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RESEARCH

Reservoir Operating Rule Optimization for California's Sacramento Valley

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ABSTRACT

Reservoir operating rules for water resource systems are typically developed by combining intuition, professional discussion, and simulation modeling. This paper describes a joint optimization–simulation approach to develop preliminary economically-based operating rules for major reservoirs in California's Sacramento Valley, based on optimized results from CALVIN, a hydro-economic optimization model. We infer strategic operating rules from the optimization model results, including storage allocation rules to balance storage among multiple reservoirs, and reservoir release rules to determine monthly release for individual reservoirs. Results show the potential utility of considering previous year type on water availability and various system and sub-system storage conditions, in addition to normal consideration of local reservoir storage, season, and current inflows. We create a simple simulation to further refine and test the derived operating rules. Optimization model results show particular insights for balancing the allocation of water storage among Shasta, Trinity, and Oroville reservoirs over drawdown and refill seasons, as well as some insights for release rules at major reservoirs in the Sacramento Valley. We also discuss the applicability and limitations of developing reservoir operation rules from optimization model results.

KEY WORDS

optimization, operating rules, reservoir release rules, system simulation

INTRODUCTION

Water scarcity is a significant and controversial challenge for California, incurring substantial economic and environmental costs (Hanak et al. 2011). To better manage these problems, California relies on an extensive interconnected system of reservoirs and aquifers. The effective operation of this system requires operating rules and priorities, established based on water rights, regulations, agreements, and the operator's experience of how the system performs. As California faces prolonged droughts and greater water demands, improving the operations of existing, new, and expanded reservoirs becomes imperative. The more formal optimization of operating rules might improve how California's water resource system performs for present and future conditions. This paper attempts to derive optimized storage allocation and reservoir release rules for major reservoirs in California's Sacramento Valley using the results of the CALVIN (California Value Integrated Network) optimization model. We refine and test these rules using a simple spreadsheet simulation model and then compared the CALVIN results with results from the CalSim II model.

Reservoir operating rules are often developed from simulation modeling results and the past experience and intuition of operators, supplemented by historical records, current observations, and future forecasts. Optimization modeling can be especially useful in system re-operation studies to explicitly include performance objectives in rule development. Optimization models can be applied to derive rules for many different economic and environmental objectives, such as flood protection, water supply, and temperature control. In reality, operating rules must balance multiple objectives; however, optimization methods can help assess ideal performance for specific objectives, and narrow the vast number of potential operations. This paper applies an economic-optimization model to develop optimized reservoir operating rules for California's Sacramento Valley (Nelson 2014). This effort, supported by a companion simulation model, is a common academic approach to developing reservoir rules and rule curves (Young 1967; Lund and Ferreira 1996). Using optimization models for the initial scoping and development of reservoir operating rules provides a more explicit and objectively defined starting point for rule development, and can improve the operational coherence of complex systems.

Many mathematical optimization techniques are available to develop reservoir operating rules. Some techniques produce analytical results that may help identify potential rule forms: other numerical optimization methods more directly and precisely specify promising operating rules (Yeh 1985; Lund and Ferreira 1996; Lund and Guzman 1999; Labadie 2004). No existing approach can perfectly derive optimal reservoir operating rules, but they can point water managers in the right direction. Applying deterministic optimization methods, which ignore or neglect uncertainty and randomness, is the simplest approach to probabilistic problems. This is often done for 'representative' conditions (particularly for streamflow) to identify promising operating procedures (Evenson and Moseley 1970; Karamouz and Houck 1982). Deterministic optimization methods can better represent the many details of large reservoir systems with less computational requirements, and have been used to develop reservoir operating rules. Inferring operating rules from deterministic optimization results, although imperfect, can provide valuable insights, and is relatively inexpensive and easily understood by operators, modelers, and policy-makers (Ferreira and Lund 1994). Some elaborate statistical and fitting methods also are available so operating rules can be inferred from deterministic optimization results (Saad and Turgeon 1988; Saad et al. 1992, 1994).

Explicit stochastic optimization, which uses probability distributions to represent uncertainty in parameters, is sometimes used to represent hydrologic systems, particularly when dealing with the uncertainty in hydrologic inflows needs to be addressed (Tejada–Guibert et al. 1993; Loucks et al. 1981); explicit representation of non-hydrologic uncertainties is rare. However, explicit stochastic techniques are often limited by computational requirements, the difficulty of representing details for extensive systems, and mathematical limitations in explicitly representing hydrologic uncertainty (Young 1967; Loucks et al. 1981). Advances in computing capacity and more sophisticated techniques have reduced, but not eliminated, such limitations. Implicit stochastic optimization, a more sophisticated application of deterministic methods, optimizes over a long representative hydrology that is based on historical record or created from synthetic streamflow generators (Jettmar and Young 1975; Lund and Ferreira 1996). Implicit stochastic optimization can yield better results than its explicit counterpart because it can more accurately represent of other aspects of the problem (Karamouz and Houck 1987).

Common rules developed from optimization results are storage allocation rules, storage target rules, and release rules. Such rules have been developed from deterministic optimization results for the Missouri River system (Ferreira and Lund 1994), the Columbia River system (Lund and Kirby 1995; Murk 1996), and some California reservoirs to address climate change issues (Medellín–Azuara et al. 2008). These rules can employ a range of techniques (Mousavi et al. 2007; Lund 1996). Storage allocation rules balance water storage among multiple reservoirs, helping set storage targets, and identifying drawdown and refill priorities across reservoirs. Release rules define how much water to release from a specific reservoir and at what time, based on state variables, such as month, storage, and inflow conditions.

CALIFORNIA'S SACRAMENTO VALLEY SYSTEM AND THE CALVIN MODEL

The Sacramento Valley is the northernmost part of California's Central Valley, surrounded by the northern coast ranges to the west, the southern Siskiyou Mountains to the north, and the northern Sierra Nevada to the east (Bailey 1966; Durrenberger 1976). It is the wettest part of the Central Valley, with its water flowing southward through the Sacramento River to the Sacramento–San Joaquin Delta, where water is diverted to the San Francisco Bay Area, the southern Central Valley, and southern California (Kelley 1998). This region is heavily dammed with major reservoirs on all large tributaries, mostly for flood protection, water supply, and hydropower (Hanak et al. 2011).

This study develops operating rules for the Sacramento Valley's five largest reservoirs (Shasta, Oroville, Trinity, Folsom, and New Bullards Bar). Shasta, California's largest surface reservoir, primarily serves the federal Central Valley Project (CVP) for water supply, hydropower, and flood storage on the upper Sacramento River, with a maximum capacity of 4.5 million acre-feet (maf). Trinity Reservoir, on the Trinity River, supplements CVP storage at Shasta with an additional 2 maf of storage capacity and supports diversions from the Trinity River into the Sacramento Valley. Oroville, California's second-largest reservoir, with a storage capacity of 3.2 maf, is the major reservoir of the State Water Project (SWP). It provides water supply storage, hydropower, and flood control on the Feather River. Folsom Reservoir, on the American River, has 1 maf of storage capacity and is operated by the CVP for water supply, hydropower, and flood control for the Sacramento region. Finally, New Bullards Bar (NBB) Reservoir on the Yuba River is locally owned and operated for irrigation water supply, hydropower, and flood control, with 0.9 maf of storage capacity. Oroville and NBB reservoirs could be operated in parallel since the Yuba River joins the Feather River, but they have separate owners. Figure 1 presents a map detailing the Sacramento Valley and the reservoirs discussed in this study.

This study uses the deterministic optimization model CALVIN to infer strategic reservoir operating rules for the major reservoirs in California's Sacramento Valley for projected water demands in 2050. CALVIN is an economic-engineering optimization model of California's water-resources system. The model's network flow-optimization algorithm suggests infrastructure operations and water-management decisions that minimize net scarcity and operating costs statewide over the entire modeled period (Lund et al. 2009). The system includes reservoir releases, groundwater pumping, water trade, water reuse, treatment, conservation, and desalination operations and costs, subject to environmental, capacity, and water-availability constraints (Draper et al. 2003). CALVIN includes many water-management options, explicitly integrating broad economic objectives. The model has been applied to a wide variety of planning, operations, and policy-making problems, including climate change (Tanaka et al. 2006; Medellín–Azuara et al. 2008; Harou et al. 2010), environmental restoration (Null and Lund 2006; Null et al. 2014), water markets (Jenkins et al. 2004), and infrastructure policy problems (Hanak et al. 2011; Lund et al. 2010; Tanaka et al. 2011).

CALVIN's agricultural and urban demands are estimated from static economic models for a future level of development (here 2050). CALVIN includes about 90% of California's urban and agricultural water demands, and about two-thirds of all runoff in the state (Medellín–Azuara et al. 2008). The model used a 72-year monthly time series of hydrology (1921–1993) to represent system variability (Draper et al., 2003). The long hydrologic time series means that CALVIN can be thought of as having an implicitly stochastic representation of California's hydrology (Lund et al. 1999). CALVIN does not use rule curves or operating rules. As an optimization model, CALVIN minimizes an objective function of total economic cost to operate California's water system. We run the CALVIN model to solve the objective function using the U.S. Army Corps of Engineer's HEC–PRM, which is a linear generalized network

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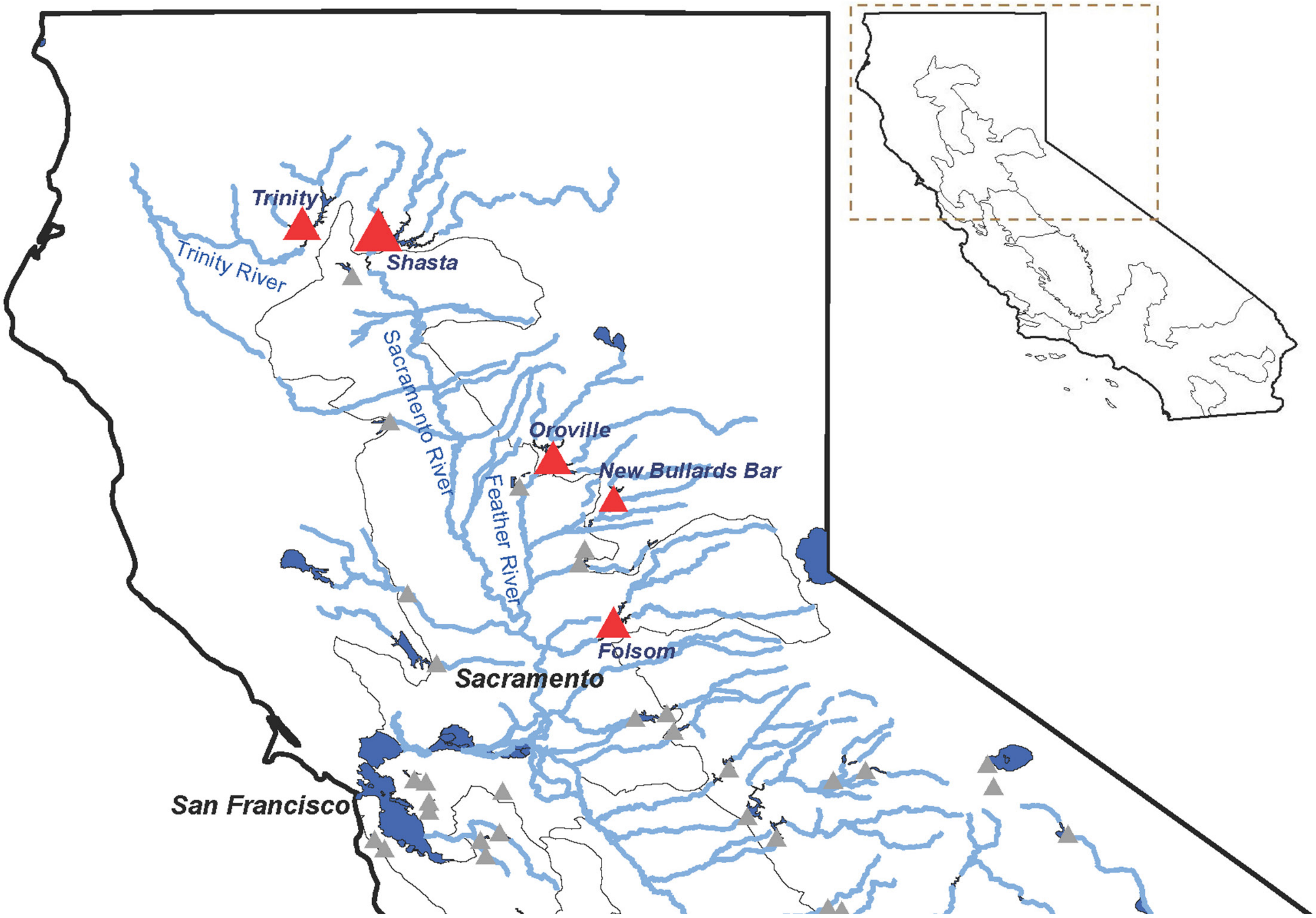

Figure 1 Major rivers and reservoirs of California's Sacramento Valley

flow-optimization solver for multi-reservoir systems. Recent updates to the CALVIN model focused on improving the representation of groundwater in the Central Valley based on C2VSim (California Central Valley Groundwater–Surface Water Simulation Model), a model that simulates groundwater flow in the Central Valley (Chou 2012; Zikalala 2012). Updates also were made to Central Valley agricultural water demands based on recent SWAP (Statewide Agricultural Production) model runs (Chou 2012; Howitt et al. 2012; SWAP c2014). In addition, constraints on Delta outflow and Delta pumping at Banks Pumping Plant were changed to reflect operations in CalSim II.

The rules developed using the CALVIN model are then compared with operational results from the CalSim II simulation model, which was developed by the California Department of Water Resources (CDWR) and the U.S. Bureau of Reclamation (USBR). The CalSim II model covers the Sacramento Valley, the upper Trinity River, and the San Joaquin Basin with connections to the Tulare Basin and southern California areas the SWP serves (Draper et al. 2004). It focuses on SWP and CVP water operations, but also includes some other facilities in California's Central Valley (Draper et al. 2004; Munévar and Chung 1999; Parker 2006). CalSim II describes the system's behavior under predefined operational priorities (Close et al. 2003; Ferreira et al. 2005; Parker 2006). The operating priorities in CALSIM II are intended to represent the water right, environmental, and legal priorities of the system.

OPERATING RULES FROM OPTIMIZATION RESULTS

This section presents the development of optimized storage allocation and reservoir release rules from the results of the CALVIN optimization model's base case for major reservoirs in California's Sacramento Valley (Nelson 2014). The Calsim II results we used for comparison are from the 2005A01A Existing Conditions Run. Representative examples are shown below, with more results available in Nelson (2014).

Storage Allocation Rules

This section presents storage allocation rules inferred from CALVIN results for several Sacramento Valley reservoir sub-systems. The systems we examined here include the two-reservoir sub-systems of Shasta–Trinity and a three-reservoir sub-system of Shasta–Trinity–Oroville. We also describe optimized storage allocation rules between Oroville and New Bullards Bar, although we could not compare them with CalSim II results because the Calsim II results used did not include the NBB Reservoir. Nelson (2014) also includes rules for a four-reservoir sub-system (Shasta, Trinity, Oroville, Folsom), and an examination of water balancing between total groundwater and surface water storage for the region. However, we could not develop clear balancing rules for groundwater–surface water storage allocation, partly because little active groundwater management occurs in the Sacramento Valley.

Shasta–Trinity Reservoir System

With the objective of maximizing net economic benefits within constraints, CALVIN prefers releases from one reservoir over another for different times and conditions. The economic objective includes incentives (e.g., hydropower benefits) and deterrents (e.g. storage depletion penalties, scarcity costs, and operating costs). Water releases from Trinity produce additional hydropower, making it more valuable than diversions from Shasta, though Shasta storage is more valuable during the refill season because of higher storage-depletion penalties (to retain cold water for summer fish flows).

Figure 2A shows CALVIN storage allocation in the Shasta–Trinity reservoir system for all months of model output, where total storage is the summed storage of both reservoirs. The black lines superimposed on the plots are the most extreme storage allocation for Shasta–Trinity operations, which here are the storage allocation rule curves. The slope of these curves is a relative drawdown or refill proportion between the two reservoirs given any total storage between them; these proportions must sum to one.

The derived drawdown rules in Figure 2A start from a high total storage and follow the storage allocation curve to the left. Derived refill rules start from a low total storage and move rightward (the reverse of the drawdown rules). When total storage exceeds 6.3 maf, all drawdown comes from Trinity, while Shasta remains at its capacity. As total storage decreases, storage allocation curves diverge into a solid line and a dashed line. If drawdown follows the solid line, Trinity continues releasing until its storage is about 0.7 maf (total storage is around 5.3 maf). Then CALVIN starts draining Shasta, with minimal Trinity releases, until Trinity storage falls to 0.4 maf (Trinity's dead pool prevents further draw down) and Shasta must take all drawdown. If drawdown follows the dashed curve, Trinity continues drawdown but at a much lower rate, and Shasta releases more water. When total storage falls to about 3 maf, drawdown priority shifts slightly back to Trinity, with Shasta draining at a lower rate. Finally, when Trinity storage falls to 0.4 maf, the dashed curve meets the solid curve and all drawdown comes from Shasta.

To refine the above rule curves, we define a Past Year Type (PYT) index based on the water availability over the previous 12 months for each reservoir, since variation in annual water supply would affect reservoir system operations. The PYT classification is similar to the five water year types (Wet, Above Normal, Below Normal, Dry, and Critical) defined by the California Department of Water Resources. Figures 2B and 2C show storage allocations for the months with only Wet PYT and Critical PYT respectively. This additional variable greatly improves the clustering of storage allocations so we can infer more precise storage allocation rules. In Figure 2B, with a wet previous year, storage in Shasta and Trinity tends to follow the dashed lines. When the drawdown season begins, Shasta starts releasing sooner since the coming refill season will likely be

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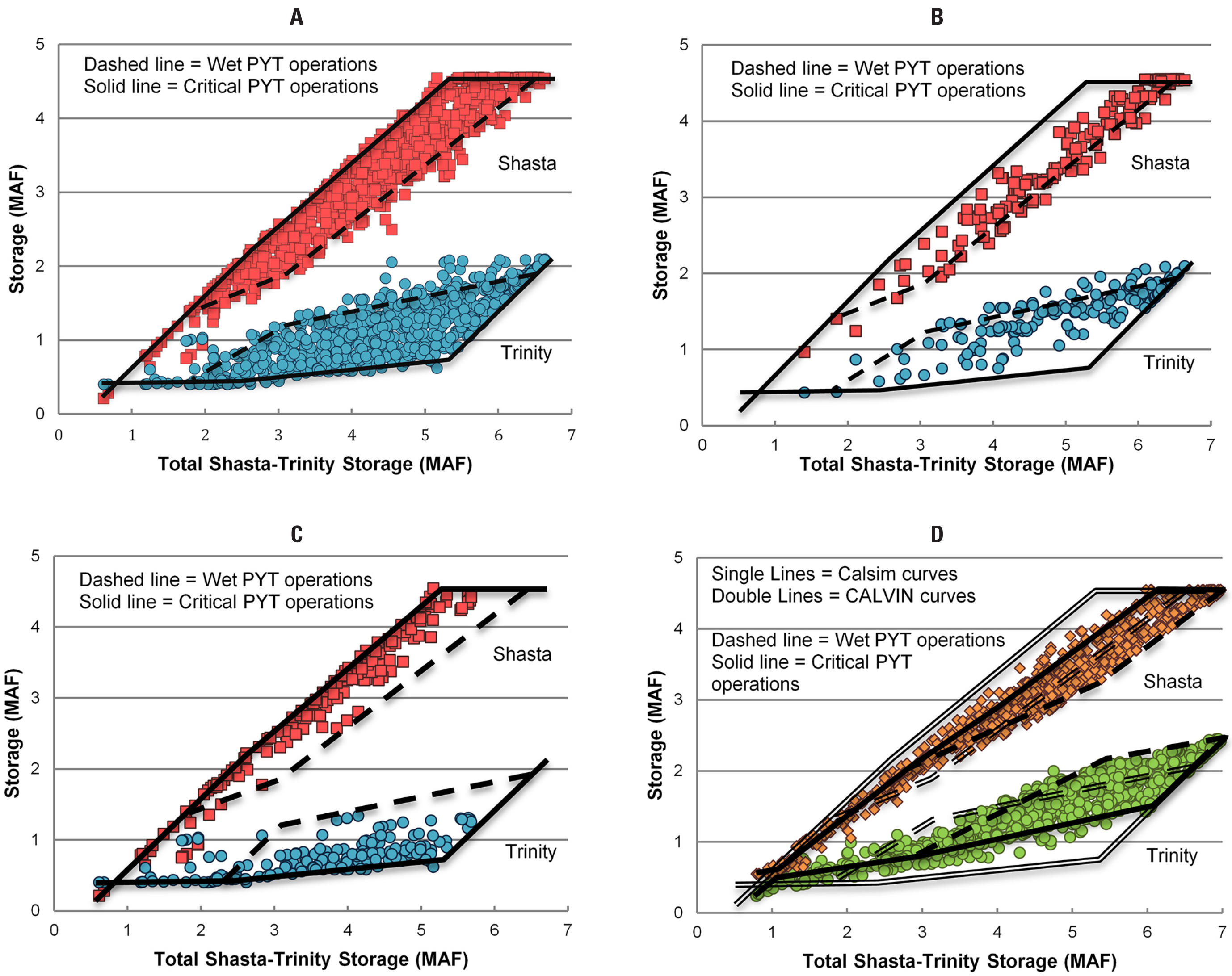

Figure 2 CALVIN storage allocation between Shasta (red) and Trinity (blue) reservoirs: (**A**) for all months, (**B**) when PYT = wet, (**C**) when PYT = critical. (**D**) CalSim II storage allocation between Shasta (orange) and Trinity (green) for all months.

wet with potential floods, thus opening up more storage and postponing spills. Trinity has much smaller inflows, so flooding and spilling are less of a problem. During the refill season, the model refills Shasta later, since there will be more spring runoff at the end of the season, which allows Trinity to store more water for future droughts. However, in Figure 2C with a dry previous year, water supply is more of a concern than floods and spills, so the model follows the solid line where most of Trinity's storage is drained before tapping into Shasta. Figure 2D shows a similar overall storage allocation plot of the Shasta–Trinity system from CalSim II results, where storage is shifted down in Shasta and up in Trinity, closer to the operations CALVIN suggested for wet periods. Here, Trinity has smaller dead pool storage (0.24 maf). CalSim II results tend to be more conservative for dealing with floods, keeping more storage space in Shasta—essentially balancing the reservoirs in all years as CALVIN does only for wet years. CALVIN can be less conservative since it has a perfect hydrologic forecast, although CALVIN does maintain seasonal flood-control pools. The overall storage allocation rules can help identify general patterns in optimal reservoir operation. Creating monthly plots reveals more detail. For this example, the optimization model suggests that it might be useful to seek a different storage balance between Trinity and Shasta in drier years.

Oroville–New Bullards Bar Reservoir System

Figure 3A–D below shows the storage allocation for the Oroville–New Bullards Bar system in CALVIN. Unlike the previous system, NBB storage allocation has different operations for refill and drawdown. Here, the dashed lines are the refill curve and the solid lines are the drawdown curve. For clarity, Figure 3B–D presents only NBB's storage allocation since it is small compared to Oroville.

Figure 3C presents NBB storage allocation during the primary drawdown months of June through September. Following the solid lines from right to left, drawdown operations suggest that NBB should provide the first 0.4 maf of drawdown while Oroville remains at capacity. Oroville has high depletion

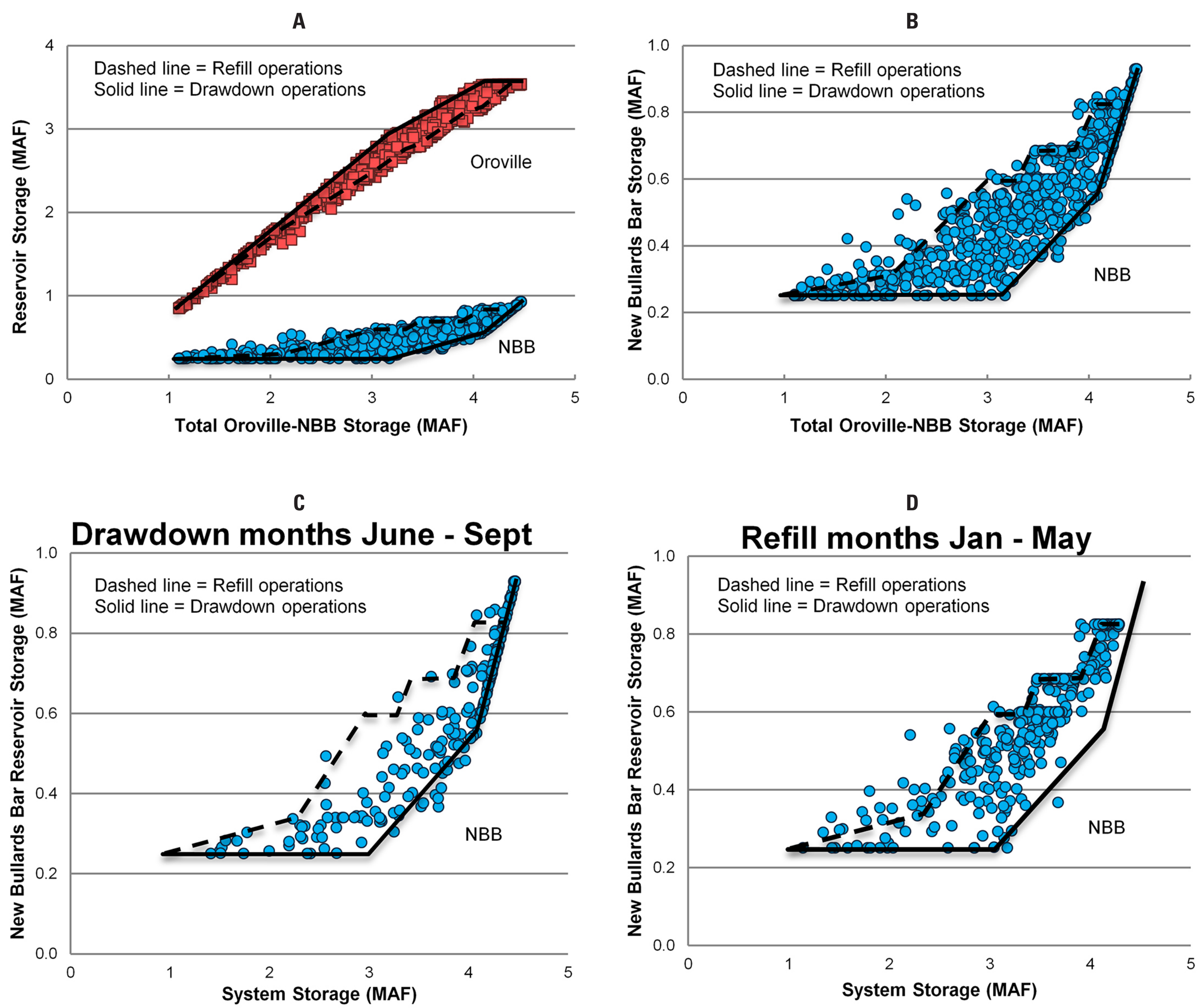

Figure 3 CALVIN storage allocation between Oroville (red) and NBB (blue) reservoirs: (**A**) both reservoirs, (**B**) NBB reservoir only, for all months, (**C**) NBB during the drawdown season: June–September, (**D**) NBB during the refill season: January–May.

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penalties at the beginning of the summer, so the model tries to keep Oroville full during that period. When total storage falls to about 4.1 maf, NBB has already emptied half of its available storage, so to preserve its remaining storage, the model starts draining Oroville faster than NBB. After total storage falls to 3 maf, NBB cannot release any more storage and Oroville must supply any further drawdown.

Figure 3D presents NBB storage allocation during the primary months of the refill season: January through May. Following the dashed line from left to right, most early refill goes to Oroville so it can regain lost drought storage. When total storage reaches about 2.4 maf, spring is beginning and NBB starts filling faster. As total storage increases, NBB refill operations follow a staircase pattern (Figure 3B). NBB reservoir has monthly capacity constraints throughout the refill season that leave open flood storage for the following months. In general, NBB should be filled to 0.6 maf by March, to 0.685 maf by April, to 0.825 maf by May, and, finally, to the overall capacity of 0.93 maf by June.

Shasta–Trinity–Oroville Reservoir System

A system with more than two reservoirs can be divided into sub-systems, where each subsystem has multiple reservoirs or secondary sub-systems. Figure 4A shows the overall storage allocation plot for the Shasta–Trinity–Oroville system for all months from CALVIN model results, with Shasta and Trinity treated as one sub-system. Here, the dashed line is the refill curve and the solid line is the drawdown curve. Figures 4B and 4C are storage allocation plots for the refill season (January to April) and drawdown season (June to September) respectively. NBB was omitted so that we could compare operations with CalSim II results.

In Figure 4B, storage during the drawdown season tends to approach the solid line. Starting at full total storage and moving leftward, the Shasta–Trinity subsystem (mostly Trinity) has drawdown priority for the first 3 maf, while Oroville remains at capacity. In CALVIN, Oroville has higher costs for storage depletion during summer than Shasta or Trinity, so it only releases water during the early summer, when storage in other reservoirs is already low. During August and September, the storage depletion penalties at Oroville decrease as the refill season approaches, encouraging Oroville to release more water to avoid potential floods. When Oroville storage falls to about 0.85 maf, further depletion of Oroville incurs large penalties so the model again solely drains Shasta and Trinity. During the refill season, storage allocation tends to follow the dashed line, starting at low total storage and moving rightward (Figure 4C). Shasta and Trinity refill first to at least 2 maf of storage. Oroville then begins refilling, although at a slower rate than Shasta–Trinity, until it has about 3 maf of storage. When spring runoff arrives, Oroville quickly fills to capacity to avoid storage-depletion penalties in summer. For drier years, the dashed refill line moves closer to the solid line. Since less inflow is available during the refill season, Oroville begins refilling earlier and faster, almost in reverse of drawdown.

Figure 4D shows CalSim II storage allocation results for the Shasta–Trinity–Oroville system, which is well approximated for both the drawdown and refill seasons by a single average allocation curve (dotted line). General storage-allocation patterns from CALVIN and CalSim II are similar for refill, but are somewhat different for drawdown. During drawdown, CalSim II tends to preserve Shasta–Trinity storage and make greater releases from Oroville. CalSim II is more likely to open up storage capacity at Oroville to prepare for potential winter floods, since it lacks CALVIN's hydrologic foresight.

Overall, the optimization results suggest several general operational strategies for this reservoir system. First, when more water is available, it is preferable to draw down the Shasta–Trinity subsystem over Oroville. Oroville storage is better used as a buffer during droughts or when Shasta–Trinity supplies run low. Second, refill should occur simultaneously for both reservoirs' sub-systems, but Oroville must stop refilling sooner, to maintain flood storage for spring runoff. Third, for a given total storage, more water should be stored in Oroville than current CalSim II operations suggest. Finally, current CalSim II refill operations are close to the optimized results; however, drawdown operations should shift more towards the Shasta–Trinity subsystem.

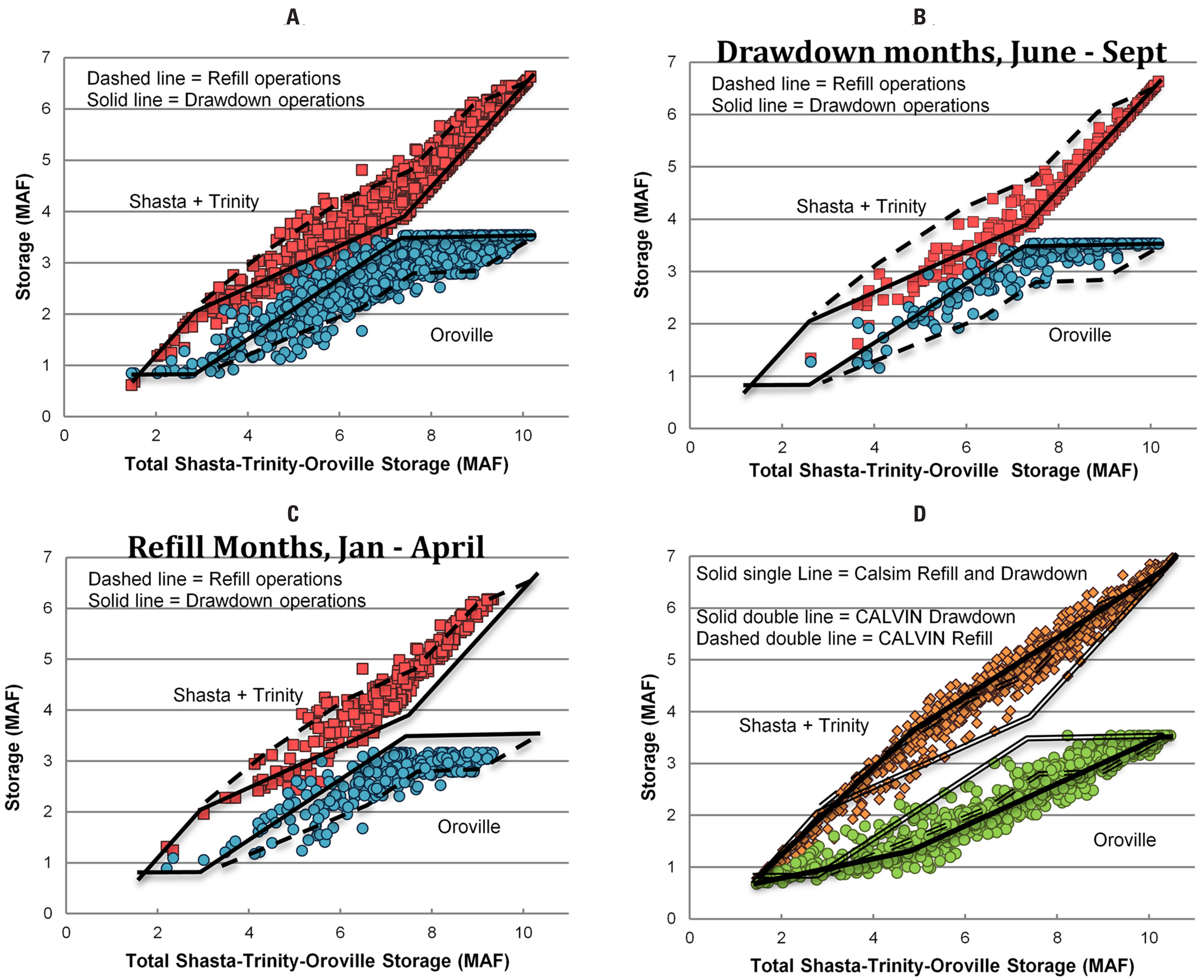

Figure 4 CALVIN Shasta–Trinity (red) and Oroville (blue) storage allocation: (**A**) for all months, (**B**) during the drawdown season: June–September, (**C**) during the refill season: January–April. (**D**) CalSim II Shasta–Trinity (orange) and Oroville (green) storage allocation for all months.

Reservoir Release Rules

Developing reservoir release rules is usually more challenging than water-storage allocation rules (Lund and Ferreira 1996). Identifying patterns in reservoir release from optimization results over long modeling periods can help produce approximate release rules, but these rules rarely reproduce optimization results exactly (Young 1967). Some patterns are easy to identify, but others are less so, because of complexity, noise, and error. The development of optimized rules relies somewhat on professional creativity and persistence, leaving many decisions up to the investigator's interpretation and discretion. This section presents some examples of optimized reservoir release rules we inferred from CALVIN model results. The derived release rules are for monthly operation of a single reservoir, usually based on available water (storage plus inflow), inflow over the past year, or total regional storage. We discuss a few examples below for illustration. Additional release operations for each month and each major Sacramento Valley reservoir are explored in Nelson (2014).

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Figure 5A shows Shasta release for January, depending on available water in January (storage plus inflow), following the Standard Operating Policy (SOP) (Klemeš 1977). A 0.2 maf monthly release target is observed regardless of the available water. When available water exceeds the release target and reservoir storage is at full capacity, the reservoir must release any surplus water as spill. However, optimization model results may reveal no clear pattern for release rules, as shown in Figure 5B for Oroville in October. Two monthly release targets are roughly chosen as an optimal release rule with substantial variation: releasing around 0.1 maf when available water is less than 2 maf, or releasing about 0.4 maf when available water exceeds 2 maf.

Release rules are sometimes driven by broader system conditions. Figure 5C shows Oroville releases in July, plotted against the total regional storage of all five major reservoirs. When regional storage is below 8 maf, the model relies on Oroville to release about 1 maf of water, but only when other reservoirs in the system are running low because of Oroville's high value for storage in July. As system storage increases from 8 maf to 9.8 maf, Oroville's release falls to about 0.1 maf, since water elsewhere is sufficient to

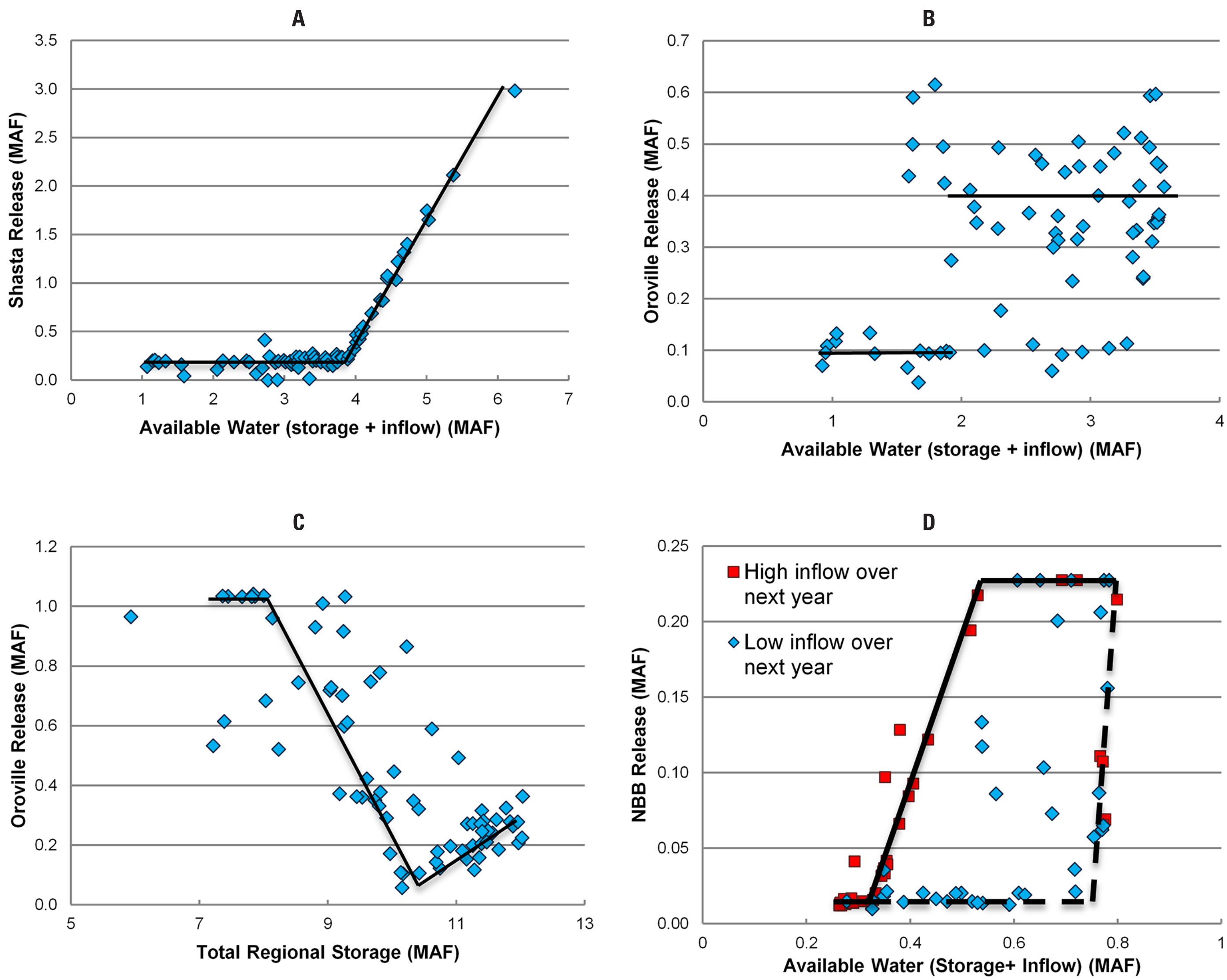

Figure 5 Illustrative release rules inferred from CALVIN: (**A**) Shasta Reservoir for January; (**B**) Oroville Reservoir for October; (**C**) Oroville Reservoir for July; (**D**) New Bullards Bar Reservoir for September

meet the demands. When system storage exceeds 9.8 maf, Oroville has enough water to increase releases again. Coordinating storage operations system-wide may have some value, and should be explored further.

The optimal release rule for NBB in September is rather different (Figure 5D). When available water is less than 0.325 maf, the monthly release target is low, at about 0.015 maf. However, releases can follow two paths when available water exceeds 0.325 maf, depending on available water for the coming year. If available water over the next year is high (red squares), NBB needs to make room for potential large inflows by following the solid black line. If little water will be available next year (blue diamonds), the optimum monthly release would stay at the low target of 0.015 maf to saves water for the following dry year, unless current available water exceeds the reservoir capacity. Here, inflow over the next year is considered high if it exceeds the median inflow over the next year, and inflow is considered low if it is less than the median value. The optimal rules for NBB require unrealistic foresight, but do show some insights and reveal the difficulties of making releases with uncertainty.

SIMULATION TESTING AND REFINEMENT

We refined and tested the optimized reservoir operating rules derived from CALVIN results (from here on called 'derived rules') by a simple spreadsheet simulation model. This model used inflows and initial conditions from the CALVIN model along with the derived rules to generate a time series of storage and release values for each of the five major reservoirs. We then compared these time series with the releases and storage time series directly from CALVIN and CalSim II results. Nelson (2014) presents comparisons of all five reservoirs. Shasta Reservoir results are presented below for illustration.

Figure 6A compares average monthly releases from Shasta for the derived rules and the direct model results of CALVIN and CalSim II. The derived-rule simulation and the actual CALVIN results are similar. Both begin the drawdown season averaging large releases of about 0.7 maf per month in May through August, then gradually decrease through the fall. From January to March, the derived rules suggest releasing a little more each month than the CALVIN results, but still follow a similar trend. However, CalSim II releases differ greatly from the derived rule simulation and modeled CALVIN results. CalSim II releases peak at 0.7 maf per month only in July, before quickly falling to 0.3 maf per month by October. Between November and March, CalSim II tries to make extra storage available for spring runoff, and releases more than in the other cases. In April, CalSim II releases fall a little, matching the results of the derived-rule simulation, before slowly increasing to the maximum in July. In general, CALVIN results have more summer releases and fewer winter releases than Calsim II.

Figures 6B and 6C show the storage comparison between the derived rule simulation and the direct CALVIN and CalSim II results for Shasta Reservoir, from 1921 to 1993. In the direct results, CALVIN storage levels fluctuate by about 2.5 maf in most years, while CalSim II has a yearly storage change of only 1.5 maf. Reservoir storage in the derived rule simulation varies more than in CalSim II, but less than in CALVIN, with about 1 maf less storage than CalSim II at the end of the drawdown season. For seasonal operations, both CALVIN and the derived rules operate surface storage more aggressively. During droughts, Shasta storage in CalSim II is quickly drained, and the reservoir is operated at lower overall storage levels. Yearly drawdown in CALVIN is reduced during dry periods to preserve storage longer, partially aided by hydrologic foresight, until the final year of the drought, when there will be enough storage in the following year to refill the reservoir. With no hydrologic foresight, drought operations for the derived rule simulation are more like CalSim II, draining reservoir storage quickly rather than preserving it.

We can compare the derived rules and the CalSim II operations by how close their performance is to the original CALVIN operations, which are the best operations to maximize defined economic benefits. Table 1 presents the percentage of all months where reservoir storage from the derived rule simulation is closer to CALVIN reservoir storage than the CalSim II reservoir storage for each PYT, for each month, and overall for all months in the 72-year time series (percentages exceeding 50% are lightly shaded). Overall, the derived rules operate Trinity and Oroville

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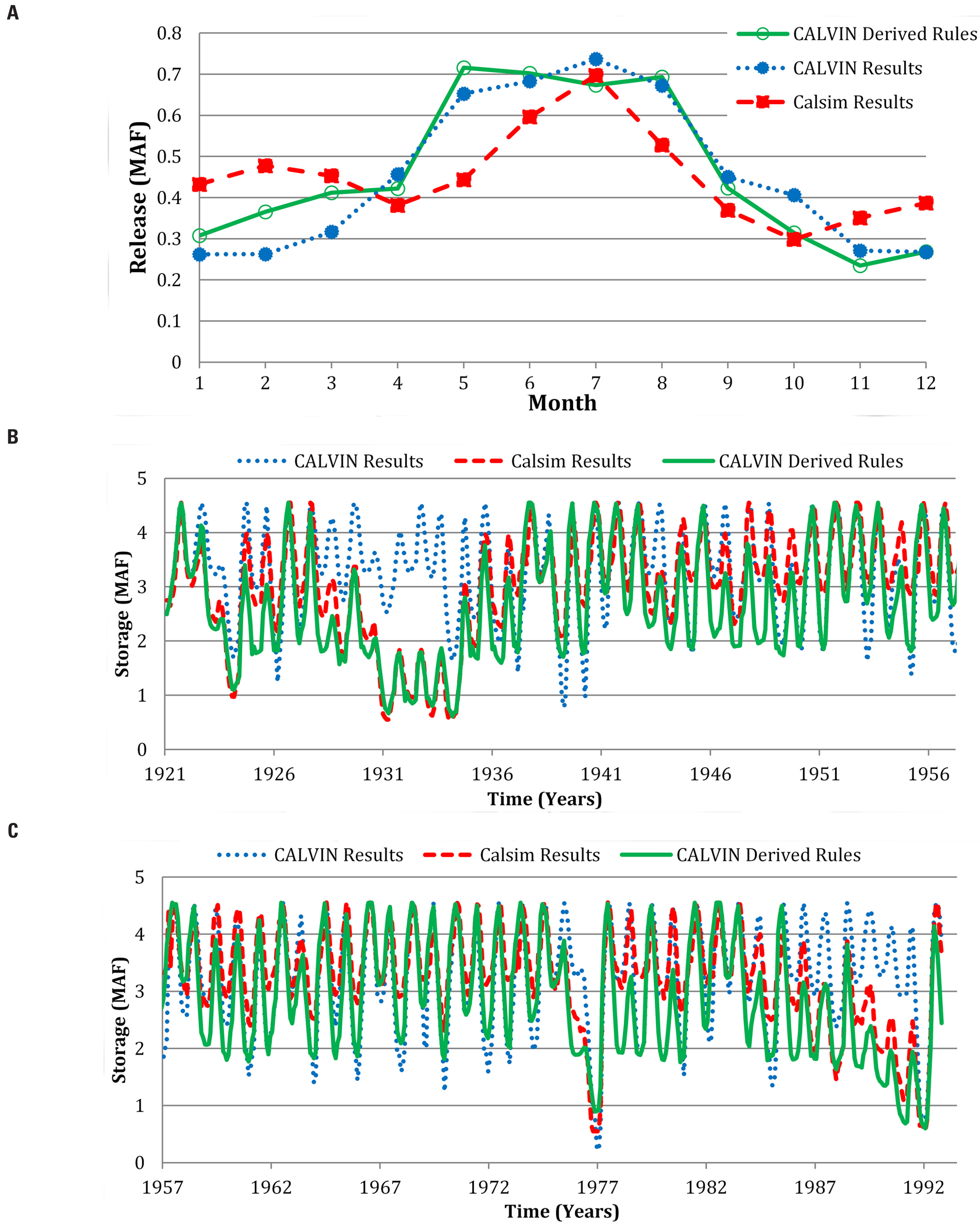

Figure 6 Comparison of the CALVIN derived rules, direct CALVIN, and CalSim II model results for (**A**) average monthly Shasta release; (**B**) Shasta storage from October 1921 to September 1957; (**C**) Shasta storage from October 1957 to September 1993.

Table 1 Percent of months in the examined 72-year period where the derived rule simulation is closer to CALVIN than CalSim II, for each past 12-month year type or each month (percentages greater than 50% are lightly shaded)

		Shasta	Trinity	Oroville	Folsom
Past (12-month) Year Type [a]	Critical	44%	60%	49%	16%
	Dry	41%	66%	55%	46%
	Below Normal	45%	80%	64%	60%
	Above Normal	59%	86%	74%	58%
	Wet	58%	94%	61%	68%
Month	January	49%	79%	54%	57%
	February	38%	76%	53%	53%
	March	43%	74%	57%	40%
	April	54%	75%	65%	36%
	May	56%	79%	78%	35%
	June	33%	79%	94%	36%
	July	43%	83%	88%	63%
	August	54%	78%	68%	56%
	September	58%	76%	38%	56%
	October	60%	76%	44%	54%
	November	58%	76%	44%	65%
	December	56%	75%	50%	56%
Overall		50%	77%	61%	50%

a. See definition of Past Year Type at bottom of page 5.

more economically than CalSim II, while Shasta and Folsom results are roughly the same. In general, the derived rules operate the system more closely to the CALVIN operations in wet years. Folsom operations are especially sensitive to water availability; simulation is better than CalSim II in only 16% of months in dry years, compared to about 60% of months in all other year types. In addition, these results also indicate that CalSim II operations are not necessarily sub-optimal.

More refinement of the derived rules might improve their performance. Adding economic performance indicators to the simulation model could guide refinements and help identify release rules that need more development. Further analysis could indicate the economic differences in performance between different operations and better quantify where and when operations might be improved. Iterative simulation methods are another alternative that is commonly used to calibrate operating rules (Lund and Guzman 1999). Additional simulation modeling, possibly by applying the rules in Calsim II, could provide a more realistic picture of how the derived rules affect California's water system as a whole. The simple rules developed here were based only on one or two variables, but more variables could be considered. Other available refinement strategies include mixed optimization and regression techniques (e.g., Bhaskar and Whitlatch 1980; Lund and Ferreira 1996; Mousavi et al. 2007).

DISCUSSION AND CONCLUSION

This paper develops preliminary reservoir operating rules from the results of CALVIN, a deterministic hydro-economic optimization model that operates over a wide range of hydrologic events, for major reservoirs in California's Sacramento Valley. These strategic rules are approximated from optimization results by graphical displays and observation of the patterns and trends in output data. Derived reservoir operating rules include: (1) monthly reservoir storage allocation rules for multiple reservoirs, and (2) monthly reservoir release rules for each major individual reservoir. We used a simple simulation

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model to refine and test the preliminary operating rules developed.

The primary conclusions of this study include the following:

1. Optimization models can help initial development of reservoir operating rules or to refine existing rules. Reservoir operating rules inferred from optimization model results are often simple, but can be effective. These methods are especially useful where rule development is desired quickly, in response to changes in infrastructure (new reservoirs, conveyance, etc.), management and environmental objectives, and climate conditions, beyond the experience of operators or policy-makers. Further studies based on these initial rules can provide more sophisticated and realistic operating rules. It is particularly valuable to have compatible simulation and optimization modeling capabilities to speed model and rule refinement and testing.

2. Optimization model results produce effective storage-balancing rules for reservoirs in California's Sacramento Valley. Refill and storage-balancing operations between Shasta and Trinity reservoirs are related to water availability over the previous year. Releasing waster from Shasta is preferred if the previous year was wet, but releasing water from Trinity should be favored if the previous year was dry. Adding Oroville into the system introduces a shift between refill and drawdown operations. Release preference should be given to the Shasta–Trinity sub-system during drawdown periods, but both sub-systems should refill simultaneously during the refill season.

3. Release rules are more difficult to define from optimization results than storage allocation rules. However, optimization results can provide preliminary rules to be further improved through simulation-based refinement and testing. The common release rules derived in this study are based on inflow, storage, available water, inflow over the past year, and regional storage.

4. Simple spreadsheet simulation models are useful to initially refine and test derived release rules. Further, refinement through more sophisticated procedures would be valuable, including more detailed simulation modeling, and comparisons of economic and environmental performance (Lund and Ferreira 1996).

5. Simulation and optimization modeling are best used as compatible companions with different strengths and weaknesses that together can help modelers, operators, and policy-makers explore the infinite range of complex solutions available to address diverse water management objectives.

It is important to note that this analysis has several limitations. For example, perfect hydrologic foresight of floods and droughts is assumed in most CALVIN runs (although it may not drastically affect results) (Draper 2001; Newlin et al. 2002). Subsequent simulation studies and more elaborate forms of optimization with limited foresight can correct these limitations (Draper 2001; Lund and Ferreira 1996). Simulation modeling using historical hydrology is not immune from the effects of hydrologic foresight either, especially for extreme events. Many operating rules used in simulation models will have been established to perform well for a repeat of the historical hydrology—and so implicitly assume greater foresight than is operationally realistic. Operating rules developed using the historical inflows may not perform well for future droughts (or floods) or with new hydrologic patterns, since they were calibrated on past conditions.

Both the CALVIN and CalSim II models use monthly time steps. The derived monthly operating rules can provide only monthly targets on total release and storage, but real reservoirs usually need daily and hourly operational targets. The geographic regions and their representations in the CALVIN and CalSim II models are not identical, so operations from the two models will not be precisely comparable. Specifically, some demand areas in CALVIN are not represented in CalSim II, and the demand levels for CALVIN (year 2050) and CalSim II (year 2005) also differ, although the models have comparable inflows. In addition, the CalSim II model run we used for comparison is for 2005 conditions, so it does not reflect the most recent biological opinions from 2008–2009 for which the SWP and CVP are now operated. Finally, the derived rules in this study are optimized for statewide economics only (within environmental and flood-storage constraints). Alternative operating rules could optimize other objectives, such as minimizing expected flood damage or adherence to strict water rights without water markets (which is closer to CalSim II's priority-based operations).

Development of system operating rules is both challenged and blessed by the abundance of near-optimal operations that are possible for water-resource systems (Rogers and Fiering 1986). Many operations can produce similar overall system performance, making it easier to find potential solutions that are practically indistinguishable in overall performance. With so many near-optimal solutions, identifying the true global optimum can be impossible. From a system-wide perspective, even in the best cases, alternative near-optimal will likely excite great differences in opinion among local stakeholders, for whom 'near-optimal' solutions, from an overall perspective, may not be nearly optimal from an individual perspective.

Our development of derived reservoir operating rules in this study is more illustrative than final. The preliminary derived rules should be further refined and tested with more detailed simulation studies and sensitivity analyses (Lund and Ferreira 1996). This would include revisions of the Calsim II and CALVIN models to more closely correspond to representations of system demands and hydrology, a fairly major effort. In addition, more recent CalSim II results that reflect current regulatory conditions would be needed to test the rules. Future work should also examine the economic and environmental implications of these alternative reservoir operations. One method to examine this could be to re-run CALVIN, constraining reservoir operations to (1) CalSim II releases and (2) derived operating rule releases. These runs would provide information on system-wide implications and allow comparison of the overall economic performance of each set of operations. Alternatively, a set of economic postprocessors could help identify economic costs and benefits for different existing or proposed system operations from both simulation and optimization models. Explicit economic and environmental performance indicators would be useful to test and refine operating rules in simulation. Potential non-economic indices could include hydropower production, Delta outflow, environmental flow reliability, or water-delivery shortage during dry periods.

Future studies could look at how optimized operating rules could change with changing conditions in California. Developing optimized rules under different climate change scenarios could help policy-makers and water managers be better prepared for potential water supply shifts; such scenarios could include shifts from snowfall to rainfall precipitation, earlier snowmelt, and increased sea level rise (Connell–Buck et al. 2011; Lund et al. 2003; Medellín–Azuara et al. 2008; Tanaka et al. 2006; USBR 2014). Another study could look at optimizing reservoir operations to help achieve groundwater sustainability in the light of recent groundwater management legislation (SGMA c2016, see *http://groundwater.ca.gov/legislation.cfm*). Finally, developing optimized rules that include dynamic flood-control curves could help better contain floods and improve water-supply reliability during droughts.

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