

Adaptability and adaptations of California's water supply system to dry climate warming

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Abstract Economically optimal operational changes and adaptations for California's water supply system are examined for a dry form of climate warming (GFDL CM2.1 A2) with year 2050 water demands and land use. Economically adaptive water management for this climate scenario is compared to a similar scenario with the historical climate. The effects of population growth and land use alone are developed for comparison. Compared with the historic hydrology, optimized operations for the dry climate warming scenario raise water scarcity and total operation costs by \$490 million/year with year 2050 demands. Actual costs might be somewhat higher where non-economic objectives prevail in water management. The paper examines the economical mix of adaptation, technologies, policies, and operational changes available to keep water supply impacts to such modest levels. Results from this screening model suggest promising alternatives and likely responses and impacts. Optimized operations of ground and surface water storage change significantly with climate. Dry-warm climate change increases the seasonal storage range of surface reservoirs and aquifers. Surface reservoir peak storage usually occurs about a month earlier under dry-warm climate change.

1 Background

This study employs downscaled hydrologic results from a dry-warm climate (GFDL-A2 GCM) for year 2085 in an economic-engineering optimization model of California's statewide water supply system (CALVIN, <http://cee.engr.ucdavis.edu/faculty/lund/CALVIN/>)

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with 2050 water demands. CALVIN (CALifornia Value Integrated Network) jointly considers the economic performance and physical feasibility of a wide variety of water management activities and economic performance, including surface and groundwater sources and storage as well as agricultural, environmental and urban water uses (Draper et al. 2003). CALVIN results go beyond simple cost-benefit analysis by using the economic value of water for different users and supply costs to develop economically promising combinations of water management activities from a broad array of options including system re-operation, conjunctive use, water reuse and desalination, water markets, and reductions in water use. The CALVIN model has been applied to various water policy and management problems including climate change impact and adaptation studies (Draper et al. 2003; Harou and Lund 2007; Harou et al. 2006; Jenkins et al. 2001, 2004; Lund et al. 2003; Null and Lund 2006; Pulido-Velazquez et al. 2004; Tanaka et al. 2006).

The approach used for this study was similar to the one employed in Lund et al. (2003) and Tanaka et al. (2006) for examining water supply impacts and adaptations in California resulting from a dry climate warming scenario (Parallel Climate Model 2 or PCM-2) for 2100, exogenous land use, population growth, and agronomic technology change affect water demands. The detailed spatial representation of California's water supply system employed in the CALVIN model is organized divided into four regions (Fig. 1). The model

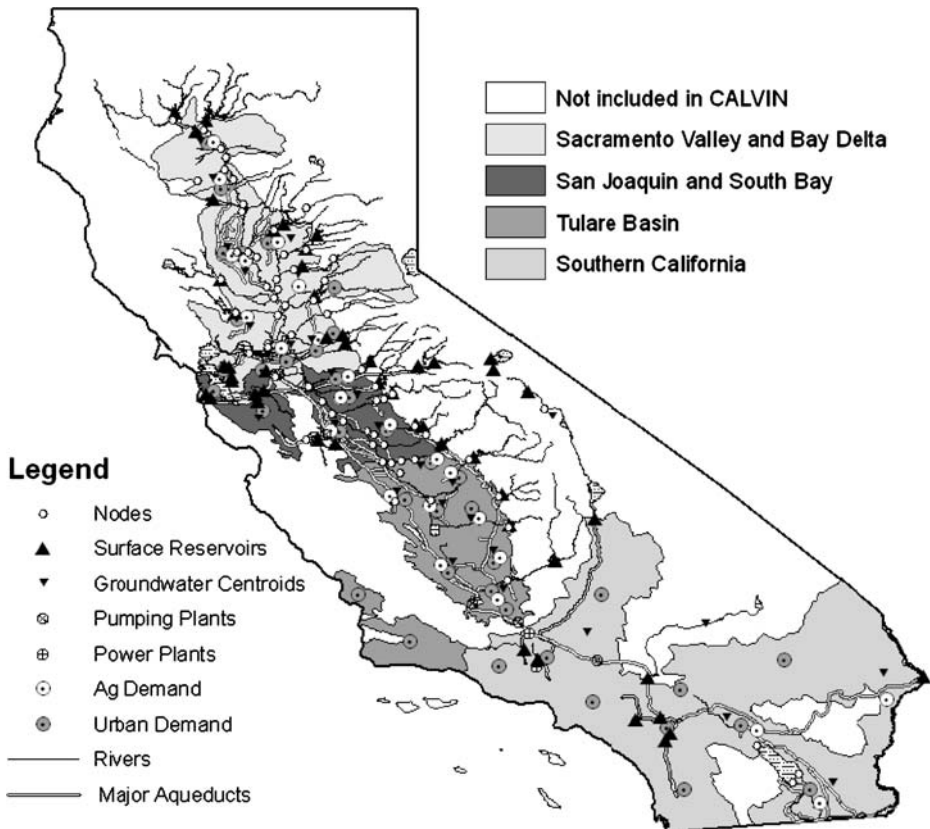


Fig. 1 Hydrologic basins, demand areas, major inflows and facilities in CALVIN (adapted from Jenkins et al. 2001)

represents about 90% of California's urban and agricultural water demands and about two-thirds of all runoff in the state.

The focus of this paper is on specific technological, policy, and operational adaptations physically available to California's water supply system and the ability of such options to mitigate potentially grave climate warming impacts found using simulation models (DWR 2006). Changes in reservoir operating rules due to dry climate warming are also examined.

2 CALVIN

CALVIN is an engineering-economic optimization model that represents California's interconnected water system (Draper et al. 2003; Jenkins et al. 2001). Included are 51 reservoirs, 28 groundwater basins, and 54 economically represented urban and agricultural demand areas, along with over 1,250 links representing the State's natural and built conveyance system.

The overall objective of CALVIN is to minimize total water scarcity and operation costs given 72-years of hydrology (1921–1993). Estimated water demand levels for agriculture and urban use in the year 2050 are used to drive the economic operations of the model. CALVIN allocates water optimally in a monthly time step. Scarcity is defined as the difference between the volume of water at which a users' willingness to pay for additional water goes to zero and the volume of water that is actually delivered. Thus, scarcity occurs whenever the user's target demand is not fulfilled. Scarcity cost is estimated from the integral between target and delivery water amounts below a water value (demand) curve, following techniques described in Gibbons (1986).

As with any model, there are limitations. In addition to data availability and quality considerations, CALVIN has a highly simplified representation of environmental constraints, groundwater, and hydropower. Further, since CALVIN is based on the HEC-PRM linear network flow optimization solver and model for reservoir systems (HEC 1991), there are the shortcomings of perfect foresight (Draper 2001) and restrictive representation of complex conditions due to the linearity requirement of HEC-PRM. As an optimization model, the results also assume that the only operating criterion is to maximize statewide water supply net benefits (minimize net costs) given a set of infrastructure and physical constraints. Actual results are likely to be somewhat worse due to institutional friction in water management, but could be better if additional water management options were considered. Overall, optimization models are more likely to be optimistic in their results, whereas simulation models are likely to be pessimistic. Additional detail on the methodology and limitations of the CALVIN model are available in Jenkins et al. (2001). Despite its limitations, the tool works as a screening model, suggesting promising alternatives and likely responses and impacts.

Results presented herein are consistent with other CALVIN climate change studies with different populations, similar extreme climate change scenarios, and changes in infrastructure (Tanaka et al. 2006; Lund et al. 2003; Harou et al. 2006). The shadow values of facilities and water demands provide sensitivity information for these parameters and representation.

3 Hydrology

The GFDL CM2.1 model (NOAA Geophysical Dynamics Laboratory, Princeton NJ) with the A2 (relatively high emissions) scenario was selected for this study. The downscaled effects of this scenario were used to estimate meteorological conditions for a 30-year period

centered on 2085. Results indicate a 2°C average increase in temperature and 3.5% decrease in precipitation in California's Central Valley. Climate-altered hydrologic inflows and reservoir evaporation for over 150 locations in California's water supply system were estimated by permuting the 72-year monthly unimpaired historically-based flow record following the method presented in Zhu et al. (2005). This approach preserves the inter-annual variability of the hydrologic system while incorporating changes in seasonal patterns and volumetric totals. Climate change ratios for monthly streamflows were obtained by comparing GCM downscaled monthly averages (Mauer, this issue) for the 30-year time periods of 1965–1994 and 2070–2099. Apart from a decrease in magnitude, ratios indicate an earlier snowmelt, with streamflows increasing slightly in January and February but decreasing in all other months. These ratios were applied to historic surface water flows to produce the new climate change time series. The streamflow permutation ratios are based on six rivers surrounding the Central Valley: Smith River at Jed Smith State Park, Sacramento River at Delta, Feather River at Oroville Dam, American River at North Fork Dam, Merced River at Pohono Bridge, and Kings River at Pine Flat Dam, based on previous work by Miller et al. (2001). Changes in deep percolation were modeled using an empirical cubic relationship between precipitation and recharge derived from the Central Valley Groundwater–Surface Water Model (CVGSM) (USBR 1997). Climate induced changes in runoff overlying groundwater basins were estimated based on changes in precipitation and deep percolation. Changes in reservoir evaporation were based on an empirical linear relationship derived between reservoir evaporation rates and temperature and precipitation. A detailed description of the methods used to derive perturbed hydrological time series is given by Zhu et al. (2005). The effects of this climate scenario are summarized in Table 1. Most significant under GFDL-A2 for year 2085 is the overall 27% decrease in annual streamflow which directly affects California's water supply. For the purposes of this paper, the GFDAL-A2 year 2085 hydrologic scenario is referred to as the dry climate warming scenario or dry-warm scenario.

Table 1 2085 Changes in California's water supply under dry-warm climate scenario GFDL-A2, (average annual totals in millions of cubic meters (MCM) per year)

	Statewide	Sacramento Valley	San Joaquin Valley	Tulare Basin	S. California
Rim inflows^a					
Historic	34,825	23,577	7,079	3,484	684
Dry warm	25,358	18,394	4,516	2,041	407
% Change	-27.2	-22.0	-36.2	-41.4	-40.5
Reservoir evaporation					
Historic	298.4	77.6	110.0	32.7	78.2
Dry warm	300.4	78.2	111.0	32.8	78.4
% Change	0.7	0.8	0.9	0.2	0.4
Local accretion^b					
Historic	5,449	4,376	577	494	–
Dry Warm	5,221	4,206	524	491	–
% Change	-4.2	-3.9	-9.3	-0.7	–
Groundwater inflows					
Historic	8,360	2,748	1,444	4,168	–
Dry warm	8,305	2,730	1,435	4,140	–
% Change	-0.6	-0.6	-0.6	-0.7	–

^a Rim inflows enter the Central Valley from mountain regions outside the major water demand areas.

^b Local accretions enter from the Central Valley floor within the major water demand areas.

4 Year 2050 water demands

Agricultural and urban water demands were projected for 2050 using the methods in Lund et al. (2003), Jenkins (2004), Jenkins et al. (2003), and Tanaka et al. (2006); and data from Landis and Reilly (2002) for a “high” estimate of year 2050 population (65 million) and resulting land use in California. This provided urban water demands and irrigated land areas for 2050. Household water conservation were based on the 2020 levels estimated by the California Department of Water Resources (1998) projected for 2050. These household demand rates might be reduced by more assertive urban water conservation (e.g. Gleick et al. 2003).

Agricultural water demands for 2050 were estimated using a recalibration of the Statewide Water and Agricultural Production (SWAP) model. Only a brief discussion of SWAP is provided herein; for more details the reader is referred to Howitt et al. (2001).

The SWAP model estimates profit-maximizing cropping and irrigation decisions for agricultural areas with limited water and land availability, using empirically calibrated crop production functions, crop prices, and production costs. By progressively limiting water availability in successive model runs, SWAP can produce estimates of the economic production value of agricultural water deliveries. The agricultural production model for 2050 water demands incorporates some improvements over previous versions of the model (Howitt et al. 2001), such as calibrating on 5 years of cropping data (1999–2004), disaggregating some crop groups, and increased statewide coverage of crops.

Technological change is represented as a yield increase of 0.5% per year for every crop across all agricultural regions over a 50-year period (2000–2050), compared with roughly a 1% per year increase in crop yields over the last 50 years. Substitution across production factors (e.g., land and water) is more limited than in past versions of the model. Irrigated land areas are adjusted for projected 2050 urbanization; nevertheless, target water demands are driven by profit maximizing farming activities. SWAP 2050 also includes endogenous crop prices from a partial equilibrium model. Price is mostly a function of the historical price-volatility of each crop which in turn determines expected demand and supply patterns for year 2050 recursively. Urbanization of agricultural land is incorporated for year 2050 using results from Landis and Reilly (2002). Shifts in demand for every major crop are estimated exogenously, while future prices are estimated within the model based on demand shifts, resulting yield changes, crop-price flexibility, and changes in resources availability.

Climate change is incorporated by adjusting crop yields based on reference agro-climatic conditions for each region and crop. Evapotranspiration adjustments were implicit in the aforesaid yield changes. Agricultural water demands are obtained using SWAP 2050 with and without the dry climate warming in year 2085.

Changes in agricultural water delivery targets from year 2020 projections appear in Table 2. Although agricultural land use is reduced for most regions, water delivery targets increase for 2050 conditions because the SWAP 2050 model includes more crops than earlier versions. Year 2050 statewide agricultural water delivery targets are 35.9 billion cubic meters (BCM) per year with the historical climate, increasing slightly to 36.62 BCM/year with dry climate warming. Almost all climate related increases in agricultural water delivery targets are in northern California, where rainfall contributes more to crop requirements historically.

Total urban water use (without water scarcity) is estimated to be 16.5 BCM/year for 2050. Urban residential demands are estimated by using empirical 1995 household economic water demand curves, modified for increased urban water conservation (as in DWR 1998) and changes in housing density (depending on location), scaled by the

Table 2 2020 and 2050 water delivery targets (MCM/year)

Region	Urban			Agricultural		
	2020	2050	% Change	2020	2050	% Change
Sacramento Valley	2,348	2,327	-0.9	11,103	11,435	3.0
San Joaquin Valley	1,893	2,240	18.4	6,484	7,822	20.6
Tulare Basin	1,478	1,893	28.0	12,050	12,665	5.1
S. California	9,157	9,996	9.2	4,582	4,033	-12.0
Total ^a	14,876	16,456	10.6	34,221	35,954	5.1

^aNumbers may not add due to rounding

estimated number of households in 2050 (Jenkins et al. 2003). The estimated urban water demand might somewhat overestimate urban target water sue and the costs of additional water conservation beyond DWR 2020 estimates (Jenkins 2004). Urban water demand growth by region appears in.

5 Results

Statewide water scarcity, economic, environmental, hydropower, and adaptation results are summarized for 2050 water demand conditions with historical and dry-warm hydrologic conditions. These optimized results show the best achievable economic performance adapting to climate and population changes in a fully-integrated way, within physical and environmental constraints. Special emphasis is given to the operation of surface and aquifer storage and how their optimized operation changes with climate.

5.1 Water scarcity, scarcity costs, and operations costs

With an estimated 2050 population of about 65 million, statewide water scarcity volumes reach 9% for the historical climatic conditions (Table 3). Agricultural water scarcities are about 2% in the Sacramento Valley, 20% in the San Joaquin Basin, 12% in the Tulare Basin, and 29% for Southern California. Urban water scarcities are almost entirely absent north of the Tehachapis and there is less than 1% in Southern California. The statewide

Table 3 Average annual statewide water scarcity, scarcity and operating costs for 2050

Climate scenario		Historical	Dry-warm
Delivery target (MCM)		51,904	51,792
Actual delivery (MCM)		47,344	43,773
Water scarcity (MCM)	Total ^a	4,561 (9%)	8,019 (15%)
	Agriculture	4,487 (12%)	7,919 (22%)
	Urban	74 (<1%)	100 (<1%)
Scarcity Cost (\$M/year)	Total ^a	240	361
	Agriculture	195	312
	Urban	44	59
Operating Costs (\$M/year)		3,896	4,265

Percentages in parenthesis represent scarcity relative to delivery target.

^aTotals may not add do to rounding.

optimized model allows water transfers across the state within physical and environmental constraints to meet economic objectives, as they would in an idealized water market.

With dry climate warming (recall that inflows are reduced and shifted seasonally) additional water scarcity occurs overwhelmingly in agricultural regions north of the Tehachapis. Agricultural water scarcities rise to 22% statewide; 20% for the Sacramento Basin, 25% for the San Joaquin Basin, 19% for the Tulare Basin, and 29% for Southern California with almost no increase in urban water scarcity. Southern California urban users see little increase in water scarcity from climate warming, in part because of limited representation of inflow changes in Southern California, and more importantly because Southern California has a large base of imported supply, made reliable by Southern California's high willingness to pay for purchased water. Agricultural water scarcity in Southern California also is unaffected by dry climate warming because of infrastructure capacity prevents additional transfers to urban areas and Colorado River availability is assumed not to change, due largely to water law which favors California among the lower basin states.

As scarcity increases, so do economic costs from reduced deliveries. Agricultural regions see large increases in scarcity cost with this form of dry climate warming (Table 3). Urban regions, with higher economic values for water use, purchase water from agricultural water users north of Southern California. Climate warming significantly raises water scarcity costs on agricultural production in the Sacramento, San Joaquin, and Tulare Basins, although some farmer losses would be compensated by revenues from water sales to urban areas. If optimally managed, water scarcity costs increase from \$240 million/year in 2050 with historical hydrology to \$361 million/year with dry climate warming.

Average annual operating costs (Table 3) are much higher than water scarcity costs, as they occur in all years, whereas water scarcity costs increase dramatically during droughts. Operating costs represented in the model include costs for pumping, water treatment (including desalination), and wastewater treatment for urban areas. CALVIN does not consider fixed and capital costs, which would generally increase the costs to urban areas of sporadically using desalination. Dry-warm climate change raises average operating costs by \$384 million/year above that of the historical climate.

5.2 Environmental opportunity costs

Environmental water requirements are represented in CALVIN as minimum instream flows and required wetland water deliveries. These flows must be met before any economically-driven allocations of water can occur. With dry climate warming some flows must be reduced to make the model feasible, typically by small amounts. The effect of these reductions on the ecosystem can be large, particularly due to its effects on temperature and other water quality parameters; however, water quality aspects and its ecosystem effects are beyond the scope of CALVIN. The largest environmental flow reduction is related to winter-run salmon flows requirements on the upper Sacramento River below Keswick Dam and the cold-water pool in Shasta Reservoir. Required flows to maintain Mono Lake levels were also unattainable under the dry-warm climate scenario. The total statewide annual infeasibilities averaged 1,075 BCM/year, which is about 4% of annual environmental flow requirements.

Table 4 contains the average marginal opportunity costs or shadow values (economic benefit to the State if the requirements were reduced by one unit of water) of small changes to environmental flow requirements for several locations. The costs of environmental flows requirements on the Trinity River, Clear Creek, and Mono Lake are high and increase

Table 4 Marginal opportunity costs of selected environmental flows (\$/thousand m³)

Environmental flow location	Climate scenario	
	Historical	Dry-warm
Trinity River ^a	28.1	58.8
Clear Creek	13.5	19.3
Sacramento River at Keswick	1.5	6.1
Feather River	0.3	4.5
American River	0.4	218.3
Delta Outflow ^a	2.0	22.0
Mono Lake ^{a,b}	780.1	1198.1
Sacramento Valley Refuges	3.1	35.2
San Joaquin Valley Refuge	34.9	64.3
Tulare Basin Refuge	39.3	82.3

^a A consumptive use environmental requirement

^b Mostly due to lost hydropower

substantially with dry climate warming. (The marginal costs associated with the Mono Lake level requirements are primarily driven by lost hydropower.) American River instream flow requirements, which have a low economic impact without climate change, rise substantially with climate warming due to increased water scarcity for urban and agricultural users. Generally, consumptive use environmental flows (i.e., those flows that cannot be used downstream for economic benefit) have the highest marginal opportunity costs. Such increases in the marginal opportunity costs of environmental flows for urban, agricultural, and hydropower water supplies could result in greater controversy in setting environmental flows.

5.3 Hydropower

The CALVIN model includes hydropower production at major water supply storage and conveyance facilities of California (Lund et al. 2003). With dry climate warming, hydropower production from the water supply system decreases. Annual average hydropower benefits are \$684 M/year and \$602 M/year for the historical and dry climate warming scenarios, respectively. The dry-warm scenario has a lower average production in every month (Fig. 2), ranging from 12% reduction in July to 50% reduction in December and January. This result can be explained by the higher value of energy and increased reservoir releases for agriculture during summer. Likewise, at any probability level, the annual hydropower generation is less for the dry-warm scenario (Fig. 3).

5.4 Water markets

Significant water scarcities under both water demand growth and climate warming conditions create economic incentives for holders of high-priority water rights and contracts with low-valued water uses to sell water to others with more economically productive water uses. This water market is implicit in the mathematics of the optimization model (Jenkins et al. 2004). In the cases presented here, water markets facilitate reallocation of water from agricultural to growing urban uses and provide incentives for more economical operation of water resources to improve the overall technical efficiency of water management (Pulido-Velazquez et al. 2004).

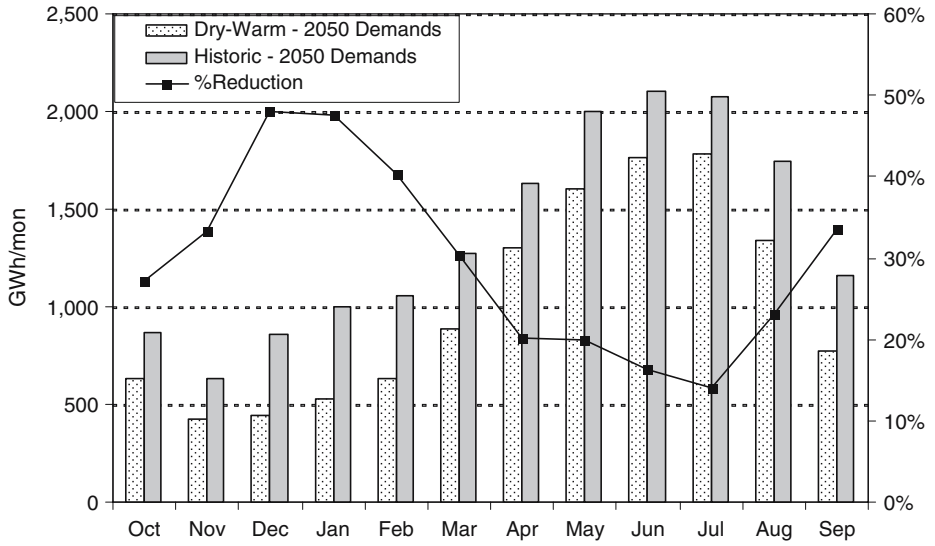


Fig. 2 Average monthly power generation and percent reduction in generation (dry warm vs. historical hydrology). Whereas power generation is always lower under the dry-warm climate, reduction is the greatest for the low-generation months (Nov–Feb), based on a 72-year monthly time span

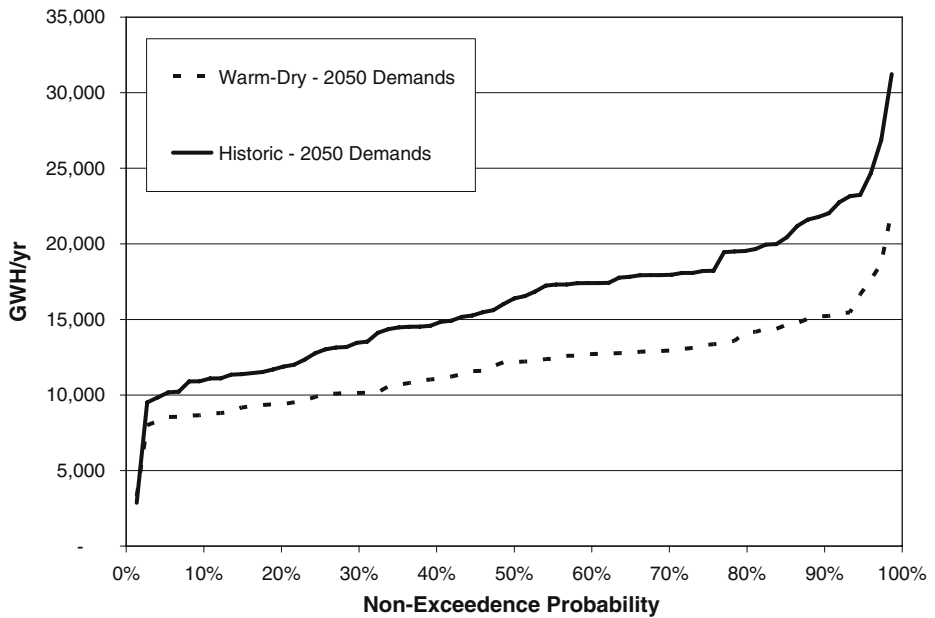


Fig. 3 Frequency of annual power generation from major water supply reservoirs (based on 72 years). Under dry-warm hydrology annual average hydropower production is less variable, due to reduced flows and storage

With dry climate warming, the value of allowing water markets to reallocate water increases. When water markets are restricted spatially, statewide economic costs increase substantially. Restricting water markets to within the four regions raises statewide water scarcity costs by \$109 M/year with historical hydrology for 2050 compared with statewide optimization of water operations and allocations. With dry climate warming, these same restrictions increase scarcity costs by \$251 M/year compared with statewide optimization.

6 Surface and groundwater storage operation

Deterministic optimization results can be interpreted to gain insights into promising realistic operating rules for complex water resource systems (Lund and Ferreira 1996). Such an analysis was performed on year 2050 model results with historical and dry climate warming hydrologies. It provides reasonable indications of how the operation of a complex water resource system should change with a dry form of climate warming. This section examines how dry climate warming changes the peak-storage month (phase) and magnitude (amplitude) of seasonal draw-down and refill cycles for surface storage, the relative use of groundwater and surface water storage over drought periods, and the balancing of water storage among major surface reservoirs in Northern California.

6.1 Phase and amplitude of seasonal drawdown and refill

Each year in California, reservoirs and aquifers refill partially or completely during the winter and spring and then are drawn down until the early fall. This seasonal cycle of reservoir peak storage and drawdown is superimposed on longer over-year cycles of dry years (drought) which further empty storage and wet years which further fill over-year reservoir storage (Hazen 1914).

The phase and amplitudes of seasonal draw-down and peak-storage can be obtained from CALVIN results (Fig. 4). In the dry-warm climate scenario (dashed lines) peak storage occurs earlier in the water year. In addition to this phase shift in storage, the seasonal range of storage has greater amplitude for this dry-warm scenario. The drier scenario also has lower levels of surface storage overall.

The phases and amplitudes of statewide seasonal water storage vary between the historical and dry-warm climates for surface water in California (Fig. 5). According to the storage-exceedence probability curves based on 72 data points, about 75% of the time the seasonal range (amplitude) of surface water storage for the dry-warm climate scenario exceeds that with the historical climate, as shown in the exceedence probability plots of annual storage range (maximum minus minimum storage for each water year). Surface water storage is used more actively with dry climate warming. The greater variability in seasonal storage cycle amplitude illustrates the considerable variability in annual streamflows in California. In wetter years, less water is removed from storage to meet water uses, with drier years leading to greater use of stored water.

The peak-storage month also varies with climate conditions. Statewide, surface water storage peak occurs roughly a month earlier in the dry-warm climate scenario in approximately 80% of years (Fig. 5). The earliest peak storage month is January for both scenarios while the latest peak storage month is June in the historical scenario and May in the dry-warm climate scenario. Overall, economically optimal operation of water storage in California should vary with climate. The warmer climate with less snowmelt recharges optimally-operated surface reservoirs earlier in the year and results in greater amplitudes in

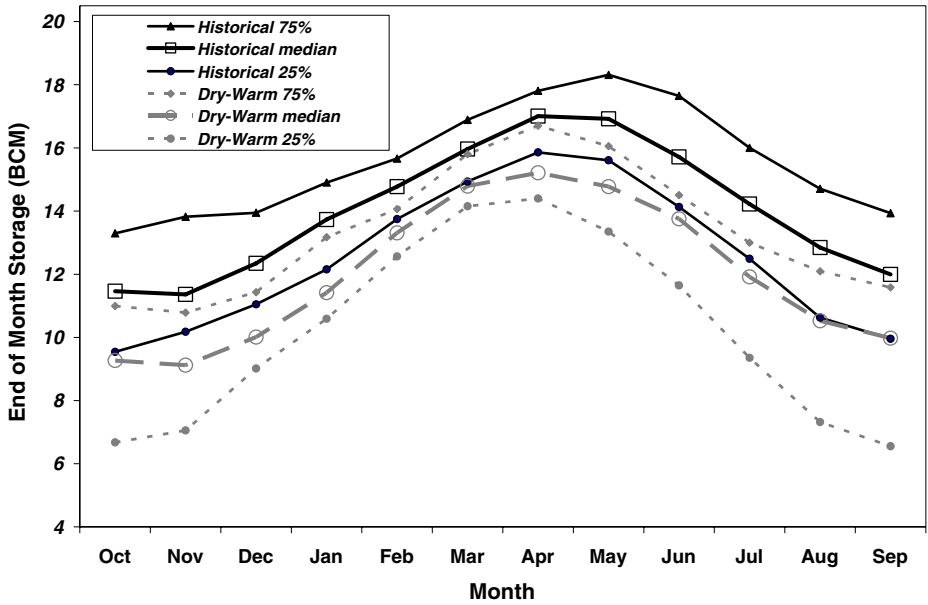


Fig. 4 Monthly surface water storage quartiles for Sacramento Valley. *Thicker lines* represent medians of end of month storage for historical and dry-warm hydrology, based on a 72-year hydrology. *Thinner lines* represent first and third quartiles for these two climatic conditions

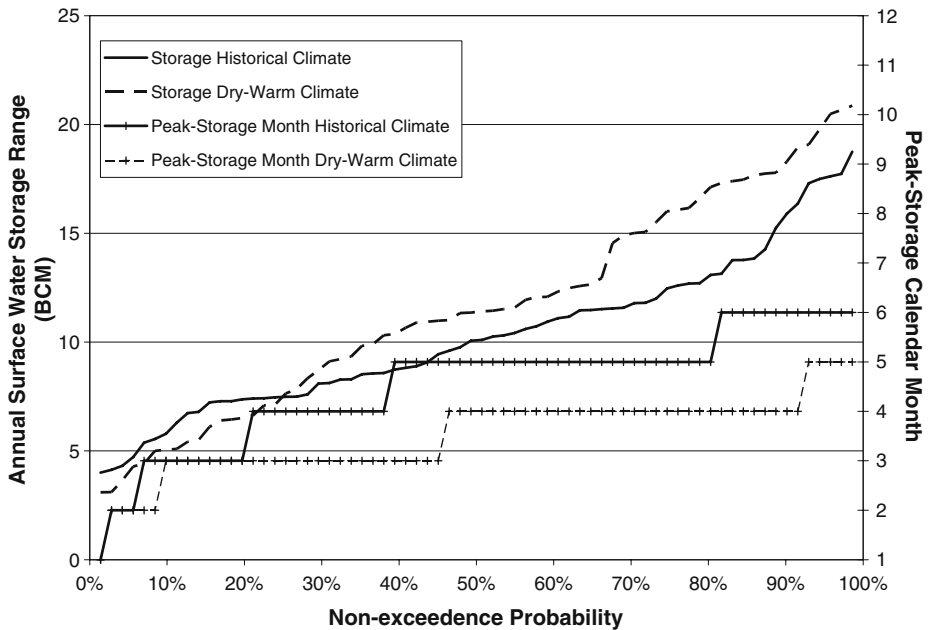


Fig. 5 Statewide surface water seasonal storage range and peak-storage month (based on a 72-year monthly time span)

seasonal drawdown and recharge; much of the precipitation formerly stored as snowpack shifts to earlier flows to surface reservoirs.

6.2 Use of surface and groundwater storage

Plots of optimal storage allocation among reservoirs often provide insights into optimal reservoir operating rules (Lund and Ferreira 1996). Figures 6 and 7 indicate the allocation of total storage in the Sacramento Valley between surface and groundwater reservoirs for the historical and warm-dry scenarios, respectively. These graphs have been generated based on the monthly storage data over the 72-year period (i.e., the storage in all the groundwater basins were summed and plotted against the total storage (both ground and surface water) in system for that month). The variability of aquifer and surface reservoir allocations for any given total storage level is considerably greater with the warm-dry climate (slightly wider scatters are observed in Fig. 7, with lower R -squares in the regression equations). The plots illustrate the greater variability of groundwater storage over the 72-year hydrologic period, due mostly to the use of groundwater for over-year drought storage. The 72-year range (the difference between minimum and maximum storage) in surface water storage is only 13.6 BCM compared with 42 BCM for groundwater. The amplitudes of the drought cycle increase slightly with the dry-warm climate. For each plot, the slopes of the surface and groundwater relationships must sum to one. The greater number of points at lower storage levels in Fig. 7 with the dry-warm climate indicates the generally lower storage levels with the drier climate (at the 50 percentile, total storage with historical hydrology is nearly 155 BCM, versus 150 BCM under climate change hydrology).

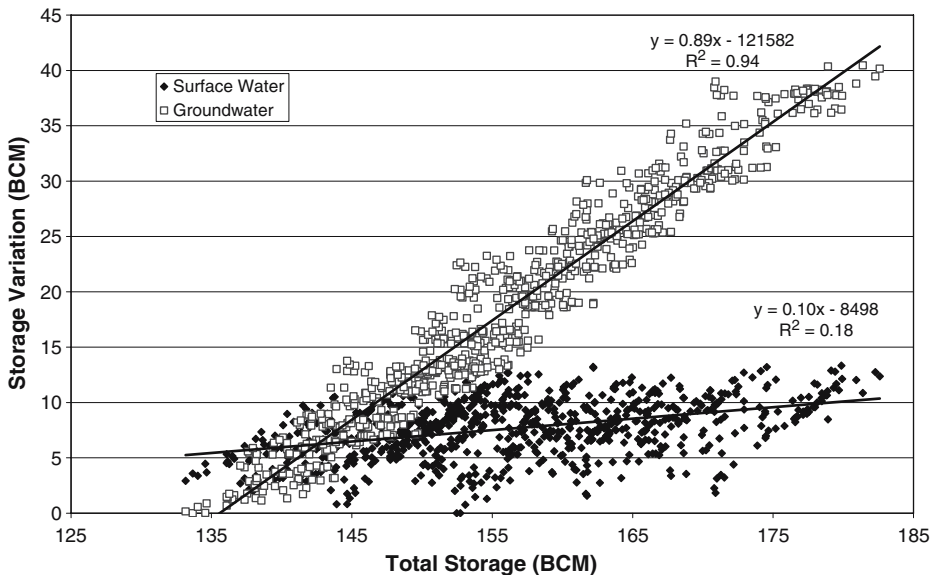


Fig. 6 Surface and groundwater storage allocation with total Sacramento Valley water storage for historical hydrology (based on monthly data points over 72 years)

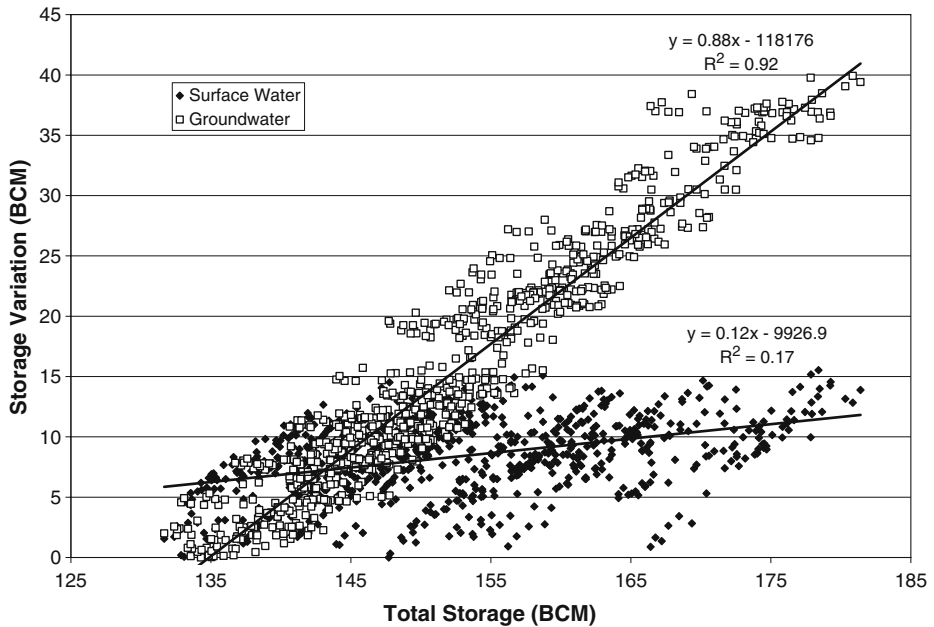


Fig. 7 Surface and groundwater storage allocation with total Sacramento Valley water storage for dry climate warming hydrology (based on monthly data points over 72 years)

6.3 Surface water storage balancing rules

Figures 8 and 9 present the allocation of surface water storage between major reservoir systems in the Sacramento Valley for the two climate scenarios. The first system consists of Shasta, Trinity and Whiskeytown (STW) reservoirs on the Shasta-Trinity sub-system. The other surface storage sub-system consists of Oroville and New Bullards Bar reservoirs (ONB) in the Feather and Yuba sub-systems. Total surface water storage is given by summing storage in the two sub-systems. Combined these reservoirs have nearly 15 BCM of storage capacity. Spline regressions using STATA™ were performed to analyze optimal storage rates and allocations for the two sub-systems under historical and dry-warm climates. For the historical climate, a kink at 8 BCM was observed (Fig. 8) where regression lines in the plot change. Kinks and slopes of regression lines indicate differences in relative subsystem storage and are useful to infer optimal operation rules. The difference in slopes on either side of this kink is statistically significant (p value < 0.02). On both sides of the kink, the larger STW sub-system stores at a higher rate than the Oroville-New Bullards (ONB) sub-system. However, above the 8 BCM threshold, the ONB sub-system fills and empties more slowly than it does below the 8 BCM threshold as evidenced by a lower slope in the regression equations (0.31 vs. 0.40 respectively in Fig. 8).

The dry-warm climate changes optimal storage allocation rules significantly as kinks become more evident (Fig. 9). The total storage range was partitioned into three segments (breakpoints at 5.4 and 11.1 BCM). The range of storage increases with the dry-warm climate. Total storage can be as low as 2.6 BCM versus a 4.3 BCM lower limit for the historical hydrology. From maximum total storage, drawdown begins with a greater rate for the STW sub-system than for the ONB sub-system until total storage falls below 11.1 BCM. The range of storage values is wider under the warm-dry climate which

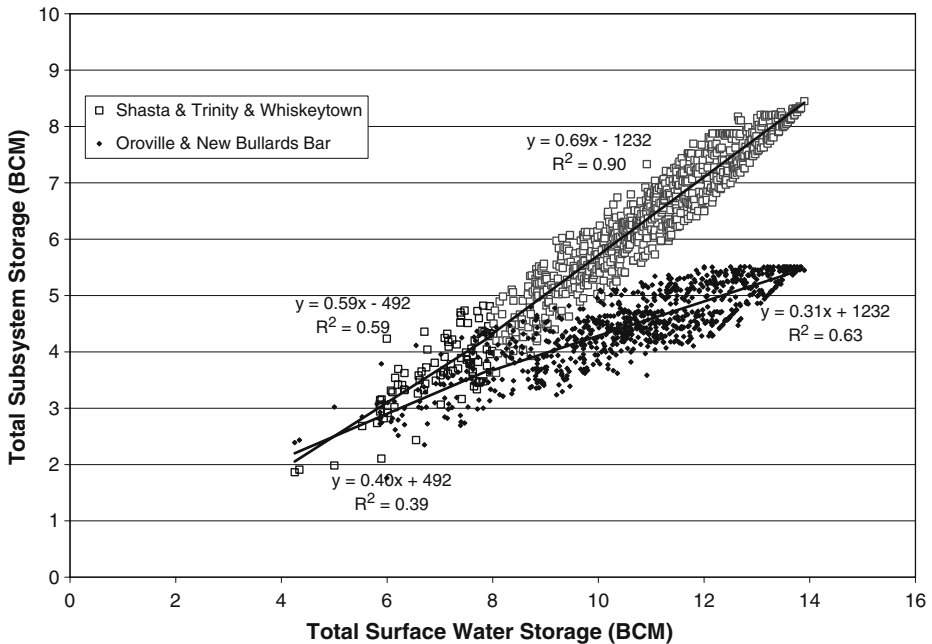


Fig. 8 Surface water storage allocation for major reservoir sub-systems in the Sacramento Valley (historical climate based on 72 years). For the Oroville-New Bullards Bar Subsystem a change in storage rate is more evident after 8 BCM

widens the scatter in Fig. 9. For a 99% confidence level, STW stores at a faster rate than ONB at lower storage levels (lowest segment in the spline regression). The same holds for total storage above 11.1 BCM. Nevertheless, STW and ONB sub-systems store water at similar rates, despite their different capacities, in the middle range. Multi-reservoir drawdown rates for historical and climate change scenarios are significantly different ($p < 0.01$). Multi-reservoir surface storage operations should change significantly with changes in climate.

7 Conclusions

At estimated 2050 water demand levels, California's water supply system can respond without catastrophic statewide costs to a fairly dry form of climate warming. While this warm-dry climate change scenario would impose \$400 M/year or more in additional water scarcity and operating costs, economical water management adaptations could minimize these costs from a statewide perspective. However, locally agriculture would see much less water deliveries and significant economic impacts, through some increases in scarcity costs would be offset by sales of water to urban areas. This approach contrasts with simulation studies which neglect integrated system adaptation to changes in climate, population, and other conditions. True performance with climate change is likely to lie somewhere between these extremes.

Major economical adaptations to climate warming include a range of water supply and demand management activities:

- Dry climate warming increases the statewide average annual water scarcity by 3.5 BCM and increases average annual water scarcity costs by \$121 million/year. Most

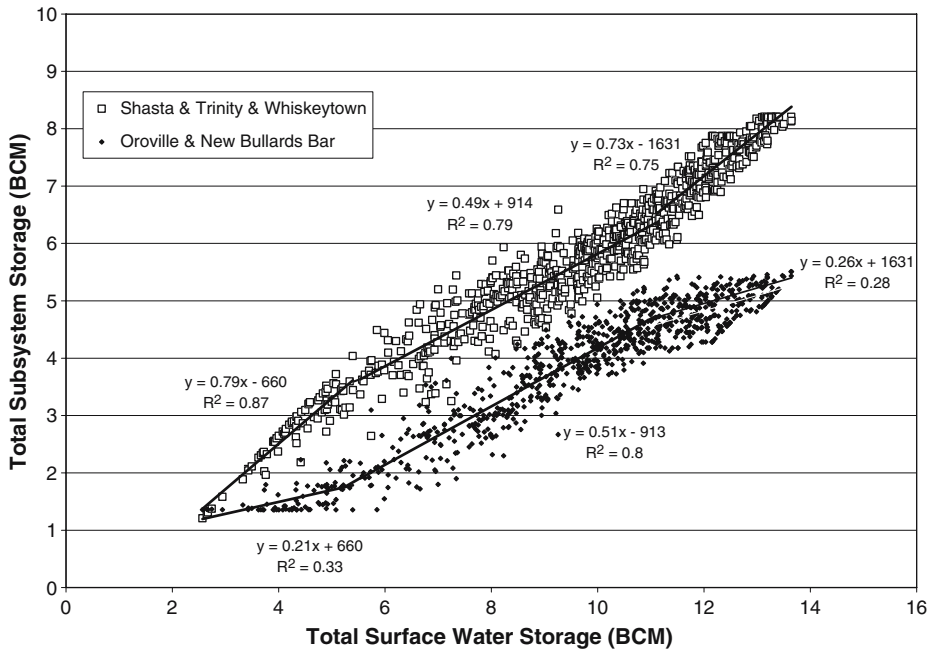


Fig. 9 Surface water storage allocation for major reservoir sub-systems in the Sacramento Valley (dry climate warming based on 72-years). Storage rates display statistically significant (p value <0.01) changes at 5.4 and 11.1 BCM

of the increased scarcity and scarcity costs are to agricultural users north of the Techachapis. Some of the increased scarcity costs to agricultural users would be offset by increased sales of water to urban areas.

- Increased flexibility and use of water management options reduce the impacts of dry climate warming. Management options include greater water conservation activities for urban and agricultural water users, greater water market activity, additional water reuse, significantly greater conjunctive operation of ground and surface waters, and changes in surface reservoir operating strategies. Such ability to adapt to climate warming has been found for other dry warming scenarios (Tanaka et al. 2006).

Further analysis of surface and groundwater storage operations indicates that:

- Climate warming results in earlier peak storage in surface water reservoirs with optimized operations. Dry climate warming also increases the economically optimal amplitude of the seasonal draw-down refill cycle.
- Conjunctive use of surface and groundwater has a significant water supply role in California and will have greater importance if the climate in California were to become drier and warmer.
- Surface and groundwater storage operating rules should change with climatic conditions. The optimal allocation of storage among surface water reservoirs changes significantly with dry climate. Existing operating rules are unlikely to perform well for future conditions, especially with a substantially altered climate. This conclusion is especially important for simulation studies of climate change impacts and adaptations.

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