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Publication Date
2021

Peer reviewed|Thesis/dissertation

The Economic Value of Carryover Storage in California's Water Supply System with Limited Hydrologic Foresight

By

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THESIS

Submitted in partial satisfaction of the requirements for the degree of

MASTER OF SCIENCE

in

Civil and Environmental Engineering

in the

OFFICE OF GRADUATE STUDIES

of the

UNIVERSITY OF CALIFORNIA

DAVIS

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2021

…to the carryover of knowledge

Abstract

The security and prosperity of California's economy depend on a large, interconnected and highly engineered water supply system with vast surface and groundwater storage operated for over-year storage. Substantial public investment is needed to maintain and improve these systems with changing climate risks, increasing demands, and aging infrastructure. Hydro-economic optimization identifies promising opportunities for managing such systems, but scientific and engineering advances are needed to better incorporate hydrologic uncertainty and conjunctive management of streams and aquifers into such models. Over two decades of research the California Value Integrated Network (CALVIN) linear programming hydro-economic model has yielded insights for California's inter-regional water system on many fronts, including climate change, groundwater sustainability, conjunctive management in southern California, water markets, and reservoir operations in Northern California. Yet there remains unrealized potential to improve the model's formulation to better represent interannual hydrologic variability while concurrently developing reservoir control rules. To address this gap, this study implements linearized quadratic carryover storage value functions on 26 surface reservoirs and linear groundwater storage penalties on 32 groundwater reservoirs to optimize California's inter-regional water system seasonal and inter-annual operations with limited seasonal foresight. A convex Pareto front tradeoff between total system cost and groundwater overdraft is developed through multi-objective evolutionary optimization of inter-annual carryover storage penalties. Resulting over-year storage valuations span a wide range of near-optimal reservoir operations, suggesting substantial system flexibility and adaptability when managed in an integrated way. Generalized relationships between carryover capacity, carryover use, and the marginal value of carryover storage are drawn for the multi-reservoir system. When compared to carryover operations based on California's current simulation model, CalSim-II, the performance of these near-optimal reservoir operations suggests room to improve currently prescribed reservoir control rules, especially in supporting more sustainable conjunctive management with aquifers. Overall, this study demonstrates the practicability, feasibility, and utility for understanding large-scale integrated multi-reservoir conjunctive use systems using limited foresight with explicit carryover storage values.

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1. Economic Optimization of Large-scale Multi-reservoir Operations

Climate change and new data and modeling capabilities create problems and opportunities for water resources planning, giving incentives for soft-infrastructural alternatives that provide flexibility, robustness, and resilience under a wide range of future conditions. A promising opportunity is the redesign of reservoir and larger water system control rules to sustainably manage human and environmental objectives, bridging surface and groundwater management. However, scientific and engineering advances are needed to support this objective, better incorporating hydrologic uncertainty and conjunctive management of streams and aquifers in hydro-economic optimization for large-scale multi-reservoir and aquifer operations.

Analyses to improve large-scale reservoir system operations have enormous computational challenges. These challenges increase with non-stationary hydrologic conditions. Stochastic dual dynamic programming has been applied to large-scale water resource issues with hydrologic uncertainty, but deterministic methods continue to be preferred by practitioners for their ease of use, greater ability to integrate diverse portfolios of actions, and lack of reliance on statistical hydrology. Draper (2001) proposed a modification to implicitly stochastic [deterministic] optimization (ISO) of reservoir operating rules that incorporates limited foresight of future conditions (i.e., hydrologic risk) and conjunctive management but stopped short of application to a large-scale multi-reservoir water system. One candidate model for implementing this method is the California Value Integrated Network (CALVIN), an economics-driven optimization model that represents over 50 surface reservoirs, 32 groundwater reservoirs, an extensive conveyance network, and over 95% of urban and agricultural water users in California's statewide water system (Jenkins et al. 2001).

Studies of California's inter-regional water system using CALVIN have yielded insights on the economic value of network and surface storage expansion, potential modifications to system operations, water markets, and the effects of changes in water policy, regulations, and hydrologic shifts driven by climate change (Dogan et al. 2019; Nelson et al. 2016; Pulido-Velazquez, Jenkins, and Lund 2004; Harou et al. 2007; Lund et al. 2003; Herman et al. 2018; Zikalala 2013). Yet throughout these studies, authors have recognized that perfect hydrologic foresight may bias estimates of the economic value of water and infrastructure and challenge the interpretation of the model's reservoir operations. With complete foreknowledge of California's highly variable climate, CALVIN perfectly allocates flow across multi-year droughts and perfectly minimizes spillage in wet winters. The idealized operations thus provide a lower bound of economic value to system constraints and opportunities for expansion.

Constraining model foresight to a feasibly predictable time horizon is the evident solution; yet limited foresight would be overly pessimistic without an economic link between periods in reservoirs for which hedging can perform better than the standard linear operating policy (SLOP) (Loucks and van Beek 2017; Draper and Lund 2004; Oliveira and Loucks 1997). Draper (2001) proposed such an economic link shortly after CALVIN's initial release: a value function, termed the "carryover storage value", connects sequential limited foresight model runs by representing the benefit of holding water in storage in the current annual period for release in following periods. This approach breaks each multi-year analysis into a connected series of annual optimizations.

CALVIN has been implemented in Python using the Pyomo optimization package (Dogan et al. 2018). The model is typically run with perfect hydrologic foresight wherein flows are optimized simultaneously across all monthly time steps for the entire analysis period (typically 83 years). The limited foresight Carryover Storage Value Function (COSVF) method was recently implemented by Khadem et al. (2018) using a non-linear CALVIN objective formulation and multi-objective evolutionary algorithm for COSVF parameter value search. The application by Khadem et al. (2018) and a follow-up investigation to infer historical levels of reservoir operator risk aversion (Khadem, Rougé, and Harou 2020) has already shown several benefits and insights to the limited foresight approach. However, the Khadem et al. application is limited to storage penalties on surface storage reservoirs (head-dependent pumping costs were used to disincentive groundwater overdraft) and excludes southern California. In this study, the open-source Python implementation of the linear CALVIN formulation is extended to limited annual hydrologic foresight with carryover storage penalties on both surface and groundwater reservoir storage nodes and over all regions in the California statewide integrated network.

2. The Search for Carryover Storage Value Functions in CALVIN

The California Value Integrated Network (CALVIN) model integrates facility operations, resource inputs, and water demands of California's inter-tied water systems into a generalized network flow optimization problem (Draper et al. 2003). The model identifies monthly operation and allocation decisions that minimize total economic cost over an 82-year historical period-of-analysis (1922-2003) while constrained by environmental flow requirements, facility capacities, and other operating limitations. The objective function of CALVIN is:

$$min\ Z_{PF} = \sum_i \sum_j \sum_k c_{ijk} X_{ijk} \tag{1}$$

subject to upper bound, lower bound, and conservation of mass constraints:

$$X_{ijk} \leq u_{ijk}, \forall (i,j,k) \in \mathcal{A} \tag{2}$$

$$X_{ijk} \geq l_{ijk}, \forall (i,j,k) \in \mathcal{A} \tag{3}$$

$$\sum_i \sum_k X_{jik} - \sum_i \sum_k a_{ijk} X_{ijk} = 0, \qquad \forall j \in \mathcal{N} \tag{4}$$

where c is the cost of flow X from node i to node j over piecewise index k for a link belonging to the network of links $\mathcal{A}$. Flows over links are constrained by upper u_{ijk} (2) and lower l_{ijk} (3) bounds and conservation of mass (4) at each node in the network $\mathcal{N}$, where the amplitude a_{ijk} is a gain/loss factor.

2.1. Quadratic Carryover Storage Value Function

Following Draper (2001), the carryover storage value function (COSVF) for surface reservoirs is assumed to be quadratic and convex:

$$P = aS^2 + bS + c \tag{5}$$

$$\frac{\partial P}{\partial S} = P' = 2aS + b \tag{6}$$

$$\frac{\partial^2 P}{\partial S^2} = P'' = 2a \tag{7}$$

where P is the penalty on end-of-period (EOP) storage S, and a, b, and c are constants. The first (6) and second (7) derivatives of the quadratic COSVF are the marginal penalty on carryover storage and diminishing returns in the value of water, respectively. Solving P' for two cases of EOP storage, at minimum marginal penalty value and maximum carryover storage ($P'|_{s=K_{cs}}$ denoted as P_{min}) and at maximum marginal penalty value and zero carryover storage ($P'|_{s=0}$ denoted as P_{max}), fully defines the quadratic COSVF constants:

$$b = P_{max} \tag{8}$$

$$a = \frac{P_{min} - P_{max}}{2K_{cs}} \tag{9}$$

$$c = -\frac{K_{cs}(P_{min} + P_{max})}{2} \tag{10}$$

The quadratic COSVF constructed from P_{min} and P_{max} is broken into k-piecewise components for the final time step in the limited foresight optimization horizon and appended to $\mathcal{A}$. The quadratic COSVF is analytically equivalent to a piecewise linear hedging rule and has been shown to fit a variety of reservoir operating circumstances (Draper 2001; Draper and Lund 2004). Even where a higher-order COSVF may be optimal, the derived policy would likely be similar to that determined based on quadratic COSVF model results (Draper and Lund 2004).

Table 1 lists the 26 surface reservoirs in CALVIN for which quadratic COSVFs are developed and applied in this study. The remaining surface reservoirs features in CALVIN for which COSVF were not developed are either 1) natural features (i.e., lakes), 2) annual inter-state allocation policies (e.g., Colorado River), or 3) reservoirs along the conveyance network with small carryover capacities relative to annual inflows and thus assumed to follow a SLOP policy with limited foresight. Carryover operations observed in perfect foresight for reservoirs in the latter category confirm that these reservoirs refill and empty on a sub-annual basis. Figure

Table 1. CALVIN Surface Reservoirs with COSVFs Applied

CALVIN SR	**Name**	**CALVIN SR**	**Name**
SR_SHA	Shasta	SR_NHG	New Hogan
SR_CLE	Clair Engle Lake	SR_NML	New Melones
SR_WHI	Whiskeytown Lake	SR_HTH	Hetch Hetchy
SR_ORO	Oroville	SR_LL_ENR	Lake Eleanor
SR_BUL	New Bullards Bar	SR_SFAGG	SF Aggregate
SR_RLL_CMB	Rollins and Lake Combie	SR_DNP	Don Pedro
SR_CLK_INV	Clear Lake	SR_MCR	McClure
SR_BER	Berryessa	SR_SNL	San Luis
SR_FOL	Folsom	SR_BUC	Eastman Lake
SR_PAR	Pardee Reservoir	SR_MIL	Millerton Lake
SR_CMN	Camanche	SR_PNF	Pine Flat
SR_LVQ	Los Vaqueros	SR_ISB	Lake Isabella
SR_EBMUD	East Bay MUD Aggregate	SR_GNT	Lake Grant

1 shows a simplified CALVIN schematic and map with locations of the surface reservoirs in the network, demand aggregation regions, and groundwater storage nodes.

2.2. Linear Penalties on Groundwater Storage

Chronic, long-term overdraft of groundwater can inflict several forms of economic and environmental damage, including subsidence impacts to infrastructure and loss of usable storage, depletion of surface water flows, water quality degradation, increased costs and use of energy from pumping, and harm to ecosystems dependent on groundwater levels. CALVIN does not account directly for the economic or environmental impacts of declining groundwater water levels. Only pumping volume capacity constraints and a constant cost of pumping, based on energy consumption of a representative pumping lift estimated from physical groundwater levels in the year 2000, is factored into operation and allocation decisions (Zikalala 2013). CALVIN's change in groundwater storage is a function of the pre-processed "external" inflows and outflows determined exogenously based on available data and physically based groundwater models, and endogenously calculated volumes of pumping, return flows, and artificial recharge.

With perfect foresight, a limit on overdraft is typically applied by constraining the lower bound of a groundwater storage node's final time step equal to the storage volume of its initial time step. This approach does not work in a limited time horizon CALVIN model as it is likely economical to sustain overdraft conditions over several limited time horizon periods until wetter conditions return. For example, previous application of perfect foresight with a no-overdraft constraint suggests two major drawdown and refill cycles for Central Valley groundwater basins – one of 12 years and one of 62 years (Dogan et al. 2019). With limited foresight, one approach to explicitly deter overdraft is to introduce a marginal cost on ending groundwater storage below the initial year's storage level. Marginal penalties on end-of-year groundwater storage, termed P_{GW} (\$/AF), are assumed to be linear and constant for any groundwater overdraft volume. A starting point for the value of P_{GW} is the dual value on the final time step of a groundwater storage node from the perfect foresight overdraft-constrained model run (Draper 2001). Since the economic values in a perfect foresight run represent the best-case (minimum) marginal penalty, a more realistic value must be found through iterative search together with COSVF parameters on surface storage. This study searches for optimal P_{GW} on each active groundwater reservoir represented in CALVIN (a total of 32 shown in Figure 1).

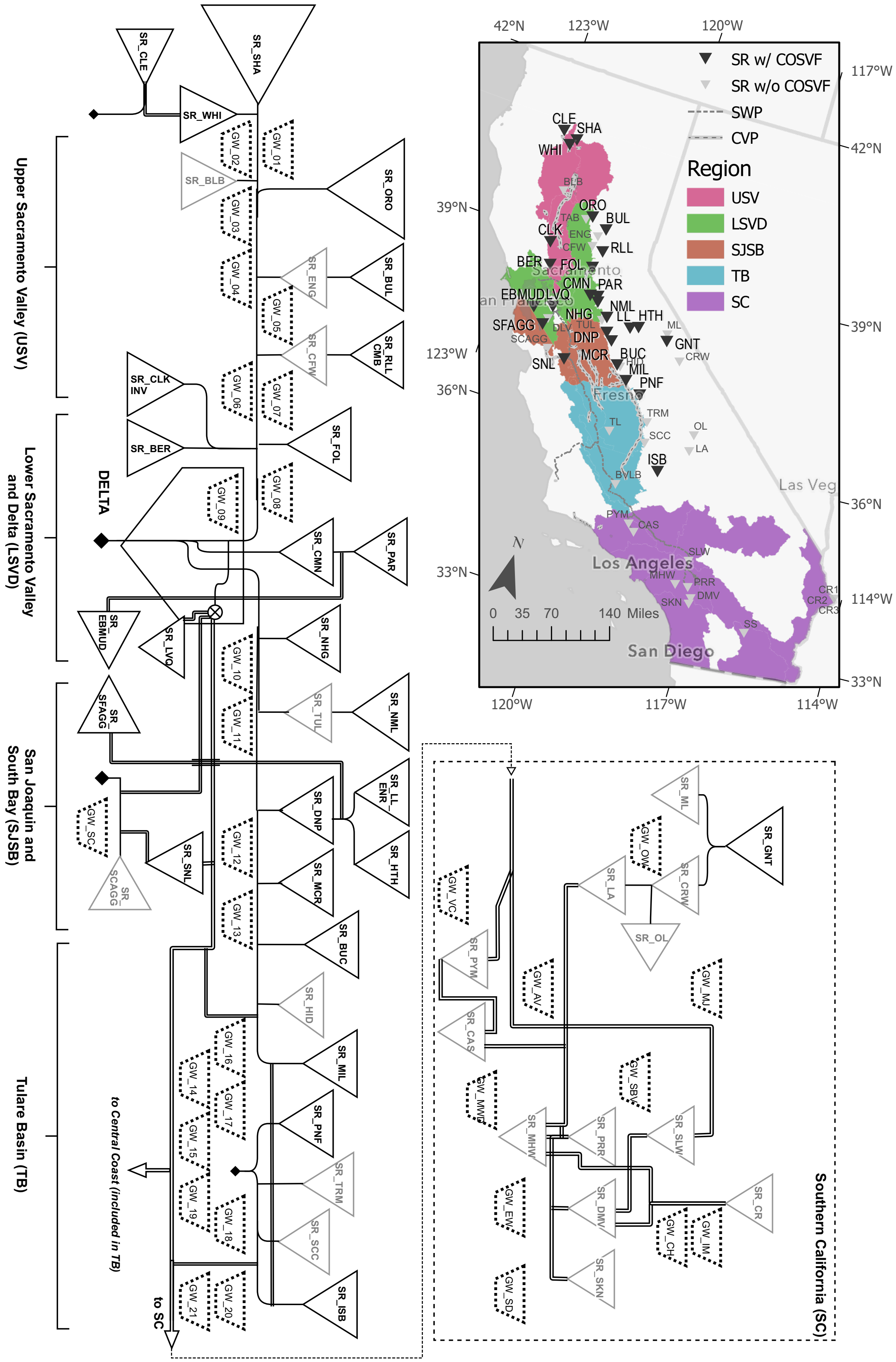


Figure 1. Simplified CALVIN Schematic of Major Reservoirs and Aquifers and Region Map

2.3. Multi-Objective Evolutionary Search for Optimal COSVF Parameter Values

Predictability of annual runoff in California's seasonal Mediterranean climate is varied but achieves some skill in early spring, making perfect foresight on an annual (water-year, defined as October-September) basis often broadly reasonable (California Department of Water Resources 2020). Therefore, the CALVIN objective (1) is revised as the summation of T-annual perfect foresight deterministic optimizations:

$$Z_{LF}(P_{COSVF}, P_{GW}) = \sum_{t}^{T}\left(min\left(Z_{PF_t} + \sum_{i}\sum_{j}\sum_{k} p_{ijk}s_{ijk} \right)\right) \tag{11}$$

where end-of-year storage s on reservoir link ijk is penalized according to stepwise marginal penalty costs p developed from set P_{COSVF} for surface reservoirs and set P_{GW} for groundwater reservoirs. Continuity across years is preserved by setting initial storage conditions of year T_t equal to ending storage conditions of T_{t-1}. Optimization of limited foresight CALVIN is done by zero-order function evaluation of (11) through iterative evolutionary search for a carryover storage policy described by P_{COSVF} and P_{GW} – a total of 84 decision variables – which minimizes (or maximizes) one or more fitness objectives, F_n:

$$\min_{\pi}(F_1, F_2, \dots F_n; P_{COSVF}, P_{GW}) \tag{12}$$

The current study employs three fitness functions. The first fitness function (F_1) represents the overall economic performance of the system and is the sum of operation and shortage costs:

$$F_1 = \sum_{t}^{T}\left(\sum_{O_{ijk}} c_O X_O + \sum_{D_{ijk}} c_D (X_D - u_D) \right) \tag{13}$$

where O_{ijk} are operational links (with positive cost), D_{ijk} are demand links (with negative cost), X_O and X_D are flows over these links determined from the output decision variables of (11), and c_O, c_D, and u_D are the respective cost and upper bound capacity inputs to (11).

The second fitness function (F_2) is the sum of period-of-analysis groundwater overdraft volumes over all individual groundwater reservoirs:

$$F_2 = \sum_j \left(\begin{cases} -\left(s_{j,T} - s_{j,T_0}\right), & \text{if} \geq 0 \\ 0, & \text{otherwise} \end{cases} \right) \tag{14}$$

where s_{j,T_0} and $s_{j,T}$ are the groundwater storage volumes in groundwater reservoir j at the beginning and end of the period of analysis, respectively, determined from the output decision variables of (11).

The third fitness function (F_3) is the average of marginal carryover and groundwater storage penalties prescribed for (11):

$$F_3 = \frac{\left(\frac{1}{n_{SR}} \sum_{SR} \left(\frac{P_{min_{SR_j}} + P_{max_{SR_j}}}{2} \right) + \frac{1}{n_{GW}} \sum_{GW} P_{GW_j} \right)}{2} \tag{15}$$

where n_{SR} and n_{GW} are the number of surface and groundwater reservoirs, respectively. The third fitness function (also used in Khadem et al. (2018)) guides the search towards the lowest marginal storage penalties that achieve the best overall economic and groundwater overdraft performance, thus avoiding exceptionally high storage penalties for smaller reservoirs in the system which result in similar economic performance on a systemwide level. Furthermore, minimizing average marginal storage penalties is a reasonable approach for expected value decision-making when the specific level of risk aversion of local water managers is unknown.

2.4. Evolutionary Algorithm and Parameters

Minimization of the multi-objective, discontinuous, differently scaled, and non-convex optimization problem (12) is done with the evolutionary computation framework Distributed Evolutionary Algorithms in Python (DEAP) (Fortin et al. 2012). Of the many multi-objective evolutionary algorithm (MOEA) structures and approaches available (Coello Coello, Lamont, and Van Veldhuizen 2007), this study uses reference-point based Non-dominated Sorting Genetic Algorithm (NSGA-III) (Deb and Jain 2014) as a selection heuristic with simulated binary crossover (SBX) (Deb and Agrawal 1994) and polynomial mutation (Deb 2001) as mating and mutation operators, respectively. An advantage of NSGA-III is its ability to take a small number of structured or randomly assigned reference points to target the evolutionary search on specific regions of the multi-objective Pareto frontier. Although not leveraged here, this approach could be useful in future applications of limited foresight CALVIN, which seek COSVF solutions that highlight promising areas for cooperation or fraught areas of conflict (Null et al. 2020).

Table 2. Evolutionary Search Parameters

Parameter	**Value**	**Description**
Number of generations	120	Number of evolutionary generations (selection + mating/mutation) to conduct.
Population count, N	92	Number of individuals in the evolutionary population.
*Divisions per objective, p	12	Number of divisions considered along each objective.
*Number of reference points, H	91	Number of reference points placed on a normalized hyperplane equally inclined to all objectives and having an intercept of 1 on each axis; expressed by: $H = \binom{M+p-1}{p} \approx N$ where M is the number of objectives.
Crossover probability, p_c	1	Probability of mating two individuals at each generation.
SBX distribution index, η_c	10	Crowding degree of the crossover; higher η_c increases probability that offspring resemble their parents.
Mutation probability, p_m	1	Probability of mutating an individual at each generation.
Attribute mutation probability, p_{m_i}	0.5	Probability of mutating an attribute of the individual undergoing mutation.
Polynomial mutation distribution index, η_m	40	Strength of mutation; higher η_m (>15) increases probability that mutated values are close to parent.

*Because $N \approx H$ in NSGA-III, the population size is dependent on M and p. In this implementation N is pre-specified and p is solved for according to the expression for H.

Table 2 lists algorithm parameters used in the limited foresight CALVIN evolutionary search. Mating and mutation parameters were set to emphasize exploration over exploitation. A high mating probability combined with a moderately low SBX distribution index produced very diverse offspring while a high mutation probability combined with a high polynomial mutation index gently nudge offspring in random directions. Exploration-weighted parameter tuning appears to work well due to the flatness of the optimal marginal storage penalty parameter (P_{COSVF}) region on each reservoir together with limited co-dependence on P_{COSVF} assigned to other reservoirs in the network. The search converges quickly on the flat near-optimal regions of P_{COSVF} and thus benefits from wider exploration that provides a broad representation of the near-optimal P_{COSVF}.

Five randomly seeded evolutionary searches were performed, each evolving a population of 92 vectors of 84 $(2n_{SR} + n_{GW})$ marginal storage penalty parameters over 120 generations. The use of five random seeds provided confidence in the reliability of algorithm convergence and allowed the grouping of multiple near-optimal, independently evolved solutions within specific regions of the Pareto frontier.

An important feature that emerged during application was F_2 (groundwater overdraft) performance's dependence on the bounds of uniform random initialization of P_{GW} on groundwater basins in southern California. Minimum P_{GW} that eliminated groundwater overdraft in these basins were generally found to be an order of magnitude larger than P_{GW} in Central Valley groundwater basins and conflicted strongly with F_1 (total cost). Thus, depending on whether P_{GW} were initialized with the same upper bounds for all groundwater basins, as was done for random seeds 34, 38, 40, and 96, or initialized heterogeneously by increasing the bounds for southern California basins by an order of magnitude, as done for random seed 27, the near-Pareto solution set concentrated on either direction of the tradeoff. Because this study of limited foresight CALVIN concentrates on one direction of the tradeoff and the knee of the near-Pareto front where either initialization scheme produced adequate solutions, this proved not a major concern. However, the completeness of the near-Pareto solution set might benefit from alternative evolutionary algorithm construction to accommodate the diverse parameter behavior.

2.5. Evolutionary Search Performance

Performance of evolutionary algorithms (EA) on a particular problem can be categorized by measures of reliability, robustness, efficiency, and effectiveness (Maier et al. 2014; Gupta et al. 2020). Figure 2 shows three measures of algorithm effectiveness: relative improvement in the hypervolume metric (Fonseca, Paquete, and Lopez-Ibanez 2006) and the average and standard deviation of population solution fitness over the evolutionary search progression. Most algorithm improvement occurs in the first 50 generations. Hypervolume improvement becomes unstable beyond 60-80 generations and is caused by NSGA-III's re-normalization of objectives at every generation and alternating association of solutions with its normalized reference points. Since the Pareto front is relatively smooth, this does not result in an overall degradation of search performance and is isolated to solutions at extreme corners of the front.

Comparing EA effectiveness for different seeds provides confidence in the reliability of the search. Seed 27's unique behavior is explained by recalling from above that seeds 34, 38, 40, and 96 were initialized with marginal storage penalties an order of magnitude higher on southern California groundwater basins. Seed 27 solutions are thus weighted towards the complete elimination of overdraft (F_2) over all basins at a much higher overall system cost (F_1) and higher average marginal (groundwater) storage penalties (F_3). All seeds show reasonably consistent performance at discovering a promising set of diverse solutions. In hindsight, and aptly demonstrated in a recent study by Gupta et al. (Gupta et al. 2020), an auto-adaptive MOEA such as Borg (Hadka and Reed 2013) would likely be more efficient, reliable, and

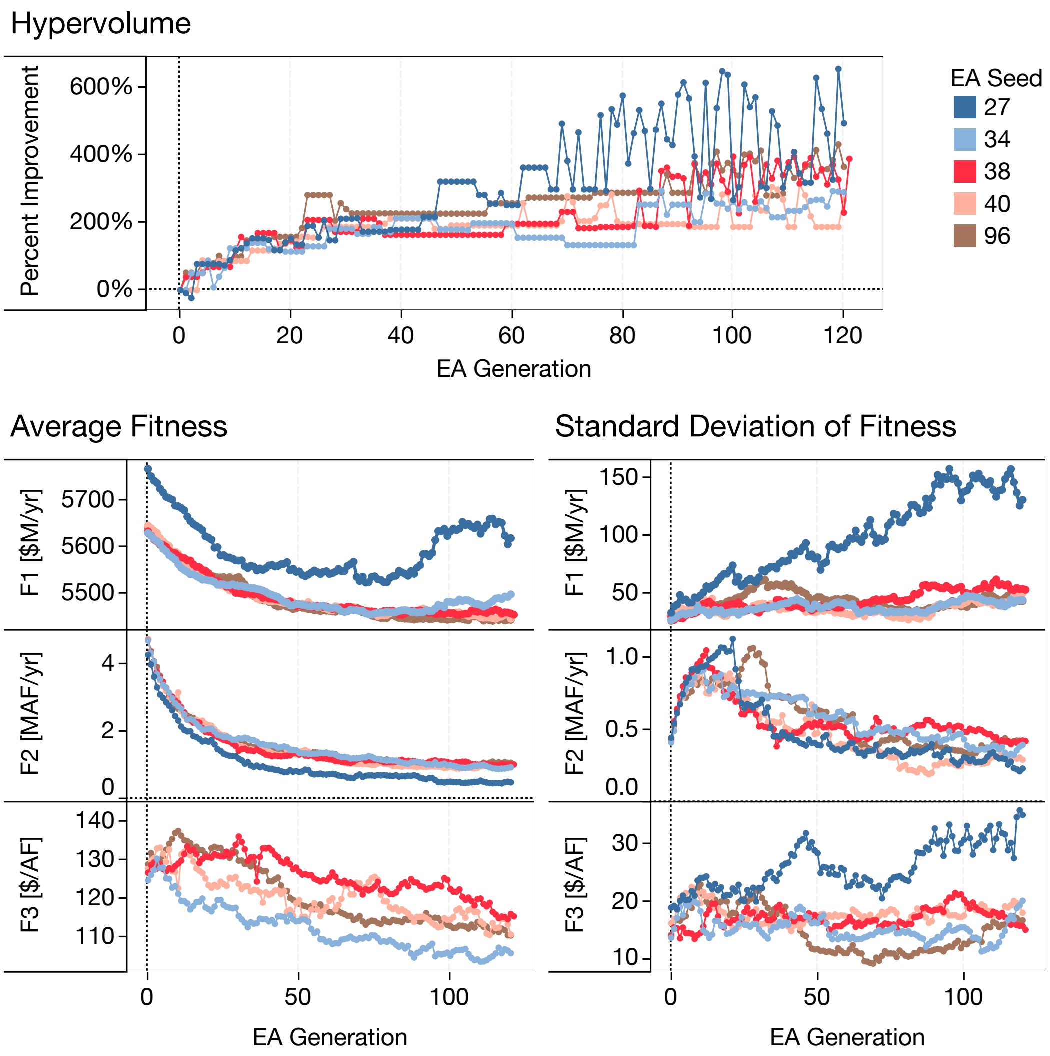


Figure 2. Hypervolume Improvement and Solution Fitness During Evolutionary Search

effective at discovering a diverse set of non-dominated solutions for this problem without dependency on knowing the “best” search parameterization.

Evolutionary computations were carried out on the UC Davis College of Engineering HPC-1 high-performance computing cluster, which contains 60 nodes each with 64 GB of RAM and two 8-core dual-threaded CPUs running at 2.4 GHz. Utilizing 92 threads on the HPC-1 cluster and the open-source COIN-OR Branch and Cut (CBC) linear programming solver, the compute time for one random seed search was about 72 hours. For comparison, a single 82-year perfect foresight run requires about 1 hour and an 82-year limited foresight run with prescribed carryover marginal penalties about 30 minutes, although approximately half of the compute time for the latter is dedicated to pre- and post-processing of each year in the sequence. More detailed runtime estimates per solver and the number of decision variables are provided in Dogan et al. (2018).

3. Results: Exploring the Pareto Frontier of Carryover Value Functions

3.1. The Pareto Frontier of Total Cost and Groundwater Overdraft Objectives

Near-Pareto (near-$\mathcal{P}$) limited foresight solutions are identified post-EA search through non-dominated sort on the first two fitness functions (total cost and groundwater overdraft) and over each random seed's entire evolutionary history. The third fitness function is not included in the final Pareto sorting since its purpose is to press downward on average marginal penalties during the evolutionary search as opposed to strict criteria for the "best" solution set. Although a Pareto reference set could be generated by non-dominated sort over all seeds simultaneously, including each evolutionary seed's non-dominated solutions show the variability and sensitivity in P_{COSVF} and P_{GW} by increasing the sample size of selected solutions within specific regions of the near-$\mathcal{P}$ front.

The fitness of the near-$\mathcal{P}$ limited foresight solutions is plotted in Figure 3 for each seed together with benchmark perfect foresight runs of varying overdraft constraints as well as the "Myopic" and "P_{GW}=0" (without any groundwater overdraft penalty) limited foresight runs (see Table 3 for run descriptions). The near-$\mathcal{P}$ solutions' knee-like shape across the two fitness objectives develops through eliminating most Central Valley (CV) groundwater overdraft (~1.5-2 MAF/yr) at relatively low marginal cost – approximately \$40/AF of overdraft eliminated – and southern California groundwater overdraft (~0.73 MAF/yr) at much higher marginal cost – approximately \$800/AF of overdraft eliminated. Perfect foresight runs PF_{CVOD} and PF_{OD} show a similar marginal cost response to eliminating overdraft in either region.

Table 3. Limited and Perfect Foresight Run Descriptions

Run	Description
PF	Perfect foresight with no groundwater overdraft constraints or penalties.
PF_{CVOD}	Perfect foresight with constraints prevent overdraft of each Central Valley groundwater reservoir.
PF_{OD}	Perfect foresight with constraints prevent overdraft on each groundwater reservoir, statewide.
Myopic	Limited foresight with no carryover storage value (reduces to SLOP rule) or groundwater overdraft penalty; persuasion penalties* include: $P_{max} = P_{min} = \$-0.02/AF$ & Sinks = \$0.01/AF.
LF	Limited foresight with evolutionary search optimizing carryover values P_{COSVF} and P_{GW}.
P_{GW}=0	Carryover storage values used from LF evolutionary search solution but with overdraft penalties set to zero for all groundwater reservoirs, statewide.

*Persuasion penalties are small unit penalties to encourage storage and discourage spill of water availability exceeding demand, making water supply reservoir operations more realistic.

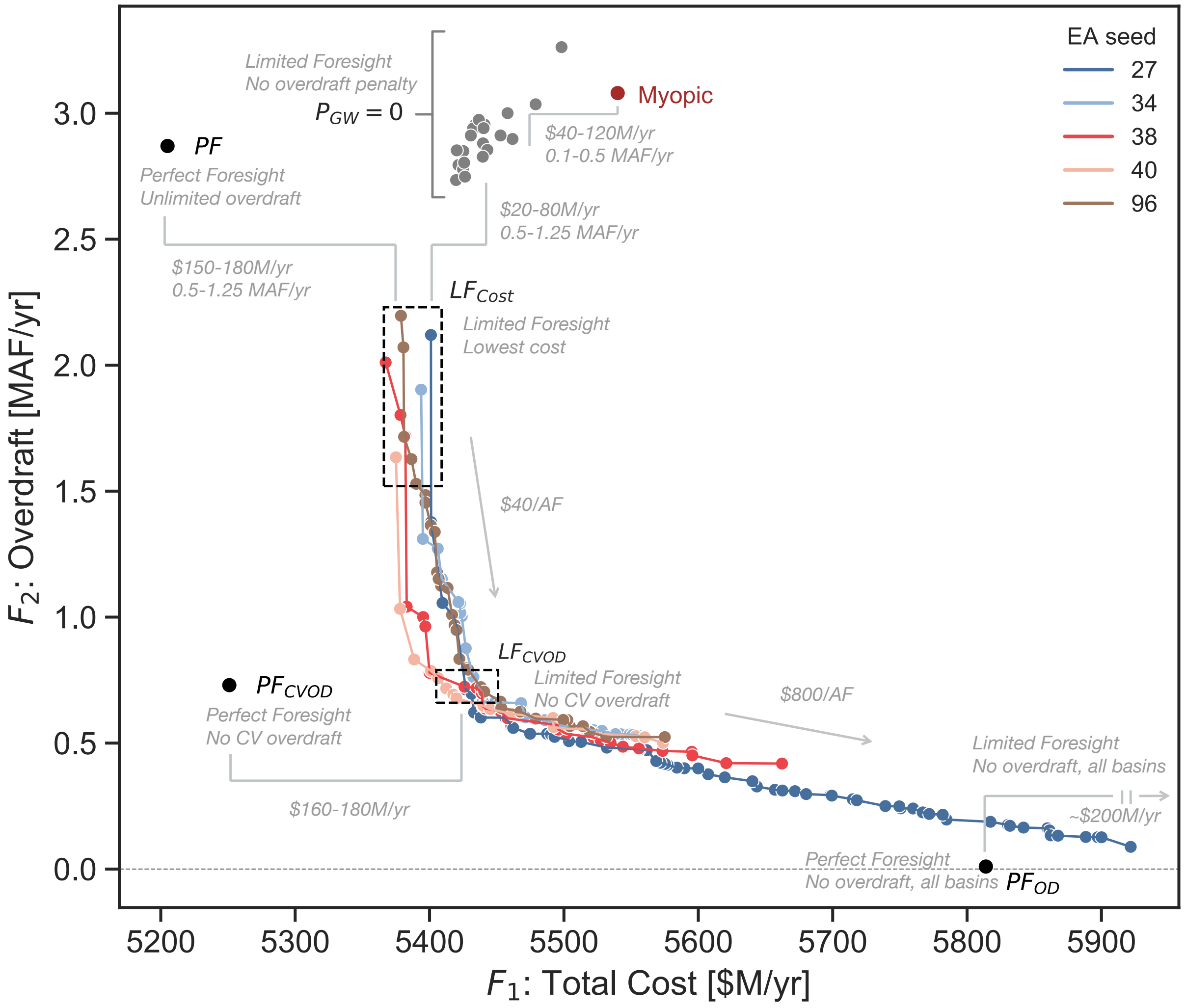


Figure 3. Total Cost and Overdraft Fitness of Limited Foresight (LF) Near-Pareto Front Solutions, as well as Myopic, No GW Penalty (P_{GW}=0), and Perfect Foresight (PF) Runs

At the "top" of the near-$\mathcal{P}$ front, where limited foresight solutions perform best on total cost, different EA seeds show varying ability to converge to the lowest cost with the lowest groundwater overdraft. The best performing individuals of EA seeds 38 and 40 eliminate much (~85%) of Central Valley overdraft with little to no increase in total costs. The importance of groundwater storage valuation to limited foresight optimization of the system is further illustrated through benchmarking the near-$\mathcal{P}$ limited foresight solutions with P_{GW} manually set to $0/AF ("$P_{GW}$=0"). The limited foresight P_{GW}=0 runs show that valuing groundwater storage improves solution fitness by $20-$80M/yr in total cost reductions while eliminating 0.5 to 1.5 MAF/yr of overdraft Central Valley groundwater basins. Indeed, the P_{GW}=0 equivalents of LF_{CVOD} solutions show that nearly all Central Valley overdraft can be eliminated with no increase in total cost (as discussed in a later section).

The difference between Myopic and $P_{GW}=0$ runs isolates the benefits of carryover storage valuation (P_{COSVF}) from the benefits of groundwater storage valuation (P_{GW}). Carryover storage management increases benefits over a Myopic (SLOP) policy by roughly \$40-\$120M/yr in total cost reduction and 0.1-0.5 MAF/yr in overdraft reduction. Thus, myopic operation is not Pareto-optimal. Operational and shortage cost details behind these improvements are explored in the following sections.

With perfect hydrologic foresight, an additional 0.5-1.25 MAF/yr of groundwater is more efficiently balanced with surface storage at about \$150-180M/yr lower total cost than can be attained with Limited Foresight (LF_{Cost}) solutions. At the knee of the near-$\mathcal{P}$ front, where Central Valley overdraft is mostly eliminated in Limited Foresight (no CV overdraft) (LF_{CVOD}) solutions, total costs are within approximately \$160-180M/yr (~3% of total cost or 24% of the maximum range of total cost) of the perfect foresight equivalent (PF_{CVOD}). At the “bottom” of the near-$\mathcal{P}$ front, limited foresight solutions approach elimination of overdraft in southern California and Santa Clara in the San Francisco Bay region as well. Approximately 90 TAF/yr of overdraft remains in the lowest overdraft solution found by EA. Extrapolation with the estimated marginal total cost of \$800/AF of overdraft eliminated suggests that the total costs of a limited foresight solution with no southern California overdraft are around \$200M/yr greater than the perfect foresight equivalent (PF_{OD}).

Limited foresight solutions that eliminate overdraft in southern California at higher total costs are not explored in detail here. In brief, of the approximately \$450M/yr in increased total costs (relative to the near-$\mathcal{P}$ “knee” where CV overdraft is eliminated), ~\$150M/y is increased shortage costs and ~\$300M/yr is increased operational costs. Increased shortage costs are split 2/3 to southern California demands and 1/3 to all other regions and increased operational costs split 1/2 for conveying additional water to southern California, 1/3 for water treatment processes (for the imported water), and remaining 1/6 for non-potable recycling and increased groundwater pumping in the Central Valley. So, while greater marginal southern California scarcity costs drive increased exports south, conveyance and treatment costs rise substantially, and southern California shortage costs rise asymmetrically due to conveyance bottlenecks such as on the East Branch of the State Water Project. These observations are supported by a ten-fold increase in willingness-to-pay for conveyance expansion on the East Branch link (which has an upper bound of ~105 TAF/month) passing through Antelope Valley and Mojave Basin demand areas that together make up 40% of groundwater overdraft in the southern California region. A more detailed analysis of eliminating groundwater overdraft in southern California basins is merited. However, this study focuses primarily on Central Valley groundwater conditions given the immediate policy relevance in addressing California’s critically overdrafted, “high-priority” groundwater basins under the Sustainable Groundwater Management Act.

3.1.1. Limited Foresight Solution Groups

Further investigation into characteristics of limited foresight that drive total system cost and groundwater overdraft fitness objectives is done by sampling and grouping “Cost” and “CVOD” solutions on the near-$\mathcal{P}$ front. A minimum overdraft of 1.55 MAF/yr was used as a lower bound on the $\mathrm{LF}_{\mathrm{Cost}}$ solution group. This lower threshold is defined somewhat arbitrarily, the intent being to gather a diversity of EA seed solutions while staying within a bandwidth of least total costs. A 40 TAF/yr minimum absolute difference of groundwater overdraft with $\mathrm{PF}_{\mathrm{CVOD}}$ (0.73 MAF/yr) was used as bounds for the selection of $\mathrm{LF}_{\mathrm{CVOD}}$ solutions. Again, the threshold of absolute difference is defined somewhat arbitrarily, the purpose being to gather a diverse sample while staying within a reasonably small range of total costs and groundwater overdraft. The range of overdraft and total costs as well as the count of solutions selected from each EA random seed are listed in Table 4 and graphically shown in Figure 3 with dashed boxes. Although some selected EA solutions are dominated by solutions in another seed, having a more diverse set of $\mathrm{P}_{\mathrm{COSVF}}$ and P_{GW} within each solution group gives a more complete view of variability in carryover storage valuations that achieve similar performance. Ultimately, differences in performance between solutions within these two groups are small compared to that of with thousands of solutions discarded through non-dominated sorting on each EA seed.

Figure 4 shows boxplots of overdraft in groundwater reservoirs across the Limited Foresight ($\mathrm{LF}_{\mathrm{Cost}}$) and Limited Foresight (no CV overdraft) ($\mathrm{LF}_{\mathrm{CVOD}}$) solution groups and the unconstrained perfect foresight run (PF). As expected, $\mathrm{LF}_{\mathrm{Cost}}$ solutions have a wide range of overdraft conditions across basins and rarely reach the total groundwater overdraft of the PF unconstrained run except in the Tulare Basin region’s (TB) GW_21. $\mathrm{LF}_{\mathrm{CVOD}}$ runs eliminate nearly all overdraft in Upper Sacramento (UC), Lower Sacramento Valley and Delta (LSVD), San Joaquin and South Bay (SJSB), and Tulare (TB) basins. Nearly all overdraft in southern California (SC) region groundwater reservoirs remains in both $\mathrm{LF}_{\mathrm{Cost}}$ and $\mathrm{LF}_{\mathrm{CVOD}}$ solution groups; however, the reduced overdraft in the Coachella (CH) and Owens Valley (OW) basins compared to perfect foresight causes some notable differences in scarcity and operating behavior, discussed in the following section.

Table 4. Selection Criteria for Sets of Near-Pareto COSVF Solutions

	Overdraft (F_1) [MAF/yr]		**Total Cost (F_2) [\$M/yr]**		**Count of Solutions in Set by EA Seed**				
Set	**Min**	**Max**	**Min**	**Max**	**27**	**34**	**38**	**40**	**96**
$\mathrm{LF}_{\mathrm{Cost}}$	1.55	2.20	5,367	5,410	1	1	3	1	4
$\mathrm{LF}_{\mathrm{CVOD}}$	0.69	0.76	5,406	5,450	2	2	3	3	2

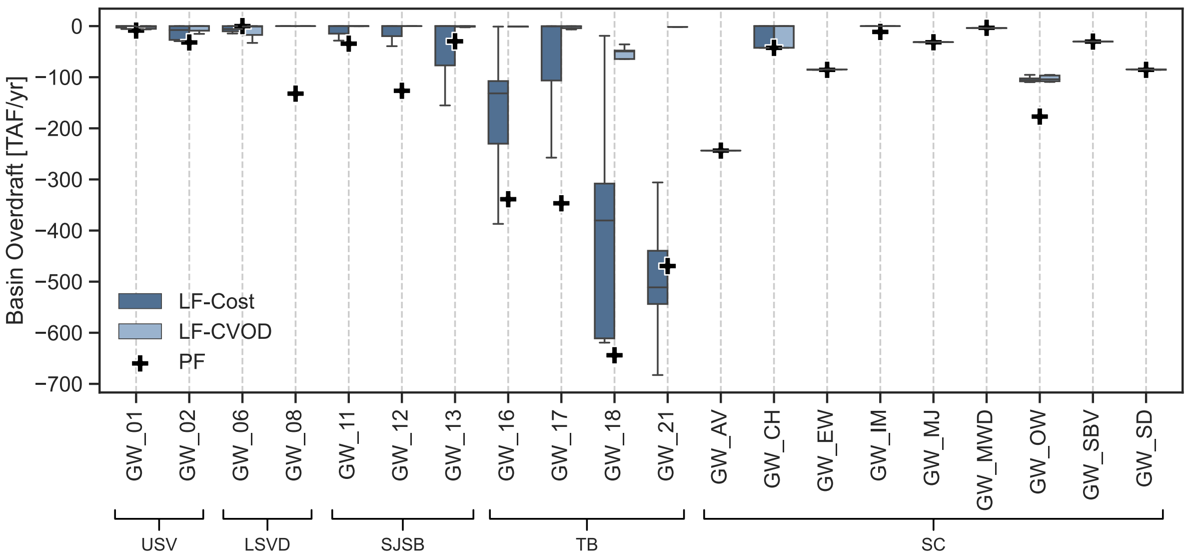


Figure 4. Groundwater Overdraft by Basin for Near-Pareto Solution Sets and Perfect Foresight Unconstrained Run

Substantial diversity in P_{COSVF} and P_{GW} of near-$\mathcal{P}$ solutions yields a variety of reservoir and groundwater operation policies (shown in section 4) and allocation decisions even within a limited foresight solution group (e.g., LF_{Cost}). Variability of costs and allocations within solution groups is not investigated in detail in this study. Unless otherwise shown or stated, the following comparisons of perfect and limited foresight are based on the average value across near-$\mathcal{P}$ solutions in either the LF_{Cost}, LF_{CVOD}, or P_{GW}=0 run groups.

3.1.2. Scarcity, Management Portfolios, and Operations

Water scarcity in CALVIN is defined as the volume of water deficit with respect to the volume at which zero marginal economic benefit is gained from an additional unit of water delivered. When water is scarce, the equimarginal principal drives CALVIN to allocate shortages where users have the same marginal loss of value. Operating constraints such as physical infrastructure capacities, minimum required flows, regional trading rules, and rights to water (if imposed) limit such optimal allocations. Limited hydrologic foresight means the model must make such allocations and operations without clairvoyance across the period of record. Finally, shortages also occur if the marginal cost of supplying water exceeds the marginal cost of shortage (e.g., the high marginal cost of desalination exceeding the marginal benefits of supplying a demand).

Table 5. Maximum, Mean, and Standard Deviation of Annual Shortage Volume and Cost by Region and Sector

Sector	Region		Shortage Cost [$M/yr]						Shortage [TAF/yr]					
			Myopic - P_{GW}=0	P_{GW}=0 - LF_{Cost}	LF_{Cost}	PF	LF_{CVOD} - LF_{Cost}	PF_{CVOD} - PF	Myopic - P_{GW}=0	P_{GW}=0 - LF_{Cost}	LF_{Cost}	PF	LF_{CVOD} - LF_{Cost}	PF_{CVOD} - PF
	Total	Max	+1,192	-15	568	234	+65	+46	+700	-250	1,580	710	+330	+290
		Mean	+39	+13	219	177	+28	+58	+10	-120	710	480	+170	+290
		SD	*+97*	*+6*	*101*	*23*	*+5*	*-1*	*+70*	*-40*	*240*	*110*	*+60*	*+10*
Agriculture	**USV**		+33	+2	15	3	+9	0	+110	-10	150	70	+50	+10
			+1	-1	2	1	+1	+1	+10	-10	50	40	+10	+10
			+3	*0*	*2*	*1*	*+1*	*0*	*+10*	*-10*	*30*	*20*	*+10*	*0*
	LSVD		+30	-9	27	9	+5	+2	+100	-130	340	150	+40	+30
			-1	-3	12	6	+1	+3	-20	-40	160	100	0	+40
			+4	*-2*	*4*	*1*	*+1*	*0*	*+20*	*-20*	*60*	*30*	*+10*	*0*
	SJSB		+37	-8	25	3	+15	+6	+180	-60	240	40	+100	+80
			+1	-3	4	0	+3	+6	+10	-50	60	0	+30	+90
			+5	*-2*	*4*	*0*	*+2*	*+1*	*+30*	*-30*	*50*	*10*	*+10*	*+10*
	TB		+47	-20	77	35	+26	+15	+150	-110	460	250	+160	+130
			0	-3	12	8	+13	+14	-10	-40	150	100	+120	+130
			+5	*-3*	*11*	*7*	*+5*	*+1*	*+20*	*-20*	*80*	*60*	*+30*	*0*
	SC		0	+1	35	27	0	0	0	0	190	100	0	0
			0	0	26	27	+1	0	0	0	130	100	0	0
			0	*0*	*6*	*0*	*-1*	*0*	*0*	*0*	*50*	*0*	*0*	*0*
Urban	**USV**		*(no shortages)*		-	-	-	-	-	-	-	-	-	-
	LSVD		+1,029	+10	2	1	+20	0	+160	0	3	<1	+ <1	0
			+28	0	1	1	+1	0	+10	0	2	<1	+ <1	0
			+117	*+1*	*0*	*0*	*+3*	*0*	*+20*	*0*	*0*	*0*	*0*	*0*
	SJSB		+14	0	0	0	0	0	+10	0	1	0	0	0
			+5	0	0	0	0	0	0	0	1	0	0	0
			+4	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
	TB		*(no shortages)*		-	-	-	-	-	-	-	-	-	-
	SC		-23	+59	401	189	+11	+19	-20	+60	350	190	+10	+20
			+5	+23	162	134	+9	+35	0	+30	160	140	+10	+30
			+2	*+8*	*89*	*17*	*-1*	*-3*	*0*	*+10*	*80*	*20*	*0*	*0*

Note: LF_{Cost}, LF_{CVOD}, PF, and PF_{CVOD} run columns are absolute values; other columns are differences between runs (e.g., "Myopic – P_{GW}=0" is the absolute difference of Myopic with P_{GW}=0).

3.1.2.1. *Perfect vs. Limited Foresight*

Perfect foresight dampens extreme shortages and their costs and lowers average shortage and cost compared to more realistic limited foresight operations. As seen in Table 5, the ratios of limited foresight's maximum to mean annual total shortage volume and cost are 2.3 (~870 TAF or ~120% greater) and 2.6 (~$350M or ~160% greater), respectively. By comparison, perfect foresight's maximum to mean annual total shortage volume and cost ratios are 1.5 (~230 TAF or ~30% greater) and 1.3 (~$60M or ~50% greater). Likewise, limited foresight's standard deviation of annual total shortage volume and cost is 130 TAF/yr (120%) and $78M/yr (340%) greater than perfect foresight. These metrics – maximum to mean cost ratio and

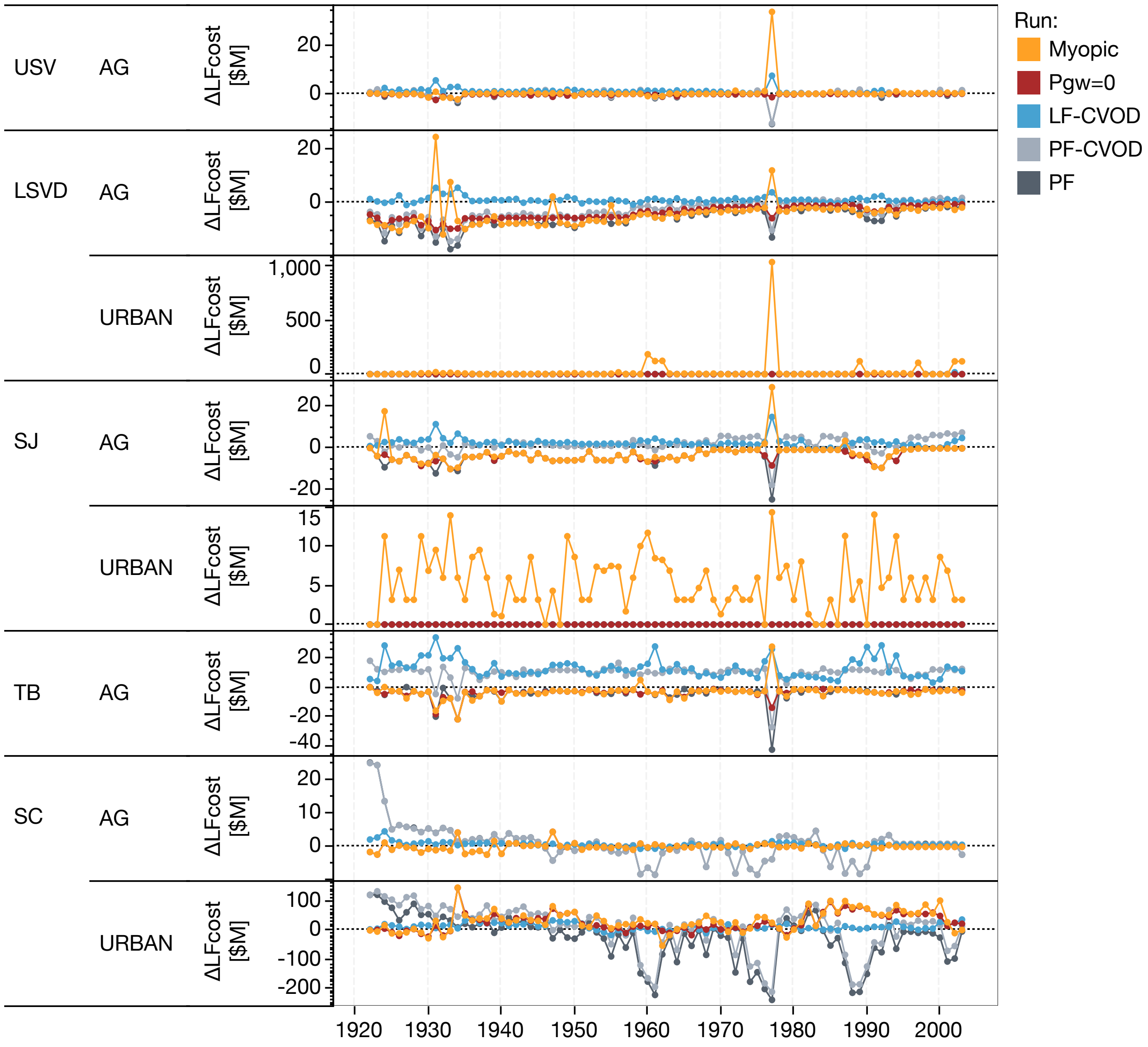


Figure 5. Time Series of Annual Shortage Cost by Region

Note: runs are plotted as the average of their absolute difference (Δ) with the annual volume of the Limited Foresight “Cost” (LF_{Cost}) solution group.

standard deviation – are aggregate estimates of the effects of interannual hydrologic variability on the system.

With limited foresight, average annual shortage volume is 230 TAF/yr (48%) more than perfect foresight, incurring over $40M/yr (24%) in additional shortage costs. While 90% of limited foresight’s increased shortage volume is to agricultural users, 70% of the increased shortage cost is to southern California urban demands. The time series of regional system shortage costs, shown in Figure 5 (see Figure 1 for region map), suggests that perfect foresight preferentially shorts southern California demands earlier in the period of record to store water for later dry periods from management of southern California groundwater reserves, shown in Figure 6. By severely curtailing extractions in wetter periods, even to the point of net recharge,

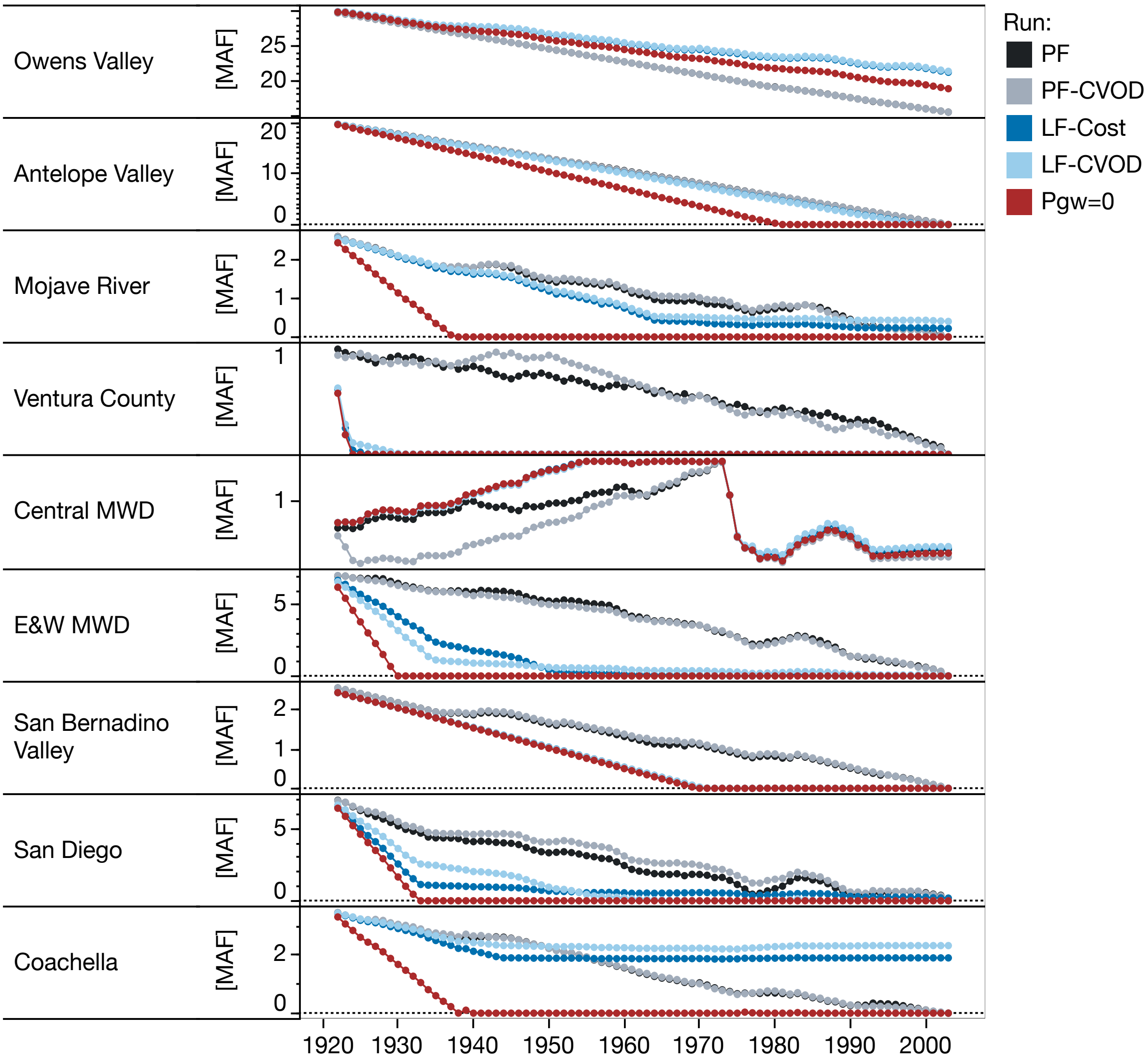


Figure 6. Annual Groundwater Storage in Southern California Basins

or through constant drawdown at an optimal rate, perfect foresight evenly (and exactly) distributes southern California groundwater reserves across the 82-yr period of record.

Perfect foresight's groundwater reserve management also can be seen in the southern California water source portfolio (Figure 7) as less use of groundwater pumping for urban demands in earlier years of record followed by greater reliance in later years, especially during droughts of 1976-77 and 1987-92. Shown in Table 5 and Figure 7, perfect foresight increases average non-potable reuse (NPR) by an additional 4 TAF/yr over limited foresight to supplement southern California groundwater pumping cuts on the margins while reducing average reliance on desalination (DESAL) by 13 TAF/yr, particularly during latter dry periods, resulting in over $40M/yr in variable operating cost savings, shown in Table 7. Perfect foresight groundwater management also has further gains from reduced State Water Project

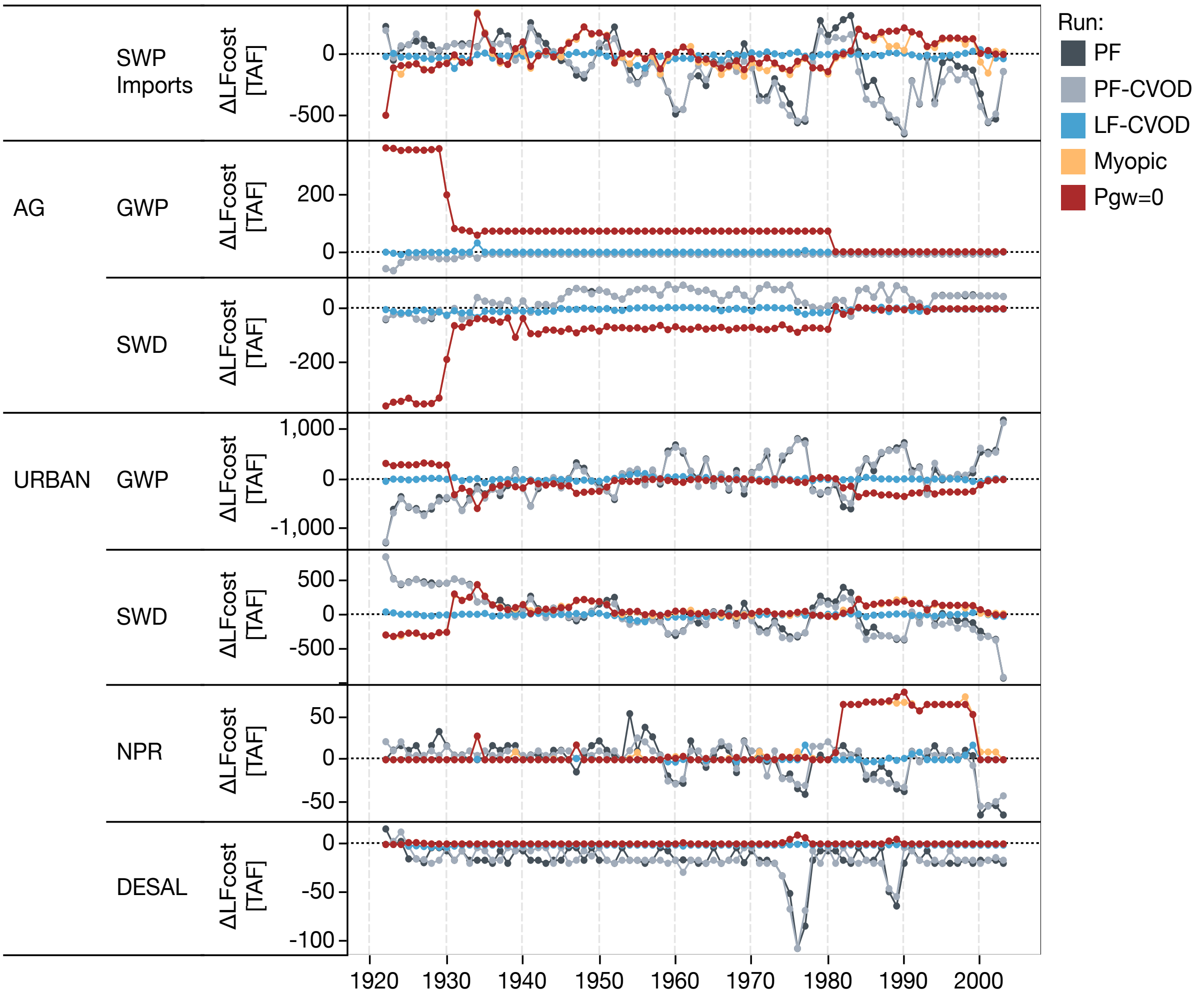


Figure 7. Annual Southern California Water Source Volume

Note: runs are plotted as the average of their absolute difference (Δ) with the annual volume of the Limited Foresight "Cost" (LF_{Cost}) solution group. SWD = surface water delivery; GWP = groundwater pumping; NPR = non-potable reuse; DESAL= ocean desalination.

(SWP) imports – over 500 TAF/yr (30%) during latter dry periods as shown in Figure 7 and on average by 90 TAF/yr (5%) as shown in Table 8 – which reduces shortage potential to San Joaquin and Tulare Basin demands and reduces conveyance costs by $60M/yr (Table 7). Finally, as shown in Table 8, perfect foresight's superior hedging and conjunctive management increase South of Delta (SOD) exports by 140 TAF/yr compared to limited foresight, almost eliminating agricultural shortages in San Joaquin and reducing Tulare Basin agricultural shortages (50 TAF/yr less in Table 5) and groundwater pumping (165 TAF/yr less in Table 6).

3.1.2.2. Isolating the Effects of Carryover Storage Management

Comparing the Myopic run to limited foresight without groundwater overdraft penalties (P_{GW}=0) isolates the benefits of carryover storage management independent of the effects of

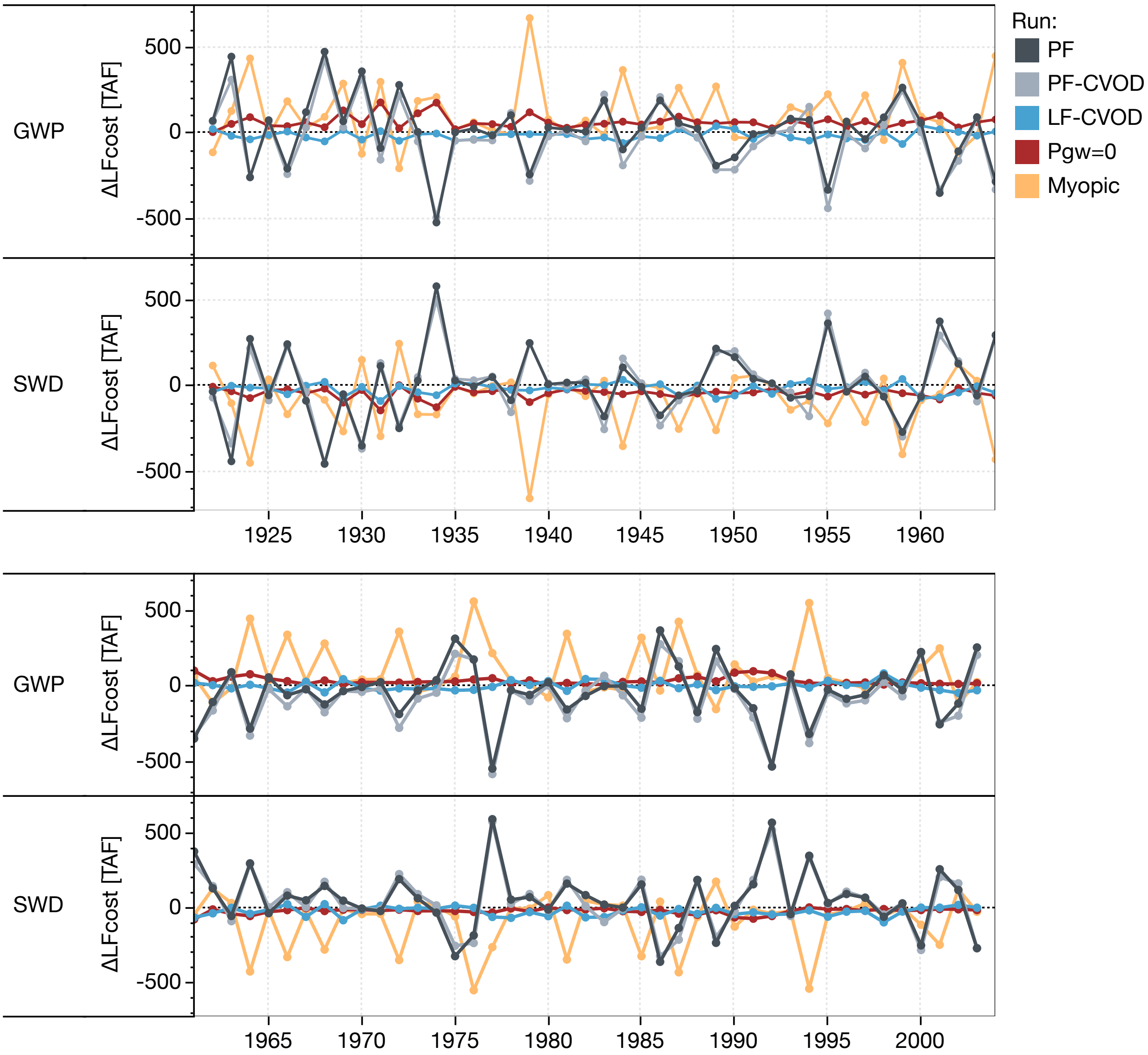


Figure 8. Central Valley Total Surface Water Deliveries and Groundwater Pumping
Note: runs are plotted as the average of their absolute difference (Δ) with the annual volume of the Limited Foresight "Cost" (LF_{Cost}) solution group. SWD = surface water delivery; GWP = groundwater pumping.

groundwater storage valuation. Carryover storage management decreases the average ($39M/yr; 15%) and standard deviation ($97M/yr; 100%) of total shortage costs, with particular benefits to agricultural shortage cost variability reductions of 30-200% in the Central Valley (USV, LSVD, SJSB, TB regions) (Table 5). The time series of Central Valley groundwater pumping and surface water deliveries in Figure 8 show that myopic operation supplies agricultural and urban demands with whatever surface water is available first, leaving following years dependent on groundwater to make up for the lack of surface storage. Because groundwater pumping capacity often is limited, Myopic operation increases the maximum annual shortage volume and cost by over 100 TAF and $1 billion (with an especially disproportionate impact on LSVD urban demands) compared to P_{GW}=0 (Table 5).

Table 6. Mean and Standard Deviation of Annual Regional Water Supply Sources

			Urban [TAF/yr]						**Agriculture [TAF/yr]**					
Sector	Source		Myopic - P_{GW}=0	P_{GW}=0 - LF_{Cost}	LF_{Cost}	PF	LF_{CVOD}	PF_{CVOD}	Myopic - P_{GW}=0	P_{GW}=0 - LF_{Cost}	LF_{Cost}	PF	LF_{CVOD}	PF_{CVOD}
USV	**SWD**	Mean	0	-5	5	0	4	0	-150	+20	1,970	2,030	1,940	2,020
		SD	*0*	*-13*	*13*	*0*	*9*	*0*	*+120*	*-40*	*500*	*380*	*580*	*350*
	GWP		0	+10	390	395	391	395	+140	-10	360	310	380	320
			0	*-10*	*13*	*0*	*9*	*0*	*+120*	*-40*	*480*	*370*	*550*	*330*
LSVD	**SWD**		+60	-100	1,180	1,050	1,205	1,130	-130	0	2,975	3,100	2,925	2,970
			+50	*+30*	*170*	*190*	*190*	*190*	*+130*	*+30*	*680*	*620*	*720*	*710*
	GWP		-80	+100	720	840	685	760	+150	+50	1,310	1,250	1,355	1,330
			+50	*+30*	*170*	*180*	*190*	*180*	*+110*	*+40*	*650*	*600*	*670*	*700*
	NPR		+10	-1	4	3	5	4	0	0	0	0	0	0
			0	*-1*	*5*	*0*	*10*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
SJSB	**SWD**		-30	-10	525	515	545	515	-210	-140	3,490	3,510	3,500	3,530
			0	*0*	*50*	*80*	*70*	*90*	*+210*	*+160*	*750*	*780*	*700*	*540*
	GWP		0	+10	760	770	740	770	+200	+190	1,300	1,340	1,260	1,230
			0	*-20*	*20*	*0*	*50*	*0*	*+200*	*+180*	*720*	*780*	*670*	*520*
	NPR		+10	0	16	16	16	16	0	0	0	0	0	0
			0	*0*	*1*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
	DESAL		+16	0	0	0	0	0	0	0	0	0	0	0
			+11	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
TB	**SWD**		-20	-30	475	430	550	570	-50	+20	6,380	6,590	6,180	6,470
			+20	*-20*	*100*	*80*	*60*	*50*	*+240*	*-110*	*1,460*	*1,140*	*1,490*	*1,340*
	GWP		+20	+30	1,065	1,110	990	980	+30	+60	3,065	2,900	3,125	2,840
			+20	*-20*	*100*	*80*	*60*	*50*	*+240*	*-110*	*1,390*	*1,080*	*1,400*	*1,270*
SC	**SWD**		-10	+50	3,190	3,210	3,180	3,180	0	-80	3,330	3,360	3,320	3,360
			0	*+60*	*310*	*130*	*300*	*100*	*0*	*+40*	*40*	*0*	*40*	*0*
	GWP		0	-90	3,450	3,470	3,450	3,470	0	+80	280	270	280	270
			0	*+80*	*340*	*240*	*340*	*220*	*0*	*+100*	*10*	*0*	*10*	*0*
	NPR		0	+15	46	50	50	50	0	0	0	0	0	0
			0	*+16*	*18*	*10*	*20*	*10*	*0*	*0*	*0*	*0*	*0*	*0*
	DESAL		0	0	23	10	20	10	0	0	0	0	0	0
			0	*+2*	*15*	*10*	*20*	*10*	*0*	*0*	*0*	*0*	*0*	*0*

Note: LF_{Cost}, LF_{CVOD}, PF, and PF_{CVOD} run columns are absolute values; other columns are differences between runs (e.g., "Myopic – P_{GW}=0" is the absolute difference of Myopic with P_{GW}=0). SWD = surface water delivery; GWP = groundwater pumping; NPR = non-potable reuse; DESAL= ocean desalination.

Compared to Myopic operation, carryover storage valuation increases the frequency of smaller shortage volumes (e.g., an increase of 20 TAF/yr and 10 TAF/yr in average shortage to LSVD and TB agriculture, respectively) to supply larger amounts of surface water in the driest years, vastly reducing urban shortages and the worst agricultural shortages (Table 5 and Figure 5). While the largest shortage cost reductions occur in the driest hydrologic conditions (due to additional surface water available where groundwater pumping capacity is limited), Table 6 shows that carryover storage management increases surface water deliveries in

Table 7. Maximum, Mean, and Standard Deviation of Variable Operating Costs

Values in \$M/yr

Operation		Myopic - P_{GW}=0	P_{GW}=0 - LF_{Cost}	LF_{Cost}	PF	LF_{CVOD} - LF_{Cost}	PF_{CVOD} - PF
Total	Max	+300	+70	5,360	4,380	+60	+40
	Mean	+50	+50	4,280	4,180	+20	-20
	SD	*+30*	*+80*	*420*	*100*	*-10*	*+10*
Groundwater Pumping		+200	-10	1,620	1,400	+40	-50
		+30	+20	930	920	0	-20
		+60	*0*	*230*	*210*	*-10*	*0*
Conveyance		-100	+90	1,020	890	+30	+10
		-30	+20	750	690	+10	-10
		-10	*+10*	*150*	*80*	*0*	*-20*
Water Treatment (Distribution)		+20	+50	1,670	1,670	+10	-20
		0	+10	1,520	1,520	0	-10
		0	*+30*	*130*	*80*	*0*	*-10*
Water Treatment (Treatment)		+10	+10	980	990	0	-10
		0	-10	910	920	+10	+10
		0	*+40*	*80*	*30*	*0*	*0*
Wastewater (to Groundwater)		-6	-1	44	40	+1	+7
		-5	-2	40	40	+2	+9
		0	*+2*	*3*	*0*	0	-1
Wastewater (to Surface Water)		+5	-1	38	40	0	-6
		+5	0	37	40	-2	-8
		0	*0*	*1*	*0*	0	0
Artificial Recharge		+3	-9	16	7	+13	+24
		+15	-1	7	6	+4	+4
		0	-1	2	0	+3	+5
Non-Potable Recycling		+40	+40	90	56	+21	-12
		+20	+10	40	33	0	+1
		+10	*+10*	*20*	*5*	*+1*	*-2*
Desalination		+95	+20	230	33	+1	0
		+40	0	50	12	-2	0
		+10	*0*	*30*	*13*	*0*	*0*

Note: LF_{Cost} and PF run columns are absolute values; other columns are differences between runs (e.g., "Myopic – P_{GW}=0" is the absolute difference of Myopic with P_{GW}=0).

agricultural and urban water source portfolios overall. Substitution of surface water availability across years reduces the amplitude of surface water delivery variation from Myopic to P_{GW}=0 shown in Figure 8 (and reduced standard deviation in Table 6) and ultimately increases average surface water deliveries North (280 TAF/yr to USV and LSVD agriculture) and South (260 TAF/yr to SJSB and TB agriculture) of the Delta (Table 6). Furthermore, preferential preservation of surface storage in SOD reservoirs makes it economical to increase average annual exports of Sacramento basin runoff to San Joaquin and Tulare Basin by 540 TAF/yr as shown in Table 8. Ultimately, including carryover storage valuations alone reduces average annual Central Valley groundwater pumping reliance by 460 TAF/yr and reduces average annual NPR and DESAL by 10 TAF/yr and 16 TAF/yr, respectively (Table 6). Altogether, the

Table 8. Average Annual Southern California Imports and Delta Flows

All values in TAF/yr

Flow	Myopic - $P_{GW}=0$	$P_{GW}=0$ - LF_{Cost}	LF_{Cost}	PF	LF_{CVOD} - LF_{Cost}	PF_{CVOD} - PF
NDO Surplus	+1,320	+210	8,220	7,950	-345	-270
SOD Exports	-540	-140	7,280	7,420	+390	+350
SWP Imports (to SC)	-20	+10	1,630	1,540	-10	-30
LA Aqueduct Imports	+20	+10	470	540	0	0
Colorado River Aqueduct Imports	0	-50	1,240	1,300	+10	0

Note: LF_{Cost} and PF run columns are absolute values; other columns are differences between runs (e.g., "Myopic – $P_{GW}=0$" is the absolute difference of Myopic with $P_{GW}=0$).

reductions in groundwater pumping, NPR, and DESAL save $110M/yr in operating costs as seen in Table 7.

The reduced SOD exports (540 TAF/yr, noted above) with Myopic operation partially contribute to increased surplus Net Delta Outflow of 1,320 TAF/yr (Table 8). Three other changes contribute to Myopic operations' larger Delta outflows: lower surface storage levels reduce surface reservoir evaporation (~320 TAF/yr) a portion of which becomes Delta outflow; a portion of the additional groundwater pumping (460 TAF/yr, noted above) becomes return flow to surface waters outflowing to the Delta; and approximately 150 TAF/yr of "debug" water used by the limited foresight run to maintain solution feasibility becomes Delta outflow (Appendix I reviews the use and implications of debug links to facilitate computational feasibility of limited foresight).

3.1.2.3. *Effects of Carryover and Groundwater Storage Management*

Valuation of groundwater storage increases agricultural shortage volume and cost by 150 TAF/yr (27%) and $10M/yr (18%), as seen from comparing LF_{Cost} with $P_{GW}=0$ equivalents in Table 5. Higher agricultural shortages are driven by reduced groundwater pumping (due to the higher marginal value of groundwater storage) not met with an equivalent increase in surface deliveries (Table 6). This behavior can be seen by comparing the relative contribution of groundwater and surface water of $P_{GW}=0$, Myopic, and perfect foresight against that of LF_{Cost} for Central Valley urban and agricultural supplies in Figure 8. For example, looking at the drought of 1987-1992, perfect foresight aggressively hedges surface water in 1986, 87, and 89 (a wetter year in the drought) supplementing surface delivery cuts with increased groundwater pumping. Limited foresight similarly hedges some surface water - more notably in 1986 and 89 - but, when compared to $P_{GW}=0$ run, does not equivalently increase groundwater pumping.

Table 9. Average Annual Artificial Groundwater Recharge Volumes

All values in TAF/yr

Groundwater Basin	Myopic - P_{GW}=0	P_{GW}=0 - LF_{Cost}	LF_{Cost}	PF	LF_{CVOD} - LF_{Cost}	PF_{CVOD} - PF
Santa Clara	+10	-10	260	240	-20	0
Tulare/SJ	0	-220	220	0	+385	+490
Tulare (SWP)	0	0	0	0	+140	+100
Owens	0	-40	40	0	0	0
S.CA Group	0	+10	40	40	0	0
Coachella	-10	-40	210	160	-10	0
Total	-20	-300	770	440	+490	+590

Note: LF_{Cost} and PF run columns are absolute values; other columns are differences between runs (e.g., "Myopic – P_{GW}=0" is the absolute difference of Myopic with P_{GW}=0).

As the drought wears on, limited foresight can provide surface water deliveries to supplement the groundwater pumping cutbacks, but not enough to cover the full deficit (as measured from P_{GW}=0).

Although groundwater storage valuation increases agricultural shortages, $20M/yr (Table 7) in reduced groundwater pumping costs more than make up for it (as previously noted, unit pumping cost is constant and thus total pumping cost is only a function of total groundwater volume pumped). When combined with southern California urban shortage cost reductions of $23M/yr (15%) and variable operating cost reductions of SWP imports (conveyance, $20M/yr) and non-potable recycling ($10M/yr) – both for southern California – groundwater storage valuation results in a net total cost savings of up to $60M/yr. Tempered groundwater drawdown in southern California groundwater basins is the primary reason for southern California cost savings from P_{GW}=0 to LF_{Cost} runs. Without groundwater penalties, limited foresight uses groundwater reserves with priority, prematurely depleting groundwater supplies. Limited foresight with groundwater penalties dampens or halts southern California groundwater drawdown (Figure 6) through preferential use of surface supply (Figure 7) or incurring shortage when the marginal cost of storage depletion exceeds that of shortage cost (Figure 5). However, more optimal P_{GW}, which would better manage depletion of groundwater reserves across the full period of analysis were not easily found by evolutionary search. In addition, Owens Valley and Coachella basin groundwater penalties reduce LA Aqueduct (LAA) and Colorado River Aqueduct (CRA) imports to southern California urban demands by 70 TAF/yr and 60 TAF/yr, respectively. Cuts to LAA imports occur from increased diversions for artificial recharge to Owens basin and reduced Owens groundwater pumping into the LAA. Reduced CRA imports

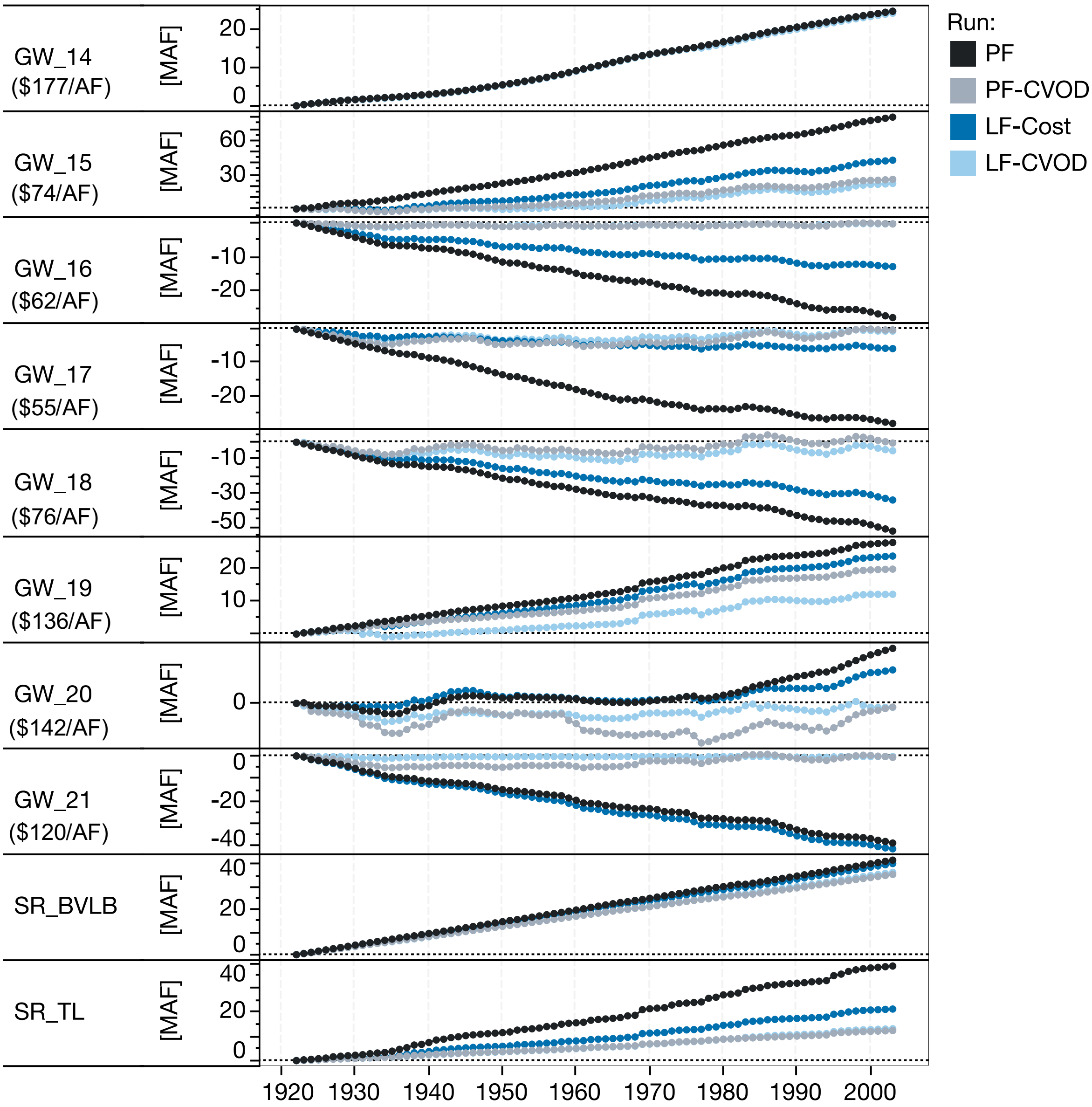


Figure 9. Cumulative Change in Storage of Tulare Basin Groundwater Reservoirs and Tulare Lake (TL) and Buena Vista Lake Bed (BVLB) Storage
Agricultural groundwater pumping costs (constant over period of analysis) are annotated for each groundwater basin.

to coastal southern California urban demands occur due to increased CRA diversions for artificial recharge to the Coachella basin (Table 9).

3.1.2.4. Elimination of Central Valley Overdraft (CVOD)

Elimination of overdraft in the Central Valley raises total shortage costs for perfect and limited foresight by \$58M/yr (33%) and \$28M/yr (13%), respectively, over their overdraft unconstrained (PF) or lower P_{GW}-valued LF solutions (Table 5). With perfect foresight, 76%

(220 TAF/yr) of shortage volume increases occur to agriculture in the southern Central Valley (San Joaquin and Tulare Basin), while 60% ($35M/yr) of shortage cost increases are incurred to southern California urban users (Table 5). With limited foresight, 88% (150 TAF/yr) of shortage volume increases occur to agriculture in the southern Central Valley, while 32% ($9M/yr) of shortage cost increase occurs to southern California urban users.

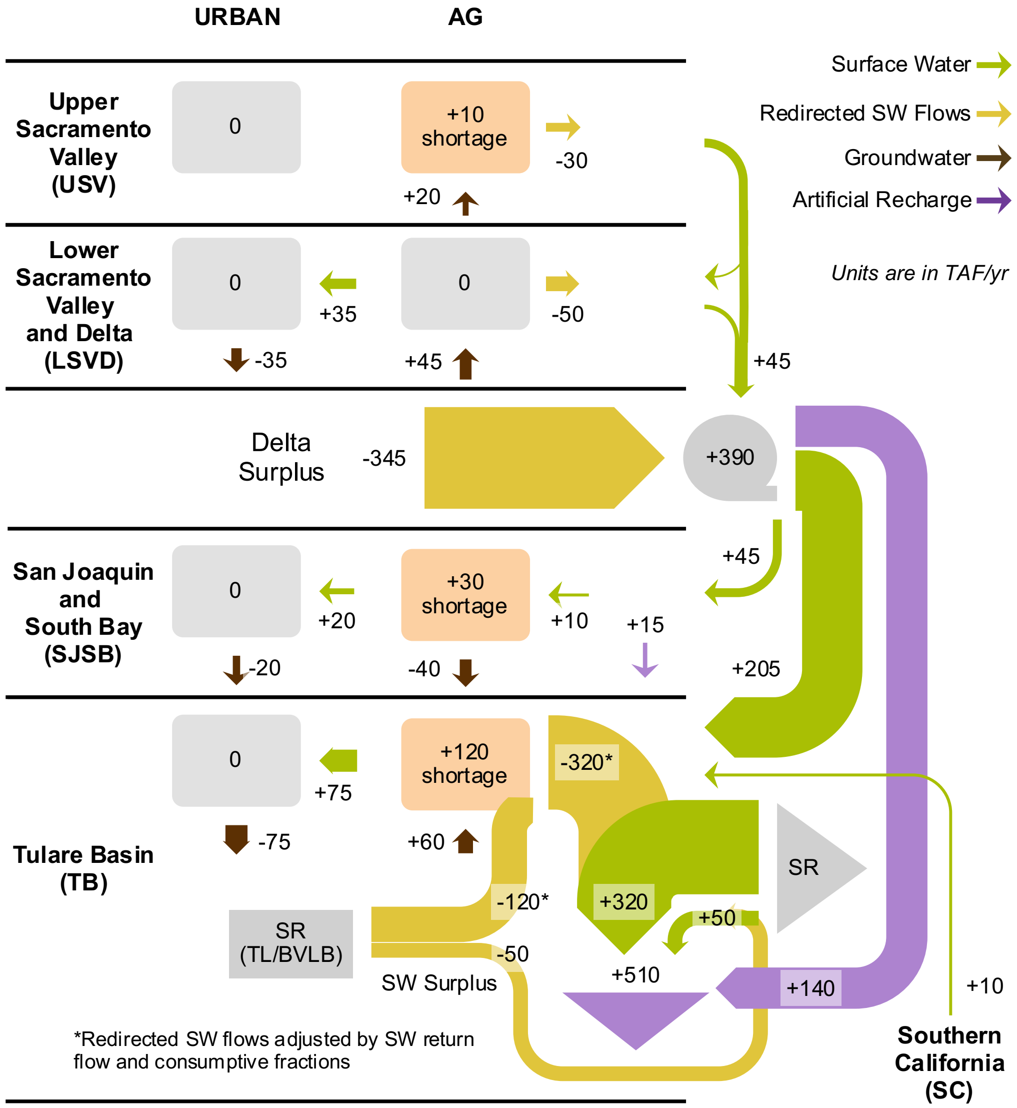
Increased southern California urban shortages with perfect and limited foresight are from redistribution of SWP imports (30 TAF/yr and 10 TAF/yr, respectively, in Table 8 and Figure 7) from southern California to Tulare Basin to equalize marginal shortage costs between the two regions (more TB scarcity is from ending groundwater overdraft). Eliminating Central Valley overdraft brings perfect foresight's average annual shortages within 92 TAF/yr (11%) and $12M/yr (5%) of limited foresight. However, limited foresight's maximum annual shortages still far exceed those of perfect foresight (905 TAF (90%) higher shortage and $353M (55%) higher cost from Table 5).

Significant potential for water shortage is expected from eliminating perfect foresight's 1.8 MAF/yr and limited foresight's 0.5-1.5 MAF/yr of Tulare Basin groundwater overdraft (see Figure 4). But, as shown in the annual storage of groundwater reservoirs in Tulare Basin in Figure 9, increased pumping in GW-15, -19, and -20 – basins with higher groundwater pumping costs which were largely gaining in storage in the unconstrained perfect foresight or lower P_{GW}-valued limited foresight runs – compensates some for pumping reductions in GW-16, -17, -18, and -21. This highlights how economic drivers and system constraints prioritize depletion in basins where it is cheaper to pump than to bring in surface water (or vice versa) and how major reallocations of pumping and surface water deliveries occur within Tulare Basin regional demands once constraints or costs are imposed on groundwater storage depletion.

Another similarity between limited and perfect foresight is reallocations of inter-regional and urban versus agricultural share of surface and groundwater supplies. The changes are depicted as a flow diagram in Figure 10 and described, moving geographically from North to South, as follows:

(1) North of Delta Reallocations and South of Delta Exports

As Table 8 shows, SOD exports increase by about 5% with both limited and perfect foresight (with respect to unconstrained perfect foresight or lower P_{GW}-valued limited foresight runs) to support changes in southern Central Valley groundwater management, a result also found by Dogan et al. for perfect foresight. The increased SOD exports, 390 TAF/yr and 350 TAF/yr with limited and perfect foresight, respectively, come from two sources: 1) water that would have otherwise become surplus Delta outflow and but is now economical to pump south (see reductions in NDO surplus of 345 TAF/yr and 270 TAF/yr



*Redirected SW flows adjusted by SW return flow and consumptive fractions

Figure 10. Change in Average Annual Water Supplies with Elimination of Central Valley Overdraft (with Limited Foresight optimization)

by limited and perfect foresight, respectively, in Table 8); and, 2) a portion (45 TAF/yr by LF_{CVOD} and 60 TAF/yr by PF_{CVOD}) of Sacramento Valley (USV and LSVD) agricultural surface water delivery cuts (80 TAF/yr by LF_{CVOD} and 140 TAF/yr by PF_{CVOD}) reallocated to LSVD urban demands to supplement groundwater pumping reductions (35 TAF/yr by LF_{CVOD} and 80 TAF/yr by PF_{CVOD}). USV and LSVD agricultural groundwater pumping increases to support reallocations but are limited by pumping capacity constraints and marginal penalties (or PF storage constraints) on overdraft, leading to increased USV and LSVD agricultural shortages, shortages which are economically efficient in that the avoided shortage to LSVD urban demands and SOD demands (avoided through reallocating LSVD agricultural surface water to SOD) would have had a higher marginal cost. Once in SJSB or TB, differences arise between perfect and limited foresight in the fate of the increased SOD exports.

(2) San Joaquin and South Bay (SJSB)

In SJSB, perfect foresight allocates 20 TAF/yr of increased SOD exports to supplement a portion of the 110 TAF/yr in cuts to agricultural groundwater pumping, incurring a 90 TAF/yr increase in agricultural shortage (Table 5 and Table 6). Limited foresight allocates 45 TAF/yr of increased SOD exports to supplement some of the 20 TAF/yr and 40 TAF/yr cuts to urban and agricultural groundwater pumping, respectively, and to increase average artificial recharge by 15 TAF/yr (no such increase occurs with perfect foresight), increasing agricultural shortages by a total 30 TAF/yr. At this point, average SJSB shortages between perfect and limited foresight are nearly equivalent, although limited foresight's maximum shortages are still much higher.

(3) Tulare Basin (TB)

The allocation of increased SOD exports and shift in groundwater and surface water allocations is more complex in Tulare Basin. Ending overdraft increases artificial groundwater recharge driven by the rising value of groundwater storage (or WTP to meet the PF overdraft constraint) by a total of 590 TAF/yr and 525 TAF/yr with perfect and limited foresight, respectively (Table 9). Approximately 100 TAF/yr of increased SOD exports with perfect foresight and 140 TAF/yr with limited foresight contribute directly to increased artificial recharge (Tulare (SWP) in Table 9). The remaining contributions to increased artificial recharge are from reallocating agricultural surface water to artificial recharge and a portion of surplus surface water in the wettest years ("excess" water that would have flowed to Tulare and Buena Vista Lake sinks – SR_TL and SR_BVLB in Figure 9). The remaining increased SOD exports, combined with 10 TAF/yr (LF_{CVOD}) and 30 TAF/yr (PF_{CVOD}) of southern California's reallocated SWP imports, supplements both surface water reallocations to artificial recharge and groundwater pumping cuts (70 TAF/yr to urban demands with limited foresight and 210 TAF/yr to urban and agricultural demands with perfect foresight). Ultimately, agricultural shortages increase by 130 TAF/yr ($14M/yr) and 120 TAF/yr ($13M/yr) with perfect and limited foresight, respectively (urban shortage remains zero). Again, although average shortage costs are quite close for both, limited foresight's maximum shortages remain far above that of perfect foresight. Limited foresight also must rely more on groundwater, which raises pumping costs ($30M/yr more than perfect foresight in Table 7) and necessitates larger surface water reallocations to groundwater recharge.

3.1.3. Willingness to Pay

Dual (Lagrange multiplier) values reported by CALVIN offer further insight into the differences between limited and perfect foresight allocations and operations. To minimize confusion of comparing too many runs, the following discussion of marginal values is generally limited to the two overdraft conditions with limited foresight (LF_{Cost} vs. LF_{CVOD}) and perfect foresight's Central Valley overdraft constrained run (PF_{CVOD}).

3.1.3.1. WTP for Raw Water Sources

The average, maximum, and standard deviation of average annual dual values on stream and conveyance junction nodes shown in Table 10 represent water user's willingness to pay (WTP) for an additional acre-foot of raw water available at that location and time. Averaged over the major water sources, WTP is 21% higher with limited foresight than with perfect foresight. The larger difference in WTP between limited and perfect foresight for Sacramento and SOD exports compared to San Joaquin River sources together with SWP's relative difference being rather small suggests that limited foresight's non-ideal North of Delta carryover management has the greatest impact on southern Central Valley and Bay Area (SJSB, and TB) water demands. Colorado River Aqueduct's larger relative difference speaks to limited foresight's non-ideal southern California groundwater reserve management. The difference in limited and perfect foresight's maximum annual WTP – up to 157% on Sacramento and SOD exports and 125% greater over all sources – underlines limited foresight's imperfect hedging and conjunctive use capability to prepare for the driest years of record. Similarly, the difference in limited and perfect foresight's standard deviation of annual WTP – on average a 179% increase for the major sources – provides an estimate of the aggregate effect of interannual hydrologic variability on the ability of the system to hedge and conjunctively manage water.

Eliminating Central Valley overdraft under limited foresight substantially increases average WTP for southern Central Valley and Bay Area (SJSB and TB) raw water sources and maximum WTP on all major Central Valley water sources. The increased WTP is expected given significant increases in groundwater storage valuation in the San Joaquin and Tulare basins, and to lesser degree groundwater basins in the Sacramento Valley. Increases in the standard deviation of WTP, many of which exceed the increased average WTP for the same source, are due to loss of groundwater's drought buffering potential because of groundwater pumping cuts made to conserve groundwater storage. As shown in section 4.3, the WTP for raw water sources is directly related to the P_{COSVF} on upstream reservoirs. Therefore, increases in WTP from elimination of overdraft also affect P_{COSVF} for reservoirs and show unique behavior for a subset of reservoirs in the southern Central Valley (SJSB and TB) where the

Table 10. Mean, Maximum, and Standard Deviation of Annual WTP for Raw Water Source

All absolute values in $/AF

Source		LF_{Cost}	LF_{CVOD}	$(LF_{CVOD} - LF_{Cost}) / LF_{Cost} \times 100$	PF_{CVOD}	$(LF_{CVOD} - PF_{CVOD}) / PF_{CVOD} \times 100$
Sacramento (D5, below SR Shasta)	Mean	29	30	+3%	26	+15%
	Max	135	149	+10%	58	+157%
	SD	*25*	*30*	*+20%*	*15*	*+100%*
Feather (C23, below SR Oroville)		30	31	+3%	25	+24%
		137	156	+14%	54	+189%
		25	*31*	*+24%*	*14*	*+121%*
Yuba (C27, below SR Bullards Bar)		33	34	+3%	28	+21%
		170	184	+8%	66	+179%
		29	*35*	*+21%*	*15*	*+133%*
American (D9, below SR Folsom)		38	30	-21%	22	+36%
		208	158	-24%	62	+155%
		49	*35*	*-29%*	*16*	*+119%*
Mokelumne (C38, below SR Pardee/Camanche)		30	36	+20%	22	+64%
		153	163	+7%	72	+126%
		29	*33*	*+14%*	*16*	*+106%*
SOD Exports (PMP Banks & Jones)		20	21	+5%	17	+24%
		100	126	+26%	49	+157%
		21	*27*	*+29%*	*13*	*+108%*
Stanislaus (D670, below SR New Melones)		47	54	+15%	52	+4%
		111	136	+23%	61	+123%
		17	*21*	*+24%*	*6*	*+250%*
Hetch Hetchy (C44)		52	62	+19%	55	+13%
		133	165	+24%	66	+150%
		22	*27*	*+23%*	*7*	*+286%*
Tuolumne (D662, below SR Don Pedro)		49	58	+18%	52	+12%
		115	156	+36%	62	+152%
		20	*26*	*+30%*	*6*	*+333%*
Merced (D642, below SR McClure)		56	80	+43%	59	+36%
		173	255	+47%	75	+240%
		26	*44*	*+69%*	*8*	*+450%*
San Joaquin (C49, below SR Millerton)		87	133	+53%	124	+7%
		312	362	+16%	217	+67%
		40	*50*	*+25%*	*32*	*+56%*
Kern (C65, below SR Isabella)		78	115	+47%	111	+4%
		147	219	+49%	156	+40%
		25	*41*	*+64%*	*25*	*+64%*
SWP (D862B, at Edmonston)		124	133	+7%	131	+2%
		184	210	+14%	145	+45%
		18	*21*	*+17%*	*7*	*+200%*
Colorado River Aqueduct (C134)		69	70	+1%	54	+30%
		108	102	-6%	54	+89%
		31	*29*	*6%*	*0*	-

average WTP for source water rises substantially. The declines in WTP for American River water (below Folsom reservoir) appear inconsistent; however, the variability in near-optimal P_{COSVF} has resulted in a sampling bias of high-valued marginal carryover penalties in the LF_{Cost} group and a more inclusive sampling of penalties in the LF_{CVOD} group (hence the decline).

3.1.3.2. WTP for Surface Reservoir Capacity Expansion

Surface reservoirs typically reach capacity only once or twice during a water year, at which time the storage capacity constraint is "activated" and a positive WTP occurs for expanded storage capacity. Therefore, WTP for reservoir capacity expansion is calculated as the average of maximum annual WTP (i.e., the month with the highest WTP) and interpreted as $/AF-year. Table 11 presents the WTP for reservoir capacity expansion and percent of years when WTP is zero (i.e., the reservoir did not reach capacity in any month) for selected major surface reservoirs. The average of limited foresight solutions' WTP for reservoir expansion is substantially less than that of perfect foresight for Shasta, Oroville, Bullards Bar, New Melones, Don Pedro, and McClure. This result appears counterintuitive given limited foresight's higher WTP for raw water sources shown in Table 10; however, as detailed in section 4.3, physical and economic factors govern the near-optimal range of marginal carryover storage values (P_{COSVF}) and, by relationship, the near-optimal range of average carryover storage use. Thus, limited foresight's lower WTP for capacity expansion on these major reservoirs is due to a tendency towards lower average carryover storage use consistent with its marginal value, making storage capacity a less frequent binding constraint. This is confirmed

Table 11. Average Annual Maximum WTP for Reservoir Capacity Expansion

	WTP [$/AF-year]		**Percent of Years Without Reaching Capacity in Any Month (WTP = $0/AF-year)**	
	LF	**PF**	**LF**	**PF**
Reservoir	*Min / Avg / Max*		*Min / Avg / Max*	
Shasta (SR_SHA)	1 / 5 / 12	17	39% / 51% / 67%	15%
Oroville (SR_ORO)	1 / 6 / 15	26	24% / 44% / 61%	1%
Bullards Bar (SR_BUL)	2 / 12 / 26	21	1% / 13% / 33%	2%
Folsom (SR_FOL)	6 / 21 / 48	20	6% / 11% / 34%	7%
Pardee (SR_PAR)	2 / 23 / 59	6	0% / 9% / 30%	31%
Los Vaqueros (SR_LVQ)	0 / 4 / 9	4	34% / 59% / 100%	56%
New Melones (SR_NML)	0 / 2 / 10	14	34% / 77% / 99%	4%
Hetch Hetchy (SR_HTH)	1 / 19 / 75	5	0% / 3% / 17%	30%
Don Pedro (SR_DNP)	0 / 2 / 14	12	22% / 76% / 99%	5%
McClure (SR_MCR)	0 / 7 / 28	10	38% / 69% / 99%	13%
San Luis (SR_SNL)	0 / 2 / 10	1	28% / 76% / 100%	91%
Millerton (SR_MIL)	16 / 33 / 55	29	1% / 17% / 48%	18%
Pine Flat (SR_PNF)	0 / 9 / 35	3	0% / 65% / 99%	26%
Isabella (SR_ISB)	8 / 27 / 65	15	10% / 54% / 82%	55%

Note: limited foresight (LF) columns indicate the average and range (minimum to maximum) across LF_{Cost} and LF_{CVOD} solutions. WTP for reservoir capacity expansion is calculated as the average of maximum annual WTP. Years in which WTP=$0/AF-year indicates the reservoir did not fill during that year.

in Table 11 by the higher frequency of years in which these reservoirs do not reach capacity with limited foresight. But given the large range of near-optimal P_{COSVF} with limited foresight on these reservoirs, solutions with greater average carryover use (and a higher percent of years that reach capacity) do show higher WTP for reservoir expansion, nearly reaching or in some cases exceeding the WTP with perfect foresight.

Limited foresight's WTP for storage expansion on remaining reservoirs in Table 11 is generally higher than that of perfect foresight. This is due either to greater average carryover storage use (e.g., Pardee, San Luis, Los Vaqueros, Millerton, Pine Flat, and Isabella) or to such highly valued carryover storage that even lower average carryover storage use relative to perfect foresight results in a greater average WTP (e.g., Folsom and Hetch Hetchy).

3.1.3.3. WTP for Conveyance and Alternative Water Sources

Table 12 lists the mean and standard deviation of annual WTP for a selection of new and expanded conveyance and alternative water sources (the subset of links is mostly arbitrary other than isolating a sample with a high WTP, many of which supply southern California urban demands). The results show that hydrologic foresight has a small effect (<20%) on the mean annual WTP for some expansion options (e.g., CCWD-EBMUD, Cross Valley Canal, Kern Exchange, and Santa Clara Valley non-potable reuse). Much larger differences in the mean annual WTP between perfect and limited foresight occur for other links such as SWP East Branch conveyance and alternative water sources of non-potable and potable reuse where no condition of scarcity warranted a WTP with perfect foresight. All links have much greater variance in WTP which would likely have significant consequences for selecting capacity expansion and water source portfolio options when risk preferences are not neutral.

With elimination of Central Valley overdraft (column 3 of Table 12), the largest increase in conveyance capacity WTP is for the Cross Valley Canal. This is not surprising given the Tulare Basin demands' increased reliance on SOD exports to support a long-term sustainable groundwater management. Increases in WTP for CCWD and EBMUD suggest that changes in groundwater storage valuation in the Central Valley increase scarcity for Bay Area urban demands and that surface water would be reallocated to reduce those shortages if capacity (transfer/conveyance) could be increased. WTP for new conveyance from Don Pedro to Hetch Hetchy Aqueduct (by the South Bay portion of SJSB demands) declines slightly, likely from increasing WTP from the San Joaquin portion of SJSB demands downstream of Don Pedro (see increase in Tuolumne WTP in Table 10).

Table 12. Average and Standard Deviation of WTP for Conveyance and Alternative Water Sources

All absolute values in $/yr/AF-month

Region	**Link**		LF$_{\text{Cost}}$	LF$_{\text{CVOD}}$	(LF$_{\text{CVOD}}$ - LF$_{\text{Cost}}$) / LF$_{\text{Cost}}$ x 100	PF$_{\text{CVOD}}$	(LF$_{\text{CVOD}}$ - PF$_{\text{CVOD}}$) / PF$_{\text{CVOD}}$ x 100
Existing Conveyance/ Transfer Expansion	CCWD-EBMUD	Mean	1,419	1,519	+7%	1,263	+20%
		SD	*241*	*383*	*+59%*	*99*	*+287%*
	Cross Valley Canal (Eastward)		235	567	+141%	517	+10%
			122	*271*	*+122%*	*215*	*+26%*
	Kern Exchange w/ CA Aqueduct via BVLB		751	855	+14%	839	+2%
			215	*255*	*+19%*	*83*	*+207%*
	SWP East Branch		511	584	+14%	186	+214%
			941	*1,013*	*+8%*	*37*	*+2,638%*
New Conveyance/ Transfer	Contra Costa Canal to EBMUD		305	394	+29%	199	+98%
			192	*338*	*+76%*	*59*	*+473%*
	Don Pedro to HH Aqueduct		154	143	-7%	54	+165%
			192	*168*	*-13%*	*37*	*+354%*
	Imperial-San Diego Canal		840	856	+2%	521	+64%
			1,503	*1,524*	*+1%*	*23*	*+6,526%*
New Potable Reuse	E&W MWD		105	104	-1%	0	-
			324	*325*	*+0%*	*0*	-
	San Bernardino Valley		270	265	-2%	0	-
			739	*735*	*-1%*	*0*	-
	San Diego		349	345	-1%	0	-
			899	*907*	*+1%*	*0*	-
Existing Non-Potable Reuse Expansion	Antelope Valley		346	386	+12%	0	-
			1,541	*1,649*	*+7%*	*0*	-
	CCWD		49	78	+59%	26	+200%
			99	*153*	*+55%*	*34*	*+350%*
	E&W MWD		498	487	-2%	0	-
			1,189	*1,174*	*-1%*	*0*	-
	San Diego		603	599	-1%	0	-
			1,369	*1,394*	*+2%*	*0*	-
	Santa Clara Valley		731	786	+8%	662	+19%
			343	*382*	*+11%*	*60*	*+537%*

Note: WTP for conveyance and alternative water sources is calculated as the annual sum of monthly dual values and interpreted as the annual WTP realized for all months in a year where units are $/yr/AF-month.

3.1.3.4. WTP for Groundwater Pumping Capacity Expansion

Table 13 lists the mean and maximum annual WTP for regional groundwater pumping capacity expansion for the Myopic, LF$_{\text{CVOD}}$, and PF$_{\text{CVOD}}$ runs. With Myopic operation, mean pumping capacity WTP is up to 156% more and maximum WTP up to nearly 700% more than

Table 13. Mean and Maximum Annual WTP for Regional Sector Groundwater Pumping Capacity

All absolute values in $/yr/AF-month

Region	**Sector**		Myopic	(Myopic - LF$_{CVOD}$) / LF$_{CVOD}$ x 100	LF$_{CVOD}$	PF$_{CVOD}$	(LF$_{CVOD}$ - PF$_{CVOD}$) / PF$_{CVOD}$ x 100
USV	**AG**	Mean	32	+129%	21	9	+133%
		Max	1,005	+154%	510	62	+723%
LSVD	**URBAN**		1,363	+35%	1,067	988	+8%
			14,577	+692%	2,154	1,192	+81%
	AG		122	-7%	161	78	+106%
			907	+91%	602	203	+197%
SJSB	**AG**		23	+156%	7	1	+600%
			649	+205%	244	21	+1062%
TB	**AG**		182	+13%	80	60	+33%
			729	+26%	510	188	+171%

LF$_{CVOD}$ runs, which confirms Myopic operation's costliest shortages are from the concurrence of exhausted carryover surface storage and limited groundwater pumping capacities. The reason for Myopic operation LSVD agriculture's mean WTP falling lower than LF$_{CVOD}$ is from the increase in smaller shortages imposed through carryover hedging operations (see section 3.1.2.2). The difference in pumping capacity WTP between limited and perfect foresight is yet another way to quantify the upper limit of limited foresight's hedging and conjunctive use capabilities. Maximum pumping capacity WTP is significantly more (up to ten times more in SJSB) with limited foresight than perfect foresight, indicating that limited foresight provides a more realistic economic estimate of drought sensitivity for the Central Valley.

4. Reservoir and Groundwater Carryover Storage Value and Operations

4.1. Decision Space for Carryover Value Function Penalties

The decision space of reservoir carryover storage value function parameter values (P_{max} and P_{min}) from near-$\mathcal{P}$ solutions in LF_{Cost} and LF_{CVOD} solution groups is shown in Figure 11 (see Figure 3 and Table 4 for reference of limited foresight solutions included in these two groups). Bivariate Gaussian kernel densities fit to P_{COSVF} of LF_{Cost} and LF_{CVOD} solutions indicate that these surface reservoirs generally have large near-optimal regions of potential carryover storage value functions. There is no discernable trend in the value of carryover storage in LF_{Cost} solutions versus LF_{CVOD} solutions for most reservoirs. Only reservoirs in the southern Central Valley on which Tulare Basin demands rely (e.g., Millerton (SR_MIL), Pine Flat (SR_PNF), and Isabella (SR_ISB)) show a slight tendency towards higher P_{COSVF} – mainly P_{min} values – in LF_{CVOD} solutions. This is further discussed in section 4.3.1.1 below.

When looking across all surface reservoirs, two broad groupings of reservoirs based on unit values of carryover storage are observed:

(1) Group 1 surface reservoirs have lower-valued carryover storage value parameters (P_{min} less than \$50-100/AF and P_{max} less than \$100-\$300/AF). This suggests that keeping these reservoirs full tends to have lower priority and value in terms of reducing total cost and groundwater overdraft. Most variability is in P_{max} which indicates that a wide range of risk aversion for these reservoirs yields similar near-optimal average systemwide cost and overdraft. Group 1 includes large project reservoirs (Shasta (SR_SHA), Oroville (SR_ORO), New Melones (SR_NML), and San Luis (SR_SNL)) and mid-size to larger non-project reservoirs (Clair Engle Lake (SR_CLE), Berryessa (SR_BER), Pedro (SR_DNP), McClure (SR_MCR), and Pine Flat (SR_PNF)).

(2) Group 2 surface reservoirs have higher-valued carryover storage value parameters (P_{min} up to \$250/AF and P_{max} up to \$500-750/AF). Keeping these reservoirs' carryover storage at or near carryover capacity generally improves systemwide total cost. However, substantial variability in the range of near-optimal carryover storage operation valuation appears in both P_{max} and P_{min}, meaning these reservoirs often can be operated to lower carryover storage targets without significantly impacting systemwide total cost and overdraft performance. Group 2 includes mid-size to smaller reservoirs (Bullards Bar (SR_BUL), New Hogan (SR_NHG), Eastman (SR_BUC)) and those supplying significant

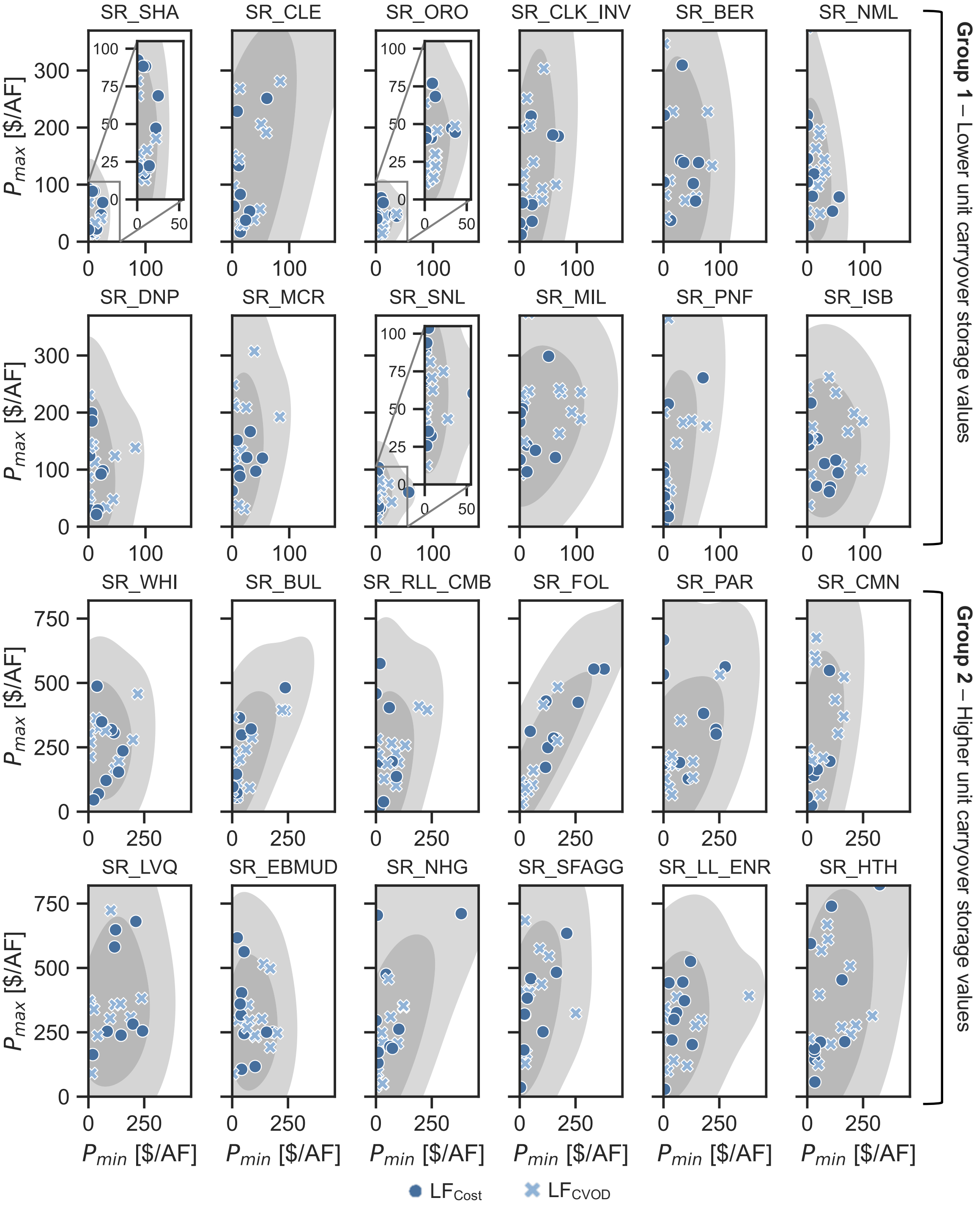


Figure 11. Decision Space of Optimized P_{max} and P_{min} in LF_{Cost} and LF_{CVOD} Solution Groups

Note: plot only includes near-$\mathcal{P}$ solutions in LF_{Cost} and LF_{CVOD} solution groups. A bivariate Gaussian kernel density estimate (KDE) of bandwidth (Scott method) scaled by 2 is fit to the P_{COSVF}. The outer (inner) light (dark) grey shaded area represents 95% (65%) cumulative density. Note scale differences between Group 1 and Group 2 reservoirs.

local urban demands (Folsom (SR_FOL), Pardee (SR_PAR), Camanche (SR_CMN), Los Vaqueros (SR_LVQ), East Bay MUD aggregate (SR_EBMUD), San Francisco aggregate (SR_SFAGG), Lake Eleanor (SR_LL_ENR), and Hetch Hetchy (SR_HTH)).

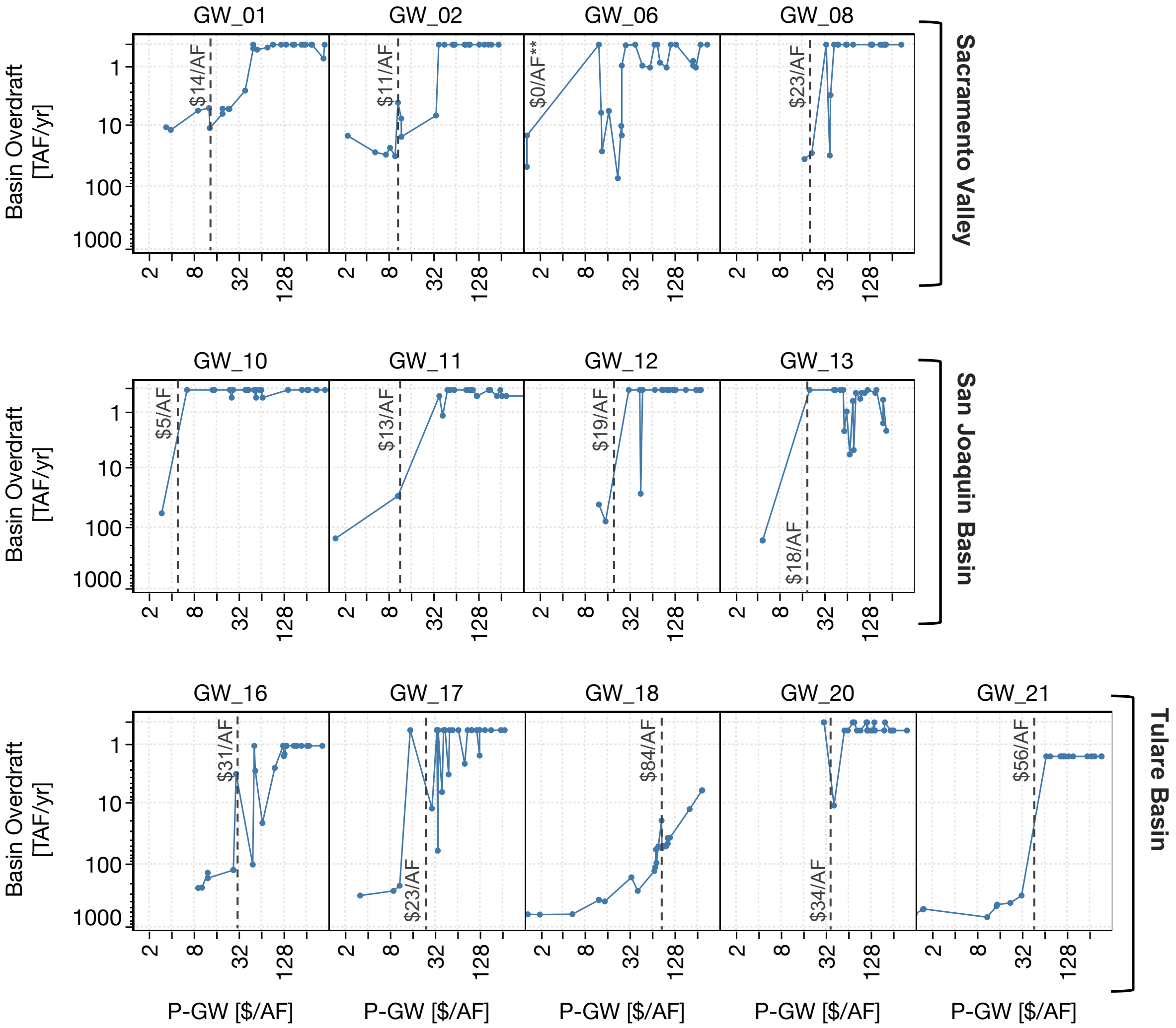


Figure 12. Relationship of Limited Foresight Unit Value of Local Groundwater Carryover (P_{GW}) with Local Groundwater Basin Overdraft

Note: PF_{CVOD} shadow values on groundwater overdraft constraint are annotated with dashed lines for comparison. Basin overdraft is plotted in log scale base10 and P_{GW} in base 2.

4.2. Minimum Carryover Groundwater Storage Value that Eliminates Overdraft

Figure 12 shows the groundwater carryover storage value (P_{GW}) and corresponding groundwater overdraft for each limited foresight solution in LF_{CVOD} and LF_{Cost} together with the PF_{CVOD} (no overdraft) run's dual values on the groundwater storage link's final time step. P_{GW} which eliminate overdraft are typically 2 to 4 times the corresponding perfect foresight shadow value. In some basins, including GW_06 (Solano and Yolo counties), GW_13 (south SJSB region), and GW_18 (Tulare county in the Tulare Basin), P_{GW} must greatly exceed PF_{CVOD} dual values to eliminate overdraft, showing that groundwater is quite valuable, and costly to cut, with limited foresight carryover operations.

4.3. Carryover Storage Operations

4.3.1. Controls on Near-Optimal Limited Foresight Carryover Operations

Panel (A) in Figure 13 shows the time series of average carryover storage across LF$_{\mathrm{CVOD}}$ and LF$_{\mathrm{Cost}}$ limited foresight solutions, carryover storage with perfect foresight, and simulated

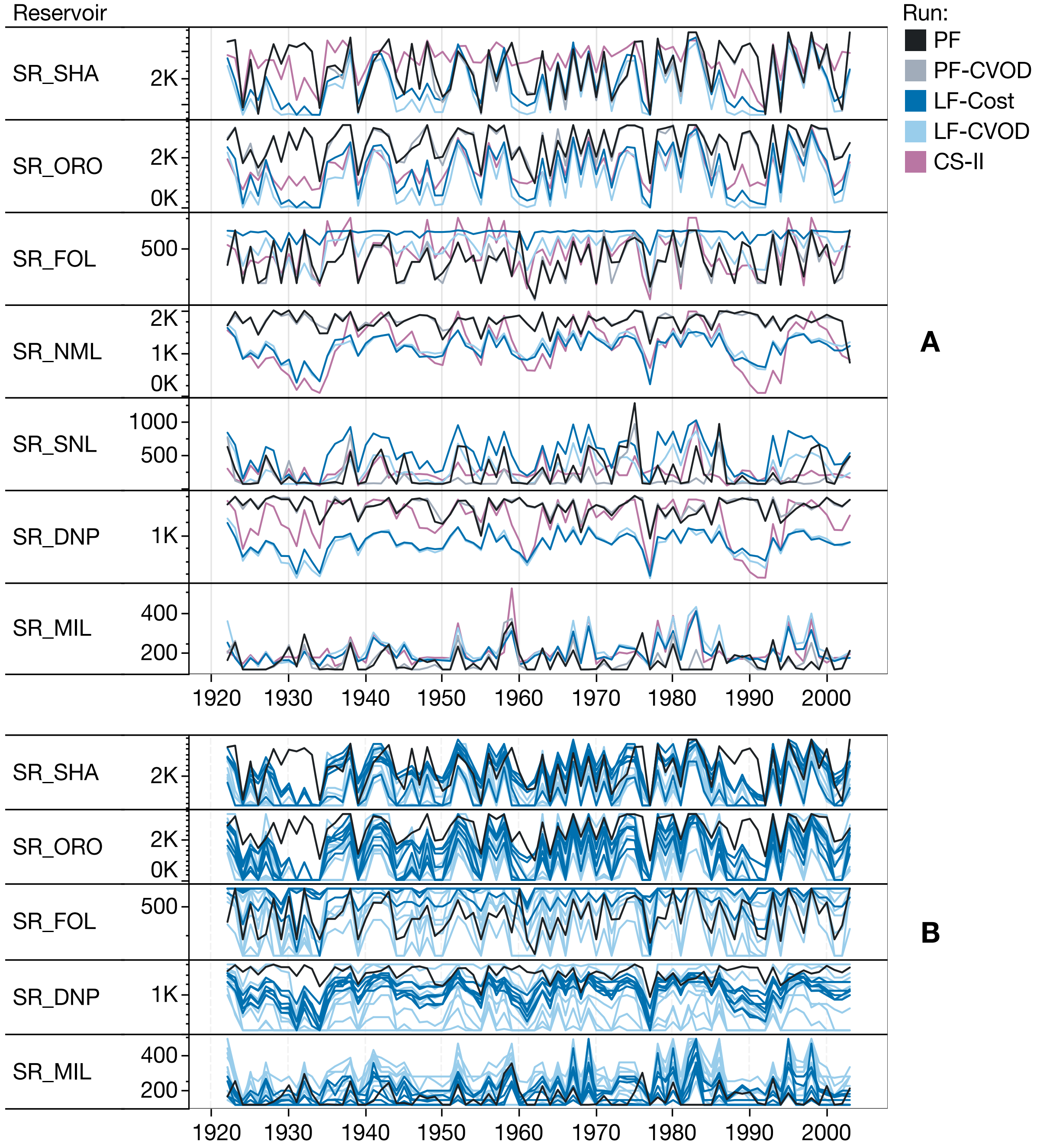


Figure 13. Carryover Storage Time Series for Selected Major Reservoirs

Note: top panel (A) shows the average of carryover storage in foresight solution groups; bottom panel (B) shows carryover storage of each individual foresight solution, colored by group.

carryover storages from CalSim-II (CalSim-II carryover operations are discussed in the following section 4.4). Compared to perfect foresight, limited foresight maintains lower carryover storage in Group 1 reservoirs Shasta, Oroville, New Melones, and the large non-project reservoir Don Pedro, especially in multi-year droughts (e.g., 1929-34; 1976-77; and 1987-92), yet higher carryover storage for the Group 2 reservoir Folsom. The major differences in perfect and limited foresight carryover management stem from: 1) physical and economic drivers of near-optimal P_{COSVF} such as relative carryover capacity and WTP for reservoir release; and 2) to a lesser but noteworthy degree, the linear valuation of groundwater storage.

4.3.1.1. Factor 1 – Physical and Economic Drivers of Near-Optimal COSVF

Figure 11 suggests an extensive range of near-optimal carryover storage policies with some limits and central tendencies to the minimum and maximum WTP for carryover storage. Physical and economic drivers of the near-optimal carryover policy range are shown by investigating relationships between mean marginal carryover storage value (P_{avg}), average carryover storage as a percent of storage capacity ($E[S]/K_{CS}$, i.e., average carryover storage use), and carryover storage capacity as a percent of average annual inflow (K_{CS}/Q_{μ}, i.e., relative carryover capacity).

The first driver of near-optimal carryover storage policies, a fixed physical constraint across all solutions, is relative carryover capacity. Figure 14 shows K_{CS}/Q_{μ} has a moderately high ($r^2 > 0.6$) linear relationship with average carryover storage use and is different for Group 1 and Group 2 reservoirs. For Group 1 reservoirs, increasing relative carryover capacity by 10% tends to increase average carryover storage use by ~1.2%. But Group 2 reservoirs show the opposite response, dropping carryover use by ~1.4%. A few reservoirs in either group do not adhere to this trend and are excluded from the linear fit. San Luis (SR_SNL; Group 1) is a large off-stream reservoir that primarily redistributes Sacramento flows seasonally from large North of Delta reservoir releases to demands South of the Delta, having diminished carryover value as reflected in the relatively low carryover storage consistent across all CALVIN runs in Figure 13. Additionally, a few smaller Group 2 reservoirs (e.g., SR_RLL_CMB and SR_GNT) have downstream flow requirements that constrain carryover volumes despite high carryover storage values. Neglecting these outliers, having more storage capacity relative to average inflow tends to increase average carryover storage use in mid-size to large reservoirs and decrease average carryover use in smaller to mid-size reservoirs on which high value demands acutely rely.

For the Group 1 reservoirs with high relative carryover capacities (e.g., Clair Engle Lake (SR_CLE) and New Melones (SR_NML)), the tendency towards increased inter-annual storage operation also tends to increase the marginal value of carryover storage. This would

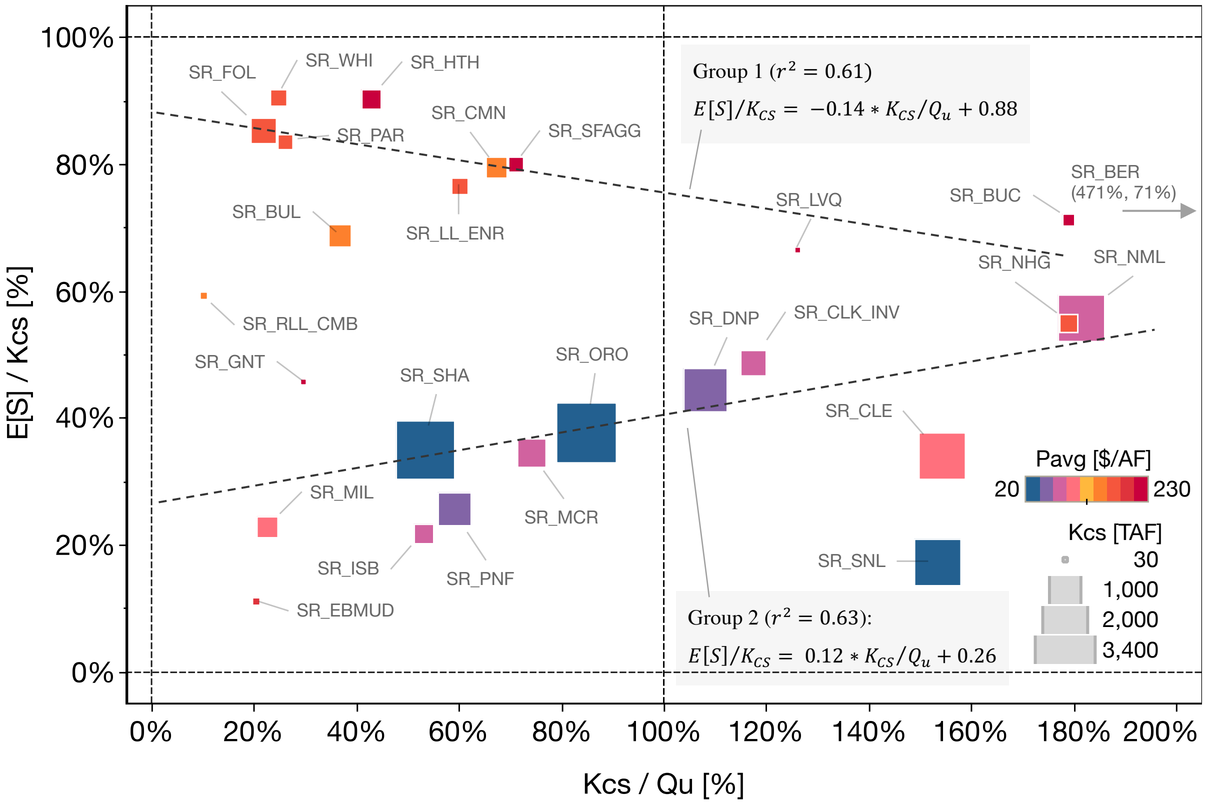


Figure 14. Relationship of Carryover Capacity as Percent of Average Annual Inflow (K_{CS}/Q_u) with Average Carryover Storage as Percent of Capacity ($E[S]/K_{CS}$)

Note: E[S] and P_{avg} are plotted as the average of LF_{Cost} and LF_{CVOD} solutions. Coefficients and r^2 of linear regression on Group 1 (excl. SR_SNL) and Group 2 (excl. SR_EBMUD, SR_GNT, SR_RLL_CMB) reservoirs are annotated. Size of plotted squares represent absolute carryover capacity (K_{CS}).

suggest increasingly valued expanded storage capacity on large reservoirs, but it isn't the case. Instead, the increased value is derived from higher marginal values of carryover storage at the reservoir's lowest storage capacity (P_{max}; shown in Figure 11), thus increasing average carryover use by avoiding low storage levels as opposed to seeking high storage levels. As a result, when wet conditions predominate, and storage capacity is reached (although rarely - e.g., New Melones averages 77% of years without reaching capacity (Table 11)), the willingness-to-pay for expanded capacity is relatively low (e.g., New Melones average WTP is $2/AF-year (Table 11)).

The second driver of the range of near-optimal carryover policies, an economic control that varies across solutions, arises from Draper and Lund (2004) who derived that an optimal carryover storage occurs where the marginal benefit of storage for future release equals the marginal benefit of current release. The average annual WTP for raw water just downstream of a reservoir (presented earlier in Table 10) can be interpreted as the expected WTP for current release. Shown in Figure 15 for four example reservoirs, expected WTP for release and P_{avg}

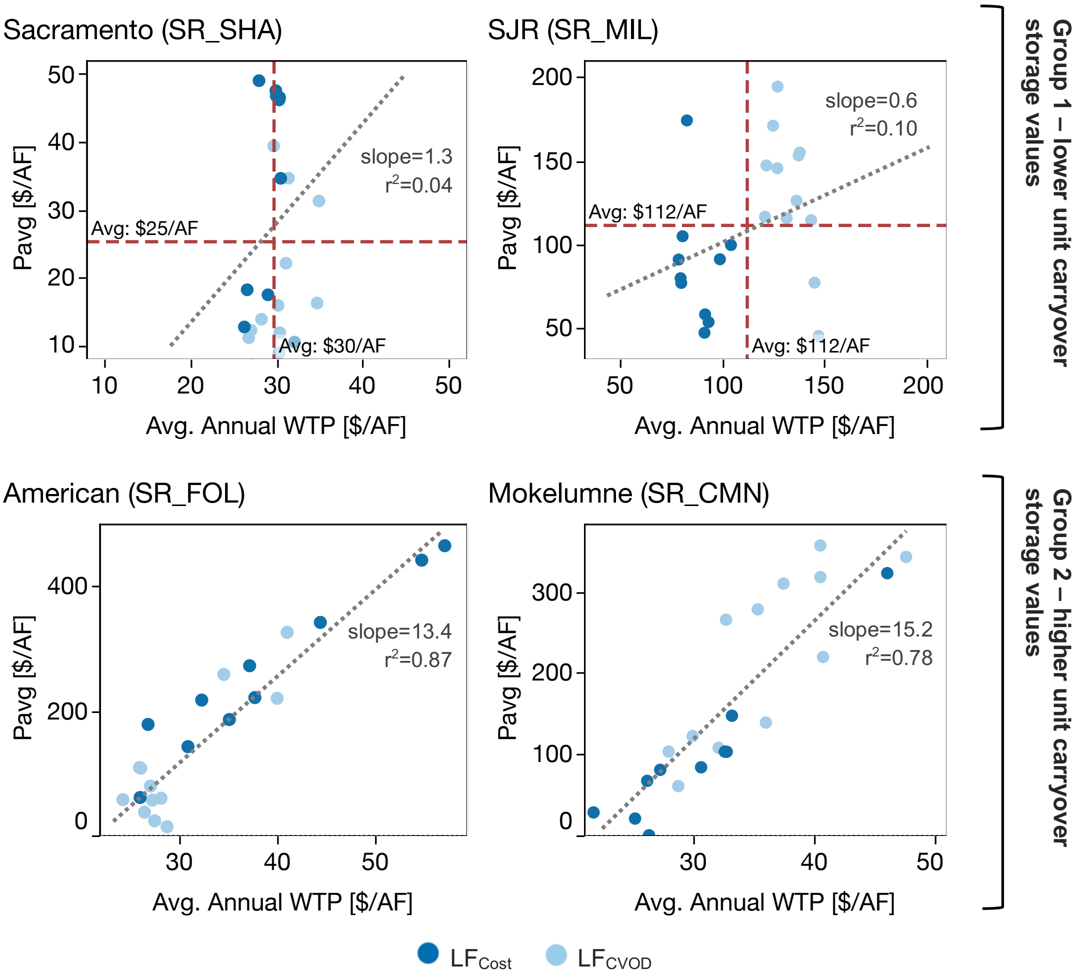


Figure 15. Relationship of Average Annual WTP for Raw Water Source with Mean Marginal Carryover Penalty (**P_{avg}**) for Select Group 1 and 2 Reservoirs

Note: each plotted point is a LF_{Cost} or LF_{CVOD} solution result. The average of these solutions is shown for Group 1 reservoirs (top row; note symmetric axes). A linear regression with unitless slope and r^2 value is shown for Group 2 reservoirs (bottom row; note axes scale differences). The average annual WTP (for raw water source) is taken from the CALVIN network node located immediately downstream of the reservoir.

are strongly connected, but in different ways for Group 1 and Group 2 reservoirs. By extension, the exponentially transformed linear relationship of P_{avg} and average carryover storage use in Figure 16 ($r^2 > 0.8$ for most reservoirs; coefficients and r^2 values listed in Table 14), shows that the expected WTP for release influences the range of near-optimal average carryover storage use. Two additional insights emerge based on Figure 16: 1) decreasing absolute carryover capacity acts as a positive shift (α) on the natural log of mean marginal carryover value; and 2) the slope (β), which can be interpreted as the mean marginal carryover price-elasticity of average carryover storage use (i.e., the change in marginal storage value per change in average carryover use), is largely consistent across all reservoirs in both Groups 1 and 2 and tends to be less elastic for larger reservoirs and more elastic for smaller reservoirs. These economic drivers are further detailed using the select Group 1 and 2 reservoirs in Figure 15:

(1) Group 1 Reservoirs - Lower unit carryover storage values

The mean marginal carryover storage penalties of Group 1 reservoirs with lower unit carryover storage values (e.g., Shasta (SR_SHA) and Millerton (SR_MIL) in Figure 15) do not covary with expected WTP for release yet their averages are in close agreement. Thus, the expected WTP for release constrains but does not drive the near-optimal range of carryover storage value for these reservoirs. Because most of P_{COSVF} variance is contained in P_{max} for Group 1 reservoirs (Figure 11), expected WTP for release largely limits the maximum carryover operated to during droughts or, on the lower valued side, the minimum level of near-optimal average carryover storage. For example, Figure 15 shows the P_{avg} for Shasta carryover not exceeding \$50/AF, which is ~1.4 times the highest average WTP for water on the Sacramento River link just downstream of Shasta (~\$35/AF). Thus, Shasta's near-optimal P_{max} (just under \$100/AF) rise toward but are limited from reaching the maximum annual WTP (\$150/AF; Table 10) on Sacramento River water because a higher P_{max} would push P_{avg} too far above the range of the expected WTP for release. The higher-valued P_{COSVF} solutions for Shasta carryover storage are shown in Figure 13 (bottom panel B) where carryover storage reaches near-full capacity with similar frequency to perfect foresight, yet drought period storage remains far lower than with perfect foresight. In sum, while an even more highly valued P_{COSVF} may better mimic the carryover hedging of perfect foresight, it is too costly under limited foresight since the marginal value of that additional carryover storage far exceeds the near-optimal expected WTP for release.

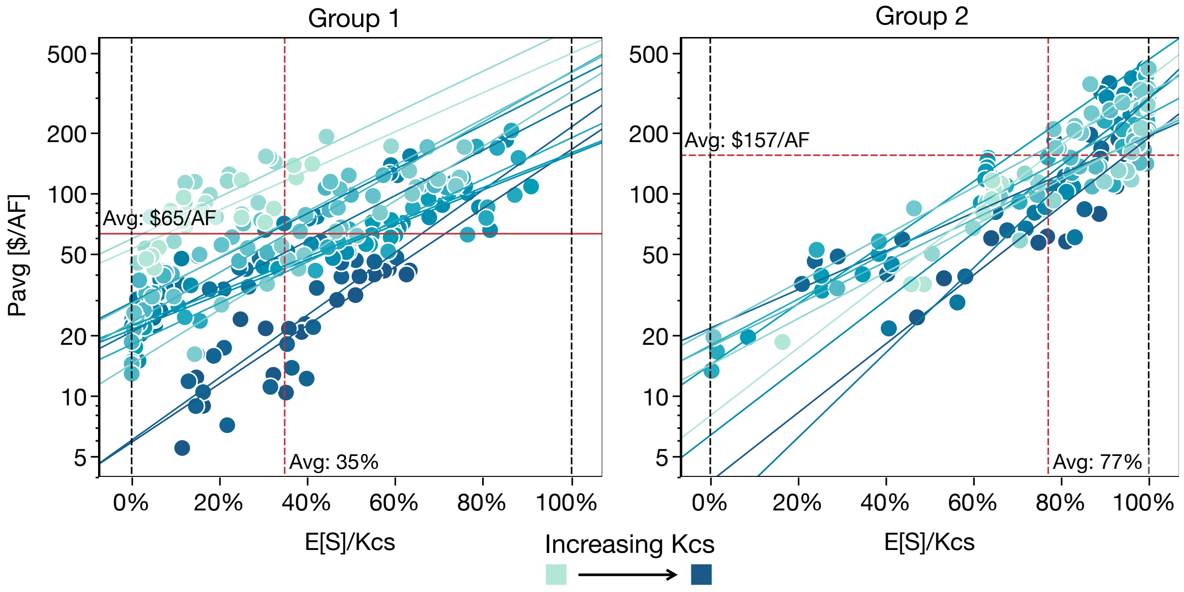


Figure 16. Relationship of Average Carryover Storage Use ($E[S]/K_{CS}$) with Mean Marginal Carryover Penalty (P_{avg})

A linearized exponential regression model is fit to each reservoirs' LF_{CVOD} and LF_{Cost} solution results. Reservoirs are colored from light teal to dark blue according to their carryover capacity (K_{CS}).

Table 14. Coefficients of Exponential Regression on Average Relative Carryover Storage Use ($E[S]/K_{CS}$) and Mean Marginal Carryover Penalty ($\mathbf{P_{avg}}$)

			P_{avg}			Exp. Fit Parameters*		
	Reservoir	K_{CS} [TAF]	P5 [\$/AF]	P50 [\$/AF]	P95 [\$/AF]	β	α [\$/AF]	r^2
Group 1 – lower unit carryover storage values	SR_ORO	3,320	9	24	42	3.3	6	0.81
	SR_SHA	3,050	9	18	48	3.6	6	0.71
	SR_SNL	1,958	19	35	49	2.6	21	0.84
	SR_CLE	1,947	22	60	165	2.5	29	0.94
	SR_NML	1,945	26	67	115	2.0	21	0.85
	SR_DNP	1,673	22	63	111	2.0	22	0.94
	SR_BER	1,592	25	86	176	2.4	18	0.79
	SR_PNF	955	13	39	112	2.9	23	0.82
	SR_MCR	736	26	71	128	2.6	29	0.89
	SR_CLK_INV	613	14	65	134	3.1	14	0.93
	SR_MIL	401	48	96	176	2.4	60	0.69
	SR_ISB	367	42	79	141	2.2	53	0.65
Group 2 – higher unit carryover storage values	SR_FOL	567	35	110	263	3.9	4	0.84
	SR_BUL	454	38	96	199	2.2	22	0.80
	SR_CMN	375	29	107	326	4.8	2	0.82
	SR_HTH	324	81	236	386	4.0	6	0.74
	SR_NHG	300	28	120	150	3.5	14	0.97
	SR_LL_ENR	271	17	170	326	2.6	18	0.92
	SR_WHI	230	97	176	263	2.4	18	0.83
	SR_SFAGG	194	83	210	358	2.7	21	0.88
	SR_PAR	191	58	118	278	2.7	15	0.61
	SR_BUC	125	33	195	396	2.2	34	0.86
	SR_RLL_CMB	59	19	89	116	3.8	8	0.90
	SR_EBMUD	51	159	215	329	0.9	190	0.44
	SR_GNT	36	151	215	439	3.8	37	0.74
	SR_LVQ	33	89	245	414	1.1	105	0.60

Exponential fit in linearized natural log form: $\ln(P_{avg}) = \ln(\alpha) + \beta * E[S]/K_{CS}$

(2) Group 2 Reservoirs - Higher unit carryover storage values

In contrast, the P_{avg} of Group 2 reservoirs (e.g., Folsom (SR_FOL) and Camanche (SR_CMN)), with higher average unit carryover storage values, have a steep linear response to the expected WTP for release. This can be interpreted as the mean marginal carryover price-elasticity of expected WTP for release; it is highly elastic for Group 2 reservoirs. For example, the sensitivity of Folsom's P_{avg} is so great that even a mid-range expected WTP for release of American River water (\$34/AF) has a high P_{avg} (~\$180/AF). Given the exponential relationship of average carryover storage use and P_{avg} (Figure 16 and

Table 14), greater mean marginal carryover price-elasticity means a prevalence of higher average carryover storage use in Group 2 reservoirs.

The relationship of Group 1 and Group 2 reservoirs' marginal carryover value with expected WTP for release remains consistent even when LF_{Cost} and LF_{CVOD} (no Central Valley overdraft) solution groups are considered separately. For example, as the expected WTP for release from Millerton increases due to the increased value of groundwater in LF_{CVOD} solutions (shown Figure 15 and for several other Group 1 reservoirs in Table 10), the near-optimal range of P_{avg}, while also driven higher, remains large and has no correlation with the expected WTP for release over that range. Likewise for Group 2 reservoirs, while the average of P_{avg} rises or falls in correspondence with the average of expected WTP across the solution group, the near-optimal range remains large and continues to show a strong linear relationship over that range.

Although not shown here, Group 1 reservoirs in the southern Central Valley show a translational scaling in the exponentially transformed linear relationships of P_{avg} and average carryover storage use shown in Figure 16 (i.e., a change in the α-intercept in Table 14). This suggests that increased expected WTP for releases on these reservoirs in connection with higher groundwater storage valuation does not increase average carryover use, but rather that a higher marginal carryover storage value is required to maintain the same level of average carryover use considered near optimal in solutions with lower groundwater storage value. However, the number of sampled solutions within each solution group is not adequate to draw conclusions about changes in this relationship for Group 2 reservoirs as well as for other major Group 1 reservoirs. Also, a solution sampling bias is the most likely cause of an inconsistent decrease in expected WTP for release from Folsom in LF_{CVOD} solutions. Additional random seeds of the evolutionary search would be needed to confirm this.

4.3.1.2. Factor 2 – Conjunctive Operation

A key operational strategy of perfect foresight is the advantageous allocation of increased groundwater pumping just before and during the onset of multi-year droughts to support greater surface storage carryover volumes. This is seen in the relative difference of perfect foresight's surface water deliveries and groundwater pumping with limited foresight in Figure 8 and perfect foresight's higher carryover in larger reservoirs like Shasta, Oroville, and Don Pedro during multi-year droughts seen in Figure 13. Perfect foresight's anticipatory conjunctive behavior suggests that a value function might be derived for the marginal value of groundwater. This unknown value function would vary the cost of groundwater overdraft to support a surface water hedge without increasing the marginal cost of carryover above the near-optimal range of average WTP for release. The function might incorporate a state variable that indicates the probable onset of drought conditions conditioned on multi-year cyclicity in cool-season precipitation which can explain a significant portion of interannual variability over the observed historical record (Dettinger et al. 1998; Meko, Woodhouse, and Touchan 2014; St. George and Ault 2011, 2014; Williams et al. 2021). On the other hand, a few of these studies conclude that the significance of these low-frequency climate signals is inconsistent over extended (>500 years) paleo dendrochronological records (St. George and Ault 2014; Williams et al. 2021) and underlying climate dynamics are not well understood, making this approach more speculative. Alternatively, the function might vary the marginal value of groundwater (P_{GW}) with the immediate hydrologic state – for example, surface storage of the largest project reservoirs added of annual inflows – reducing P_{GW} during drought and increasing it in wetter years to induce a better drawdown-refill cycle for groundwater. Granted, the currently applied assumption in limited foresight that P_{GW} should be constant due to much longer time scales of hydrogeologic response compared to that of surface water is valid; but the conjunctive behavior of perfect foresight suggests there might be potential to formulate groundwater storage value to vary with drought conditions.

Based on shortage differences observed and discussed in section 3.1.2.4 and focusing only on solutions that eliminate Central Valley overdraft, any potential increase in the performance of limited foresight carryover hedging through improved conjunctive use would accrue almost exclusively to Central Valley agricultural demands. More specifically, any improvement in limited foresight's conjunctively supported hedging would not greatly affect average shortages as they are quite close between limited foresight (LF_{CVOD}) and perfect foresight (PF_{CVOD}) runs. The primary benefit would be reducing maximum agricultural shortages in multi-year droughts, as inferred by comparing relative shortage costs from LF_{CVOD} and PF_{CVOD} runs in Figure 5 and Table 5.

4.4. Comparison of Limited Foresight with CalSim-II Carryover Operations

Carryover storage operations simulated by CalSim-II (CS-II), a California Department of Water Resources model of water resources infrastructure operations in the Central Valley of California, were applied in the limited foresight CALVIN model to compare performance with carryover storage operations determined with optimized carryover storage penalty operations. The particular CS-II run used here was produced as part of California's Proposition 1 Water Storage Investment Program (WSIP) for the analysis of public benefits from major new supply projects (California Water Commission 2014). The largest reservoirs for system operations are included in both CALVIN and CS-II models. Table 15 crosswalks surface reservoirs for which CS-II simulated carryover storage values were set as fixed constraints in limited foresight with COSVF runs (for each solution in LF_{Cost} and LF_{CVOD} solution groups). The remaining CALVIN surface reservoirs not represented in CS-II were assigned the optimized carryover penalty

Table 15. Surface Reservoirs Included in Fixed CalSim-II Carryover Operations

Reservoir	CALVIN Node	CalSim-II Node
Claire Engle	SR_CLE	S1
Whiskeytown	SR_WHI	S3
Shasta	SR_SHA	S4
Black Butte	SR_BLB	S42
Oroville	SR_ORO	S6
Folsom	SR_FOL	S8
New Hogan	SR_NHG	S92
New Melones	SR_NML	S10
Don Pedro	SR_DNP	S81
McClure	SR_MCR	S20
San Luis	SR_SNL	S12
Buchanan	SR_BUC	S53
Hensley	SR_HID	S52
Millerton	SR_MIL	S18

values from the respective LF_{Cost} or LF_{CVOD} solution. P_{GW} for all groundwater reservoirs were also preserved in limited foresight runs with CS-II fixed carryover storage.

Figure 17 shows the differences in the average annual total cost and groundwater overdraft for LF_{Cost} and LF_{CVOD} CS-II fixed carryover storage runs compared with the LF_{Cost} and LF_{CVOD} solution results. For almost all solutions, CS-II carryover storage operation results in higher total economic cost and overdraft – about $10M/yr and 100 TAF/yr on average, respectively. To put these differences in perspective, CS-II's higher total cost is about 4% of average annual shortage costs (nearly all total cost residual is related to shortages) and higher groundwater overdraft about 10% of total Central Valley overdraft. CS-II's larger differences with limited foresight solutions that eliminate Central Valley overdraft (LF_{CVOD}) suggest that carryover storage policies derived from limited foresight increase in value with rising groundwater storage value in the Central Valley, especially for supporting overdraft reductions. Otherwise, CS-II carryover operation economic performance can be considered relatively close to that found by limited foresight COSVF optimization.

In this analysis, differences between CS-II and limited foresight with COSVF stem only from differences in carryover operations, so it is fitting to discuss how carryover is determined CS-II. In general, target carryover storage in CS-II is a function of a two-step process. First, water supply indices (WSI) – the sum of beginning-of-month storage and forecasted inflow – guide selection of a demand index (DI) level – the pool of water available for carryover storage or delivery – from a WSI:DI curve. The WSI:DI curve is developed through semi-automated calibration with the objective of minimizing State Water Project (SWP) and Central Valley

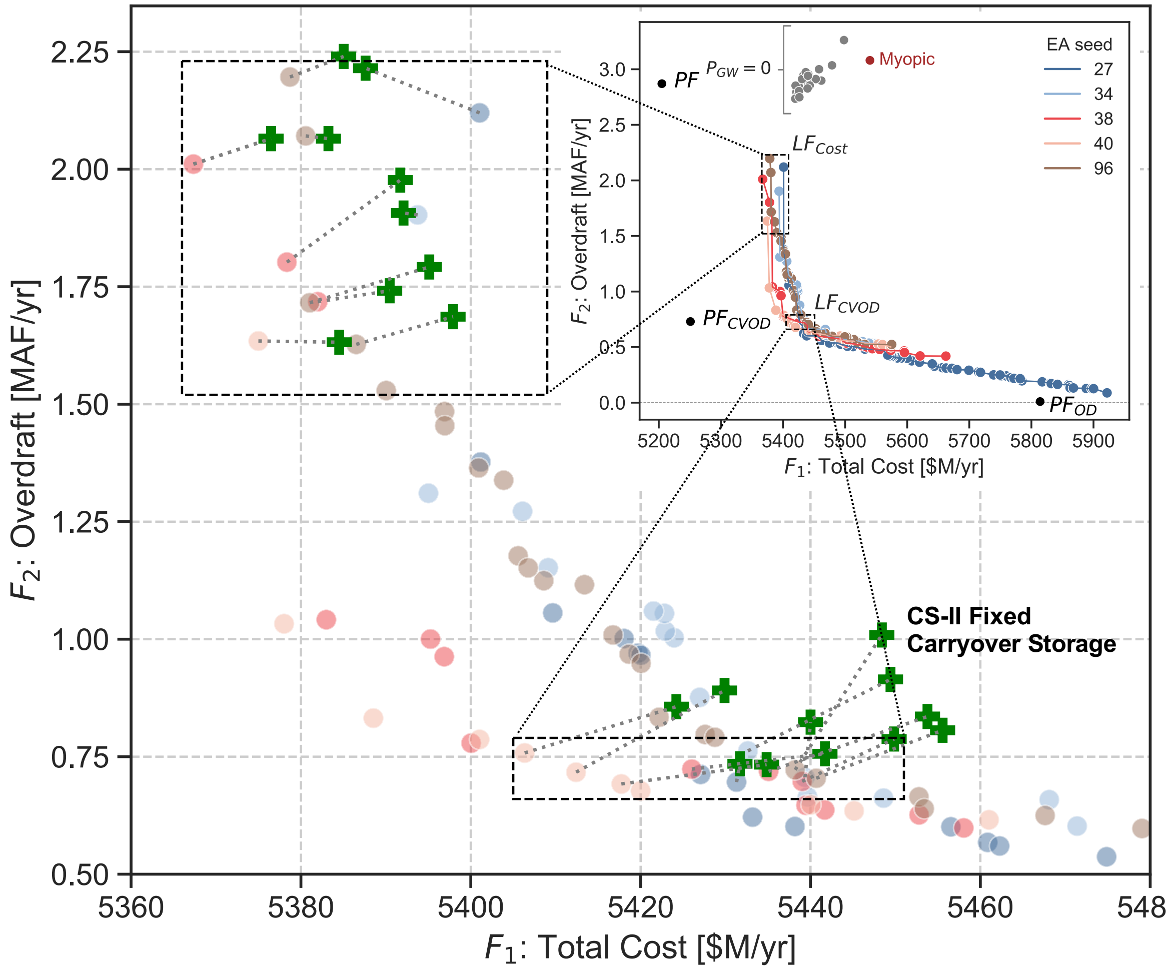


Figure 17. Differences of Average Annual Total Cost and Groundwater Overdraft Using CalSim-II Fixed Carryover Operations in Limited Foresight CALVIN

Note: dotted lines connect CS-II fixed carryover storage runs with their original LF_{Cost} or LF_{CVOD} counterpart.

Project (CVP) delivery shortages. Second, a "delivery versus carryover risk curve" specifies the apportionment of the DI pool into deliveries or carryover storage (Draper et al. 2004). Beyond the WSI:DI, several operational objectives (with weights) are used in CS-II to affect carryover operations, including highly detailed Sacramento-San Joaquin Delta flow objectives and constraints.

Compared to the average of LF_{Cost} and LF_{CVOD} carryover storage for selected reservoirs in Figure 13-A, CS-II maintains higher carryover storage in Shasta and Oroville, especially through multi-year droughts, and lower carryover storage in San Luis. On the CVP side, CS-II prioritizes draws on Folsom and New Melones storage to meet environmental and water quality objectives in lower Sacramento and San Joaquin rivers and the Delta, which likely contributes to Shasta's ability to operate at even higher carryover storage. But a major driver of CS-II's higher Shasta carryover use is the CVP's environmental objective criteria of preserving a cold water pool to protect endangered winter-run Chinook salmon (United States Bureau of

Reclamation 1992). CALVIN's representation of environmental constraints is not as detailed in this regard, particularly with limited foresight where carryover operations are driven only by its marginal economic value and minimum operating pool. Another driver of CS-II's higher Shasta carryover storage is its prioritization of meeting contractual water delivery obligations to Sacramento basin users. These demands see significant maximum annual shortage cost reductions with CS-II fixed carryover operations (e.g., \$24M with limited foresight COSVF versus \$8M with CS-II) albeit at the expense of increased average shortage costs to all Central Valley agriculture demands.

Whereas CS-II cautiously maintains carryover in Shasta for environmental and contractual objectives in the Sacramento Valley, limited foresight with COSVF tends to balance more of this carryover storage in the South of Delta off-stream San Luis reservoir during wetter periods. Limited foresight's San Luis balancing achieves 120-240 TAF/yr in greater South of Delta exports, water which helps reduce both groundwater overdraft and agricultural shortages in the San Joaquin and Tulare basins. However, if CS-II's San Luis fixed operations were lifted (but Shasta's left in place), it's likely that limited foresight would increase South of Delta exports to fill San Luis with the higher "surplus" Delta outflows seen in CS-II fixed operations (270-550 TAF/yr). In other words, limited foresight's additional San Luis storage is not necessarily reduced spillage from Shasta – a rare occurrence – but Delta outflow with the more detailed environmental flow regulations in CS-II.

On the SWP side, CS-II maintains higher Oroville carryover storage in dry periods primarily due to a minimum "floor" of target carryover storage. Otherwise, CS-II's operation is less conservative as shown in smaller carryover recovery levels (i.e., releases tend to be larger in CS-II than limited foresight with COSVF when water is less scarce). CS-II's minimum carryover target for Oroville is related to the State Water Project's objective to maintain average deliveries through multi-year droughts while concurrently meeting Delta flow requirements and contractual obligations to Feather river basin users.

Despite these notable differences in CS-II's simulated carryover with the average of limited foresight COSVF solutions, CS-II's carryover operations fall within the range of near-optimal limited foresight carryover operation policies as shown in Figure 13-B. Shasta, Oroville, and Don Pedro carryover operations lie towards the high-valued limits of P_{COSVF} while Folsom or Millerton lie towards mid- or lower-valued carryover storage policies. The overall effect of CS-II's more cautious hedging operation is slightly reduced maximum shortages, specifically to Sacramento Valley and San Joaquin agricultural demands, but at a higher average total cost to Central Valley-wide agricultural demands and southern California Urban demands. CS-II's conservative operation – specifically for Shasta and the minimum carryover for Oroville in multi-year droughts – also tends to increase groundwater overdraft as the WTP for groundwater is forced above the P_{GW} on groundwater storage (which was assigned by the limited foresight solution) to meet the higher marginal cost of induced shortages.

In summary, these results suggest two points. First, CS-II simulated carryover operations, intended to represent current reservoir storage management decisions, are consistent with expected-value economic utility principles because they lie in the range of carryover policies optimized to the long-run expected willingness-to-pay for storage releases. And secondly, CS-II's carryover storage management of the major project reservoirs can be considered risk-averse due to environmental and contractual requirements as opposed to economic objectives.

5. Conclusions

Implementation of CALVIN limited foresight with quadratic COSVF and linear groundwater penalties has demonstrated its practicability, feasibility, and utility for understanding California's large multi-reservoir system. The results show that the system can operate under a wide variety of carryover policies which yield similar levels of systemwide total cost and groundwater overdraft performance. Physical infrastructure changes most valuable to the system are reducing conveyance bottlenecks, increasing groundwater pumping capacities, and addition of small amounts of recycled and desalinated water to major coastal urban areas (particularly in southern California). Both demand management and Delta exports are crucial in alleviating over-reliance on groundwater in the southern Central Valley (SJ and TB regions). Increased artificial recharge in SJ and TB regions is likewise important in this regard and supported through increased Delta exports. In general, perfect foresight results provide similar conclusions.

Limited foresight results stand apart from perfect foresight in revealing the flexibility and sensitivity of near-optimal carryover storage operating policies while providing more realistic economic valuation of water and infrastructure consistent with the interannual hydrologic variability the system must manage. Water rights, more complex environmental constraints, and changing climate conditions will constrain and shift the range and central tendency of near-optimal operating policies. These are important lines of future inquiry. Some key findings and conclusions are summarized below:

Costs

- The variance of total system shortage and operation costs is two to four times greater with limited foresight than with perfect foresight – an aggregate measure of perfect foresight's economic under-valuation related to managing inter-annual hydrologic risk. But long-term expected value cost differences are small, within 3-5% for runs that eliminate groundwater overdraft in the Central Valley. Perfect and limited foresight generally provide similar answers when decisions are based on the expected value but will diverge when risk preferences are not neutral.

- More than half of limited foresight's greater average shortage cost relative to perfect foresight is related to non-ideal management of southern California groundwater reserves from premature exhaustion of groundwater supplies over the period of analysis. Non-ideal southern California groundwater management increases operational costs through greater reliance on costly desalination and SWP imports (conveyance costs) during multi-year droughts in the latter period of record once groundwater reserves have been exhausted. In reality, several of these southern California groundwater basins have been managed to prevent long-term depletion of usable storage, thus making this aspect of limited foresight's differences less relevant. But if the objective were to find an optimal long-term drawdown rate constrained by a usable storage limit, limited foresight would struggle to find it. Further investigation into perfect and limited foresight solutions that eliminate Southern California overdraft might better isolate sources of limited foresight's increased costs.

- Compared to Myopic (SLOP) operation, the use of quadratic carryover storage valuation reduces total average shortage costs by 15% and the inter-annual variance of total shortage costs by 35%. Improvements are largely in the driest years when additional carryover water is available to meet demands subject to groundwater pumping capacity constraints. Thus, SLOP operation, which is normally expected to reduce average shortages (and in fact does lower shortage volumes to some Sacramento Valley and Tulare Basin agricultural demands) results in greater average annual shortage costs compared with COSVF hedging policies from disproportionately large shortages in the driest years. In addition, SLOP operation's preferential use of available surface supply leads to overreliance on groundwater (~0.5 MAF/yr increase) due to the lack of carryover storage hedged from previous years combined with the lower marginal expense of pumping versus incurring a shortage.

- Including marginal groundwater storage penalties in limited foresight increases Central Valley agricultural shortage costs by 18% ($10M/yr) but reduces southern California urban shortage costs by 15% ($23M/yr) and operational costs by ~$50M/yr, thus resulting in total system cost savings while eliminating 0.5-1.25 MAF/yr in groundwater overdraft. Groundwater storage valuation more optimally manages long-term drawdown of southern California groundwater reserves which reduces the region's urban shortages and reliance on SWP imports and non-potable recycling in latter drought periods.

- With limited foresight, Central Valley groundwater overdraft is eliminated at a low marginal cost ($40/AF of overdraft eliminated) and southern California groundwater overdraft at a much higher marginal cost ($800/AF of overdraft eliminated). The low marginal cost of Central Valley overdraft is from CALVIN's flexibility in rebalancing Tulare Basin groundwater pumping to under-utilized (but higher pumping expense) groundwater basins, relatively inexpensive increased South of Delta exports, and relatively inexpensive increased artificial recharge. For southern California overdraft, greater marginal southern California scarcity costs drive increased exports south, but conveyance and treatment costs rise substantially, and southern California shortage costs rise asymmetrically due to conveyance bottlenecks such as on the East Branch of the State Water Project. Detailed analysis of eliminating groundwater overdraft in southern California basins is merited in future studies. Finally, perfect foresight has roughly the same marginal cost response to eliminating overdraft in either region, which further supports that changes in long-run expected costs at the systemwide scale in response to increased water scarcity are relatively unaffected by interannual hydrologic foresight.

Value of Infrastructure

- The variance in WTP for expanding capacities for conveyance, groundwater, and alternative water sources increases substantially with limited foresight, by 200-400% in the Central Valley and up to 2,000-6,000% in Southern California. This has significant implications for selecting infrastructure and water source portfolio options when risk preferences are not neutral.

- For some expansion options, hydrologic foresight has a small effect on the long-term expected annual WTP. Much larger differences occur for conveyance links crucial to conjunctive and interregional management and expanded non-potable and potable reuse where lack of scarcity eliminated WTP with perfect foresight. Nevertheless, the relative WTP prioritizations of infrastructure for expansion remain similar for the two representations of hydrologic foresight, thus either will provide similar ordinal values of infrastructure.

- Based on the relative geographic differences in WTP for raw water sources, limited foresight's non-ideal North of Delta carryover management appears to have the greatest impact on southern Central Valley and Tulare Basin demands.

- The average of limited foresight solutions' WTP for reservoir capacity expansion is somewhat lower than with perfect foresight for some of California's major reservoirs. This is due to lower average carryover storage use consistent with its near-optimal marginal value, making storage capacity a less frequent binding constraint on these reservoirs. Greater average carryover storage use or reservoirs with highly valued carryover storage show greater WTP than perfect foresight, but all storage expansion WTPs are low compared to other infrastructure expansion options. This strongly underlines that increased storage capacity is not a panacea to water scarcity despite prolonged lobbying for public investment in storage projects. Only a portion of limited foresight's more realistic carryover operations may actually take advantage of any additional storage.

- Maximum WTP for groundwater pumping capacity is significantly higher – up to an order of magnitude in the San Joaquin region – with limited foresight than perfect foresight, indicating that limited foresight provides a much more realistic economic estimate of drought sensitivity for the Central Valley.

Carryover and Groundwater Storage Value and Operations

- Reservoirs in California's water system fall into two broad groups according to their near-optimal range of marginal carryover penalties. Group 1 includes mid-size to larger reservoirs with lower unit values for carryover storage that vary mostly according to the marginal value of carryover storage when the reservoir is at minimum carryover storage capacity. Group 2 includes smaller reservoirs with higher unit values for carryover storage that vary more over the range of the reservoir's storage.

- As carryover capacity rises relative to average annual inflow, so does expected carryover storage for Group 1 reservoirs. The opposite trend occurs for Group 2 reservoirs. So, as mean annual inflow declines (increases) or absolute carryover capacity is increased (reduced), Group 1 reservoirs should target increased (reduced) expected carryover storage and Group 2 reservoirs should target the reverse.

- Average marginal carryover penalties strongly govern average carryover storage use. And the expected WTP for release (in the current period) governs the range of near-optimal average marginal carryover penalties on a reservoir. Although more highly valued carryover storage on mid-size to large reservoirs may better mimic carryover hedging seen in perfect foresight, it is too costly under limited foresight since the marginal value of that additional carryover storage use far exceeds the near-optimal expected WTP for release.

- The relationship of average carryover storage use and mean marginal carryover penalties suggests two generalized insights into the range of near-optimal carryover storage policies. 1) Decreasing the absolute carryover capacity of a reservoir tends to raise WTP for carryover storage and 2) all reservoirs (both Groups 1 and 2) have largely consistent marginal carryover price-elasticities of average carryover storage use, which tend to be more (less) elastic for smaller (larger) reservoirs. In other words, larger reservoirs are less sensitive to changes in the expected WTP for release than smaller reservoirs.

- The major source of the difference between Group 1 and 2 reservoirs appears related to the marginal carryover price-elasticity of expected WTP for release (i.e., a change in the value of carryover storage due to a change in the value of water from that source).

While Group 1 reservoirs are constrained by the range of expected WTP for release, their carryover storage value is insensitive to changes (i.e., inelastic) within this range. In contrast, Group 2 reservoirs are highly elastic and thus driven rapidly towards higher valued carryover storage (and higher average carryover use) with only slight increases in the expected WTP for release. Group 2 reservoirs' high marginal carryover price-elasticity is likely connected to the higher-valued urban demands they serve.

- Limited foresight marginal groundwater storage penalties which fully eliminate overdraft are typically 2 to 4 times that of perfect foresight. The difference is of much larger magnitude relative to long-run expected shortage costs and WTP for infrastructure expansion and is due to groundwater's buffering role during years of increased water scarcity. Limited foresight relies more on groundwater to meet agricultural demands in the Central Valley – both on average and with more variability – thus raising groundwater's marginal storage value much higher than with perfect foresight.

- Compared to the State's CalSim-II simulated carryover operations, limited foresight's optimized carryover policies yield about 4% in average shortage cost reductions while pumping 10% less groundwater. As Central Valley overdraft is eliminated (CVOD), the potential utility of carryover storage rules derived from limited foresight over that of currently prescribed operations increases, both to expected shortage costs and especially to supporting overdraft reductions. However, compared to CALVIN, CalSim-II has greater detail in environmental flow constraints and prioritizes meeting contractual obligations, both of which necessitate higher carryover storage targets, particularly during California's notorious multi-year droughts. Thus, although CS-II's carryover storage management can be considered risk-averse, it is largely due to environmental and contractual requirements rather than economic objectives.

6. Appendix

I. System Infeasibility

With limited foresight CALVIN, flow constraints in future year(s) are unknown which often result in infeasibilities from insufficient carryover storage to meet minimum flows, minimum storage bounds, and (pre-processed) stream depletion requirements. Although rare, infeasibilities also may occur under very wet conditions when spill volumes exceed downstream capacities from excess incoming carryover storage. To address infeasibilities, the Python CALVIN package includes an option to run in "debug mode", which adds two additional nodes, "super-source" and "super-sink" to all nodes in the network for all timesteps (Dogan et al. 2018). These debug links supplement or eliminate as much water as needed to meet flow constraints but at a cost orders of magnitude greater than any other economic cost in the network to ensure the model uses them as a last resort.

Once the debug flow volumes and timing are known, an automated process, multiple iterations of which may be needed, can be used to decrease lower bound constraints and increase upper-bound constraints after which debug links are removed and the model can be solved. Because the evolutionary search for P_{COSVF} and P_{GW} requires many thousands of CALVIN limited foresight model evaluations, the automated debug removal process would increase runtime impractically. So, the current evolutionary search approach treats solutions the same (in terms of their fitness) regardless of the debug flow volume used. The assumption is that elimination of debug flows could take place after the best performing individuals have been found if the modeler is interested to evaluate a limited foresight solution's performance in the strictest sense. Another approach (not taken here) might be to penalize solutions' debug volumes during the evolutionary search.

Table 16 lists cumulative debug volumes over the 82-yr period of analysis and the count of years with debug flows occurring for each super-source destination link for the Myopic run and the average across limited foresight with COSVF. With Myopic operation, a total of 21 MAF (~250 TAF/yr) debug source volume is used to satisfy minimum flow constraints in a large proportion of years in the period of analysis. Limited foresight with COSVF (LF_{Cost} & LF_{CVOD}) reduces the total debug source volume to 3.2 MAF (~40 TAF/yr) and greatly reduces the frequency of years with debug flows. In LF_{Cost} and LF_{CVOD} solutions, 80% of the debug source volume accumulates to Pine Flat, Grant, Clair Engle, Bullards Bar, McClure, Folsom, and Oroville reservoirs. The debug volume to these reservoirs is needed to meet lower bound

Table 16. Cumulative Debug Volume and Year Count in 82-yr Period of Analysis

		Myopic		**$LF_{Cost} + LF_{CVOD}$***	
Type	Link	Total [TAF]	Year Count	Total [TAF]	Year Count
Source	SR_PNF	1,135	27	624	16
	SR_GNT	1,193	76	583	41
	SR_CLE	5,926	73	503	23
	SR_BUL	2,485	70	395	10
	C53	270	19	266	14
	SR_MCR	940	62	227	16
	SR_FOL	2,991	64	147	3
	SR_ORO	350	5	88	2
	C35	675	43	83	6
	SR_BLB	51	53	52	55
	SR_CLK_IN	40	2	31	4
	C58	21	9	28	10
	SR_TRM	16	5	28	6
	SR_RLL_C	287	30	28	4
	C77			23	1
	SR_NML	257	31	23	3
	D17	328	18	18	1
	SR_SCC	7	5	16	8
	C56	21	6	13	5
	SR_NHG	487	29	12	1
	C150	35	7	11	2
	HSR101	457	27	11	1
	SR_CMN	812	52	6	1
	C40	276	7	6	1
	SR_SCAGG	2	11	3	12
	C51	119	6	3	1
	C52	7	2	3	1
	SR_PAR	429	42	3	1
	HSR301	13	6	2	1
	C54			2	1
	C89	4	1	2	1
	C57			1	1
	SR_LL_ENR	516	48	1	2
	HSUR101	90	6	1	1
	D517	55	8	1	1
	C155	14	14	1	1
	SR_CFW	5	2		
	SR_BUC	2	54		
	SR_BER	298	40		
	R101	84	6		
	N202	6	5		
	N201	108	25		
	HSD202	12	6		
	D98	137	17		
	C41	95	5		
	Total	**21,056**		**3,245**	

*Values represent the average of the limited foresight solutions in group

storage constraints in the current period because of inadequate carryover storage from the previous period. As shown for a few examples in Figure 18, the total debug volume to these reservoirs strongly correlates with the P_{max} and P_{min} of the LF solution. Each reservoir's debug

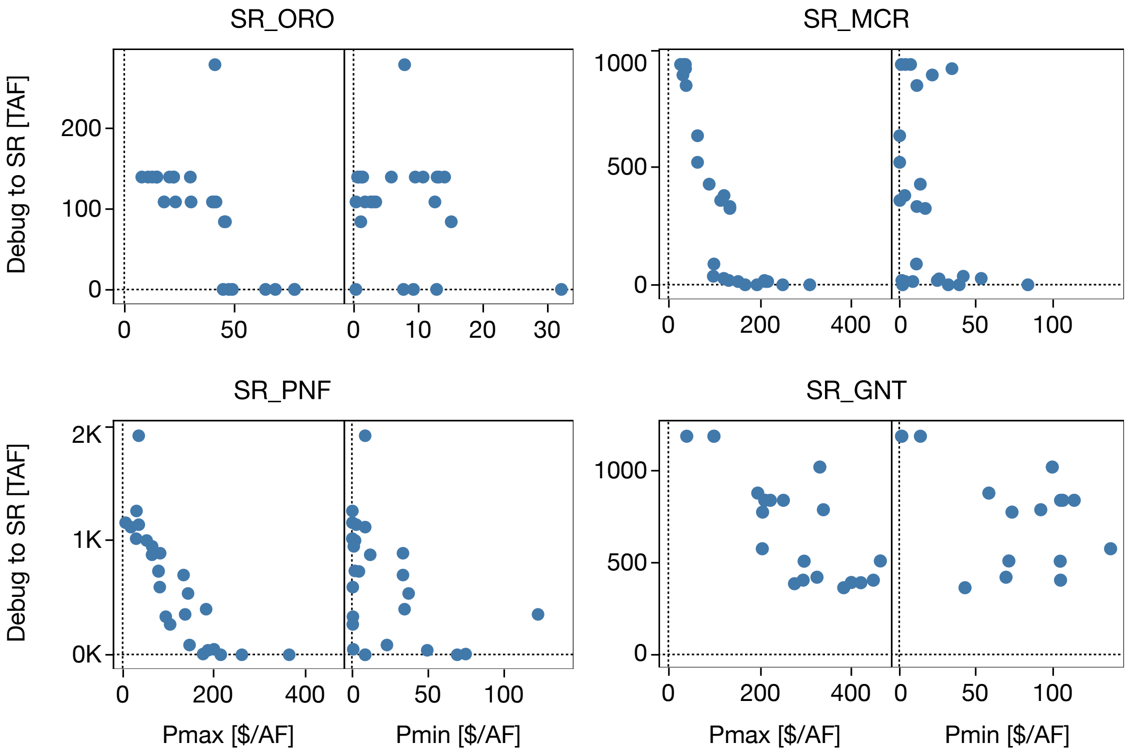


Figure 18. Total Debug Volume to Oroville (SR_ORO) McClure (SR_MCR), Pine Flat (SR_PNF) and Grant (SR_GNT) Reservoirs as a Function of P_{min} and P_{max}

volume, apart from Grant, is fully eliminated after reaching a defined P_{max} level (e.g., ~$50/AF for SR_ORO, ~$110 for SR_MCR, ~$195 for SR_PNF). Grant reservoir does not reach full debug elimination likely because a very high P_{avg} would be necessary to operate carryover storage with hedging extreme enough to forgo downstream hydropower benefits. Although not shown here, other debug source volumes in Table 16 (e.g., C35, C53, and C58 stream depletion constraints) also correlate strongly with the P_{max} of their respective upstream reservoirs.

There are several options to further refine limited foresight CALVIN with quadratic COSVF based on the observed debug volume behavior. One option might be to conduct a second iteration of the full evolutionary search with lower bounds on P_{max} (per reservoir) found from the first evolutionary search as above. Another would be to manually fine-tune solutions found in the first evolutionary search. Yet another might be to penalize the total debug flow volume of a solution as part of the evolutionary search itself. Whatever option is taken, the general insights of limited foresight CALVIN found in this study would not be significantly affected given the trivial amount of debug water relative to volumes flowing annually through the system.

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