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Assessing the sensitivity of an Alpine reservoir to hydrological change and improving its operation by adaptive optimization

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Abstract The "scenario-based" approach traditionally used in planning and management of water systems can fail to cope with the non-stationary nature of hydro-climatic conditions and the deep uncertainty in their prediction. In this paper, we contribute to the development of new analytical tools for reservoir management, and specifically for: (i) assessing the sensitivity of water resource systems to hydrological changes; (ii) increasing the adaptation capacity of reservoir systems by adaptive optimization. We use the multipurpose regulated Lake Maggiore, at the border between Switzerland and Italy, as a case study. The application of trend detection techniques shows that significant hydrological changes are already undergoing in the investigated watershed. Historical time series can thus be exploited as a testing ground of adaptation strategies, for instance adaptive optimization of the lake operating policy. Simulation results show that the adaptive approach improves the system performances with respect to the scenario-based one in terms of irrigation supply, while it performs slightly worse for flood control.

Key words water resources management; climate change; adaptation; trend analysis

INTRODUCTION

There is a great concern about climate change as a threat to future water availability. In the past, research has been mainly devoted to develop future climatic and hydrological scenarios (e.g. Groves *et al.*, 2008; Abbaspour *et al.*, 2009) and to assess the related water system vulnerabilities (e.g. Christensen *et al.*, 2007; Schaefli *et al.*, 2007; Anghileri *et al.*, 2011). In recent years increasing attention has been paid to the design of adaptation strategies (e.g. Lempert & Schlesinger, 2000; Georgakakos *et al.*, 2012; Steinschneider & Brown, 2012), since current water management practices may prove not to be robust against climate change (Bates *et al.*, 2008). In fact, the traditional scenario-based approach to water resources planning and management is deemed to be inadequate to cope with the non-stationarity and deep uncertainty of future climate scenarios (Milly *et al.*, 2008), and new approaches are called for to support policy makers and water managers in taking decisions.

In this paper we analyse the case of a multi-purpose water system, Lake Maggiore on the Italian and Swiss Alps and the downstream irrigated area. First, we analyse the time series of inflows to the lake from 1916 to 2010 and we show that significant hydrological changes are already undergoing. On the one hand this confirms that the "stationary principle" underpinning most of our modelling and planning activities is far from being satisfied. On the other hand it means that historical time series can be exploited as a testing ground for the design of future adaptation strategies, e.g. adaptive optimization of the lake operating policy. We thus use historical horizons for assessing and comparing two alternative management strategies: the one in which the catchment hydrology is supposed to be perfectly stationary, and an adaptive one, in which the operating policy of the lake is re-optimized every year in order to adapt to the ongoing hydrological trends. The impacts of these different strategies are evaluated in terms of water supply to the downstream irrigated area and control of flooding events around the lake shores.

THE CASE STUDY AREA AND ONGOING HYDROLOGICAL CHANGE

Lake Maggiore is an Alpine regulated lake at the border between Italy and Switzerland. The lake is fed by a catchment of about 6600 km^2 and its hydrologic regime follows a strong seasonal pattern. The low flow seasons are summer, when rainfall is at a minimum, and winter, when precipitation is mainly accumulated as snow in the upper part of the catchment. The high flow seasons are spring, due to the contribution of both snowmelt and rainfall events, and autumn, when severe floods due rainfall may occur.

The lake was dammed in 1943 in order to supply the large downstream irrigated area which is fed by the lake release through a wide distribution network of canals. The lake has an active storage of about 420 million m^3. Currently, the lake regulation must also consider other interests besides irrigated agriculture. For example, the lake storage is used to reduce flooding events on the lake shores and in recent years increasing attention has been given to environmental protection in the lake and the effluent river. A Minimum Environmental Flow constraint has been progressively increased in time from an original value of 3 m^3/s up to 13 m^3/s, and a further increase is currently under discussion.

The hydrology of the lake catchment is also influenced by the operation of several hydropower reservoirs that were constructed from the beginning of the 20th century to 1973. Although distributed in many and often small storage facilities, their overall capacity is larger than the capacity of the lake (Ciapittiello, 1999). Besides hydrological changes induced by the operation of upstream reservoirs, there is evidence of ongoing climate trends in the area, with an increase in average temperature, a reduction of snowfall and a shift in rainfall distribution along the year (Anghileri *et al.* 2012). We analysed the overall effects of such changes on the seasonal pattern of lake inflows using the historical time series over the period 1916–2010.

Figure 1(a) shows the results of the Mann Kendall test for trend detection (Kendall, 1975) and the Sen's Slope (Sen, 1968) for the 12 time series of total monthly inflows. The length of the bar represents the trend intensity computed as the Sens's Slope for each month, while the colour indicates the *p*-value of the Mann-Kendall test.

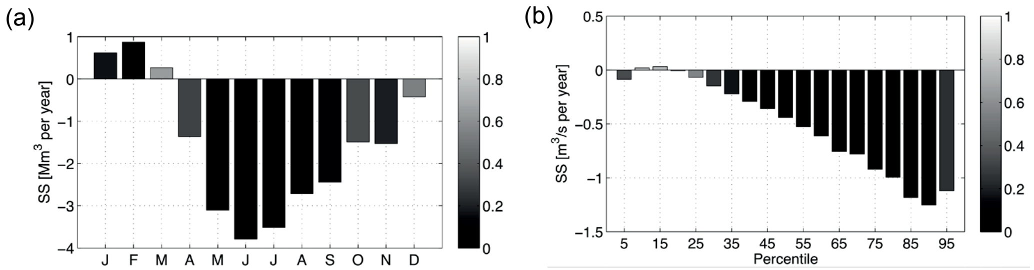

Fig. 1 Results of the Mann-Kendall test and the Sen's Slope (SS) of the time series (1916–2010) of (a) monthly inflows to Lake Maggiore, (b) percentiles of the flow duration curve. The length of the bar represents the SS while the colour represents the p-value of the statistical test.

The analysis shows that there are different trends depending on the month considered. There is an increase of winter flow from January to March (although only in February is the trend statistically significant below a significance level of 0.05). All the other months show a decreasing trend with different intensity (June, July, and August being significant below 0.05). Figure 1(b) shows the results of the Mann Kendall test and the Sen's Slope when applied to the time series of percentiles of the inflow duration curve over one year. Most of the percentiles show a decreasing trend with intensity growing with the percentile value and statistically significant at generally low significance level (below 0.1 for the 35th–85th percentiles). This seems to suggest that the entire distribution of inflows has changed in time, especially with respect to high flows, and the stationarity principle, besides being questionable for the future, does not hold true over the last decades.

MODELS AND METHODS FOR ADAPTIVE MANAGEMENT

In this study, we assess and compare two different approaches to the management of the lake, the scenario-based approach and the adaptive management approach. To this purpose, we firstly built a mathematical model of the water system, composed of a mass balance equation describing the lake dynamic at daily time step and a model of the downstream network of canals that distributes the daily lake release among the different irrigation districts.

To compare the scenario-based management paradigm and the adaptive management paradigm, we focus on the two interests that historically have driven the lake regulation: flood protection along the lake shores and irrigation supply. The performance indicator for flood protection is the average flooded area (km^2) in Locarno and Verbania, the two cities on the lake shores which are mainly affected in case of flooding. It is computed as a superlinear function of the lake level. The irrigation indicator is the squared supply deficit, computed as the sum of the squared deficit of each irrigation district. The deficit is computed with respect to an *a priori* water demand computed from the irrigation abstraction licences and the historical diverted flow. Squaring in the indicator definition is used to account for the farmers' risk aversion, i.e. the fact that, for reducing crop stress, they prefer to distribute a given total deficit volume over time since the damage of a sequence of small deficits is lower than the damage of a single large deficit. A more comprehensive description of these indicators and their identification process is given in Soncini-Sessa *et al.* (2007).

Using this model and objective functions, we compared the two different optimization approaches depicted in Fig. 2, one grounded into a scenario-based paradigm and one based on an adaptive paradigm.

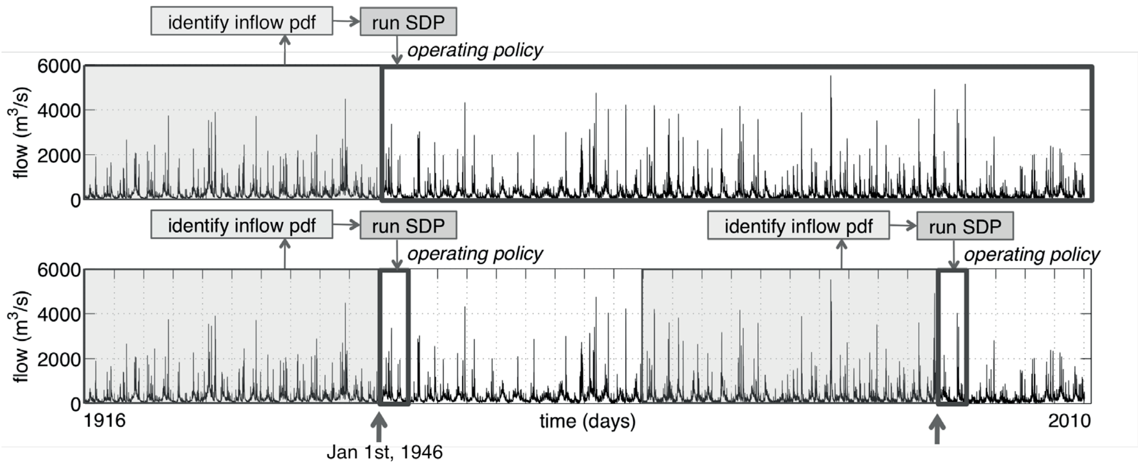

Fig. 2 In the scenario-based approach (top panel) historical inflows over the first 30 years (grey box) are used to design the lake operating policy, and the remaining time series is used for simulation. In the adaptive management approach (bottom panel), the operating policy is designed every year considering the last 30-years inflows, and then simulated for one year ahead (as an example, this iterative procedure is reported only twice, at the time instants indicated by the arrows).

In the former, scenario-based approach, hydrological time series over the 30-years horizon from 1916 to 1945 are used to derive the cyclostationary statistics of the lake inflows, i.e. daily mean and standard deviation in each day of the year, and Stochastic Dynamic Programming (SDP) is used to design an operating policy balancing the two above described objectives of flood control and irrigation supply. Since SDP is a single objective method, the objectives were lumped into one objective function by weighted sum. Different combinations of the weights have been tested and the one corresponding to the compromise solution (i.e. the solution along the Pareto frontier which is closest to the utopia point) was selected and used in the remainder of the work. The policy so obtained is then evaluated against historical inflows by deterministic simulation from January 1946 to 2010.

In the latter, adaptive approach, SDP is re-run every year on the 1st January using inflow statistics based on the last 30 years. The 30-year period was chosen in agreement with World

Meteorological Organization (WMO) climate standards. The resulting operating policy is simulated against historical inflows in the following year. The evaluation of this approach thus consists in a sequence of optimization and 1-year deterministic simulation runs. At each optimization run, the aggregation weights of the irrigation and flooding objectives are maintained constant to the value selected for the scenario-based approach.

By construction, the first year of simulation (1946) produces the same results in both approaches, while the policies and simulated system trajectories tend to diverge as time passes by. The comparison of simulated lake levels and releases in the two approaches allows us to estimate the distance in system performances between the two opposite management paradigms: the one where the stationarity principle is assumed to hold true throughout the entire life time of the water system, and the one where the stationary principle is abandoned, old data are progressively discarded, and there is a learning process that spans over the entire life time of the system.

RESULTS AND DISCUSSION

Figure 3 shows the value of the performance indicators, flooded area and deficit in irrigation supply, for every year in the evaluation horizon 1946–2010 and the mean indicator value over the entire horizon.

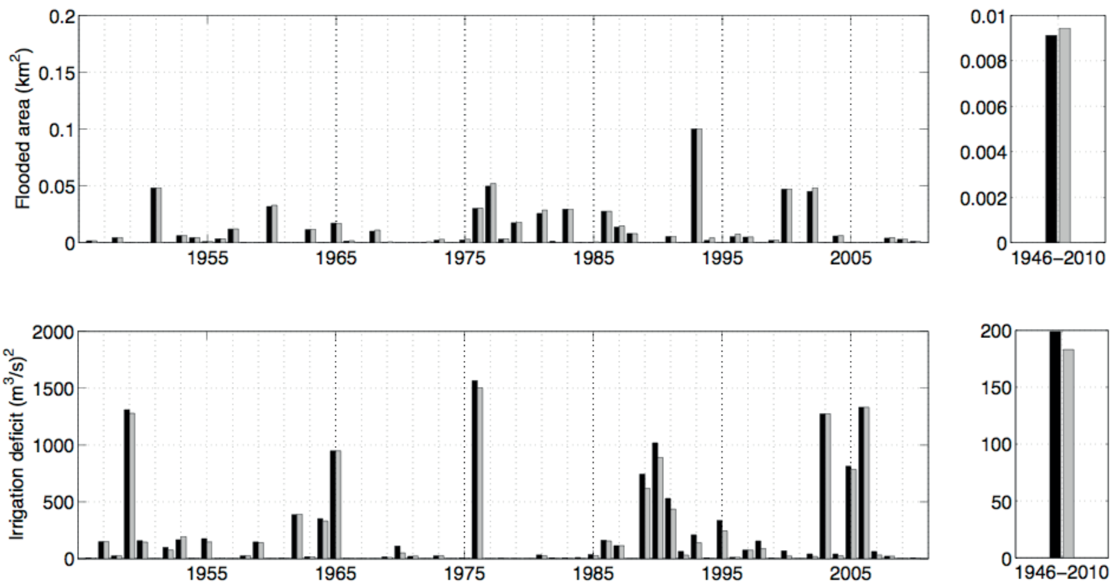

Fig. 3 Performance indicators for each year in the evaluation horizon 1946–2010 and overall average produced by the scenario-based management (black) and the adaptive management (grey).

The scenario-based paradigm produces better performance when looking at the flooded area in every flooding event. A deeper analysis of the simulated system trajectories seems to suggest that the scenario-based policy is more risk adverse than the adaptive one. The reason may be that the inflow probability distribution in the flooding season computed over the first 30 years has a higher standard deviation with respect to the updated distributions used in the adaptive paradigm.

On the other hand, the adaptive paradigm produces better performance in terms of irrigation supply, as it is able to reduce the irrigation deficit in almost all the drought events. Figure 4 shows the relative enhancement of the irrigation performances from the scenario-based to the adaptive management. It is computed as the difference between the indicator value in the adaptive and scenario-based approach, normalized by the indicator value in the scenario-based approach. The figure shows that the enhancement increases in time, meaning that, following the adaptive paradigm, the lake operation is able to adapt to summer seasons which become increasingly dry, while the stationary policy becomes increasingly unsuitable to supply the irrigation demand.

The above results can be sensitive to the length of the period considered in the computation of the inflow probability distribution. Indeed a sensitive analysis with respect to the length of the horizon revealed that trends in the monthly inflow statistics are rather robust, but for the autumn flood period, when detected trends are qualitatively different as the number of years varies (Anghileri *et al.*, 2013). This suggests that the flooding objective could be particular sensitive as well to this choice.

Another remark, when analysing the performances of the adaptive approach, is that using the same combination weights at each optimization run does not guarantee to obtain the same trade-off solution. To investigate this issue, the entire Pareto front should be computed at each year, either re-running the optimization for different combinations of the weights, although it will be computationally expensive, or using a non-parametric multi-objective approach, e.g. Multi Objective Genetic Algorithms, that provide the approximation of the entire Pareto front in one optimization run.

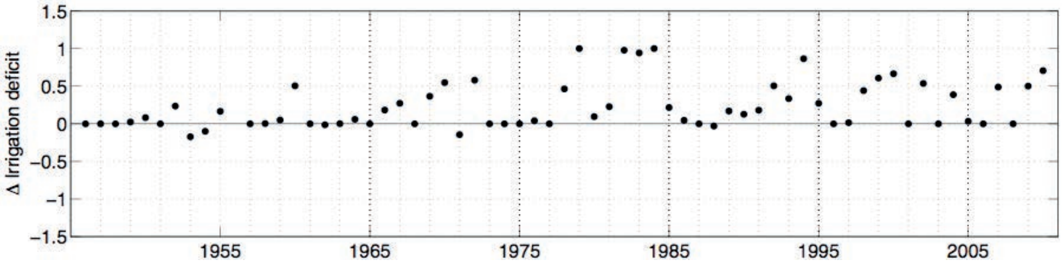

Fig. 4 Relative variation of the irrigation performance indicator over the evaluation horizon 1946–2010.

CONCLUSIONS

In this paper, we investigated hydrological changes in the catchment of the multipurpose regulated Lake Maggiore, at the border between Switzerland and Italy, and compared two different management paradigms for the regulation of the lake, the traditional "scenario-based" paradigm and a novel, adaptive paradigm, where the operating policy is re-designed every year using updated statistics of the lake inflows. Through optimization and simulation over the historical period 1916–2010, we show that the adaptive approach produces better performances than the scenario-based approach in terms of irrigation supply, thanks to its ability in adjusting to increasingly dry conditions. On the other hand, the scenario-based approach is better for flood protection. The differences between the two objectives could have different explanations. First, the trade-off between the two objectives could change while re-optimizing the operating policy in the adaptive approach. Second, when considering objective functions that are affected only by extreme events, as flood protection, it is not sufficient to take into account inflow statistics computed over 30 years, but it is necessary to consider a longer time horizon. Therefore, the updating schemes of the inflow statistics should be different depending on the considered objective. Further research will aim at testing more deeply these hypotheses and their effects on the adaptive approach performances.

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