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Storage water value as a signature of the climatological balance between resource and uses

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Abstract

Water is stored in reservoirs to adapt in time the availability of the water resource to the various water demands like hydropower production, irrigation or ecological constraints. Deterministic dynamic programming retrospectively identifies optimal reservoir operations that could have been achieved to balance resource and demand during a given time period in the ideal configuration where future inflows and demand are perfectly known. A by-product of dynamic programming is the estimation of the storage water value (SWV) which is the marginal value of the future benefits potentially obtained from an additional unit of water volume stored in a reservoir and which determines the optimal storage strategy. The SWV depends on the reservoir level and shows seasonal as well as inter-annual variations. This paper uses the SWV as an index of the adequacy between water resources and water demands for a simplified water resource system in a mountainous region in France. It characterizes how and why the adequacy and optimal strategy could change for this system if the climate and/or demand change. Changes in mean regional temperature (increase) and/or precipitation (decrease) are analyzed. The influence of the nature of water demand on the SWV is also described (energy production or minimum lake level maintenance).

In the studied case, the adequacy between water resources and demand either improves or degrades depending on the considered future scenario. In all scenarios, the seasonality of SWV changes with for example earlier water storage is to efficiently satisfy increasing summer water demand.

1 Introduction

Mountain catchments present a large potential for hydroelectric production. At high elevation, spatial and temporal variations of the snowpack make the hydrological regimes of rivers highly seasonal with low and high flows respectively in the snow-accumulation and snowmelt seasons. On the other hand, the demand for electricity is also highly seasonal, with consumption peaks that mainly occur during the winter (e.g. Schaefli et al., 2007). Reservoirs are designed and managed to put in phase these two seasonal signals. Reservoirs in mountainous regions were historically managed on the basis of the joint analysis of inflows from past hydrological regimes and the seasonality of electricity demand, the main economic interest being to store water in spring when hydrological inflows are high and use it in winter when electricity demand is high. Daily reservoir operations can be determined by rule curves based on historical inflow data from past decades and designed to fill the reservoir before the arrival of winter low flows and the high demand season (Marnezy, 2008; Fatichi et al., 2013).

Over time, many mountain reservoirs have been assigned additional management objectives related to maintaining low flows as well as irrigation and drinking water supply (Loucks et al., 2005) which complicates their management. The operational management of such systems can be ruled using optimization techniques coupling decision in time under uncertain future like stochastic dynamic programming (SDP) (Labadie, 2004). Prospective and retrospective analyses of the balance between hydropower production, electricity demand and environmental constraints can be carried on with simpler optimization techniques.

This paper uses Deterministic Dynamic Programming (DDP) in the ideal configuration where the future resources and demand are perfectly known (Yakowitz, 1982). A first step of DDP is to obtain the day-to-day optimal storage operating strategy that maximizes the chosen benefit function over the whole period. The storage strategy and the resulting day-to-day operations are optimal with respect to the a priori known time series of water inflow, constraints and demands for the period. They can be described by the marginal Storage Water Value (SWV) for different levels in the reservoir. The SWV represents the future benefit that would be obtained at any given time from an additional unit of water volume stored in the reservoir. It is basically governed by two terms: (i) the priority levels assigned to each management objective defined by weights and economical values and (ii) the adequacy between water availability and water demands, in both quantity and timing.

The variations of SWV with time for different reservoir levels are an indicator of the temporal goodness of fit between the resource and the demand given the constraints. They highlight the role played by a reservoir in redistributing water throughout the year and from one year to another. They can be used to index water scarcity (Tilmant et al., 2008).

The present study looks at how the temporal patterns of SWV are modified by changes in climate or demand and as such can be considered as a signature of the climatological balance between resource and demand. Climate change influences the seasonality of the hydrological regimes of rivers in mountainous regions. Warmer temperatures will reduce the snow/rainfall ratio and shorten the snow accumulation period, reducing the spring snowmelt flood and shifting it two weeks to one month earlier in the year (Horton et al., 2006). At the same time, warmer temperatures are expected to modify the seasonal pattern of electricity demand with lower consumption for heating during the winter and greater needs for cooling during the summer (Alcamo et al., 2007). The temporal fit between resource and demand is thus expected to drastically change with respect to past conditions, which will in turn significantly influence the mean and seasonal pattern of SWV.

We compute the variations of SWV with time for a simplified water resource system considering a single storage reservoir located in a catchment of the southern French Alps under the present climate and a suite of future climate scenarios. We analyze the SWV sensitivity to a mean regional temperature increase and/or to a precipitation decrease. We also explore the influence of the nature of water demand on the SWV (energy production and/or water level maintenance).

The paper is organized as follows. Section 2 briefly describes the basic principles of deterministic dynamic programming used to estimate the marginal values of storage water. Section 3 presents the simplified water resource system, the data and the simulation models considered in the application to the Upper Durance Basin (France). It also describes the future climate scenarios considered in the work. The mean daily values of SWV through the calendar year obtained for the present and future climate

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contexts are presented and discussed in Sects. 4 and 5, as bearing the signature of climate change. Section 6 presents the conclusions.

2 Methods

2.1 Deterministic dynamic programming

Dynamic programming is an optimization method developed by Masse (1946) and Bellman (1957) for multistage dynamic decision processes. Yakowitz (1982) proposed a comprehensive review of dynamic programming applications in the context of water resource system optimization.

In Deterministic Dynamic Programming (DDP), the optimal operation decisions for each time step t_i of the considered planning horizon $[t_0,t_N]$ are identified in order to maximize the sum, over the whole planning horizon, of the current benefits, i.e. the benefits that would result from an immediate use of water (including costs of failures), and of the future benefits, i.e. the benefits that would result from release operations over the future planning horizon $[t_{i+1}, t_N]$.

In a classical reservoir optimization problem, the current benefit function is a weighted sum of (i) the benefits for the current production of different services and goods and/or (ii) the costs of current system failures resulting from the non-satisfaction of operating constraints related to downstream water demand or to other objectives assigned to the water system. This function reads:

$$g\left(u_{t_i},s_{t_i},t_i\right) = \sum_j c_j \cdot g_j\left(u_{t_i},s_{t_i},t_i\right) \quad (1)$$

where g_j is a function representing the monetary benefits and costs associated to the different served by operation u_{t_i} at the storage level s_{t_i} during $[t_i, t_i+\Delta t]$ and c_j is a weighting constant defined according to the priority level assigned to use j.

For each time step t_i an immediate use of water reduces the availability of stored water for future use. The current benefits must therefore be balanced against losses in future benefits. To identify optimal operations for the current time step, it is thus necessary to first estimate the marginal value of conserving water in the reservoir from the current time step to the next. This estimation is made thanks to a preliminary optimization step in which the future benefits are estimated, for each time step, for different reservoir storage levels.

The future benefit $F_{t_i}(s_{t_i})$ that would be obtained over $[t_{i+1},\, t_N]$ from a hypothetical reservoir level s_{t_i} at time t_i is often referred to as the Bellman Value for this storage/time configuration. It is obtained from a backward recursive calculation from the future benefits estimated for time t_{i+1}:

$$F_{t_i}\left(s_{t_i}\right) = \max_{u_{t_i}}\left\{g\left(u_{t_i}, s_{t_i}, t_i\right) + F_{t_{i+1}}\left(s_{t_{i+1}}\right)\right\} \tag{2}$$

where the different terms are subject to upper and lower bounds and mass conservation constraints. The state and decision variables are such that:

$$s_{\min} \le s_{t_i} \le s_{\max} \tag{3}$$

and

$$u_{\min} \le u_{t_i} \le u_{\max} \tag{4}$$

where $s_{\min}$ and $s_{\max}$ are minimum and maximum bounds for water storage volumes in the reservoir and $u_{\min}$ and $u_{\max}$ the minimum and maximum bounds for release discharges. The mass conservation equation is:

$$s_{t_{i+1}} = s_{t_i} + q_{t_i}\_u_{t_i} - o_{t_i} \tag{5}$$

where q_{t_i} is the inflow to the reservoir during the period $[t_i,\, t_i + \Delta t]$,o_{t_i} the losses (evaporation above the reservoir, controlled and uncontrolled withdrawals from the reservoir for irrigation, drinking water and other uses).

A discrete approach can be used to estimate the benefit function $F_t(s)$ when the dimension of the problem is quite small (Yakowitz, 1982). The final result is a table that gives the future benefits for different water levels and each time step of the planning period. For storage levels in-between the a priori selected states, $F_t(s)$ can be obtained via interpolation. In our case, $F_t(s)$ is estimated at a daily time step and at 51 storage levels uniformly distributed between the minimum and maximum storage bounds $s_{\min}$ and $s_{\max}$. A cubic spline interpolation method is used when needed (Foufoula-Georgiou and Kitanidis, 1988).

Values of $F_{t_N}(s)$ are required for $F_t(s)$ at the final time of the planning horizon t_N. They could have a critical influence on $F_t(s)$ values. Different methods were proposed to avoid the use of boundary conditions in a deterministic way (e.g. Vicuna et al., 2008). In the present study, end values are estimated as proposed by Wolfgang et al. (2009) based on the assumption that all years after the end of the planning horizon are identical to the final year. In practice, the duration of the planning horizon is artificially increased with several duplications of the final year so that the storage water values at t_N are no longer influenced by the boundary conditions.

2.2 Storage water value

The derivative of the future benefit function $F_t(s)$ for a given storage level s in the reservoir gives the benefit for a future use of one additional unit of water stored at this storage level Eq. (6). It corresponds to the marginal value of storage water for this storage level s and time t.

$$V_t(s) = \frac{\partial F_t(s)}{\partial s} \tag{6}$$

As shown in Eq. (6) and discussed below, the marginal value of storage water V is time and storage level dependent.

The above mentioned optimization stage provides the future benefit $F_t(s)$ for all storage levels s of the state-time table. This table can be used to derive the storage water values V for the same state-time grid. In a discrete approach, the derivatives are calculated with finite differences from neighboring water level states in the table.

In the following, the marginal value of storage water V will be referred to as storage water value (SWV). SWV is expressed in value units per cubic meter and is denoted as SWV m^{-3}.

SWV vs. time curves will be plotted for different water levels in the reservoir. Note that these curves do not correspond to a trajectory of optimal operational decisions. At any point in time, they simply describe the unique storage strategy corresponding to optimal management of the system for a given water level taking into account a given benefit function and a given known future evolution of both water needs and inflows over the considered period. They provide a useful signature to analyze the balance between climate and uses for the current context and also for any modified context, should this context change.

Note finally that, as previously mentioned, the SWVs are classically used in a second optimization stage to identify the optimal operation decision for the current time t_i, given the water level in the reservoir s_{t_i}. This operation maximizes the following equation:

$$\max_{u_{t_i}} \left[g\left(u_{t_i}, s_{t_i}, t_i\right) + \left(s_{t_{i+1}} - s_{t_i}\right) \cdot V_{t_{i+1}}\left(s_{t_{i+1}}\right) \right]. \tag{7}$$

The forward iterative optimization of Eq. (7) can therefore give the optimal sequence of operations and future reservoir water levels for the entire simulation horizon $[t_0, t_N]$. This simulation method is usually referred to as the water value method (e.g. Hveding, 1968). It simultaneously produces the evolution of different system outputs such as benefits and/or penalties for goods and services.

3 Case study and data

3.1 Catchment characteristics and hydro-climatic context

The Upper Durance River (UDR) basin is a meso-scale basin (3580 km^2) located in the southern French Alps. Its outlet is the Serre-Ponçon Lake, a storage reservoir that is part of a complex hydroelectric system operated by Electricité de France (EDF). It also plays a key role in the supply of water to the Provence region that extents from the Alps to the Mediterranean shore. Lake operations are optimized by dynamic programming to take into account objectives and constraints related to hydroelectric production, irrigation, drinking water supply, recreational activities and preservation of downstream ecological integrity.

Contrary to most French mountain basins of this size, UDR discharges are almost natural. Climate is much drier than in the northern French Alps (Durand et al., 2009) due to the Mediterranean influence and to protection from oceanic disturbances provided by the high Ecrins Mountains. With elevations ranging from 700 to 4100 m, the catchment presents highly seasonal flows due to snow accumulation and melt. Winter low flows can last three months or more. Late summer and fall maximum discharges also present a number of marked recession sequences. They can last several weeks after the end of the snow-covered period for years with negligible precipitation during these seasons. Major floods can also be observed in fall with intense liquid precipitation events (Lafaysse et al., 2011).

3.2 Model implementation

In this study our purpose is not to represent all the constraints and objectives applying to the real resource management system. There is not enough data available, and we simply want to appreciate the dynamic balance between the resource and the uses. We therefore consider a simplified water resource system inspired by the Upper Durance Water System (UDWS) with two basic uses: hydroelectric production (HEP) and/or maintenance of a minimum water level in the lake during the summer season for recreational activities such as water sports or fishing (Lake Level Maintenance denoted as LLM). We thus reduced the system to the lake and its upstream catchment. As we will see below, we chose HEP and LLM because these two objectives present important differences in term of adequacy with the water resource availability and are important for the real system of Serre-Ponçon. Other water uses could have been taken into account using an adapted current benefit function. To the cost of complexity of the result analysis, we decided to avoid. The SWV sensitivity analysis for the UDWS assumes a storage capacity of the lake $s_{\max}$ equal to the mean annual outflow (3500 $\mathrm{M\,m^3}$) from its upstream catchment under present climate conditions.

The current benefit function used in Eq. (1) for system optimization is the sum of possible benefits from HEP as defined by Eq. (8) and benefits from LLM during a summer season as defined by Eq. (9):

$$g_{\mathrm{HEP}}\left(u_{t_i}, s_{t_i}, t_i\right) = \mathrm{HEPI}_{t_i} \cdot u_{t_i} \cdot r(s_{t_i}) \tag{8}$$

where u_{t_i} in $\mathrm{m^3\,s^{-1}}$ is the discharge released from the lake for HEP, HEPI being the daily interest of HEP in value units $\mathrm{kWh^{-1}}$ (see Sect. 3.4) and r being the hydropower production coefficient in $\mathrm{kWh\,m^{-3}\,s^{-1}}$ that depends on the water head in the reservoir.

$$\begin{cases} g_{\mathrm{LLM}}\left(s_{t_i}, t_i\right) = K\left[1 - b\left\{\max\left(s^* - s_{t_i}, 0\right)\right\}^2\right] & \text{if } t_i, \in \text{ summer season} \\ g_{\mathrm{LLM}}\left(s_{t_i}, t_i\right) = 0 & \text{if not} \end{cases} \tag{9}$$

In this equation, K is the maximal value of daily benefits (value units) that can be obtained during the summer period. It is achieved as soon as the water storage in the lake is greater than or equal to $s^* = 3000\,\mathrm{M\,m^3}$, the volume below which recreational activities are expected to be reduced. The corresponding decrease in LLM benefits is assumed to be a quadratic function of the difference between the actual water storage and s^*. In Eq. (1), the values of the weighting parameters c_j, subsequently referred to respectively as c_{HEP} and c_{LLM} for HEP and LLM objectives, will be set either to 1 when the objective is satisfied or to 0 when it is not.

In the water balance of the lake, the only water input and output discharges are respectively the inflow from the upstream UDR basin and the optimized water release. Direct precipitation to the lake as well as evaporation from the lake is assumed negligible due to the important depth/width ratio of the reservoir.

In France like in many countries where hydropower is not dominant, hydroelectric production is used to replace more expensive power generation facilities and the objective for HEP is to minimize the expected sum of other energy production costs for the national network as a whole. In this study, we consider a simplified daily interest of HEP estimated from local daily temperature index (see Sect. 3.4) and the benefits are optimized for the system independently from other cost considerations (in accordance with Paiva et al., 2010).

On the other hand, summer LLM maintenance is currently a priority objective: an empirical rule is used for reservoir operations (applied mostly in the spring season) and HEP optimization roughly applies to the water inflows that are not needed to satisfy the LLM objective.

The expected increase of future energy costs will increase the interest of HEP and, as a consequence, benefits from recreational activities will be balanced on the midterm with respect to benefits from HEP (or with respect to the reduction of other production costs allowed by HEP). In this study, a benefit function (Eq. 9) was therefore used for LLM instead of a rule curve. This provides a rough estimate of the marginal value of storage water to satisfy the LLM objective. Recreational benefits are expressed as a function of water storage in the reservoir, similarly to Ward et al. (1996). A more precise formulation was not possible in the present case due to lack of appropriate data in the region. The value for K in Eq. (9) was chosen so that, in the case of a single-objective configuration, the maximum benefits that could be respectively obtained from either recreational activities or HEP are of same order of magnitude. This made it possible to analyze a double-objective configuration with objectives of equivalent value, a situation that could occur in the future.

The UDR inflows are modeled with CEQUEAU (Morin et al., 1975), a semi-distributed hydrological model already applied by EDF for previous climate change impact studies on different mesoscale French basins (Hendrickx, 2001; Manoha et al., 2008). Snow accumulation and melt, effective rainfall, infiltration and evapotranspiration fluxes are estimated for each of the 99 hydrological units of the basin from daily series of mean areal precipitation and surface air temperature. Discharges produced by all hydrological units are routed through the river network to produce the total water inflow into the lake. The CEQUEAU model of UDR was calibrated and validated with a split sample test procedure on the 1959–2005 period (Bourqui et al., 2011).

3.3 Climate scenarios

The observed precipitation and temperature data for the 1960–2001 control period are obtained from the daily meteorological reanalyses developed by Gottardi et al. (2012) for French mountainous regions. The reference discharges to the lake for the control period are those obtained from CEQUEAU simulations.

Simple climate change scenarios were constructed and used first in a sensitivity analysis that shows how precipitation and temperature changes SWV and in turn the match between water resources and uses. The local-scale time series of temperature and precipitation for the future climate period 2070–2099 are obtained by perturbing the observed time series of the control period (Hingray et al., 2007). Six synthetic regional climate change scenarios are defined as absolute changes of the mean annual temperature and as relative changes of the mean annual precipitation. The magnitude of changes is derived from a suite of climate modeling experiments conducted in the EU PRUDENCE project (Christensen, 2004) for SRES scenario A2 (Nakicenovic et al., 2001). It roughly corresponds to the 50 and 90 % percentiles of changes estimated by the climate model experiments, representing respectively a 10 and 20 % decrease in precipitation and a 3 and 5 °C increase in temperature.

Future hydrological regimes obtained from CEQUEAU simulations for these scenarios are presented in Fig. 1. A temperature increase leads to reduced snow accumulation in winter and an earlier melting season. This in turn induces a higher winter low flow and a lower snowmelt flood peak (Fig. 1, left panel). The snowmelt flood peak shifts by one month for the highest warming scenario (+5 °C). Besides this change in flow seasonality, an increase in temperature also leads to a slight reduction of the mean annual inflow to the lake due to increased evapotranspiration losses in summer (up to 22 % for the +5 °C scenario). Without temperature change, precipitation change scenarios modify the magnitude of the hydrological cycle (Fig. 1, middle panel). The mean inter-annual daily discharges decrease with the mean inter-annual precipitation, except for the winter period during which flows are mainly sustained by deep underground storage. The large decrease of the snowmelt flood peak is the result of a smaller snowpack extent and thickness, induced by lower winter to spring solid precipitation.

Scenarios with both precipitation and temperature changes lead to a modification of the hydrological regime that combines in a non-linear manner the modifications resulting from either temperature or precipitation change considered separately.

3.4 Economic interest of hydroelectric production

The price of hydroelectricity and its fluctuations with time are difficult to simulate because of the complex interaction with other energy production means and the high variability of the energy market. It results from versatile spot markets and management strategies of a large panel of stakeholders and operators. A detailed representation of electricity prices was beyond the scope of this work. However, electricity prices in France tend to be higher for periods of high electricity consumption. Moreover, electricity consumption tends to be higher in the cold season and daily time variations of consumption are highly correlated with the daily time variations of regional temperatures below an approximate heating threshold $T_{\text{heat}} = 15\,^{\circ}\text{C}$ below which the demand for heating starts.

As a result, a convenient index for daily HEP benefits, termed HEPI, can be based on daily regional temperatures. HEPI has already been used in a previous climate change impact study by EDF (Paiva et al., 2010). In a future climate with much higher summer temperatures, an additional demand for hydroelectric production is expected for cooling purposes in this season. The daily HEP interest expected in the future during the hot season is here similarly assumed to depend on regional temperatures above a cooling threshold $T_{\text{cool}} = 25\,^{\circ}\text{C}$ (similarly to Buzoianu et al., 2005). In the following, the daily HEPI is defined as a piece-wise linear function of daily temperature, as defined by Eq. (10).

$$\begin{cases} \text{HEPI}_{t_i} = \text{HEPI}_0 + \text{HEPI}_\text{h} \cdot \left(T_{\text{heat}} - T_{t_i}\right) & \text{if } T_{t_i} < T_{\text{heat}} \\ \text{HEPI}_{t_i} = \text{HEPI}_0 & \text{if } T_{\text{heat}} < T_{t_i} < T_{\text{cool}} \\ \text{HEPI}_{t_i} = \text{HEPI}_0 + \text{HEPI}_\text{c} \cdot \left(T_{t_i} - T_{\text{cool}}\right) & \text{if } T_{t_i} > T_{\text{cool}} \end{cases} \tag{10}$$

where HEPI_0 is the HEPI when temperatures are in-between cooling and heating temperature thresholds, HEPI_h and HEPI_c are respectively the additional HEPI for each additional heating and cooling degree day. The HEPI is expressed in value units per kWh denoted V hereafter. HEPI_0 and HEPI_h were set to unity in accordance with Paiva et al. (2010). An arbitrarily higher value was set for HEPI_c ($\text{HEPI}_\text{c} = 2.5V\,^{\circ}\text{C}^{-1}$).

Time series of daily HEPI were obtained for each scenario of daily temperatures. The corresponding mean inter-annual values of daily HEPI are presented in Fig. 2.

4 Sensitivity of SWV temporal variations to water use

We here discuss how the SWV varies with time and how its seasonal variations are related to the temporal variations of both the operating objectives and the amount of water available from the upstream catchment. We first consider separately two single-objective configurations and subsequently we consider both objectives simultaneously.

4.1 Hydroelectric Production (HEP)

The single-objective optimization of HEP, corresponds to $C_{\mathrm{HEP}} = 1$ and $C_{\mathrm{LLM}} = 0$ in Eq. (1). For this configuration, the efficiency of the hydroelectric production system is an increasing function of water head in the reservoir. If HEPI were constant throughout the year, the best storage strategy would be to maintain the water level at its highest possible value throughout the year, which may be lower than the full reservoir level to avoid future spillage (see for example Turgeon, 2007). Except before large inflow periods such as the snowmelt season, this strategy would lead to high SWV for most reservoir levels, especially the lowest ones. In the studied configuration, this storage strategy is of course modulated by the high seasonality of HEPI, SWV being higher during the periods before highest HEPI.

Figure 3 presents the variation of HEPI and water inflow to the lake with time over a four-year period (1 January 1977 to 1 January 1981). The corresponding variation of SWV with time is also given for different reservoir levels (corresponding to 10, 50 and 90 % of storage capacity).

At any given time t_i of the optimization period, SWV decreases with increasing storage level in the lake. The higher the current storage level, the more water is available for the future. Surplus storage water will be turbined during periods with lower HEPI or if necessary spilled. The interest of additional storage water is thus lower, leading in turn to lower SWV. If the storage level is high (e.g. 90 % storage level, dashed lines), SWV is therefore low to very low except in the case of an imminent period with very high HEPI that would justify storing more water (e.g. during winter periods). If the reservoir storage level is low (e.g. 10 % storage level), SWV is high to very high (up to 10 value units) except during periods with high HEPI and high future inflows (e.g. during spring periods). The priority for low storage levels when SWV is high is to increase water storage for future use.

For any given storage level s, SWV varies with time reflecting the role of the reservoir in adjusting the adequacy between the future HEPI and the future availability of water from upstream catchments. Future resource abundance (respectively scarcity) decreases (respectively increases) the value of more storage water like for example in May 1977 (respectively September 1977). As periods of high HEPI alternate with periods of high inflow discharges (Fig. 3, bottom panel), SWV presents high seasonal variations for all reservoir levels. Maxima are observed during the first months of the cold season (DJF) followed by minima during the spring months. During the winter and early spring transition period, the interest of more storage water decreases as a result of the concomitant decrease of HEPI in the late winter period and the rapid increase of snowmelt inflow during the spring period. The increase of SWV observed afterwards is more abrupt. It begins as soon as spillage is no longer required for the known future inflows. For the year 1979, this increase can be seen for example in June for a storage level of 50 % and in September for a storage level of 90 % due to a large flood event that occurred in fall of this year. The best operation strategy is again to increase the water storage for the following winter.

In addition to a marked seasonality, SWV shows year-to-year variations. Whatever the storage level, the SWV is related proportional to the ratio of future HEPI to the future inflow. It is high in year 1980 and lower in 1977 that illustrates the opposite configuration.

The variation of SWV with time for different water levels thus reflects the temporal desynchronization between the interest of water use and inflows, highlighting the different mechanisms that define the optimal storage strategy. In the following, and because the temporal variations of SWV are mainly seasonal, the mean inter-annual cycle of SWV for different reservoir levels will be used as a signature of the balance between water resources and demand under climatic and economical forcing. The signature obtained for the studied upper Durance system under the present hydro-economical context is presented in Fig. 4 for three storage levels (10, 50 and 90 % of storage capacity). In addition, the inter-annual variability is described for each storage level by two envelope curves corresponding respectively to the 10 or 90 % percentiles of the SWV calendar values obtained for the 42 yr of the 1960–2001 simulation period. For the sake of conciseness, the expression “SWV signature” will subsequently be used for the mean intra-annual variability of SWV, i.e. the seasonal variations of SWV for different storage levels.

4.2 Summer Lake Level Maintenance (LLM)

In this section, we consider a system for which the only management constraint is to maintain a minimum water level in the reservoir during the summer months (i.e. $C_{\mathrm{HEP}} = 0$ and $C_{\mathrm{LLM}} = 1$ in Eq. 1). In this case, the constrained summer season is assumed to run from 15 June to 31 August and the minimum assigned storage level is $s^* = 3000\,\mathrm{M\,m}^3 = 85\,\%$ of $s_{\max}$ during this period, $s^* = 0$ outside this period.

The SWV signature is as expected to be different in this case. The possibility to achieve the objective depends on the current storage level and on the volume of inflow that will enter the reservoir from the current date to the beginning of the next constrained period. At a given date of a given year, the higher the current storage level, the easier is to achieve the objective. For a given storage level, the longer the future period until the beginning of the constrained period, the larger the total future inflows to the reservoir and the easier it is to achieve the objective.

Penalty costs are incurred in the event of failure to achieve the objective. The SWV corresponds to the additional reduction of penalty costs that would be achieved by storing one more cubic meter of water at the current date. SWV therefore slowly increases over the year to reach a maximum in early summer. According to Fig. 5 this maximum is nearly one month before the beginning of the constrained period for the most adverse situations (90th percentile envelope curve – corresponding to the driest spring years) or as late as mid-July for the most favorable situations (10th percentile envelope curve – corresponding to the wettest spring years). The lowest SWV is zero, indicating that forthcoming inflows will fill the reservoir to the required level on time (Fig. 5). This is here the case for almost all reservoir levels in September, after the end of the constrained period (an exception is for the driest years if the storage level is lower than 10 % of the storage capacity). Thanks to the large inflows from the spring snowmelt flood, this applies also for a significant sub-period of the year (from mid-September to mid-April) at reservoir levels equal or higher than 50 %.

For this LLM objective, the SWV signature presents again a marked seasonality. The periods of high and low SWV are roughly in phase opposition with those obtained previously for the HEP objective.

4.3 Double-objective configuration

Figure 6 presents the SWV signature obtained when both HEP and LLM objectives must be fulfilled (i.e. $C_{\mathrm{HEP}} = 1$ and $C_{\mathrm{LLM}} = 1$ in Eq. 1). This double-objective configuration is denoted as HEP + LLM in the following. The obtained SWVs are logically higher than those obtained for each single-objective configuration (Figs. 4 and 5).

It is actually not possible to produce as much HEP and to fulfill the LLM objective as well as in the single-objective configurations. To limit the costs of failures to achieve the LLM objective, water allocations determined for the single HEP objective must be re-allocated to periods with lower HEPI. This is made possible by higher SWV for all reservoir levels, since high SWV reduces the interest of immediate water use.

The SWV signature for the double-objective configuration is a combination of the two single-objective signatures. It is however not exactly the sum of the two, reflecting the non-linearity pertaining to the optimization. The most significant residuals are observed for the winter season at low reservoir levels.

5 Sensitivity to climate change

We will now explore how the SWV signature and especially its variations with time depend on the hydroclimatic context. We therefore analyze its sensitivity to a modification of the characteristics of inflow and demand signals resulting from an annual temperature increase, an annual precipitation decrease and finally from both modifications simultaneously.

For the LLM objective, the lower mean inflow to the reservoir and the earlier snowmelt flood resulting from warmer temperatures increases SWV earlier in the year for reservoir levels lower than the summer objective level. The objective is therefore more difficult to meet on time than for the control period. For a reservoir storage level less than or equal to 10 %, the positive SWV obtained in September even shows an incapacity to meet the objective.

Finally, the signature obtained for the double HEP + LLM configuration is as for the present climate approximately an additive combination of the two single-objective signatures. For example, for the 50 % storage level, the large SWV decrease observed in the control climate during the six first months of the year tends to disappear as a consequence of the smaller flood snowmelt and the increased HEP interest during the summer months.

Regarding now a precipitation decrease, the SWV signature for the HEP + LLM configuration is presented for two scenarios in Fig. 8 (top panel). As changes in precipitation do not influence the seasonality of inflow (Fig. 1), the seasonality of SWV is maintained, whatever the reservoir level. The decrease in precipitation leads to a reduced mean inflow to the reservoir and in turn, to an increased SWV mean value at all storage levels and all seasons (expected the summer season for the 90 % storage level where SWV is zero). This means more severe conditions with a concentration of water allocations to HEP in the periods with the highest HEPI.

Finally, the SWV signature resulting from a modification of both precipitation and temperature changes is shown for three storage levels in Fig. 8 (bottom panels). Both seasonality and mean value of SWV are modified. As previously, changes of SWV for this combined configuration are approximately an additive combination of the partial ones.

6 Conclusions

For an ideal water reservoir system configuration in which both future water inflows and water demand are known, the marginal storage water value (SWV) can be obtained for different water storage levels in the reservoir using deterministic dynamic programming. SWV variation over the studied period results from the desynchronation between water demand and inflows. In a system where water demand and/or inflows are seasonal, SWV variation is also seasonal and its mean intra-annual variations defined on a calendar day basis can be used as a signature of the socio-climatic match between water resources and demand. This signature synthetizes the optimal storage strategy that would result from temporal co-variations between inflow and demand and how it could change if these co-variations change as expected from changes in climate and/or demand.

Real water resource systems deal generally with many objectives and constraints. With dynamic programming, a large variety of constraints and requirements can be integrated quite easily (e.g. irrigation water demand, dam safety management during floods or minimum flow maintenance for ecosystem integrity). In the usual case of multipurpose systems with conflicting uses and water scarcity, SWV estimates are not necessary equal to a simple linear combination of the individual SWV signatures obtained for each objective considered separately.

In the present work, a double-objective reservoir system was considered, involving year-round hydroelectric production and lake level maintenance during the summer season. In this case, the signature is a roughly additive combination of individual signatures. Analyzing the multipurpose signature along with each individual signature therefore provides a better understanding of why, how and to what extent each objective impacts the optimal storage strategy obtained for the multipurpose system. This may also reveal the potentially non-linear impact of interactions or competition between objectives. In this work, a simple sensitivity analysis with different future scenarios of temperature and/or precipitation changes showed that changes in SWV seasonality are mainly due to temperature increase and changes in the mean SWV result from precipitation decrease.

In the present work, the simulation of future hydrological scenarios was driven by observed precipitation and temperature time series modified according to synthetic climate change scenarios using a classical perturbation methodology. The temporal variability of future meteorological variables is therefore the same as that of the historical period. In particular, no changes in the sequences of wet and dry periods are considered from seasonal to pluri-annual time scales. Such changes are however expected to be potentially as critical as changes in the means of meteorological driving variables. They at least fully determine changes in the temporal variability of natural inflows into a lake, in particular their inter-annual variability, a determinant factor in system performance (McMahon et al., 2006). A higher variability of annual or pluri-annual inflows into the reservoir is for example expected to lead to longer and/or more frequent periods of resource scarcity. Such an analysis will be done with scenarios recently developed for the studied region using different statistical downscaling models from a suite of GCM experiments (Lafaysse et al., 2013).

SWV signatures can also be derived for other contexts than the one considered in the present work. SWV is also an output of strategy optimization methods for multi-reservoir systems. In such cases, SWV, which is time and storage level dependent, is also site dependent (Tilmant et al., 2008, 2009; Wolfgang et al., 2009). It would also be relatively easy to produce SWV signatures for each reservoir. Such signatures could help to better assess the relative value of each reservoir and, when needed, to better identify if and where additional water conservation measures should be implemented.

Moreover, as mentioned in the introduction, SWV is also frequently estimated for determining an operating strategy for real-time management of a water system. In such a case, the SWV can be obtained using stochastic dynamic programming in a configuration in which future inflows and water uses are unknown. The SWV is known to increase in this case when compared to the SWV obtained with perfect foresight, as a result of inflow variability and forecastability. Nevertheless, SWV signatures obtained for an uncertain future are also potentially very informative with regard to how an operational strategy is organized, what are their key features and how it could change should the climate and/or demand change. Changes in the variability and forecastability of future inflows and demand are expected to also have a critical impact on changes in SWV. Analyzing these signature changes would probably improve our understanding of modifications of system performance classically reported on the basis of a variety of performance criteria in climate change impact analyses.

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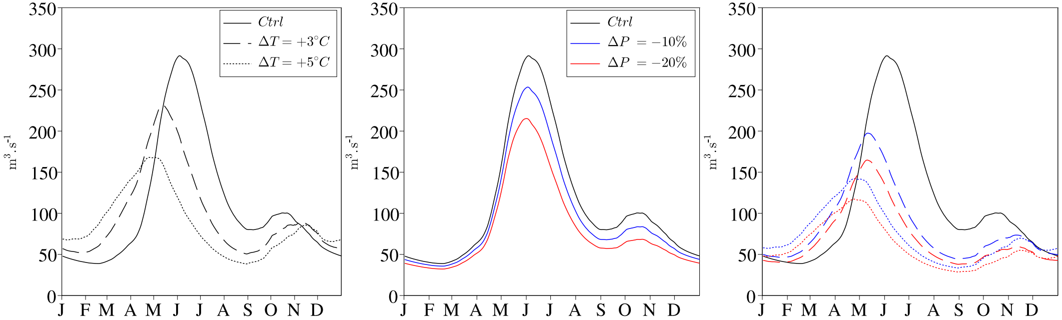

Fig. 1. Mean inter-annual cycles of daily inflow to the reservoir for control data (black curve in all graphics, period 1960–2001) and two future meteorological scenarios (with prescribed changes of the mean annual temperature (ΔT) and precipitation (ΔP) over the period 2070–2099). Left: changes in mean annual temperature only. Middle: changes in mean annual precipitation only. Right: changes in both annual precipitation and temperature.

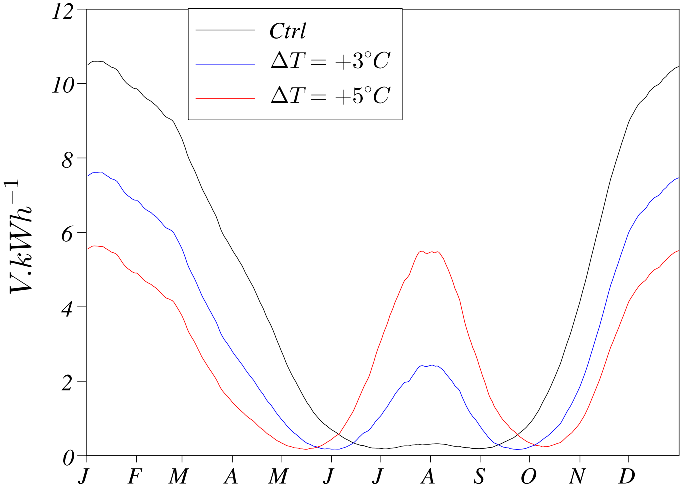

Fig. 2. Mean inter-annual cycles of the interest hydroelectric production (HEPI) for the control period and two different future scenarios of annual temperature increase ΔT.

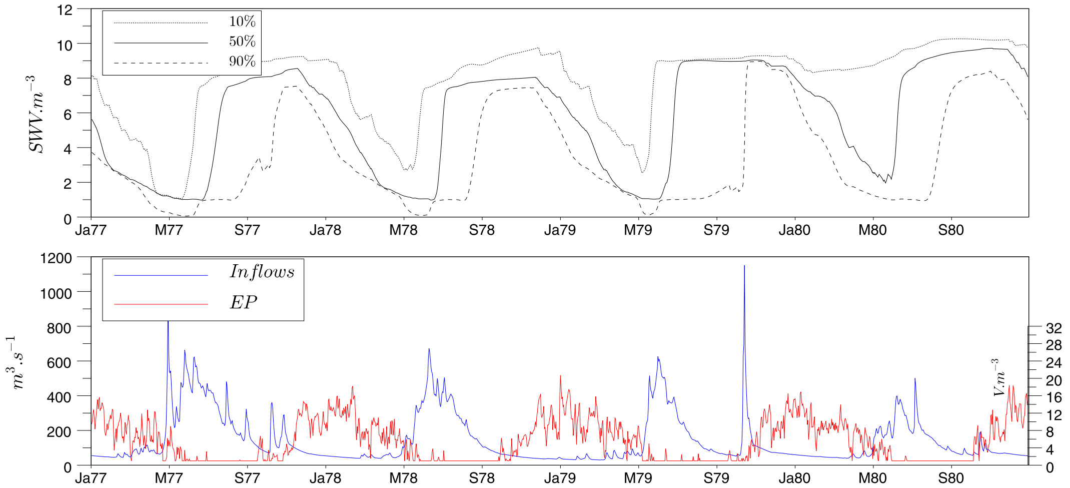

Fig. 3. Variations of SVW and inflows from January 1977 to January 1981 for the meteorological control scenario (Ja: January, M: May, S: September). Top panel: storage water value (SWV) for different reservoir storage levels corresponding to 10, 50 and 90 % of the capacity. Bottom panel: water inflow to the lake (blue curve) and interest of hydroelectric production (red curve).

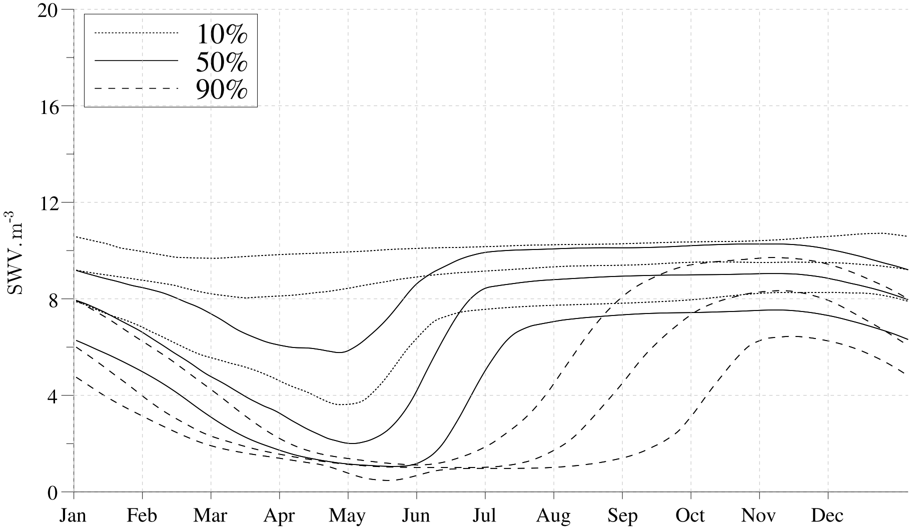

Fig. 4. SWV signature for the single hydroelectric production objective (HEP). The mean inter-annual SWV variation obtained for the 1960–2001 period is plotted for three reservoir storage levels (10, 50 and 90 % of storage capacity). For each storage level, the upper, middle, and lower curves correspond respectively to the 90th percentile, the mean and the 10th percentile of SWV calendar values obtained for the 42 yr of the period.

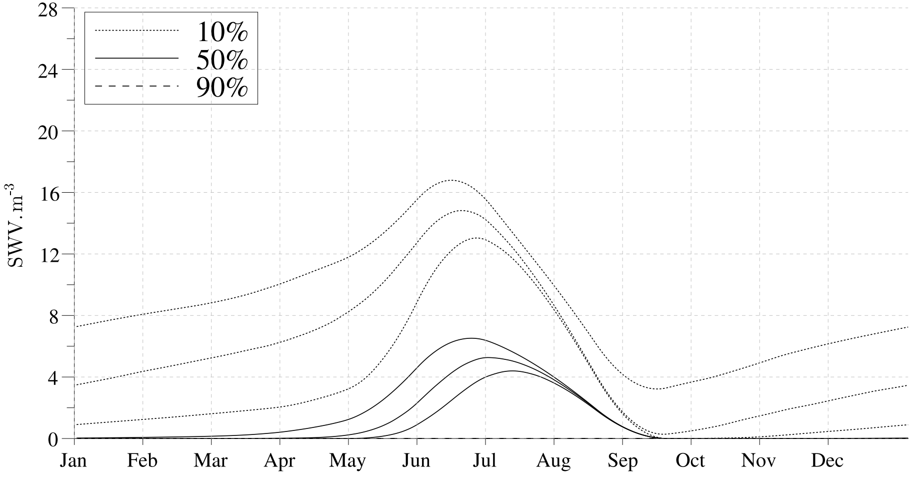

Fig. 5. SWV signature for the lake level maintenance objective (LLM). See Fig. 4 for caption details. The 90 % curves are confounded with the x-axis.

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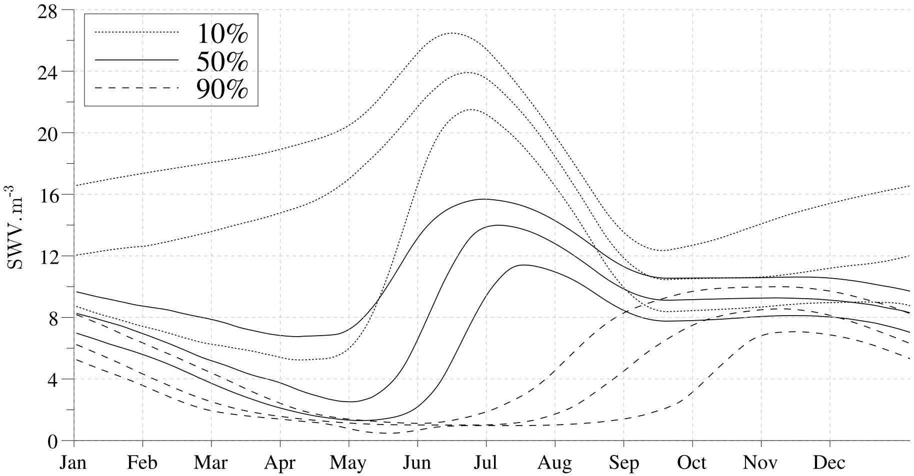

Fig. 6. SWVsignature for the double-objective configuration (HEP + LLM). See Fig. 4 for caption details.

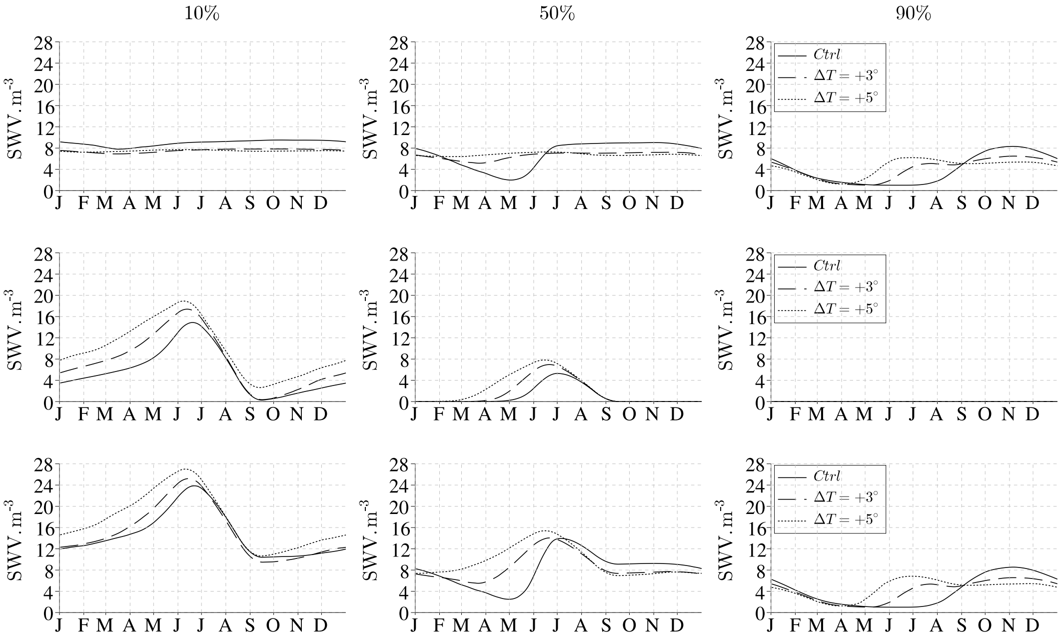

Fig. 7. Sensitivity of SWV signatures to temperature. The different curves correspond to the control data set and to two scenarios of warming. The different columns correspond to storage levels of 10 % (left panels), 50 % (middle panels) and 90 % (right panels) of storage capacity. The objectives considered are the HEP (top panels), the LLM (middle panels) and a combination of the two (bottom panels).

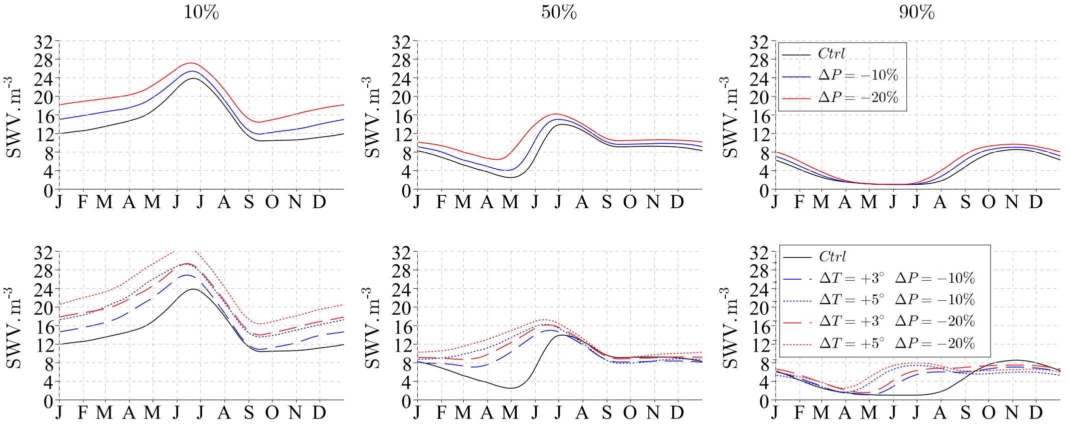

Fig. 8. Sensitivity of SWV to precipitation changes (top panels) and to combined changes of both precipitation and temperature (bottom panels) in case of combined HEP and LLM objectives.