CLIMATE WARMING AND WATER SUPPLY MANAGEMENT IN CALIFORNIA

A Report From:
California Climate Change Center

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Energy Commission), annually awards up to $62 million to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

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The California Climate Change Center (CCCC) is sponsored by the PIER program and coordinated by its Energy-Related Environmental Research area. The Center is managed by the California Energy Commission, Scripps Institution of Oceanography at the University of California at San Diego, and the University of California at Berkeley. The Scripps Institution of Oceanography conducts and administers research on climate change detection, analysis, and modeling; and the University of California at Berkeley conducts and administers research on economic analyses and policy issues. The Center also supports the Global Climate Change Grant Program, which offers competitive solicitations for climate research.

The California Climate Change Center Report Series details ongoing Center-sponsored research. As interim project results, these reports receive minimal editing, and the information contained in these reports may change; authors should be contacted for the most recent project results. By providing ready access to this timely research, the Center seeks to inform the public and expand dissemination of climate change information; thereby leveraging collaborative efforts and increasing the benefits of this research to California's citizens, environment, and economy.

For more information on the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/pier/ or contact the Energy Commission at (916) 654-5164.

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Abstract

This paper examines economic water management adaptations, effects, and other implications of a GFDL-A2 year 2085 dry climate warming scenario for California's water supply system with estimated year 2050 water demands and land use. The GFDL-A2 year 2085 scenario was chosen because it is the driest of the four scenarios in the overall study. Economically adaptive water management activities for this climate scenario are compared with a similar modeling scenario with a continuation of the historical climate. The effects of population growth and land development alone to 2050 are developed and compared with those where dry climate warming also occurs.

Overall, such a dry climate warming scenario would impose large costs and challenges on the state. While this scenario would severely affect the economies of some rural and agricultural regions of California, the state's overall predominantly urban economy would survive and remain largely unhindered by water supply limitations. The dry climate scenario reduces average annual water availability by 27%, which results in an average annual water scarcity of 17%. Statewide, average agricultural areas see water deliveries 24% lower than demand targets, and urban areas see an average of 1% less deliveries than their demand targets. However, there are great regional disparities. Southern California experiences almost all of the urban water scarcity.

Economic water scarcity costs increase by $118 million/year from 2020 to 2050, with population and land use change. Adding dry climate warming to 2050 water demands raises water scarcity costs by an additional $121 million/year. Of the $360 million/year in average water scarcity costs for 2050 with dry climate warming, $302 million/year results from lost agricultural production and $59 million/year is from urban water shortages. Of the $302 million/year seen by agricultural water users, over two-thirds occur in the Tulare Basin and Southern California. Almost all urban water scarcity costs occur in urban Southern California, which has limited ability to increase water imports to accommodate growth without expanding the Colorado River or California Aqueducts. Dry climate warming imposes an additional increase of $384 million/year in system operating costs. Statewide costs increase over $100 million/year if interregional water transfers are limited to 2020 conditions, without climate warming. With the climate warming, the costs of policies limiting interregional water transfers increases to $250 million/year. Although these costs are sizable, they remain a small proportion of California's economy (which is today $1.5 trillion/year). However, the greater part of this cost is borne by rural parts of the state.

1.0 Introduction

This study employed downscaled hydrologic results from the new GFDL-A2 GCM model run for year 2085 in an economic-engineering optimization model of California's statewide water supply system (CALVIN). This climate warming scenario was chosen because it is the driest of the four scenarios in the overall study, and so likely to be of the most interest for regional water supply studies. The CALVIN model has been used for several years for water policy and management studies and some previous climate change and climate warming adaptation studies (Jenkins et al. 2001; Draper et al. 2003; Lund et al. 2003; Jenkins et al, 2004; Pulido-Velázquez et al. 2004; Null and Lund in press; Tanaka et al. in press; and http://cee.engr.ucdavis.edu/faculty/lund/CALVIN/). In general, the approach used was that employed in Lund et al. (2003) and Tanaka et al. (in press) for examining implications of climate warming for water supply impacts and adaptations in California of a PCM2 climate warming scenario in the year 2100, including exogenous land use, population growth, and agronomic technology change effects on water demands. The hydrologic basins and spatial representation of California's water supply system employed in the CALVIN model appear in Figure 1. Overall, the model represents about 90% of California's urban and agricultural water demands and about two-thirds of all runoff in the state. The regions are numbered from north to south: Regions 1 and 2 – Sacramento Valley; Region 3 – San Joaquin River Valley (and South Bay Area); Region 4 – Tulare Basin; and Region 5 – Southern California. In general, this is a results report, and not a model description report. Those interested in the details of the original model are referred to Appendix A and the extensive descriptions available in cited reports, papers, and websites.

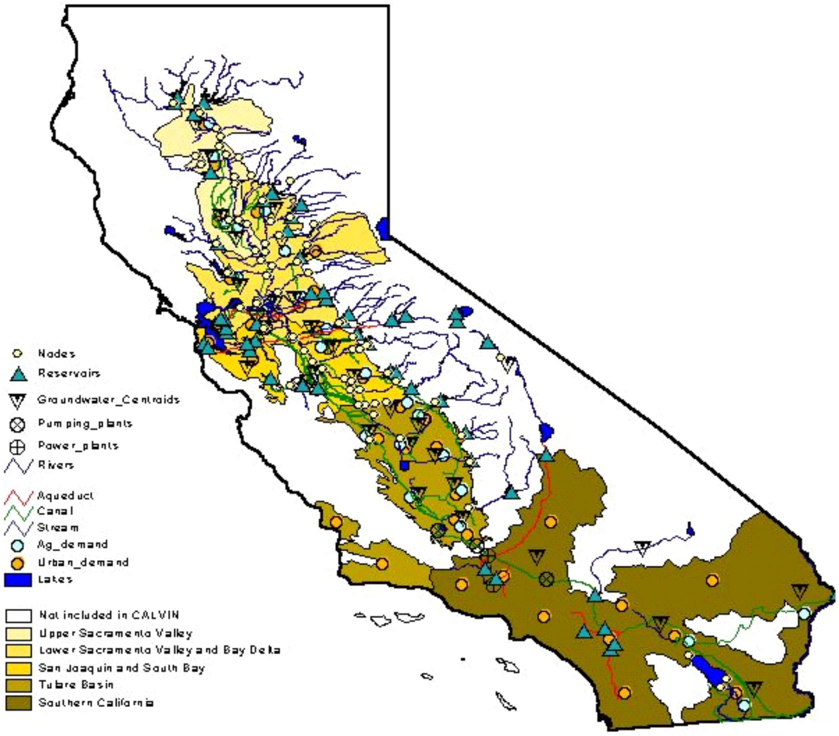


Figure 1. Hydrologic basins, demand areas, and major inflows and facilities represented in CALVIN

2.0 Changes from Earlier CALVIN Model

Compared with previous studies of climate warming and California's water supply system using CALVIN (Lund et al. 2003; Tanaka et al. in press), the model's representation system was modified and updated in several ways. Climate change hydrology was represented by the GFDL-A2 scenario for the years 2070–2099, and some modest improvements were made to historical inflow estimates for some parts of the Tulare basin. Agricultural and urban water demands were developed for the year 2050, and improvements were made in representing water management infrastructure in the Tulare Basin.

2.1. Hydrology

Two GCM models and two GHG emissions scenarios were recommended by Cayan et al. (2005) for the Governor's Climate Change Study. Each of these models was examined in the context of our study to determine (1) what its affect would be on the Central Valley's climate (Table 1a) and (2) what effect it would have on streamflow volumes for six representative rivers distributed throughout California (Table 1b). The Central Valley's climate is a key factor in the economic agricultural production model (the Statewide Water and Agricultural Production, or SWAP model), which is used to estimate the economic value of agricultural water deliveries. Thus climate change in the Central Valley was explicitly quantified to help choose a scenario. The six studied rivers are the Smith River at Jed Smith State Park, Sacramento River at Delta, Feather River at Oroville Dam, American River at North Fork Dam, Merced River at Pohono Bridge, and Kings River at Pine Flat Dam. These locations were selected based on previous work by Miller et al. (2001). For both Central Valley climate variables and the six streamflow locations, percent changes were calculated by comparing annual averages for the 30-year time periods of 1965–1994 and 2070–2099.

Table 1a. Average monthly precipitation and temperature changes in Central Valley under four climate scenarios for 2085

	Precipitation (inch/month)			Temperature (degrees C)		
Climate Scenario	**Historic Precip.**	**Future Precip.**	**% Increase**	**Historic Temp.**	**Future Temp.**	**% Increase**
A2 GFDL	1.16	1.12	-3.5	16.68	18.73	11.0
A2 PCM	1.14	1.15	1.0	16.74	17.96	6.8
B1 GFDL	1.16	1.10	-5.2	16.67	18.60	10.4
B1 PCM	1.14	1.22	6.1	16.73	17.57	4.8

Table 1b. Percent Increase in Total Streamflows at Six Reference Locations for 2085

Climate Scenario	% Increase in Streamflow
A2 GFDL*	-27.9
A2 PCM	3.0
B1 GFDL	-18.4
B1 PCM	9.3

* Scenario used here

The model chosen for this study is the GFDL CM2.1 model (NOAA Geophysical Dynamics Laboratory, Princeton, New Jersey) with the A2 (relatively high emissions) scenario. The GFDL model was chosen because it leads to both a warming and drying of California. The PCM model leads to more precipitation and more streamflow and so was not used in this water supply study. The A2 emissions scenario was chosen because it decreased streamflows at selected locations by 28% for the year 2085, while the B1 scenario reduced flows by only 18%. GFD 2.1 A2 in the year 2085 thus provides the "worst case scenario" of the four alternatives for negative effects of climate warming on California's water supply.

Hydrologic inflows and reservoir evaporation for over 150 locations in California's water supply system are estimated for a monthly representation of 72 years of hydrology, by permuting the 72-year monthly unimpaired flow record. These calculations were done in the same manner as in Lund et al. (2003) and Tanaka et al. (in press), and as detailed by Zhu et al. (2005). The effects of the chosen climate scenario are summarized in Table 2. Most significant under GFDL A2 for year 2085 is the overall 27% decrease in annual streamflow, which directly affects California's water supply.

Table 2. 2085 Changes in components of California's water supply under climate scenario GFDL A2

	Rim Inflows (TAF/year)*			Reservoir Evaporation (TAF/year)		
	Future	Historic	% Increase	Future	Historic	% Increase
Statewide	20,566	28,244	-27	243.6	242.0	1
Sacramento Valley	14,918	19,122	-22	63.4	62.9	1
San Joaquin Valley	3,663	5,741	-36	90.0	89.2	1
Tulare Basin	1,655	2,826	-41	26.6	26.5	0
Southern California	330	555	-41	63.6	63.4	0

*TAF = thousands of acre-feet; Rim inflows are inflows from the rim of the Central Valley or mountain regions outside the major water demand areas.

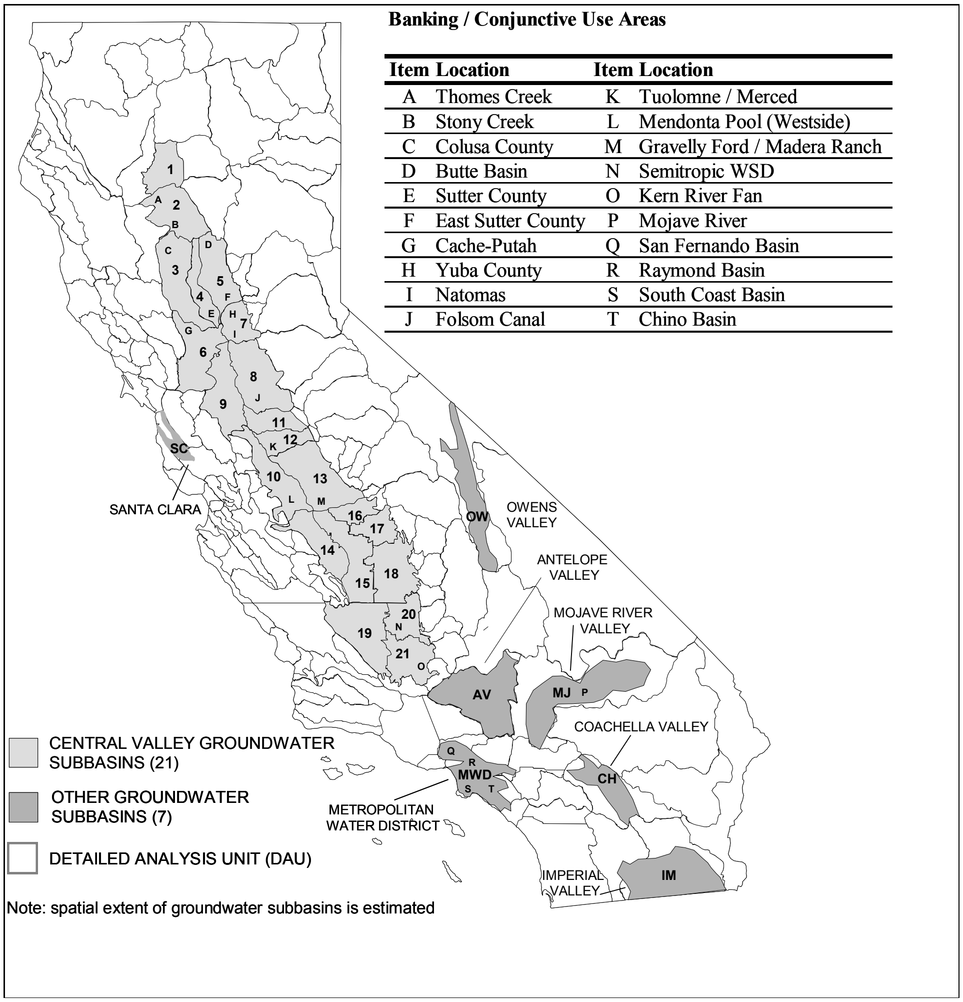
	Local Accretion (TAF/year)*			GW inflow (TAF/year)		
	Future	Historic	% Increase	Future	Historic	% Increase
Statewide	**4,234**	**4,419**	**-4**	**6,736**	**6,780**	**-1**
Sacramento Valley	3,411	3,549	-4	2,214	2,229	-1
San Joaquin Valley	425	468	-9	1,164	1,171	-1
Tulare Basin	398	401	-1	3,358	3,380	-1
Southern California	-	-	-	-	-	-

* Local accretions are inflows from the Central Valley floor, within the major water demand areas.

2.2. Water Demands

Agricultural and urban water demands were projected to 2050. The methods used in Lund et al. (2003), Jenkins et al. (2003), and Tanaka et al. (in press) were employed, using data from Landis and Reilley (2002) for a "high" estimate of year 2050 population (65 million) and resulting land use in California. This was used to develop 2050 urban water demands and set land areas for irrigation areas in 2050.

Agricultural water demands for 2050 were estimated using a recalibration of the SWAP model (Howitt et al. 2001). The SWAP model (like the more common CVPM and CALAG models) estimates the profit-maximizing cropping, water use, and irrigation decisions for an agricultural area with limited water and land availability, with empirically calibrated crop production functions, crop prices, and production factor costs. By progressively limiting water availability in successive model runs, SWAP can produce estimates of the economic production value of agricultural water deliveries for a wide range of water deliveries. The agricultural production model (SWAP) for 2050 water demands has some improvements with respect to earlier versions (i.e., Howitt et al. 2001). The 1995 base observations were updated to include a more recent five year period (1999–2004) and some crop groups were disaggregated. Technological change is represented as a yield increase of 29% for every crop across all the agricultural regions over the 50-year period, compared with roughly a 1%/year increase in crop yields due to technology improvements over the last 50 years. Substitution across production factors (e.g., land and water) is more limited than in past versions of the model. Irrigation land areas are adjusted for projections of 2050 urban land use. Agricultural land areas represented by SWAP, and the CALVIN model, appear in Figure 2. Reference to these CVPM regions (referring to regions established by a prior economic model of Central Valley agricultural production) is made throughout this report.



Banking / Conjunctive Use Areas

Item	Location	Item	Location
A	Thomes Creek	K	Tuolomne / Merced
B	Stony Creek	L	Mendonta Pool (Westside)
C	Colusa County	M	Gravelly Ford / Madera Ranch
D	Butte Basin	N	Semitropic WSD
E	Sutter County	O	Kern River Fan
F	East Sutter County	P	Mojave River
G	Cache-Putah	Q	San Fernando Basin
H	Yuba County	R	Raymond Basin
I	Natomas	S	South Coast Basin
J	Folsom Canal	T	Chino Basin

Figure 2. Location of CVPM agricultural water demand areas (numbers) and groundwater basins (letters) represented in the CALVIN model

Land conversion from agriculture to urban is incorporated for year 2050 according to Jenkins (2004) using results from Landis and Reilley (2002). Shifts in demand for every crop in California are estimated exogenously, while future prices are estimated within the model based on demand shifts, resulting yield changes, crop-price flexibility, and changes in resources availability. Climate change is incorporated as a set of adjustments to yields either up and down dependent on the reference agro-climatic conditions for each region and crop. Adjustments to evapotranspiration have not been included in this analysis. Two sets of agricultural water demands are obtained using SWAP: year 2050 with and without the relatively dry GFD 2.1 A2 climate warming in year 2085. Year 2050 agricultural water delivery targets statewide are 29.3 million acre-feet (MAF) per year with the historical climate, and increase slightly to 29.7 MAF/year with dry climate warming. Almost all of this increase in agricultural water delivery targets is in the Sacramento Valley, where historically rainfall contributes significantly to crop water requirements.

Total urban water demands (water use quantities where water scarcity is absent) are estimated to become 12.06 MAF/year for 2020 and 13.35 MAF/year for 2050 using the methods of Jenkins et al. 2003). Urban residential demands are estimated by using empirical 1995 household economic water demand curves, modified for some increased availability of urban water conservation and increased or decreased housing density (depending on the location), scaled by the estimated population of households in 2050. We tend to think that this estimation of urban household water demand might somewhat overestimate the actual costs of additional urban water conservation, but this is difficult to determine. Details appear in a technical note applying previously applied methods for projected 2050 conditions. Urban water demand growth by region appears in Table 3. Of the 13.35 MAF in 2050, 12.81 MAF/year are represented economically in the 2050 scenario.

Table 3. 2020 and 2050 Urban Water Demand Targets (TAF/year)

Region	2020	2050	Increase
Sacramento Valley	1,904	1,887	-16
San Joaquin Valley	1,535	1,817	283
Tulare Basin	1,199	1,535	336
S. California	7,427	8,107	679
Total	12,065	13,346	**1,281**

2.3. Network and Facilities

Improvements in representing water management infrastructure in the Tulare Basin were made and compared with earlier model representations (Lund et al. 2003; Jenkins et al. 2001). These changes are detailed in the Appendix. This newer representation improves the accuracy of some groundwater inflows and the representation of conjunctive use facilities and capabilities in the Tulare Basin. A comparison of the improvements in Tulare Basin region water delivery and scarcity performance appears in Table 4.

Table 4. Performance improvements with updated Tulare Basin infrastructure (2020 water demands, historical hydrology)*

		Updated Representation				Earlier Representation (Lund et al. 2003)			
Region	**Target**	**MWTP**	**Scarcity Cost**	**Delivery**	**Scarcity**	**MWTP**	**Scarcity Cost**	**Delivery**	**Scarcity**
Units	TAF	$/AF	$K/yr	TAF	TAF	$/AF	$K/yr	TAF	TAF
CVPM14	1,496	29.7	8,118	1,416	80.5	65.5	15,865	1,363	133.3
CVPM15	1,992	26.2	1,781	1,947	45.1	26.7	2,623	1,925	66.4
CVPM16	496	16.6	121	491	4.9	16.6	121	491	4.9
CVPM17	835	18.2	361	821	13.9	18.7	361	821	13.9
CVPM18	2,160	36.0	10,156	1,995	165.0	80.0	32,172	1,857	302.9
CVPM19	957	33.2	2,973	911	45.4	42.5	3,193	908	48.8
CVPM20	677	40.1	2,654	640	36.2	52.3	2,809	638	38.2
CVPM21	1,162	32.2	1,310	1,141	21.3	40.3	1,423	1,139	23.1
Fresno	380	0.0	0	380	0.0	0.0	0	380	0.0
Bakersfield	261	0.0	0	261	0.0	0.0	0	261	0.0
SB-SLO	139	0.0	0	139	0.0	0.0	0	139	0.0
Total	10,553		27,474	10,141	412	-	58,568	9,921	631
Agricultural	9,773	40	27,474	9,361	412	80	58,568	9,142	631
Urban	779	0	0	779	0	0	0	779	0

*CALVIN run for Tulare Basin portion only; MWTP is the average marginal willingness to pay for additional water deliveries.

3.0 Results

The model results presented here represent the combined results of a statewide CALVIN model of California's water supply system and four independent regional CALVIN models—for the Sacramento Valley and Delta, the San Joaquin Valley and South Bay area, the Tulare Basin, and Southern California. The four regional models retain the policies for major interregional water transfers in California from year 2020 policies projected to year 2020 conditions (populations and land use). For these regional models, Delta pumping, Delta outflows, San Joaquin diversions to the Tulare Basin, and California Aqueduct deliveries to the Tulare and Southern California regions remain unchanged from 2000 policies applied to 2020 conditions. Thus, for these results, no major institutional changes in interregional water allocations in California were assumed, but each region has great internal flexibility to reoperate and reallocate water for maximum regional economic effectiveness, within feasible environmental constraints. The advantage of this presentation is that it does not risk major interregional water transfer changes and it avoids alteration of Delta pumping operations (which are controversial and difficult to represent in a model). The statewide optimization model runs are unhindered by these interregional water transfer policy constraints, but remain constrained by environmental policies and the physical capacities of storage, conveyance, and other infrastructure.

Results are presented for the statewide and regional optimization model runs, for 2050 and 2020 water demand conditions and historical and GFDL-A2 year 2085 hydrologic conditions. In these results the GFDL-A2 year 2085 hydrologic scenario is referred to as the dry-warm climate.

It should be recognized that water management studies for climate changes in the distant future is a rather speculative business. The future is an uncertain place. Nevertheless, some qualified conclusions, rough relative magnitudes of impacts, and suggestions of promising directions for adaptation can be inferred from modeling results.

3.1. Water Scarcity

The drier form of climate warming substantially increases water scarcity substantially in some regions, and very little for others (Tables 5a, b, c, and d). For 2020 conditions, where optimization is allowed, water scarcities are relatively benign, at about 2% of statewide water demands. Scarcity is essentially zero in the Sacramento Valley, and generally small for agriculture and zero for urban users in the San Joaquin and Tulare Basins. Scarcity is generally a few percent for Southern California urban users (except 17% for Coachella urban users), but greater, about 20%, for Southern California agricultural users, who have sold their supplies to Southern California urban users to the limit of the Colorado River Aqueduct's conveyance capacity.

With population growth to roughly 65 million in the year 2050, statewide water scarcity increases to 9% (Table 5a). Agricultural water scarcities increase for agricultural areas north of the Tehachapi Mountains, to about 2% in the Sacramento Valley, 20% in the San Joaquin Basin, and 12% in the Tulare Basin. Southern California agricultural water scarcity increases to 29%, but is limited by the capacity limit on the Colorado River Aqueduct and recharge for use in a the Coachella urban area. Given that California is assumed to retain 4.4 MAF/year of Colorado River flows, water scarcity in the Imperial, Palo Verde, and Coachella irrigation districts (IDs) is entirely due to water sales to urban areas in Southern California. Urban water scarcities remain almost entirely absent north of the Tehachapis. These results are for statewide optimized model runs which allow water to be shifted between large regions of the state to meet economic objectives, as they would in an economically ideal water market. When population growth to the year 2050 is not accompanied by policy flexibility to transfer water beyond 2020 conditions, water scarcities (and scarcity costs) increase slightly, by 200 TAF/year statewide (Table 5b). Details of how local demand areas are affected appear in Tables 5c and 5d.

With the dry form of climate warming (reducing overall water inflows statewide by 27% and seasonally shifting inflows) and 2050 populations, additional water scarcity is seen overwhelmingly by agricultural regions north of the Tehachapis. Agricultural water scarcities rise to 24% statewide, 24% in the Sacramento Basin, 26% in the San Joaquin Basin, and 20% in the Tulare Basin, with almost no increase in urban water scarcity. Southern California urban users see only a small increase in water scarcity from climate warming, in part because this study represents only some of the changes in inflows that would occur in Southern California, but more importantly because Southern California has a large base of imported supply, made reliable by Southern California's high willingness to pay for purchased water.

Overall, climate warming has a greater effect on agriculture north of the Tehachapis and population growth has the greatest effect in Southern California, when this region is prevented by conveyance capacity constraints from importing additional water from north of the Tehachapis.

Table 5a. Average water scarcities, statewide optimization

	2050 Demands								2020 Demands			
	Dry - Warm Hydrology				Historical Hydrology				Historical Hydrology			
	Target	Delivery	Scarcity		Target	Delivery	Scarcity		Target	Delivery	Scarcity	
	TAF	TAF	TAF	%	TAF	TAF	TAF	%	TAF	TAF	TAF	%
Total	**42,505**	**35,442**	**7,063**	**17**	**42,084**	**38,405**	**3,683**	**9**	**37,901**	**36,997**	**903**	**2**
Total Agriculture	29,696	22,715	6,981	24	29,275	25,656	3,623	12	27,754	26,974	779	3
Total Urban	12,808	12,727	81	1	12,808	12,749	60	0	10,147	10,023	124	1
Sacramento V. Ag.	9,682	7,376	2,306	24	9,262	9,090	171	2	9,005	9,005	0	0
San Joaquin V. Ag.	6,345	4,725	1,620	26	6,344	5,107	1,240	20	5,259	5,256	3	0
Tulare Basin Ag.	10,399	8,284	2,115	20	10,399	9,128	1,270	12	9,773	9,755	19	0
S. California Ag.	3,271	2,329	942	29	3,271	2,330	941	29	3,716	2,959	758	20
Sac. V. Urban	1,661	1,656	5	0	1,661	1,662	0	0	1,374	1,374	1	0
SJ Valley Urban	1,634	1,634	0	0	1,634	1,634	0	0	894	894	0	0
Tulare Basin Urban	1,406	1,406	0	0	1,406	1,406	0	0	779	779	0	0
S. California Urban	8,107	8,031	76	1	8,107	8,047	60	1	7,099	6,976	123	2

When dry climate warming and population growth occur together, but interregional transfers of water are restricted to optimized 2020 conditions, water scarcities increase substantially, from 17% to 21% statewide. Almost all of this change occurs to agricultural water uses. Limiting water imports and exports diminishes water scarcity for the Sacramento Valley (from 24% to 21%), but increases scarcity to 52% of desired deliveries in the San Joaquin Basin and 25% in the Tulare Basin. As will be seen in later sections, this increase in scarcity leads to disproportionate and large increases in scarcity costs.

Table 5b. Average water scarcities, regional optimization, 2050 water demands*

	Dry - Warm Hydrology				**Historical Hydrology**			
	Target	**Delivery**	**Scarcity**		**Target**	**Delivery**	**Scarcity**	
	TAF	**TAF**	**TAF**	**%**	**TAF**	**TAF**	**TAF**	**%**
Total	**42,505**	**33,396**	**9,109**	**21**	**42,016**	**38,127**	**3,889**	**9**
Total Agriculture	29,696	20,792	8,904	30	29,207	25,513	3,694	13
Total Urban	12,809	12,605	204	2	12,809	12,614	195	2
Sacramento V. Ag.	9,682	7,607	2,074	21	9,193	9,130	63	1
San Joaquin V. Ag.	6,345	3,060	3,285	52	6,344	5,060	1,284	20
Tulare Basin Ag.	10,399	7,796	2,603	25	10,399	8,994	1,405	14
S. California Ag.	3,271	2,329	942	29	3,271	2,330	942	29
Sacramento V. Urb.	1,661	1,656	6	0	1,661	1,662	0	0
San Joaquin V. Urb.	1,634	1,634	0	0	1,634	1,634	0	0
Tulare Basin Urban	1,406	1,406	0	0	1,406	1,406	0	0
S. California Urban	8,107	7,908	199	2	8,107	7,912	195	2

*CALVIN runs aggregated from four independent regional runs with 2020 interregional flows.

Table 5c. Average water scarcities (2050 water demands), regional optimization*

	2050 Water Demands							
	Climate Warming				Historical Hydrology			
	Target	Delivery	Scarcity		Target	Delivery	Scarcity	
Demand Areas	taf	taf	taf	%	taf	taf	taf	%
CVPM 1	188	139	49	26%	163	162	1	1%
CVPM 2	775	624	151	20%	743	743	0	0%
CVPM 3	1,664	1,393	272	16%	1,713	1,712	0	0%
CVPM 4	1,185	890	295	25%	1,153	1,151	2	0%
CVPM 5	2,065	1,558	507	25%	1,784	1,784	0	0%
CVPM 6	1,327	1,120	207	16%	1,098	1,090	8	1%
CVPM 7	493	410	82	17%	511	489	22	4%
CVPM 8	1,018	843	175	17%	878	868	10	1%
CVPM 9	966	631	336	35%	1,149	1,131	19	2%
Napa	175	175	0	0%	175	175	0	0%
CCWD	114	114	0	0%	114	114	0	0%
EBMUD	261	260	1	0%	261	261	0	0%
Stockton	119	119	0	0%	119	119	0	0%
Redding	115	115	0	0%	115	115	0	0%
Galt	86	86	0	0%	86	86	0	0%
Sacramento	702	698	4	1%	702	702	0	0%
Yuba Urban	89	89	0	0%	89	89	0	0%
CVPM 10	2,126	1,525	601	28%	2,126	1,696	430	20%
CVPM 11	1,000	243	757	76%	1,000	822	178	18%
CVPM 12	861	91	769	89%	860	605	255	30%
CVPM 13	2,358	1,200	1,158	49%	2,358	1,937	421	18%
San Francisco	219	219	0	0%	219	219	0	0%
Modesto	254	254	0	0%	254	254	0	0%
Merced	249	249	0	0%	249	249	0	0%
Turlock	197	197	0	0%	197	197	0	0%
Santa Clara	715	715	0	0%	715	715	0	0%
CVPM 14	1,061	863	198	19%	1,061	961	100	9%
CVPM 15	2,479	1,952	527	21%	2,479	2,234	245	10%
CVPM 16	414	194	220	53%	414	352	62	15%
CVPM 17	893	419	474	53%	893	647	246	28%
CVPM 18	2,399	1,690	709	30%	2,399	1,922	477	20%
CVPM 19	1,168	983	185	16%	1,168	1,075	94	8%
CVPM 20	706	571	136	19%	706	634	73	10%
CVPM 21	1,278	1,124	154	12%	1,278	1,169	109	9%
Fresno	374	374	0	0%	374	374	0	0%
Bakersfield	285	285	0	0%	285	285	0	0%
Sanger	160	160	0	0%	160	160	0	0%
Visalia	230	230	0	0%	230	230	0	0%
Delano	153	153	0	0%	153	153	0	0%
Santa Barbara-SLO	205	205	0	0%	205	205	0	0%
Palo Verde ID	618	432	185	30%	618	432	185	30%
Coachella ID	146	102	44	30%	146	102	44	30%
Imperial ID	2,507	1,795	713	28%	2,507	1,795	712	28%
San Bernardino	238	234	5	2%	238	234	4	2%
San Diego	1,109	1,100	9	1%	1,109	1,100	8	1%
Coachella Urban	985	985	0	0%	985	985	0	0%
East MWD	856	835	22	3%	856	835	21	2%
Mojave Urban	809	724	85	11%	809	724	85	11%
Ventura	246	246	0	0%	246	246	0	0%
El Centro	121	121	0	0%	121	121	0	0%
Castaic Lake	142	134	8	6%	142	135	7	5%
Central MWD	3,292	3,236	57	2%	3,292	3,237	55	2%
Blythe	55	54	2	3%	55	53	2	4%
Antelope Valley Urban	253	241	12	5%	253	241	12	5%

*CALVIN runs aggregated from four independent regional runs with 2020 interregional flows.

Table 5d. Average water scarcities, statewide optimization

	2050 Water Demands								2020 Water Demands			
	Climate Warming				Historical Hydrology				Historical Hydrology			
	Target	Delivery	Scarcity		Target	Delivery	Scarcity		Target	Deliver	Scarcity	
Demand Areas	taf	taf	taf	%	taf	taf	taf	%	taf	taf	taf	%
CVPM 1	188	135	53	28%	163	161	2	1%	153	153	0	0%
CVPM 2	775	622	153	20%	743	743	0	0%	697	697	0	0%
CVPM 3	1,664	1,366	298	18%	1,713	1,712	0	0%	1,629	1,629	0	0%
CVPM 4	1,185	869	317	27%	1,153	1,150	3	0%	1,098	1,098	0	0%
CVPM 5	2,065	1,520	545	26%	1,853	1,746	107	6%	1,737	1,737	0	0%
CVPM 6	1,327	1,117	210	16%	1,098	1,090	8	1%	1,048	1,048	0	0%
CVPM 7	493	407	86	17%	511	489	22	4%	565	565	0	0%
CVPM 8	1,018	852	165	16%	878	871	7	1%	894	894	0	0%
CVPM 9	966	487	479	50%	1,149	1,127	22	2%	1,184	1,184	0	0%
Napa	175	175	0	0%	175	175	0	0%	115	115	0	0%
CCWD	114	114	0	0%	114	114	0	0%	135	135	0	0%
EBMUD	261	260	1	0%	261	261	0	0%	297	297	1	0%
Stockton	119	119	0	0%	119	119	0	0%	95	95	0	0%
Redding	115	115	0	0%	115	115	0	0%	-	-	-	-
Galt	86	86	0	0%	86	86	0	0%	-	-	-	-
Sacramento	702	698	4	1%	702	702	0	0%	679	679	0	0%
Yuba Urban	89	89	0	0%	89	89	0	0%	53	53	0	0%
CVPM 10	2,126	1,645	481	23%	2,126	1,606	521	24%	1,698	1,698	0	0%
CVPM 11	1,000	825	175	18%	1,000	866	135	14%	867	865	2	0%
CVPM 12	861	524	337	39%	860	763	98	11%	803	802	1	0%
CVPM 13	2,358	1,731	627	27%	2,358	1,872	487	21%	1,891	1,891	0	0%
San Francisco	219	219	0	0%	219	219	0	0%	238	238	0	0%
Modesto	254	254	0	0%	254	254	0	0%	-	-	-	-
Merced	249	249	0	0%	249	249	0	0%	-	-	-	-
Turlock	197	197	0	0%	197	197	0	0%	-	-	-	-
Santa Clara	715	715	0	0%	715	715	0	0%	656	656	0	0%
CVPM 14	1,061	959	102	10%	1,061	958	103	10%	1,496	1,496	0	0%
CVPM 15	2,479	2,004	475	19%	2,479	2,241	238	10%	1,992	1,992	0	0%
CVPM 16	414	247	167	40%	414	375	39	9%	496	491	5	1%
CVPM 17	893	649	244	27%	893	733	160	18%	835	821	14	2%
CVPM 18	2,399	1,694	706	29%	2,399	1,941	458	19%	2,160	2,160	0	0%
CVPM 19	1,168	992	177	15%	1,168	1,073	95	8%	957	957	0	0%
CVPM 20	706	572	135	19%	706	639	68	10%	677	677	0	0%
CVPM 21	1,278	1,168	110	9%	1,278	1,168	110	9%	1,162	1,162	0	0%
Fresno	374	374	0	0%	374	374	0	0%	380	380	0	0%
Bakersfield	285	285	0	0%	285	285	0	0%	261	261	0	0%
Sanger	160	160	0	0%	160	160	0	0%	-	-	-	-
Visalia	230	230	0	0%	230	230	0	0%	-	-	-	-
Delano	153	153	0	0%	153	153	0	0%	-	-	-	-
Santa Barbara-SLO	205	205	0	0%	205	205	0	0%	139	139	0	0%
Palo Verde ID	618	432	185	30%	618	432	185	30%	789	502	287	36%
Coachella ID	146	102	44	30%	146	102	44	30%	195	181	14	7%
Imperial ID	2,507	1,795	713	28%	2,507	1,795	712	28%	2,732	2,276	456	17%
San Bernardino	238	238	0	0%	238	238	0	0%	283	283	0	0%
San Diego	1,109	1,101	7	1%	1,109	1,101	7	1%	988	988	0	0%
Coachella Urban	985	985	0	0%	985	985	0	0%	601	501	100	17%
East MWD	856	837	19	2%	856	837	19	2%	740	740	0	0%
Mojave Urban	809	765	44	5%	809	781	28	3%	352	346	6	2%
Ventura	246	246	0	0%	246	246	0	0%	-	-	-	-
El Centro	121	121	0	0%	121	121	0	0%	-	-	-	-
Castaic Lake	142	139	3	2%	142	140	2	2%	128	119	9	7%
Central MWD	3,292	3,292	0	0%	3,292	3,292	0	0%	3,731	3,731	0	0%
Blythe	55	54	2	3%	55	53	2	4%	-	-	-	-
Antelope Valley Urban	253	253	0	0%	253	253	0	0%	277	268	9	3%

3.2. Scarcity and Operating Costs

As water becomes scarcer with this dry form of climate warming, water scarcity costs also increase. Water scarcity costs are the costs seen by local water users from receiving less water than their ideal economic water delivery. For instance, an agricultural water user receiving full economic water deliveries sees no marginal value for additional water deliveries, and no water scarcity or water scarcity cost. Lesser water deliveries imply that water availability at that delivery location is scarce, incurring a reduction in profits from agricultural production, termed a scarcity cost. This scarcity cost for the water demand area includes both reductions in agricultural production (and crop revenues) and increases in crop production costs (perhaps to increase irrigation efficiency). Where farmers reduce water deliveries to allow them to sell water to other water users, it is likely for those farmers to profit, because they would only sell water for more than their scarcity costs.

Water scarcity costs are felt particularly by agricultural regions, which see a small rise in scarcity with population growth from 2020 to 2050 (with historical hydrology), and a large additional increase in scarcity cost with the advent of this dry form of climate warming (Tables 6a and 6b). For the Tulare Basin, a 66% increase in scarcity volume with dry-warm climate warming leads to a 168% increase in scarcity cost over 2050 conditions with historical inflows. Urban regions, with higher economic values for water use, manage to acquire water by purchasing from existing sources north of the Tehachapis. Climate warming imposes significant costs on agricultural production in the Sacramento, San Joaquin, and Tulare Basins. Some farmer losses from water scarcity would be compensated by revenues from water purchases by cities. In Southern California, the major economic impact of water scarcity is from population growth from 2020 to 2050, with relatively little additional cost from climate warming. If optimally managed, water scarcity costs increase from $123 million/year for 2020, to $240 million/year with 2050 water demands, to $360 million/year with 2050 water demands and dry-warm climate warming. The statewide economic effects of population growth and climate change are of similar magnitudes.

If 2020 interregional water transfer and Delta pumping volumes are retained, statewide water scarcity costs for historical hydrology and 2050 population and land use average $349 million/year. The addition of this dry climate warming scenario raises this cost by $263 million/year, statewide, to $612 million/year. Increased agricultural water scarcity costs from interregional inflexibility are $145 million/year with the drier climate warming alone. Urban areas see an increase in scarcity costs of $106 million/year, almost all of which is in Southern California. Interregional inflexibility with dry climate warming reduces agricultural scarcity costs in the Sacramento Valley by $6 million/year and Southern California $3 million/year, but increases agricultural scarcity costs $115 million in the San Joaquin Basin and $38 million/year. An ability to revise interregional water allocations becomes considerably more important for the state economically, with dry climate warming.

Average annual operating costs (Table 7) tend to be much higher than water scarcity costs, as they occur in all years ; whereas many water scarcity costs increase dramatically during drought. Operating costs represented in the model include variable operating costs for pumping, water treatment, wastewater treatment, and salinity costs to urban areas. CALVIN does not consider fixed capital investment costs.

Growth in population could increase water operating costs by $413 million/year (or five times the $82 million/year increase in average water scarcity costs). The additional of dry-warm climate warming raises operating costs by $384 million/year above that for 2050 water demands and historical hydrologic conditions. These costs would arise from greater pumping and treatment costs for the acquisition and movement of water to provide water to the higher-valued water demands. This $384 million/year increase in operating costs contrasts with the $255 million/year increase in average scarcity costs, or a $1.50 increase in operating costs for every dollar increase in climate warming–related increases in water scarcity costs. The greatest water supply costs of dry-warm climate warming would be paid by water system ratepayers in their water bills, with additional costs borne by water customers (particularly agricultural customers) in lesser water deliveries (and scarcity costs).

Table 6a. Average scarcity costs ($K/yr)

Demands	**2050**				**2020**
Optimization Area	**Statewide**		**Regional**		**SW**
Hydrology	**Dry-W**	**Hist.**	**Dry-W**	**Hist.**	**Hist.**
Total	**360,661**	**240,065**	**611,936**	**348,757**	**122,513**
Total Agriculture	302,051	195,675	447,467	193,814	33,108
Total Urban	58,610	44,390	164,470	154,943	89,404
Sacramento Valley Ag.	41,434	1,836	35,662	293	0
San Joaquin Valley Ag.	49,100	33,958	164,836	28,296	103
Tulare Basin Ag.	82,247	30,653	120,471	35,987	482
Southern California Ag.	129,270	129,228	126,498	129,238	32,524
Sacramento Val. Urban	5,553	0	5,767	41	630
San Joaquin Val. Urban	21	8	8	21	0
Tulare Basin Urban	0	0	0	0	0
S. California Urban	53,036	44,382	158,695	154,880	88,775

Table 6b. Average water scarcity costs for each demand area ($K/yr)

Demands	2050				2020*
Optimization Area	**Statewide**		**Regional#**		**Statewide**
Hydrology	**Dry-Warm**	**Hist.**	**Dry-Warm**	**Hist.**	**Hist.**
CVPM 1	755	11	695	9	0
CVPM 2	3,332	1	3,268	1	0
CVPM 3	4,622	2	4,123	2	0
CVPM 4	3,537	12	3,238	9	0
CVPM 5	7,200	1,552	6,540	5	0
CVPM 6	4,509	14	4,436	14	0
CVPM 7	1,368	117	1,308	115	0
CVPM 8	4,546	49	4,775	74	0
CVPM 9	11,564	77	7,281	66	0
Napa	0	0	0	0	0
CCWD	0	0	0	0	0
EBMUD	1,525	0	1,525	0	630
Stockton	0	0	214	41	0
Redding	0	0	0	0	-
Galt	0	0	0	0	-
Sacramento	4,028	0	4,028	0	0
Yuba Urban	0	0	0	0	0.0
CVPM 10	11,688	15,482	20,187	9,335	0
CVPM 11	3,089	1,771	36,495	2,890	59
CVPM 12	9,898	930	34,235	4,972	44
CVPM 13	24,424	15,775	73,918	11,099	0
San Francisco	0	0	0	0	0
Modesto	14	14	0	14	-
Merced	8	8	8	8	-
Turlock	0	0	0	0	-
Santa Clara	0	0	0	0	0
CVPM 14	2,547	2,578	9,664	2,512	0
CVPM 15	19,938	5,712	24,292	5,869	0
CVPM 16	7,461	320	10,713	989	121
CVPM 17	5,541	2,021	24,488	5,624	361
CVPM 18	30,031	12,778	30,230	13,528	0
CVPM 19	8,131	2,498	8,800	2,468	0
CVPM 20	5,167	1,333	5,238	1,596	0
CVPM 21	3,431	3,413	7,046	3,401	0
Fresno	0	0	0	0	0
Bakersfield	0	0	0	0	0
Sanger	0	0	0	0	-
Visalia	0	0	0	0	-
Delano	0	0	0	0	-
Santa Barbara-SLO	0	0	0	0	0.0
Palo Verde ID	16,396	16,396	16,015	16,396	10,194
Coachella ID	4,833	4,844	4,946	4,844	869
Imperial ID	108,041	107,988	105,538	107,997	21,461

Table 6b. (continued)

Demands	2050				2020*
Optimization Area	**Statewide**		**Regional#**		**Statewide**
Hydrology	**Dry-Warm**	**Hist.**	**Dry-Warm**	**Hist.**	**Hist.**
San Bernardino	0	0	3,098	2,919	0
San Diego	8,113	8,366	9,576	9,093	0
Coachella Urban	0	0	206	206	73,846
East MWD	20,779	20,821	23,188	22,319	64
Mojave Urban	21,403	12,894	48,103	48,062	2,935
Ventura	2	2	2	2	-
El Centro	0	0	0	0	-
Castaic Lake	2,129	1,604	6,493	5,859	5,411
Central MWD	0	0	55,911	54,219	0
Blythe	609	695	609	695	-
Antelope Valley Urb	0	0	11,508	11,508	6,518

* CALVIN runs aggregated from four independent regional runs with 2020 interregional flows; Small discrepancies with the 2020 model reflect network improvements for the 2050 model.

Table 7. Average annual operating costs, 2050 demands, statewide optimization ($K/year)

Hydrology	Warm-Dry	Historical	Historical
Water Demands	**2050 Demands**	**2050 Demands**	**2020 Demands**
Sacramento	190	195	200
San Joaquin	444	385	375
Tulare	1071	977	920
Southern Cal.	2,560	2,324	1,974
Total	**4,265**	**3,881**	**3,468**

3.3. Environmental Water Shortages (and Reduced Fixed Diversions)

With the dry form of climate warming, some minimum instream flows and diversions are simply infeasible. These are listed in Table 8, with their average overall, and drought and non-drought quantities and changes. These reductions in environmental flow quantities are typically small. However, additional water-related environmental effects of climate warming would occur due to increases in water temperature, which, unfortunately, are not modeled here. The largest environmental flow reduction is for flows in the upper Sacramento River, below Keswick Dam, related to winter-run salmon flows and cold-water pool in the Shasta Reservoir. Required flows to maintain Mono Lake levels are also unattainable under the dry-warm climate change scenario.

In addition, for the San Joaquin regional model run, an average of 218.5 TAF/year of reduced San Joaquin River exports via the Friant-Kern Canal was needed to make operations of Millerton Reservoir physically feasible with climate warming. This would raise water scarcity in the Tulare Basin for its regional model run by roughly 10%–15%.

Table 8. Infeasible environmental flow requirements and depletions under climate change and historical hydrologies (TAF/year)

Flow Location	Annual Average			Drought Years			Non-Drought Years		
	Historic	Dry-Warm	Change	Historic	Dry-Warm	Change	Historic	Dry-Warm	Change
American River (various locations)	1,854	1,849	-5	1,364	1,363	-1	1,972	1,966	-6
Trinity River	599	599	-1	437	437	0	638	638	-1
Upper Sac River	4,069	3,252	-817	3,301	2,641	-660	4,254	3,400	-855
Lower Sacramento River	11,966	11,960	-6	11,967	11,967	0	11,966	11,958	-8
Exports to Mono Basin*	119	75	-44	76	60	-15	130	79	-51
Bear River local diversion*	49	30	-19	52	30	-21	48	30	-18
DA12 local depletion*	24	23	-1	57	56	-2	16	16	-1
SJ exports to Tulare *#	1,125	906	-219#	673	516	-157*	1,234	1,001	-233#
Total	**19,805**	**18,694**	**-1,111**	**17,927**	**17,071**	**-856**	**20,259**	**19,086**	**1,172**

*Reduction in local diversions required for feasibility in upper watershed reaches.
Only for Regional Model; San Joaquin regional model, operating independently, is unable to export this quantity to the Tulare Basin under climate change.

Delta outflows and exports are often of interest for water management in California. Figures 3 and 4 show monthly average results from the three statewide model runs. Delta exports do not change much (with possible exceptions for June and July) with water demand changes from 2020–2050. Dry-warm climate warming, however, increases Delta exports in winter months (when runoff would be more plentiful), decreases significantly during the present spring snowmelt season, and decreases a little during the summer. Surplus Delta outflows (Figure 4) do not change much with population change alone from 2020 to 2050, but decrease greatly with dry-warm climate change.

Table 9 contains the average marginal economic costs of additional environmental flow requirements for various locations in the system under different sets of assumptions. These are the opportunity costs of these environmental flows to urban, agricultural, and hydropower users of this water supply system. Many environmental requirements have rather low economic costs to other water supply users. However, environmental flows for the Trinity River, Clear Creek, and Mono Lake have high values, which increase substantially with dry climate warming. American River instream flow requirements, which have a low economic impact without climate change, rise substantially with climate warming. The high marginal cost of American River environmental flows with the dry form of climate warming arises from some actual increase in water scarcity for urban or agricultural users as a result of this constraint.

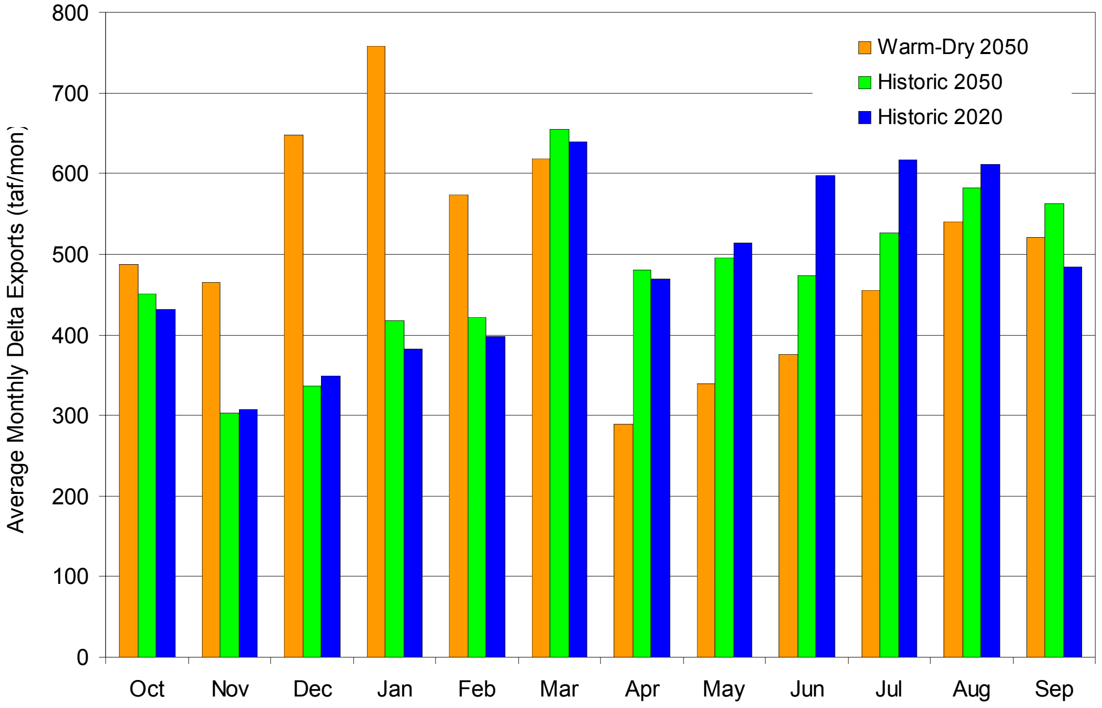


Figure 3. Monthly average delta exports, statewide optimizations (TAF/month)

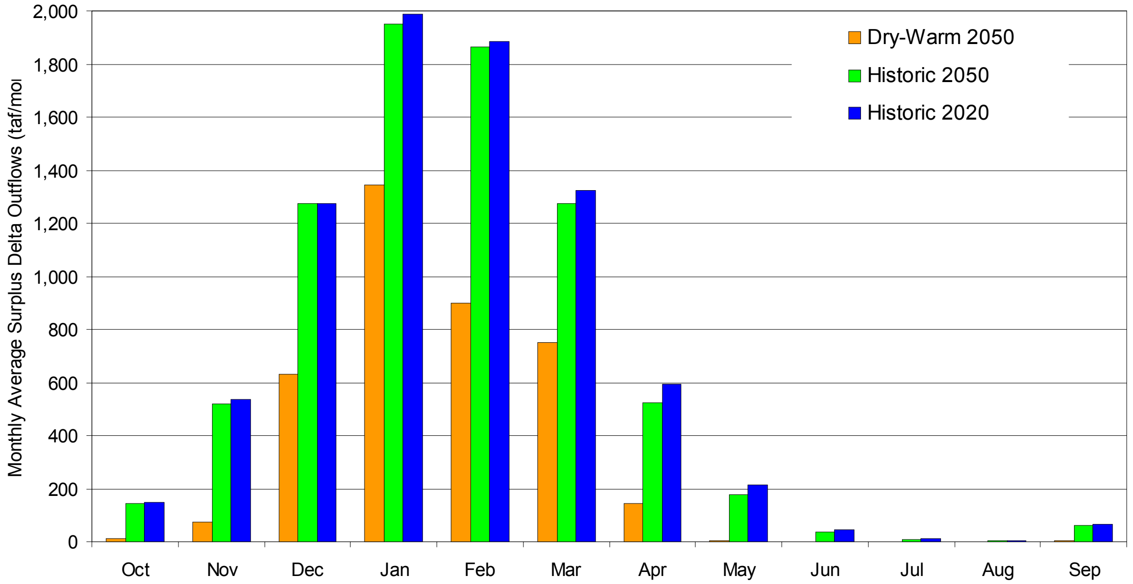


Figure 4. Monthly average surplus delta outflows, statewide optimizations (TAF/month)

Table 9. Marginal values of environmental flows, 2050 water demands ($/acre-foot)

Hydrology	**Historical**		**Dry-Warm**	
Optimization Area **Environmental Flow**	**Regional**	**Statewide**	**Regional**	**Statewide**
Trinity River	33.76	34.68	64.32	72.48
Clear Creek	16.45	16.70	22.94	23.85
Sacramento River	0.18	0.12	0.86	0.70
Sacramento River at Keswick	1.64	1.84	6.67	7.53
Feather River	0.54	0.33	4.99	5.54
American River	0.54	0.50	273.47	269.17
Calaveras River	0.00	0.00	0.00	0.00
Delta Outflow	1.78	2.40	20.26	27.13
Mono Lake	1259.41	961.93	1857.14	1477.31

3.4. Adaptive Actions

A wide variety of actions are possible for California to respond to the water supply effects of climate change. These adaptive actions range from traditional water supply reservoir operations, aqueducts, and treatment plants, to urban and agricultural water use efficiency practices, to conjunctive use of surface and ground waters, to desalination, to water markets and portfolios of such actions that go together well to provide more stable and productive use of a region's water resources. Many of these adaptive actions are discussed elsewhere (Lund et al. 2003; Tanaka et al. in press). Some preliminary model results on economical adaptive actions are discussed below.

3.4.1. Groundwater Storage and Use

Figures 5 and 6 show patterns of seasonal and over-year statewide groundwater storage from statewide and summed regional optimization results. In both sets of results, seasonal draw-down and refill indicates annual wet and dry season refill and use of aquifers. The amplitude of these seasonal variations averages about 2–3 MAF of storage annually. The much longer period variations in groundwater levels, about 10–20 years, indicate the use of groundwater for long-term drought storage. This long period use of over-year storage has an amplitude of about 20–30 MAF.

For the statewide optimization results, a drier-warmer climate leads to greater use of groundwater during dry years, essentially more conjunctive use of ground and surface water storage. For the more isolated regional model results, there is similar variability, but groundwater storage tends to be higher, perhaps reflecting the more limited ability to employ groundwater storage conjunctively between major regions of California.

Figure 7 is a cumulative frequency plot of the percent of all annual systemwide water deliveries coming from groundwater for the three statewide model runs. The figure indicates the variability of groundwater deliveries over wet and dry years, illustrating interannual conjunctive use of ground and surface waters for different climate or management scenarios. Adaptation to the dry-warm scenario relies considerably on groundwater deliveries, particularly during drier years, indicating somewhat more conjunctive use with this climate change scenario.

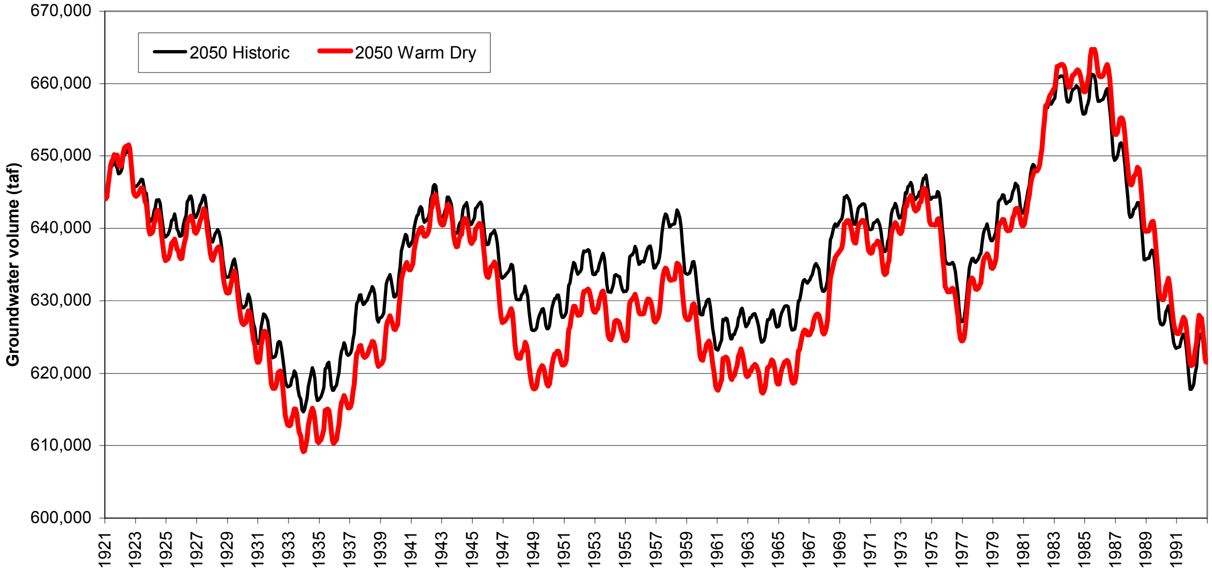


Figure 5. Central Valley groundwater storage for 2050 with historical and climate warming scenarios, statewide optimization

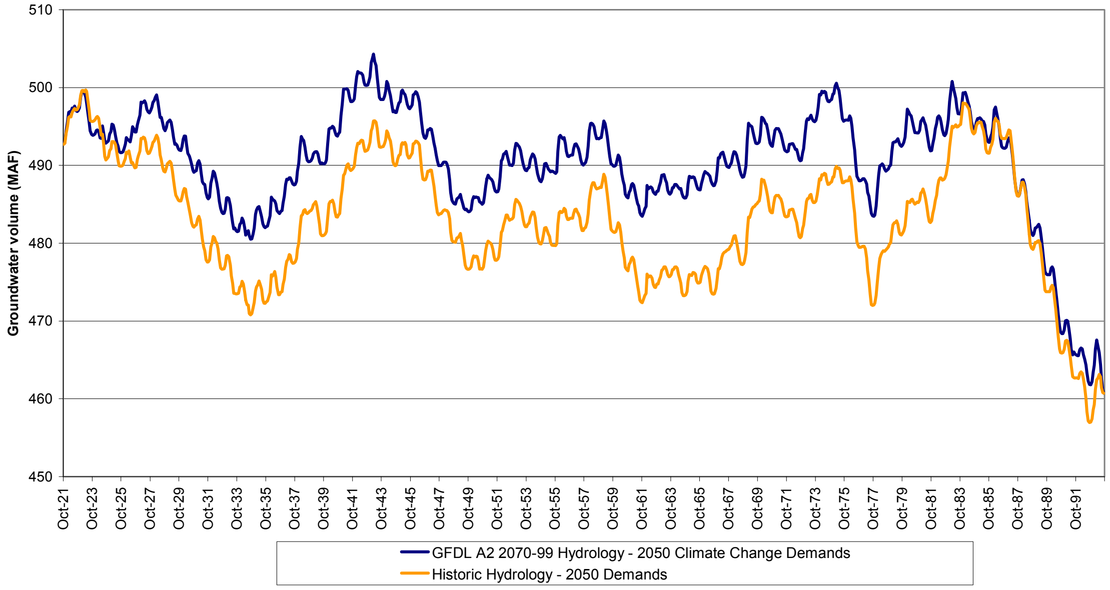


Figure 6. Central Valley groundwater storage for 2050 with historical and climate warming scenarios, regional optimization

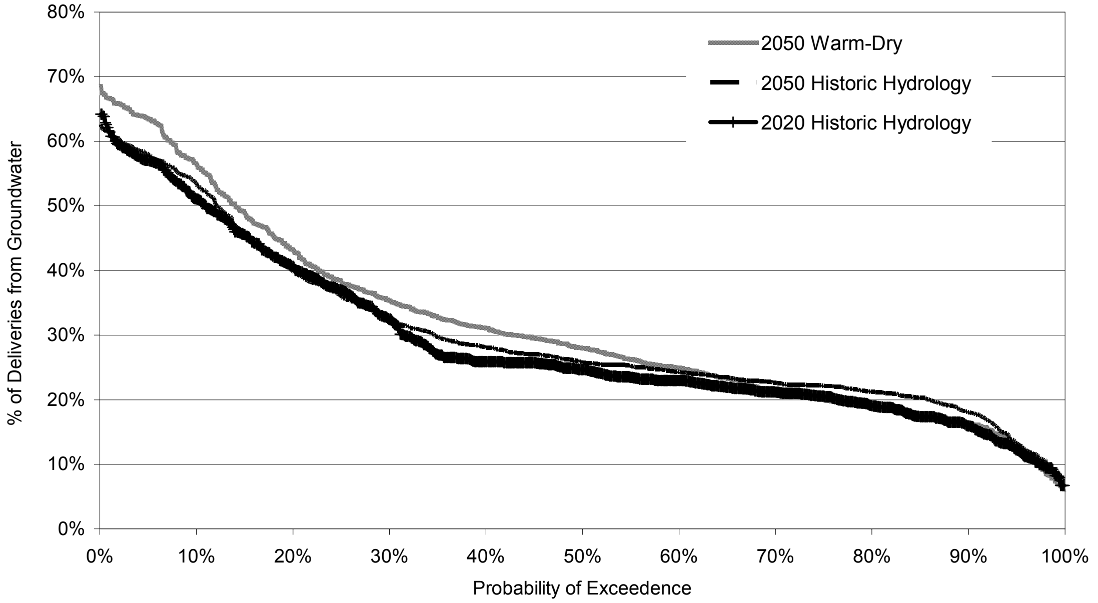


Figure 7. Percent of total water deliveries from groundwater with historical and climate warming scenarios, statewide optimizations

3.4.2. Reservoir Storage

Figure 8 depicts the time series of total water surface storage in monthly time-steps over the 72-year historical hydrologic period and the climate change period. Surface water storages for the two climate scenarios tend to follow similar interannual patterns. However, the dry-warm climate scenario tends to result in more use of the reservoir's lower reaches. This apoproach would tend to encroach more into what is now the drought storage pool for major reservoirs. The model's response to this is to use groundwater more for drought storage, making more storage capacity available in surface water reservoirs for the more variable seasonal flows.

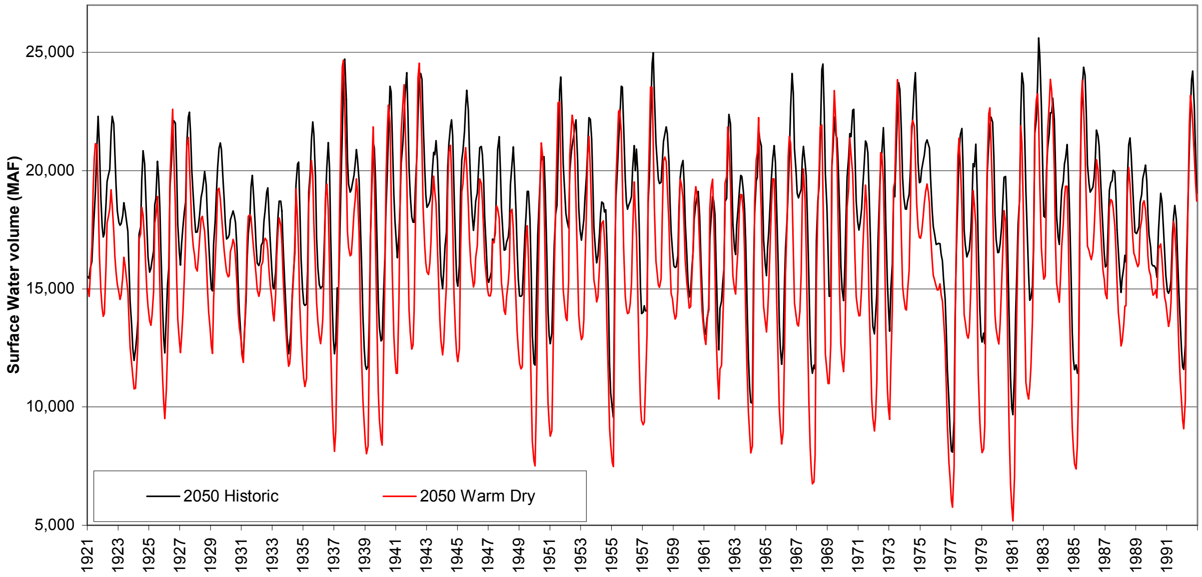


Figure 8. Statewide surface water storage for 2050 with historical and dry climate warming scenarios, statewide optimization

3.4.3. Water Markets

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

With dry climate warming, the value of allowing water markets to reallocate water is likely to increase. When water markets are restricted spatially, statewide economic costs increase substantially. As seen in Figure 5a, for 2050 water demands and the historical climate, restricting water markets to within the four regions raises statewide water scarcity costs by $108 million/year, compared with the statewide integration of water operations and allocations. With dry climate warming, these same restrictions increase scarcity costs by $151 million/year, compared with statewide optimization.

3.4.4. Seawater Desalination

Seawater desalination is made available to all coastal areas in unlimited amounts at $1,400/acre-foot. In all runs with the historical hydrology, no urban area finds seawater desalination economical. As can be seen from the average marginal willingness to pay for additional water, seawater desalination would have to be much less expensive for it to become a significant source of water supply. Under the climate change dry-warm climate scenario, seawater desalination is only used in Southern California, for a total annual average of 5.93 TAF/year.

Except where limited by conveyance capacity constraints, urban coastal areas have sufficient access to less-expensive sources (or demand reductions) for water. These alternatives include water markets (representing conserved or foregone agricultural and urban water use outside a local jurisdiction), improved surface and groundwater operations with improved operational efficiencies, and foregone water use (through conservation and other use reductions) in their own service areas.

3.4.5. Hydropower

The CALVIN model includes hydropower production associated with the major water supply storage and conveyance facilities of California. This representation is described by Lund et al. (2003), particularly in Appendix D on Hydropower (Ritzema 2002).

With population growth, there is some reduction in power production from the water supply system. Presumably this results from the greater economic value of water operations for water supply, relative to under 2020 demands. Thus, on some occasions when water could be retained in storage for later hydropower generation or to increase hydropower head, the water is used instead for urban or agricultural water supply. With dry climate warming, hydropower production from the water supply system further decreases. Losses of hydropower revenues seem particularly apparent in the Sacramento Valley and Southern California. Seasonally, all three demand-climate scenarios show similar seasonal patterns of power generation, with the drier scenario having the lowest average production in every month (Figure 9). Interannual variability in hydropower production appears in Figure 10.

Table 10. Annual averages of hydropower benefits ($M/yr)

	Warm-Dry Hydrology	**Historical Hydrology**	**Historical Hydrology**
	2050 Demands	**2050 Demands**	**2020 Demands**
Sacramento	150	203	203
San Joaquin	48	48	46
Tulare	9	10	11
Southern CA	394	423	477
Sum	**602**	**684**	**737**

A separate spreadsheet analysis was used to explore the effects of the Warm-Dry (GFDL A2) scenario and the wetter warm PCM A2 scenario for 2085 on higher-elevation hydropower units not included in the CALVIN model, using unit generation data from the California Energy Commission. This very simple and coarse spreadsheet analysis underestimates the ability of higher-elevation hydropower units to shift water and energy generation from the winter and spring months to summer, when hydropower unit prices are significantly higher. The results of this spreadsheet analysis appear in Figure 11. The paleodrought generation estimates employ an estimate of the hydrologies of two severe droughts from the prehistoric record, roughly 800–1200 years ago, developed by Scott Stine.

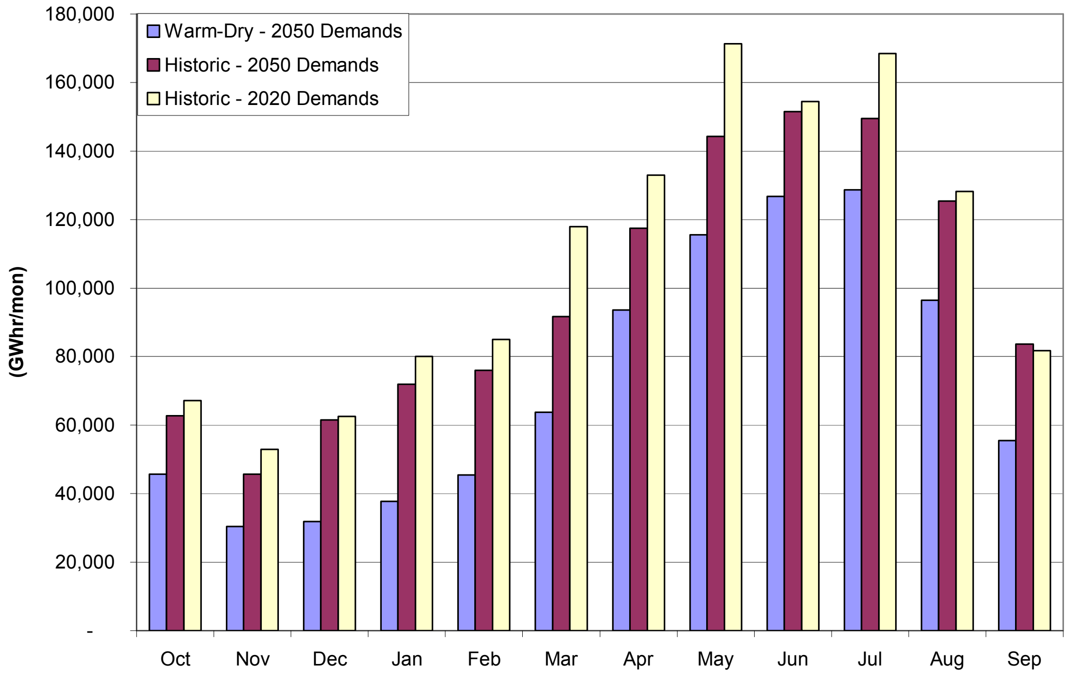


Figure 9. Monthly reservoir hydropower generation, statewide optimizations

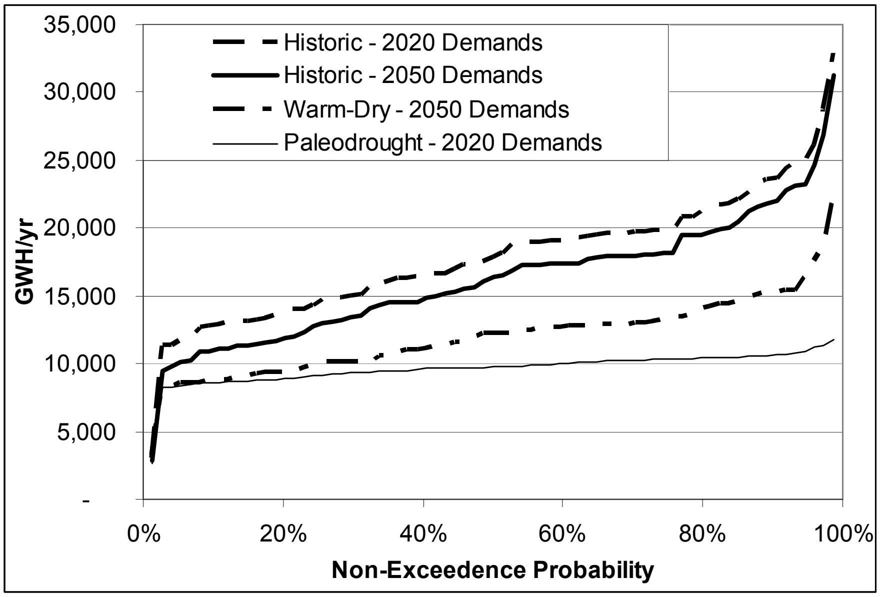


Figure 10. Frequency of annual power generation from major water supply reservoirs

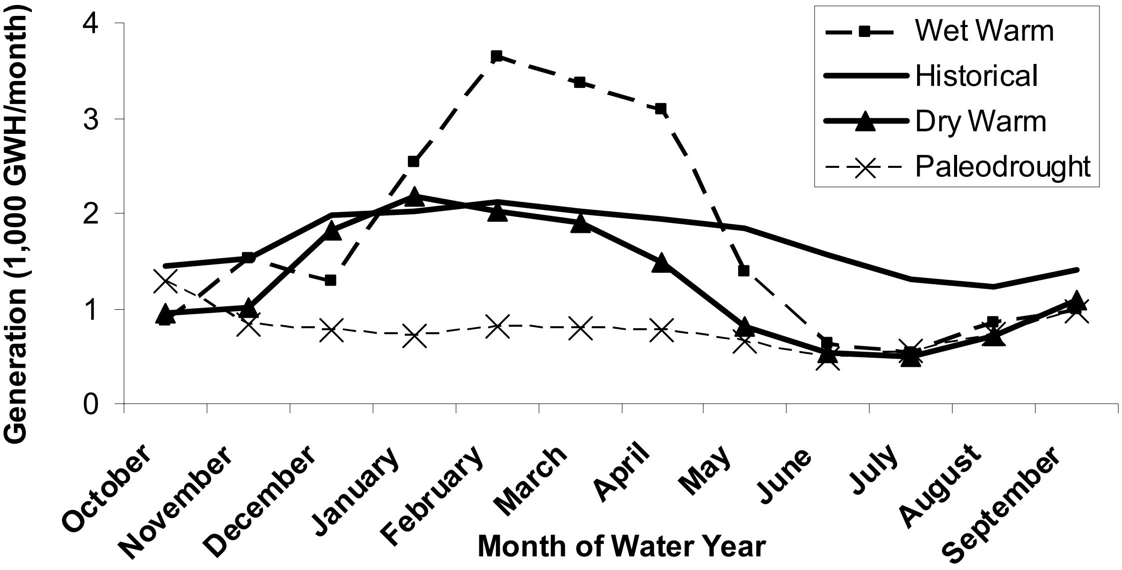


Figure 11. Seasonal hydropower generation from 130 high-elevation units not included in the CALVIN model

3.5. Marginal Values

Shadow values (or Lagrange multipliers) on constraints in the optimization model provide insightful information on various aspects of the water supply system. This section examines the marginal economic values of increased local water deliveries, changes in interregional water transfers, changes in environmental flow requirements, and changes in storage and conveyance capacities. The use of these economic interpretations, which are readily derived from an economic-engineering optimization model, are discussed in several sections above and below. However, it should be realized that these values assume that there are no "transaction costs" to any market transactions or other institutional or physical changes that must be made to effect any of the examined changes.

3.5.1. Economic Value of Additional Water to Water Users

Reflecting increased water scarcity, dry climate warming significantly increases the marginal willingness of agricultural regions to pay for additional water supplies (Table 11). Since the model employs an economic representation of agricultural and urban water demands, water users can decrease water use at some water conservation cost represented by their demand curve; thus, supply and demand management are examined integrally. For the San Joaquin Basin and the Tulare Basin, the marginal value of additional water more than doubles with increased water scarcity. This higher marginal willingness to pay for water would affect willingness to invest in water use efficiencies, additional water imports, and reuse of drainage water. For urban Southern California, higher willingness to pay for additional water encourages wastewater reuse and desalination, as well as water conservation/demand management. However, the effectiveness of improvements in applied water use efficiencies and return flow reuse will be limited for the Tulare Basin to locations where return flows enter saline sinks, since the Tulare Basin is essentially a closed basin in most years. Only reductions in consumptive use will have value for improved water quantity in such situations.

Table 11. Marginal Willingness to Pay for Additional Water ($/acre-foot)*

Optimized area	Statewide			Regional[#]	
Demands	2050		2020[+]	2050	
Hydrology	Dry-W	Hist.	Hist.	Dry-W	Hist.
CVPM 1	13.0	3.3	0.0	11.9	3.3
CVPM 2	19.6	0.1	0.0	19.0	0.0
CVPM 3	13.6	1.8	0.0	12.1	1.8
CVPM 4	11.9	2.0	0.0	10.5	1.8
CVPM 5	13.8	9.5	0.0	12.3	0.0
CVPM 6	19.7	1.1	0.0	18.6	1.1
CVPM 7	13.7	2.9	0.0	12.5	2.8
CVPM 8	24.9	4.3	0.0	24.6	4.2
CVPM 9	14.7	1.9	0.0	11.3	1.8
Napa	0.0	0.0	0.0	0.0	0.0
CCWD	0.0	0.0	0.0	0.0	0.0
EBMUD	163.9	0.0	27.6	163.9	0.0
Stockton	0.0	0.0	0.0	16.4	0.0
Redding	0.0	0.0	-	0	0
Galt	0.0	0.0	-	0	0
Sacramento	56.7	0.0	0.0	56.7	0.0
Yuba Urban	0.0	0.0	0.0	0.0	0.0
CVPM 10	27.0	29.8	0.0	33.5	21.5
CVPM 11	15.5	12.8	1.1	40.0	16.1
CVPM 12	26.0	7.4	0.7	39.4	23.6
CVPM 13	43.5	34.6	0.0	67.4	28.6
San Francisco	0.0	0.0	0.0	0.0	0.0
Modesto	321.4	321.4	-	321	321
Merced	253.1	253.1	-	253	253
Turlock	0.0	0.0	-	0	0
Santa Clara	0.0	0.0	0.0	0.0	0.0

Table 11. (continued)

Optimized area	Statewide			Regional[#]	
Demands	**2050**		**2020[+]**	**2050**	
Hydrology	**Dry-W**	**Hist.**	**Hist.**	**Dry-W**	**Hist.**
CVPM 14	19.7	20.9	0.0	50.3	19.3
CVPM 15	42.0	18.1	0.0	49.8	17.8
CVPM 16	37.4	9.1	16.6	41.4	19.7
CVPM 17	28.0	12.8	18.3	55.0	28.4
CVPM 18	49.5	27.2	0.0	48.0	29.7
CVPM 19	46.8	21.4	0.0	49.0	20.1
CVPM 20	45.1	16.0	0.0	42.4	21.8
CVPM 21	25.4	25.3	0.0	34.1	23.7
Fresno	0.0	0.0	0.0	0.0	0.0
Bakersfield	0.0	0.0	0.0	0.0	0.0
Sanger	0.0	0.0	-	0	0
Visalia	0.0	0.0	-	0	0
Delano	0.0	0.0	-	0	0
Santa Barbara-SLO	0.0	0.0	0.0	0.0	0.0
Palo Verde ID	121.2	121.2	71.2	118.4	121.2
Coachella ID	151.5	151.7	61.4	155.0	151.7
Imperial ID	196.3	196.3	74.5	191.7	196.2
San Bernardino	0.0	0.0	0.0	306.7	285.1
San Diego	150.1	153.7	0.0	177.2	168.8
Coachella Urban	0.0	0.0	1,019	807.3	807.3
East MWD	342.8	343.1	1.8	396.3	380.5
Mojave Urban	502.5	471.6	170.6	622.9	622.1
Ventura	2.6	2.6	-	2.6	2.6
El Centro	0.0	0.0	-	0.0	0.0
Castaic Lake	397.4	284.8	662.1	873.9	855.4
Central MWD	0.0	0.0	0.0	420.4	414.0
Blythe	335.5	338.7	-	335.5	338.7
Antelope Valley Urban	0.0	0.0	748.0	595.3	595.3

* In some cases, non-zero willingness-to-pay appears where zero scarcity appears in earlier tables; these are due to very small scarcities in the lesser significant figures.

CALVIN runs aggregated from four independent regional runs with 2020 interregional flows

+ 2020 agricultural shadow values are not comparable, due to recalibration of underlying SWAP model.

3.5.2. Changes in Interregional Water Transfers

The model results presented for four independent regional model runs produce a time series of shadow values for each boundary flow (inflows and outflows). These can be interpreted as the economic gradient which drives inter-basin water transfers or markets in the statewide model runs. These marginal values of water at the system boundaries are consistent with the marginal willingness of agricultural and urban water users to pay for changes in both water imported to their regions and water exported from their regions, restricted by conveyance capacities and also affected the potential for reuse of various imported flows. These results appear in Table 12. Where there is a difference in the willingness of one region to be paid for a reduction in exports and the willingness of the adjacent region to pay for an increase in imports, there would be some economic advantage to both regions from changing this inter-basin water transfer. While such transactions are prohibited in the model results so far, these economic values do represent the costs of continuing to adhere to the 2020 inter-basin water allocation policies in the year 2050. Clearly, these marginal values of water reflect the marginal willingness to pay of internal water demands areas. The drier-warmer climate increases water scarcities in all regions, and so increases the costs to each region of losing exporting water to other regions and increases the economic value of additional water imports from other regions.

Table 12. Average willingness to pay for changes in interregional flows, 2050 ($/acre-foot)*

			Historic		Dry-Warm	
Transfer	**From**	**To**	**Export**	**Import**	**Export**	**Import**
Tracy pumping export	Sacramento	San Joaquin	2	29	23	80
Banks pumping export	Sacramento	San Joaquin	2	33	23	84
San Joaquin outflow at Vernalis	San Joaquin	Sacramento	47	2	88	23
Stanislaus diversion to SEWD	San Joaquin	Sacramento	49	31	105	84
California Aqueduct flow	San Joaquin	Tulare	66	37	117	57
Friant-Kern Canal from Millerton	San Joaquin	Tulare	56	49	108	79
California Aqueduct flow	Tulare	S. California	122	414	144	428
Colorado exports	Colorado	S. California	-	205	-	200

CALVIN runs aggregated from four independent regional runs with 2020 interregional flows

3.5.3. Environmental Flows

The shadow values of environmental flow restrictions are presented in Table 9, and discussed in Section 3.3.

4.0 Major Limitations

Any model for future conditions will have significant limitations. The major limitations of this study arise from the following factors:

1. Data limitations in representing the infrastructure, hydrology, and water demands in California's water supply system
2. Limitations arising from the generalized network flow optimization formulation and solution algorithm (which includes perfect hydrologic foresight)
3. Exclusion of flood control, recreation, and water system management purposes other than urban and agricultural water supply and hydropower
4. Limitations in the ability to predict hydrologic and water management conditions in 2050, including the availability and cost of desalination and water conservation options, future environmental flow requirements, and characterization of changes in the agricultural economy, technology, and climate

The general limitations of this approach are well discussed elsewhere, but are not diminished for having already been discussed (Jenkins et al. 2001; Tanaka et al. in press). These results and conclusions are at best an exploratory analysis, based on mostly reasonable assumptions from the present-day perspective. It is, of course, impossible to conduct an analysis of this situation that is entirely reasonable from all perspectives. Nevertheless, some qualitative conclusions seem reasonable.

5.0 Conclusions

Economic water management adaptations, effects, and other implications of a GFDL-A2 2085 dry scenario of climate warming were examined for California's water supply system in the year 2050. Water management activities for this climate scenario were compared with a similar modeling scenario that continues the historical climate. The effects of population growth and land development alone were developed and compared with those where climate change also occurs.

Overall, such a dry climate warming scenario would impose large costs and challenges on the state. Such a dire scenario would severely affect the economies of some rural and agricultural regions of California. However, the overall state economy, which is predominantly urban, would survive and remain largely unhindered by the water supply limitations. Overall, the climate scenario reduces average annual water availability by 27%, which results in an average annual reduction in water deliveries of 17%. Statewide, average agricultural areas see water deliveries 24% lower than demand targets and average urban areas see 1% less than their demand targets. There are great regional disparities as well. Urban Southern California sees almost all scarcity in urban water deliveries; urban water scarcity is almost absent north of Southern California.

Economic water scarcity costs increase by $118 million/year from 2020 to 2050, with population and land use change. The overall economic effects of the dry-warming scenario compared with the historical hydrology for 2050 water demands averages $238 million/year more than in 2020, and $120 million/year more than 2050 demands with historical hydrology. Enforcing 2020 constraints on interregional water transfers would significantly increase these costs.

Flexibility and cooperation are essential to future water management in California, and are highly valuable economically for adapting to dry forms of climate warming. Although the economic costs of dry climate warming are sizable, they remain a small proportion of California's economy, which is currently $1.5 trillion/year. However, these costs fall disproportionately in rural parts of the state.

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Appendix A

CALVIN Economic-Engineering Optimization Modeling of Climate Change

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"… research, to be productive, has to be the "disorganizer," the creator of a different future and the enemy of today. In most industrial laboratories, "defensive research" aimed at perpetuating today, predominates." Peter F. Drucker (1967), *The Effective Executive*, p. 117

INTRODUCTION

CALVIN (CALifornia Value Integrated Network), the integrated economic-engineering optimization model of California's inter-tied water system, was developed for water policy, planning, and operations studies (Jenkins et al. 2001; Draper et al. 2003). The generalized network flow-based optimization model minimizes the economic operating and scarcity costs of water supply, subject to water balance, capacity, and environmental constraints for a range of hydrologic and operational conditions represented by a monthly 72-year time series of inflows. The CALVIN model is an enhancement of the HEC-PRM (Hydrological Engineering Center Prescriptive Reservoir Model) code developed by the U.S. Army Corps of Engineers (HEC 1991). This model solves the following equations:

Minimize: $$Z = \sum_{\mathrm{i}} \sum_{\mathrm{j}} \mathrm{c}_{\mathrm{ij}}\ \mathrm{X}_{\mathrm{ij}}\,, \tag{1}$$

Subject to: $$\sum_i X_{ji} = \sum_i a_{ij} X_{ij} + b_j \text{, for all nodes j,} \tag{2}$$

$$X_{ij} \le u_{ij} \qquad \text{for all arcs,} \tag{3}$$

$$X_{ij} \ge l_{ij} \qquad \text{for all arcs,} \tag{4}$$

where Z is the total cost of flows throughout the network, X_{ij} is flow leaving node i towards node j, c_{ij} = economic costs (ag. or urban), b_j = external inflows to node j, a_{ij} = gains/losses on flows in arc ij, u_{ij} = upper bound on arc ij, and l_{ij} = lower bound on arc ij.

The objective function, Equation 1, represents the minimum costs of all flows in the network each weighted by a unit cost that can vary between arcs. Equation 2 represents conservation of mass at each node in the network, the sum of all flows from a node must equal the sum of all flows to that node. Flows leaving other nodes for node j are weighted by the loss factor (1=no loss). The numerical solution of these problems is fairly fast and such algorithms are in the public domain.

This simple formulation can be adapted to solve a wide variety of problems. If the arcs are seen as flows not only in space, but also in time, the optimization can occur over an optimization period as well as a spatial network. This allows for surface and groundwater reservoir storage. For CALVIN, the network is the model's spatial schematic in many layers, with one layer for each time-step. Each time layer is connected with arcs for each surface reservoir and aquifer, going forward in time with upper bounds of the reservoir's storage capacity. Storage is just a flow forward in time.

Some other extensions to the simple model can be achieved. Convex piece-wise linear cost functions on single arcs can be represented by using several arcs to represent one physical arc, with each sub-arc having an appropriate upper bound and unit cost. The losses a_{ij} in Equation 2 can be used to represent reservoir evaporation, conveyance losses, consumptive use, and reuse, for example.

Software for solving fairly general large-scale water resource problems using this formulation has been developed by the U.S. Army Corps of Engineers Hydrologic Engineering Center in their HEC-PRM software. This code uses a network solver developed by Paul Jensen of the University of Texas. This code has been applied to many water systems in the Western Hemisphere in the last decade and is the numerical core of the CALVIN model.As a combined economically driven engineering and optimization model, it produces traditional engineering outputs as well as useful economic results and shadow values for infrastructure capacities and environmental and policy constraints. This modeling approach is used to illustrate how the infrastructure and management of California's water might economically adapt and respond to changes in climate, in the context of higher future populations and changes in land use and technology. Unlike traditional simulation modeling approaches, this economically optimized re-operation of the system is not limited by present-day water system operating rules and water allocation policies.

METHODOLOGICAL CONTRIBUTIONS

The method facilitated by the CALVIN model contributes several advances to understanding the long-term effects of climate warming on California's water system and water management (Lund et al. 2003). These include:

(1) Climate warming effects are represented for all major hydrologic inputs statewide. Hydrologic inputs included all major streams, groundwater, and local streams, as well as reservoir evaporation for twelve distinct climate-warming scenarios, three of which were examined in operational detail using CALVIN. The addition of groundwater, while preliminary and approximate, is a major improvement over previous studies. Groundwater is a major water source in California, and represents most of the storage capacity available for within-year and over-year water storage.

(2) Population-induced changes in water demands are integrated into the analysis. Since climate change will have its greatest effects some decades from now, studies should incorporate future growth and changes in water demands.

(3) Water supply impacts and adaptation are essentially statewide, covering the entire California inter-tied water system (Figure A-1). For 2020, this represents roughly 90% of

statewide urban and irrigation water demands. Previous explorations of climate change's implications for California have examined only a few isolated basins or one or two major water projects. However, California has a very integrated and extensive water management system, which continues to be increasingly interdependent in its planning and operations over time and across scales from statewide down to household-level operations. Quantification of the ability of this integrated system to respond to climate change is likely to require examination of dynamic integration of the entire system and its adaptive potential.

(4) Economically driven adaptation is assumed with multiple types and scales of responses. In addition to being integrated statewide, adaptation to climate change will not be through a single response (such as reservoir re-operation alone), but will involve a concert of many traditional and new water supply and management activities. The CALVIN economic-engineering optimization model explicitly represents and integrates a wide variety of responses, summarized in Table A-1. Most option costs and details regarding CALVIN methodology are presented in Jenkins et al. (2001); Draper et al. (2003). For this study additional technologies for wastewater reuse (up to 50% of urban demands) were available to all urban demand areas at $1,000/acre-ft, and seawater desalination was available in unlimited quantities to coastal communities for $1,400/acre-ft (all costs are in 1995 dollars).

California's diverse and complex water management system has considerable long-term physical flexibility. Californians have become adept at developing and integrating many diverse water supply and demand management options locally, regionally, and even statewide. The mix of options available to respond to climate change, population growth, and other challenges is only likely to increase in the future with development of water supply and demand management technologies, such as improved wastewater and desalination treatment methods and water use efficiency improvements.

In water management, water in itself is not important. The ability of water sources and a water management system to provide water for environmental, economic, and social purposes are the relevant measures of the effects of climate change and adaptations to climate change. Most previous climate change impact studies on water management have been simulation-based and examine only a few potential system responses to significant changes. Since major climate changes are most likely to occur only after several decades, it seems unreasonable to employ current system operating rules and water management activities in such studies. Fifty years from now, today's rules will be outdated (Johns 2003). However, changes in operating rules and management might not occur given the inherent conservative nature of water managers. Nevertheless, it is important to explore the potential for mitigating the effects of climate change, to help water managers and policy makers understand the full range of options available. Given that water management systems commonly adapt to changing conditions, especially over long time periods, an optimization approach seems more reasonable than simulation to evaluate climate change impacts.

Figure A-2 illustrates the assembly of a wide variety of relevant data on California's water supply, its systematic organization and documentation in large databases for input to a computer code (HEC-PRM) which finds the "best" water operations and allocations for maximizing regional or statewide economic benefits, and the variety of outputs and uses of outputs which can be gained from the models results.

Over a million flow, storage, and allocation decisions are suggested by the model over a 72-year statewide run, making it among the most extensive and sophisticated water optimization models constructed to date. A wide range of water management and economic outputs are produced.

Table A-1. Summary of available climate change responses (*represented in CALVIN)

Response Category	Response
Facilities	Surface reservoirs*
	Groundwater recharge*
	Well-field expansion
	Water treatment, reuse, and desalination*
	Wastewater reuse treatment*
	Water conveyance*
	Rainwater harvesting
Operations	Seasonal changes*
	Over-year changes*
	Improved forecasts*
	Conjunctive use*
	Groundwater banking*
	Cooperative reservoir operations*
Water Allocation	Contract changes*
	Markets and exchanges*
	Water rights*
	Pricing*
	Water scarcity*
Water Use Efficiency	Urban*
	Agricultural*
	Environmental
Institutions	Governance and finance

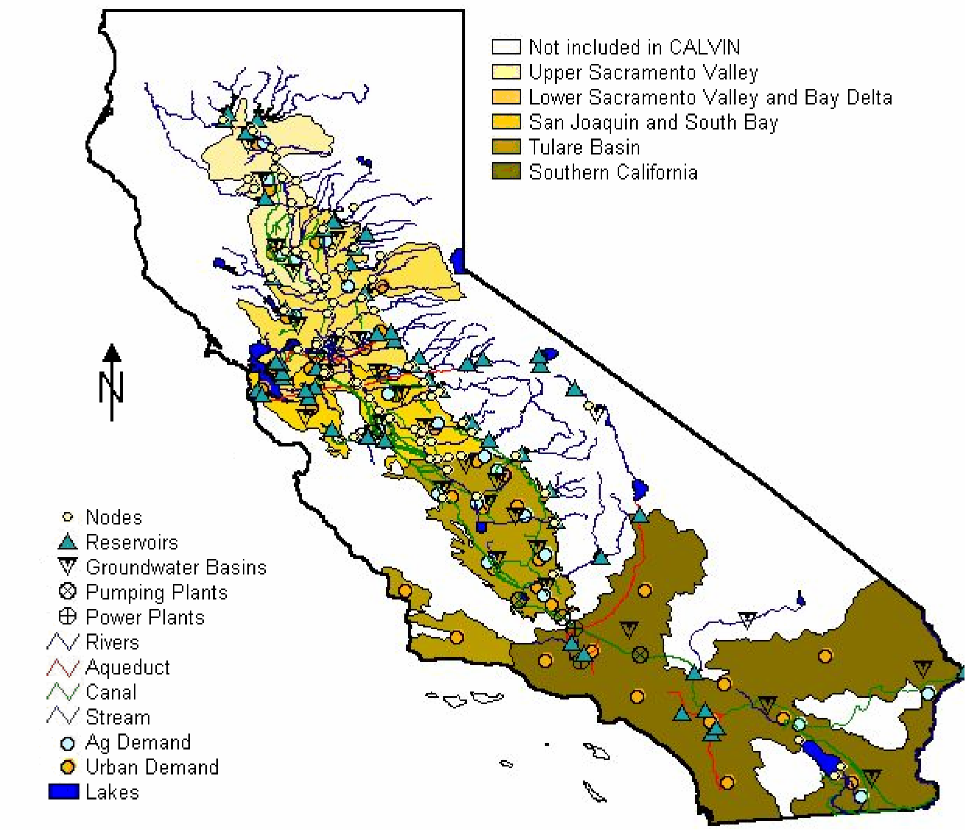

Figure A-1. Demand areas and major inflows and facilities represented in CALVIN

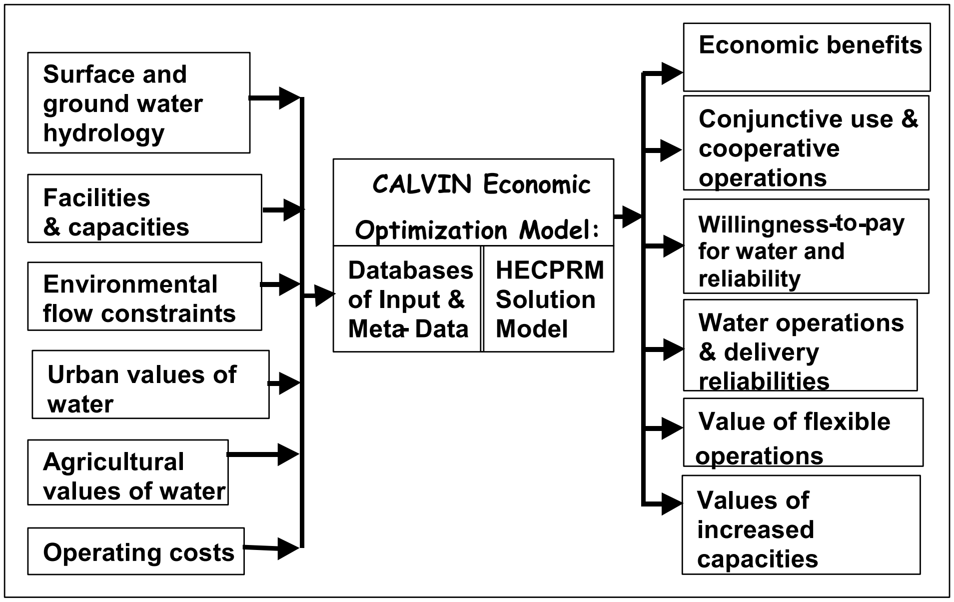

Figure A-2. Data flow schematic for CALVIN

USES

Results from the CALVIN model can be used for a wide variety of policy, planning, and operations planning purposes. These uses include:

- Identification of economically promising changes in reservoir, conveyance, recharge, and recycling facility capacities at the local, regional, and statewide levels
- Identification of promising operational opportunities, such as:
    - conjunctive use of surface water and groundwater
    - cooperative operations of supplies
    - water exchanges and transfers
    - water conservation and recycling
    - improved reservoir operations
- Assessing user economic benefits or willingness-to-pay for additional water
- Independent and relatively rigorous presentation of physically possible and economically desirable water management
- Providing promising solutions for refinement and testing by simulation studies
- Preliminary economic evaluations of proposed changes in facilities, operations, and allocations.

In addition, the model demonstrates several improvements in analytical methods that should be of long-term value to the state. These technical improvements include:

- Feasibility of economic-engineering optimization of California's water supplies
- Data assessment, documentation, and partial reconciliation for surface water, groundwater, and water demand data statewide
- Demonstrating advances in modeling technique, documentation, and transparency.

These improvements in data management, methods, and concepts offer potential for significant and sustained long-term improvements in California water management.

INNOVATIONS

The CALVIN model and approach differs from current large-scale simulation models of California and from other optimization models of parts of California. The major innovations of CALVIN include the following:

1. Statewide modeling with all major parts of California's inter-tied system from Shasta-Trinity to Mexico, allowing for more statewide examination of water supply issues.
2. Groundwater is explicitly included and operated in all regions represented in the model, aiding examination of conjunctive use alternatives.

3. Economic performance is the explicit objective of the model, facilitating economic evaluation of capacity alternatives, conjunctive operations, and water transfers and estimation of user willingness to pay for additional supplies.
4. Surface and groundwater supplies and water demands are operated in an integrated manner, allowing for the most economic system adaptation to new facilities or changes in demands or regulations.
5. Economic values of agricultural and urban water use are estimated consistently for the entire inter-tied system.
6. Data and model management have been fundamental to model development with all major model components in the public domain and extensive documentation of model assumptions.
7. Systematic analytical overview of statewide water quantity and economic data was undertaken to support the model.
8. New management options for water exchanges and markets, cooperative operations, conjunctive use of ground and surface waters, and capacity expansion are suggested by the model.
9. Use of optimization allows rapid and impartial preliminary identification and screening of promising alternatives for more detailed consideration and analysis.

Such innovations are crucial to support the search for technically workable, politically feasible, and socially desirable solutions to water problems in California.

The HEC-PRM network flow solution software and the general approach of the CALVIN model have been applied to numerous other locations over the past decade. These are listed in Table A-2 below. While CALVIN is the largest such application, other applications include some of the largest water resource systems in the nation.

Table A-2. Previous Optimization Studies Using HEC-PRM

Year(s)	Basin (No of Reservoirs)	Study Purpose(s)	Citation(s)
1990-1994	Missouri River (6)	Economic-based Reservoir System Operating Rules	USACE 1991a, 1991c, 1992a, 1992b, 1994b; Lund and Ferreira 1996
1991-1996	Columbia River System (14)	Economic-based Reservoir Operating Rules, Capacity, Expansion, and Multi-Purpose Operations Seasonal Operations	USACE, 1991b, 1993, 1995, 1996
1997	Carson-Truckee System (5)	Prioritization of Uses and Performance Assessment	Israel 1996; Israel and Lund 1999
1997	Alamo Reservoir (1)	Multi-objective reservoir operation	Kirby 1994; USACE 1998b,c
1998	South Florida System (5)	Capacity Expansion and Multi-objective performance	USACE 1998a; Watkins et al. 2003
1999	Panama Canal System (5)	Drought Performance and Economic Reservoir Operations	USACE 1999
1999 - present	Models of 5 California Regions	Calibration of Statewide Model and study of regional market potentials	Appendices 2A, 2B, 2C, 2D, and 2E of Jenkins et al. 2001, Newlin et al. 2001
1999 - present	California Inter-tied System (79)	Economic Capacity Expansion, Water Markets, and Financing	Howitt, et al. 1999 Jenkins et al. 2001 Draper et al., in press

Note: For references, see Jenkins, et al. 2001.

The method employed for this study contributes several advances over previous efforts to understand the long-term effects of climate warming on California's water system, and long-term water management with climate change in general. These include the following:

- <u>Comprehensive hydrologic effects of climate warming</u>, including all major hydrologic inputs, including major streams, groundwater, and local streams, as well as reservoir evaporation. Groundwater, in particular, represents 30%–60% of California's water deliveries and 17% of natural inflows to the system.
- <u>Integrated consideration of groundwater storage</u>. Groundwater contributes about 75% of the storage used in California during major droughts.
- <u>Statewide impact assessment</u>. Previous explorations of climate change's implications for California have examined only a few isolated basins or one or two major water projects. However, California has a very integrated and extensive water management system. This system continues to be increasingly integrated in its planning and operations over time. Examination of the ability of this integrated system to respond to climate change is likely to require examination of the entire system.
- <u>Economic-engineering perspective</u>. Water in itself is not important. It is the ability of water sources and a water management system to provide water for environmental, economic, and social purposes that is the relevant measure of the effect of climate change and adaptations to climate change. Traditional "yield"-based estimates of climate change effects do not provide results as meaningful as economic and delivery-reliability indicators of performance.
- <u>Incorporation of multiple responses</u>. Adaptation to climate change will not be through a single option, but a concert of many traditional and new water supply and management options. The CALVIN model can explicitly represent and integrate a wide variety of response options.

- Incorporation of future growth and change in water demands. Climate change will have its greatest effects some decades from now. During this time, population growth, and other changes in water demands are likely to exert major influences on how water is managed in California and how well this system performs.
- Optimization of operations and management. Most previous climate change impact studies on water management have been simulation-based. Since major climate changes are most likely to occur only after several decades, it seems unreasonable to employ current system operating rules in such studies. Fifty years from now, today's rules will be archaic. Since water management systems always have (and must) adapt to future conditions, an optimization approach seems to be more reasonable. The limitations of optimization seem less burdensome than the limitations of simulation for exploratory analysis of climate change policy and management problems.

LIMITATIONS

All computer models have limitations. This modeling approach has its own limitations, but provides useful insights on the potential for operating the current or proposed infrastructure for very different future conditions (Jenkins et al. 2001, Chapter 5; Lund et al. 2003). Among the limitations are: (a) great and arguably unavoidable uncertainty in the climatic and hydrologic drivers of the system (Klemes 2000a, 2000b), (b) significant data problems with underlying historical hydrology and water demands, particularly groundwater estimates and return flows for some parts of California (Jenkins et al. 2001), (c) uncertainties in 2100 population levels and distributions, as well as effects of changes in water conservation technologies and wealth changes on per-capita economic water demands, (d) lack of a land urbanization adjustment of the CALVIN agricultural water demands in the Central Valley (This accounts for approximately 2 maf/year in excessive agricultural water demands and is corrected in the reported post-processing results), (e) great uncertainty in crop and energy prices affecting demands for agricultural products, the value of hydropower, and the costs of pumping and treatment, and (f) neglect of flood control and recreation benefits and costs, and limitations arising from the generalized network flow optimization algorithm used to solve the mathematical formulation of this problem (Draper et al. 2003).

Optimization approaches also have limitations from their optimistic view of what can be done institutionally or in terms of hydrologic foresight. Optimization also can provide pessimistic results; water crises often lead to significant innovations in technology, demands, and management, which were often not foreseen beforehand, and so would not be represented in any modeling study (Morgan 1951; Kelley 1989). Our modeling results for this problem will be wrong as a forecast, but we hope they are nevertheless thought-provoking, insightful, and useful. The overall intent of this work is to see how such a complex system could respond to multiple major stresses (climate change and population growth). In light of these limitations, more specific or definitive conclusions should be drawn with caution.

MODEL RESULTS

As an economic-engineering model, CALVIN produces both a full range of engineering outputs expected from a typical engineering water resources operations planning model, but also produces many of the outputs expected from an economic model of a water resource system. In addition, the model produces results which allow economic interpretations of engineering output and engineering interpretations of economic results (Figure A-2). This is a benefit of integrated modeling integrating academic disciplines.

Nevertheless, model results are merely deductive conclusions from a variety of premises and should be interpreted carefully, with respect paid to the uncertainty in the premises. There is nothing magical about model results, especially for climate change or long-term planning applications. The objective of modeling in these situations is not to be right, but to be less wrong. Modeling provides only a basis for more explicit definition of the premises and a more powerful engine for working through the logic of the implications of the many premises for discussion and exploration of issues.

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