation supply. In that study, the equivalent hydropower reservoir and lake Como were modelled by two mass balance equations. The reservoir inflows were modelled as stochastic processes with a periodic probability distribution estimated over historical inflow time series. The indicators defined by the Stakeholders were used as objective functions of the stochastic optimal control problem. Both indicators were defined as the average value over the simulation horizon of a daily benefit/cost. For the hydropower equivalent reservoir, this is the daily energy revenue from hydropower production, while, for the farmers downstream of lake Como, the daily cost is the squared deficit in the water supply with respect to an a priori defined water demand. The joint management policies were simulated over the period 1967-1984, thus obtaining the points, in the space of the hydropower and irrigation objectives, shown in Figure 3. Note that, even if produced by Pareto-optimal policies, these points do not necessarily belong to the Pareto Frontier of the two-objective control problem, as they are obtained via simulation under historical inflow and not under the stochastic inflow model used in the optimization. For this reason we use the term Image of the Pareto Frontier (IPF), instead of Pareto Frontier. Figure 3 shows that the joint management of the lake and the equivalent hydropower reservoir can greatly improve the satisfaction of both the water users with respect to the historical management (cross) and can represent an effective tool to mitigate the conflict.
In this study the performances of these Pareto-optimal policies will be evaluated under climate change scenarios.

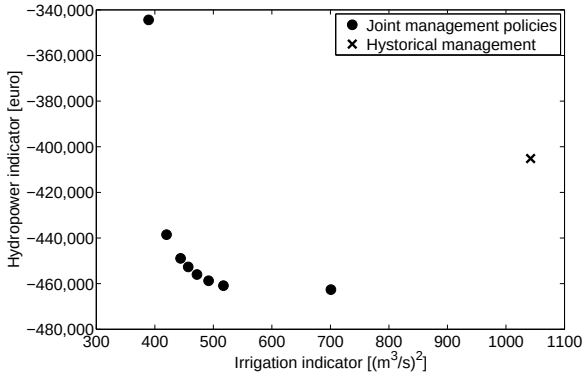

Figure 3: The Image of the Pareto Frontier under historical climatic conditions (1967-1984), in the following historical IPF. Negative hydropower revenue is considered to resort to a minimization problem.

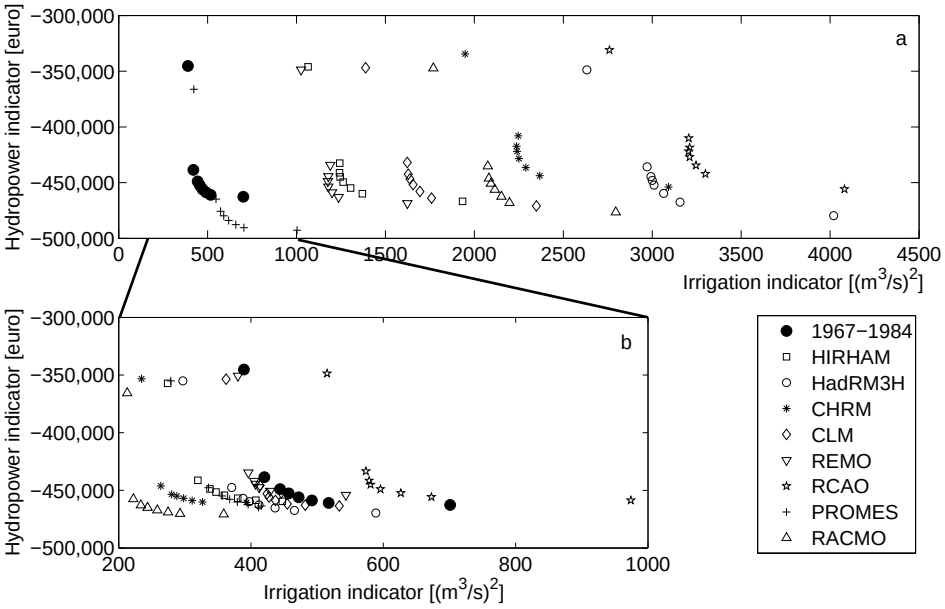

Figure 4: The Image of the Pareto Frontier under historical climatic conditions (black dots) and under RCMs' climate scenario in the future period 2071-2100 (a) or in the control period 1961-1990 (b) (other symbols).

4 SIMULATION UNDER CLIMATE CHANGE SCENARIOS

Potential impacts of CC on water-related activities in the lake Como system were assessed by projecting future climatic scenarios, at first, into discharge scenarios and, ultimately, into hydropower production and irrigation supply, through the four modelling tools described in previous section. The analysis was conducted considering the current water system configuration: except for discharge scenarios, no other potential modification of the system due to CC (e.g. variation in energy prices or in irrigation demand) was considered. The Pareto-optimal joint management policies designed by Amodeo et al. [2007] were used to mimic the behaviour of the system managers. Mind that these policies have been designed by optimizing the performance indicators under the assumption of stationary hydro-meteorological conditions, and thus they are likely to perform sub-optimally under the new discharge scenarios.

Figure 4a shows the system performances derived via simulation of the system under 8 different RCMs' climate scenarios over the period 2071-2100. For the sake of comparison, the figure also shows the historical IPF of Figure 3. It can be noticed that CC will negatively affect the water system: the hydropower revenue is expected to reduce and the squared downstream deficit to increase. The deficit increase is two orders of magnitude larger than the revenue decrease. The reason is that all the RCMs' climate scenarios predict a significant reduction of water availability just in late spring and summer, when the water demand from irrigation is higher. On the contrary, hydropower producers are much more resilient to temporal reallocation of their water supply.

Figure 4a shows also that different climate scenarios produce performance indicators very far from one another. This is in line with recent studies [Schaefli et al., 2007; Déqué et al., 2007] suggesting that climate scenarios are a major source of uncertainty in estimating CC impacts. To measure the variability of the RCMs' scenarios in terms of system performances, the system management was also simulated under the 8 different RCMs' climate scenarios over the control period 1961-1990 (backcast). Results are shown in Figure 4b: it can be noticed that the performance indicators are rather scattered and far from the historical IPF.

5 CONCLUSIONS AND FURTHER RESEARCH

We proposed a procedure for the quantitative assessment of CC impact on water-system and tested it on the real world case study of lake Como (Italy). The study constitutes one of the first quantitative study on the impact of CC on water use in the alpine and lowland areas south of the Alps, and provides a general framework for the quantitative assessment of the effect of CC on water-related activities which can be further applied to other case studies.
The proposed procedure relies on four modelling tools that are used to (1) downscale climate scenarios derived from different RCMs; (2) simulate catchment outflows; (3) simulate Pareto-optimal management policies of the water system; and (4) evaluate the potential impact of CC by means of performance indicators defined together with the Stakeholders' representatives. The simulation results here reported focus on two sectors: hydropower production in the alpine reservoirs upstream of lake Como and irrigation in the downstream areas. The analisys shows that CC may affect negatively both sectors, but with different intensities.
Several topics for future research remain open. First, evaluation of CC impacts should be extended to the other interests in the system (e.g. flood control, ecosystem conservation). Second, the modelling tools can be improved, particularly the hydrological model of the catchment that, in its current version, does not include the glacier dynamic and the evapotranspiration contribution to runoff formation, two processes that may be affected by CC. Also, since the impact analisys relies on the strong assumption that the hydrological model, calibrated over historical time series, can reproduce also future relation between climatic forcing and catchment outflows, a sensitivity analysis is required to assess the robustness of the results with respect to parameter uncertainty. Uncertainty analysis should also be extended to other modelling units to confirm the preliminary conclusion discussed in this paper, i.e. that the RCMs' projections are the major source of uncertainty in the assessment procedure. Finally, as discussed in the introduction of this paper, the proposed procedure opens up the way for the rational design of adaptation measures. In our case study, this means to re-optimize the management policies including the new climatic scenarios into the description of the reservoir inflow and to assess whether such adaptation policies can reduce the impact of CC as measured by the performance indicators.

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