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Surface Reservoir Reoperation for Managed Aquifer Recharge: Folsom Reservoir System

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Abstract: As is much of the world, California increasingly is challenged by water scarcity. A recent multiyear drought depleted surface reservoir and groundwater storage in many places of the state. The Sustainable Groundwater Management Act (SGMA), passed in 2014, promises sustainable groundwater management in California and suggests managed aquifer recharge (MAR) as one of the key practices to eliminate groundwater overdraft by groundwater sustainability agencies. Questions remain, however, about the amount of water available for MAR. Conjunctive management provides the opportunity to modify reservoir operations and enhance recharge long before any drought occurs. However, the amount by which reoperation of surface reservoirs can increase the available water for MAR has not been thoroughly investigated. Folsom reservoir is operated to meet a variety of objectives, including flood control, water supply, hydropower, and environmental flow. The inclusion of water discharge for groundwater recharge adds another objective for the operation of the reservoir and complicates the decision-making. Various management strategies were developed and applied to evaluate performance of the system during a historical period, and a new objective was added to maximize the available water for recharge from Folsom reservoir. Although the reoperation strategy offers additional storage in the system and increases the expected value of recharge from 280 to 430 million cubic meter (mcm) per year, trade-offs between different objectives showed that new operating rules perform quite satisfactorily, with nonsignificant deficits and violations of old objectives. **DOI: 10.1061/(ASCE)WR.1943-5452.0001305.**

Introduction

The periodicity of wet and dry years shows the need for new management strategies in California. Excess water during peak flows is released from surface reservoirs to reduce the risk of flooding. Although high peak flows cannot be captured in surface reservoirs, groundwater appears to be a great potential storage to keep water within the system for a longer period. Groundwater depletion in California's Central Valley aquifer system alone has made room for more than 170 km^3 of storage capacity for further groundwater recharge, which amounts to more than 3 times the surface reservoir capacity of the entire state (Dahlke et al. 2018; TNC 2016). In theory, excess water can be stored underground through managed aquifer recharge (MAR) practices during wet periods and recovered during droughts. In the southwestern US, the El Nino Southern Oscillation (ENSO) increases the intensity of wet and dry periods, which can increase the recharge as much as three times more than in La Nina years and offers a great source of water for MAR (Hanson et al. 2004; Scanlon et al. 2006). However, importantly, most water systems were designed and developed and are operated based on the assumption of stationarity (Milly et al. 2008). For instance, the hydroelectric facilities of Folsom Reservoir in California were designed in the mid-1950s based on historical flow patterns. Similarly, most of California's major reservoir were built during 1950–1970, but the hydroclimate conditions have changed significantly in the state, and are anticipated to change in the future as well (Dettinger 2011).

The hydroclimate condition in the Central Valley can be characterized by the two seasons of wet and dry, wherein the majority of precipitation (90%) falls during November–April (Dettinger 2013; Gershunov et al. 2019). Owing to a higher rate of snowmelt in the Sierra Nevada Mountains in spring, peak flows historically are observed during the spring season. During this season, the reservoirs are refilled as much as possible, above the flood control zone, to store enough water for summer demand. Captured water then is released gradually during summer for hydropower generation, supplying irrigation and municipal demands, and other water demand sectors. Studies have confirmed the decreasing trend in spring runoff in the American River, especially after 1970 (Goharian et al. 2018b; Freeman 2002). Moreover, general circulation models (GCMs) project wetter and warmer conditions for this region (Yao and Georgakakos 2001), raising the risk of warm winter storms, including rain-on-snow events, and winter flood conditions resulting in pass-through of much of the runoff that formerly was stored in the snowpack (Gershunov et al. 2019). If the changes in timing and magnitude of snowmelt remain as they are observed and projected, the reduction in snowpack and increase in winter flows will result in less water stored in surface reservoirs, even if annual precipitation does not decrease (Knowles et al. 2006). These changes not only increase the potential severity and vulnerability of the reservoir system to flood, but also will cause a decrease in water system performance (Goharian et al. 2016a, 2017, 2018a). Under such circumstances, the only storage alternative to compensate for this loss

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Table 1. Charectristics of north, middle, and south forks of American River

River branch	Area [km^2 (mi^2)]	Stream length [km (mi)]	Origination	Hydroelectric plants
North fork	743 (287)	137 (85)	Eastern Placer County in Tahoe National Forest	—
Middle fork	808 (312)	105 (65)	Tahoe National Forest	5
South fork	2,201 (850)	145 (90)	High Sierra in El Dorado National Forest	11

and remediate the potential severity in reservoir will be groundwater storage facilitated by MAR and reoperation of reservoirs.

Conjunctive use is a similar concept to what it is proposed in this study. This practice focuses on storing surface water underground during wet years, and subsequently, in a relatively short period, withdrawing stored water when it is needed. Conjunctive use mainly suggests harmonious use and appropriate combination of water withdrawal from both surface water and groundwater to supply water demand. Multiple studies have explored the use of simulation-optimization models to schedule the conjunctive use of surface water and groundwater (e.g., Singh 2014; Safavi and Enteshari 2016; Wu et al. 2016; Zeng et al. 2017; Milan et al. 2018). As opposed to conjunctive use, whole management of a watershed's total water storage involves more than just alternatively using these resources. This study focused on how reoperation of surface reservoir systems supports integrated management of surface and groundwater stores, especially by storing high peak flows for dry years. This requires better understanding how much water is actually available for MAR, considering high peak flows, i.e., flood flows. Few studies have addressed the availability of surface water for MAR in the Central Valley of California (e.g., Dahlke and Kocis 2018; CADWR 2018; PPIC 2018). However, those studies focused on and identified the amount of available water at the large watershed scale and based on historical river flows and water allocation policies.

Gailey et al. (2019) and Maples et al. (2019) focused on the groundwater side of the storage problem and showed that the American–Cosumnes groundwater basin of California could accommodate an average of at least 333 million cubic meter per year (mcm/year) (270,000 acre-ft/year) of recharge through off-season flooding of agricultural lands and geologically strategic locations. This study explored the potential role of surface reservoir reoperation for increasing water availability for MAR in the American–Cosumnes Basin. Available water for recharge here is defined as excess water which potentially is available for recharge, after accounting for local water demand and required flow for the Sacramento–San Joaquin Delta (based on historical information), and after meeting minimum environmental flow requirements downstream.

This study examined possible reoperation strategies of the Folsom Reservoir for implementation of MAR in the American–Cosumnes Basin, California. We introduced a new surface reservoir model, FolSim, for the purpose of estimating potential benefits of reoperation in a MAR context.

Hydrologic Setting and Folsom Reservoir

The American River originates in the Sierra Nevada Mountains and drains a total area of 4,823 km^2 to its confluence with the Sacramento River. In the upper watershed, the American River is formed by three forks, the North, the Middle, and the South forks, where small dams and diversions have been developed for generating hydroelectricity, controlling peak flows, and maintaining baseflow in dry seasons (Table 1), including French Meadows, Hell Hole, Union Valley, Ice House, Lake Valley, Loon Lake, Silver Lake, Slab, Creek, and Stumpy Meadows. Folsom Reservoir, located about 40 km (25 mi) east of Sacramento, is where all the forks merge and drain to the reservoir (Fig. 1).

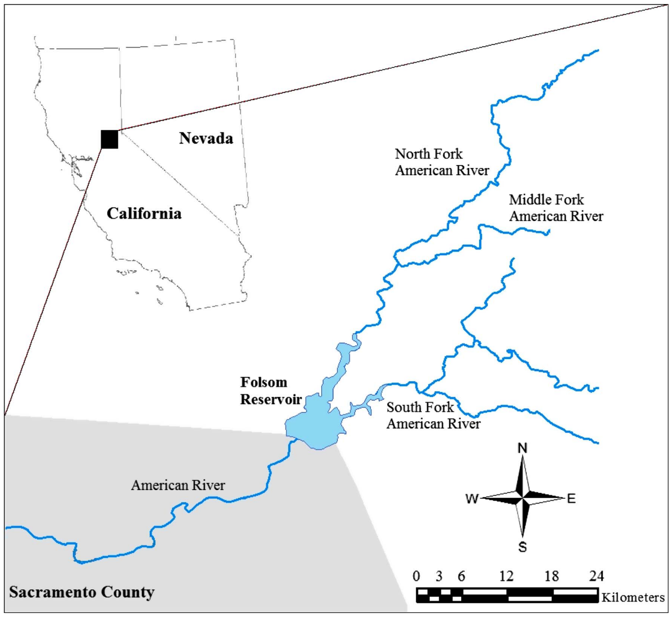

Fig. 1. Schematic of American River and Folsom Reservoir.

As a part of the Central Valley Project (CVP), the USACE built Folsom Dam in 1956. The United States Bureau of Reclamation (USBR) operates the multipurpose reservoir for regulating flow, generating hydropower, and providing water for municipal and irrigation demands. This reservoir captures high peak flows in the American River resulting from snowmelt and heavy precipitation to reduce the flood risk downstream of the dam and in the Sacramento metropolitan region. Folsom Dam's structure is a concrete gravity dam with a reservoir storage capacity of about 1,200 mcm (975,000 acre-ft) at the elevation of 142 m (466 ft). The reservoir's total capacity is about one-third of the average annual inflow from the American River basin, which is about 3,300 mcm (2.7 MAF). Hence, the total annual average releases from the reservoir are about 2,097 mcm (1.7 MAF). The dam's structure has three hydropower penstocks that send water to a 162-MW powerplant, which supplies about 10% of the total annual power demand in Sacramento (USBR 2019; USBR and SAFCA 2004). Table 2 lists the total capacity and elevation of spillways, penstocks, and outlets of Folsom Dam.

The USACE and the Sacramento Flood Control Agency (SAFCA) manage the operation of Folsom Reservoir for flood control based on a rule curve. Considering the policies forced by the rule curve, the USBR operates the reservoir for multiple purposes, including the Sacramento–San Joaquin Delta flow requirement. Two notable flood events that occurred in the American River in 1986 and 1997 led to the re-evaluation of the river's probable maximum flood (PMF), and therefore the updating of the reservoir rule curve. The rule curve was modified in 2004 (Fig. 2). Folsom Reservoir has a variable flood control space of about 493–826 mcm

Table 2. Outlet strcuture charectristics of Folsom Reservoir

Dam outlets	Release capacity (m^3/s)	Elevation[a] (MASL)	Quantity
Spillway	16,055 at 145 m	127	Five service gates and three emergency spillways
Power penstocks	226 s	93	Three power penstocks
River outlets	702 at 127 m	Upper tier: 84 Lower tier: 63	Two rows of four (lower and upper tiers)

Note: MASL = meters above sea level.

[a] Horizontal bottom of the gate/outlet.

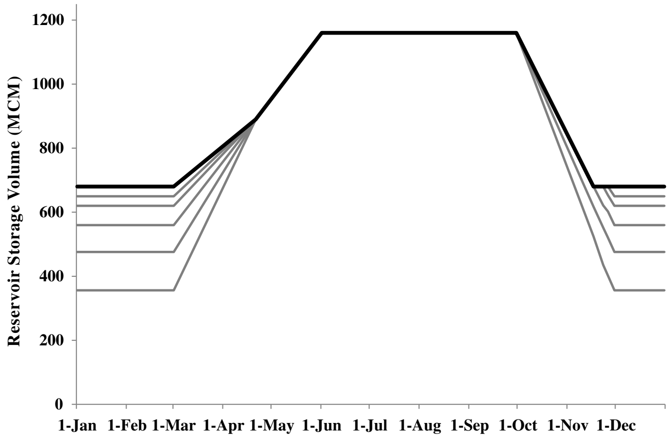

Fig. 2. SAFCA flood control diagram.

[400–670 thousand acre-ft (TAF)]. The exact flood storage is identified based on basin wetness parameters and water storage in smaller upstream reservoirs. Before the level of reservoir reaches the spillway levels (45% of the flood pool), the total capacity of the reservoir release is about 928 m^3/s (sum of penstocks and outlets from Table 2). This is much less than the capacity of the downstream channels (3,256 m^3/s). Therefore, the releases cannot be managed optimally to use the full capacity of the downstream flood capacity. Recently a new spillway was built at a lower elevation than the old spillways, and the downstream channel capacity was increased to 4,531 m^3/s. These changes will allow the reservoir to be emptied faster and at a lower elevation, and will increase the flood capacity downstream. At the time of this study, these changes to Folsom Dam and the channel and system operations were still in progress, so this study used the 2004 rule curve.

Lake Natoma, with a total capacity of about 10×10^6 m^3 (8,700 acre-ft), is located downstream of Folsom Lake. This dam is used to regulate the flow in the Lower American River, for hydropower generation, and to divert water toward the Folsom South Canal. The Folsom South Canal (Fig. 3) delivers water from the American River to the southern part of the watershed to meet irrigation, industrial, and municipal water demands. The potential use of the existing Folsom South Canal conveyance capacity was investigated in this study as an existing unused potential in the system to transfer water to the South American River basin and the Cosumnes River basin for MAR.

Underneath and west of Folsom South Canal lies the massive Central Valley aquifer system, composed primarily of alluvial sediments. The portion of this aquifer system lying in central and southern Sacramento County (Fig. 1) has been the subject of considerable work on the potential for managed aquifer recharge, particularly with respect to wet-season high-magnitude flows in the upstream reservoir and river system (Gailey et al. 2019; Maples et al. 2019). Although this part of the aquifer system generally is not considered to be in serious overdraft, the portion lying largely south of the American River and extending underneath the Cosumnes River has been sufficiently depleted in groundwater storage to pose problems for the endangered fall run of the Chinook salmon in the Cosumnes River due to lack of groundwater-driven baseflow (Fleckenstein et al. 2006; Niswonger and Fogg 2008). Furthermore, in the part of the aquifer system lying between the American and Cosumnes Rivers and east of the Sacramento River (Fig. 1), enough groundwater storage depletion has occurred to provide nearly enough space for subsurface water storage as the storage capacity of Folsom Lake itself (Gailey et al. 2019). In other words, the conditions in this American–Cosumnes basin system are excellent for augmenting the total system storage by an amount equivalent to adding another Folsom Lake.

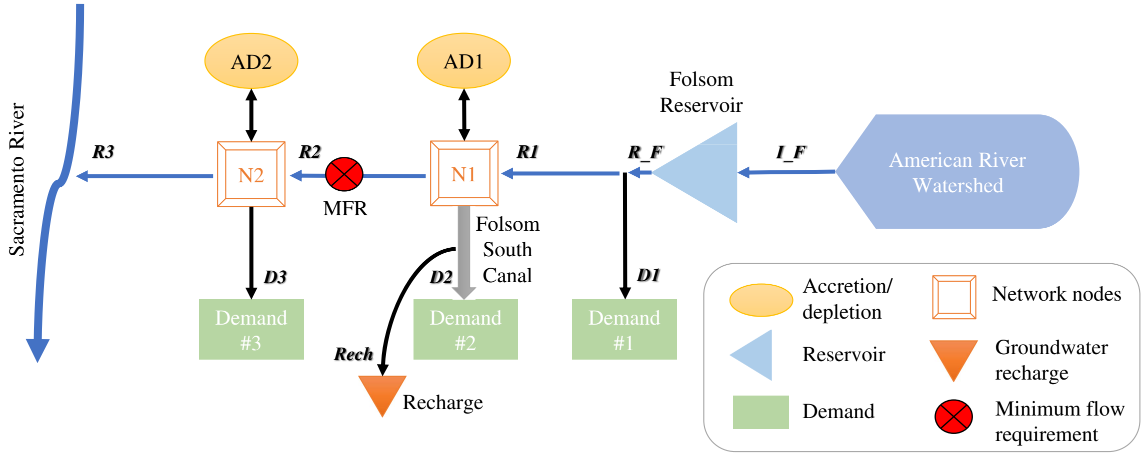

Fig. 3. American River water system schematic in FolSim.

Available Folsom Reservoir Models

Two main groups of water management models are relevant for this study of American River Basin and Folsom Reservoir, as well as for the whole complex Central Valley water system (Jenkins et al. 2004; Dogan et al. 2018). One is CalSim [CalSim I (Draper et al. 2004); CalSim II (Close et al. 2003); CADWR and USBR 2017; and SacWAM, which is the CalSim version of the Sacramento Basin developed by the State Water Resources Control Board (Fleenor et al. 2016)] and its screening version, CalLite (Islam et al. 2011), which were developed by the California Department of Water Resources (2020) and the USBR, and are used for the planning and management of the State Water Project (SWP) and the federal Central Valley Project. Objectives in CalSim are structured based on the relative priorities and weights for allocation and storage within the system. CalSim uses mixed-integer linear programming (MILP) to allocate water between different users and track water within the network system using a mass balance at nodes and storages. The Folsom Dam, as a part of the CVP, is represented in CalSim. CalSim's equations and objectives are linearized and integrated using a prioritization weighting method. The equations in CalSim are structured to drive the MILP solution to satisfy the regulatory requirements in the order of their priority.

CalSim simulates the operation of the integrated SWP and CVP infrastructure system in California, i.e., operation of reservoirs is simulated in tandem instead of individually simulating a reservoir in detail, and thus this model was used as the benchmark to evaluate the performance of the FolSim model. CalSim was considered a suitable modeling tool for this study; however, it was not selected because the aim of this study was to draw insights into reservoir operation and MAR at a daily time scale, and CalSim has a monthly time step, so it would have been very challenging to build a daily operation model of the CVP and SWP. This study could have developed assumptions to link monthly releases with daily operations, but the authors decided to address the daily operations natively. FolSim is a good theoretical compromise between a simplified and an exploratory modeling tool for the Folsom Dam that represents its operation without including the CVP-SWP complex operation of the California's water system, and is a fine-detail tool that considers daily time-step operations for MAR. The new model developed in this study is not intended to replace existing models of the reservoir, but rather to enable a focus on the issue of release quantities and timings for MAR. The rule curve estimates the flood pool elevation/volume needed to reduce the flooding risk.

To properly implement the use of a rule curve, the USACE developed a HEC-ResSim model for the Folsom Reservoir (USACE 2011). As opposed to CalSim, HEC-ResSim focuses on flood operation rules, and less on water supply and demand simulation, and thus supply diversions—for example, the Folsom South Canal—are not represented in this model. HEC-ResSim simulates the operation of reservoir with an hourly time step, which is appropriate for representing the flood flows, but also greatly increases the runtime of the model. The HEC-ResSim model specifies releases from the reservoir based on a group of operation rules for each reservoir zone. These operation rules were described by Kindel (2013) and USACE (2017). Additionally, the groundwater representation in both models is limited. CalSim III, the latest version of CalSim, overcomes this deficiency by integrating surface and groundwater models. In general, the HEC-ResSim model is appropriate for simulating the operation of the Folsom Reservoir during the flooding season, and CalSim is appropriate for larger-scale operation and planning purposes.

In this study, relevant operation rules were extracted from these two models to develop a joint set of operation rules needed for both simplified representation of Folsom Reservoir, but also appropriate for the simulation of reoperation impact and MAR. The new model, FolSim, represents significant features of both models and has additional capabilities. This model was developed with the goal of building upon the CalSim and HEC-ResSim models, but also of adding new features for future simulation-optimization assessments. Adding a new objective for MAR requires optimized reoperation of a surface reservoir, simulation of the recharge process, and representation of dynamics between groundwater and surface water systems. Table 3 compares CalSim II, HEC-ResSim, and the FolSim model of this study.

FolSim Model

The basis of developing FolSim model was the continuity equation to maintain mass balance at each point of the whole system and in the reservoir [Eq. (1)], which was coded in MATLAB version 9.4.

Table 3. Existing models for American River and Folsom Reservoir systems

Model	FolSim	CalSim II	ResSim
Simulation			
Purpose	Operation and planning	Planning (CVP and SWP)	Operation
Time steps	Monthly/daily	Monthly	15 min
Execution time	Seconds	Minutes to hours	—
Hydrologic period	1921–2003	1921–2003	1921–2003
Flood Management			
Rule curve	Yes	Yes	Yes
Upstream reservoirs	No	Yes	Yes
Bathymetry	Yes	No	Yes
Outlets capacity as a function of reservoir elevation	Yes	No	Yes
Allocation			
Hydropower	Yes	No	No
Tail water	Yes	No	Yes
Minimum instream flow requirements	Yes	Yes	Yes
M&I&A demand	Yes	Yes	No
Infrastructure (Folsom South Canal)	Yes	Yes	No
SW-GW			
SW-GW interaction	Semidynamic	Static	Yes
MAR simulation	Yes	Monthly estimation	No

Note: SW = surface water; GW = groundwater; and M&I&A demand = municipal, industrial, and agricultural demand.

The state of the system (storage in reservoir) and the net inflows for the next time interval are determined for each time step. The optimal operating decision (release from reservoir) consistent with the system's constraints, operating policies, and downstream conditions then is estimated. The Folsom Reservoir and its downstream points of diversion are represented in the network system as nodes using the out-of-kilter algorithm (Sigvaldason 1976). In the out-of-kilter concept, the reservoirs and channels (inflows, channel flows, return flows, or diversions) are represented by network of nodes and arcs, similar to an electric circuit. Reservoir and channel junction points are represented by nodes, and arcs represent the flow of water into or out of nodes. Fig. 3 depicts a simple schematic of the American River network.

The formulation used in the FolSim model includes (1) a mathematical expression of the reservoir operation rules (mainly if-then functions), and (2) constraints downstream of the reservoir. In this study, FolSim maximizes the recharge during the periods specified by users to define a feasible solution that satisfies all other constraints. The decision variables are shown in Fig. 3 (except I_F); I_F, R_F, Rech, R_i, and D_j are the time series of reservoir inflows, total reservoir releases, available water for recharge, flows entering node i, and water supply provided for demand node j, respectively. Except for I_F, the time-series values for these decision variables are calculated by the simulation-optimization model.

The time series of demands, demand_j, is obtained from CalSim II (Table 4). These demands are the sum of agricultural demand, calculated from cropping patterns and soil moisture budget, and urban demand, estimated from contract amounts and historical data (Draper et al. 2004).

Accretion/depletion at node i (AD_i) is the losses/gains for each node. The values for AD_i are derived from CalSim II and the California Central Valley Groundwater-Surface Water Simulation Model (C2VSim), which simulates water movement in aboveground and underground systems in California's Central Valley. These values, negative or positive, represent the local flow including groundwater–surface water interaction, return flows, and storm water at each node.

The diversion points at the Nimbus Dam and H Street are denoted N_1 and N_2, respectively; N_3 represents the convolution point of the American River and Sacramento River. The mass balance equation for each node is

$$\left(\sum \text{inflow}\right)_i - \left(\sum \text{outflow}\right)_i = 0 \tag{1}$$

For example, at Nimbus Dam ($i = 2$):

$$(R_1 + \text{AD}_1) - (D_2 + \text{Rech} + R_2) = 0$$

Finally, the minimum flow requirement is denoted MFR. In 1958, as part of State Water Resources Control Board (SWRCB) Decision 893 (D-893), the aquatic resources protection requirements for the lower American River were established. According to D-893, minimum flows in the lower American River should be $7\ \text{m}^3/\text{s}$ ($250\ \text{ft}^3/\text{s}$) from January through mid-September, and 14–$57\ \text{m}^3/\text{s}$ (500–$2{,}000\ \text{ft}^3/\text{s}$) for the remainder of the year. Minimum required flows in the lower American River are designated where the American River discharges into the Sacramento River. To increase the protection requirements afforded by D-893, a new flow management standard (FMS) was developed for the lower American River (Water Forum 2007). Generally, the minimum flow requirement ranges between 23 and $56\ \text{m}^3/\text{s}$ (800–$2{,}000\ \text{ft}^3/\text{s}$) based on the Four Reservoir Index (FRI) (an index of the end-of-September combined carryover storage in Folsom, French Meadows, Hell Hole, and Union Valley reservoirs), the Sacramento River Index (SRI), and the Impaired Folsom Inflow Index (IFII) (an index of the flow volume into Folsom Reservoir after all legal diversions take place in the upstream watershed). FMS details are given in Table 5.

Although both the FMS and D-893 standards are incorporated in the FolSim model, the latter was used in this paper. A prominent constraint at the downstream of the reservoir is that the release after the Nimbus Dam should be more than the minimum flow requirement for each month, i.e., $R_2 \geq \text{MFR}$. Although the MFR recommends that minimum flows below the Nimbus Dam should follow the values in Table 5, MFR does not prohibit releases with higher flows at this point (Water Forum 2007).

The function of the Folsom Reservoir primarily is to control flooding, generate power, supply water, allow recreational uses, and fulfill environmental purposes. These roles are defined as the objective and constraints for the Folsom Reservoir, and are incorporated into the model as mathematical expressions. Therefore, the FolSim model is able to estimate the release from the reservoir and satisfy the constraints and goals in each timesteps. Other factors which affect the operation of the reservoir are introduced in the reservoir's rule curve (Fig. 2). In 1994, the USBR and the Sacramento Area Flood Control Agency developed a rule curve for the Folsom Reservoir. The flood space in the rule curve varies between 493 and 826 mcm based on the storage of reservoirs upstream of the American River and Folsom system. The refill of reservoir starts in the beginning of March with different rates which are based on the depth of the flood pool. During the refill period, regardless of the depth of the flood pool, the top of conservation (TOC) should reach 1,100 mcm by April 21. The TOC increases up to the maximum storage of the reservoir by June 1, and stays constant until the

Table 4. Summarized water rights, CVP contract amounts, and demand amounts for each diverter in American River system

Diverter	Diversion location (node)	CVP M&I contracts ($10^6\ \text{m}^3/\text{year}$)	Water rights ($10^6\ \text{m}^3/\text{year}$)	Diversion limit (demand) ($10^6\ \text{m}^3/\text{year}$)
City of Folsom	Folsom Reservoir (Folsom)	0.15	0.17	0.32
Folsom Prison				
San Juan Water District				
El Dorado Irrigation District				
City of Roseville				
Southern California Water District	Folsom South Canal (N1)	0.04	0.03	0.07
Arden Cordova Water District				
California Parks and Recreation				
SMUD				
City of Sacramento	Lower American River (N2)	0	0.29	0.29
Carmichael Water District				

Source: Data from Draper et al. (2004); CADWR (2020).

Note: M&I = municipal and industrial; and SMUD = sacramento municipal utility district.

Table 5. Required monthly minimum flow requirements below Nimbus Dam based on FMS indexes

Month	FMS index	MFR (m^3/s)	Primarily goal
January	SRI	23–50	Fall-run Chinook salmon egg incubation and steelhead spawning
February	SRI	23–50	Fall-run Chinook salmon egg incubation and steelhead spawning
March	IFII	23–50	Steelhead spawning and egg incubation and fall-run Chinook salmon and steelhead juvenile rearing and downstream movement
April	IFII	23–50	Steelhead spawning and egg incubation and fall-run Chinook salmon and steelhead juvenile rearing and downstream movement
May	IFII	23–50	Steelhead spawning and egg incubation and fall-run Chinook salmon and steelhead juvenile rearing and downstream movement
June	IFII	23–50	Steelhead juvenile over-summer rearing
July	IFII	23–50	Steelhead juvenile over-summer rearing
August	IFII	23–50	Steelhead juvenile over-summer rearing
September	IFII	23–[a]	Steelhead juvenile over-summer rearing and adult fall-run Chinook salmon immigration
October	FRI	23–42	Fall-run Chinook salmon spawning
November	FRI	23–57	Fall-run Chinook salmon spawning
December	FRI	23–57	Fall-run Chinook salmon spawning

[a] 50 m^3/s from September 1 through Labor Day, and 42 m^3/s subsequently.

beginning of the drawdown period. The drawdown period starts on October 1 and decreases with different rates to reach the flood space in the beginning of December. Although the FolSim model does not include the simulation of upstream reservoirs (French Meadows, Hell Hole, and Union Valley reservoirs), the historical storages of these reservoirs are used to pick Folsom's variable rule curve (depth of the flood pool). The FolSim release decisions are based on the physical characteristics of dam outlets (Table 2), downstream channels, bathymetry of the reservoir (Fig. 4), hydropower intakes and turbine capacity, and rule-based operational objectives and constraints. Moreover, the FolSim model accounts for outlet prioritization and maximum flow rates from outlets based on reservoir elevation to represent details of reservoir operation. The elevation-storage relationship for the Folsom Reservoir is estimated by interpolating each time step using bathymetry of the reservoir. The governing equation for the reservoir is the following mass balance equation:

$$S_{t+1} = S_t + Q_t - R_t - L_t - \mathrm{Spill}_t \tag{2}$$

where S_t, Qt, R_t, L_t, and Spill_t = storage of reservoir, inflow to reservoir, released water from reservoir, evaporation losses (Table 6), and spill from reservoir, respectively, at period t. Released water in this equation is the sum of the releases from different outlets.

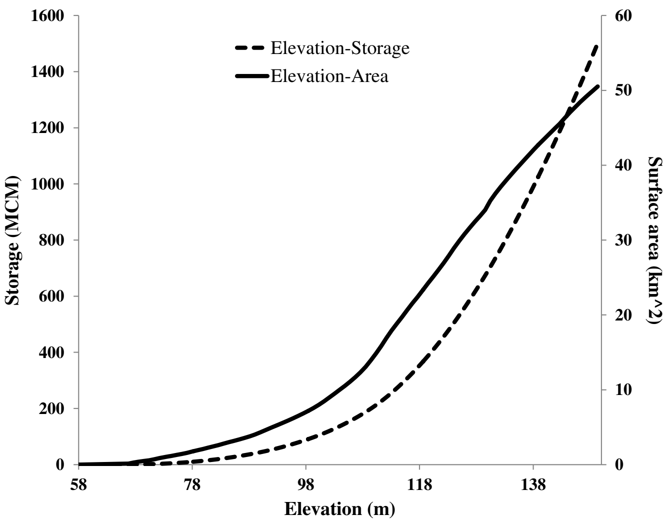

Fig. 4. Elevation-area-storage of Folsom Reservoir.

The water allocation between different outlets and users modeled in FolSim are determined based on sets of rules that are embedded in the model as constraints. Storage zones are specified for the Folsom Reservoir based on the rule curve and the physical properties of dam. They represent the volume between physical and operational levels. At each zone, the following limitations exist:

$$S^{\min} \le S_t \le S^{\max} \quad t = 1, \ldots, N+1 \tag{3}$$

$$R_t^{\min} \le R_t \le R_t^{\max} \quad t = 1, \ldots, N \tag{4}$$

where $S^{\min}$ = minimum reservoir volume. According to the existing rule curve, the capacity related to the TOC is the maximum possible reservoir storage at period t, $S_t^{\max}$, and varies with time (Fig. 2). In Eq. (4), $R_t^{\min}$ is the minimum total water release, and $R_t^{\max}$ is the maximum total water release from the reservoir; both depend on the minimum and maximum flow constraints at the downstream of reservoir. Moreover, each outlet has a maximum rate of outflow, which varies based on the water level and bathymetry of the reservoir

$$0 \le R_{t,j} \le R(H_t)_j^{\max} \quad t = 1, \ldots, N, j = 1, \ldots, M \tag{5}$$

where M = total number of outlet sets from Table 2; H_t = elevation of water in reservoir at time t; and $R_{t,j}$ = water release at time t from outlet j. For example, Fig. 5 shows the variable maximum releases from the river outlets for the lower and upper tiers. Similar graphs exist for power penstocks, emergency spillways, and spillway service gates.

Table 6. Monthly evaporation rates for Folsom Reservoir

Month	Evaporation (cm)
January	2.3
February	4.1
March	8.9
April	8.9
May	20.5
June	25.6
July	29.2
August	25.9
September	19.4
October	12.7
November	5.2
December	2.3

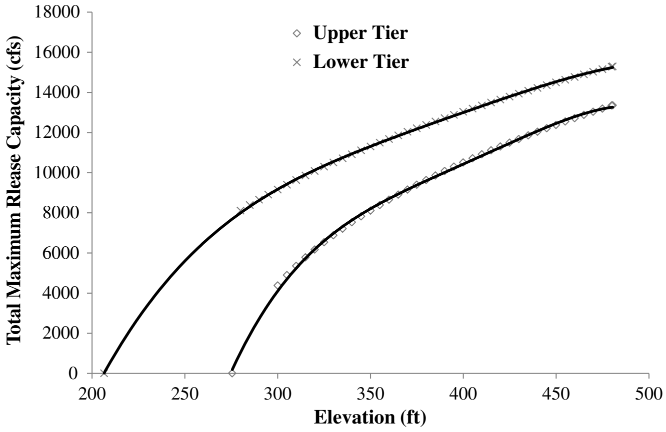

Fig. 5. Maximum release capacity of upper and lower outlet of Folsom Reservoir.

To estimate the hydropower generated by the Folsom powerplant, the effective head of the hydropower plant (h_t) is calculated using the following equation:

$$h_t = \left(\frac{H_t + H_{t+1}}{2}\right) - \mathrm{TWL}_t \tag{6}$$

where TWL_t = downstream water elevation of hydroelectric plant at period t. Downstream water elevation depends on the amount of releases from the reservoir, and is estimated by the following polynomial equation, which considers release as a variable:

$$\mathrm{TWL}_t = a_1 + a_2 \times R_t + a_3 \times R_t^2 + a_4 \times R_t^3 \tag{7}$$

where constant coefficients a_1, a_2, a_3, and a_4 are obtained by fitting the preceding equations into the available data. For the Folsom Reservoir, the constant coefficients are 165.54, 0.0001, 1×10^{-10}, and 2×10^{-16}, respectively. Finally, power can be calculated based on

$$P_t = \left(\frac{g \times \eta \times R_{t,2} \times h_t}{P_f \times \mathrm{time}}\right) \tag{8}$$

where g = gravity acceleration (9.81 m^2/s); η = efficiency of hydroelectric plant; P_f = plant factor; time = number of hours in period; and h_t = effective head of hydropower plant. Total installed capacity of turbines and efficiency of the plants are 196.72 MW and 85%, respectively.

The flood control operation in the Folsom Reservoir is designed based on the storage in the flood space and on the downstream channel and the levee's capacity. Operating strategies are developed to use the storage until the flood peaks or the flood pool is exceeded.

The Folsom Reservoir releases about 850 m^3/s before reaching a level of 127 m, at which the spillway gates are located. At this level, the flood storage is about 30% of the total flood capacity. Using the rates of change, releases from the reservoir are increased slowly to keep the storage low early in the flood season. Release can be increased up to 4,248 m^3/s when the reservoir reaches about 50% of the total flood capacity, which is the downstream channel capacity. Releases from the reservoir stay at about 3,256 m^3/s until inflow to the reservoir exceeds 5,663 m^3/s. At this rate, releases from the reservoir should be increased to 4,531 m^3/s. When the flood space is full, the release rate can be greater than 4,531 m^3/s to prevent overtopping of the dam.

Results

Model Verification

Simulation results for October 1922–2003 from FolSim are compared with those from CalSim in Fig. 6, which, along with Fig. 7, shows that the FolSim model was able to simulate adequately the historical operation of Folsom Reservoir. The FolSim results were satisfactory, especially during above-normal and wet years. As discussed previously, the FolSim model does not represent the

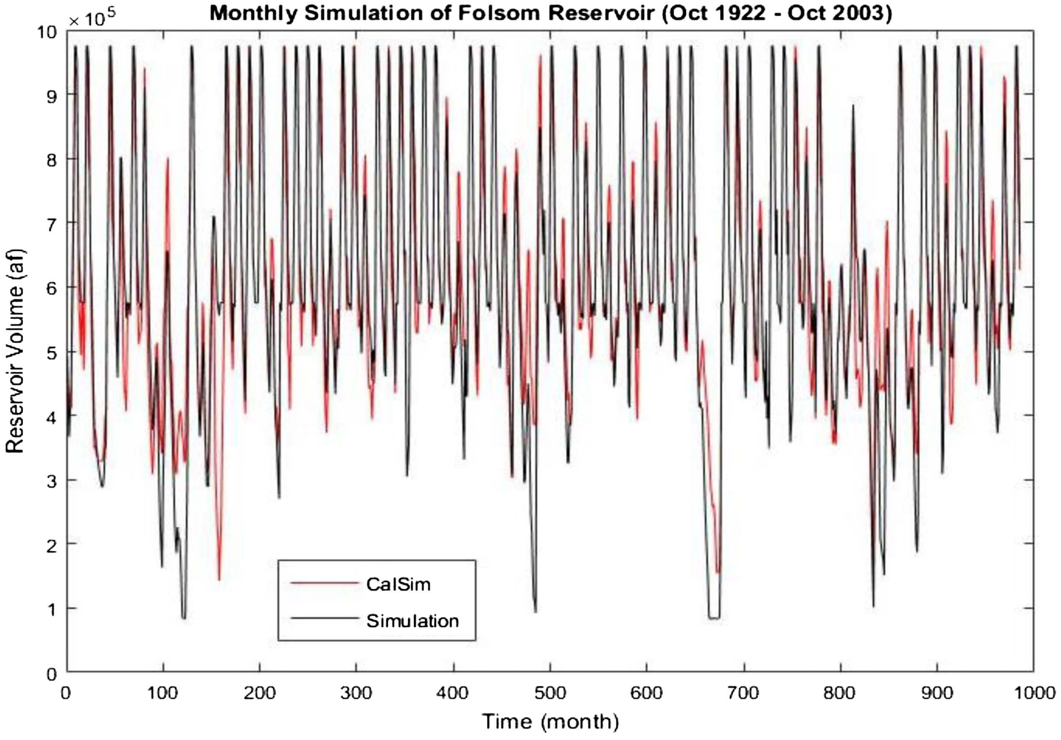

Fig. 6. Monthly time series of Folsom Reservoir Storgae from CalSim and FolSim.

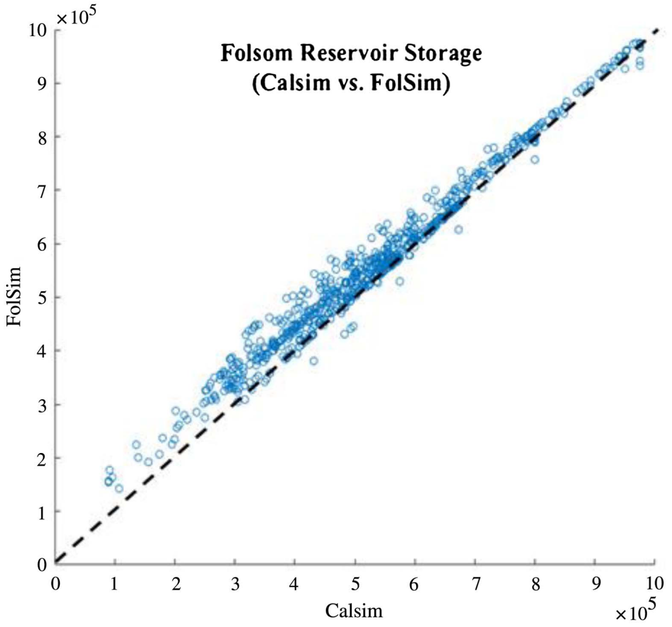

Fig. 7. Average monthly storage of Folsom Reservoir by CalSim and FolSim.

entire interaction between different elements of the Sacramento–San Joaquin water system, because the focus is on water storage potential based on operations in only the American–Cosumnes watershed. Thus, the overestimation of storage and differences between the FolSim and CalSim simulations during dry years, and slightly during wet years, have two causes (1) the CalSim model operates Folsom Reservoir based on an optimization of allocation for the whole system, whereas the FolSim model represents the operation of Folsom Reservoir independent from a larger system; and (2) during dry years, there is an extra demand associated with the Sacramento–San Joaquin Delta requirement, which should be extracted from Folsom Reservoir. Although these issues should be addressed in the future, for the purpose of this study, which was using the high peak flows for MAR, estimated available water for recharge results were not greatly sensitive to the water storage in Folsom during years with below normal conditions.

Finally, although the existing FolSim model has some limitations, its capabilities make it a promising tool as an explanatory model for future reservoir reoperation in support of increasing total system storage through MAR operations. Noteworthy limitations and capabilities are as follows:

- Although the current inflow time series to the reservoir is based on RIMS flows, the FolSim model is linked to the Precipitation-Runoff Modeling System (PRMS) hydrologic model and can incorporate generated stream flows from the PRMS into the modeling process. As a result, different types of headwater scenarios and their impacts on reservoir operation, including climate change, deforestation, forest fire, and so forth, can be investigated via the FolSim model.
- Although not implemented in this paper, the FolSim model is coupled with a groundwater model for the California Central Valley (C2VSim). This link between these two models enables capturing feedback between surface and groundwater storage, assessing a further feasibility study of managed aquifer recharge, and managing hybrid optimization and conjunctive use of surface water reservoir and groundwater storage.
- The current version of FolSim has a simple graphical user interface (GUI). Users have access to the GUI to run the model, modify the simulation period, test different scenarios, and visualize and download different types of results.
- The FolSim model is coded in MATLAB. The source code is available for public use, which makes this research fully reproducible. Managers and researchers can access to the source code of model, build new models based on the current version of FolSim, expand the model boundaries, create new scenarios, add new capabilities, change the operation rules, and incorporate changes in facilities.
- The FolSim model can be used as a simulation engine for future integration with optimization models, uncertainty analysis, sensitivity analysis, performance assessment of the system, and other studies of system analysis. For example, FolSim easily can be used for optimizing reservoir operations for hydropower, fish survival, supply reliability, and so forth.
- The current FolSim model is based on Folsom Reservoir's rule curve. However, this model can be modified to incorporate the inflow forecasts and to forecast informed reservoir operation with or without using the rule curve.
- Although we presented the FolSim model as a platform for managed aquifer recharge applications, the model can incorporate further supply or demand management scenarios, such as changes in agricultural demand and patterns, environmental requirements, population growth, and so forth.
- The existing FolSim model was developed to represent the individual operation of the Folsom Reservoir; however, the source code can be adapted for other reservoir systems for reoperation and MAR studies. Furthermore, the code can be extended and modified to include the whole complex Central Valley water network system.

Available Water for Recharge by Reservoir Reoperation

One of the potential sources of groundwater recharge is the excess surface water in streams, lakes, or reservoirs. Generally, wherever the river's discharges or water demands are highly variable, there is a chance to store water by building a dam or deep basin to regulate releases. During high flows, water can be stored for a short time (a few months), and released subsequently to meet water demand during low-flow and dry seasons. This section used the FolSim model to maintain the same level of service for the Folsom Reservoir based on adhering to specific operation rules introduced in previous sections. Moreover, the FolSim model maximizes the water available for recharge by regulating releases (decision variables) from the reservoir. The reservoir system follows a simplified operation and physical constraints; however, future refinements are needed to include the impact of tandem operation of the whole California complex water network. The reservoir system first provides water to meet local demand and downstream minimum flow requirements, then transfers excess water to the recharge site through the Folsom South Canal, and finally stores the remaining water in the Folsom Reservoir.

Fig. 8 illustrates the FolSim estimates of water available for recharge during the period 1922–2002. These results were classified based on water year type and were compared with other scenarios. Available water varies between 283 and 582 mcm (230–472 TAF) and 379 to 871 mcm (307–706 TAF) for winter (December–February) and extended winter (November–March) recharge periods, respectively. Therefore, the FolSim model indicates that a good amount of recharge water during dry and critical years potentially could be available due to the high peak flows. During below-normal, above-normal, and wet years, FolSim provides slightly more water for recharge.

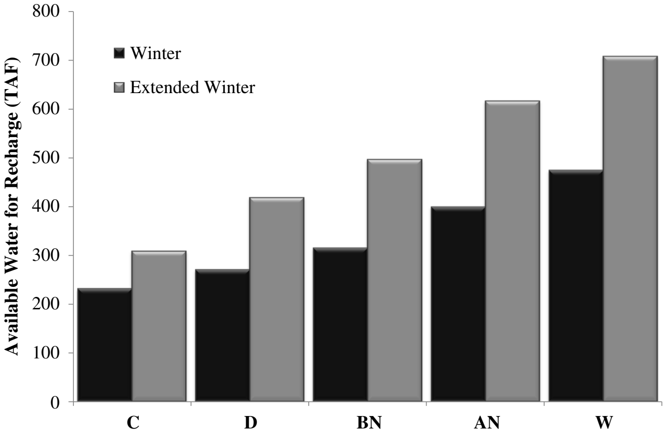

Fig. 8. Avaialable water for recharge from Folsom Reservoir based on different water year type.

Fig. 9 shows the annual available water recharge from the FolSim model during the study period. The FolSim model identifies the years when more water is in the basin and the surface reservoir, and increases the water available for recharge during those years. The benefits of extending the recharge period increase when wet years follow critical years (Fig. 9). This figure shows the consequences of wet and dry years, and the frequency of reaching the maximum physically feasible recharge amount [about 760 mcm/year (616 TAF/year) for winter and 1,264 mcm/year (1,025 TAF/year) for extended winter].

Depending on the water year type, the FolSim analysis indicates that about 379–871 mcm are available on average for recharge during an extended winter. Fig. 10 compares downstream flow in the American River after diverting water for recharge. The vertical axis shows the downstream discharge of the American River to the Sacramento River. When discharge is higher than 141.6 m^3/s (5,000 ft^3/s), there are meaningful differences between the no-recharge and extended-winter recharge scenarios (Fig. 10). The differences between the dotted and the solid lines are the amounts of water that are that are saved and stored, either in the reservoir or downgradient in the groundwater system. Thus, the FolSim model aims to capture high flows in the American River and potentially transfer excess water for groundwater recharge.

Differences in streamflow time series between the no-recharge and recharge scenarios can be stored in the surface reservoir or used for recharge. To better understand how the system balances the storage between these two storage functions, consider the Folsom Reservoir storage (Fig. 11). Although the FolSim discharges to the Sacramento River are almost the same as those in the no-recharge scenario (historical discharges) during low-flow years, the model indicates that a great amount of water (283–582 mcm) potentially is available for groundwater recharge. Available water during critical, dry, and below-normal years mainly comes from draining the surface storage and not from the high peak flows (Fig. 11). Therefore, in these years there is a risk of losing the storage in the surface reservoir to fill the groundwater storage. Although even during these years (below-normal conditions) local demand and minimum flow requirements are met, there is a potential conflict between storing water in the surface reservoir and in the subsurface. Therefore, the MAR will be deployed if the peak flow happens during above normal and wet years (Fig. 11). This issue should be investigated further using integrated hydroeconomic and risk models and involvement of experts and decision makers, as well as consideration of public opinion. Storing water underground in the long term could be much more beneficial for longer droughts. However, to avoid the concern about recharging water during dry and below-normal years, where the Delta requires higher freshwater inflow, we suggest using only wet and above-normal years for MAR. During the above-normal and wet years, not only does the FolSim model indicate a significant amount of water available for recharge, it also offers a slight increase in water storage in the surface reservoir. This shows that Folsom Reservoir reoperation can maximize the storage of water in the whole basin and balance the water stored in different portions of the watershed. Consequently, these results suggest that groundwater recharge during above-normal and wet years not only can increase the security of water for longer and more-frequent drought incidents, it also can maintain the same amount of water that has been stored in surface reservoir during these years.

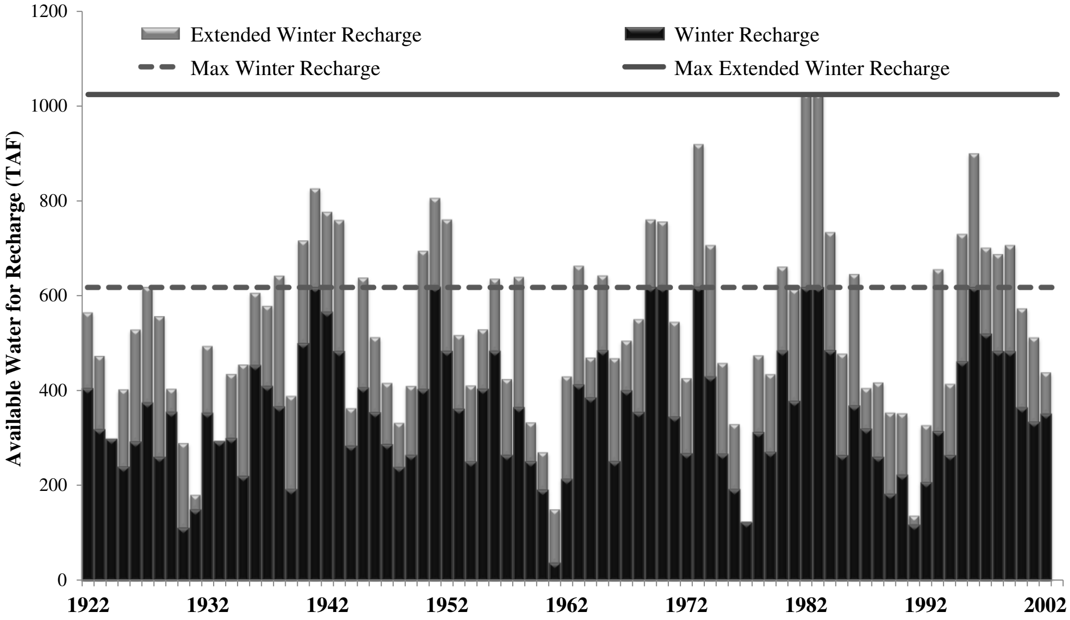

Fig. 9. Annual time series of available water for recharge from Folsom Reservoir.

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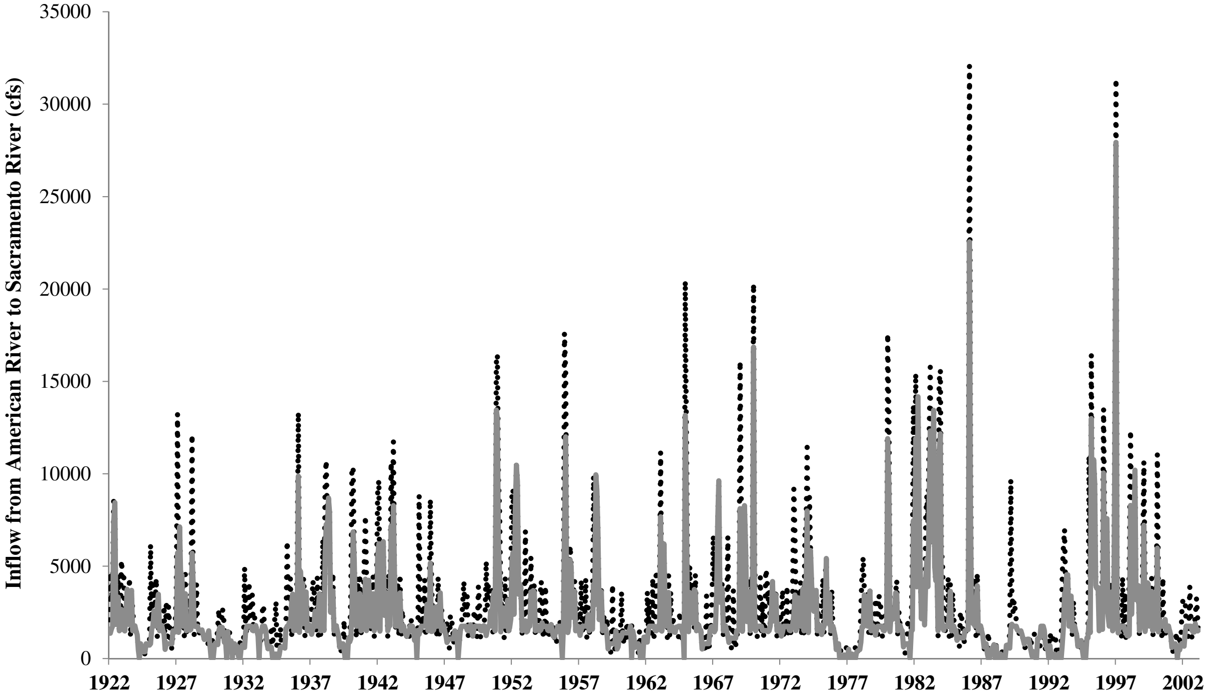

Fig. 10. Streamflow estimation of American River downstream of recharge diversion based on historical (dotted line) and water available for recharge during extended winter (solid line).

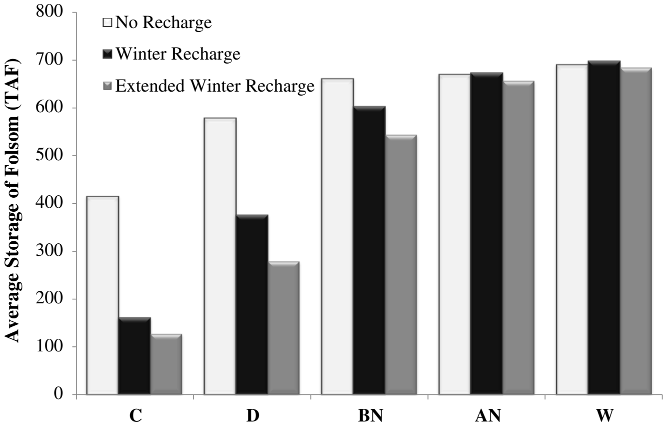

Fig. 11. Folsom Reservoir storage for different water year type with and without recharge.

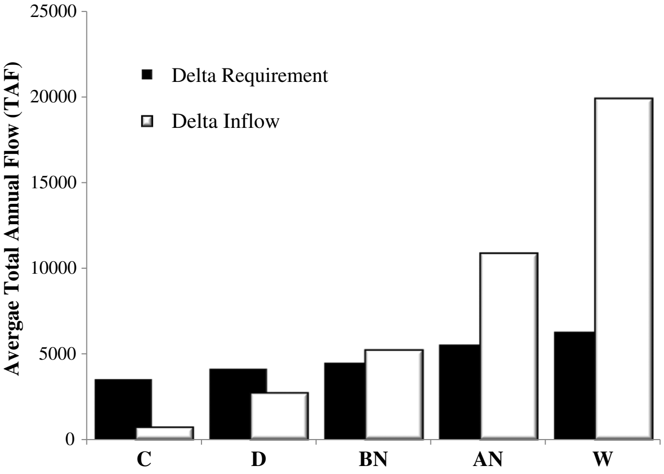

Fig. 12. Sacramento–San Juaquin Delta inflow and requirement.

Thus, water available for recharge during wet and normal years is provided mainly by cutting the high instream flows and releases from the Folsom Reservoir.

Finally, during the simulation period, results showed that in both winter and extended-winter recharge scenarios, FolSim is able to keep the reservoir system's level of service, such as providing water for local demand and meeting downstream flow requirements, at an acceptable level. The reliability of the system to supply the demand and meet minimum flow requirements at the confluence of the American and Sacramento Rivers was 100% and 98.5%, respectively.

Results Discussion

One of the main concerns about storing water upstream of the Sacramento–San Joaquin River Delta is the maintenance of sufficient freshwater into the Delta. Thus, one of the main questions which should be answered is whether storing high flows in upstream of Delta significantly jeopardizes the Delta. To address this question, first the historical Delta requirement and inflows to Delta were collected from an economic-engineering optimization model of California developed at the University of California, Davis, the California Value Integrated Network model (CALVIN) (Draper et al. 2003). Fig. 12 represents the amount of Delta inflow and requirement during the simulation period of this study, and classifies it based on water year type. During wet, above-normal, and below-normal years, the amount of fresh water entering the Delta exceeds the Delta requirement. Therefore, wet and above-normal years are good candidates for groundwater recharge in American River basin; because during these years there is high streamflow in river and lots of water in surface reservoir. Moreover, during these years, there are high flows in-stream, and as FolSim model offered the

Table 7. Available water for managed aquifer recharge based on different scenarios and during winter (mcm)

Available water for MAR (mcm)		Scenarios		
		Pre-development	Post-development	Reoperation
Annual average	C	100	80	280
	D	170	250	330
	BN	300	400	390
	AN	320	490	490
	W	400	620	580
Expected value (EV)		280	400	440
EV for W & AN		170	270	250

storage in the surface reservoir still would be almost full. Secondly, during these years there is less concern about downstream effects, because there is surplus inflow to the Delta. Groundwater recharge during these years not only provides water supply for droughts, but also increases groundwater levels and recharge to natural streams over a long period, which can benefit the environment and the Delta as the end point of the system.

Goharian et al. (2016b) estimated the water available for recharge based on the full natural flow of the American River (predevelopment) and based on historical discharges from the Folsom Reservoir (postdevelopment). Table 7 lists the amount of available water for recharge in these two scenarios and in the reoperation scenario presented in this paper. Using the results summarized in this table, local groundwater management agencies will be able to estimate the timing and amount of available water. The expected value (EV) of recharge during the 80-year period used in this study was about 440 mcm/year based on FolSim model simulations for winter recharge (Table 7). This value for the predevelopment condition was about 280 mcm/year. Therefore, the surface reservoir facilitates the management of water for conjunctive use, including managed aquifer recharge in this basin. Moreover, reoperation of Folsom Reservoir offers even more water availability during this period. In the wet and above-normal conditions, considering the Delta's requirement, the FolSim simulation shows that expected value for water available for recharge in the American River during the winter recharge is about 250 mcm/year. In extended winter, which adds 2 months to the recharge period, extended winter, the expected value of water available for recharge can increase to 380 mcm/year (about one-third of the total Folsom Reservoir). Therefore, the total that is available for recharge is about 7%–11% of total inflow into Folsom Lake, 1.1%–1.7% of the Sacramento flow to the Delta, and 0.9%–1.4% of total inflow to the Sacramento–San Juaquin Delta. These results can support local managers and groundwater sustainability agencies in their plans for balancing groundwater budgets and water available for recharge for the specific projects. The same framework can be used by local entities, especially those that are in charge of operating surface reservoirs in California, throughout the state, to reoperate the reservoir systems to free water for groundwater recharge in accordance with the SGMA.

Conclusion and Closing Remarks

Recent multiyear droughts make it crucial that the reservoir operation adopts with an integrated long-term approach to surface water–groundwater conjunctive use. Integrated management of surface water and groundwater stores, especially during increasingly extreme wet and dry conditions, provides an attractive opportunity to increase the total amount of water storage in the whole basin, to be better prepared for facing longer and frequent potential future droughts. To accomplish this goal, surface reservoirs can be operated such that the excess water is used to recharge the groundwater storage when it is available during high peak flows. This study modeled the Folsom Reservoir system using a new simulation tool, FolSim, to represent the availability of water for recharge and simulate the multipurpose operation of the total system stores, including surface water and groundwater. This approach indicated new opportunities for managed aquifer recharge while improving the current operation of the system. However, this study and the developed FolSim model are not free of assumptions and limitations. FolSim model, because it was developed solely to simulate and reoperate Folsom Reservoir, does not represent the integrated operation of the more-extensive SWP and CVP systems. Simulating daily operation of CVP-SWP reservoirs is a challenging task and is computationally intensive. As was discussed, the FolSim model tries to mimic these tandem rules which affect the Folsom model by deriving implicit rules in CalSim. Moreover, temperature and water quality parameters also affect the operation of the Folsom Reservoir. For example, water temperature management is important for anadramous fishes in the Sacramento and American Rivers. These considerations are not modeled directly in FolSim, and we suggest that future studies investigate environmental impacts of implementing MAR and reoperation surface reservoirs more carefully by using statewide models such as CalSim. Although we suggested the implementation of MAR during above-normal and wet water years, to prevent possible risks in the Delta, more-accurate estimates should be developed to account for not only simulated Delta requirements for different water year types, but also required flows to maintain salinity in the Delta. Finally, the FolSim model and the estimated numbers in this study do not deliver any information about the capacity for actual recharge in the American River basin. Our ongoing research is focused on estimating how much of the estimated water in this research potentially can be recharged (e.g., Gailey 2018; Goharian et al. 2018b; Gailey et al. 2019; Maples et al. 2019).

Concerning the modeling methods, FolSim benefits from an optimization toolbox that maximizes the total available water for recharge considering all constraints of the system. The capability of the proposed model was demonstrated by developing different management scenarios, and the results indicated that FolSim performs quite satisfactorily, with nonsignificant deficits and violations of other, established objectives. Although it was developed for Folsom Reservoir operation, FolSim easily can be applied to other surface water–groundwater systems.

Data Availability Statement

The simulation-optimization code generated for this study along with all the input data and results and their metadata files are available online (https://github.com/erfangoharian). More data, parts of the models used, and codes generated or used during the study are available from the corresponding author by request.

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References

Manage. 142 (2): 04015051. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000579.

CADWR and USBR (California Department of Water Resources and United States Bureau of Reclamation). 2017. “A water resources system planning model for State Water Project (SWP) and Central Valley Project (CVP).” Accessed September 16, 2020. https://data.cnra.ca.gov/dataset/calsim-3/resource/2ea38378-fb63-4321-80df-d7e45f899c90.

CADWR (California Department of Water Resources). 2018. “Water available for Replenishment 2018.” Accessed September 16, 2020. https://cawaterlibrary.net/document/water-available-for-replenishment-2018/.

CADWR (California Department of Water Resources). 2020. “CalSim 2.” Accessed September 16, 2020. https://water.ca.gov/Library/Modeling-and-Analysis/Central-Valley-models-and-tools/CalSim-2.

Close, A., W. M. Haneman, J. W. Labadie, D. P. Loucks, J. R. Lund, D. C. McKinney, and J. R. Stedinger. 2003. *A strategic review of CalSim II and its use for water planning, management and operations in Central California*. Oakland, CA: California Bay Delta Authority Science Program Association of Bay Governments.

Dahlke, H., A. Fisher, G. Fogg, E. Goharian, T. Harter, A. Hutchinson, J. McHugh, T. Parker, and S. Sandoval Solis. 2018. “Recharge roundtable call to action: Key steps for replenishing california groundwater. Accessed September 16, 2020. https://ucmerced.app.box.com/v/rechargeroundtable.

Dahlke, H., and T. Kocis. 2018. “Streamflow availability ratings identify surface water sources for groundwater recharge in the Central Valley.” *California Agric.* 72 (3): 162–169. https://doi.org/10.3733/ca.2018a0032.

Dettinger, M. 2011. “Climate change, atmospheric rivers, and floods in California—A multimodel analysis of storm frequency and magnitude changes.” *J. Am. Water Resour. Assoc.* 47 (3): 514–523. https://doi.org/10.1111/j.1752-1688.2011.00546.x.

Dettinger, M. D. 2013. “Atmospheric rivers as drought busters on the US West Coast.” *J. Hydrometeorol.* 14 (6): 1721–1732. https://doi.org/10.1175/JHM-D-13-02.1.

Dogan, M. S., M. A. Fefer, J. D. Herman, Q. J. Hart, J. R. Merz, J. Medellin-Azuara, and J. R. Lund. 2018. “An open source Python implementation of California’s hydroeconomic optimization model.” *J. Environ. Modell. Software* 108 (Oct): 8–13. https://doi.org/10.1016/j.envsoft.2018.07.002.

Draper, A. J., M. W. Jenkins, K. W. Kirby, J. R. Lund, and R. E. Howitt. 2003. “Economic-engineering optimization for California water management.” *J. Water Resour. Plann. Manage.* 129 (3): 155–164. https://doi.org/10.1061/(ASCE)0733-9496(2003)129:3(155).

Draper, A. J., A. Munévar, S. K. Arora, E. Reyes, N. L. Parker, F. I. Chung, and L. E. Peterson. 2004. “CalSim: Generalized model for reservoir system analysis.” *J. Water Resour. Plann. Manage.* 130 (6): 480–489. https://doi.org/10.1061/(ASCE)0733-9496(2004)130:6(480).

Fleckenstein, J. H., R. G. Niswonger, and G. E. Fogg. 2006. “River-aquifer interactions, geologic heterogeneity, and low-flow management.” *Ground Water* 44 (6): 837–852. https://doi.org/10.1111/j.1745-6584.2006.00190.x.

Fleenor, W., S. Sandoval-Solis, D. Sereno, L. Condon, and J. H. Viers. 2016. *Independent peer review of the Sacramento water allocation model (SacWAM)*. Sacramento, CA: Delta Science Program.

Freeman, G. J. 2002. “Looking for recent climatic trends and patterns in California’s Central Sierra.” In *Proc., 19th Annual Pacific Climate (PACLIM) Workshop*. Sacramento, CA: Interagency Ecological Program for the San Francisco Estuary.

Gailey, R. M. 2018. “Approaches for groundwater management in times of depletion and regulatory change.” Ph.D. dissertation, Dept. of Civil and Environmental Engineering, Univ. of California, Davis.

Gailey, R. M., G. E. Fogg, J. R. Lund, and J. Medellín-Azuara. 2019. “Maximizing on-farm groundwater recharge with surface reservoir releases: a planning approach and case study in California, USA.” *Hydrogeol. J.* 27 (4): 1183–1206. https://doi.org/10.1007/s10040-019-01936-x.

Gershunov, A., et al. 2019. “Precipitation regime change in Western North America: The role of Atmospheric Rivers.” *Sci. Rep.* 9 (1): 1–11. https://doi.org/10.1038/s41598-019-46169-w.

Goharian, E., S. J. Burian, T. Bardsley, and C. Strong. 2016a. “Incorporating potential severity into vulnerability assessment of water supply systems under climate change conditions.” *J. Water Resour. Plann. Manage.* 142 (2): 04015051. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000579.

Goharian, E., S. J. Burian, and M. Karamouz. 2018a. “Using joint probability distribution of reliability and vulnerability to develop a water system performance index.” *J. Water Resour. Plann. Manage.* 144 (2): 04017081. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000869.

Goharian, E., S. J. Burian, J. Lillywhite, and R. Hile. 2017. “Vulnerability assessment to support integrated water resources management of metropolitan water supply systems.” *J. Water Resour. Plann. Manage.* 143 (3): 04016080. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000738.

Goharian, E., R. Gailey, J. Medellin-Azuara, S. Maples, L. E. Adams, S. Sandoval Solis, G. E. Fogg, H. E. Dahlke, T. Harter, and J. R. Lund. 2016b. “Whole watershed management to maximize total water storage: Case study of the American-Cosumnes River Basin.” In *Proc., AGU Fall Meeting Abstracts*. Washington, DC: American Geophysical Union.

Goharian, E., R. M. Gailey, S. Maples, S. Sandoval-Solis, and G. Fogg. 2018b. “Maximizing whole watershed storage through optimized reservoir reoperation and managed aquifer recharge.” In Vol. 20 of *Proc., EGU General Assembly Conf. Abstracts*, 867. Munich, Germany: European Geosciences Union.

Hanson, R. T., M. W. Newhouse, and M. D. Dettinger. 2004. “A methodology to asess relations between climatic variability and variations in hydrologic time series in the southwestern United States.” *J. Hydrol.* 287 (1–4): 252–269. https://doi.org/10.1016/j.jhydrol.2003.10.006.

Islam, N., S. Arora, F. I. Chung, F. Reyes, R. Field, A. Munevar, D. Sumer, N. L. Parker, and Z. Q. R. Chen. 2011. “CalLite: California Central Valley water management screening model.” *J. Water Resour. Plann. Manage.* 137 (1): 123–133. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000089.

Jenkins, M. W., J. R. Lund, R. E. Howitt, A. J. Draper, S. M. Msangi, S. K. Tanaka, R. S. Ritzema, and G. F. Marques. 2004. “Optimization of California’s water system: Results and insight.” *J. Water Resources Plann. Manage.* 130 (4): 271–280. https://doi.org/10.1061/(ASCE)0733-9496(2004)130:4(271).

Kindel, A. A. 2013. “Development of a Folsom Reservoir release rule using flow forecasts.” M.S. thesis, Dept. of Civil and Environmental Engineering, Univ. of California, Davis. https://watershed.ucdavis.edu/shed/lund/students/KindelThesis2013.pdf.

Knowles, N., M. D. Dettinger, and D. R. Cayan. 2006. “Trends in snowfall versus rainfall in the western United States.” *J. Clim.* 19 (18): 4545–4559.

Maples, S., G. E. Fogg, and R. Maxwell. 2019. “Modeling recharge processes in a highly heterogeneous, semi-confined aquifer system.” *Hydrogeol. J.* 27 (8): 2869–2888. https://doi.org/10.1007/s10040-019-02033-9.

Milan, S. G., A. Roozbahani, and M. E. Banihabib. 2018. “Fuzzy optimization model and fuzzy inference system for conjunctive use of surface and groundwater resources.” *J. Hydrol.* 566 (Nov): 421–434. https://doi.org/10.1016/j.jhydrol.2018.08.078.

Milly, P. C. D., J. Betancourt, M. Falkenmark, R. M. Hirsch, Z. W. Kundzewicz, D. P. Lettenmaier, and R. J. Stouffer. 2008. “Stationarity is dead: Whither water management?” *Earth* 4: 20.

Niswonger, R. G., and G. E. Fogg. 2008. “Influence of perched groundwater on baseflow.” *Water Resour. Res.* 44 (3): W03405. https://doi.org/10.1029/2007WR006160.

PPIC (Public Policy Institute of California). 2018. *Replenishing groundwater in the San Joaquin Valley.* Edited by E. Hanak, J. Jezdimirovic, S. Green, and A. Escriva-Bou, 36. San Francisco: PPIC.

Safavi, H. R., and S. Enteshari. 2016. “Conjunctive use of surface and ground water resources using the ant system optimization.” *Agric. Water Manage.* 173 (Jul): 23–34. https://doi.org/10.1016/j.agwat.2016.05.001.

Scanlon, B. R., K. E. Keese, A. L. Flint, L. E. Flint, C. B. Gaye, W. M. Edmunds, and I. Simmers. 2006. “Global synthesis of groundwater recharge in semiarid and arid regions.” *Hydrol. Processes* 20 (15): 3335–3370. https://doi.org/10.1002/hyp.6335.

Sigvaldason, O. T. 1976. “A simulation model for operating a multipurpose multireservoir system.” *Wat. Res. Res.* 12 (2): 263–278.

Singh, A. 2014. "Simulation–optimization modeling for conjunctive water use management." *Agric. Water Manage.* 141 (Jul): 23–29. https://doi.org/10.1016/j.agwat.2014.04.003.

TNC (The Nature Conservancy). 2016. *Groundwater and stream interaction in California's Central Valley: Insights for sustainable groundwater management*. Arlington County, VA: TNC.

USACE. 2011. "Accelerated Corps Water Management System (CWMS) deployment campaign." Accessed September 16, 2020. https://www.hec.usace.army.mil/publications/ProjectReports/PR-79.pdf.

USACE. 2017. "Folsom Dam Modification Project water control manual update." Accessed September 16, 2020. https://www.spk.usace.army.mil/Portals/12/documents/civil_works/JFP/Water%20Control%20Manual%20Update/DSEAandAppendices2017/IndividualDocs/WCMUpdateDraftSEAEIR_06022017.pdf?ver=2017-06-07-115751-173.

USBR and SAFCA (US Bureau of Reclamation and Sacramento Area Flood Control Agency). 2004. "Long-term reoperation of Folsom dam and reservoir. Final environmental assessment." Accessed September 16, 2020. https://cvfpb.ca.gov/wp-content/uploads/2019/01/FINAL-Folsom-WCM-Update-SEAEIR.pdf.

USBR (US Bureau of Reclamation). 2019. "Folsom Dam." Accessed September 16, 2020. https://www.usbr.gov/projects/index.php?id=74.

Water Forum. 2007. "Summary of the lower American River flow management standard." Accessed September 16, 2020. http://www.waterforum.org/wp-content/uploads/2015/09/FMS-Outreach-Report-2007.pdf.

Wu, X., Y. Zheng, B. Wu, Y. Tian, F. Han, and C. Zheng. 2016. "Optimizing conjunctive use of surface water and groundwater for irrigation to address human-nature water conflicts: A surrogate modeling approach." *Agric. Water Manage.* 163: 380–392.

Yao, H., and A. Georgakakos. 2001. "Assessment of Folsom Lake response to historical and potential future climate scenarios: 2. Reservoir management." *J. Hydrol.* 249 (1–4): 176–196.

Zeng, Y., Z. Xie, and S. Liu. 2017. "Seasonal effects of irrigation on land–atmosphere latent heat, sensible heat, and carbon fluxes in semiarid basin." *Earth Syst. Dyn.* 8 (1): 113–127. https://doi.org/10.5194/esd-8-113-2017.