Bring the Heat, but Hope for Rain:
Adapting to Climate Warming for California

By

CHRISTINA RENE CONNELL
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Abstract

This thesis explores the independent effects of precipitation and temperature on California's hydrology and potential water management adaptations. Two climate scenarios are compared: 1) warmer-drier conditions, and 2) warmer conditions without change in total runoff (i.e. warm-dry and warm-only conditions). CALVIN, an economic-engineering optimization model of California's intertied water supply system is applied to explore water supply adaptation strategies 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 the early snowmelt from the warm-dry scenario while maintaining mean annual flows from historical hydrology. This separates the runoff volume and temperature effects of climate change on water availability and management adaptations. Model results predict earlier snowmelt and peak storage and significant management adaptation to warm-dry and warm-only climates, both of which increase water scarcity. Warm-only scarcity costs, however, are much less than costs for warm-dry conditions. Conjunctive use and surface water operations are explored as adaptation strategies. Results suggest increased temperatures alone affect reservoir operation yet have little hydrologic and economic effect on water supply performance compared to that of a combined warmer-drier change in climate.

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1.0 Introduction

A changing climate, such as precipitation and temperature changes, affects various parts of the hydrologic cycle with implications for California's economy. Downscaled global climate models applied to California and the western United States have explored possible changes in streamflow, snowmelt, snow water equivalent, evapotranspiration, and changes in magnitude of annual peak flows (Cayan et al. 2008b; Hamlet et al. 2007; Miller et al. 2003). Early studies indicate a shift in spring runoff since the 1940s as warming temperatures affect the centroid of mean annual runoff making it earlier in the year (Dettinger and Cayan 1995). This shift in volume and magnitude of streamflows may influence water management and the extent and character of ecosystems and changes in estuarine inflows and salinity in the Sacramento-San Joaquin Delta (Cayan et al. 2001; Cayan et al. 2008a; Knowles and Cayan 2004).

Characterized by a Mediterranean climate, California's urban and agricultural water supply depends heavily on storage of water in snowpacks, reservoirs, and aquifers. Warming in the western United States is reducing snow water equivalents (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). In addition to higher water supply risks, state water managers may have increased flood management challenges due to increased peak storm runoff (Anderson et al. 2008). Mid to low elevation basins are most sensitive to initial shifts in temperatures. These basins, where moderate shifts in temperature could cause large shifts in hydrologic response, may also be more susceptible to floods since changes in temperatures affect volume, form of precipitation (rain versus snow), and seasonal timing of streamflow (Fissekis 2008; Knowles et al. 2006; Regonda et al. 2005). Efforts have been made to incorporate global climate model forecasts into operations of individual reservoirs as well as more integrated system operations (Carpenter and Georgakakos 2001; Georgakakos et al. 2005).

Climate change studies with regard to hydrologic response largely assess surface water effects, yet groundwater response to climate change has also 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). However, regional or general conclusions about climate change effects on groundwater and combined groundwater and surface water management is lacking and may be inappropriate due to complexities of local influences in groundwater basins.

Previous studies have assessed economic impacts and California water management adaptation to combined warmer and drier climates (Medellin-Azuara et al. 2008; O'Hara and Georgakakos 2008; Tanaka et al. 2006). Tanaka et al. (2006) applies the CALVIN model to explore integrated management adaptations to a warmer-drier climate and a warmer-wetter climate for 2100 demands. Medellin-Azuara et al. (2008) explored optimized adaptations (particularly multi-reservoir operations) to a warm-dry climate scenario with year 2050 demands. This paper compares the effects of increased temperature and decreased runoff to explore their independent and combined effects on California water management adaptation by comparing a warmer climate scenario with a warmer-drier scenario with updated 2050 water demand estimates. Conjunctive use, adapted surface water operations, and additional storage are explored as strategies to mitigate economic costs incurred by warmer and warmer-drier climate perturbed hydrology.

2.0 Project Approach and Methods

2.1 CALVIN

The California value integrated network (CALVIN) is an economic-engineering optimization model of California's statewide water supply system. Using a network flow optimization solver provided by the U.S. Army Corps of Engineers (*HEC-PRM*), CALVIN operates surface and groundwater resources and allocates water over the historical hydrologic record to maximize statewide net economic values of agricultural and urban water use within physical and environmental constraints (Draper et al. 2003). Applications of CALVIN have explored various water problems in California. This includes but is not limited to previous climate change related studies, exploring effects of removing O'Shaughnessy Dam in Hetch Hetchy, and exploring conjunctive use operations in southern California (Draper et al. 2003; Jenkins et al. 2001; Jenkins et al. 2004; Lund et al. 2007; Medellin-Azuara et al. 2008; Null and Lund 2006; Pulido-Velazquez et al. 2004; Tanaka et al. 2008; Tanaka and Lund 2003; Tanaka et al. 2006).

CALVIN includes most of the state's intertied water supply network including 44 reservoirs, 28 groundwater basins, and 54 urban and agricultural demand areas represented economically (Figure 1). The model covers 92% of the population and 88% of irrigated acreage. Inputs in the model include surface and groundwater hydrology, physical facilities and capacities, urban and agricultural values of water, environmental flow constraints, and operating costs. Outputs can be analyzed for economic benefits of alternatives, conjunctive use and water marketing operations, willingness to pay for additional water, water operations and delivery reliability, and values of increased facility capacity (Draper et al. 2003).

Economically driven, CALVIN allocates water to minimize total statewide water scarcity and operation costs. Scarcity is defined as the amount of water the user is willing to pay for above the volume of water delivered to that user. Whenever a user's economic target use is not met, scarcity occurs. Agricultural and urban water demand levels are estimated for year 2050 demands, population, and land-use. Values for agricultural water use are derived using the Statewide Agricultural Production model (SWAP), a separate optimization model that maximizes farm profit for each agricultural demand area (Howitt et al. 2001). For each agricultural production region, an economic loss function is derived to estimate the cost of water scarcity. Water use estimates in SWAP are based on land-use projections for 2050 (Landis and Reilly 2002). Urban water use penalties follow the methods described in Jenkins et al. (2003) with population growth projections and urban water demands for year 2050 (Jenkins et al. 2007).

CALVIN uses 72 years of monthly hydrology (1921-1993) to represent hydrologic variability. Hydrologic representation includes surface water inflows (rim inflows), groundwater inflows, and return flows to surface and groundwater resulting from urban and agricultural uses. Referred to as local accretions and depletions (or net local accretions), these flows connect aquifer gains and losses with surface water runoff. Historical flow data comes from existing surface and integrated surface-groundwater models (Draper et al. 2003; Jenkins et al. 2001; Zhu et al. 2005).

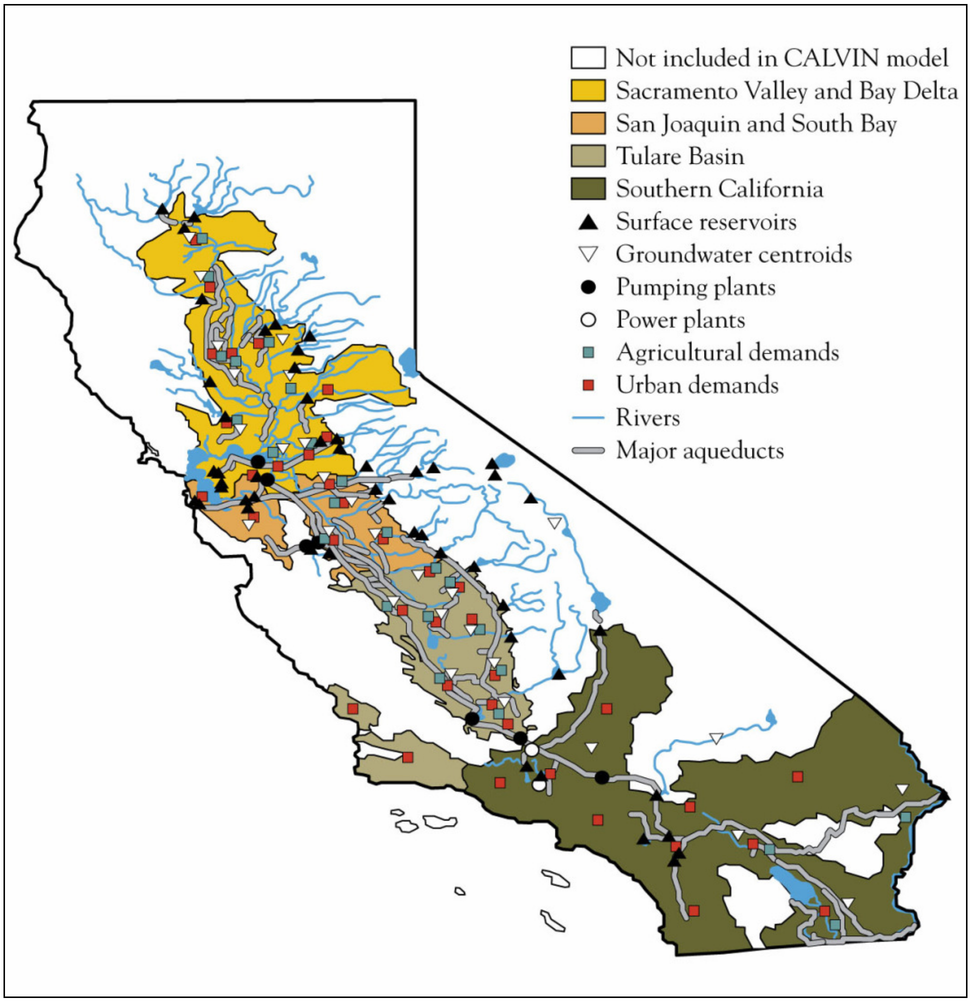

Figure 1. Hydrologic basins, demand areas, major inflows and infrastructure represented in CALVIN (Lund et al. 2007)

Although offering insights in its applications, as with any model, CALVIN has limitations. With a model of this size and extent, data availability and quality can be problematic. It has simple representations of environmental constraints, groundwater storage and flow, and hydropower. Costs of groundwater pumping do not vary by year, year type (i.e. wet, dry, or normal years), or amount of water in storage (reflection of groundwater elevation). As an optimization model, there are shortcomings of perfect foresight (Draper et al. 2003) and it sometimes optimistically combines management alternatives. Limitations of CALVIN are discussed more completely elsewhere (Jenkins et al. 2001; Jenkins et al. 2004). Nevertheless, CALVIN can provide insights on promising management alternatives, relative costs, and the system's response to various hydrologies or other conditions.

2.2 Perturbed Hydrology

2.2.1 General Circulation Models (GCMs)

The basis for global climate change hinges on the climate's response to changes in the radiation balance of the Earth. Three fundamental ways to change this energy balance are: by changing the incoming solar radiation; by changing the fraction of solar radiation reflected (changes in cloud cover, atmospheric particles or vegetation); or by altering the longwave radiation from Earth back towards space (i.e. changing greenhouse gas concentrations) (IPCC 2007). Components of the climate system that affect the Earth's energy balance are termed forcing factors. These include increased solar input, volcanic eruptions, increased concentrations of green-house gases, increased tropospheric ozone, decreased stratospheric ozone, increased loading of tropospheric sulfate aerosol and carbonaceous aerosol, and changes in land-use and land cover. All these factors can influence the annual global average temperature and cause differing temperature trends (Karl et al. 2006).

The IPCC Fourth Assessment Report (2007) identifies 23 GCMs each of which couples models for atmosphere, ocean, sea ice, and land processes. These models are built on accepted physical principles (i.e. conservation of mass) and have reproduced observed features of current and past climate changes (IPCC 2007). Confidence in model estimates is higher for some variables such as temperature, than for others (i.e. precipitation), yet these mathematical models of the climate system have been shown to successfully simulate important aspects of our current climate. GCMs have helped increase understanding of climate and climate change, and can provide credible quantitative estimates of future climate change, especially at large scales (IPCC 2007).

With the inherent uncertainty of climate change studies, scenarios are developed as alternative futures, defined images of how the future may unfold. These lie somewhere between quantitative modeling and qualitative storytelling (Nakicenovic et al. 2000). Greenhouse gas (GHG) emissions are an important forcing factor affecting global climate. Future levels of global GHG emissions are impossible to predict accurately and will result from a complex, inter-connected dynamic system driven by such forces as population growth, socio-economic development, and technological progress. For the purposes of standardization, IPCC produced the Special Report on Emissions Scenarios (SRES) defining several emissions scenarios to enable coordinated studies of climate change. IPCC developed four families of storylines: A1, A2, B1, and B2. A1 describes a future world of rapid economic growth, low population growth, rapid introduction of new and efficient technologies with collaborating regions and increased cultural and social interactions. A2 describes a heterogeneous world with regionally oriented economic growth, high population growth and slower, more fragmented technological change. B1 describes a world with low population growth as in A1, but with changes in economic structure toward a service and information economy and introduction of resource-efficient technologies. Finally, the B2 storyline emphasizes local solutions to economic, social, and environmental sustainability, with moderate population growth and intermediate levels of economic development (Nakicenovic et al. 2000). A2 is generally regarded as the upper-bound, relatively pessimistic, scenario for climate change studies whereas B1 generally represents a best-case future emissions scenario (Maurer 2007).

The Geophysical Fluid Dynamics Laboratory (GFDL) of the National Oceanic and Atmospheric Administration (NOAA) developed two global coupled climate models, CM2.0 and CM2.1. These models were designed to simulate atmospheric and oceanic climate and variability for both seasonal to interannual forecasting, as well as the study of global climate change over multiple centuries. Both models can simulate the main features of observed warming of the twentieth century and have been used for a suite of climate change simulations for the 2007 Intergovernmental Panel on Climate Change (IPCC) assessment report (Delworth et al. 2006).

The IPCC Fourth Assessment Report 2007 describes emission scenarios considered by GCMs and summarizes regional climate change projections regarding temperature and precipitation changes (Christensen et al. 2007). Cayan et al (2008b) describes a selection of these models and emission scenarios from California's perspective. For California, the Parallel Climate Model (PCM1) and NOAA GFDL CM2.1 model provide simulations suggesting warming temperatures ranging from 1.5 to 4.5 ^{o}C by the end of the century, depending on the emissions scenario. Precipitation changes range from a decrease of 26% for the high emissions scenario to an increase of 7% for the low emissions case (Cayan et al. 2008b). Results of several simulations suggest California's Mediterranean climate will not change structurally or introduce stronger thunderstorm activity. However, precipitation may increase some in winter and decrease in spring (Cayan et al. 2008b).

The GFDL CM2.1 model with a higher emissions scenario (A2 scenario) was selected for this study. Downscaled effects of the scenario using bias correction and spatial downscaling (BCSD) (Maurer and Hidalgo 2008) estimated temperature and precipitation effects on streamflow and groundwater fluxes for a 30-year period centered on 2085 (Maurer 2007; Maurer and Duffy 2005). Outputs from the global climate model simulated a warm-dry scenario with 4.5°C (8.1°F) increases in annual temperature by the end of the century and variable degrees of decreased precipitation for watersheds and groundwater basins statewide (Cayan et al. 2008b). A warm-only scenario was also examined with adjusted hydrology based on the perturbed warm-dry and historical hydrology, since the global climate model did not directly simulate a warm-only scenario. Overall precipitation changes for California are uncertain with most models showing little change in average levels; yet 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). To explore management adaptations to this scenario, the warm-only scenario was designed to maintain the average annual streamflow of historical hydrology while capturing the shift in runoff timing expected from warming temperatures. Construction of warm-only streamflows, described later in greater detail, neglects increased evapotranspiration and decreased soil moisture effects on annual runoff volumes due to increased temperatures. Initial results from WEAP, 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 neglect these effects.

Temperature shifts, precipitation changes, and monthly streamflow at 18 index basins were used to perturb CALVIN hydrology following methods detailed in Zhu et al. (2003) and described in short in the following sections. Hydrologic processes perturbed for climate change include rim inflows (streamflows entering the boundaries of CALVIN), net evaporation rates at reservoirs, groundwater inflow, and net local accretions. Perturbing time series for these hydrologic processes adjusts the hydrology for each climate change scenario to represent its effect on California’s water supply.

2.2.2 Rim Inflows

Data from downscaled global climate models (Maurer and Hidalgo 2008) generated for the California Energy Commission’s Climate Change Assessment 2008 were made available for this study. These time series included streamflows for select rivers in California, referred to here as index basins. Using GCM-based streamflows for these 18 index basins (Table 1), permutation ratios capturing the effects of magnitude and timing shifts in streamflows were used to perturb all CALVIN rim inflows. This method maps hydrologic changes in index basin streamflows to CALVIN’s 37 rim inflows producing a new climate change time series for each rim inflow (Zhu et al. 2003). This requires each CALVIN inflow to be matched with a representative index basin. In a previous climate change study using CALVIN, six index basins with flows for 1950–2099 representing different climate change scenarios were available from downscaled global climate models. Perturbation ratios from these six basins were applied to each of CALVIN’s 37 rim inflows to produce climate-adjusted flows for the model. The six representative basins were: Smith River at Jedediah 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. For the current study, 18 index basins (Table 1) were available to aide in matching CALVIN rim inflows to appropriate basins. These additional basins include a range of tributaries of the Sacramento and San Joaquin Rivers from the east side of the valley, and the Trinity River in the north, a tributary to the Klamath.

Table 1. Index basins for the current and previous study

Index Basins
Sacramento R at Shasta Dam
Stanislaus R at New Melones Dam
San Joaquin R at Millerton Lake
Merced R at Lake McClure
Yuba R at Smartville
American R at Folsom Dam
Cosumnes R at McConnell
Feather R at Oroville**
Tuolumne R at New Don Pedro
Mokelumne R at Pardee
Calaveras R at New Hogan
Sacramento R at Bend Bridge
Sacramento R at Delta**
NF American R at NF Dam**
Merced R at Pohono Bridge**
Kings R at Pine Flat Dam**
Trinity R at Trinity Reservoir
Smith R at Jed Smith**

** 6 previous index basins

Similar methods from a previous study (Zhu et al. 2005) were applied and adjusted as needed to select appropriate index basins for each CALVIN rim inflow. CALVIN rim inflow time series extend from October 1921 to September 1993, a period of 72 years. The streamflow data available for the 18 index basins extends from January 1950 to December 2099 with historical flows being 1950-2000. Therefore, the corresponding time series for correlating index streamflows with CALVIN rim flows was water years 1950 to 1992. To improve representation, the water year was divided into wet and dry seasons (October through March and April through September, respectively). This break in the year was applied for some of the statistical analysis.

Several statistical methods were used to assess possible matches:

1. Maximum annual flow correlation coefficient between CALVIN inflows and index basin flows
2. Maximum monthly flow correlation coefficient for each water year from 1950-1992 between CALVIN inflows and index basin flows
3. Maximum monthly flow correlation coefficient for wet season and for dry season between CALVIN inflows and index basin flows
4. Minimum least sum of squared error (SSE) for monthly flow on an annual basis over the period of record between CALVIN inflows and index basin flows
5. Minimum least sum of squared error (SSE) for monthly flow seasonally, for wet and dry seasons independently, between CALVIN inflows and index basin flows

This statistical analysis resulted in a table indicating potential annual or seasonal matches of index basins for each CALVIN inflow. Visual comparisons of average monthly time series of these potential index basins and CALVIN flows were then made to help select the best match. Magnitude and timing of flows were compared graphically. Finally, expert judgment considering geographic location and knowledge of hydrologic processes of each basin (e.g., rain-dominated, snowmelt runoff) played a definitive role in establishing a match. For example, low elevation, rain dominated basins were matched with similar basins and when possible, general spatial location was considered in the final decision process such that the Smith basin (one of the few rain-dominated index basins in the previous study) was replaced instead by the Cosumnes River basin which is closer to most CALVIN rim flows (see Appendix A for mapping matrix).

Perturbation ratios from each index basin were applied to the corresponding CALVIN flow to shift the time series of flow in time and magnitude. This generates the warm-dry climate adjusted rim inflow times series input to CALVIN. Perturbation ratios for the warm-dry scenario indicate a general decrease in magnitude of flow as well as a shift in timing indicating an earlier snowmelt, as shown for the Sacramento and San Joaquin Rivers in Figure 2.

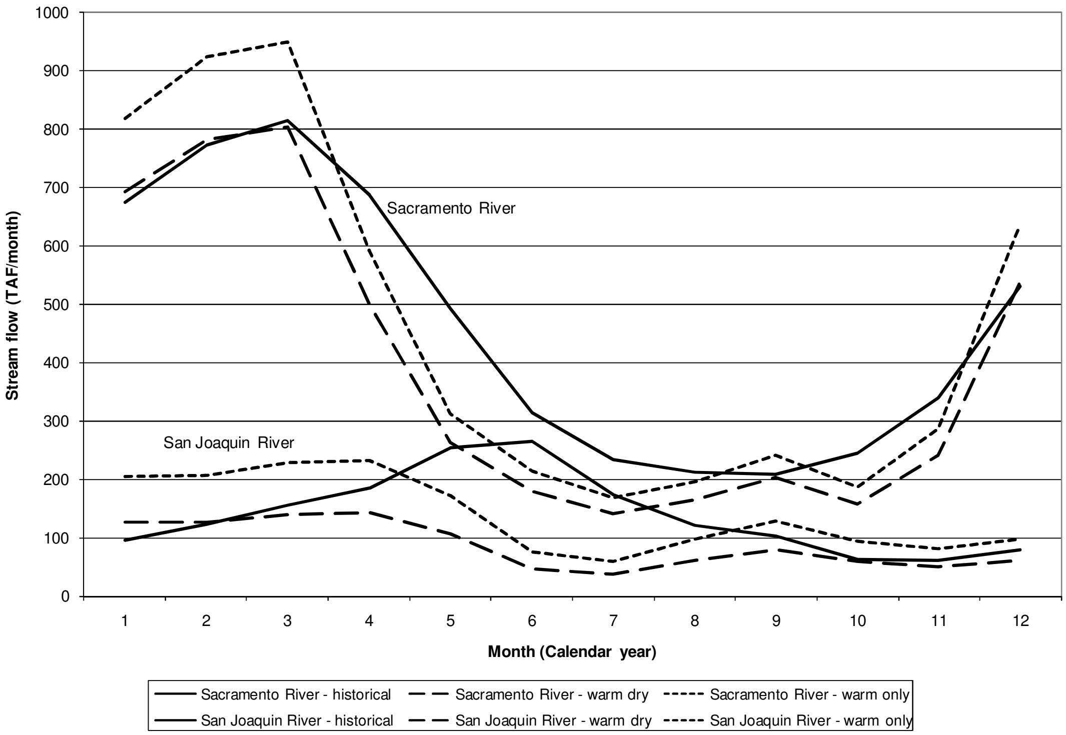

Figure 2. Sacramento River (at Shasta Dam) and San Joaquin River (at Millerton) mean monthly streamflows, 1921–1993, for each modeling scenario

A downscaled global climate model was unavailable to represent a warm-only hydrology. Therefore, warm-dry rim inflow time series were adjusted to develop new time series to represent this additional scenario. The following equation was used to develop climate change time series representing a warm-only scenario; having the same average annual runoff as historical flows:

$$Q_{i,t}^{WO} = \alpha_{i,t}^{WD}\left(\frac{\overline{Q}_i^{\,H}}{\overline{Q}_i^{\,WD}}\right)Q_{i,t}^{H}$$

where:

$\alpha_{i,t}^{WD}$ - permutation ratio adjusts time series to the warm-dry scenario (Zhu et al. 2003)

$\overline{Q}_i^{\,H}$ - Historic average flow

$\overline{Q}_i^{\,WD}$ - Average annual flow of the warm-dry series

$Q_{i,t}^{H}$ - Historic time series of flow

$Q_{i,t}^{WO}$ - Warm-only time series of flow

Indices *i* and *t* indicate the 37 rim inflow locations and monthly time steps over the 72-year period, respectively. As with the warm-dry series, permutation ratios were applied to the historical time series to capture the effect of warming (shift in hydrograph timing).

To reverse the effect of decreased runoff, this perturbed time series was 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 scenario but with greater flows so average annual streamflow equals that of the historical scenario (Figure 2). The method is limited by the permutation ratio's dual representation of warming and reduced precipitation. Since the method assumes that both warming and drying effects are present in every time step at every location, the approximation could overcompensate precipitation adjustments in months where the permutation ratio in fact primarily represents effects of warming. This could overestimate streamflows during these times.

2.2.3 Other Climate Perturbed Hydrologic Processes

In addition to rim flows, climate-adjusted hydrologic processes include net reservoir evaporation, groundwater inflows, and net local accretions following the method described in Zhu et al. (2003), described in short below.

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. The resulting perturbed reservoir net evaporation time series provides estimates of changed evaporation rates under the warm-dry climate change scenario. For the warm-only scenario, we assume annual volume of precipitation is unchanged; therefore change in precipitation was set to zero and only changes in temperature increased net reservoir evaporation.

Groundwater storage is calculated by changes in deep percolation modeled using an empirical cubic relationship between precipitation and recharge derived 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, the historical time series of groundwater inflow was used for the warm-only scenario. As a result, effects on groundwater recharge of reduced snowpack and earlier melting are not represented in the warm-only scenario; however, timing and magnitude of historical and warm-dry scenario time series of groundwater storage were similar, so this approximation seems 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.

3.0 Results and Discussion

3.1 Hydrology Results

Perturbing hydrologic processes statewide for warm-dry and warm-only climate scenarios affects the overall water supply available for statewide water demands. The overall magnitude of precipitation and streamflow for the state remains unchanged for the warm-only scenario. As previously mentioned, this neglects effects of increased evapotranspiration in watersheds on streamflows. Under the warm-dry scenario, precipitation decreases across all 21 groundwater basins by 27%, a total of 3,834 TAF, shown in Table 2. This reflects decreased precipitation on the valley floor. This amounts to about 2.3 inches/yr less precipitation statewide and in the Sacramento and San Joaquin valleys, and 2.4 inches/yr less in the Tulare Basin.

Drier conditions also affect rim inflows, net evaporation rates from reservoirs, groundwater inflow, and net local accretions. Figure 3 compares warm-dry perturbed rim inflows, net evaporation, and groundwater inflow to historical values (indicated by the dashed line at 100%). In all regions, rim inflows and groundwater inflows decrease while evaporation from the reservoirs increase. This works together to decrease the total volume of water available to meet water demands, and therefore creates this drier scenario.

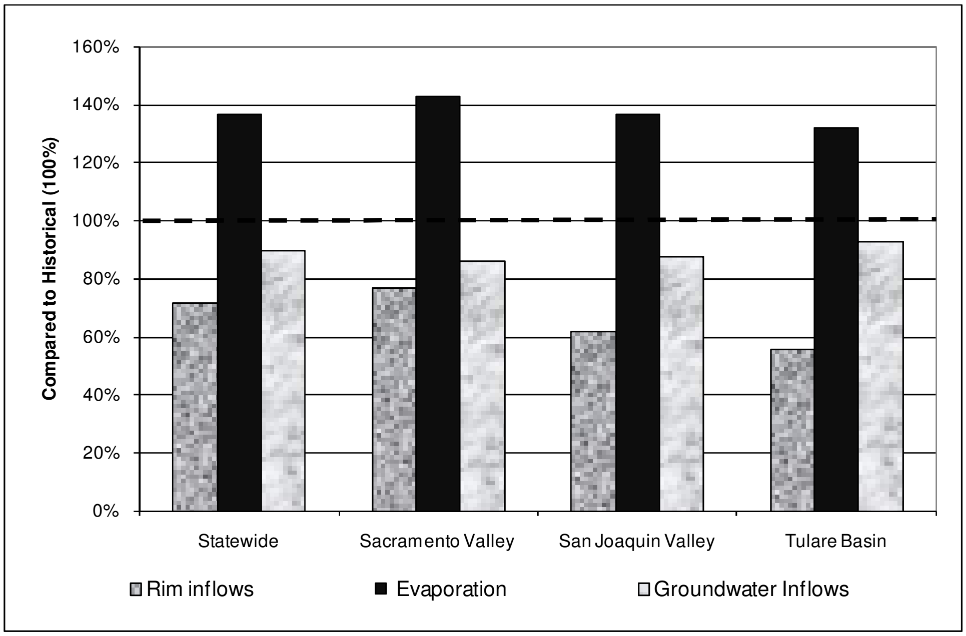

Figure 3. Perturbed hydrology of warm-dry scenario compared to historical hydrology (100% baseline)

A complete summary of changes in volumes and percent change for each scenario compared to historical hydrology is presented in Table 2. This summarizes the statewide and regional (across the columns) effects of the warm-only and warm-dry climate scenarios on California's water supply. Compared to the historical climate scenario, rim inflows decrease by 28% in a warm-dry climate. Rim flows in the warm-only scenario maintain the same average annual flow as in the historical climate. Net reservoir evaporation statewide increases by 37% in a warm-dry climate, driven by increasing temperatures and decreased precipitation rates in the last third of the century. For the warm-only scenario, evaporation increases 15% statewide. Net evaporation is significantly greater for a warmer and drier climate scenario than just a warmer scenario. Groundwater inflows decrease moderately with a 10% reduction from historical conditions statewide. Net local accretions (accretions minus depletions) decrease significantly statewide and regionally in the warm-dry scenario, leading to a large loss of available water to the system. Local accretions decrease from the historical scenario and local depletions significantly increase, especially in the San Joaquin Valley.

Table 2. Changes in California's water supply under 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	-27%	-24%	-30%	-33%	---
Inches/year	-2.3	-2.3	-2.3	-2.4	---
Rim inflows (TAF/yr)					
Historical	28244	19122	5741	2826	554
Warm-dry	20301	14804	3546	1584	367
% Change	-28%	-23%	-38%	-44%	-34%
Net Reservoir Evaporation (ft/yr)					
Historical	5.1	3.7	6.4	6.6	5.3
Warm-dry	7.1	5.3	8.7	8.7	7.2
% Change	37%	43%	37%	32%	36%
Warm only	5.9	4.3	6.9	8.1	6.3
% Change	15%	17%	9%	23%	19%
Groundwater Inflows (TAF/yr)					
Historical	6780	2229	1171	3380	---
Warm-dry	6103	1920	1035	3147	---
% Change	-10%	-14%	-12%	-7%	---
Local Accretion (TAF/yr)					
Historical	4419	3549	468	401	---
Warm-dry	3092	2617	272	203	---
% Change	-30%	-26%	-42%	-49%	---
Local Depletions (TAF/yr)					
Historic	1448	510	54	884	---
Warm-dry	3217	1111	359	1747	---
% Change	122%	118%	566%	98%	---

3.2 Water Supply Results

Optimized water deliveries are compared to delivery targets for each urban and agricultural demand in the statewide network to estimate regional water scarcity. The difference between water delivered and the quantity one is willing to pay for, is defined as the region's water scarcity. Cost curves (economic loss functions) assign a corresponding scarcity cost for each area having scarcity. The state network includes agricultural demand areas and urban demand areas. Table 3 shows scarcity volumes and scarcity costs for each scenario for agricultural and urban demands aggregated statewide. The second column also indicates each sectors' willingness to pay, which gives an indication of how water economically moves 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 the agricultural sector, where senior water right holders are paid to forego use. This pattern of water scarcity under optimized operations is common in previous CALVIN studies as well (Draper et al. 2003; Medellín-Azuara et al. 2008; Tanaka et al. 2006). Agricultural water uses are the most prone to water scarcity for all three hydrologic scenarios: historical, warm-only, and warm-dry.

Table 3. Statewide water scarcity, scarcity cost, willingness to pay and percent of water deliveries by 2050 (in $2008)

Scenario	Willingness to Pay ($/AF)	Scarcity Cost ($K/yr)	Scarcity (TAF/yr)	Delivery (% of Target)
Historical				
Agriculture	232	200,894	869	96.4
Urban	381	31,091	31	99.8
Total		231,985	900	
Warm-Only				
Agriculture	232	206,843	893	96.3
Urban	381	32,405	32	99.7
Total		239,249	1,925	
Warm-Dry				
Agriculture	251	808,119	5,074	78.9
Urban	658	62,822	90	99.3
Total		870,941	5,164	

Statewide water scarcity increases by 114%, [(1925-900)/900] with warm-only conditions compared to the historical climate scenario. In a warm-dry scenario, scarcity increases by 474%, [(5164-900)/900] (Table 3). Climate warming decreases water deliveries and increases water scarcity, yet drier conditions combined with climate warming proves far more costly. Increases in scarcity costs are less for warm-only conditions with a 3.5% [(239,249-231,985)/ 231,985] increase compared to 275% [(870,941-231,985)/231,985] increase for a warmer-drier climate. Relatively small additional scarcity from the warm-only climate arises from the ability of large storage reservoirs, especially when operated conjunctively with groundwater, to effectively adapt to the seasonal shift of runoff. This is in line with classical reservoir operations theory (Hazen 1914), that reservoirs with over-year storage capability are affected much less by seasonal changes in flows. Most large reservoirs in California have both seasonal and over-year (drought) storage.

Water transfers from agriculture to urban uses support the 2050 population and counteract the effects of reduced rim flows, increased evaporation, and other potentially affected elements of the water cycle. This assumes that market transaction costs are small and institutional infrastructure exists to support such water transfers (Pulido-Velazquez et al. 2004). Under the less severe climate scenarios, such as historical or warm-only, greater agricultural water shortages seem to arise mostly due to population growth. Thus, water scarcity is more sensitive to changes in precipitation than to changes in temperature if water is economically managed. However, this conclusion can be better tested when a downscaled hydrology of a warm-only scenario becomes available and the effect of increased evaporation and decreased soil moisture can be incorporated into perturbed streamflows.

3.2.1 Agricultural Regional Results

Agriculture suffers the most water scarcity under the warm-dry scenario; less than 80% of statewide target deliveries (last column Table 3) are achieved due to reduced water availability and the higher opportunity cost of urban scarcity. Estimates for target agricultural water demands follow previous CALVIN applications for the year 2050 and are based on future land use projections (Landis and Reilly 2002; Medellin-Azuara et al. 2008). Table 4 allows regional comparison of targets, scarcity, delivery, and scarcity cost for each climate scenario. For warm-only conditions, Southern California agriculture is most affected by reduced water resources, incurring a scarcity cost of $193 million (Table 4). Only CVPM 3, CVPM 12, Coachella, and Imperial Valley agricultural demands experience scarcity under historical or warm-only conditions. Scarcity increases for both perturbed climate scenarios compared to historical hydrology for all regions. The Central Valley regions experience the most drastic increase in water scarcity between historical and warm-dry conditions whereas the increase for Southern California is more moderate. Nearly all CVPM regions (except CVPM 14 and 19) have some scarcity under warm-dry conditions. Under this climate scenario, the Sacramento Valley incurs the greatest volume of scarcity (1,771 TAF), however Tulare Basin has the greatest scarcity cost, almost $276 million. With high valued agriculture, their water scarcity is more costly than other regions.

Table 4. Regional agricultural target, delivery, and scarcity cost for each climate scenario

Demand Area	Target (TAF)	Scarcity (TAF)			Delivery (% of Target)			Scarcity Cost ($K/yr)		
	all scenarios	Hist.	WO	WD	Hist.	WO	WD	Hist.	WO	WD
CVPM 1	126	0	0	81	100%	100%	36%	0	0	9,091
CVPM 2	497	0	0	103	100%	100%	79%	0	0	11,327
CVPM 3	2,196	93	93	411	96%	96%	81%	12,745	12,745	60,509
CVPM 4	956	0	0	206	100%	100%	78%	0	0	17,791
CVPM 5	1,313	0	0	361	100%	100%	72%	0	0	29,642
CVPM 6	619	0	0	174	100%	100%	72%	0	0	17,276
CVPM 7	429	0	0	153	100%	100%	64%	0	0	14,970
CVPM 8	802	0	0	132	100%	100%	84%	0	0	17,237
CVPM 9	926	0	0	150	100%	100%	84%	0	0	13,413
CVPM 10	919	0	0	69	100%	100%	92%	0	0	10,580
CVPM 11	855	0	0	277	100%	100%	68%	0	0	31,561
CVPM 12	772	4	4	230	99%	99%	70%	391	391	27,292
CVPM 13	1,506	0	0	444	100%	100%	71%	0	0	57,764
CVPM 14	1,358	0	0	0	100%	100%	100%	0	0	0
CVPM 15	1,701	0	0	193	100%	100%	89%	0	0	36,563
CVPM 16	345	0	0	105	100%	100%	70%	0	0	16,331
CVPM 17	797	0	0	235	100%	100%	71%	0	0	35,430
CVPM 18	1,759	0	0	690	100%	100%	61%	0	0	137,743
CVPM 19	887	0	0	0	100%	100%	100%	0	0	0
CVPM 20	829	0	0	79	100%	100%	90%	0	0	21,378
CVPM 21	1,195	0	0	116	100%	100%	90%	0	0	28,499
Palo Verde	494	0	0	0	100%	100%	100%	0	0	0
Coachella	654	154	154	200	76%	76%	69%	39,945	39,948	53,873
Imperial	2,187	618	642	665	72%	71%	70%	147,814	153,759	159,843
Regional Results:										
Sacramento Valley	7,864	93	93	1,771	99%	99%	77%	12,745	12,745	191,256
San Joaquin Valley	4,052	4	4	1,021	100%	100%	75%	391	391	127,198
Tulare Basin	8,871	0	0	1,417	100%	100%	84%	0	0	275,944
Southern California	3,336	772	796	865	77%	76%	74%	187,759	193,707	213,716

3.2.2 Urban Regional Results

Urban demands have less scarcity because of their high willingness to pay for water, although they would have to pay farmers for much of their water. The highest willingness to pay for additional water occurs for cities east of Los Angeles, as high as $472 per acre-ft (Table 3). Overall, urban uses are supplied at their target demand (Table 3, fifth column) such that delivery is greater than 99% of their target. Small shortages close to 31 TAF/yr are likely in Southern California for historical and warm-only hydrologies. The warm-dry scenario triples shortages for urban locations to 90 TAF/yr (Table 3). Scarcity occurs under all three climate conditions for San Diego County, Riverside County, Castaic Lake Water Agency, and Blythe (Table 5). In the case of Castaic Lake Water Agency and Blythe, scarcity remains the same or decreases for warm-only conditions compared to historical. Additional urban centers incur scarcity under warm-dry conditions. The Mojave Water Agency and Hi-Desert Water District experience the greatest scarcity by far at a cost of 24.5 million dollars per year.

Table 5. Local urban water scarcity and scarcity costs for each climate scenario

	Scarcity (TAF)			Scarcity Cost ($K/yr)		
	Hist	WO	WD	Hist	WO	WD
San Diego County	7.4	8.5	8.5	8,366	9,599	9,645
Mainly Riverside County	19.5	19.6	19.7	20,821	20,987	21,008
Castaic Lake Water Agency	1.1	0.9	5.9	724	640	4,428
Blythe	3.2	3.2	3.3	1,177	1,177	1,244
Additional areas with scarcity for warm-dry scenario:						
East Bay MUD	0	0	0.9	0	0	1,168
Turlock	0	0	0.8	0	0	84
Mojave Water Agency and Hi-Desert Water District	0	0	49.9	0	0	24,497
Antelope Valley Area	0	0	0.8	0	0	747

3.3 Changes in Storage Operations and Values

CALVIN results give monthly storage volumes for the 72 year model run for each groundwater basin and surface water reservoir. Storage results presented here include groundwater and surface water storage aggregated statewide across 21 groundwater basins and 44 surface water reservoirs. Analysis of these times series show average annual patterns in statewide storage for groundwater and surface water as well as months of maximum storage volume for each climate scenario.

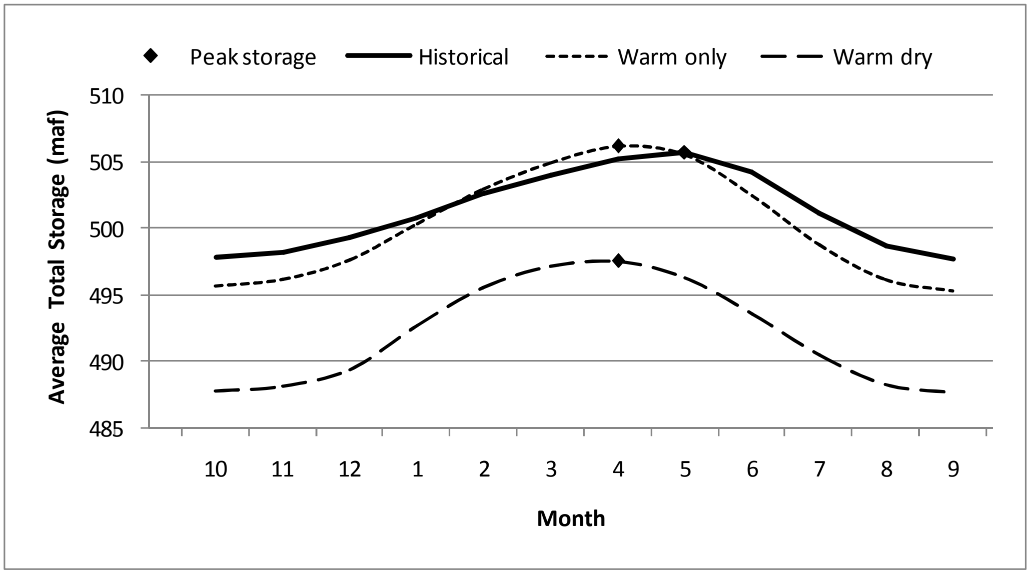

Figure 4. Average monthly total storage (groundwater and surface water) statewide

Figure 4 above aggregates average monthly storage volumes for surface and groundwater storage statewide over the 72 year model period. The warm-only storage hydrograph closely follows the historical pattern of storage, but with a slightly elevated shifted peak and decreased beginning of year and end of water year storage. This indicates a greater amplitude (increased swing from lowest storage to maximum storage) intra-annually under warm-only conditions. The overall storage under warm-dry conditions follows a similar pattern to the warm-only storage, yet is reduced in every month. The average peak storage associated with spring runoff and snowmelt for warm-dry conditions is 1.6% lower than the average peak storage for historical hydrology, 497.5 and 505.7 maf respectively.

Patterns in total storage can be compared to statewide groundwater storage and surface water storage disaggregated. The majority of the state's storage capacity and water resources are stored in groundwater basins, an order of magnitude greater storage. Figure 5 and 6 show how surface and groundwater resources are influenced differently by optimized operation of facilities and conjunctive use of water resources. Average maximum groundwater storage occurs in March or April with magnitudes of 484.0, 484.8, and 480.2 maf for the historical, warm-only, and warm-dry conditions, respectively (Figure 5).

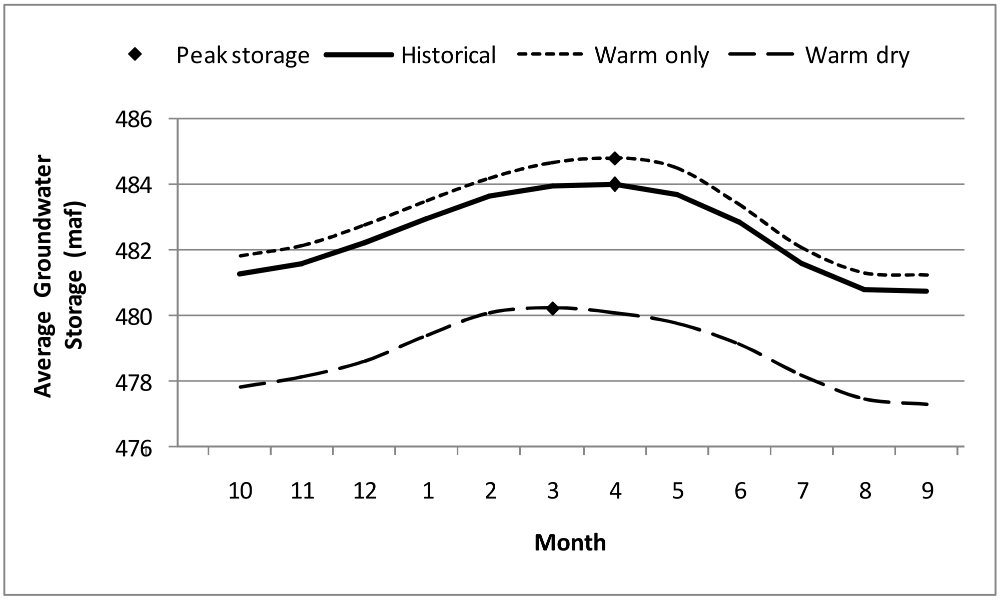

Figure 5. Average monthly groundwater storage statewide

The different climate conditions also affect statewide average levels of surface water storage. Under both warm-only and warm-dry hydrologies, the average annual peak in surface water storage is less than historical storage. Although warm-only peak runoff volumes for some basins exceed those for the historical hydrology (as shown previously for the Sacramento and San Joaquin Rivers in Figure 2), this pattern is not reflected in statewide surface water storage (Figure 6).

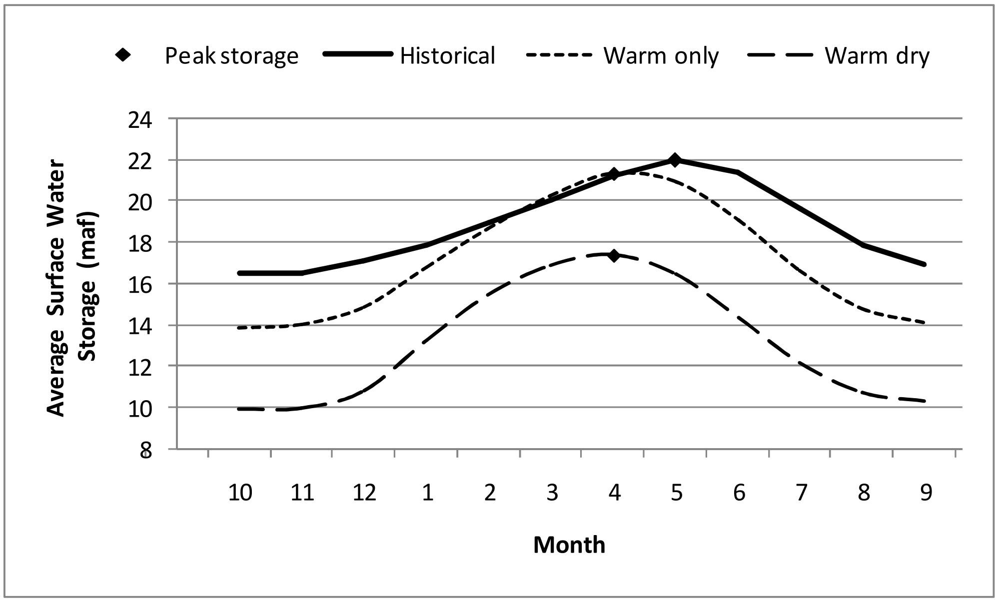

Figure 6. Average monthly surface water storage in reservoirs statewide

Reservoirs in California typically have a regular drawdown-refill cycle, as reservoirs fill in the winter and spring (wet season) and are drawn down in the dry season. The normal amplitude of this cycle represents seasonal reservoir storage. A deeper drawdown-refill cycle often occurs during droughts, which last several years in California. Annual amplitudes of statewide surface water storage increase for warm-only and warm-dry conditions compared to historical hydrologic conditions. This amounts to a 36% and 39% increase in average amplitudes compared to historical amplitudes for warm-only and warm-dry, respectively (Table 6). This greater swing in drawdown-refill storage within the water year reflects the value of capturing winter and spring flows for use in the dry season.

Table 6. Average annual seasonal amplitude (TAF) of statewide surface water storage

	Average	Drought Years	Non-Drought Years	1929-1934	1976-1977	1987-1992
Historical	7016	5605	7357	5244	7185	5440
Warm-only	9545	7524	10033	7177	8665	7492
% Change	36%	34%	36%	37%	21%	38%
Warm-dry	9721	6477	10504	6019	8999	6094
% Change	39%	16%	43%	15%	25%	12%

Larger amplitudes for surface water reservoirs indicate increasingly aggressive reservoir operations. This is especially true for many of the reservoirs for warm-only climate conditions such that most of the storage amplitude ratios of warm-only to historical are greater than one (Figure 7). The dashed lines in Figure 7 show the average amplitude ratios for the 1987-1992 drought. Drought widens this distribution showing that during drought years, increases in amplitude for the perturbed climate scenarios compared to historical amplitudes are even greater. Most reservoirs have larger annual storage amplitudes, for the warm-only climate, but often have smaller amplitudes with a warm-dry climate. For drought years under climate warming, annual storage amplitudes tend to be larger than historical amplitudes for warm-only conditions. For warm-dry conditions average amplitudes are similar to historical amplitudes, but there is much greater variability in amplitudes among reservoirs.

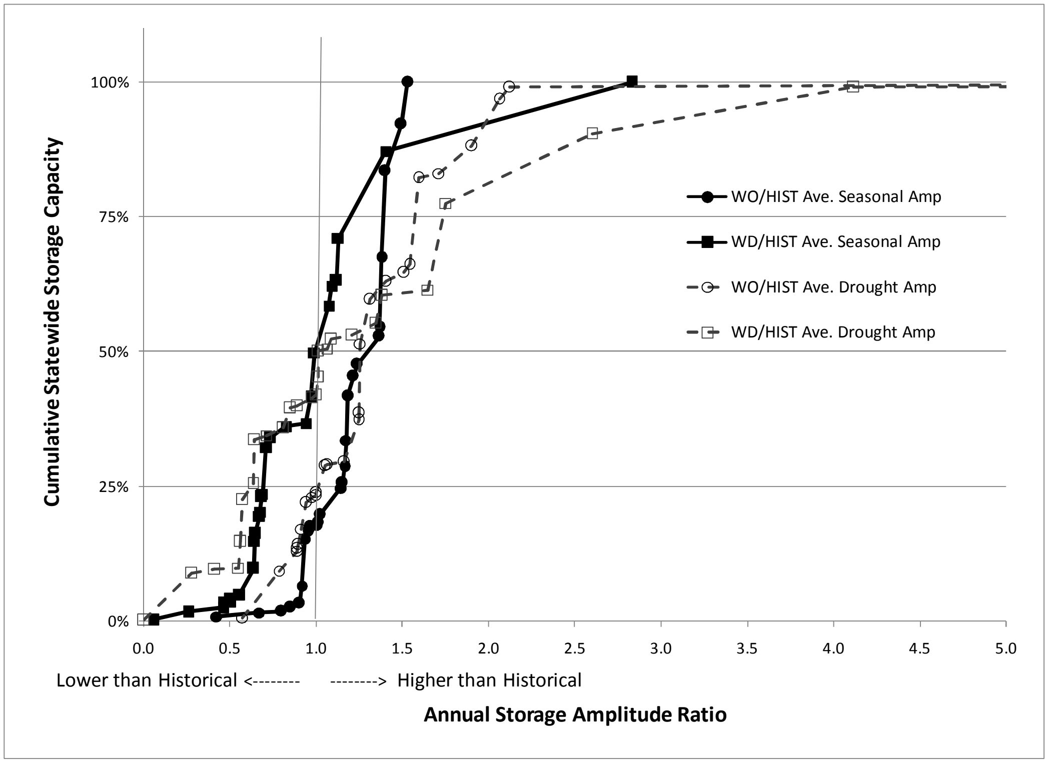

Figure 7. Comparison of seasonal storage amplitudes for warm-only and warm-dry

Comparing storage in the three climate scenarios, a shift in peak average storage earlier in the year is shown for each perturbed hydrology compared to historical hydrology. Due to hydrologic processes, timing of average peak storage differs depending on whether you look at total storage, groundwater storage only, or surface storage only (Table 7). Other studies (Anderson et al. 2008), suggest a shift in peak reservoir storage of about a month earlier.

Table 7. Timing of average annual peak storage for each climate scenario

	Historical	Warm-only	Warm-dry
Total Storage	May	April	March
Groundwater	April	April	March
Surface water	May	April	April

This shift in timing of peak storage is also reflected in the pattern of monthly maximum storage over the 72 year period, see Figure 8 below. Figure 8 plots the maximum storage for each month over the model period. The total system storage is plotted at 29.3 maf which was derived by summing the storage capacities of the 44 surface reservoirs. Maximum storage over the model period aggregated statewide is well under the system storage capacity in all hydrologic scenarios. Maximum storage volumes for both the warm-only and warm-dry conditions are less than the historical maximum storage suggesting additional system storage may not be beneficial or utilized under a warming climate.

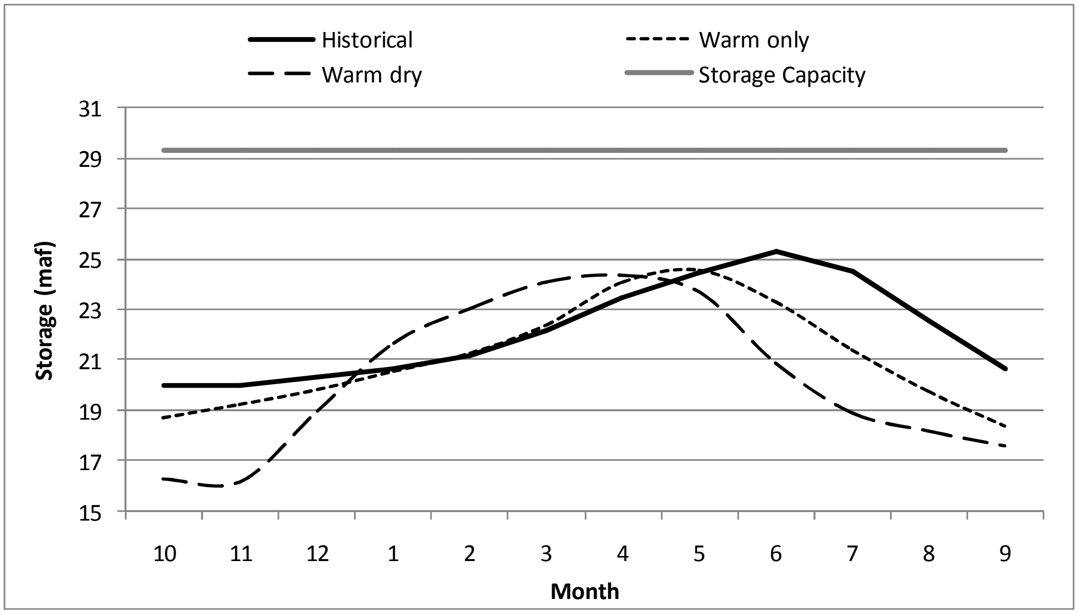

Figure 8. Monthly maximum surface water storage (maf) for 44 reservoirs statewide

3.3.1 Surface Storage and Operations

As an economically driven optimization model, CALVIN allocates water statewide to minimize costs from incurred scarcity and operations. Average annual monthly volumes of storage and releases can indicate effects of climate on surface water operations. Shasta, Lake Oroville, New Don Pedro, and Pine Flats were chosen as representative reservoirs in the Sacramento and San Joaquin Valleys for a local and regional analysis of storage and releases. These are multi-purpose reservoirs for flood control, water supply, power generation, and recreation. Shasta, along the Sacramento River and Lake Oroville, on the Feather River, are in northern California and are the head of the federal Central Valley Project and State Water Project, respectively. They are two of the largest surface reservoirs in the state with capacities of 4.5 and 3.5 maf. New Don Pedro is along the Tuolumne River with a smaller reservoir, Hetch Hetchy, above it. New Don Pedro has a capacity of 2.03 maf. Pine Flat Lake stores the waters of the Kings

River and is operated by the U.S. Army Corp of Engineers with a storage capacity of 1.0 maf.

Figure 9 shows the average monthly storage for each of these reservoirs under each hydrologic scenario compared to the monthly storage capacity of the reservoir. Most significantly, the average storage of New Don Pedro and Pine Flat under warm-dry conditions never approaches storage capacity levels. This suggests that under a warm-dry climate additional storage in these basins would rarely if ever be utilized for water supply. Also, drastic changes in seasonal amplitudes occur for warm-dry conditions for Lake Oroville and warm-only conditions for Pine Flat Lake. This supports the idea that reservoir operations in the future will likely tend toward greater swings in drawdown-refill cycles seasonally. In most cases, peak reservoir storage occurs one to two months earlier than historically.

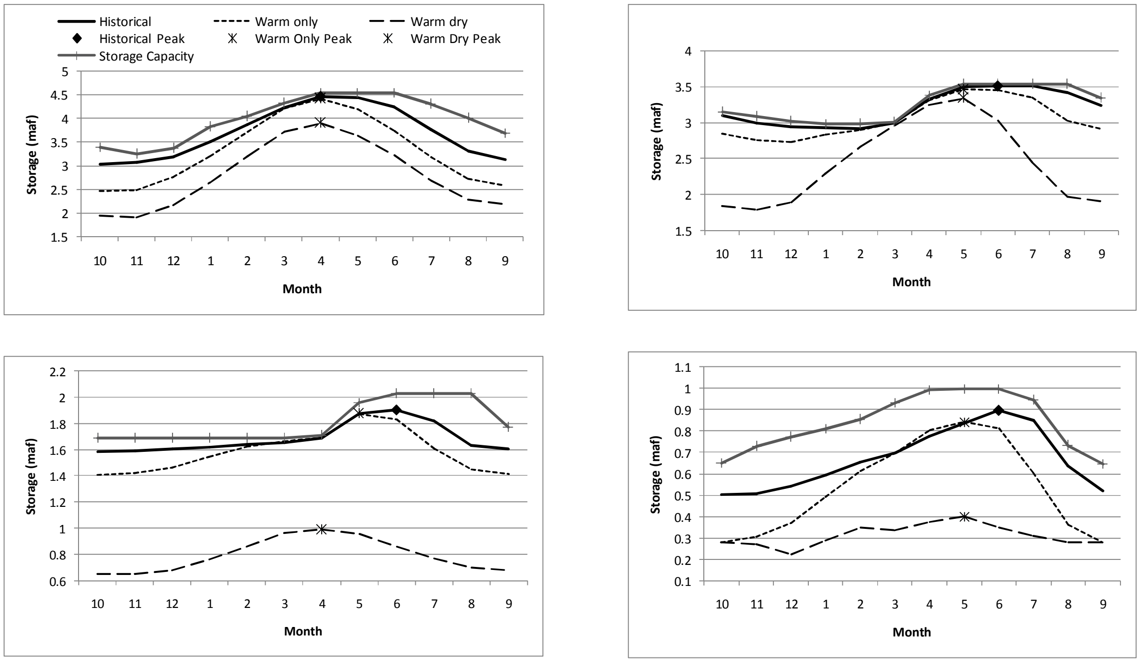

Figure 9. Average Annual Monthly Storage for Shasta, Oroville, New Don Pedro, and Pine Flat Reservoirs (left to right, top to bottom) for each climate scenario

Reservoir releases with warmer and warmer-drier climates tend to be greater in winter, with a reduced or absent spring pulse, especially for the warm-only climate (Figure 10). Statewide, winter releases for the warm-dry climate are significantly less reflecting reduced precipitation and water availability. Releases from reservoirs in the Sacramento Valley increase during summer presumably to meet demands from Central Valley agriculture and Southern California. This suggests storage in these large northern California reservoirs becomes increasingly important for meeting demands as storage and releases of reservoirs in the San Joaquin valley are more affected by a warm-dry and warm-only climate (Table 2). Release operations may also be influenced by economic benefit derived from hydropower generation.

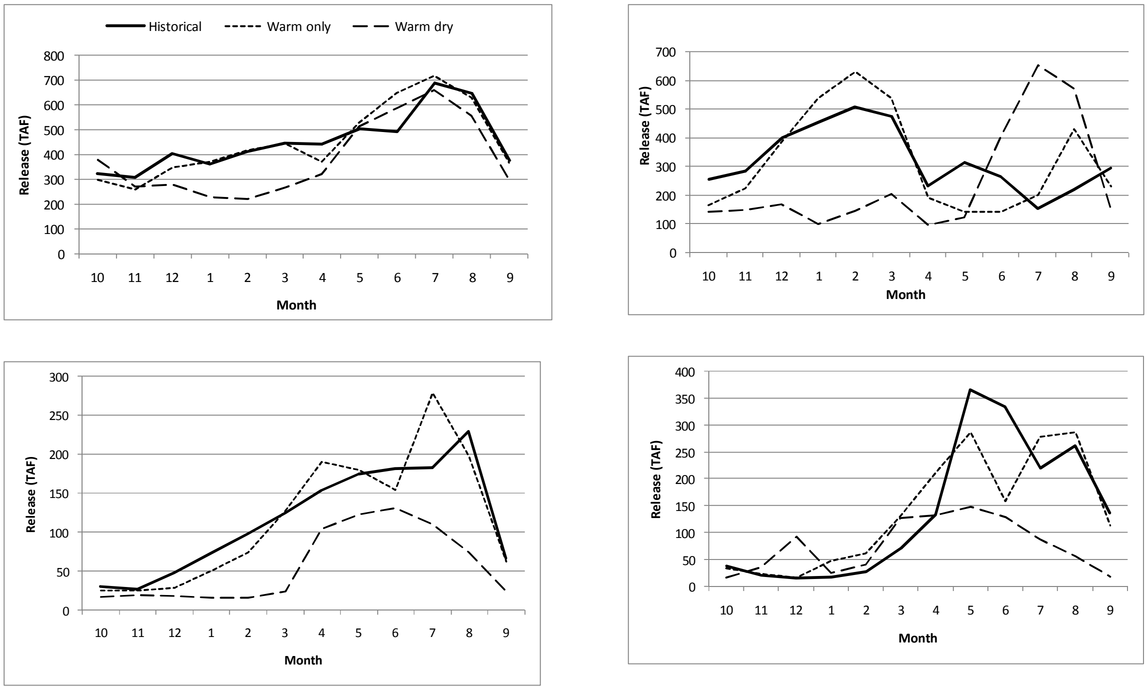

Figure 10. Average monthly releases from Shasta, Oroville, New Don Pedro, and Pine Flat Reservoirs (left to right, top to bottom) for each climate scenario

3.3.2 Economic Values of Storage

Optimization solution outputs include shadow values 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 value is the amount by which the objective function value would improve if the storage capacity was increased by one unit. In CALVIN, which is driven by an economic objective function, shadow values are dollars per acre-feet per month, and can therefore shed light on the value of expanding facilities.

Upper-bound shadow values indicate the value of additional storage and also serve to identify the months in which reservoir capacity is reached. Table 8 shows a selection of surface reservoirs and the percent of years they fill based on the number of years out of 72 for which any given month has a shadow value. The frequency of reservoirs reaching their capacity is much less under warm-dry conditions. Most reservoirs might not fill in most years if California's climate tends toward warmer-drier conditions. Although filling less frequently, the storage capacity does become more valuable since water is scarcer overall. This is shown by increased average annual values for an additional unit of storage (Table 8, column 4) for warm-dry conditions. However, for six reservoirs the reduction in fill frequency is important enough to reduce the overall value of storage for the warmer-drier climate. This is the case for New Melones, New Don Pedro, Lake Lloyd/Lake Eleanor, Turlock Reservoir, Grant Lake and Long Valley.

Table 8. Percent of years filled, the months in which storage capacity is reached, and the corresponding average annual upper-bound shadow values for selected surface water facilities under each climate scenario

	% Years Filled			Peak Storage Month												Average Annual Value ($/taf per year)			Storage MAI
Facility	Hist.	WO	WD	1	2	3	4	5	6	7	8	9	10	11	12	Hist.	WO	WD	
Clair Engle Lake	64	53	22	*	*+-	*+-	*+-	*	*						*	-2.1	-2.7	-23.0	1.24
Whiskeytown Lake	100	100	63	*+-	*+-	*+-	*+-	*-	*	*					*-	-4.5	-5.7	-35.0	0.13
Shasta Lake	97	100	54	*+-	*+-	*+-	*+-	*+-	*	*	*	*+	*	*+-	*+-	-5.2	-5.5	-36.4	0.54
Black Butte Lake	100	97	74	*+-	*+-	*+-	*+-	*+-	*+-	*+-			*+-	*+	*+-	-4.0	-5.6	-109.8	0.35
Lake Oroville	100	100	92	*+-	*+-	*+-	*+-	*+-	*-			*	*+	*+	*+-	-8.9	-10.3	-41.6	0.61
Camp Far West Reservoir	94	94	79	*+-	*+-	*+-	*+-	*+-	*+-			*	*+	*+	*+-	-2.5	-4.7	-73.2	0.29
Clear Lake & Indian Valley Res	43	36	18	*+	*+-	*+-	*+-	*+-	*	*+-				*	*	-0.7	-1.2	-19.6	1.20
Folsom Lake	100	99	57	*+-	*+-	*+-	*+-	*+	*+	*		*		*+	*+	-7.5	-9.5	-66.4	0.68
Englebright Lake	100	100	100	*+-	*+-	*+-	*+-	*+-	*+-	*+-	*+-	*+-	*+-	*+-	*+-	-29.7	-29.5	-142.7	0.01
Lake Berryessa	33	11	3	*	*	*+-	*+-	*+							*	-0.2	-0.2	-3.0	4.28
Los Vaqueros Reservoir	4	11	36	-	-	+-	*+-	+-			*+-					0.0	-0.3	-31.1	1.22
New Bullards Bar Res	99	100	81	*+-	*+-	*+-	*+-	*+-	*+-	*	*	*	*+-	*+	*+	-11.3	-15.8	-68.4	0.56
New Hogan Lake	51	49	17	*+-	*+-	*+-	*								*+	-0.9	-1.4	-19.8	1.61
Pardee Reservoir	81	94	35	*+-	*+-	*+-	*+	*+-	*+-			*-	*+-	*+	*+	-1.0	-1.6	-27076.1	0.29
New Melones Reservoir	97	94	4	*+-	*+-	*+-	*+	*+	*+	*+	*+	*+	*+	*+	*+	-6.4	-6.3	-2.9	1.51
Millerton Lake	46	88	28	*+-	*+-	*+-	*+-	*+-	*	*						-4.2	-62.7	-35.3	0.24
Lake McClure	90	89	11	*+	*+-	*+-	*+	*+	*+	*			*-	*	*	-4.5	-5.3	-8.5	0.98
Hensley Lake	56	54	18	*+-	*+-	*+-	*+		*					*+	*+	-2.2	-3.7	-28.1	1.02
Eastman Lake	43	32	3	*+	*+-	*+-	*+							*+	*+	-1.6	-2.1	-2.8	2.00
New Don Pedro Reservoir	92	96	7	*+	*+	*+-	*+-	*+	*+	*			*+	*+	*+	-5.1	-5.5	-3.3	1.39
Hetch Hetchy Reservoir	63	75	8	*+	*+	*+-	*+-	*+	*+-	*+-	*+	*+	*+	*+	*+	-3.2	-3.4	-5.8	0.43
Lake Lloyd/Lake Eleanor	38	35	1	+	+	+-	+	*+-	*+	*			*		*+	-9.6	-6.3	-2.4	0.62
Lake Isabella	32	46	13	*+-	+-	*+-	*+-	*+	*				*+	*+-	*+-	-1.7	-36.7	-24.0	0.77
Lake Kaweah	100	100	63	*+-	*+-	*+-	*+-	*-	*					*+-	*+-	-32.1	-102.2	-158.7	0.32
Lake Success	89	90	74	*+-	*+-	*+-	*+-	*+-	*+-	*+-			*+-	*+-	*+-	-28.6	-76.9	-211.6	0.61
Pine Flat Reservoir	99	99	10	*+-	*+-	*+-	*+-	*+-	*+	*					*+-	-3.5	-7.8	-13.9	0.59
Turlock Reservoir	81	88	3	*+	*+	*+-	*+	*+	*	*	*	*+	*+	*+	*+	-3.4	-4.6	-2.7	0.07
Grant Lake	24	3	0					+	*	*	*					-35.4	-0.1	0.0	0.36
Long Valley Reservoir	3	0	0								*	*	*			-6.5	0.0	0.0	0.90

Key: * Hist + WO - WD

The peak storage month column in Table 8 indicates which months the reservoir hits its storage capacity for each scenario. A few reservoirs feeding the Los Angeles Aqueduct never fill with the changed climate. Typically, there are fewer months for warm-dry conditions in which the reservoirs reach capacity. For example, Shasta reached capacity at least once over the 72 year model period in every month under historical conditions, compared to only winter, spring and fall months for warm-only and warm-dry. Long Valley Reservoir (Lake Crowley) never reaches capacity under the perturbed climate scenarios. New Melones Reservoir rarely reaches capacity and then only in January, February, and March for warm-dry hydrology. By contrast, Englebright and Lake Oroville are less affected by the differing climate scenarios with regards to percent of years filled.

Comparing warm-only and warm-dry to historical scenarios as a ratio of percent of years the reservoir fills, Figure 11 plots these ratios versus the ratio of storage capacity to mean annual inflow (MAI), indicating relative storage availability for each local basin (from Table 8). This graphically shows that the percent of years filled decreases as storage availability increases for most locations for warm-dry compared to historical conditions. Reservoirs with higher ratios of storage to MAI tend to fill less often under warm-dry conditions. To a lesser extent, this is the case for warm-only conditions as well.

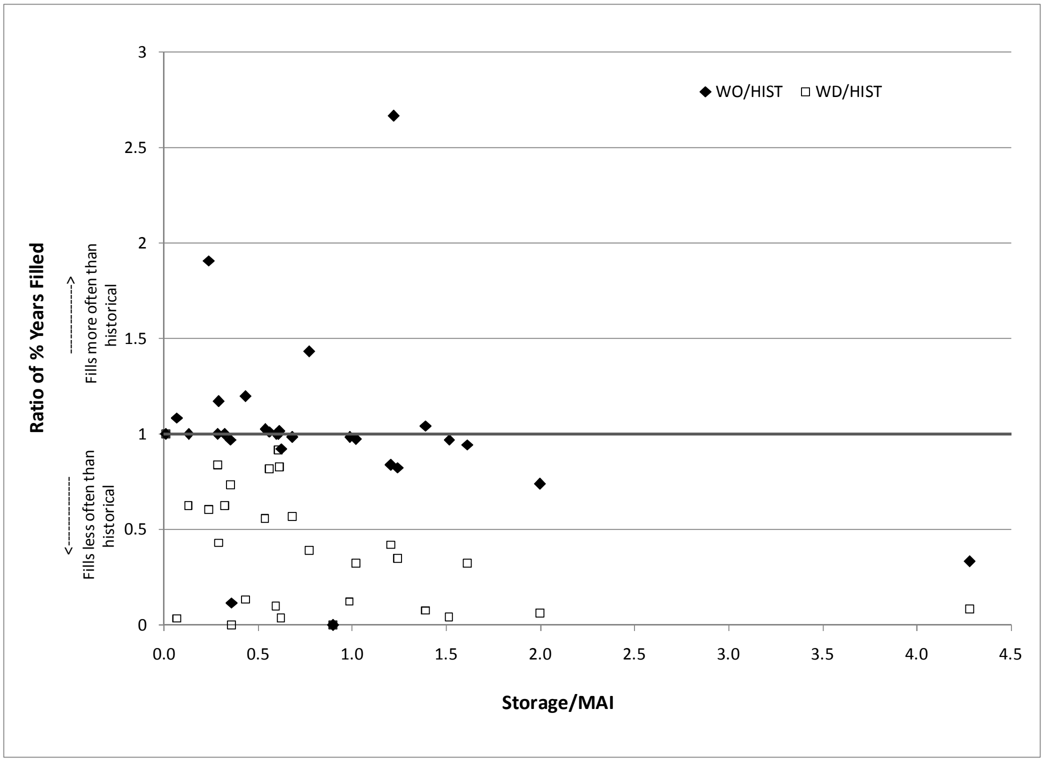

Figure 11. Ratio of percent of years filled versus storage-MAI ratio for select surface water reservoirs

In contrast to warm-dry effects on fill frequency, warm-only hydrology usually increases the frequency of filling and almost always increases the value of increased storage (Figure 11, ratio of % years filled often close to or greater than 1 for WO/Hist). Millerton Lake, New Bullards Bar, Pardee Rerservoir, New Don Pedro, Hetch Hetchy, Lake Isabella, and Turlock Reservoir fill more frequently with warm only hydrology than historical, due to earlier and higher peak spring and winter flows. 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.

3.3.3 Groundwater Storage

Figure 12 shows optimized statewide groundwater storage over the period of record and its annual and inter-annual oscillations indicating periods of drawdown during droughts and periods of net recharge during wet years. The warm-dry scenario generally makes greater use of groundwater storage than in the historical and warm-only scenarios by having higher highs and lower lows.

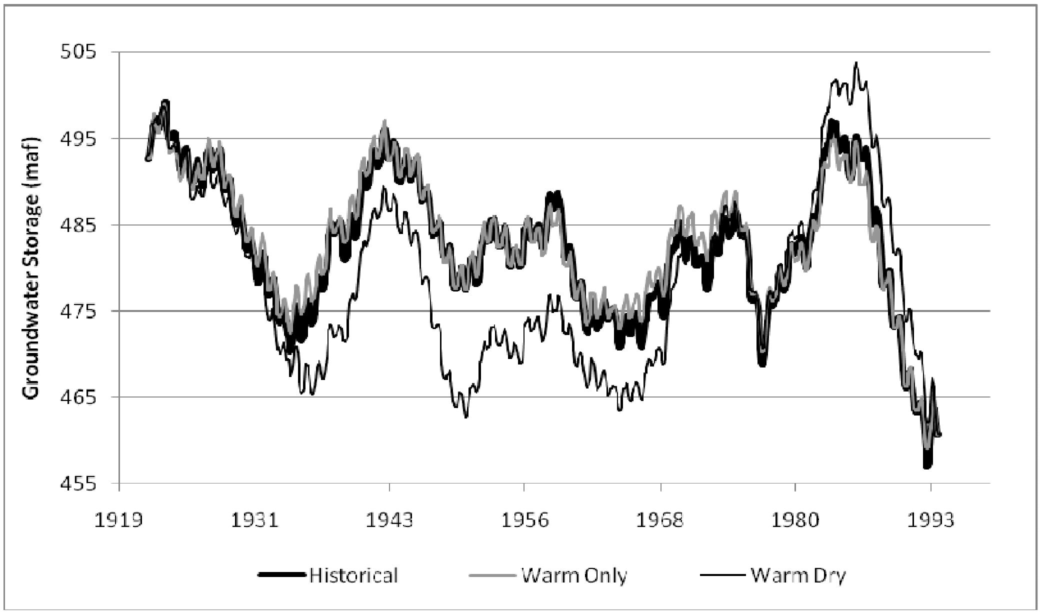

Figure 12. Monthly Central Valley groundwater storage over the 72-year period

Figure 13 shows the proportion of deliveries coming from groundwater. The majority of deliveries come from groundwater during dry years. The steeper slope and greater variation in percent groundwater use in the warm-dry climate suggests greater coordination of ground and surface waters. Consistent with other analysis, the warm-only scenario shadows results of the historical hydrology, for over-year conjunctive use.

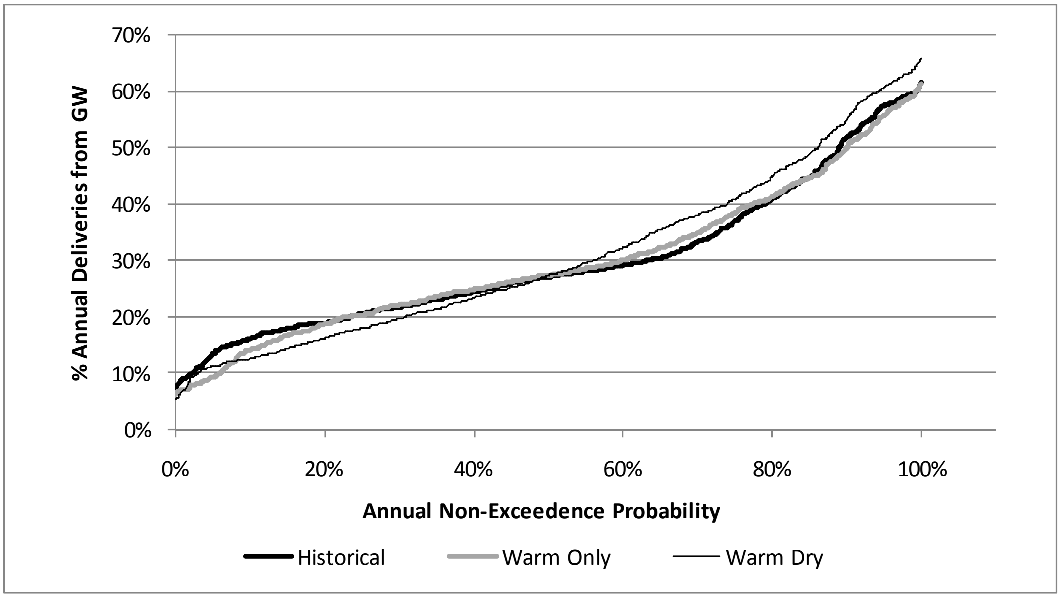

Figure 13. Annual variability in statewide use of groundwater

As a measure of seasonal within-year variations in groundwater storage, annual amplitudes of groundwater storage were calculated for the period of record. Annual amplitude was defined as the difference between the annual maximum and minimum storage for each water year. This analysis suggests that intra-annual swings in groundwater storage may decrease with climate warming, and decrease more with drier conditions (Table 9). Larger amplitudes during drought years also suggest conjunctive use as an adaptive strategy to intra and inter annual variation.

Table 9. Average annual seasonal amplitude (TAF) of statewide groundwater storage

Scenario	Drought Years	Non-Drought Years	1929-1934	1976-1977	1987-1992	Average
Historical	6393	4540	4873	8299	7277	4900
Warm dry	5504	3862	4133	5947	6727	4181
% Change	-14%	-15%	-15%	-28%	-8%	-15%
Warm only	5972	4418	4821	7451	6629	4720
% Change	-7%	-3%	-1%	-10%	-9%	-4%

3.4 Conjunctive Use

Conjunctive use is the coordinated management of surface and groundwater resources. The CALVIN model optimally uses 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 (Pulido-Velazquez et al. 2004). Pulido-Velazquez et al. (2004) showed that conjunctive use programs, in coordination with water transfers, can add operational flexibility to the system. 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 (Figure 14). In general, a larger portion of Tulare’s water supply comes from groundwater pumping compared to the Sacramento Valley which relies more 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 Tulare Basin. Therefore, to minimize economic costs to the system as a whole, available water preferentially goes to these higher paying demands first and shorts demands in the north. Likewise, under warm-dry conditions when surface water resources are less available, the Sacramento Valley pumps additional groundwater, decreases its surface water use, and incurs a greater percentage of scarcity than does the San Joaquin Valley or Tulare Basin (Figure 14). In all cases, deliveries from groundwater increase in drought years when surface water is less available. Groundwater pumping is a much larger piece of the pie in all regions for drought years compared to non-drought years. This highlights the economic value of switching between supply sources during wet and dry periods.

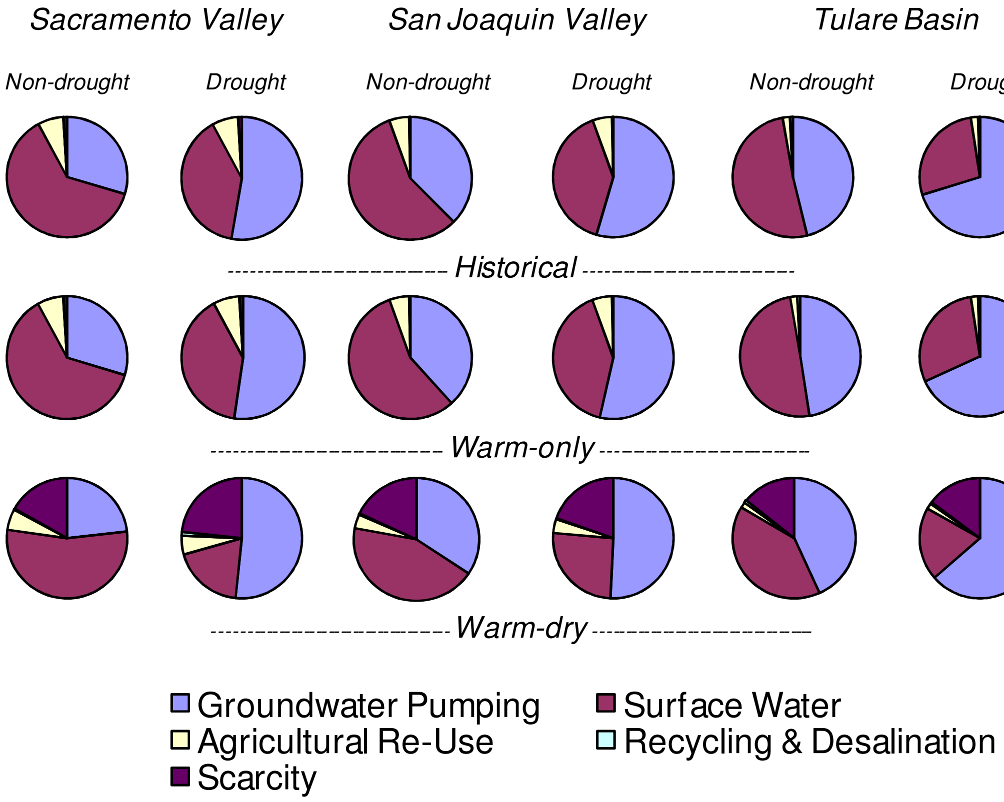

Figure 14. Supply portfolio for each region, climate scenario, and year type. Drought years include 1929-1934, 1976-1977, 1987-1992. Non-drought years are all others in the historical record (1921-1993)

3.5 Delta Exports and Surplus Delta Outflow

Warming climates affect optimal pumping from the Banks and Tracy pumping plants which export water from northern California to the Central Valley and southern California agriculture and urban demands. Overall, average exports under a warm-dry scenario are 6.0 maf/year, 33% more than with historical hydrology (4.4 maf/yr). Climate warming also affects the seasonal timing of optimal delta exports (Figure 15). Under a warm-dry climate, exports increase in almost every month and especially during winter months, November through February. Exports with a warm-only climate are overall slightly greater than with the historical hydrology (6% increase), increasing in some months and decreasing in others.

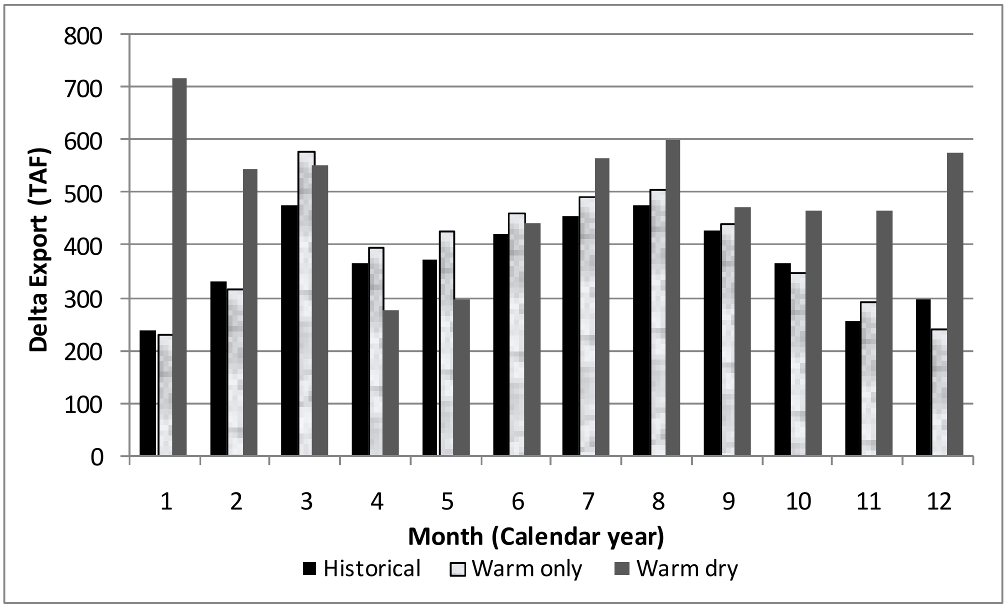

Figure 15. Average monthly Delta exports from Banks and Tracy pumping plants over 72 year period of record for all three climate scenarios

Not only are pumping operations affected by changing climate conditions, the volume of surplus Delta outflow also changes for each climate scenario. A monthly time series in CALVIN specifies the volume of water required to flow out of the Delta. This serves as a minimum flow requirement. Any additional water flowing out of the system, "water wasted to the sea" in old-time parlance, is referred to as surplus Delta outflow. Figure 16 shows changes for each perturbed hydrology compared to historical hydrology. Under warm-dry conditions, volumes of surplus outflow decrease in every month, 53-98% (Table 10) depending on the month. Warm-only conditions cause an increased pulse on average during the winter months, compared to flows under historical hydrology. Table 10 compares flows between climate scenarios on an annual and monthly basis.

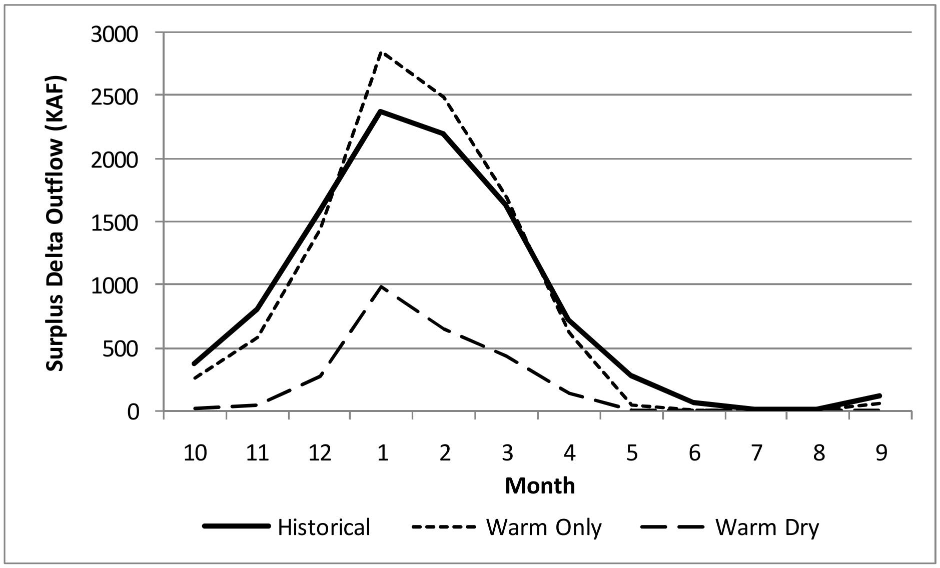

Figure 16. Average monthly surplus delta outflow

Table 10. Surplus Delta Outflow

	Historical	Warm-only	% Change	Warm-dry	% Change
Annual Ave. (TAF/year)	10152	10029	-1	2522	-75
Maximum (TAF/month)	11650	12723	9	7063	-39
Monthly Ave (TAF/month):					
Oct.	371	259	-30	7	-98
Nov.	804	580	-28	39	-95
Dec.	1583	1445	-9	277	-83
Jan.	2371	2851	20	986	-58
Feb.	2201	2482	13	649	-71
Mar.	1627	1689	4	431	-73
Apr.	724	620	-14	129	-82
May	278	46	-84	0	-
Jun.	65	0	-	0	-
Jul.	9	0	-	0	-
Aug.	6	1	-90	0	-
Sept.	112	57	-49	4	-97

4.0 Limitations

Limitations inherent to large-scale and optimization models and CALVIN have been explored and discussed elsewhere (Jenkins et al. 2001; Jenkins et al. 2004). For this particular study a couple of specific limitations should be mentioned. First, urban water use and scarcity cost is assumed constant for all three hydrologic scenarios and does not account for conservation measures that may be employed if the climate were indeed to become warmer and drier as simulated. A warm-dry hydrology may reduce yields for some crops in California (Adams et al. 2003; Lobell et al. 2007). Similar estimates are not available for urban water use. 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 can be met in part with 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 CALVIN water supply results.

A second limitation is related to the bias implicit in the estimated warm-only hydrology. Having a mean annual streamflow ratio between the historical and warm-dry scenario for the entire time span can impose a positive bias for flows in the winter runoff. 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.

Furthermore, groundwater pumping costs do not reflect dynamic groundwater levels because CALVIN has a simple representation of groundwater. 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 the groundwater-surface water use proportion ratio.

5.0 Conclusions

California has many management options for adapting and mitigating costs of climate induced changes in water supply. However, agriculture remains the most vulnerable user to water shortages under all climate scenarios. Water shortages of more than 20% of agricultural target demands are expected for warm-dry conditions, resulting in incurred annual costs to agricultural production of over $800 million. Water scarcity and its cost as well as storage volumes and releases appear to be more sensitive to reductions in precipitation than to temperature increases alone. Temperature rise alone does not tend to increase water shortages significantly if system operations adapt. This is in line with classical reservoir operation theory for a system with over-year water storage capacity (Hazen 1914). Yet surface water storage volumes are lower during summer and surface water operations confirm findings of other studies that reservoir storage levels peak earlier in the year under warmer climates.

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. Conjunctive use has a larger role in a warmer and drier climate compared to just a warmer climate. Reoperation adaptations are aided by conjunctive use shifting some drought storage from surface reservoirs to groundwater.

Exporting water through the Delta to meet Central Valley and southern California water demands becomes increasingly desirable and valuable in a warm-dry climate. Transportation of water south during wet winter months increases for warm-dry conditions. Under a warm-only climate, exports also increase, yet increasing temperatures alone has less effect on Delta pumping and operations than warm-dry conditions. With more water exported south and less water available in general, surplus Delta outflow also decreases significantly under warm-dry conditions, as much as 98% in fall months. Flow to the ocean increases under warm-only conditions during months of winter rainfall and early snow melt (January, February, and March), but flow during other times of the year decreases relative to historical flows. Climate effects on exports and "water to the sea" should be considered in future Delta management and infrastructure alternatives.

Analysis of percent of years filled for surface water reservoirs for warm-only and warm-dry scenarios suggests that increasing the system's surface storage capacity may not alleviate climate induced water scarcity. Under warm-dry conditions, there seems to be excess storage capacity in the statewide surface storage system. This suggests that under a warmer-drier climate, additional storage may not be utilized simply because the water will not be available to store. In contrast, for the warm-only scenario, increased storage capacity in wet months may be valuable to help capture increased peak flows in winter months. Under either scenario, changing reservoir operations in conjunction with a suite of management adaptations (i.e. conjunctive use, water recycling, water markets) serves well to reduce water scarcity and economic cost of climate change.

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Appendix A: Technical Note- Sensitivity of Mapping Matrix

1.0 Introduction

As part of the California Energy Commission's California Climate Change Center Report Series, Update 2008, effects of warming climates on water resources management adaptation were explored using the California Value Integrated Network (CALVIN). CALVIN is an economic-engineering optimization model of the state's inter-tied water supply system (Jenkins et al. 2001).

Methods for perturbing CALVIN hydrology are described in detail elsewhere (Zhu et al. 2003; Zhu et al. 2005). In short, index basins from downscaled global climate models are matched to CALVIN rim inflows to apply appropriate perturbation ratios developed from downscaled global climate model streamflows to historical streamflows to yield "warmer-drier" time series for each CALVIN rim inflow. To improve representation, the water year was divided into wet and dry seasons (October through March and April through September, respectively) for the purposes of matching. Six basins with downscaled climate perturbed streamflows were available for the previous climate change study completed for the Energy Commission: Smith River at Jedediah 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. The current study used 18 index basins to match climate perturbed streamflows with CALVIN's 37 rim inflows (Table 11). These additional basins included a range of tributaries of the Sacramento and San Joaquin Rivers from the east side of the valley, and the Trinity River in the north, a tributary to the Klamath. Rim inflows generated using mapping of the 6 index basins from the previous study are compared here to streamflows generated by mapping with 18 index basins in the current study. In the original study, sources of data used to correlate index basins and CALVIN rim inflows differ since they come from different modeling efforts. The effect on perturbed hydrology of maintaining internal consistency by using CALVIN time series that correspond to index basins for statistical correlation is also explored and presented.

2.0 6 vs. 18 Basins

The mapping matrix used to assign perturbation ratios from the index basins to the corresponding CALVIN flows for this study as well as the previous study, is shown below. Table 11 lists the index basins and their corresponding code used to indicate which one was matched to each rim inflow, as shown in Table 12.

Table 11. Eighteen Index Basins

Code	Index Basin
SHAST	Sacramento River at Shasta Dam
N_MEL	Stanislaus River at New Melones Dam
MILLE	San Joaquin River at Millerton Lake
LK_MC	Merced River at Lake McClure
SMART	Yuba River at Smartville
FOL_I	American River at Folsom Dam
CONSU	Consumnes River at McConnell
OROVI*	Feather River at Oroville
DPR_I	Tuolumne River at New Don Pedro
PRD-C	Mokelumne River at Pardee
N_HOG	Calaveras River at New Hogan
SAC_B	Sacramento River at Bend Bridge
SACDL*	Sacramento River at Delta
NF_AM*	North Fork American River at North Fork Dam
MERPH*	Merced River at Pohono Bridge
KINGS*	Kings River at Pine Flat Dam
TRINI	Trinity River at Trinity Reservoir
SMITH*	Smith River at Jedediah Smith State Park

* indicates index basins for previous study

Table 12. Index Basin matches to CALVIN Rim Inflows with 18 and 6 index Basins

CALVIN Rim Inflows	18 Index Basins		6 Index Basins	
	Wet Season	Dry Season	Wet Season	Dry Season
TRINITY RIVER	TRINI	TRINI	SACDL	SACDL
CLEAR CREEK	FOL_I	SMITH	SMITH	SMITH
SACRAMENTO RIVER	SHAST	SHAST	SACDL	SACDL
STONY CREEK	CONSU	CONSU	SMITH	SMITH
COTTONWOOD CREEK	CONSU	CONSU	SMITH	SMITH
LEWISTON LAKE INFLOW	TRINI	PRD-C	OROVI	NF_AM
M & S FORK YUBA RIVER	FOL_I	FOL_I	NF_AM	NF_AM
FEATHER RIVER	OROVI	OROVI	OROVI	SACDL
N AND M FORKS AMERICAN RIVER	N_MEL	FOL_I	NF_AM	NF_AM
S FORK AMERICAN RIVER	DPR_I	FOL_I	OROVI	OROVI
CACHE CREEK	CONSU	CONSU	SMITH	SMITH
PUTAH CREEK	FOL_I	CONSU	SMITH	SMITH
N FORK YUBA RIVER	DPR_I	PRD-C	OROVI	OROVI
CALAVERAS RIVER	N_HOG	N_HOG	SMITH	SMITH
MOKELUMNE RIVER	N_MEL	N_MEL	OROVI	KINGS
CONSUMNES RIVER	CONSU	CONSU	NF_AM	OROVI
DEER CREEK	FOL_I	CONSU	SMITH	SMITH
DRY CREEK	CONSU	CONSU	SMITH	SMITH
FRENCH DRY CREEK	FOL_I	CONSU	SMITH	SMITH
GREENHORN CREEK AND BEAR RIVER	N_HOG	N_HOG	NF_AM	NF_AM
KELLY RIDGE	N_HOG	N_HOG	SMITH	SMITH
STANISLAUS RIVER	N_MEL	N_MEL	OROVI	KINGS
SAN JOAQUIN RIVER	MILLE	MILLE	OROVI	KINGS

MERCED RIVER	KINGS	DPR_I	OROVI	KINGS
FRESNO RIVER	N_HOG	N_HOG	SMITH	SMITH
CHOWCHILLA RIVER	N_HOG	N_HOG	SMITH	SMITH
INFLOW NEW DON PEDRO	FOL_I	FOL_I	SACDL	NF_AM
TUOL RIVER	KINGS	KINGS	MERPH	MERPH
CHERRY & ELNOR CRK	KINGS	KINGS	KINGS	MERPH
SCV LOCAL	CONSU	CONSU	SMITH	SMITH
KERN RIVER	KINGS	KINGS	KINGS	KINGS
KAWEAH RIVER	MILLE	MILLE	KINGS	MERPH
TULE RIVER	CONSU	CONSU	OROVI	OROVI
KINGS RIVER	KINGS	KINGS	KINGS	KINGS
LV-HAIWEE	MERPH	MERPH	MERPH	KINGS
MONO BASIN	MERPH	MERPH	MERPH	KINGS
UPPER OWENS	MERPH	N_MEL	KINGS	SACDL

With 18 available index basins, 8 of them were directly mapped to a CALVIN rim flow (eg. Trinity River mapped to Trinity River). These basins include the Trinity River, Sacramento River at Shasta Dam, Feather River at Oroville, Calaveras River at New Hogan, Cosumnes River at McConnell, Stanislaus River at new Melones Dam, San Joaquin River at Millerton, and the Kings River at Pine Flat Dam. The only river directly matched in the previous study for wet and dry seasons was the Kings River.

On a local scale, the improved mapping can have a significant effect on the annual average streamflow, as in the case of the Feather River (Table 13). Mapping it to the Feather River at Oroville for wet and dry seasons led to a decrease in annual average flow of 170 TAF/yr compared to the climate adjusted flow of the previous study. However, in other cases, as with the Stanislaus, the improved mapping had little effect on the projected climate perturbed streamflow.

Table 13. Annual average streamflow compared between studies

	Current Study	Previous Study		% Change from Historic		Annual Ave. Difference (TAF/yr)
CALVIN Rim inflow	Wet & Dry Months	Wet Months	Dry Months	18 Basins	6 Basins	
Trinity River	Trinity	Sacramento R. at Delta	Sacramento R. at Delta	-15%	-21%	71
Sacramento River	Sacramento R. at Shasta	Sacramento R. at Delta	Sacramento R. at Delta	-15%	-15%	0
Feather River	Feather R.	Feather R.	Sacramento R. at Delta	-24%	-20%	-170
Calaveras River	Calaveras R.	Smith R.	Smith R.	-27%	-12%	-24
Cosumnes River	Cosumnes R.	North Fork American R.	Feather R.	-30%	-16%	-53
Stanislaus River	Stanislaus R.	Feather R.	Kings R.	-38%	-38%	4
San Joaquin River	San Joaquin R.	Feather R.	Kings R.	-38%	-41%	53
Kings River	Kings R.	Kings R.	Kings R.	-47%	-47%	0

When a direct match could not be made, a representative index basin was mapped to the CALVIN inflow (e.g. Cosumnes mapped to Stony Creek). Statistical analysis, geographic location, and knowledge of hydrological processes characterizing each basin helped assign appropriate matches. For example, low elevation, rain dominated basins were matched with basins sharing similar characteristics. When possible, general spatial location was considered in the final decision process such that the Smith basin (one of the few rain-dominated index basins at the far northern end of the state which was used widely in the previous study) was replaced instead by the Cosumnes River basin. This is also a rain dominated basin closer to most of the CALVIN rim flows.

The addition of Cosumnes River index basin improved representation of several relatively small east side streams. For example, Cache Creek was previously matched to the Smith River for both wet and dry seasons. As shown in Figure 17, relating Cache Creek to the Smith River does not appear to be a good match, yet generally the pattern of streamflow distribution is similar with high flow in January that steadily drops through the spring and summer and increases again in the fall. Yet the magnitude of flow and variation is not well captured. Comparing the hydrographs, Cosumnes River significantly better represents Cache Creek. This is similar for other CALVIN rim flows including Dry Creek, Stony Creek, and Cottonwood Creek.

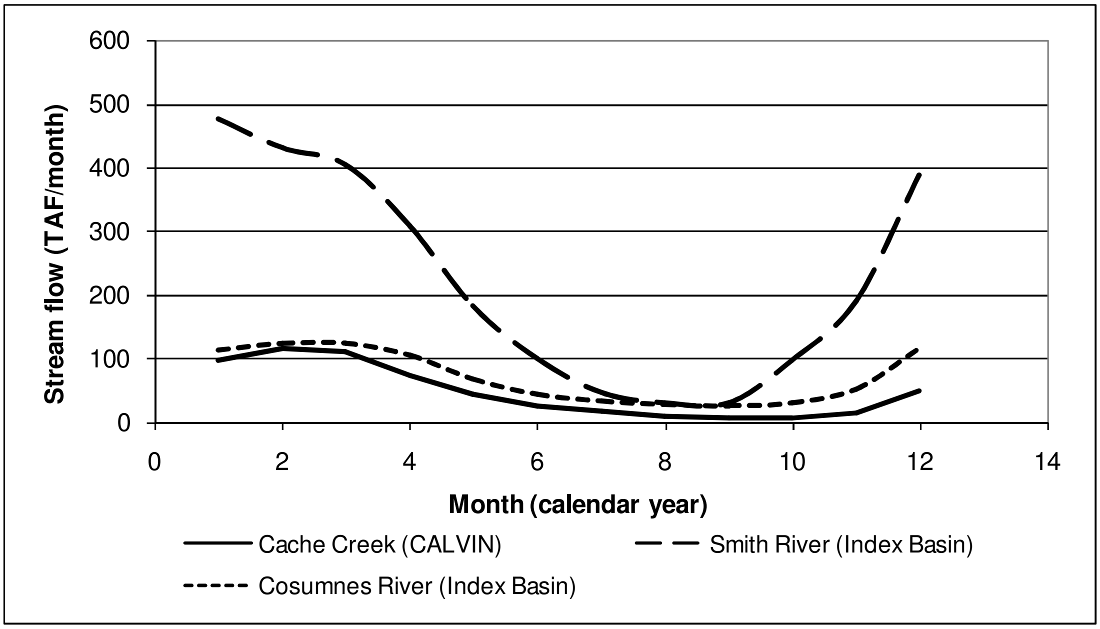

Figure 17. Monthly average streamflow (TAF/month) over the period of record (1950-1993)

The above analysis shows the improvements and effects that using 18 index basins to perturb streamflows have locally. However, on a regional and statewide scale, increasing the level of detail in representing the basins does not greatly affect the estimates of overall climate warming impacts on California's water supply. Table 14 shows the percent change in average annual inflow statewide and for each region with respect to historic rim inflows for each of these methods. On a regional and statewide level, using the newly available 18 index basins compared to the original 6 did not lead to a significantly different percent change in inflows with regards to CALVIN inputs.

Table 14. Average annual warm dry rim inflows (TAF/yr) for 6 and 18 index basins

	Statewide		Sacramento Valley		San Joaquin Valley		Tulare Basin		S. California	
Historic Inflow	28243		19121		5740		2826		554	
Number of Index Basins	18	6	18	6	18	6	18	6	18	6
Climate Perturbed Inflow	20300	20913	14803	15352	3546	3603	1583	1622	367	335
% Change from Historic	-28	-26	-23	-20	-38	-37	-44	-43	-34	-40

Water supply results are not as clearly comparable. Other components of these two CALVIN model runs are not the same. For instance, the most recent study included updated economic penalty functions from the ancillary model, SWAP. This could account for the difference in volume of scarcity, yet it is interesting to note that scarcity as a percent of target delivery turns out to be the same in both cases (Table 15). Since the inputs of streamflows are not significantly different, it is not surprising that water supply results are similar.

Table 15. CALVIN water supply results for warm dry scenario for case with 6 and 18 index basins

	6 Index Basins		18 Index Basins	
	Scarcity	% of Target	Scarcity	% of Target
Agricultural	6438	78%	5074	78.9%
Urban	81	> 99%	90	99.3%
Total	6520		5164	

Adapted from (Medellin-Azuara et al. 2008)

3.0 Mapping CALVIN to CALVIN

CALVIN rim inflows were originally developed by pooling preexisting streamflows from sources including the California Data Exchange Center (CDEC), as described in Appendix I of the CALFED Report (2001) detailing CALVIN model development (Draper 2000). In this study conducted for the Energy Commission, different data sources for streamflows from the downscaled global climate models and CALVIN rim flows made correlation of these time series poor. This section explores what difference it makes to use time series of CALVIN rim flows that directly correspond to the basins from the downscaled climate models for correlation and mapping.

3.1 Methods and Results

Mapping methods using statistical correlation as described in the main report were repeated except that time series for the 18 index basins used to correlate with CALVIN’s 37 rim inflows were also CALVIN time series (those which directly correspond to a given index basin). This resulted in much stronger statistical correlations and a different mapping matrix (Table 16).

Table 16. Complete mapping matrix for different methods including results for correlation of CALVIN to CALVIN time series

CALVIN Rim Inflows	18 Index Basins		CALVIN to CALVIN		6 Index Basins	
	Wet Season	Dry Season	Wet Season	Dry Season	Wet Season	Dry Season
TRINITY RIVER	TRINI	TRINI	TRINI	TRINI	SACDL	SACDL
CLEAR CREEK	FOL_I	SMITH	SHAST	SHAST	SMITH	SMITH
SACRAMENTO RIVER	SHAST	SHAST	SHAST	SHAST	SACDL	SACDL
STONY CREEK	CONSU	CONSU	SHAST	SHAST	SMITH	SMITH
COTTONWOOD CREEK	CONSU	CONSU	SHAST	SHAST	SMITH	SMITH
LEWISTON LAKE INFLOW	TRINI	PRD-C	TRINI	TRINI	OROVI	NF_AM
M & S FORK YUBA RIVER	FOL_I	FOL_I	SMART	SMART	NF_AM	NF_AM
FEATHER RIVER	OROVI	OROVI	OROVI	OROVI	OROVI	SACDL
N AND M FORKS AMERICAN RIVER	N_MEL	FOL_I	NF_AM	NF_AM	NF_AM	NF_AM
S FORK AMERICAN RIVER	DPR_I	FOL_I	FOL_I	FOL_I	OROVI	OROVI
CACHE CREEK	CONSU	CONSU	CONSU	SHAST	SMITH	SMITH
PUTAH CREEK	FOL_I	CONSU	N_HOG	SHAST	SMITH	SMITH
N FORK YUBA RIVER	DPR_I	PRD-C	NF_AM	NF_AM	OROVI	OROVI
CALAVERAS RIVER	N_HOG	N_HOG	N_HOG	N_HOG	SMITH	SMITH
MOKELUMNE RIVER	N_MEL	N_MEL	PRD-C	PRD-C	OROVI	KINGS
CONSUMNES RIVER	CONSU	CONSU	CONSU	CONSU	NF_AM	OROVI
DEER CREEK	FOL_I	CONSU	CONSU	CONSU	SMITH	SMITH
DRY CREEK	CONSU	CONSU	N_HOG	N_HOG	SMITH	SMITH
FRENCH DRY CREEK	FOL_I	CONSU	FOL_I	FOL_I	SMITH	SMITH
GREENHORN CREEK AND BEAR RIVER	N_HOG	N_HOG	CONSU	CONSU	NF_AM	NF_AM
KELLY RIDGE	N_HOG	N_HOG	OROVI	OROVI	SMITH	SMITH
STANISLAUS RIVER	N_MEL	N_MEL	N_MEL	N_MEL	OROVI	KINGS
SAN JOAQUIN RIVER	MILLE	MILLE	MILLE	MILLE	OROVI	KINGS
MERCED RIVER	KINGS	DPR_I	LK_MC	LK_MC	OROVI	KINGS
FRESNO RIVER	N_HOG	N_HOG	N_HOG	LK_MC	SMITH	SMITH
CHOWCHILLA RIVER	N_HOG	N_HOG	N_HOG	LK_MC	SMITH	SMITH
INFLOW NEW DON PEDRO	FOL_I	FOL_I	DPR_I	DPR_I	SACDL	NF_AM
TUOL RIVER 07072000	KINGS	KINGS	KINGS	DPR_I	MERPH	MERPH
CHERRY & ELNOR CRK	KINGS	KINGS	DPR_I	DPR_I	KINGS	MERPH
SCV LOCAL	CONSU	CONSU	N_HOG	N_HOG	SMITH	SMITH
KERN RIVER	KINGS	KINGS	KINGS	KINGS	KINGS	KINGS
KAWEAH RIVER	MILLE	MILLE	LK_MC	KINGS	KINGS	MERPH
TULE RIVER	CONSU	CONSU	MILLE	MILLE	OROVI	OROVI
KINGS RIVER	KINGS	KINGS	KINGS	KINGS	KINGS	KINGS
LV-HAIWEE	MERPH	MERPH	KINGS	KINGS	MERPH	KINGS
MONO BASIN	MERPH	MERPH	DPR_I	DPR_I	MERPH	KINGS
UPPER OWENS	MERPH	N_MEL	MILLE	MILLE	KINGS	SACDL

CALVIN index basins to CALVIN rim inflows matching relied only on correlation results with less consideration for knowledge of basin characteristics or geographic location as was done for the original mapping. One thing to note is that with 18 index basins, a number of them have very similar average monthly flows in relation to timing and magnitude such that mapping one or the other index basin to a certain CALVIN rim flow does not have a significant effect. For example, the seasonal hydrograph in terms of timing and magnitude of OROVI and SHAST are very similar, as is KINGS and MILLE.

This new matching matrix was used to produce a new set of perturbed warm-dry time series for CALVIN rim flows. Aggregated statewide, the different mapping has little effect on total water inflow, however regionally it can make a significant difference (Table 17). This different mapping matrix leads to 1.81 maf/yr additional inflow to the Sacramento valley and 1.13 maf/yr less inflow to the San Joaquin Valley. With a highly developed system of conveyance and storage in California this difference in geographical location of streamflow may have a profound effect on how the system allocates available water resources.

Table 17. Annual average (TAF/yr) perturbed warm-dry hydrology from mapping using different sources of time series for correlation

	Climate model	CALVIN	% Change	Volume Change
Statewide	20,301	20,289	-0.1%	-12
Sacramento Valley	14,804	14,985	1.2%	181
San Joaquin Valley	3,546	3,433	-3.2%	-113
Tulare Basin	1,584	1,570	-0.9%	-14
Southern California	367	301	-17.9%	-66

4.0 Conclusions

Overall, adding index basins does not lead to a large difference in estimated streamflows entering the system under a warm-dry climate scenario. On a large scale, the change to the system is virtually the same using 6 or 18 index basins (Table 14).

Perturbed hydrology representing climate change scenarios is somewhat sensitive to the mapping matrix used to apply perturbation ratios of index basins to represented river basins in CALVIN, especially on the watershed scale. However on the large scale, overall water supply remains relatively unchanged although the geographic source of that supply can change significantly depending on how the index basins are matched to CALVIN rim flows. This points out the value of informing basin matching with knowledge of the watersheds and an understanding of the hydrologic characteristics locally and regionally. Internal consistency of data source also leads to greater levels of correlation of streamflows useful for helping match index basins to rim flows, however statistical results should not be relied upon alone. Since climate change studies inherently encompass great uncertainty, it is valuable to assess the sensitivity and responsiveness of modeling efforts in representing various hydrologic scenarios to explore broad ranges of outcomes and effects. In conclusion, we find that on a statewide scale, differences in the mapping matrix have little effect on the total change in volume of water available to meet statewide water demands.

5.0 References

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