Economic valuation of inter-annual reservoir storage in water resource systems

Majed Khadem[1], Charles Rougé[1,2], and Julien Harou[1]

[1] School of Mechanical, Aerospace and Civil Engineering, University of Manchester, Manchester M13 9PL, United Kingdom

[2] Department of Civil and Environmental Engineering, Cornell University, Ithaca, NY 14850, United States

1. Motivation & Objective

- Inter-annual reservoir operation in large-scale water resource systems has long been a challenge.
- Excessive release will threaten future supplies while unnecessary hedging creates economic hardship downstream.
- We tackle this problem for complex large-scale water resource systems using economic valuation of end-of-year carry-over storage.
- A generalizable approach is proposed to estimate the economic value of inter-annual reservoir storage. The approach can handle non-convexity involved in most real-world cases and is not affected by curse of dimensionality.

2. Methodology

The proposed approach discretizes the full planning horizon to shorter periods (often a hydrological year) and performs sequential runs. The final state from the previous year provides the initial condition to each year-long problem and carry-over storage value function (COSVF) acts as a boundary condition representing the value of stored water for future use. The approach uses an evolutionary search algorithm linked to a hydro-economic optimization model (a model that uses economic incentive to determine allocation while maximizing system-wide economic benefit).

- We propose dividing the whole planning horizon [1,T] into K year-long time frames $[t_k+1, t_{k+1}]$. For instance with a monthly time step and K years, $t_k=(k-1)\times 12$ so $[t_1+1, t_2]=[1,12]$ and $[t_K+1, t_{K+1}]=[T-11, T]$. A maximization sub-problem can be proposed for each year:

$$Z_k(Q,p) = \sum_{t=t_k+1}^{t_{k+1}} f_t(x_t,u_t,q_t) + COSVF_k(p; x_{t_{k+1}}, u_{t_{k+1}})$$

$f_t(.)$ = benefit function at stage t
u_t = decisions taken at t
x_t = state of the system (typically including reservoir storage)
q_t = vector of stochastic inflows
$v_{T+1}(.)$ = a final value function
$Q=(q_t)_{t\in[1,T]}$ = predetermined sequence of inflows

- Assuming a functional form, reservoirs' COSVF can be described by the parameters p of this function – e.g., in this work, two parameters for a quadratic COSVF with zero value at dead storage.

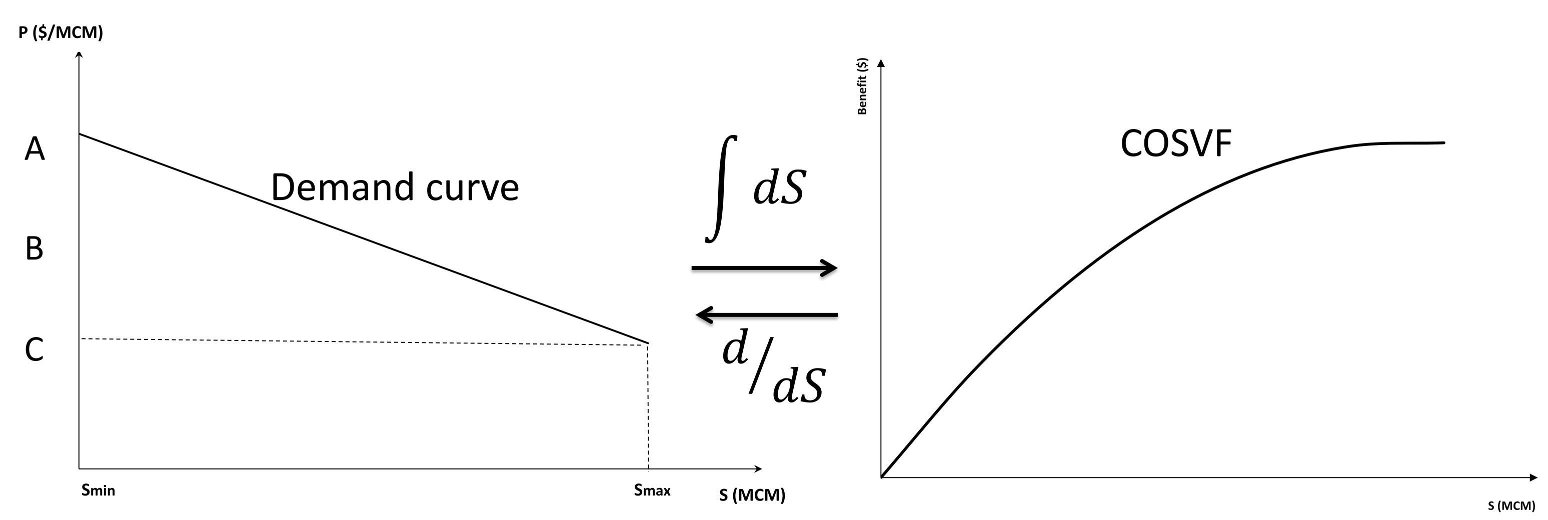

Figure 1. A quadratic COSVF and its corresponding demand curve

- The K sub-problems described are solved sequentially. The initial condition of sub-problem $k+1$ is given by the final state from sub-problem k. The sequential optimization of objectives Z_1 to Z_K leads to maximizing a limited foresight objective Z_{LF}:

$$Z_{LF}(Q,p) = \sum_{k=1}^{K}\left(\max_{u_t}\{Z_k(Q,p)\} - COSVF_k(p; x_{t_{k+1}}, u_{t_{k+1}})\right)$$

3. Solution Strategy

Finding $max\, Z_{LF}(Q,p)$ is a double maximization problem, with (i) a series of within-year deterministic hydro-economic optimizations, and (ii) an optimization in the parameter space of the COSVF. Maximization (i) is used to simulate the system and is carried out for a given set of COSVF parameter values p. Maximization (ii) is then implemented through evolutionary computation, taking COSVF parameter space as the evolutionary algorithm's decision space.

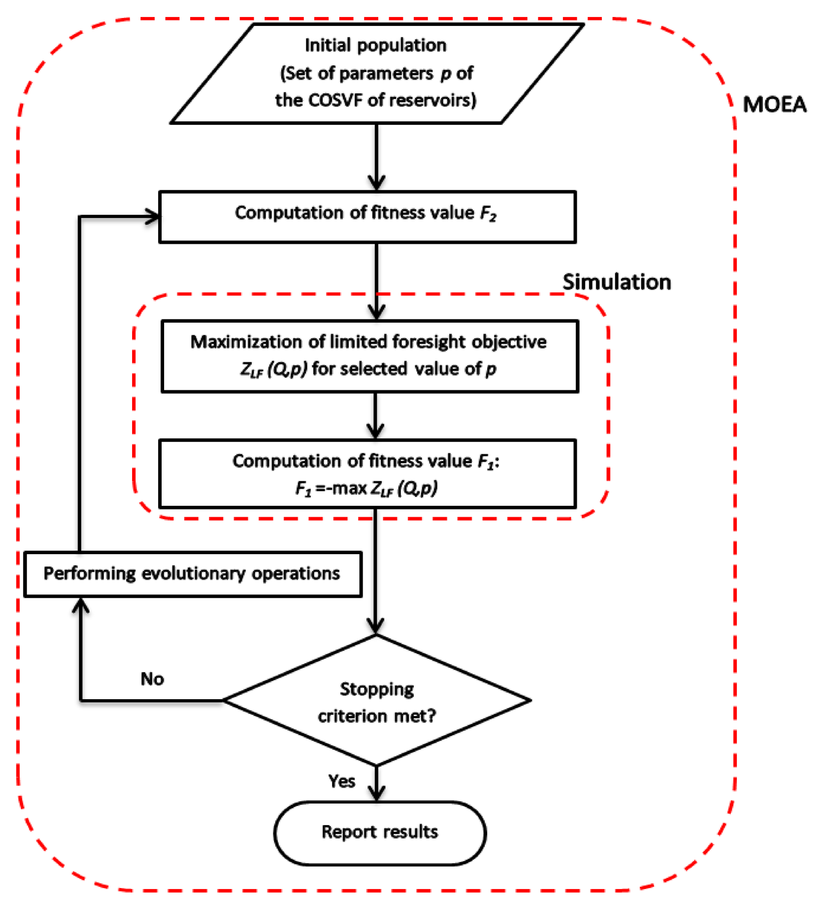

Figure 2. Proposed model workflow

If the valuation of a given reservoir (characterized by p) is enough to fill that reservoirs at the end of each year, any other valuation of carry-over storage above the "true" value will also fill that reservoir every year. To avoid this, a second objective is added aiming to eliminate sets of parameters that lead to unreasonably high marginal values of water, and therefore, unreasonably high values of carry-over storage – recall that the marginal value of storage is a COSVF's derivative. Therefore, maximization (ii) will become a multi-objective optimization problem with the following fitness functions:

$$\min(F_1, F_2)\ with\ F_1 = -Z_{LF}(Q,p) \text{ and } F_2 = \frac{1}{n_{sr}}\sum_{sr} M_{sr}$$

M_{sr} = arithmetic mean of marginal water value at dead and full storages
n_{sr} = number of reservoirs

4. Study Area

- A regional model of the California Central Valley water resource system is used.
- 30 surface reservoirs, 10 power plants, 22 aquifers, and 51 urban and agricultural demand sites.
- Suffering from many droughts including 1918-20, 1923-26, 1928-35, 1947-50, 1959-62, 1976-77, 1987-92, 2007-09, and 2012-16.

Figure 3. Severe drought in Oroville Lake in July 2011 (left) and August 2014 (right).

5. Results

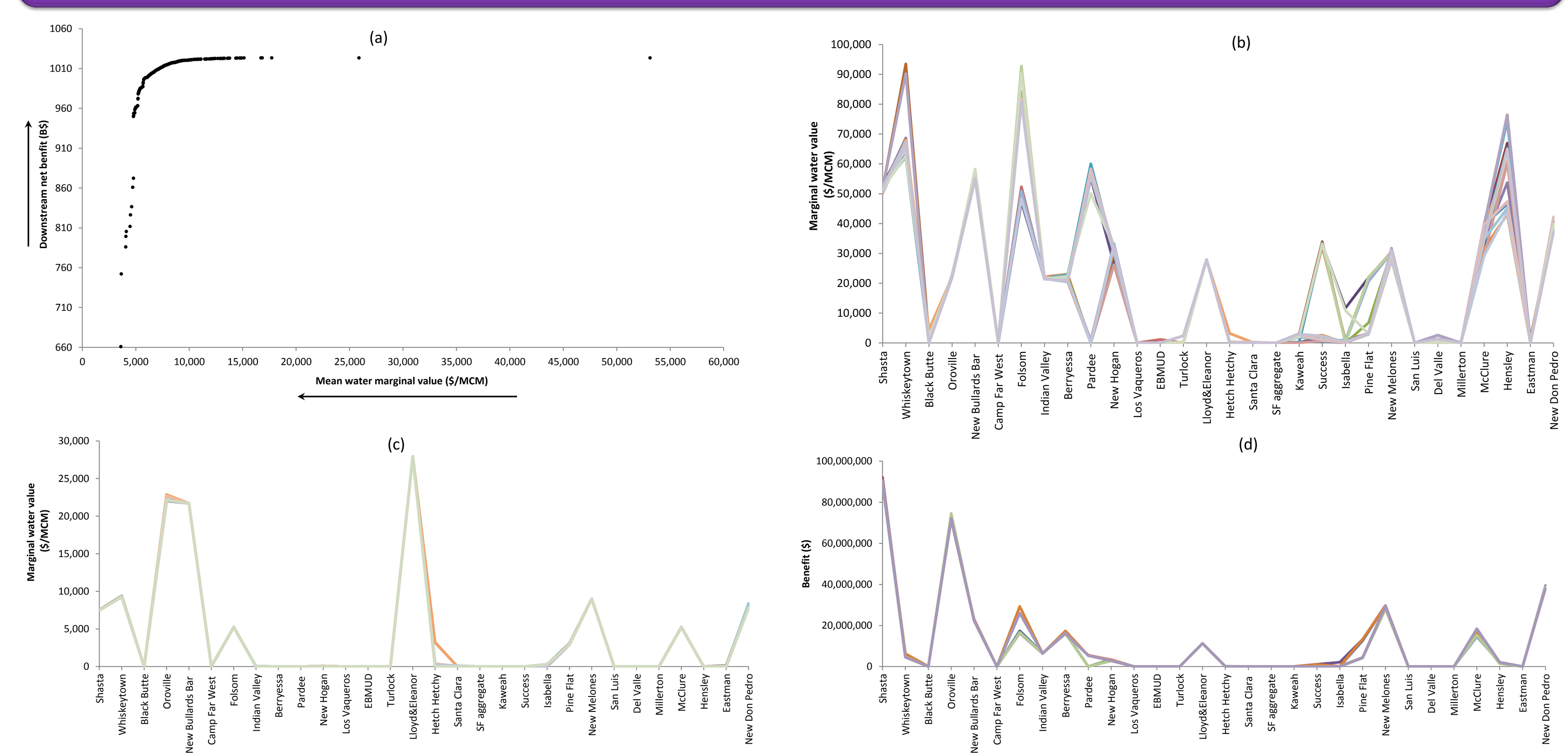

Figure 4. Results of the multi-objective optimization problem: a) Pareto non-dominated solutions (arrows show the direction of preference); b) maximum water marginal value solutions (A in Figure 1); c) minimum water marginal value solutions (C in Figure 1); and d) maximal total value of end-of-year carry-over storage (i.e. total value of carry-over storage if reservoirs are full). Note that colors represent different solution point from the flat part of the Pareto front.

6. Conclusion & Outlook

- The proposed approach obtained storage marginal values that can be used to aid decision-makers for new policy decisions.
- Results showed an improvement in scarcity management evidenced by a reduction of scarcity (80% in scarcity volume and 98% in scarcity costs) compared to a historical approximation.
- Using a many-objective search algorithm offers the flexibility to consider more objectives, if needed.

Acknowledgments
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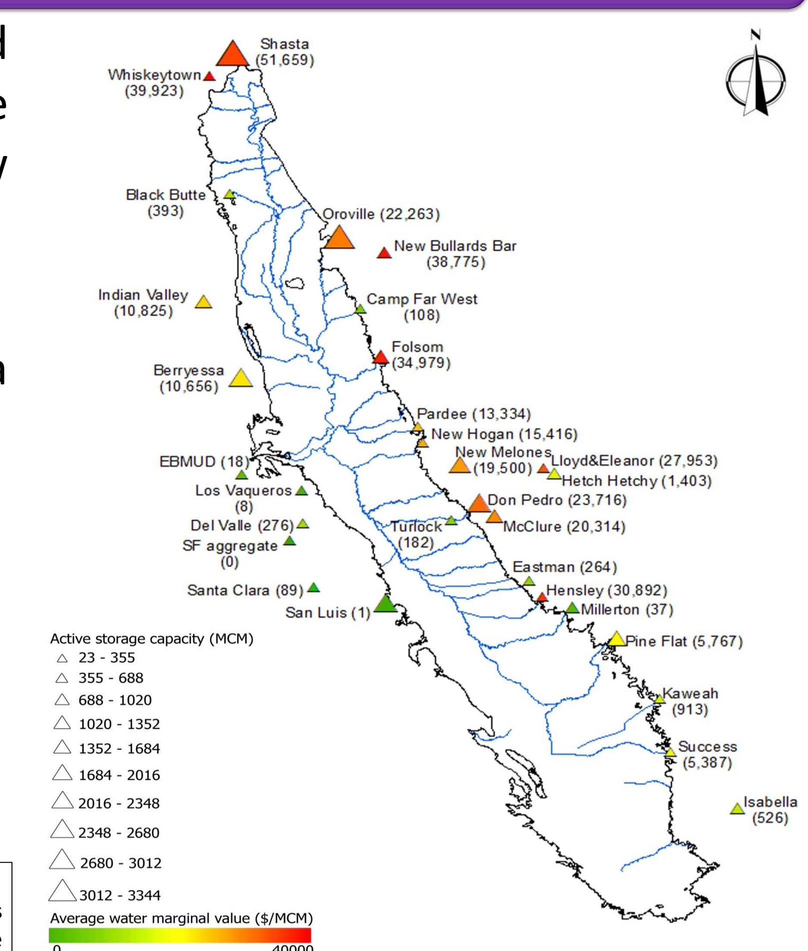

Figure 5. Distribution of average stored water marginal value in the Central Valley.