

Adapting California's water system to warm vs. dry climates

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Abstract This paper explores the independent and combined effects of changes in temperature and runoff volume on California's water supply and potential water management adaptations. Least-cost water supply system adaptation is explored for two climate scenarios: 1) warmer-drier conditions, and 2) warmer conditions without change in total runoff, using the CALVIN economic-engineering optimization model of California's intertidal water supply system for 2050 water demands. The warm-dry hydrology was developed from downscaled effects of the GFDL CM2.1 (A2 emissions scenario) global climate model for a 30-year period centered at 2085. The warm-only scenario was developed from the warm-dry hydrology, preserving its seasonal runoff shift while maintaining mean annual flows from the historical hydrology. This separates the runoff volume and temperature effects of climate change on water availability and management adaptations. A warmer climate alone reduces water deliveries and increases costs, but much less than a warmer-drier climate, if the water supply system is well managed. Climate changes result in major changes in reservoir operations, cyclic storage of groundwater, and hydropower operations.

1 Introduction

Climate change can have many forms and impacts, including rising sea level, melting permafrost, increased flooding, decreased snowpack, and more frequent wildfires. Yet

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rising temperatures and changes in precipitation (and related runoff) drive most such changes. These two major drivers can have independent and combined effects on California's water resources and economy. Characterized by a Mediterranean climate (wet winters and warm, dry summers), California's urban and agricultural water supply depends heavily on water storage in snowpack, reservoirs, and aquifers to meet demands through the dry growing season. Warming in the western United States is reducing snow water equivalents (depth of water in the snowpack if melted) (Hamlet et al. 2005) and has affected deliveries and reservoir storage levels for the State Water Project and Central Valley Project (Anderson et al. 2008).

Downscaled global climate models applied to California and the western United States have been applied to explore possible changes in streamflow peaks, timing and volume, snowmelt, snow water equivalent, and evapotranspiration (Cayan et al. 2008b; Hamlet et al. 2007; Miller et al. 2003). Field data as well as modeling indicate a shift in spring runoff since the 1940s as warming temperatures shift runoff to earlier in the year (Dettinger and Cayan 1995; Maurer 2007; Stewart et al. 2004). This shift in streamflows may influence water management, the extent and character of ecosystems, and changes in estuarine inflows and salinity in the Sacramento-San Joaquin Delta (Cayan et al. 2001, 2008a; Knowles and Cayan 2004).

Climate change studies largely assess hydrologic response of surface water characteristics. However, groundwater response to climate change also has been investigated by linking global climate models to regional groundwater models, to estimate climate influences on conjunctive management of surface and groundwater resources (Hanson and Dettinger 2005; Scibek and Allen 2006). Changes in both surface and groundwater components of the hydrologic system will affect water management challenges and opportunities.

The IPCC Fourth Assessment Report 2007 describes emission scenarios used in General Circulation Models (GCMs) and summarizes regional climate change projections for temperature and precipitation (Christensen et al. 2007). Cayan et al. (2008b) describe some of these models and emission scenarios as they pertain to California. The Parallel Climate Model (PCM1) and NOAA's GFDL CM2.1 model provide simulations for California suggesting warming temperatures ranging from 1.5 to 4.5°C by the end of the century, depending on the emissions scenario. Warming is projected to decrease the share of precipitation falling as snow and to increase the portion falling as rain (Bedsworth and Hanak 2008; Cayan et al. 2008b; Hanak and Lund 2008). Unlike the warming trend for temperatures, climate models present less consensus regarding changes in precipitation. Projections of annual precipitation for northern and southern California range widely from a decrease of 26% to an increase of 18%, though most global climate models indicate moderate changes (Cayan et al. 2008b).

Changing hydrologic conditions have important implications for California water management. Previous studies have assessed economic impacts and water management adaptation to combined warmer, wetter, and drier climates (Medellin-Azuara et al. 2008; O'Hara and Georgakakos 2008; Tanaka et al. 2006). Since precipitation projections include both drier and wetter conditions, Tanaka et al. (2006) applied the CALVIN model to explore integrated management adaptations to a warmer-drier climate and a warmer-wetter climate for 2100 demands. Changing runoff patterns may necessitate changing reservoir operations, thus Medellin-Azuara et al. (2008) explored optimized multi-reservoir operation adaptations to a warm-dry climate with year 2050 demands. Other work assesses the economic impacts of climate change and population growth in semi-arid urban environments and considers the effectiveness of adaptation strategies including storage capacity expansions (O'Hara and Georgakakos 2008).

The two primary drivers affecting water supply, temperature and precipitation, have not before been parsed out to analyze their independent and combined effects on California water management adaptation. This paper uses CALVIN model results to compare a warmer climate scenario and a warmer-drier scenario centered on 2085 with updated 2050 water demand estimates. This results in effects on California's water supply and water management adaptations for a year 2050 level of development using the more extreme climate change model results (temperature and precipitation effects centered on 2085). This is meant to test the system with the greatest amount of temperature increase and reduction in precipitation to see how it performs and adapts. Results indicate that temperature rise alone does not tend to increase water shortages greatly if system operations adapt. Modified surface water operations, conjunctive use of ground and surface waters, and hydropower generation are explored as strategies to mitigate economic costs from warmer and warmer-drier climates.

2 Methods

This study's approach to perturbing the hydrology for climate change conditions involves mapping streamflows to corresponding index basins and then applying perturbation ratios (Connell 2009). Perturbed hydrology is then input to CALVIN to assess economic impacts and water management adaptations to changed water supply volume and timing. The approach used is similar to that employed in Tanaka et al. (2006) and Medellin-Azuara et al. (2008). Two climate change scenarios were developed to explore the independent and combined effects of temperature and precipitation. A warm-dry hydrology was developed from downscaled results of the GFDL CM2.1 (A2 emissions scenario) global climate model for a 30-year period centered at 2085 (Connell 2009; Zhu et al. 2003). A warm-only climate was developed by adjusting warm-dry and historical hydrologies to maintain historical average annual runoff while capturing the shift in runoff timing expected from warming temperatures (Connell 2009). Global climate models simulating a warm-only scenario for California were not available.

2.1 The CALVIN model

CALVIN (CALifornia Value Integrated Network) is a hydro-economic optimization model of California's statewide water supply system (<http://cee.engr.ucdavis.edu/calvin/>). The CALVIN model includes 44 reservoirs, 28 groundwater basins, and 54 economically-represented urban and agricultural demand areas (Fig. 1). Using HEC-PRM, a network flow reservoir optimization solver developed by the U.S. Army Corps of Engineers, CALVIN operates surface and groundwater resources and allocates water over a historical (1921–1993) hydrologic record. Economically driven, CALVIN allocates water to minimize total statewide water scarcity of agricultural and urban water use within physical and environmental constraints (Draper et al. 2003). Water scarcity occurs whenever a user's economic target for water is not met. This results in a corresponding scarcity cost for each demand. Historical flow data from existing surface and integrated surface-groundwater models are typically used (Draper et al. 2003; Zhu et al. 2003).

2.1.1 Agricultural and urban water demands

Agricultural and urban water demands are estimated for year 2050 level of development, and account for population growth, urban water conservation, agricultural land use

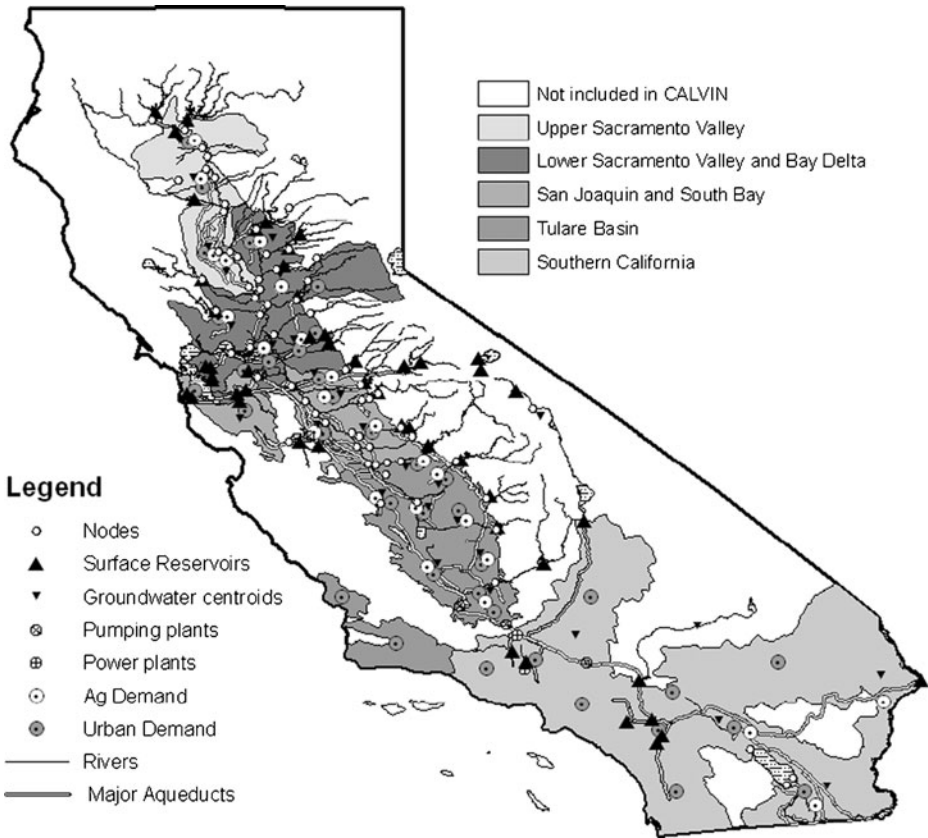


Fig. 1 Hydrologic basins, demand areas, major inflows and infrastructure represented in CALVIN (adapted from Lund et al. 2007)

conversion, likely crop price conditions, and technology-related crop farming yield improvements. Values for agricultural water use are derived using the Statewide Agricultural Production model (SWAP <http://swap.ucdavis.edu>), an ancillary optimization model that maximizes farm profit for each agricultural demand area using positive mathematical programming (Howitt 1995). The version of SWAP used for this paper includes 21 Central Valley Project Model (or CVPM after USBR 1997) regions in the Central Valley plus Coachella, Imperial, and Palo Verde irrigation districts in Southern California. A detailed description of the marginal value of water in agriculture for these regions appears in Howitt et al. (2009). For each agricultural production region, a loss function is derived for the economic losses from water scarcity, obtained by numerical integration of the marginal value of water in agriculture, for every month. Data from geo-referenced land use surveys from the California Department of Water Resources (DWR) are employed. Average applied water by CVPM and/or hydrological regions and crop groups is employed in the base case from DWR estimates of applied water per crop group.¹ Land conversion from agricultural to urban uses follows Landis and Reilly (2002) 2050

¹ Available at: <http://www.water.ca.gov/landwateruse/anaglwu.cfm#>

urbanization trends. Technological change is assumed to increase crop yields by 29% by 2050 (Howitt et al. 2009). For the regions covered in CALVIN (representing 89% of statewide applied water use for 2005), 2050 agricultural water use totals 29.7 BCM/yr (compared to total water availability of about 43 BCM/year, as detailed in Table 1). The effect of climate change on the economic value of water for agriculture in SWAP is represented as changes in yields from changing temperature, precipitation, and CO₂ concentrations (Howitt et al. 2009). Thus cropping patterns under historical, warm-only, and warm-dry scenarios allow adaptation such as shifts to higher value and more climate tolerant crops.

Urban water shortage loss functions follow methods described in Jenkins et al. (2003) with population growth projections and urban water demands for year 2050 (Jenkins et al. 2007). Constant price-elasticity demand functions for water are estimated for every economically-represented urban area in CALVIN. Total base urban water use in CALVIN by 2050 is projected at 16.4 BCM/yr, representing about 92% of estimated

Table 1 Changes in California's water supply for warm-dry and warm-only climate scenarios (average annual totals)

	Statewide	Sacramento Valley	San Joaquin Valley	Tulare Basin	Southern California
Warm-dry Change in Precipitation					
% Change ^a	-27%	-24%	-30%	-33%	-
cm/year	-5.8	-5.8	-5.8	-6.1	-
Rim Inflows (MCM/yr)					
Historical/Warm-only	34,824	23,577	7,078	3,485	684
Warm-dry	25,031	18,253	4,372	1,953	453
% Change	-28%	-23%	-38%	-44%	-34%
Net Reservoir Evaporation (m/yr)					
Historical	1.6	1.1	1.9	2.0	1.6
Warm-only	1.8	1.3	2.1	2.5	1.9
% Change	15%	17%	9%	23%	19%
Warm-dry	2.2	1.6	2.7	2.7	2.2
% Change	37%	43%	37%	32%	36%
Groundwater Inflows (MCM/yr)					
Historical/Warm-only	8,359	2,748	1,444	4,168	-
Warm-dry	7,525	2,368	1,277	3,880	-
% Change	-10%	-14%	-12%	-7%	-
Local Accretion (MCM/yr)					
Historical/Warm-only	5,449	4,377	577	495	-
Warm-dry	3,812	3,226	336	250	-
% Change	-30%	-26%	-42%	-49%	-
Local Depletions (MCM/yr)					
Historical/Warm-only	1,786	629	66	1,090	-
Warm-dry	3,966	1,370	442	2,154	-
% Change	122%	118%	566%	98%	-

^aPercent change relative to historical in all cases

Adapted from (Connell 2009)

statewide urban demands in 2050. Water conservation includes per capita use reduction from 908 to 837 l/per capita/per day in 2050 with an estimate of 54 million² people in CALVIN covered urban areas (Jenkins et al. 2007).

2.1.2 Perturbed hydrology

CALVIN uses 72 years of monthly hydrology (1921–1993) to represent hydrologic variability. Hydrologic processes perturbed for climate change include flows into Central Valley reservoirs (rim inflows), net evaporation rates at reservoirs, groundwater inflows, and net local accretions. The GFDL CM2.1 model with a higher emissions scenario (A2 scenario) was selected for this study. Outputs from the global climate model simulated a warm-dry scenario with 4.5°C increases in annual temperature by the end of the century and variable amounts of decreased precipitation for watersheds across the state (Cayan et al. 2008b). Downscaling the A2 scenario, using bias correction and spatial downscaling (BCSD) (Maurer and Hidalgo 2008), yields estimated temperature and precipitation effects on streamflow for 18 index basins and 21 groundwater basins for a 30-year period centered on 2085. This unpublished data follows methods presented in Maurer (2007) and Maurer and Duffy (2005), and was made available for this study.

A two step process was employed to perturb CALVIN rim inflows, 1) mapping index basin streamflows from a downscaled climate model to CALVIN rim inflows, 2) applied permutation ratios from the index basins to the corresponding historical CALVIN streamflows. Streamflows for select rivers in California are referred to as index basins. Of the 18 available index basins, 13 were used to map to CALVIN rim inflows. From north to south, these include: Smith River at Jedediah Smith State Park, Trinity River at Trinity Reservoir, Sacramento River at Shasta Dam, Feather River at Oroville, American River at Folsom Dam, Cosumnes River at McConnell, Mokelumne River at Pardee, Calaveras River at New Hogan, Stanislaus River at New Melones Dam, Merced River at Pohono Bridge, Tuolumne River at New Don Pedro, San Joaquin River at Millerton Lake, and Kings River at Pine Flat Dam. Statistical analysis, geographic location, and knowledge of hydrological processes characterizing each basin guided assignment of appropriate matches (Connell 2009).

Using GCM-based streamflows for these 18 index basins, permutation ratios capturing the effects of magnitude and timing shifts in streamflows were used to perturb all CALVIN rim inflows for the warm-dry scenario. This method maps hydrologic changes in index basin streamflows to CALVIN's 37 rim inflows producing a new climate change time series with historical hydrologic variability for each rim inflow (Connell 2009; Zhu et al. 2003). The permutation ratio approach captures the hydrologic variability present in the historical record, but does not allow for increasing variability driven by climate change. It also assumes stationarity of mapping such that a single index basin represents the flows at the rim inflows overtime.

For the warm-only hydrology, as with the warm-dry series, permutation ratios were applied to the historical time series to capture the effect of warming, reflecting a shift in the timing of peak flow. The warm-dry time series was then multiplied by the ratio of average historical flows to average warm-dry flows. As a result, the warm-only time series mirrors the timing of the warm-dry climate but preserves historical average annual streamflow volume.

² Department of Finance 2050 population estimate available at <http://www.dof.ca.gov/research/demographic/reports/projections/p-1/>

2.1.3 Other climate perturbed hydrologic processes

In addition to rim flows, climate-adjusted hydrologic processes include net reservoir evaporation, groundwater inflows, and net local accretions. Changes in reservoir evaporation were based on an empirical linear relationship derived between historical monthly average net reservoir evaporation rates and monthly average air temperature and precipitation (Zhu et al. 2003). For this study the main drivers for net evaporation rates are temperature and precipitation. For the warm-only scenario, annual volume of precipitation is assumed unchanged; therefore change in precipitation was set to zero and only changes in temperature increased net reservoir evaporation.

Changes in groundwater storage are calculated as changes in deep percolation, obtained from an empirical cubic relationship between precipitation and recharge from the Central Valley Groundwater-Surface Water Model or CVGSM (USBR 1997). This relationship was used to perturb groundwater inflows for the warm-dry scenario. Since estimates of deep percolation depend solely on precipitation in the present study, historical time series of groundwater inflows were not perturbed for the warm-only scenario. As a result, effects from reduced snowpack and earlier melting on groundwater recharge are not represented in the warm-only scenario. However, timing and magnitude of historical and warm-dry scenario time series of groundwater storage were close, suggesting this simplifying approach is appropriate.

Rim inflows (over 70% of valley inflows) enter the Central Valley from the mountain regions outside the major water demand areas, whereas net local accretions enter the valley floor within the major demand areas. Net local accretions combine local accretions and local depletions. Changes in local surface water accretion are affected by changes in deep percolation and precipitation. Changes in these factors from the downscaled global climate model for groundwater basins were used to perturb net local accretions for the warm-dry scenario. Since precipitation was assumed unchanged from historical hydrology, the historical time series for local accretions and depletions were used in the warm-only scenario.

Permutation ratios for the warm-dry scenario generally decrease flow and shift flow timing with earlier snowmelt. Under the warm-dry climate, precipitation decreases across the Central Valley by 27%, a total of 4.7 BCM, (Table 1). This amounts to 5.8 cm/yr less precipitation in the Sacramento and San Joaquin valleys, and 6.1 cm/yr less in the Tulare Basin. Drier conditions also affect rim inflows, net evaporation rates from reservoirs, groundwater inflow, and net local accretions. In all regions, rim inflows and groundwater inflows decrease while evaporation from reservoirs increases. Average rim inflow volumes aggregated across the state decrease 28% from historical levels (Table 1).

3 Results and discussion

3.1 Water supply results

Optimized water deliveries are compared to delivery targets for each urban and agricultural demand area to estimate water scarcity and its costs. The difference between water allocated by CALVIN at each demand site and the target water demand defines the region's water scarcity. Economic loss functions assign a scarcity cost to each region's scarcity. Table 2 shows statewide scarcity volumes and costs in agriculture and urban centers for each economically optimized scenario. The second column also indicates each sector's

Table 2 Statewide average annual water scarcity, scarcity cost, willingness to pay and percent of water deliveries by 2050 (in \$2008)

Scenario	Willingness to Pay (\$/TCM ¹)	Scarcity Cost (\$/yr)	Scarcity (MCM ² /yr)	Delivery (% of Target)
Historical				
Agriculture	188	201.1	1,075	96.4
Urban	457	46.8	39	99.8
Total		247.9	1,114	
Warm-only				
Agriculture	188	207.0	1,104	96.3
Urban	457	48.5	40	99.7
Total		255.5	1,144	
Warm-dry				
Agriculture	215	1423.0	9,456	68.2
Urban	1043	108.5	134	99.2
Total		1531.5	9,590	

1. TCM is Thousand Cubic Meters

2. MCM is Million Cubic Meters

willingness to pay for additional water, an indication of how water is economically allocated in the system. For this reason, urban demands (with a high willingness to pay) incur little scarcity and the brunt of water scarcity falls on agricultural production, where more senior water rights holders are paid to forego use. This pattern of water scarcity under optimized operations is common in previous CALVIN studies (Draper et al. 2003; Medellin-Azuara et al. 2008; Tanaka et al. 2006). Low willingness to pay in some urban areas indicates that some level of urban water scarcity is economically optimal, likely a result of low water retail prices or high supply costs.

Statewide water scarcity increases by 2.7%, with warm-only conditions compared to the historical climate. In contrast, scarcity under warm-dry conditions is over eight times higher than scarcity with historical conditions (Table 2). Climate warming decreases water deliveries and increases water scarcity, however, drier conditions combined with climate warming proves far more costly. Increases in scarcity costs for warm-only conditions are only 3.1% higher than historical costs, whereas warm-dry scarcity costs are over six times higher than historical costs. Relatively small additional scarcity from the warm-only climate arises due to the ability of large storage reservoirs to adapt to the seasonal shift of runoff. This is in line with classical reservoir operations theory that reservoirs with over-year storage capability are affected much less by seasonal changes in flows (Hazen 1914). Many approaches are available to quantify the over-year storage character of a reservoir (Hoshi et al. 1978; Lettenmaier and Burges 1977; Vogel et al. 1999). All are imperfect. Here we present both the simple ratio of storage capacity to mean annual flow, and the Coefficient of Variation (C_v) as presented in Vogel et al. (1999). C_v is the standard deviation of annual inflow divided by the mean of annual inflows. Seasonal storage characterizes reservoirs with C_v less than .3 (Vogel et al. 1999). This indicates that all reservoirs presented in Table 3 have some over-year storage capability. However, only eight of the presented reservoirs have storage capacities greater than their historical mean annual inflow (MAI). Therefore, most large reservoirs in California have both seasonal and over-year (drought) storage which serves well to buffer the changes in water supply related to warmer conditions.

Table 3 Percent of years filled and ratio of storage capacity to mean annual inflow (MAI) under each climate scenario, and the Coefficient of Variation for selected surface water facilities

Facility	% Years filled			Storage :Hist/WO MAI	Storage : WD MAI	C _v
	Hist.	WO	WD			
Clair Engle Lake	53	46	22	1.68	1.97	0.46
Shasta Lake	97	92	49	0.80	0.95	0.36
Whiskeytown Lake	100	100	53	0.25	0.34	0.51
Black Butte Lake	99	97	67	0.35	0.46	0.74
Lake Oroville	100	99	88	0.90	1.18	0.48
New Bullards Bar Reservoir	100	99	76	0.56	0.81	0.51
Englebright Lake	100	100	100	0.01	0.02	0.46
Camp Far West Reservoir	92	92	79	0.24	0.36	0.51
Clear Lake & Indian Valley Res	42	38	17	1.14	1.53	0.79
Lake Berryessa	14	8	4	4.15	4.89	0.73
Folsom Lake	100	99	50	0.33	0.45	0.49
Pardee Reservoir	81	88	35	0.29	0.45	0.50
New Hogan Lake	44	40	22	1.94	2.67	0.76
New Melones Reservoir	86	83	3	2.19	3.55	0.50
Turlock Reservoir	75	75	3	0.07	0.10	0.44
Lake Lloyd/Lake Eleanor	40	31	1	0.62	1.04	0.41
Hetch Hetchy Reservoir	51	54	8	0.43	0.88	0.40
New Don Pedro Reservoir	76	83	6	1.29	2.56	0.49
Lake McClure	75	81	7	0.99	1.53	0.57
Eastman Lake	19	19	1	2.02	2.85	0.97
Hensley Lake	39	44	17	1.02	1.55	0.86
Millerton Lake	49	76	29	0.24	0.38	0.50
Pine Flat Reservoir	99	100	13	0.57	1.03	0.54
Lake Kaweah	100	100	54	0.31	0.58	0.63
Lake Success	89	90	74	0.60	0.87	0.79
Lake Isabella	29	44	15	0.79	1.32	0.64
Grant Lake	24	3	0	0.36	0.52	0.36
Long Valley Reservoir	4	0	0	0.90	1.55	0.41

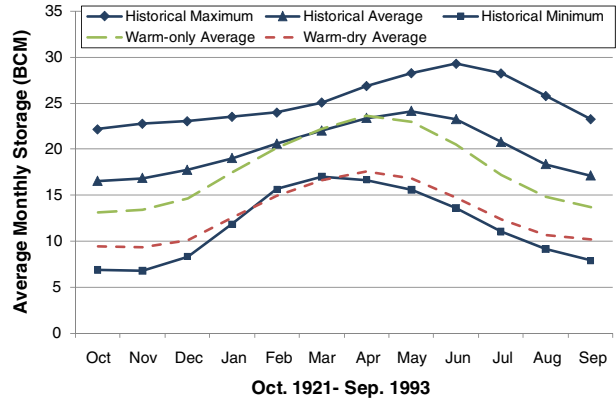
¹ Hist/WO MAI is Mean Annual Inflow for the historical and warm-only scenarios

² WD MAI is Mean Annual Inflow for the warm-dry scenario

3.2 Changes in storage operations

A changing climate affects average levels of aggregated statewide surface water storage. Both warm-only and warm-dry hydrologies reduce the average annual peak from historical levels (Fig. 2). Fig. 2 compares average monthly volumes of aggregated statewide surface storage for warm-only and warm-dry climates to the maximum, average, and minimum storage levels with historical hydrology. For example, the historical minimum storage series in Fig. 2 is comprised of the minimum statewide aggregated storage volume for each month in the 72 year modeling period. Both warmer and warmer-drier hydrologies shift the peak average storage earlier in the year. Other studies (Anderson et al. 2008; Madani and Lund

Fig. 2 Monthly aggregated statewide surface water storage (over period of record, 1921–1993) for historical, warm-only, and warm-dry climates

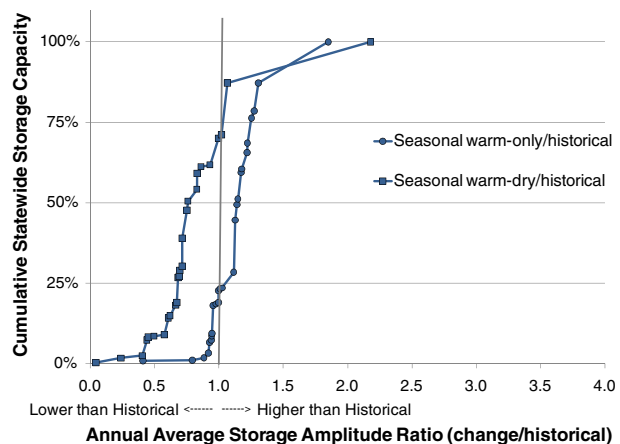


2009) also suggest about a month earlier shift in peak reservoir storage. Storage with warm-only hydrology shadows historical storage levels during February through April, but has lower levels the rest of the year. This suggests a changing pattern of drawdown and refill for reservoirs statewide. This trend is present in the Columbia River Basin as well (Lee et al. 2009). Surface storage with warm-dry conditions is close to the minimum monthly storage conditions from historical hydrology (Fig. 2). Recall that in CALVIN, all reservoirs and other infrastructure exist and are operated for the entire 72 years of hydrology.

Reservoirs in California typically have a regular drawdown-refill cycle, as reservoirs fill in winter and spring (wet season) and are drawn down in the dry season. The amplitude of this cycle represents seasonal reservoir storage. Annual amplitudes of aggregated statewide surface water storage increase for warm-only and warm-dry conditions compared to historical hydrologic conditions (Fig. 2). This amounts to a 28% and 2% increase in average amplitudes compared to historical amplitudes for warm-only and warm-dry, respectively. This greater swing in drawdown-refill storage within the water year (October–September) reflects the value of capturing winter and spring flows for use in the dry season.

For individual reservoirs, larger amplitudes for surface water storage indicate greater activity in reservoir operations to store and release water to meet water demands. This is especially true for warm-only conditions such that most of the storage amplitude ratios of warm-only to historical exceed one (Fig. 3). This reflects the case that reservoirs are refilling in the wet season

Fig. 3 Comparison of seasonal storage amplitudes for warm-only and warm-dry hydrologies for 26 reservoirs



to higher levels than with historical hydrology, but are still drawn down to meet water demands in the dry season. Figure 3 shows that 75% of the statewide storage capacity under warm-only conditions has larger seasonal storage amplitudes than occurs with historical hydrology. Amplitudes with warm-dry hydrology decrease since the reservoirs do not refill to the extent they do with historical hydrology, even though they are drawn down further. About 70% of statewide storage has smaller seasonal amplitudes with a warm-dry climate (Fig. 3).

3.2.1 Frequency of filling surface water storage facilities

Linear optimization model outputs include shadow prices or Lagrange multipliers for infrastructure capacity constraints and environmental and policy constraints. These values estimate the marginal benefit to the objective function of small changes in each constraint. For example, when a reservoir reaches capacity (an upper-bound constraint), the shadow price is the amount by which the objective function value would improve if the storage capacity was increased by one unit.

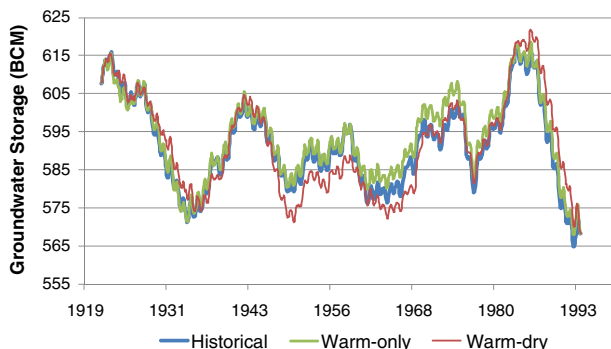
Additionally, capacity constraint shadow prices can identify months in which reservoir capacity (or constraint for the conservation pool) is reached. Table 3 shows a selection of surface reservoirs in geographic order north to south and the percent of years they fill based on the number of years (of 72) for which any given month has a negative shadow value. Warm-only hydrology usually increases the frequency of filling and almost always increases the value of increased storage. Pardee Reservoir, Millerton Lake, Lake McClure, Hensley Lake, New Don Pedro Reservoir, Hetch Hetchy Reservoir, Lake Isabella, Lake Success, and Pine Flat fill more frequently with warm-only hydrology than historical, due to earlier and higher peak spring and winter flows. Otherwise, reservoirs often fill the same number of years or slightly less frequently. In contrast to the warm-only response, the frequency of reservoirs reaching their capacity is much less with warm-dry conditions. Many reservoirs will not fill in most years if California's climate tends toward warmer-drier conditions.

The nature of climate change is crucial as to whether additional storage relieves water scarcity and adds flexibility to operating the system or goes unused if the reservoirs are rarely filled. The warm-dry climate decreases the frequency of filling as the reservoirs are now on streams with reduced flow volumes.

3.2.2 Cyclic groundwater storage and conjunctive use

Optimized statewide groundwater storage over the period of record is shown in Fig. 4. Its annual and inter-annual oscillations indicate periods of drawdown and refill seasonally and

Fig. 4 Monthly Central Valley aggregated groundwater storage over the 72-year period



between drought and wet years, the latter referred to as cyclic storage. Using groundwater in dry periods when surface water is scarce, and banking peak flows to groundwater storage during multi-year wet periods is what cyclic storage is all about. Results reflect economically optimal groundwater storage but do not explicitly suggest artificial groundwater recharge facilities are in operation. CALVIN includes a limited number of artificial recharge facilities: Owens Valley, Mojave, Coachella, MWD, and Santa Clara Valley (Ritzema et al. 2001).

Warm-only storage generally traces historical levels or are slightly higher. The warm-dry scenario drives operational changes that make greater use of groundwater storage than in the historical and warm-only scenarios. Higher highs and lower lows in groundwater storage volume for warm-dry conditions on a decadal time scale reflect this (Fig. 4).

The proportion of deliveries from groundwater are shown in Fig. 5. More deliveries come from groundwater during dry years. Consistent with other analyses, the warm-only scenario shadows results of the historical hydrology, for over-year cyclic groundwater storage. The steeper slope and larger range in percent groundwater use with warm-dry conditions suggests greater coordination of ground and surface waters.

Conjunctive use is defined as the coordinated management of surface and groundwater resources. The CALVIN model economically-optimizes use of groundwater and surface water resources conjunctively to meet urban and agricultural demands. The role of conjunctive use for southern California water supply was previously explored in which the value of conjunctive use programs along the Colorado River Aqueduct, in Coachella Valley, and north of the Tehachapi Mountains were examined, showing that conjunctive use programs, in coordination with water transfers, can add operational flexibility to the system and decrease reliance on water imports (Pulido-Velazquez et al. 2004). Here, conjunctive use within the Central Valley is assessed as a management adaptation to a warm-only and warm-dry climate.

As with scarcity, percent of groundwater use for each region’s supply portfolio is comparable between historical and warm-only climate scenarios (Table 4). In general, a larger portion of Tulare’s water supply comes from groundwater pumping. In contrast the Sacramento Valley relies mostly on surface water, especially in non-drought years. Only the Sacramento Valley incurs scarcity (about 1%) under historical and warm-only conditions. This occurs because the willingness to pay for water is greater in the San Joaquin Valley and the Tulare Basin. Therefore, to minimize system-wide economic costs, available water preferentially goes to these higher paying demands first and shorts demands in the north (through water transfers). Likewise, under warm-dry conditions when surface water resources are less available, the Sacramento Valley pumps additional groundwater,

Fig. 5 Annual variability in statewide use of groundwater

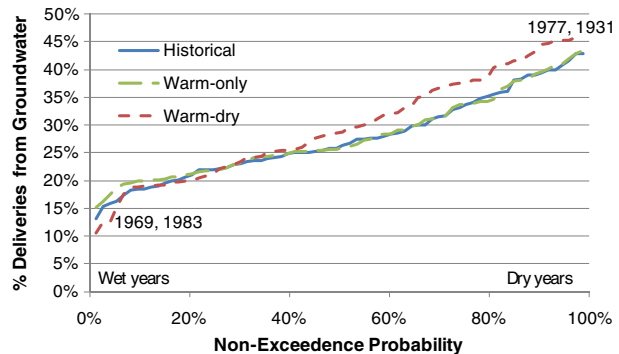


Table 4 Water portfolios for Sacramento Valley, San Joaquin Valley, and the Tulare basin for each scenario for drought and non-drought periods

Supply source per region	Drought period			Non-drought period		
	Historical	Warm-only	Warm-dry	Historical	Warm-only	Warm-dry
Sacramento Valley						
Groundwater Pumping	54%	54%	46%	28%	28%	22%
Surface Water	38%	38%	19%	63%	63%	48%
Agricultural Re-Use	7%	7%	5%	7%	7%	5%
Recycling & Desalination	0%	0%	0%	0%	0%	0%
Scarcity	1%	1%	30%	1%	1%	25%
San Joaquin Valley						
Groundwater Pumping	49%	48%	48%	32%	33%	26%
Surface Water	46%	46%	21%	62%	62%	45%
Agricultural Re-Use	5%	5%	3%	5%	5%	3%
Recycling & Desalination	0%	0%	0%	0%	0%	0%
Scarcity	0%	0%	27%	0%	0%	26%
Tulare Basin						
Groundwater Pumping	67%	67%	58%	41%	43%	39%
Surface Water	30%	30%	16%	56%	54%	37%
Agricultural Re-Use	2%	2%	2%	2%	2%	2%
Recycling & Desalination	0%	0%	0%	1%	1%	1%
Scarcity	0%	0%	23%	0%	0%	22%

decreases its surface water use, and incurs a greater percentage of scarcity than the San Joaquin Valley or Tulare Basin (Table 4). In all cases, deliveries from groundwater increase during drought periods when surface water is less available. Groundwater pumping is a much larger contributor to supply in all regions for times of drought compared to non-drought years. This highlights the economic value of using surface supplies during wet periods and increasing use of groundwater supplies during dry periods over the variable hydrologic record.

3.3 Hydropower

In-state hydropower is supplied by two major resources, namely low elevation (lower than 305 m) and high elevation systems. CALVIN includes large, low elevation multi-purpose reservoirs in California which produce 26% of in-state hydropower. For historical hydrology, low-elevation hydropower benefits for an average year are \$445 million/yr. With the warm-only climate, hydropower benefits are virtually unchanged (less than 2% decrease). This is mainly due to the fairly large size of most low-elevation reservoirs in California which provide significant operational flexibility for seasonal shifts in streamflow (Madani and Lund 2009). However, this system is directly affected by changes in total annual inflow reduction. Therefore, hydropower generation and revenue losses are much greater when the climate gets drier or streamflows are reduced from increases in evapotranspiration, reducing the “fuel” available to hydropower plants. This amounts to a 4.5% decrease (20 \$M/yr decrease) in hydropower benefit for warm-dry conditions in an average year and 6.5% decrease (388 \$M/yr from 415 \$M/yr for historical) for a dry year.

Climate change effects on the high elevation hydropower system, which includes more than 150 hydropower plants located below low-storage, high-head, single-purpose hydropower reservoirs that produce the rest of the in-state hydropower, have been explored in another study by Madani and Lund (2010), using CALVIN's complementary hydropower model, EBHOM (Energy-Based Hydropower Optimization Model) (Madani and Lund 2009). Their results also indicate 2% revenue reduction from the current 1,791 \$M/yr for the warm-only climate. The average high-elevation hydropower revenue reduction for warm-dry conditions was found to be 14%, mainly due to the changes in the runoff pattern, lower snowpack volumes, earlier peaks, and the limited flexibility in operations due to small storage capacity.

4 Limitations

Like any large-scale hydro-economic optimization model, CALVIN has limitations (Harou et al. 2009). With a model of this size and extent, data availability and quality present challenges. It has simple representations of environmental constraints, groundwater storage and flow, and hydropower. There is no inter-annual variability on groundwater pumping costs, by year type (i.e. wet, dry, or normal years), or groundwater in storage (reflection of groundwater elevation). As an optimization model, there are shortcomings of perfect foresight (which can reduce the economic value of optimally-operated storage by a factor of 2–5) (Draper et al. 2003) and it optimistically combines management alternatives. Considerations of water quality (except as it relates to water treatment costs) are not represented. Limitations of CALVIN are more comprehensively discussed elsewhere (Jenkins et al. 2001; Jenkins et al. 2004).

For this particular study three specific limitations should be mentioned. First, urban water use and scarcity costs are assumed constant for all three climate conditions. This approach does not account for use of additional conservation measures if the climate becomes warmer and drier. Second, urban footprint projections from Landis and Reilly (2002) do not take into account shocks in the housing market that may slowdown conversion from agricultural to urban land uses. Thus agricultural water scarcity may be lower for all three modeled scenarios. Third, a warm-dry hydrology may reduce yields for some crops in California (Adams et al. 2003; Lobell et al. 2007). Similar estimates of changes to urban water use in response to warmer-drier conditions are not available. Thus, water demands for these three scenarios are a static projection towards year 2050; the bias introduced will depend on whether warmer climate increases per capita use, or whether reductions in supply lead to additional urban water conservation. Also, since CALVIN economically optimizes water deliveries based on scarcity cost curves, water allocations are driven by the water demand targets and willingness to pay assigned to agricultural and urban regions. Uncertainty in estimates for these target levels for 2050 introduces uncertainty into the overall model results.

Another limitation relates to the bias implicit in the estimated warm-only hydrology. The permutation ratio's dual representation of warming and reduced runoff may introduce a bias for flows in months where the permutation ratio mostly represents effects of warming. This could overestimate streamflows during these times. Additionally, construction of warm-only streamflows neglects increased evapotranspiration and decreased soil moisture effects on annual runoff volumes due to increased temperatures. Initial results from WEAP (Yates et al. 2005), a rainfall run-off model, suggest mean annual runoff may decrease as much as 11% with increased climate warming even if historical precipitation is maintained (Null et al. 2009). Warm-only

streamflows in this study do not capture these effects. This limitation can be addressed either by using mean annual streamflow ratios by year type or by using a downscaled simulation of hydrology that follows a warm-only pattern, when available. In addition, future work on the response of evaporation rates to changes in precipitation and temperature would be useful in refining the approach used to perturb net reservoir evaporation.

The index mapping approach assumes the paired CALVIN/index basin matches are static. Additionally, perturbation of CALVIN's 72 years of historical hydrology limits climate changed hydrology to the inter-annual variation present in the historical record. Therefore, this study does not explore effects of increased climate variability.

There is also uncertainty in how groundwater will be affected by a changing climate and the warm-only scenario in this study assumes historical conditions for groundwater. Losses in groundwater storage and variable pumping costs could increase variability in groundwater versus surface water use. Despite these limitations, CALVIN provides some insights on promising management alternatives, relative costs, and the system's response to a wide range of hydrologic and other system-wide conditions.

5 Conclusions

California has many management options for adapting and mitigating costs of climate induced changes in water supply volume and timing. Combining these options and employing many of them, water scarcity and its cost as well as storage volumes appear to be more sensitive to reductions in runoff than to temperature increases alone. Temperature rise alone does not tend to increase water shortages greatly if system operations adapt to respond to the timing shift of peak runoff and storage. However, agriculture remains the most vulnerable user to water shortages under all climate scenarios. Total agricultural scarcity statewide increases less than 3% for warm-only compared to historical conditions with annual losses just over \$206 million. In contrast, water shortages exceeding 20% of agricultural target deliveries occur for warm-dry conditions, reducing annual agricultural production by over \$800 million, as determined by scarcity costs. This amounts to about 2% of California's annual agricultural value.³

With recurring wet and dry periods in the hydrologic record, groundwater resources are important in helping meet demands during droughts when surface water is unavailable. Cyclic groundwater storage has a larger role in a warmer and drier climate compared to just a warmer climate. Reoperation adaptations are aided by shifting some drought storage from surface reservoirs to groundwater during multi-year wet periods.

These climate scenarios also affect surface water storage and operations. Surface water operations confirm findings of other studies that reservoir storage levels peak earlier in the year under warmer climates. Surface water storage volumes are lower during summer and statewide storage is exercised more (having greater amplitudes) under warmer-drier conditions. For warm-only conditions, increased storage capacity in wet months may be valuable to help capture increased peak flows in winter months, though recharging peak flows to groundwater is an alternative to surface storage. Under a warmer-drier climate, increasing the system's surface storage capacity may not alleviate climate induced water scarcity. Additional surface storage may not be utilized in most years simply because less water is available to store. Under either scenario, changing reservoir operations in conjunction with a suite of management adaptations

³ Available at <http://www.cdfa.ca.gov/statistics/>.

(i.e. conjunctive use, water markets, adapted hydropower generation) serves well to reduce water scarcity and economic cost from climate change.

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