Title

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Journal
JAWRA Journal of the American Water Resources Association, 55(3)

ISSN
1093-474X

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Publication Date
2019-06-01

DOI
10.1111/1752-1688.12745

JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION

AMERICAN WATER RESOURCES ASSOCIATION

Does More Storage Give California More Water?

D.M. Nover, M.S. Dogan, R. Ragatz, L. Booth, J. Medellín-Azuara, J.R. Lund, and J.H. Viers

Research Impact Statement: Under baseline conditions, expanding storage provides benefits in some northern California locations. In a warm-dry climate, benefits from expanding storage in southern California are negligible.

ABSTRACT: Increasing reservoir storage is commonly proposed to mitigate increasing water demand and provide drought reserves, especially in semiarid regions such as California. This paper examines the value of expanding surface reservoir capacity in California using hydroeconomic modeling for historical conditions, a future warm-dry climate, and California's recently adopted policy to end groundwater overdraft. Results show expanding surface storage capacity rarely provides sizable economic value in most of California. On average, expanding facilities north of California's Delta provides some benefit in 92% of 82 years modeled under historical conditions and in 61% of years modeled in a warm-dry climate. South of California's Delta, expanding storage capacity provides no benefits in 14% of years modeled under historical conditions and 99% of years modeled with a warm-dry climate. Results vary across facilities between and within regions. The limited benefit of surface storage capacity expansion to statewide water supply should be considered in planning California's water infrastructure.

(KEYWORDS: climate variability/change; water resources economics; water supply; planning.)

INTRODUCTION

California's statewide water system helps rebalance the state's spatial and temporal mismatch in water supplies and demands, with more water available in northern and mountainous parts of the state during winter and concentrated human water demands in the central and southern parts of the state during the summer. Practically speaking, these geographic and climatic differences are most pronounced between areas North of the Sacramento–San Joaquin Delta and South of the Sacramento–San Joaquin Delta (hereafter referred to as NOD and SOD — see Figure 1) (Luoma et al. 2015). As cities and agriculture developed farther from water sources and into drier and more distant regions, storage and conveyance facilities were built to facilitate water distribution and management. The mismatch in time and space between water supply and demand is central to the design and operation of California's water infrastructure and vulnerabilities in the system reflect current stresses related to population growth, changing land-use patterns, and climate change (Hanak 2011). Contemporary water management in the state depends not only on vast infrastructure but also on complex legal frameworks, management strategies at various spatial and temporal scales and, increasingly, water accounting to address growing system stress due to increasing demands and increasing scarcity (Hanak et al. 2009; Hanak 2011).

Water transfers, which move water from regions of supply to regions of demand, are limited by the capacity in aqueducts and pumps in the Sacramento–

Paper No. JAWRA-18-0064-P of the *Journal of the American Water Resources Association* (JAWRA). Received April 12, 2018; accepted March 1, 2019. **Discussions are open until six months from issue publication**.

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Citation: Nover, D.M., M.S. Dogan, R. Ragatz, L. Booth, J. Medellín-Azuara, J.R. Lund, and J.H. Viers. 2019. "Does More Storage Give California More Water?" *Journal of the American Water Resources Association* 1–13. https://doi.org/10.1111/1752-1688.12745.

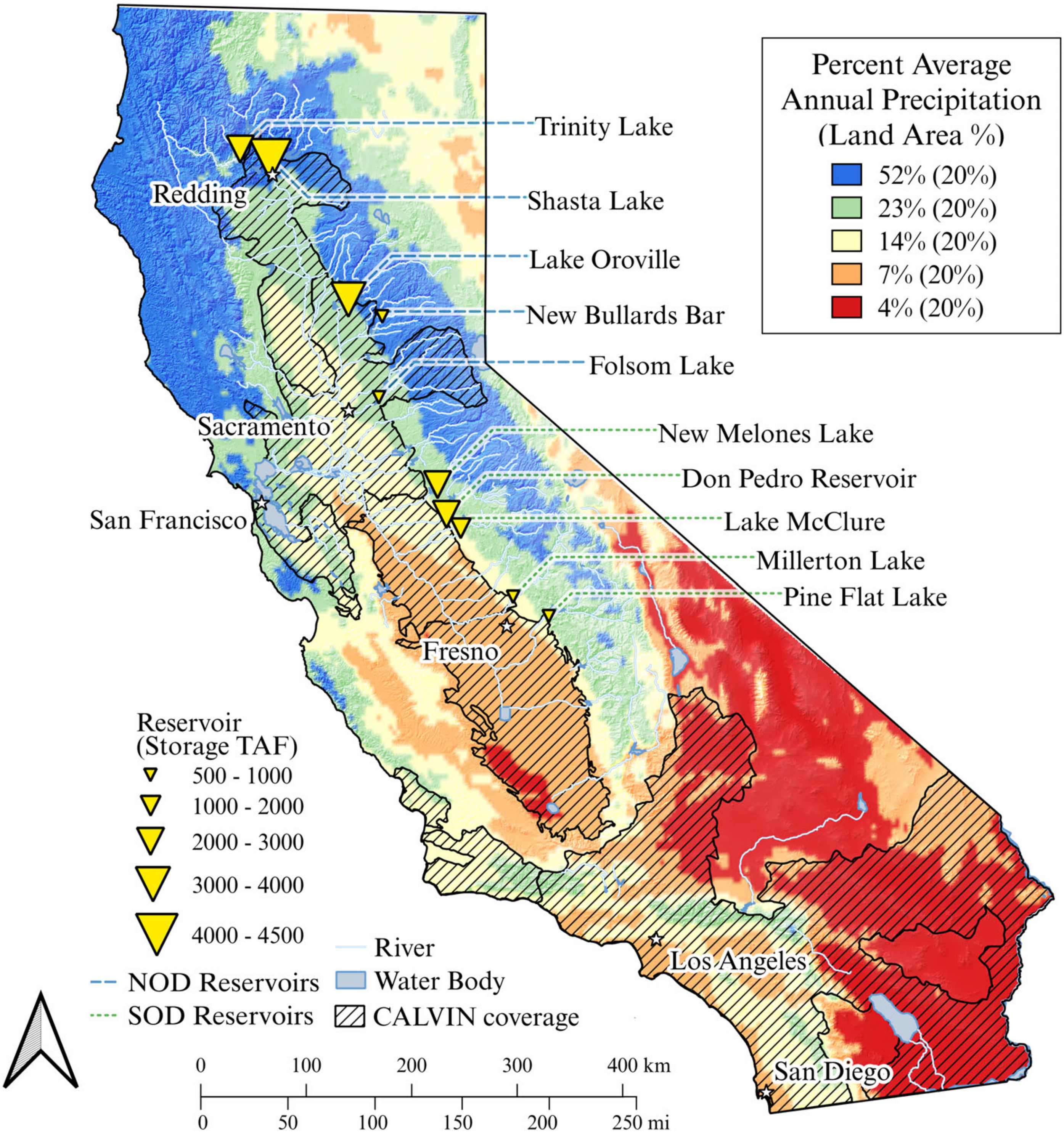

FIGURE 1. Precipitation distribution in California with major conveyance and reservoirs included in this study's analysis of California's water management infrastructure. Shading shows quintiles of land area per fraction of average annual precipitation. Location and size of reservoirs considered in this study are indicated with yellow triangles. Black dots show California Value Integrated Network (CALVIN) coverage in the state. NOD, North of Delta; SOD, South of Delta.

San Joaquin Delta and elsewhere, as well as legal constraints on water rights and environmental protection. California's 40 million acre-feet of surface storage includes an elaborate statewide network of reservoirs, conveyance structures, pumps, and related infrastructure (Figure 1). This system was designed based on historical hydrology and has performed reliably in historical extreme events, although growing populations and agricultural demands, exacerbated by extreme droughts and floods, are testing the system (Lund et al. 2018). The 12-year period from 2006 to 2017 included three designated wet years — including one of the wettest on historical record (2017) following one of the driest periods (2012–2016). Recent water stress has increased interest in expanding surface storage capacity in the public consciousness, among farmers and the business community, and at the level of county and state government (Forgie and Salzman 2017; Lund 2018).

Water management problems and solutions in California have long been studied extensively. For example, the United States (U.S.) Bureau of Reclamation specifically examined the potential for enlargement of Shasta, Pine Flat, and Friant dams, and building Temperance Flat and Sites reservoirs (USBR 2007) to meet present and future water demand. However, costs for expanding surface storage are high. The cost of expansion, annualized per acre foot of storage capacity, at Temperance Flat is approximately $633 and the cost of expanding Sites reservoir might cost over $482 (calculated based on data obtained from the California Water Commission — Water Storage Investment Program — https://www.wildlife.ca.gov/Conservation/Watersheds/WSIP).

Research also has examined likely climate change impacts on water availability in California (Lettenmaier and Sheer 1991; Barnett et al. 2005; Schlenker et al. 2007; Mann and Gleick 2015). Although projections differ in the timing and magnitude of climate change impacts on California's water, all agree that warming will shift runoff from spring snowmelt to rainfed runoff in winter, a pattern already observable in recent history (Roos 1991; Tanaka et al. 2006; Mirchi et al. 2013). Recent analyses have suggested that pronounced wet and prolonged dry periods will become more frequent (Swain et al. 2018). Connell-Buck et al. (2011) showed a warm-dry form of climate change reducing surface water inflows (rim inflows) by roughly 26%, groundwater inflows by 10%, and increasing surface reservoir evaporation by 37% statewide. Such climatic changes will have cascading effects on California's hydrology and the state's ability to store surface runoff and will affect the value of storage capacity expansion on regional and statewide water management.

The climate change research community has focused on the idea of nonstationarity — that historical water resources planning depended on static temperature and precipitation patterns that are now changing (Milly et al. 2008). This shift has been observed globally, in many different regional contexts, and in California (Dettinger et al. 2016). In California, historical data have provided the guiding information used to plan for future water resource needs. However, contemporary and likely future changes in California's climate complicate discussions of water management as observed conditions are increasingly divergent from historical patterns of rainfall, temperature, drought, and flood frequency and severity (Diffenbaugh et al. 2015). Effective contemporary approaches to water resources management might be more or less useful in the future conditions — for example, expanding storage now might be beneficial under current hydroclimatic conditions, but less useful if rainfall declines dramatically or more useful as seasonal inflows shift from snow dominant to rain dominant in the Sierra Nevada (Anderson et al. 2008; Schwarz et al. 2018).

California recently adopted the Sustainable Groundwater Management Act (SGMA), a policy that aims to regulate groundwater, empower local agencies for sustainable management, and eliminate overdraft and adverse effects of overdraft, such as land subsidence, increased pumping cost, degraded water quality, seawater intrusion, and reduced streamflow if hydraulically connected to underlying aquifers. Although California's overdraft occurs mostly in its Central Valley (DWR 2016), eliminating groundwater overdraft is expected to have statewide effects (Nelson et al. 2016). Scanlon et al. (2012) showed that more surface water deliveries can reduce groundwater overdraft and expanding storage might help resolve temporal disconnection between supply and demand. Nelson et al. (2016) and Escriva-Bou et al. (2017) have concluded that ending groundwater overdraft requires reducing net water use or increasing surface water imports. Modeling of this policy, and its implications for storage, is discussed in the Methods section below.

Engineers have been working to understand the relationship between inflow and storage for single and multiple reservoir systems beginning with the pioneering work of Hazen (1914), and better data and more sophisticated modeling now allow for the elaboration of earlier work to more complicated settings with more available data specific to California (see, among many, Yeh 1985; Wurbs 1993; Draper et al. 2003). This paper uses a hydroeconomic optimization model to improve our understanding of the value of storage expansion, similar to other studies (e.g., Maas et al. 2017), but extend this work to include institutional constraints and hydroclimatic conditions that may influence future infrastructure planning. We examine whether adding storage to California's water supply system is likely to alleviate stress in California's water system and at what cost, under "current" climate conditions and a projected warmer, drier climate, and "no overdraft" policy that SGMA implements.

METHODS

Model Description

The California Value Integrated Network, or CALVIN, is a network flow-based economic-engineering optimization model of California's water system (Draper et al. 2003; Dogan et al. 2018). CALVIN suggests surface water and groundwater operations and allocations that minimize water scarcity and operating costs across California. CALVIN represents 90% of the state's urban and agricultural water demands and about two-thirds of all California's runoff (Figure 1). CALVIN allocates available water to the most economically valued uses at the lowest operating cost, considering environmental requirements and infrastructure capacities. In CALVIN, environmental demands do not have an economic representation and so their dedicated deliveries are constrained to be made before any other water deliveries. In addition to operating groundwater and surface water conjunctively, CALVIN uses alternative water supply options, such as desalinated, potable, and non-potable recycled water, and water conservation where and when warranted by economic demands, costs, and water availability.

Historical Case

CALVIN uses observed monthly historical hydrology (1921–2003) to represent hydrologic variability across space and time. Since CALVIN foresees what happens in all 82 years of hydrology, the model anticipates droughts and floods before they happen, creating somewhat optimistic hedging outcomes (Draper et al. 2003). Nevertheless, results from CALVIN are useful in indicating when and where costs occur due to water scarcity or limited infrastructure availability. CALVIN has been used to study California water managements in many ways, looking, for example, at economic and supply effects of different Delta water export levels (Tanaka et al. 2011) and the effects of climate change on California's water resources (Tanaka et al. 2006; Medellín-Azuara et al. 2008; Connell 2009; Harou et al. 2010; Connell-Buck et al. 2011).

No Overdraft Case

CALVIN uses fixed groundwater recharge values and coefficients from C2VSim model (Dogrul et al. 2016) and optimizes groundwater pumping. The "no overdraft" case presented here eliminates long-term groundwater overdraft from the Central Valley aquifer by limiting groundwater supply. Groundwater basins are still subject to short-term overdraft, however, which can help alleviate drought effects. In our base historical and climate change cases, the Central Valley aquifer has a cumulative historical overdraft of 84 million acre-feet (MAF) over the 82-year period (1921–2003). The no overdraft case is modeled with historical hydrology but without the 84 MAF of overdraft, bringing ending groundwater levels back to initial conditions by changing operations. Reduced groundwater withdrawal increases water shortages in this case and accounts for modest reduction in surface storage compared to historical conditions (see Figure 4). However, contemporary rates of groundwater overdraft are approximately double this modeled historical rate in the San Joaquin Valley and Tulare Lake Basin at two MAF annually (Hanak et al. 2017; Escriva-Bou et al. 2017), so this modeled case is conservative.

Climate Change Case

The warm-dry climate case employed here is derived from a downscaled version of the GFDL A2 CM2.1 used by Maurer et al. (2010) in the California Energy Commission's Climate Change Assessment 2008 study. This warmer, drier climate has 26% less average annual runoff, 10% less groundwater inflow, and increased surface reservoir evaporation by 37% statewide (Tanaka et al. 2008, 2011; Connell-Buck et al. 2011). Although the climate change case reported here is somewhat dated, it has modest warming compared to more recent climate simulations. Recent research has reached consensus that future climate in California will be warmer, although projections diverge in terms of future precipitation timing, intensity, distribution, and total amount (Swain et al. 2018). Despite these differences, even if total precipitation volumes remain at historical levels, frequency of extended drought periods are expected to increase (Diffenbaugh et al. 2015; Swain et al. 2018). This exercise is not intended to "accurately" project California's water operations under climate change, but rather to take a fixed change in temperature and precipitation and perturb historical modeled data to explore how that impacts reservoir storage, scarcity, and system costs. The warm-dry case employed effectively adds about a 30% scarcity, similar to the scarcity experienced in California's recent drought (Lund et al. 2018). In the end, optimal use only matters when demand exceeds supply, so insights from this case are intended to provide insights to system behavior under reasonable assumptions of substantial scarcity.

Figure 2 shows the basic operation of CALVIN, which includes a mass balance for each major water sources and sinks in California and includes supplies, demands, and seasonal flood operating capacities of reservoirs. All economic and cost values reported here are indexed to 2008 dollars for ease of comparison. All projections hold development constant at projected 2050 levels. With flows and storage as decision variables, CALVIN minimizes cost of water allocation (Equation 1), subject to three constraints: upper bound, lower bound, and mass balance (Equations 2–4). CALVIN is an application of simplified linear programming, so each constraint produces a time-series of dual marginal values (Lagrange multipliers) for each constraint location, indicating the rough economic value of incremental loosening or tightening of that constraint at each time-step. Where additional storage would improve the state's ability to manage water supply, the model outputs a negative marginal value for that constraint. Since CALVIN's objective is to minimize total operating and scarcity costs, negative marginal values indicate benefits (negative cost = benefit). We report all marginal values as positive economic benefits. When storage constraints are never limiting (i.e., there is sufficient storage), CALVIN shows "zero" marginal value of storage capacity, meaning those constraints are nonbinding. When there is so little water that reservoir dead pool has value, the model outputs a positive marginal value of water (the economic value of adding a pump to access the dead pool). Also, some reservoirs, such as Shasta, have mandated minimum environmental storage requirements, although cold water pool benefit of storage only matters if the reservoir is full as a nearly empty reservoir contains only warm water. In this case, the lower bound constraint (Equation 3) is minimum storage requirement rather than dead pool constraint. In our analysis, we only consider negative values, or instances where there is some economic benefit to adding surface storage to the system, as both "zero" and positive marginal values reflect conditions when there is literally no benefit to adding storage.

The objective function:

$$\min z = \Sigma_i \Sigma_j \Sigma_k c_{ijk} X_{ijk} \tag{1}$$

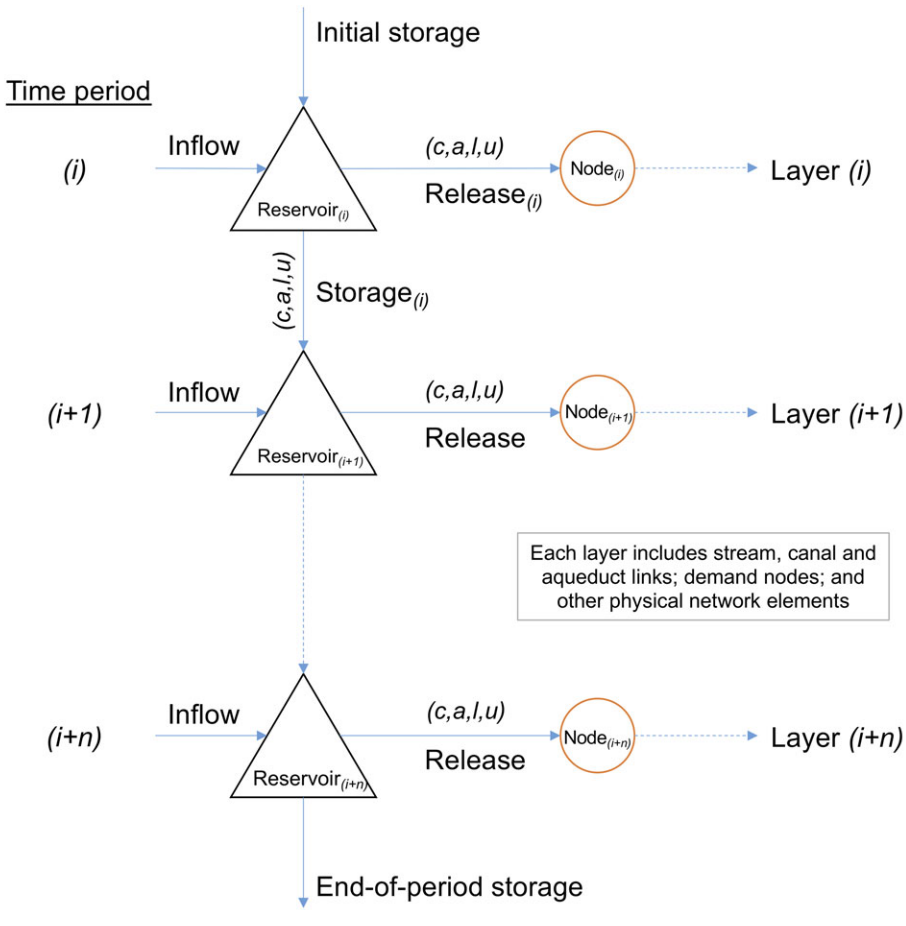

FIGURE 2. Schematic showing theoretical treatment of flows and storage in CALVIN.

TABLE 1. Attributes and summary results of selected reservoirs.

Selected reservoirs ordered from NOD to SOD						82-Year average of maximum annual marginal value of storage capacity ($/AF-year)		
Facility location and ID		Facility name (basin)	Owner	Capacity (TAF, km^3)	Year built	Historic	No overdraft	Climate change
NOD	CLE	Trinity (Trinity)	USBOR	2,448 (3.02)	1963	6.76	7.59	98.03
	SHA	Shasta (Sacramento)	USBOR	4,552 (5.62)	1945	10.25	11.07	110.53
	ORO	Oroville (Feather)	CADWR	3,538 (4.36)	1961	15.30	16.69	82.23
	BUL	New Bullards Bar (Yuba)	YCWA	970 (1.20)	1970	16.18	17.37	174.99
	FOL	Folsom (American)	USACE	976 (1.20)	1956	13.15	14.71	201.16
SOD	NML	New Melones (Stanislaus)	USBOR	2,400 (3.00)	1979	10.79	10.46	0.02
	DNP	New Don Pedro (Tuolumne)	Modesto ID/Turlock ID	2,030 (2.50)	1971	9.08	8.86	0.06
	MCR	McClure (Merced)	Merced ID	1,032 (1.27)	1967	7.67	8.28	0
	MIL	Millerton (San Joaquin)	USBOR	521 (0.64)	1942	20.14	19.52	0
	PNF	Pine Flat (Kings)	USACE	1,000 (1.20)	1954	1.42	2.94	0

CADWR, California Department of Water Resources; TAF, thousands of acre-feet; USACE, U.S. Army Corps of Engineers; USBOR, U.S. Bureau of Reclamation; YCWA, Yuba County Water Agency.
Notes: Results reflect the 82-year averages of the largest monthly marginal value of additional storage capacity in each year ($/AF, in 2008 dollars).

subject to

$$X_{ijk} \leq u_{ijk} \quad (2)$$

$$X_{ijk} \geq l_{ijk} \quad (3)$$

$$X_{jik} = \Sigma_i \Sigma_k a_{ijk} X_{ijk}, \quad (4)$$

where X is flow (decision variable); c is unit cost; a is amplitude or loss factor; u is the upper bound; and l is the lower bound. The physical system is represented by a set of network nodes, such as reservoirs, plants, and demand locations, and network links, such as rivers, canals, and pipelines. Links are defined by (i, j, k), where i is origin node, j is terminal node, and k represents a piecewise linear component. Equation (1) is summation of total cost over all links in time and space. Equations (2–4) enforce the upper bound, lower bound, and mass balance constraints, respectively. CALVIN employs freely available state-of-the-art solvers to solve its network flow problem. Dogan et al. (2018) provide a discussion of performances of different solvers and runtime.

RESULTS AND DISCUSSION

Model Output

A principal insight from CALVIN results is that NOD and SOD reservoirs show differences in operations and their potential to provide economic benefits from storage expansion both in baseline conditions and, more dramatically, with climate change. We focus on a select group of reservoirs as a broad subsample of reservoirs from NOD and SOD locations and avoid focusing on any single reservoir that might be unique in local hydrology or operations. Our discussion includes NOD basins at Trinity, Sacramento, Feather, Yuba, and American, and SOD basins of Stanislaus, Tuolumne, Merced, San Joaquin, and Kings (Table 1 lists basins, associated reservoirs considered in this study and their characteristics). Below we present CALVIN output from Shasta reservoir as an example of CALVIN results for an individual reservoir (Figure 3). Model output for the other nine facilities is not presented in entirety, but rather in summary statistics for brevity and clarity. Results summarize data for these 10 reservoirs.

Model Output — Shasta Reservoir Example

Figure 3 shows that storage varies in Shasta monthly and seasonally, as might be expected (red line). Similarly, the marginal value of expanding storage capacity varies monthly (dashed blue line). When a reservoir is full, a large marginal value denotes conditions under which the storage constraint is limiting and in which expanding storage capacity has a positive economic benefit. We report model output as positive economic benefit ($). In the case of all facilities, and in the Shasta results, the marginal value of expanding storage capacity is zero in most months;

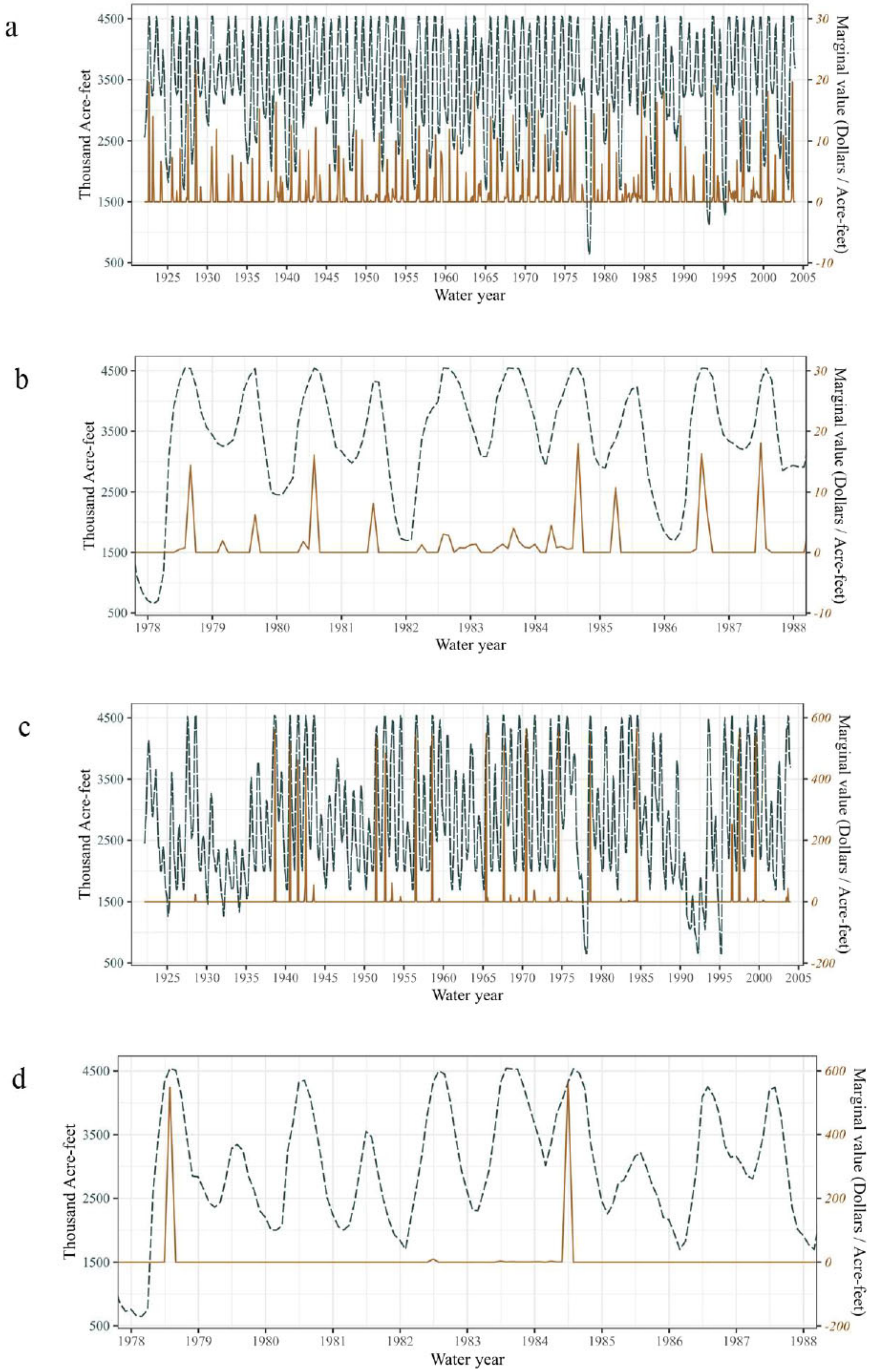

FIGURE 3. Monthly reservoir storage (primary y axis) and marginal value of expanding storage capacity for Shasta (secondary y axis) for the modeled period and for ~10 years. Panel (a) shows modeled output for Shasta under historical climate conditions and panel (b) shows the same for a 10-year subperiod. Panel (c) shows modeled output for Shasta under climate change conditions for the full data record and panel (d) shows the same for a 10-year subperiod.

whenever the storage capacity is not filled, the storage capacity constraint does not limit operations, so there is no value in expanding storage capacity in that specific month. There also are times when the marginal value of expanding storage capacity is positive, indicating there is so little water in the reservoir that managers would pay to relax the minimum storage constraint (to access dead pool storage or reduce a minimum environmental storage constraint). To summarize results for Shasta, some economic benefits for expanding storage (i.e., positive economic benefit for expanding storage capacity) occur in 100% of years modeled under historic conditions, 99% of years modeled with "no overdraft," and 40% of years modeled in a warmer and drier climate. Although some benefit would be seen in these years, it is worth noting that in years where the state would benefit by expanding storage at Shasta, the economic benefit is often extremely small (see Figure 6). In remaining years (0% in historical conditions, 1% under the "no overdraft" policy, and 60% in the climate change scenario), there is zero economic benefit to expanding storage.

Figure 4 shows boxplots of the distribution of storage in select facilities monthly over the entire modeled period for the three cases (historical, no overdraft, and climate change). The selected reservoirs NOD are generally larger and receive more runoff than those SOD, so the NOD facilities are more valuable than the SOD facilities under baseline (historical) conditions. The no overdraft policy leads to a slight reduction in storage as removing 84 MAF of pumped water over the full model period increases demand for surface storage. The reduction in surface storage from this policy is modest relative to the effect of climate change, suggesting the possibility that California might continue to meet its allocation needs and eliminate groundwater overdraft simultaneously. However, warm-dry climate change conditions induced scarcity and reduced storage significantly in all facilities. The reduction in storage SOD with climate change is much more severe than the reduction in storage NOD, compounding the importance of the NOD facilities, already prominent in safeguarding California's overall water supply. Expanding storage can only have value in months when water is limited by water storage capacity. This finding has important implications both for the value of existing storage and for the potential value of expanding reservoir storage capacity in California.

Figure 5 summarizes results from CALVIN showing cumulative distribution functions (CDFs) of annual maximum (monthly) marginal economic value ($) for adding one unit of storage capacity (acre-feet) over the entire 82-year period (NOD facilities on the left and SOD facilities on the right). The CDFs show the distribution of the maximum monthly positive economic benefit from expanding storage in a given year for all 82 modeled years for each scenario (82 values per facility per scenario). The CDFs are useful to understand the central points of this manuscript: (1) there are marked differences between the facilities

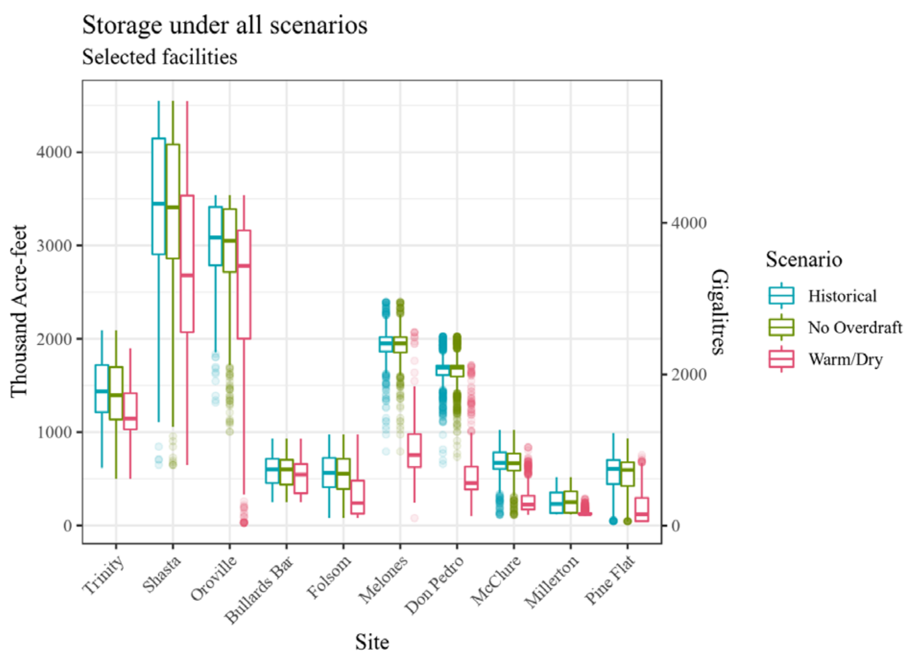

FIGURE 4. Boxplots show modeled monthly water storage in TAF in selected facilities with historical, no overdraft, and climate change conditions, arranged from north (left) to south (right) over the 82-year period.

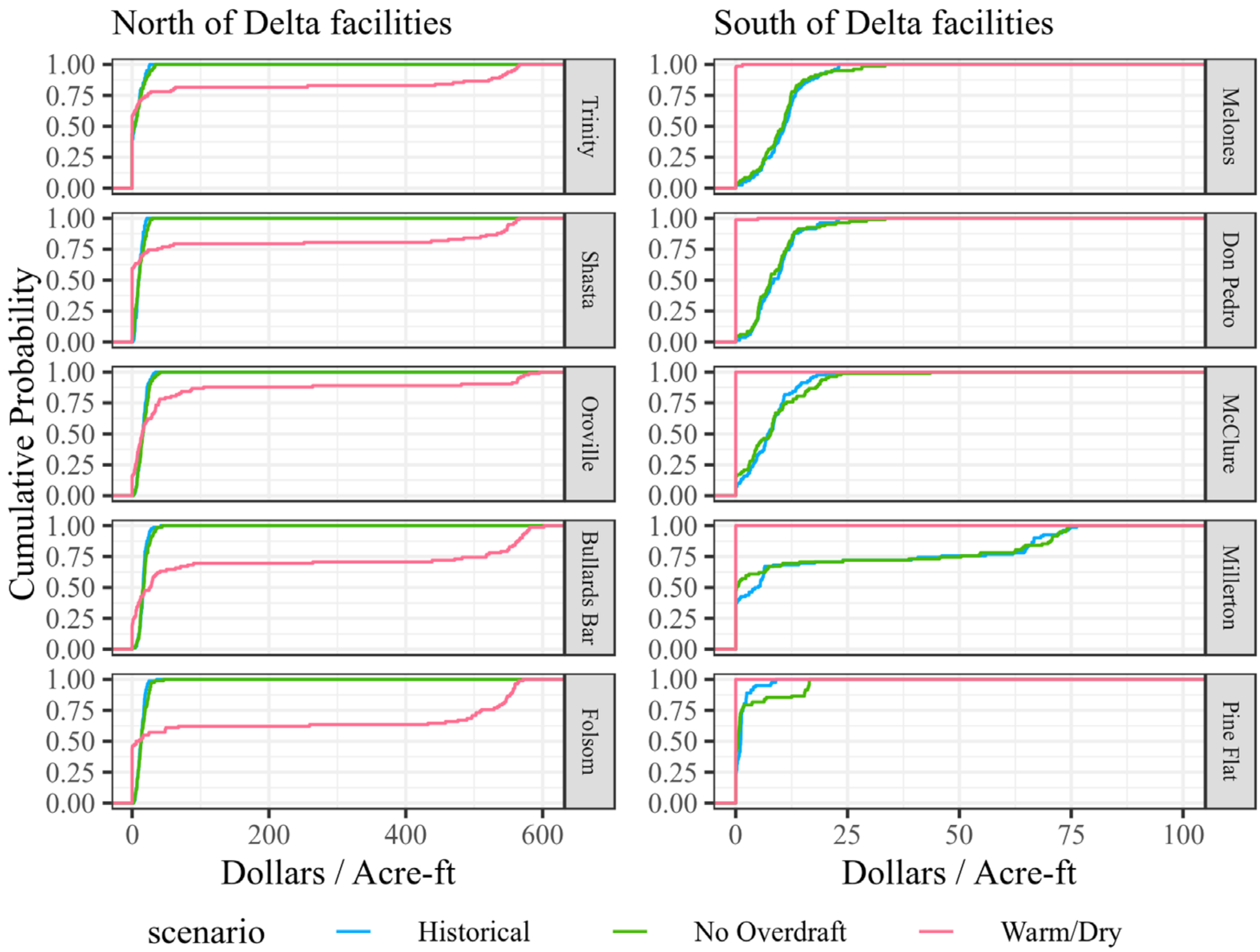

FIGURE 5. Cumulative distribution functions of annual maximum (monthly) marginal economic value ($) for adding one unit of storage capacity (acre-feet) over the entire 82-year simulation period arranged north (left) to south (right) under three scenarios. Note different x-axis maxima.

NOD and SOD in terms of the frequency and magnitude of storage expansion benefits. The NOD facilities are, overall, more valuable for storage and the value is experienced more frequently in the modeled period than in the SOD (not difference in x-axis scale); (2) stopping overdraft in the "no overdraft" scenario has a detectable but small impact on the benefit of storage expansion, particularly when compared to a warmer-drier climate, suggesting that current concern over the recently enacted SGMA may be overstated; and (3) under climate change, the value of expanding storage system-wide, but especially SOD, ranges from small to zero.

There are instances of benefits from expanded storage in some months in all facilities under historical conditions, both NOD and SOD. CALVIN output indicates that the economic benefit of storage expansion in these months is extremely small, generally below $10/acre-ft-year (with notable exceptions during intermittent extreme rainfall events — see Figure 6 below) — so any actual benefit of storage expansion would need to be weighed against the feasibility and cost of expanding storage in any of these locations, an exercise that is beyond the scope of this paper. The "no overdraft" policy and a warmer-drier climate increase the value of adding storage in most NOD facilities, except for Trinity (CLE), where value of storage expansion decreases slightly. SOD, although the "no overdraft" policy does not substantively differ from historical conditions, there is generally little or no value in expanding storage under the climate change conditions. Overall, these results point to very limited value in expanding storage in California, particularly SOD with a warmer, drier climate.

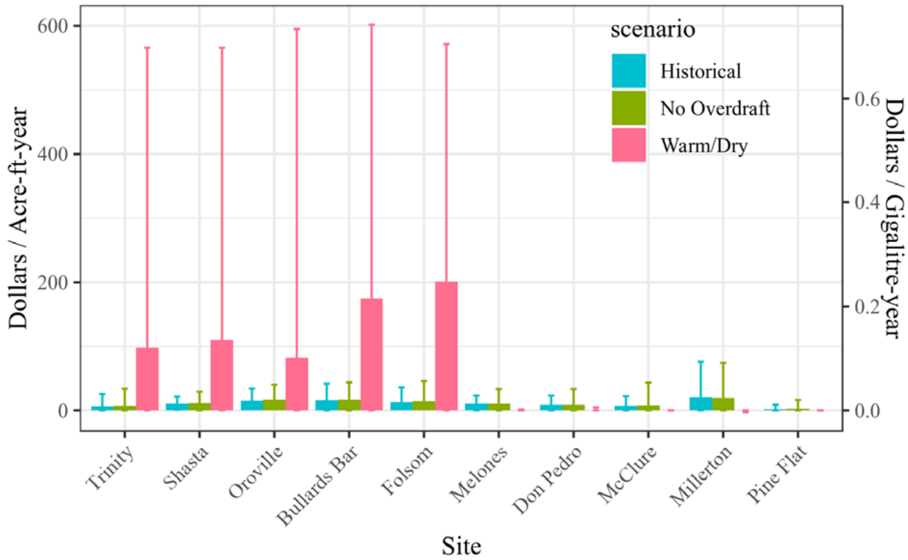

FIGURE 6. Bars show 82-year averages of the largest monthly economic benefit for expanding storage for each year in the modeled period for selected facilities from north (left) to south (right). Whiskers show value range.

To get a better sense of the value that might be achieved by expanding storage in each facility, since reservoirs in California for water supply usually do not refill more than once per year, the largest marginal value for each of the 82 modeled years is a more relevant indicator of the annual value of expanded water storage capacity. Figure 6 shows the 82-year average of the largest monthly benefit for each year in expanding storage. There is little economic benefit to expanding storage under current climate conditions for any of the facilities. With a drier climate, the economic benefit to expanding storage in NOD reservoirs grows substantially, but there is nearly no benefit to expanding storage SOD. There are several reasons for this. First, runoff already limit SOD storage in most years, and, with climate change, precipitation is expected to remain the same or decline and drought periods are expected to increase (Diffenbaugh et al. 2015; Swain et al. 2018). This means that the frequency when increased storage capacity could provide an economic benefit to the system will decline. Even under current conditions, storage capacity is rarely limiting SOD. In NOD, the same is true in most months. However, there are occasional, severely wet periods, like the winter of 2016–2017, that resulted in enormous precipitation statewide. These anomalous occurrences are expected under future conditions with nonuniformity in water year distributions (Null and Viers 2013). During these rare wet water years, having more storage capacity provides a large, but infrequent benefit following the wet event, although given current limitations in the ratio of annual flow to reservoir volume in select facilities, feasibility and extent of possible storage expansion must be considered. In short, high demand for scarce water coupled with increased hydrologic variability (i.e., precipitation extremes) means that there are infrequently times where expanding storage would yield large economic benefits.

Table 2 summarizes the results of all runs for all facilities by tabulating the percent of months having no value for expanding storage. Although there are months in all cases and in all facilities where there is some economic benefit to expanding storage, the vast majority of those instances are very small values (see Figure 6). Meanwhile, most months modeled show no value to storage expansion, as the reservoirs are rarely full — for both NOD and SOD locations — although in the NOD facilities with a drier climate, there are regularly months in which having more storage would provide a (small) economic benefit and in the SOD, there are rarely years where the system sees any benefit from expanding storage (actually zero years in the full modeled period for three of five facilities).

MANAGEMENT IMPLICATIONS

Water management in California is complex. Integrated hydroeconomic models, such as CALVIN, use economic optimization to generate insights to complex system behavior. Such models can elucidate the economic benefit of expanded surface storage, which

TABLE 2. Summary of frequency of value to adding storage in select reservoir — percentages are the fraction of years during the 82-year modeled period in which there was no value to the statewide water system by increasing storage in the selected facility.

Reservoirs considered in this study ordered from NOD to SOD		Percent (%) of years in 82-year simulation with no month exhibiting any storage expansion benefit		
Location	**Facility name**	**Historical**	**No overdraft**	**Warm-dry**
NOD	Trinity	39	44	59
	Shasta	0	1	60
	Oroville	0	0	16
	New Bullards Bar	1	1	18
	Folsom	0	0	44
SOD	New Melones	2	4	98
	New Don Pedro	1	4	99
	McClure	7	16	100
	Millerton	37	48	100
	Pine Flat	22	40	100

varies in time and space but often appears to have small value. However, CALVIN is somewhat optimistic for value of water storage for water supply because of many model assumptions, including perfect foresight (as described above), but does not include water quality, emergency supply, flood safety, and other potentially sizable values. Actual management of California's water must address concerns absent from the model, including politics, a complex system of water rights, nonideal water markets, and imperfect foresight. There are other reasons why reservoirs might be built or expanded, including flood protection and water quality improvement, storage for emergency outages, such as earthquakes, contaminant spills, and mechanical failures, although the potential benefits for flood control track the same pattern reported here for storage expansion in that flood control benefits occur infrequently during extreme storms, a pattern that will only increase as the climate changes. Water quality improvements, such as cold pool storage, may be another benefit of reservoir expansion, but our goal was to examine the benefits of expanding storage for water allocation as this is generally the motivating factor behind current proposals to expand surface storage facilities. We also do not consider the feasibility of expansion or the cost of expansion, which is often the critical factor in infrastructure investment decision making.

We focus on storage as a topical issue in California water management, but it would be possible to similarly focus on other infrastructure separately, as well as their interactions. For example, a major constraint in California's water availability is the pumping capacity in the Delta, which is used to move water from north to south. Even if more water was available NOD, if pumping demand exceeded pump capacity, much of this water could not become available SOD without expansion of pump capacity. The current version of CALVIN uses allowable capacities for Delta exports, water transfers from the Banks and Tracy pumping plants via the California Aqueduct and the Delta-Mendota Canal, respectively. Allowable capacity in CALVIN was gleaned from the California Department of Water Resources CALSIM II model (Draper et al. 2004) and thus lower than physical pumping capacity, due to fish, environmental, and salinity requirements. These constraints are described in more detail by others (Draper et al. 2003; Tanaka et al. 2006, 2011; Medellín-Azuara et al. 2008; Connell 2009; Harou et al. 2010; Connell-Buck et al. 2011).

CONCLUSIONS

California's water infrastructure system is sufficiently developed such that additional storage capacity rarely has high economic value, and its economic benefit changes significantly with location, climatic conditions, and ability to overdraft groundwater. Although reservoir operators likely prefer more operating capacity, the benefits of additional capacity for water supply are generally small, and likely outweighed by expansion costs and/or feasibility. Results from a hydroeconomic optimization model offer insights into when additional reservoir capacity is economically valuable within California's complex and extensive water capture, storage, and conveyance system.

Additional water storage capacity is not generally of high value, although its economic value can be high at some times and in some facilities. With the current climate, economic values for expansion are typically higher in the north of the state, where more water is available, and in southern reservoirs with less storage capacity relative to annual inflows. Ending groundwater overdraft slightly increases the value of reservoir expansion, primarily to aid in increasing Delta exports, although results here suggest that any difference from historical water supply value is modest. In other words, newly imposed constraints to groundwater overdraft are not likely to impose starkly increased scarcity to California's water supply. With a drier climate, however, the number of years with zero economic benefit to storage expansion increases greatly, although in certain years, large precipitation events yield relatively large economic benefits in storage expansion, mainly NOD. However, SOD reservoirs rarely fill due to historically dry conditions, thus almost eliminating the economic benefit of expanding these reservoirs for an even drier climate.

Although this paper focuses on the use of hydroeconomic optimization to explore surface water reservoir expansion, this modeling approach also has value in examining potential expansions of other facilities, as well as the optimization of water management portfolios. In light of current climatic and water demand trends, it is increasingly clear that adding surface storage does not, in a very simple sense, create more water for Californians. In a more sophisticated sense, in the context of California's water management system, more surface storage will not generally improve management of California's water supply.

DATA AVAILABILITY

CALVIN reports and data are archived in the UC Davis Watershed Center webpage: https://watershed.ucdavis.edu/user/8/projects.

ACKNOWLEDGMENTS

This work was funded in part by the California Energy Commission (Award#300-15-004) Department of Energy U.S.-China CERC-WET program (Award#DE-1A0000018) and support from the University of California Office of the President's Multi-Campus Research Programs and Initiatives (MR-15-328473) through UC Water, the University of California Water Security and Sustainability Research Initiative. This work would not have been possible without the cooperation and guidance of many researchers from the UC Davis Center for Watershed Sciences.

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