CLIMATE WARMING & CALIFORNIA'S WATER FUTURE

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PREFACE

In Hades, the mythical Tantalus was burdened by a great thirst, only to have the water rise to his neck threatening to drown him, but then recede when he tried to drink. At the same time, ever present above him was a large rock, ready to crush his head at some uncertain time. Like Tantalus, California's water managers are tantalized by the prospects of quenching California's thirsts, but constantly contend with floods and droughts, while living in a world of such grave prospects as earthquakes, government budgets, population growth, and climate changes.

This report presents the method and results of an application of the CALVIN economic-engineering optimization model to provide insights into the potential effects of climate changes on California water management in the distant future, 2100. Much will happen in California in the coming 100 years. No one can be sure exactly what will happen, but prudence asks that we examine a range of reasonable scenarios.

While this time-frame is distant and well beyond the careers (and lives) of most readers and far beyond the election cycles of political leaders, the year 2100 is not beyond the lifetime of most water management infrastructure (dams, canals, rivers) or many of the institutions which govern water management. A century is also not infrequently required to develop and establish extensive innovations in water management. The first plan for large-scale irrigation in the Central Valley was in 1873. Major elements modified from this plan were not in place until the 1940s and 1950s. As increasing population, activity, and human expectations continue to accumulate in California, perhaps the time needed to make major infrastructure and water management changes will increase.

This project is part of a major multi-disciplinary effort to examine possible water-related impacts of climate change on California, and potential adaptations of Californians to response to such changes, led by Robert Mendelson (Yale University), Tom Wilson (EPRI), and Joel Smith (Stratus Consulting) under program manager Guido Franco (California Energy Commission). The work presented here relies on data and information provided by John Landis (UC Berkeley), Norm Miller (Lawrence Berkeley National Labs), Russell Jones (Stratus Consulting), and Richard Adams (Oregon State University) and relies extensively on earlier work on the CALVIN model, funded by CALFED and the State of California Resources Agency.

We greatly appreciate the comments and suggestions from Guido Franco (CEC), Alan Sanstad (LBNL), Maury Roos (DWR), and Doug Osugi (DWR) who reviewed drafts of this report for their insights, suggestions, and corrections. Jamie Anderson (DWR) is thanked for her examination of climate change operations for Delta water quality implications.

EXECUTIVE SUMMARY

In California, concern for climate change has increased in recent years with research on global climate change applied to California and as it has become apparent that California's climate has changed recently (Gleick and Chalecki 1999; Dettinger and Cayan 1995; Lower American river flood frequencies) and in recent millennia (Stine 1994). Several decades of studies have shown that California's climate is variable over history and in the present (Cayan et al. 1999), is experiencing continuing sea level rise, and may experience significant climate warming (Lettenmaier and Gan 1990; Snyder et al. 2002). The potential effects of climate change on California have been widely discussed from a variety of perspectives (Wilkinson 2002; Gleick and Chalecki 1999; Lettenmaier and Sheer 1991). Forests, marine ecosystems, energy use, coastal erosion, water availability, flood control, and general water management issues have all been raised.

This study focuses on the likely effects of a range of climate warming estimates on the long-term performance and management of California's water system. We take a relatively comprehensive approach, looking at the entire inter-tied California water supply system, including ground and surface waters, agricultural and urban water demands, environmental flows, hydropower, and potential for managing water supply infrastructure to adapt to changes in hydrology caused by climate warming. We use an integrated economic-engineering optimization model of California's inter-tied water system called CALVIN (CALifornia Value Integrated Network), which has been developed for general water policy, planning, and operations studies (Jenkins et al 2001; Draper et al. in press). This modeling approach allows us to look at how well the infrastructure of California water could adapt and respond to changes in climate, in the context of higher future populations, changes in land use, and changes in agricultural technology. Unlike traditional simulation modeling approaches, this economically optimized re-operation of the system to adapt to climate and other changes is not limited by present-day water system operating rules and water allocation policies, which by 2100 are likely to be seen as archaic. This 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).

PROJECT METHOD

Many types of climate change can affect water and water management in California. This study examines climate warming, and neglects, for the time being climate variability, sea level rise, and other forms of climate change. Twelve climate warming hydrologies are examined to develop integrated statewide hydrologies covering changes in all major inflows to the California water system. For each climate warming scenario, permutations of historical flow changes were developed for six representative basins throughout California by researchers at LBNL (Miller, et al. 2001). These changes were used as index basins for 113 inflows to the CALVIN model, an extensive economic-engineering optimization model of California's inter-tied water system, developed for CALFED (Figure ES-1). This more comprehensive hydrology includes inflows from mountain streams, groundwater, and local streams, as well as reservoir evaporation for each of the twelve hydrologies. The gross implications of these twelve comprehensive changes in

California's water availability are then estimated, including effects of forecasted changes in 2100 urban and agricultural water demands.
Owing to limited time and budget, only two of these climate warming scenarios are modeled explicitly using the integrated economic-engineering optimization model (CALVIN). For this particular climate change study, for the year 2100 time horizon with 2100 demands, several modifications were made to the CALVIN model:

- Changes in hydrology and water availability were made for surface and groundwater sources throughout the system to represent different climate warming scenarios.

- Estimates of year 2100 urban and agricultural economic water demands were used.

- Coastal areas were given unlimited access to sea water desalination at a constant unit cost of $1,400/acre-ft.

- Urban wastewater reuse was made available beyond 2020 levels at $1,000/acre-ft, up to 50% of urban return flows.

- Local well, pumping, and surface water diversion and connection and treatment facilities were expanded to allow access to purely local water bodies at appropriate costs.

- Several corrections to the earlier CALFED version of the model were made, including revision of environmental requirements on system operations.

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:

- Comprehensive hydrologic effects of climate warming, from 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.
- Integrated consideration of groundwater storage. Groundwater contributes well over half of the storage used in California during major droughts.
- Statewide impact assessment. 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 requires examination of the entire system.
- Economic-engineering perspective. 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.

- Integration of multiple responses. 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 explicitly represents and integrates 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 (Johns 2003). Since water management systems commonly adapt to changing conditions, especially over long time periods, an optimization approach seem more reasonable. Optimization approaches have limitations (Jenkins et al. 2001), particularly their optimistic view of what can be done. The limitations of optimization seem less burdensome than the limitations of simulation for exploratory analysis of climate change policy and management problems.

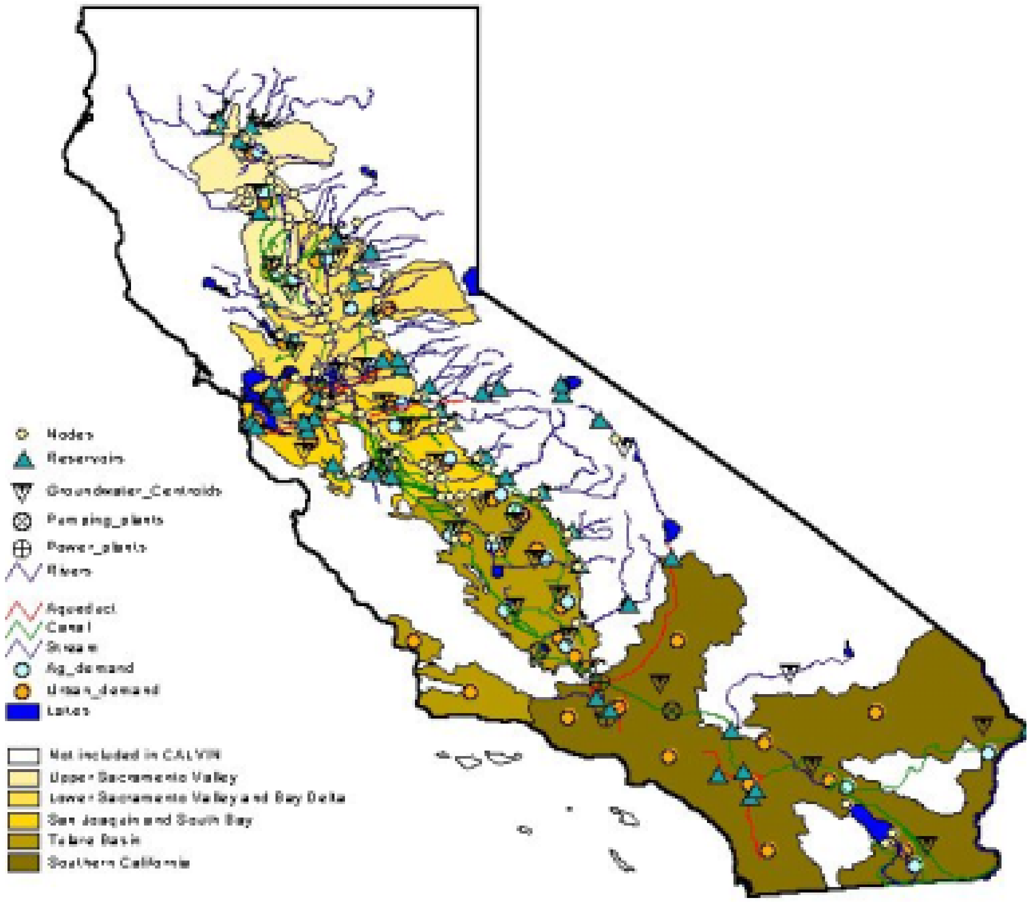

Figure ES-1. Demand Areas and Major Inflows and Facilities Represented in CALVIN

RESULTS

The overall supply and demand results of this study are presented below, followed by model results estimating the effects of climate and population change on the performance of California's inter-tied water supply system.

Changes in Water Demands

An important aspect of future water management is future water demands. California's population continues to grow and its urban areas continue to expand, with likely implications for urban and agricultural water demands. Population growth in California is expected to continue from today's 32 million, to 45 million in 2020, to an estimated at 92 million for 2100 (the high population scenario for the larger study – the lower scenario is 67 million). The demands in the inter-tied system (Table ES-1) represent about 90% of those in California.

Table ES-1. Land and Applied Water Demands for California's Inter-tied Water System (millions of acres and millions of acre-ft/year)

Use	2020 Land	2100 Land	2020-2100 Decrease	2020 Water	2100 Water	2020-2100 Change
Urban				11.4	18.6	+7.2
Agricultural	9.2	8.4	0.75	27.8	25.1	-2.7
Environmental	-	-	-	-	-	-
Total	**-**	**-**	**-**	**39.9**	**44.5**	**+4.5 maf/yr**

Changes in California's Water Supplies

The twelve climate warming scenarios examined, and their overall effects on water availability appear in Table ES-2. While these are merely raw hydrologic results, adjusted for groundwater storage effects, they indicate a wide range of potential water supply impacts on California's water supply system. These effects range from +4.1 million acre-feet (maf)/yr to -9.4 maf/yr. Figure ES-2 shows the seasonal hydrologic streamflow results for the twelve warming scenarios for mountain rim inflows, about 72% of California system inflows. For all cases spring snowmelt is greatly decreased with climate warming, and winter flows are generally increased (except for some PCM scenarios). These results indicate the overall hydrologic effect of climate warming on inflows to California's water supplies. These seasonal changes in runoff have long been identified, based on studies of individual or a few basins (Lettenmaier and Gan 1990).

Table ES-2. Raw water availability (without operational adaptation, in maf/yr)

Climate Scenario	Average Annual Water Availability		Climate Scenario	Average Annual Water Availability	
	Volume maf	Change maf (%)		Volume maf	Change maf (%)
1) 1.5T 0%P	35.7	-2.1 (-5.5%)	7) HCM 2010-2039	41.9	4.1 (10.8%)
2) 1.5T 9%P	37.7	-0.1 (-0.4%)	8) HCM 2050-2079	40.5	2.7 (7.2%)
3) 3.0T 0%P	33.7	-4.1 (-10.9%)	9) HCM 2080-2099	42.4	4.6 (12.1%)
4) 3.0T 18%P	37.1	-0.8 (-2.0%)	10) PCM 2010-2039	35.7	-2.1 (-5.6%)
5) 5.0T 0%P	31.6	-6.2 (-16.5%)	11) PCM 2050-2079	32.9	-4.9 (-13.0%)
6) 5.0T 30%P	36.2	-1.6 (-4.3%)	12) PCM 2080-2099	28.5	-9.4 (-24.8%)
Historical	**37.8**	**0.0 (0.0%)**			

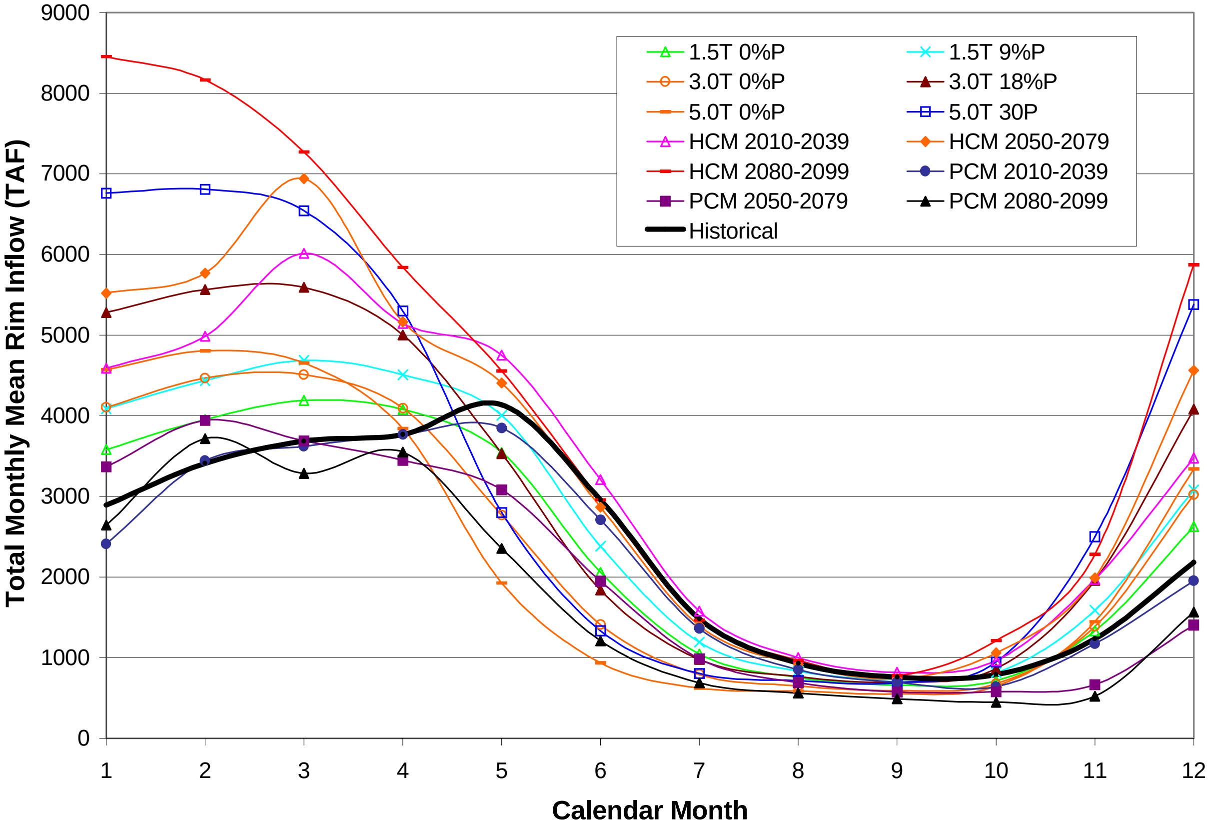

Figure ES-2. Monthly Mean Rim Inflows for the 12 Climate Scenarios and Historical Data

Adaptive Changes for Water Management

California has a diverse and complex water management system, which has considerable long-term physical flexibility. Californians are becoming increasingly 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.

Several statewide scenarios were run using the CALVIN economic-engineering optimization model to evaluate the potential impact of climate change on California with and without population growth and adaptation. The modeled scenarios included:

- **Base 2020**: This run represents projected water supply operations and allocations in the year 2020, assuming continuation of current operation and allocation policies. This run was prepared for CALFED and extensively documented elsewhere (Jenkins et al, 2001; Draper, et al. in press).

- **SWM 2020**: This run represents operations, allocations, and performance in the year 2020 assuming flexible and economically-driven operation and allocation policies. This optimized operation can be understood as representing operation under a statewide water market, or equivalent economically-driven operations. This run also was prepared for CALFED and extensively documented elsewhere (Jenkins et al, 2001; Draper, et al. in press).

- **SWM 2100**: This run extends the SWM 2020 model and concept for 2100 water demands, but retains the same (historical) climate used in Base 2020 and SWM 2020.
- **PCM 2100**: Using the same 2100 water demands as SWM 2100, this run employs the dry and warm PCM 2100 climate warming hydrology.
- **HCM 2100**: Using the same 2100 water demands as SWM 2100, this run employs the wet and warm HCM 2100 climate warming hydrology.

Future Performance with Climate Warming

Population growth will significantly affect the performance and management of California's vast inter-tied water system. Climate warming could have large additional effects on this system, especially for the agricultural sector of the economy. These effects are summarized in Table ES-3 and Figures ES-3 and ES-4 that contain economic, delivery, and scarcity effects of population growth and climate warming for urban and agricultural water users. Overall, population growth alone raises costs by $4.1 billion/year, with the driest climate warming hydrology increasing costs a further $1.2 billion/year. The wet climate warming hydrology decreases total costs by about $0.3 billion/year. The effects of the driest climate warming scenario are most severe for agricultural users. Given optimized water allocations and operations, water scarcity costs for 2100 without climate changes are less than in year 2020 without changes in current water allocation policies. (Most of this difference is due to water transfers from Colorado River agricultural users to Southern California urban users.)

Table ES-3. Summary of Statewide Operating# and Scarcity Costs

Cost	Base 2020	SWM2020	SWM2100*	PCM2100*	HCM2100*
Urban Scarcity Costs	1,564	170	785	872	782
Agric. Scarcity Costs	32	29	198	1,774	180
Operating Costs	2,581	2,580	5,918	6,065	5,681
Total Costs	**4,176**	**2,780**	**6,902**	**8,711**	**6,643**

* - Agricultural scarcity costs are somewhat overestimated because about 2 maf/year of reductions in Central Valley agricultural water demands due to urbanization of agricultural land are not included.

- Operating costs include pumping, treatment, urban water quality, recharge, reuse, desalination, and other variable operating costs for the system. Scarcity costs represent how much users would be willing to pay for desired levels of water delivery.

Hydropower production from the major water supply reservoirs in the California system would not be greatly affected by population growth, but would be reduced by the PCM2100 climate warming scenario. Base2020 hydropower revenues average $161 million/year from the major water supply reservoirs, compared with $163 million/year for SWM2100. However, the dry PCM2100 scenario reduces hydropower revenue 30% to $112 million/year. While this does not include the hydropower impacts of climate change on other hydropower plants in California, the percentage reduction is probably reasonable overall. With the wet HCM2100 hydrology, hydropower production greatly exceeds current levels ($248 million/year).

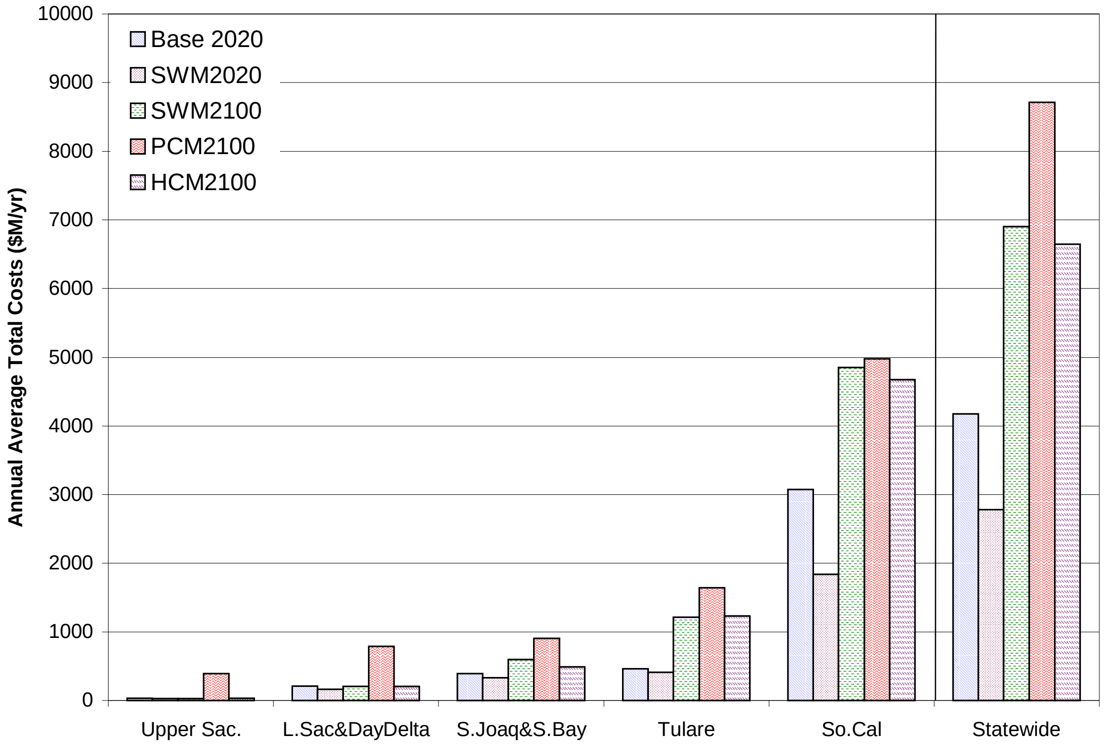

Figure ES-3. Total Scarcity and Operating Costs by Region and Statewide

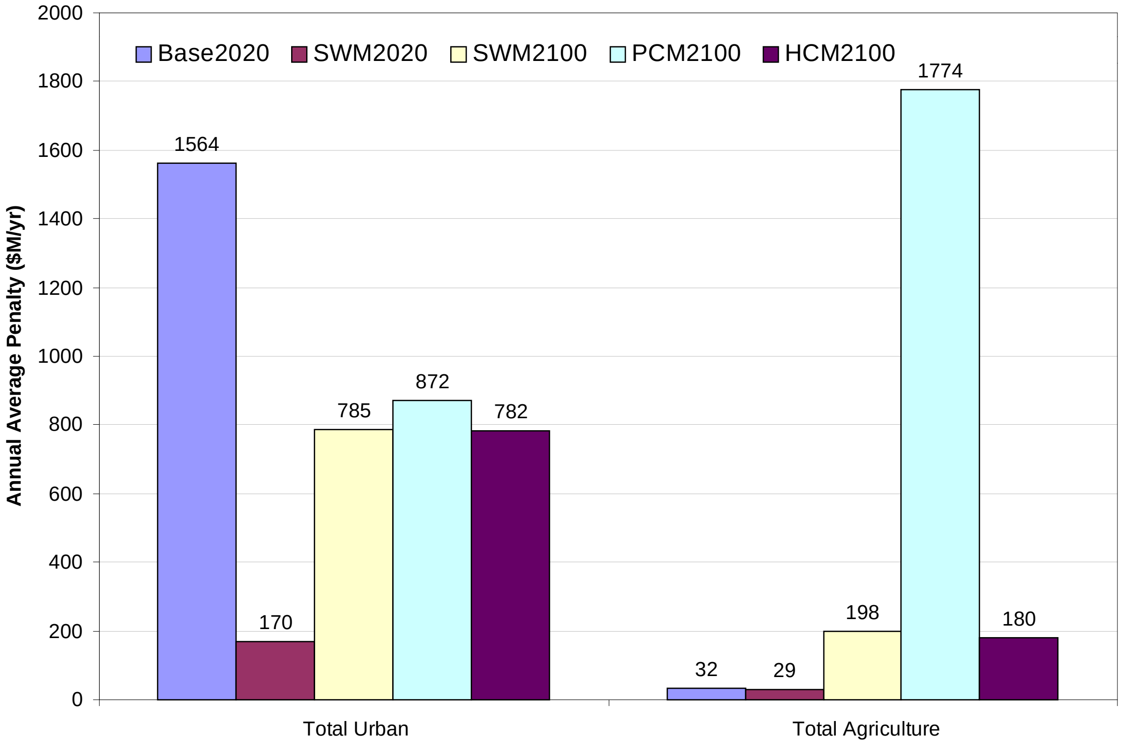

Figure ES-4. Average Annual Economic Scarcity Cost by Sector

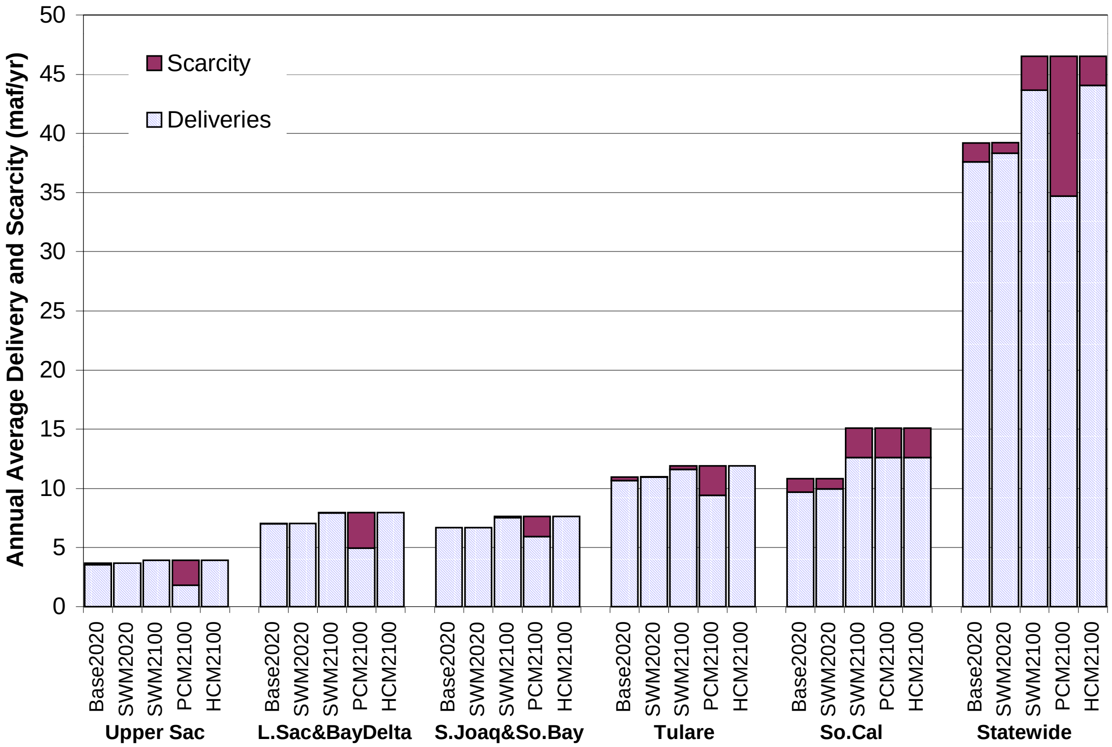

Figure ES-5. Total Water Deliveries and Scarcities by Region and Statewide

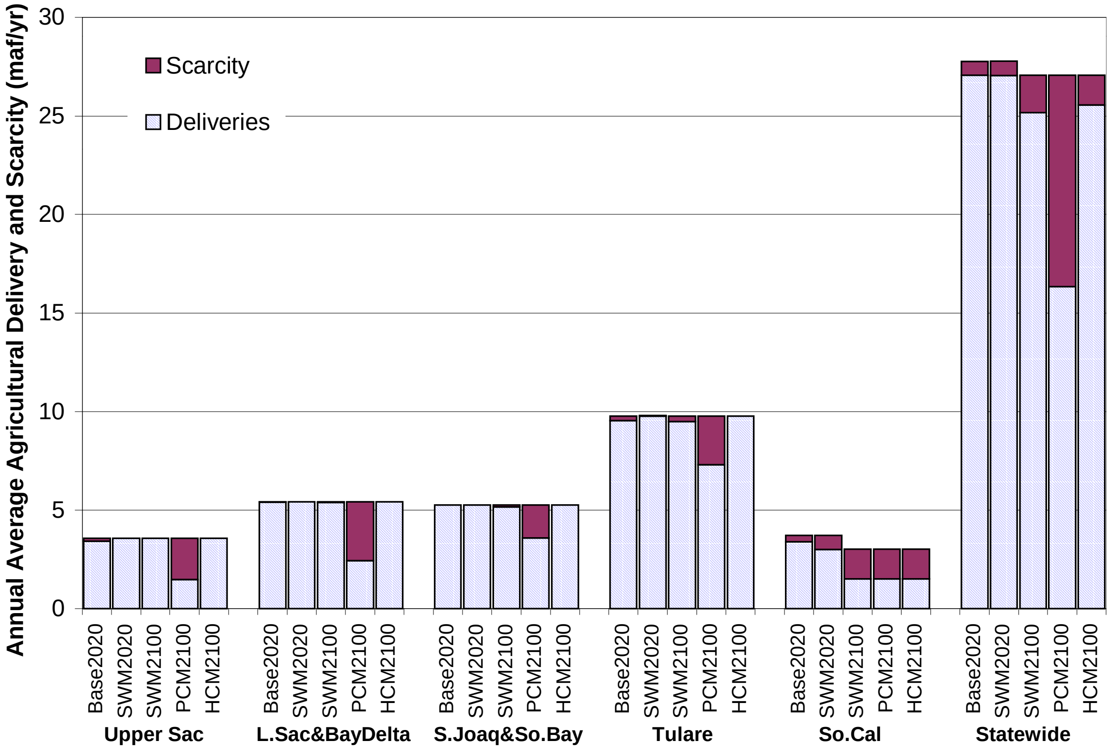

Figure ES-6. Agricultural Water Deliveries and Scarcity by Region and Statewide

CALVIN model results indicate several promising and capable adaptations to population growth and climate change. All 2100 scenarios show increased market water transfers from agricultural to urban users, additional urban water conservation (~1 maf/yr), use of newer water reuse treatment (~1.5 maf/yr) and sea water desalination technologies (~0.2 maf/yr), increased conjunctive use of ground and surface waters, and urbanization of agricultural land. For the dry PCM2100 scenario, several million acre-feet/year of reductions in agricultural use due to land fallowing occur. All of these indicate a much more tightly managed (and controversial) California water system, where water is increasingly valuable because water and conveyance capacity is increasingly scarce. The costs of growth and climate change can be large locally and are comparable to the revenues of today's largest water district ($900 million/year), but are small compared with the size of California's economy (currently $1.3 trillion/year) or State budget (~$100 billion/year).

Some operational results for overall surface and groundwater storage in California appear in Figures ES-7 and ES-8. As seen in these figures, the model operates using a 72-year sequence of inflows based on the historical record to represent hydrologic variability and various complex expressions of wet and dry years, which is quite important for actual operations and water allocations, and the evaluation of system performance. Most storage available and used in California is underground. As appears in the figures, over two thirds of the storage used between wet and dry periods takes the form of groundwater. The PCM2100 scenario provides noticeably more challenge for the surface water system overall. All optimized and future scenarios make greater use of groundwater storage for drought management than current policies (Base2020).

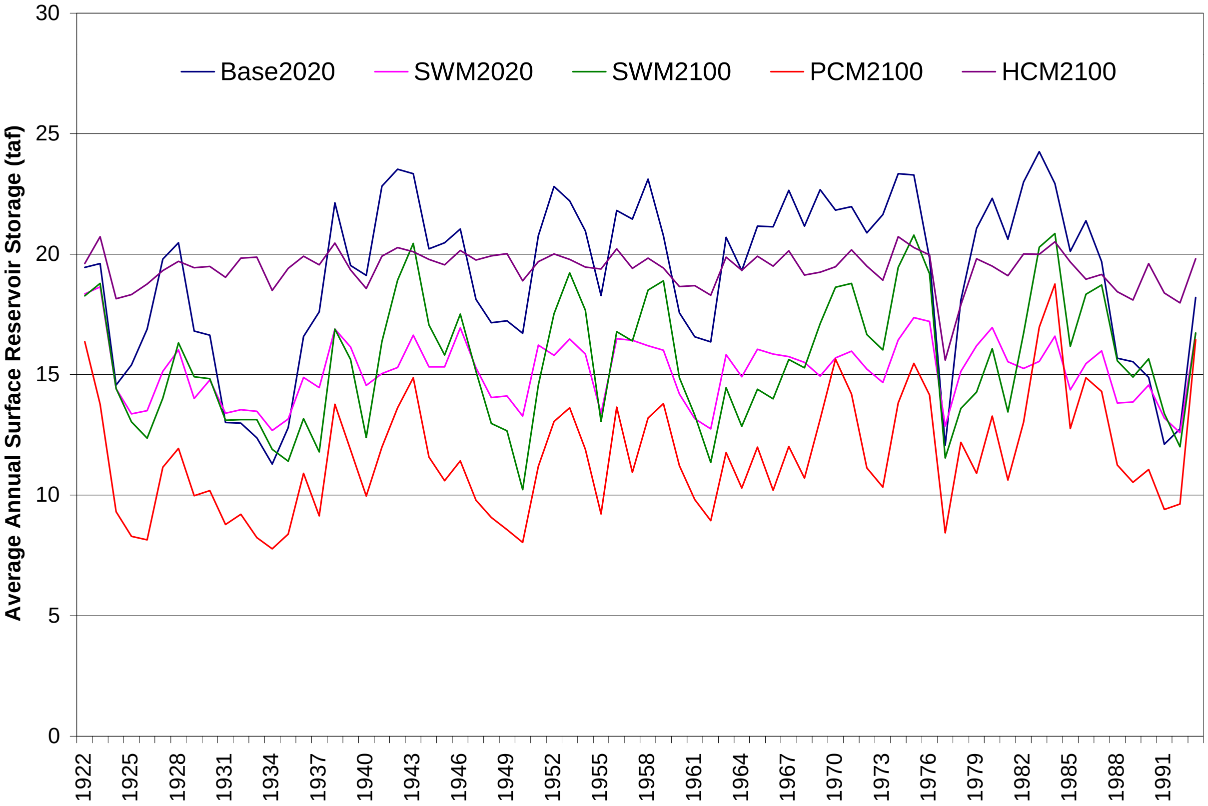

Figure ES-7. Statewide Surface Water Storage over 72-year Period

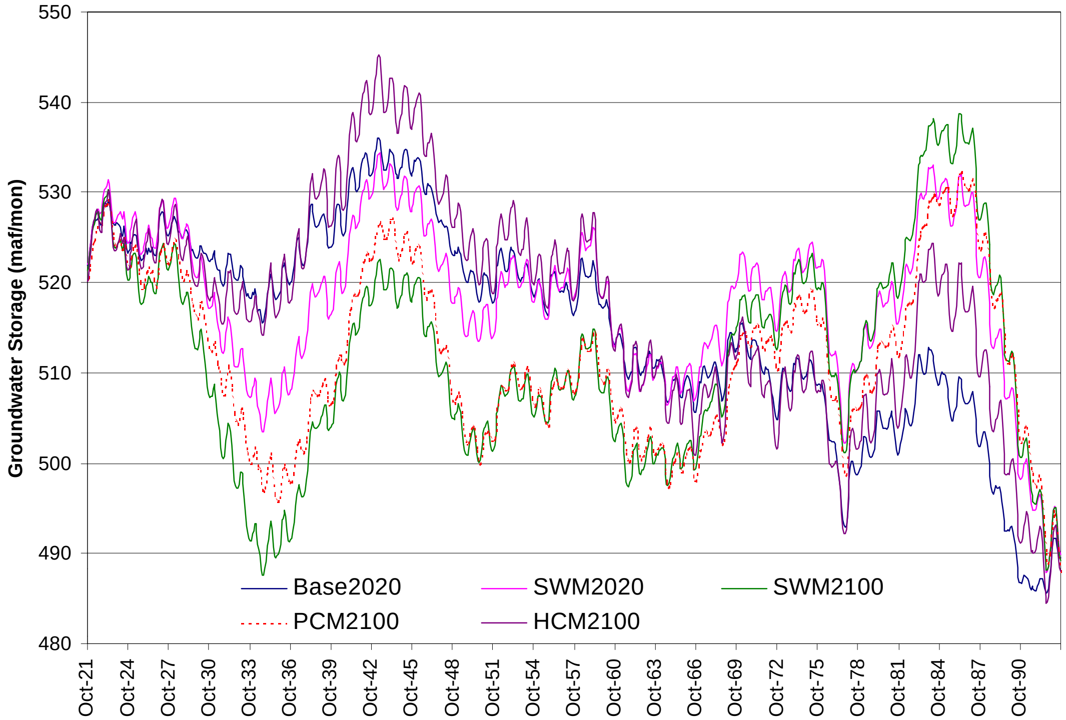

Figure ES-8. Groundwater Storage over the 72-year Period

Table ES-4. Shadow Costs of Selected Environmental Requirements#

	Average WTP ($/af)			
Minimum Instream Flows	**SWM2020***	**SWM2100**	**PCM2100**	**HCM2100**
Trinity River	0.6	45.4	1010.9	28.9
Clear Creek	0.4	18.7	692.0	15.1
Sacramento River	0.2	1.2	25.3	0.0
Sacramento River at Keswick	0.1	3.9	665.2	3.2
Feather River	0.1	1.6	35.5	0.5
American River	0.0	4.1	42.3	1.0
Mokelumne River	0.1	20.7	332.0	0.0
Calaveras River	0.0	0.0	0.0	0.0
Yuba River	0.0	0.0	1.6	1.0
Stanislaus River	1.1	6.1	64.1	0.0
Tuolumne River	0.5	5.6	55.4	0.0
Merced River	0.7	16.9	70.0	1.2
Mono Lake Inflows	819.0	1254.5	1301.0	63.9
Owens Lake Dust Mitigation	610.4	1019.1	1046.1	2.5
Refuges				
Sac West Refuge	0.3	11.1	231.0	0.1
Sac East Refuge	0.1	0.8	4.4	0.5
Volta Refuges	18.6	38.2	310.9	20.6
San Joaquin/Mendota Refuges	14.7	32.6	249.7	10.6
Pixley	24.8	50.6	339.5	12.3
Kern	33.4	57.0	376.9	35.9
Delta Outflow	0.1	9.7	228.9	0.0

*- SWM2100 results do not include hydropower values (except for Mono and Owens flows).
#Shadow costs are the cost to the economic values of the system (urban, agricultural, hydropower, and operations) of a unit change in a constraint, in this case environmental flow requirements.

Population growth and climate warming also impose serious environmental challenges. While in 2020 and with 2100 population growth alone, it appears possible to comply with environmental flow and delivery requirements, some small reductions in environmental flows are required for the PCM2100 scenario. However, increased water demands and decreased water availability do raise substantially the costs of environmental requirements to urban, agricultural, and hydropower users, as shown in Table ES-4. Increased economic costs of complying with environmental requirements could raise incentives to dispute and evade such requirements, as well as incentives to creatively address environmental demands.

CONCLUSIONS

The main conclusions of this work are:

1) Methodologically, it is possible, reasonable, and desirable to include a wider range of hydrologic effects, changes in population and water demands, and changes in system operations in impact and adaptation studies of climate change than has been customary. Overall, including such aspects in climate change studies provides more useful and realistic results for policy, planning, and public education purposes.

2) A wide range of climate warming scenarios for California shows significant increases in wet season flows and significant decreases in spring snowmelt. This conclusion, confirming many earlier studies, is made more generally and quantitatively for California's major water sources. The magnitude of climate warming's effect on water supplies can be comparable to water demand increases from population growth in the coming century.

3) California's water system can adapt to the population growth and climate warming modeled, which are fairly severe. This adaptation will be costly in absolute terms, but, if properly managed, should not threaten the fundamental prosperity of California's economy or society, although it can have major effects on the agricultural sector. The water management costs are a tiny proportion of California's current economy.

4) Agricultural water users in the Central Valley are the most vulnerable to climate warming. While wetter hydrologies could increase water availability for these users, the driest climate warming hydrology would reduce agricultural water deliveries in the Central Valley by about a third. Some losses to the agricultural community in the dry scenario would be compensated by water sales to urban areas, but much of this loss would be an uncompensated structural change in the agricultural sector.

5) Water use in Southern California is likely to become predominantly urban in this century, with Colorado River agricultural water use being displaced by urban growth and diverted to serve urban uses. This diversion is limited only by conveyance capacity constraints on the Colorado River Aqueduct deliveries of Colorado River water and California Aqueduct deliveries of water from the Central Valley. Given small proportion of local supplies in southern California, the high willingness-to-pay of urban users for water, and the conveyance-limited nature of water imports, this region is little affected by climate warming. Indeed, even in the dry scenario, Southern California cannot seek additional water imports. Population growth, conveyance limits on imports, and high economic values lead to high use of wastewater reuse and lesser but substantial use of seawater desalination along the coast.

6) Flooding problems could be formidable under some wet warming climate scenarios. Flood flows indicated by the HCM2100 scenario would be well beyond the control capability of existing, proposed, and probably even plausible reservoir capacities. In such cases, major expansions of downstream floodways and changes in floodplain land uses might become desirable.

7) While adaptation can be successful overall, the challenges of population growth and climate warming are formidable. Even with new technologies for water supply, treatment, and water use efficiency, widespread implementation of water transfers and conjunctive use, coordinated operation of reservoirs, improved flow forecasting, and the close cooperation of local, regional, state, and federal government, the costs will be high and there will be much less “slack” in the system compared to current operations and expectations. Even with historical hydrology and continued population growth, the economic implications of water management controversies will be greater, motivating greater intensity in water conflicts, unless management institutions can devise more efficient and flexible mechanisms and configurations for managing water in the coming century.

8) The limitations of this kind of study are considerable, but the qualitative implications seem clear. It behooves us to carefully consider and develop a variety of promising infrastructure, management, and governance options to allow California and other regions to respond more effectively to major challenges of all sorts in the future.

9) Further climate change work on water in California should be expanded from this base to include flood damage costs, sea level rise, other forms of climate change, such as various forms of climate variability, some refinements in hydrologic representation, and some operations model improvements discussed in the report. Other general improvements in the CALVIN model, particularly representations of the Tulare basin, Central Valley groundwater, and agricultural water demands also are desirable.

CHAPTER 1

INTRODUCTION

The earth's climate has changed over the course of history and pre-history and shows prospects of continuing to change (Lamb 1982). Climate appears to change in various ways. Some changes appear to us as variability in climate, seeming to oscillate over periods of several years or perhaps decades (Trewartha 1954; Cayan and Riddle 1999). Other changes are more long-term, occurring over many decades. These long-term changes can take the forms of climate warming, sea level rise, or other forms (Olsen et al 1999).

Any long-term changes in climate will have implications for how water is managed, as well as many other aspects of our society, economy, and environmental resources. However, in the future when we must manage such changes in climate, there will be other significant changes in our society and economy, not the least of which will be population and accompanying changes in land use and economic structure. The relative roles and importance of such different uncertainties in the design of future water systems is a common topic of professional discussion. In these discussions, climate change is often judged less important than other aspects of the future (Klemes 2000a, 2000b; Rogers 1993). At a global scale, Vörösmarty et al. (2000) find that population growth overshadows climate change as a driver of future water problems. Others point out the great adaptive capacity of water resource systems and the societies and economies they serve, particularly over long periods of time (Stakhiv 1998). In this report, we are concerned with climate change's role in the future of California water management, a future that will be different from today even without climate change.

In California, concern for climate change has increased recently with research on global climate change applied to California and as it has become apparent that California's climate has changed significantly in recent times (Roos 2002; Dettinger and Cayan 1995; Lower American river flood frequencies) and over recent millennia (Stine 1994). Several decades of studies have shown that California's climate is variable over history and in the present (Cayan and Riddle 1999), is experiencing continuing sea level rise (Logan 1990), and may experience significant climate warming (Lettenmaier and Gan 1990; Gleick and Chalecki 1999).

Many studies exist of climate changes and their potential wide-ranging effects on California. These are nicely reviewed by Wilkinson (2002) and Gleick and Chalecki (1999). Among the direct hydrologic effects include:

- Sea level rise, affecting coastal areas somewhat, but mostly affecting flooding and water quality in the Sacramento-San Joaquin Delta

- Increased mountain runoff in winter months and reductions of spring runoff, due to lessened storage in mountain snowpacks, worsening winter flood problems and making it more difficult to capture and store large quantities of wet season runoff for dry season water supplies

- Increases in evaporation rates statewide, due to higher temperatures

- Increases, or perhaps decreases, in precipitation in California, raising, or reducing, annual runoff volumes

- Potential changes in the duration and severity of droughts and/or floods.

This study focuses on the effects of a range of climate warming estimates on the long-term performance and management of California's water system. This is a complex and somewhat speculative business, because so much can change in the long-term. So much can change in the future that it makes little sense to look at an individual change without the context of other likely changes and reasonable adaptations that our society and economy would make to a future change in climate. Thus, in our preliminary integrated analysis of how California could respond to climate change, we examine adaptive response to climate warming in the context of increased population, continued conversion of agricultural land to urban uses, and changes in crop yields from climate change and sustained technological improvements in agriculture.

This report is organized as follows. Chapter 2 contains a presentation of climate warming scenarios reasonably expected for California and how these changes in climate were transformed into detailed spatially-distributed surface and groundwater hydrologies for California's water supply system for the year 2100. This represents the first comprehensive quantification of the implications of climate change for the diverse water sources of California's extensive and highly diversified water supply system. Chapter 3 contains a discussion of non-climate changes that can reasonably be expected in the year 2100, providing a more realistic context for assessing the implications of climate change in the distant future. Changes in population, land use, and technology are discussed, and reasonable quantitative characterizations are made for 2100, though these are not the only reasonable characterizations of the future. Chapter 4 presents the variety of options available for California to adapt to future changes in water supplies and demands. These adaptations include changes in facilities, demands, allocations, and water management institutions. Chapter 5 presents the analytical approach of this study where climate and non-climate changes are used to modify a quantitative understanding of California's integrated water management system, in the form of the CALVIN economic-engineering optimization model. Results from this model are also presented in this chapter. Chapter 6 contains a discussion of these results in terms of the economic and adaptation implications of climate and other changes for California's very long-term water supplies (and demands).

Several appendices accompany this project, sparing the reader the gorier details of this work but making these details available for fellow water wonks. Appendix A presents the details of how comprehensive climate warming hydrologies were developed. Appendix B contains details of urban water demand estimation and estimates for 2100. Appendix C does the same for estimation of agricultural water demands for 2100. Hydropower valuation, a newly added feature for the CALVIN model, appears in Appendix D. Appendix E contains a revision of environmental water constraints in the CALVIN model also developed as part of this project. A discussion of sea level rise appears in Appendix F.

CHAPTER 2

CLIMATE CHANGES IN CALIFORNIA'S WATER RESOURCES

This chapter summarizes a fuller review of climate change and climate change hydrologies appropriate for water supply studies in California provided in Appendix A. The chapter begins with brief discussions of historical and prehistoric experiences with climate change and prospects for future climate changes. The chapter concludes with a summary of the method and results of statewide estimates for twelve climate change scenarios for California.

PAST CLIMATE CHANGES

In terms of runoff and temperature, there is historical and pre-historic evidence of both great consistency in California's climate, as well as great variability during the last few thousand years. Streamflow records since about 1900 and estimated streamflows from tree-ring studies going back to about 900 A.D. generally indicate similar annual variability in streamflows (Meko, et al. 2001). However, other detailed studies California's climate have indicated prolonged drier periods before European settlement. Stine (1996) argues that the period 1650-1850 was significantly drier and cooler than the current era, with perhaps 23-24% less runoff annually, and that this dry cool period was anomalous for this post-ice-age period overall (past 8,000 years). While these studies are unable to indicate the seasonality of flows, a cooler climate would generally delay snowmelt, with a greater proportion of flows occurring in spring and summer. Elsewhere, Stine (1987) argues that extreme and prolonged droughts have occurred in California, related to large-scale global climate fluctuations. Haston and Michaelsen (1997) also find long term spatial and temporal variability in California's climate related to global scale atmospheric circulation patterns.

Sea level is another important aspect of climate change affecting water management in California. Sea level has a significant effect on coastal wetlands and ecology, as well as salinity levels in the San Francisco Bay-Delta estuary, with its environmental, economic, and water supply importance. It is generally thought that sea level has risen over the past few thousand years. Estimates of the rate of rise in sea level range from 0.1m to 0.9m/century (IPCC 2001; Roos 2002).

FUTURE CLIMATE CHANGES

While a variety of changes in California's climate have been seen in historical and pre-historic periods or could occur in the future, three forms of climate change are most frequently discussed for California's future (Roos 2002; Wilkinson 2002): sea level rise, climate variability, and climate warming.

Sea Level Rise

Sea level rise is probably the most certain and predicable climate change occurring in California. Perhaps the most important aspect of sea level rise for California's water supply system is its likely effects on the Sacramento-San Joaquin Delta (Logan 1990; Anderson 2002). The Delta estuary is a central hub of California's water system, with a degree of mixing of seawater and fresh water as water is pumped from the Delta for export to most of California's agricultural and urban activity centers. The Delta itself is also a major agricultural production area as well as a major environmental habitat and recreation area. Expected levels of sea level rise are likely to increase already problematic risks of flooding in this region (Logan 1990; Williams 1989) and increase the salinity of water at major export pumping locations unless addressed with changes in Delta outflows, channels, or operations. Increased exports of sea salts from the Delta would increase salt disposal problems in the San Joaquin and Tulare Basins. The increased presence of disinfection by-product precursors (particularly bromides) from seawater would also raise health risks or water treatment costs for urban water users in much of the state (Hutton and Chung 1992a, 1992b; Anderson 2002).

Climate Variability

Variability in climate refers to changes in the persistence and frequency of wet and dry periods over time. Do droughts become more frequent and severe? Are floods more frequent, or less so? Variability of climate has long been known to exist (Trewartha 1954, p.232). Recent works by Cayan and others have shown several global and regional circulation mechanisms that can drive the variability of California's climate, the now well-known El Niño and Pacific Decadal Oscillation events (Cayan et al 1999, Biondi et al. 2001; Haston and Michaelsen 1997).

One of the more interesting aspects of research into climate variability is the prospect it might give for better weather and climate prediction (Masutani and Leetmaa 1999). If droughts and floods can be better predicted, then it should be possible to operate water resource systems with greater foresight. For example, if floods can be predicted meteorologically and climatologically, then more water could be captured and carried over during the winter months to increase water supplies. If droughts can be better predicted, it should be possible to begin water conservation efforts earlier to better conserve water supplies during droughts and perhaps draw down reserves with greater confidence of a drought's end. (Yao and Georgakakos 2001; Carpenter and Georgakakos 2001).

Climate Warming

Perhaps the most-debated form of climate change for California is climate warming, usually attributed to increasing concentrations of carbon dioxide and other gasses from increased industrialization over the last century (Wigley and Raper 2001; Snyder et al 2002). There have been many studies of the potential effects of climate warming on streamflows in California (Gleick and Chalecki 1999; Cayan et al. 1993; Lettenmaier and Sheer 1991; Lettenmaier and Gan 1990; Miller, et al 2001; Roos 2002). The degree of warming is usually estimated based on the results of computer models of the Earth's climate, known as general circulation models (GCMs). These studies all indicate that warming of California's climate, would change the seasonal distribution of runoff, with a greater proportion of runoff occurring during the wet winter months, and less snowmelt runoff during spring. Some sets of GCM results indicate that higher precipitation volumes are likely to accompany any climate warming, arising in part from higher global evaporation rates. There is some reason to think that seasonal shifts in runoff patterns from spring to winter are already occurring in California (Aguado et al. 1992; Dettinger and Cayan 1995). Changes is the persistence of wet and dry periods with climate warming are only beginning to be explored (Huber and Caballero 2003).

TWELVE CLIMATE CHANGE SCENARIOS

This study focuses on examining the effects of a range of climate warming scenarios on the long-term performance and management of California's water system.

Twelve Views of Future California Climate with Global Warming

Twelve climate change scenarios are used to represent the range of climate warming likely to be experienced in California in the coming century. Six of these scenarios are taken from two major GCM studies, the generally much wetter and warmer HadCM2 (HCM) model and the much drier and warmer PCM model. For each GCM, three periods into the future are examined, 2010-2039, 2050-2079, and 2080-2099. In addition, six parametric changes are examined for California with temperature increases ranging from 1.5 degrees Celsius to 5 degrees Celsius and precipitation increases from zero percent to thirty percent.

The twelve climate change scenarios examined are then:

(1) 1.5 ºC temperature increase and 0% precipitation increase (1.5T 0%P);
(2) 1.5 ºC temperature increase and 9% precipitation increase (1.5T 9%P);
(3) 3.0 ºC temperature increase and 0% precipitation increase (3.0T 0%P);
(4) 3.0 ºC temperature increase and 18% precipitation increase (3.0T 18%P);
(5) 5.0 ºC temperature increase and 0% precipitation increase (5.0T 0%P);
(6) 5.0 ºC temperature increase and 30% precipitation increase (5.0T 30%P);
(7) HadCM2 2010-2039;
(8) HadCM2 2050-2079;
(9) HadCM2 2080-2099;
(10) PCM 2010-2039;
(11) PCM 2050-2079;
(12) PCM 2080-2099.

These climate change scenarios represent a range of results found from a wide variety of GCM results, as shown in Figure 2-1 and Table 2-1.

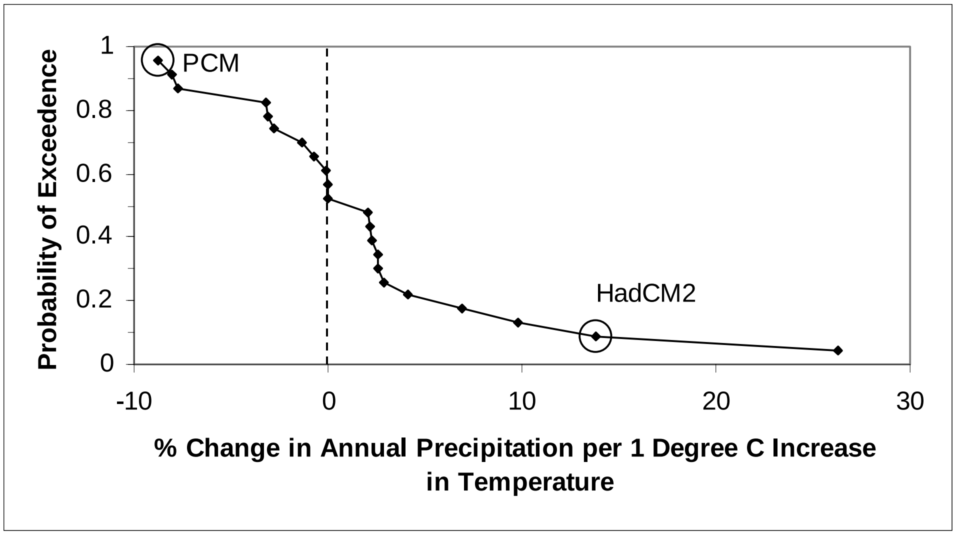

Figure 2-1. Probability of Precipitation Effect of Temperature Rise from Data in Table 2-1

Table 2-1. Average Precipitation Changes for California Grid Cells (percent change per 1°C global-mean warming)

	Annual	December-February	June-August
BMRC	-8.0	-6.5	-9.9
CCC	6.9	14.0	3.5
CSIR1	-0.7	-1.8	-1.0
CSIR2	2.6	5.3	-2.7
ECH1	9.8	8.4	2.8
ECH3	-3.2	9.9	-22.5
GFDL	0.0	1.8	-0.1
GISS	2.2	1.5	3.6
LLNL	0.0	1.5	-2.7
OSU	-1.3	0.6	-5.2
UIUC	2.3	0.3	34.7
UKHI	2.6	6.2	-5.2
UKLO	4.1	6.1	-0.2
UKTR	2.9	12.4	0.3
CCCTR	26.3	56.0	7.1
JAPAN	-7.7	-10.7	0.7
CSITR	-2.8	7.7	-10.0
ECH4	-3.1	8.7	-8.1
GFDTR	-0.1	-3.4	-4.6
NCAR	2.1	0.4	7.4
HADCM2	13.8	23.1	7.8
PCM	-8.8	-	-
Overall mean	**1.8**	**6.7**	**-0.2**
Median	**1.05**	**5.3**	**-0.2**
Max	**26.3**	**56.0**	**34.7**
Min	**-8.8**	**-10.7**	**-22.5**

Grid box central points (5° by 5° grid), Latitude range 32.5 to 42.5 N and Longitude range -122.5 to -117.5 E
Sources: Tom M.L. Wigley, NCAR, personal communication. June 21, 2000; PCM added based on changes in precipitation and temperature for California from Miller et al. 2001.

Components of California's Water Supply

The water supply to California's vast inter-tied water system can be divided into several components:

- Mountain rim inflows, providing 72% of inflows (28.2 maf/yr) supplies to California's inter-tied water system, come from mountain rainfall and snowmelt. When they enter the rims of California's Central Valley floor, they are often intercepted by sizable storage reservoirs, which help control floods and even the seasonal distribution of water to support agriculture and urban uses.

- Local accretions to surface water, about 11% of inflows (4.4 maf/yr) to the inter-tied system, arrive directly from rainfall on the Central Valley and local stream runoff.

- Groundwater recharge from rainfall, about 17% of inflows (6.8 maf/yr), accounts for the rainfall on the Central Valley that does not runoff or evaporate during wet seasons.

- Reservoir evaporation is a loss the system pays for the storage of water in surface reservoirs. Currently, reservoir evaporation amounts to about 4% of annual inflow to the system (1.6 maf/yr).

This study estimated changes in all of these system components for each of the twelve climate warming scenarios for the entire California inter-tied water supply system.

Hydrologic Modeling for Six Index Basins

Estimates of changes in rim inflows were based on detailed studies by Lawrence Berkeley National Laboratory of six index basins distributed over California (Miller et al 2001). These basins, shown in Figure 2-2, represent a range of snowmelt and rainfall dominated catchments. Each of the twelve climate warming scenarios was used to drive standard rainfall-runoff models for each of these six basins, based on existing National Weather Service rainfall-runoff models of these basins. The results from these model runs were examined for internal consistency and consistency across basins.

Figure 2-2. Location of the six index basins (Miller, et al. 2001)

Development of Statewide Surface and Groundwater Hydrologies

As described in detail in Appendix A, the results of these six index basins were used to develop rim inflows for each of 37 major surface inflows to California's water supply system. Streamflow changes for each of the six index basins was then mapped to the 37 major surface inflows to the system, perturbing the 72-year historical flow record to represent historical spatial and temporal variability of inflows given a generally warmer (and for some scenarios wetter or drier) climate. The climate used for each climate warming scenario model run then was used to estimate changes in flows for mountain rim inflows, local runoff, rain-fed deep percolation to groundwater, and reservoir evaporation (Appendix A). These results of these analyses appear below, with more detail appearing in Appendix A. The variety of surface, groundwater, reservoir evaporation, and local inflow locations appear in Figure 2-3.

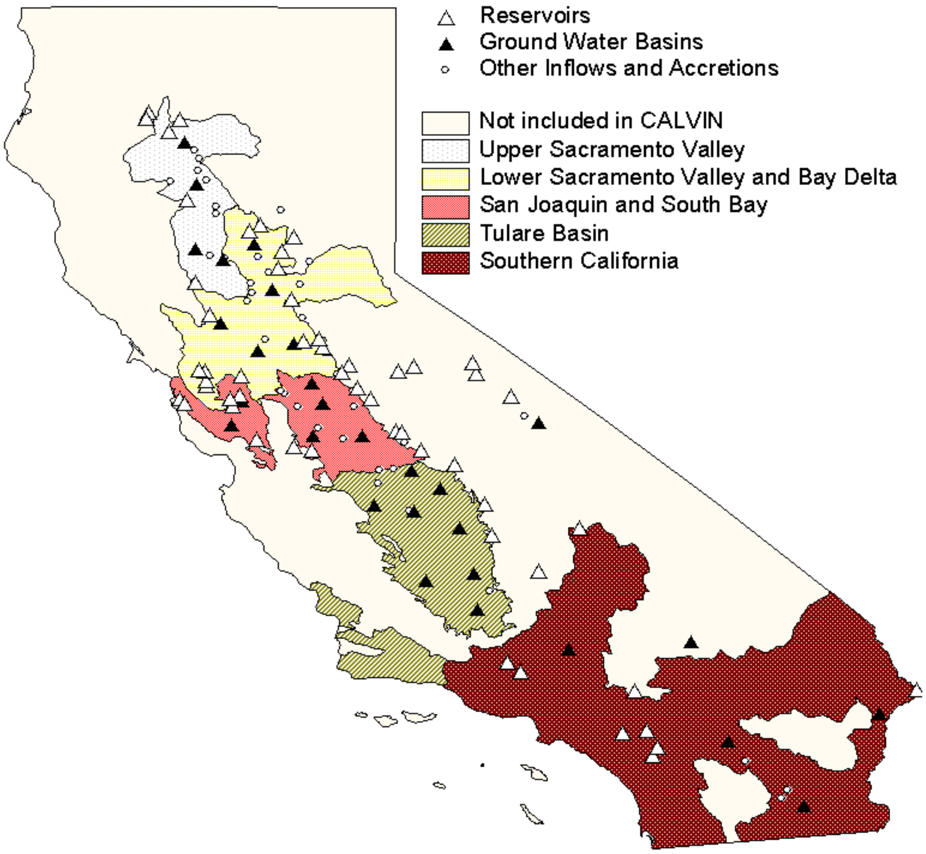

Figure 2-3. CALVIN model regions, inflows, and reservoirs

Mountain Rim Runoff Results

Rim inflow quantities and changes for the twelve climate warming scenarios appear in Table 2-2 below. For most cases, overall inflows into the system are greater with climate warming, driven by accompanying precipitation increases. Only for the three very dry PCM runs and the high-temperature with low precipitation scenario did overall rim inflow decrease. However, any increases in annual runoff occurred only during the wet winter months (October through March), the only exception being the very wet HCM GCM results. The general impression of these results confirms widespread concerns that climate warming would worsen California's already skewed seasonal hydrology, making wet winters wetter and more flood-prone, and reducing runoff during the snowmelt portion of the dry season. Figure 2-4 shows these results graphically.

The classical concern for climate warming in California and the West is that increased winter flooding and decreased snowmelt would pose a double threat to water supplies from surface reservoirs in mountain foothills (Lettenmaier and Gan 1990). Such reservoirs would have to maintain greater empty space to maintain current levels of flood protection from increased winter storm runoff. This empty space would then be less likely to refill at the end of the flooding season because of reductions in snowmelt after the storm season's end. Estimated implications for overall water supply reliability are discussed later in this chapter, without the benefit of operations model results. Operations model result refinements to these estimates appear in Chapter 5.

Table 2-2. Overall rim inflow quantities and changes

Climate Scenario	Annual		Oct-Mar		Apr-Sep	
	Quantity (maf)	Change	Quantity (maf)	Change	Quantity (maf)	Change
1) 1.5T 0%P	28.6	1.1%	16.4	15.6%	12.2	-13.4%
2) 1.5T 9%P	32.4	14.6%	18.7	31.7%	13.7	-2.7%
3) 3.0T 0%P	28.5	0.9%	18.2	28.0%	10.3	-26.5%
4) 3.0T 18%P	36.2	28.1%	23.3	64.4%	12.8	-8.7%
5) 5.0T 0%P	27.9	-1.1%	19.5	37.1%	8.5	-39.7%
6) 5.0T 30%P	40.6	43.7%	28.9	103.8%	11.7	-17.0%
7) HCM 2010-2039	38.5	36.4%	22.0	54.9%	16.5	17.6%
8) HCM 2050-2079	41.3	46.4%	25.8	82.0%	15.5	10.4%
9) HCM 2080-2099	49.8	76.5%	33.3	134.3%	16.6	18.1%
10) PCM 2010-2039	26.5	-6.2%	13.2	-6.7%	13.2	-5.7%
11) PCM 2050-2079	24.4	-13.6%	13.7	-3.8%	10.7	-23.5%
12) PCM 2080-2099	21.1	-25.5%	12.2	-14.2%	8.9	-36.9%
Historical	28.2	0.0%	14.2	0.0%	14.0	0.0%

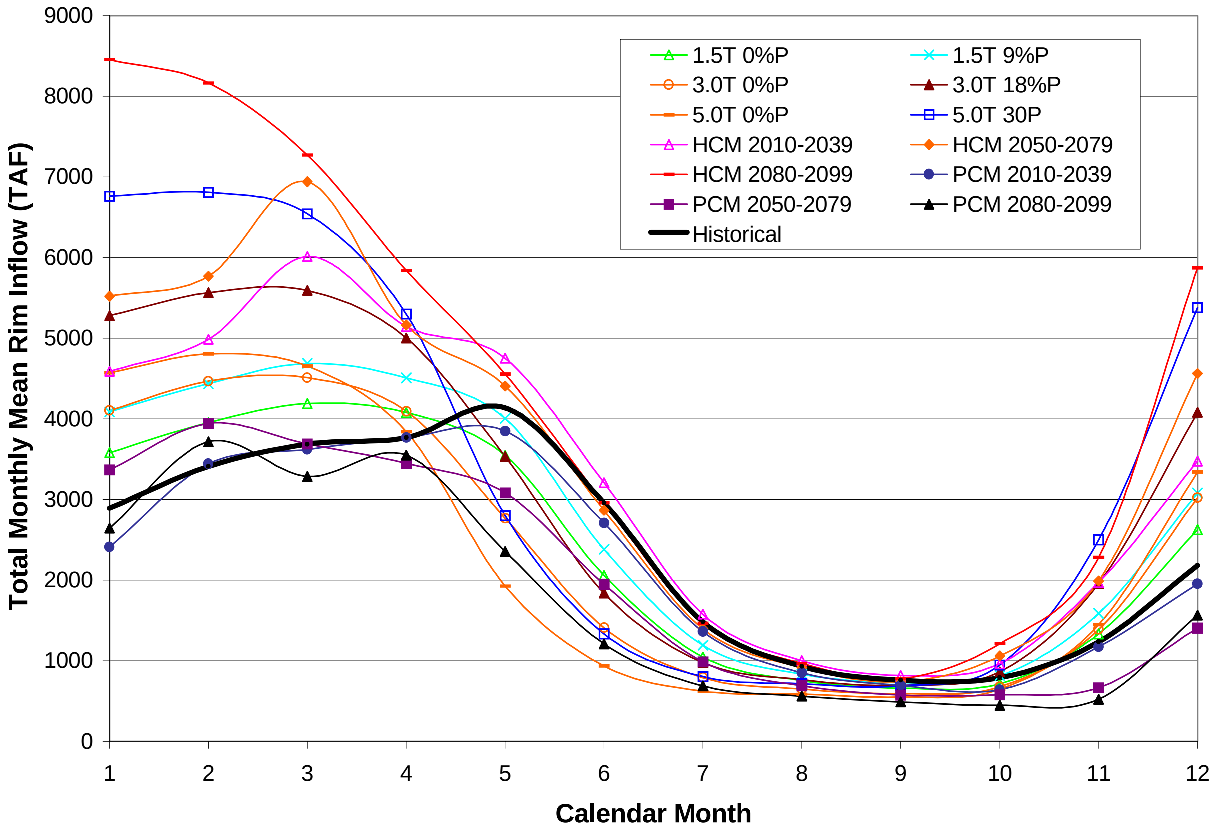

Figure 2-4. 72-Year Monthly Mean Rim Inflows for the 12 Climate Scenarios and Historical Data

Local Runoff Results

Local valley runoff changes with climate warming are estimated from precipitation change assumptions for the six parametric scenarios and the six GCM scenarios. These results for the 38 local runoff inflows appear in Table 2-3. Except for the PCM GCM, these results are more benign for water supply, with general increases or no effect on dry season runoff, but frequent substantial increases in winter runoff. The volumetric flow changes are much less for local runoff than rim flows, however.

Table 2-3. Local Surface Water Accretion Quantities and Changes

Climate Scenario	Annual		Oct-Mar		Apr-Sep	
	Quantity (maf)	Change	Quantity (maf)	Change	Quantity (maf)	Change
1) 1.5T 0%P	4.42	0.0%	3.54	0.0%	0.88	0.0%
2) 1.5T 9%P	5.45	23.3%	4.39	23.9%	1.06	21.1%
3) 3.0T 0%P	4.42	0.0%	3.54	0.0%	0.88	0.0%
4) 3.0T 18%P	6.48	46.6%	5.23	47.7%	1.25	42.1%
5) 5.0T 0%P	4.42	0.0%	3.54	0.0%	0.88	0.0%
6) 5.0T 30%P	7.85	77.7%	6.36	79.5%	1.49	70.2%
7) HCM 2010-2039	7.94	79.7%	6.04	70.4%	1.91	117.4%
8) HCM 2050-2079	8.55	93.4%	7.04	98.7%	1.51	72.0%
9) HCM 2080-2099	11.41	158.1%	9.72	174.3%	1.69	92.8%
10) PCM 2010-2039	4.26	-3.5%	3.23	-8.8%	1.03	18.0%
11) PCM 2050-2079	3.89	-12.0%	3.08	-12.9%	0.81	-8.2%
12) PCM 2080-2099	3.17	-28.2%	2.36	-33.2%	0.81	-7.8%
Historical	4.42	0.0%	3.54	0.0%	0.88	0.0%

Deep Percolation to Groundwater Results

Like local valley runoff, deep percolation to groundwater from precipitation is estimated based on precipitation changes for each climate warming scenario, by methods described in Appendix A. These results are summarized for CALVIN's 28 groundwater basins in Table 2-4. Except for the dry PCM GCM, annual groundwater availability increases for the climate warming scenarios. Even with the dry PCM GCM precipitation, reductions in groundwater availability are small.

Groundwater inflow changes have an important difference from rim inflow changes. Additional groundwater inflows during the wet season are stored and become available for use during the dry season. The water supply implications of this will be explored later in this chapter and become an important part of the operations model results. Groundwater, already an important part of California's water supply system, would somewhat mitigate the larger water supply impacts of climate warming on rim inflows.

Table 2-4. Groundwater inflow quantities and changes

Climate Scenario	Annual		Oct-Mar		Apr-Sep	
	Quantity (maf)	Change	Quantity (maf)	Change	Quantity (maf)	Change
1) 1.5T 0%P	6.78	0.0%	3.60	0.0%	3.18	0.0%
2) 1.5T 9%P	7.01	3.4%	3.80	5.5%	3.21	1.0%
3) 3.0T 0%P	6.78	0.0%	3.60	0.0%	3.18	0.0%
4) 3.0T 18%P	7.24	6.8%	4.00	11.1%	3.24	1.9%
5) 5.0T 0%P	6.78	0.0%	3.60	0.0%	3.18	0.0%
6) 5.0T 30%P	7.55	11.3%	4.27	18.5%	3.28	3.2%
7) HCM 2010-2039	7.51	10.7%	4.17	15.8%	3.33	5.0%
8) HCM 2050-2079	7.68	13.3%	4.42	22.7%	3.26	2.5%
9) HCM 2080-2099	8.37	23.5%	5.08	41.1%	3.29	3.5%
10) PCM 2010-2039	6.61	-2.5%	3.42	-5.0%	3.19	0.3%
11) PCM 2050-2079	6.44	-5.0%	3.33	-7.6%	3.11	-2.0%
12) PCM 2080-2099	6.21	-8.5%	3.08	-14.5%	3.12	-1.7%
Historical	6.78	0.0%	3.60	0.0%	3.18	0.0%

Reservoir Evaporation Results

Results for the 47 surface reservoirs in our representation of California's inter-tied water system appear in Table 2-5. Substantial increases in reservoir evaporation occur for all climate warming scenarios.

Table 2-5. Surface reservoir evaporation quantities and changes

Climate Scenario	Annual		Oct-Mar		Apr-Sep	
	Quantity (maf)	Change	Quantity (maf)	Change	Quantity (maf)	Change
1) 1.5T 0%P	1.83	12.4%	0.46	27.0%	1.36	8.1%
2) 1.5T 9%P	1.81	11.6%	0.45	24.3%	1.36	7.9%
3) 3.0T 0%P	2.03	24.8%	0.56	54.0%	1.46	16.3%
4) 3.0T 18%P	2.00	23.2%	0.54	48.5%	1.46	15.8%
5) 5.0T 0%P	2.30	41.3%	0.70	90.0%	1.60	27.1%
6) 5.0T 30%P	2.25	38.6%	0.66	80.9%	1.59	26.3%
7) HCM 2010-2039	1.77	9.0%	0.43	16.8%	1.34	6.7%
8) HCM 2050-2079	1.90	16.9%	0.49	33.3%	1.41	12.1%
9) HCM 2080-2099	1.98	21.7%	0.52	40.7%	1.46	16.2%
10) PCM 2010-2039	1.68	3.6%	0.40	8.0%	1.29	2.3%
11) PCM 2050-2079	1.84	13.5%	0.48	30.8%	1.37	8.5%
12) PCM 2080-2099	1.98	21.6%	0.55	49.9%	1.43	13.4%
Historical	1.62	0.0%	0.37	0.0%	1.26	0.0%

Total Water Quantity Changes

The summed changes in water quantities from changes in rim inflows, valley floor inflows, groundwater inflows, and reservoir evaporation appear in Table 2-6. They indicate a wide range, positive and negative, of potential overall changes in annual water inflows to California's inter-tied system. However, there is consistency in the seasonal shift in inflows, with less spring snowmelt, and typically much more winter flows. The next section modifies these results to crudely estimate overall changes in water supply availability for these scenarios, without detailed operations modeling.

Table 2-6. Overall water quantities and changes

Climate Scenario	Annual		Oct-Mar		Apr-Sep	
	Quantity (maf)	Change	Quantity (maf)	Change	Quantity (maf)	Change
1) 1.5T 0%P	37.9	0.3%	23.1	10.1%	14.9	-11.8%
2) 1.5T 9%P	43.0	13.7%	26.4	26.0%	16.6	-1.5%
3) 3.0T 0%P	37.7	-0.4%	24.8	18.0%	12.9	-23.4%
4) 3.0T 18%P	47.9	26.6%	32.0	52.7%	15.9	-5.9%
5) 5.0T 0%P	36.8	-2.6%	25.9	23.6%	10.9	-35.1%
6) 5.0T 30%P	53.7	42.1%	38.9	85.5%	14.8	-11.9%
7) HCM 2010-2039	52.2	38.0%	31.8	51.5%	20.4	21.2%
8) HCM 2050-2079	55.7	47.2%	36.8	75.5%	18.9	12.0%
9) HCM 2080-2099	67.6	78.9%	47.5	126.6%	20.1	19.3%
10) PCM 2010-2039	35.7	-5.6%	19.5	-7.0%	16.2	-3.9%
11) PCM 2050-2079	32.9	-13.0%	19.6	-6.6%	13.3	-21.0%
12) PCM 2080-2099	28.5	-24.8%	17.1	-18.6%	11.4	-32.5%
Historical (1921-1993)	37.8	0.0%	21.0	0.0%	16.8	0.0%

Changes in Water Availability

Table 2-7 contains the estimated changes in overall water availability for water supply purposes as a result of the twelve climate warming scenarios. These changes reflect crude assumptions that no increases in winter runoff can be captured (because of needs to operate reservoirs for flood control) and that all reductions in spring and dry season inflows are directly lost for water supplies. However, increases in wet season inflows to groundwater are captured and become available for water supply. These results are generally more pessimistic than the overall annual estimates in the previous table (Table 2-6). The effects of groundwater somewhat reduce the dramatic seasonal changes of rim inflows.

The water quantity losses in Table 2-7 are sizeable for some scenarios, and insignificant or even gains, for others. Plausible water supply impacts of climate warming to California range from a loss of 9.4 million acre-feet/year to a gain of 4.6 million acre-feet per year, or a 25% decrease to a 12% increase in water supply availability. All of the climate warming scenarios, except for the HCM GCM model results, show some to considerable loss of water supply, although in some cases losses are only slight. These are but crude estimates of changes in water supply availability from climate warming, and might be pessimistic. The ability of California's water management system to adapt to these changes in water availability would generally be expected to improve these effects on water supply availability. The capacity of the California's water management infrastructure to adapt to such climate warming scenarios appears is explored in Chapter 5.

Table 2-7. Raw water availability estimates and changes (without operational adaptation, in maf/yr)

Climate Scenario	Average Annual Water Availability	
	Volume maf	Change maf (%)
1) 1.5T 0%P	35.7	-2.1 (-5.5%)
2) 1.5T 9%P	37.7	-0.1 (-0.4%)
3) 3.0T 0%P	33.7	-4.1 (-10.9%)
4) 3.0T 18%P	37.1	-0.8 (-2.0%)
5) 5.0T 0%P	31.6	-6.2 (-16.5%)
6) 5.0T 30%P	36.2	-1.6 (-4.3%)
7) HCM 2010-2039	41.9	4.1 (10.8%)
8) HCM 2050-2079	40.5	2.7 (7.2%)
9) HCM 2080-2099	42.4	4.6 (12.1%)
10) PCM 2010-2039	35.7	-2.1 (-5.6%)
11) PCM 2050-2079	32.9	-4.9 (-13.0%)
12) PCM 2080-2099	28.5	-9.4 (-24.8%)
Historical	37.8	0.0 (0.0%)

CHAPTER 3

MAJOR NON-CLIMATE CHANGES

Most aspects of modern society change significantly in 100 years. Over each century for the past 1000 years, population usually grows significantly, population demography and composition changes significantly, wealth usually increases substantially, major economic sectors come and go, the structure of cities and daily life changes, governmental activities and the role of government evolve, the values of the society develop, language, culture, and art all change significantly. A century brings many profound changes. Recently, our society has begun to examine the possibility of climate changing over such time-frames. Vörösmarty et al. (2000) examine the comparative roles of population and climate changes globally, finding that population growth has important interactions in response to climate change. However California's climate changes over the coming century, the way Californians respond and are affected by climate change will be driven largely by the fundamental non-climate changes which characterize California's society and economy.

This chapter presents plausible quantitative projections or speculations of some major non-climate changes that could reasonably be expected in the coming century. Such speculations are unavoidably subject to errors and critical commentary, for just as no one can know detailed weather at some distant day, no one can know details of the climate, population, demography, wealth, major modes of transportation, role of government, stock market, structure of the economy, or popular music of the year 2100. (Merely knowing that these things will continue to exist in 2100 would relieve many of us considerably.) Nevertheless, given the planning and policy lead times often needed to make profound changes in water infrastructure, perhaps 100-year projections are themselves unavoidable to allow us to begin preparing ourselves.

POPULATION AND URBAN WATER DEMANDS

"In the long run, we will all be dead." John Maynard Keynes

As individuals, we will all be dead in the long term. However, as a society and population, there probably will be many more of us in California in the future. California has experienced a steady and sometimes explosive growth for over 100 years, and the climate, economic, and cultural attractions of California seem persistent. More recently, California's population growth has become more driven by natural internal increases, and less by immigration.

Current official population forecasts for California extend to the year 2040, and indicate a state population of approximately 60 million. Plausible long-term projections of California's population in 2100 have California's population at 92 million (Landis and Reilly 2002). For the larger Energy Commission project, this is the "high" population growth scenario. This estimated 2100 population is distributed over California's landscape using detailed models of land use conversion (Landis and Reilly 2002). Appendix B describes how these population estimates and accompanying urban land uses and land use densities are used to estimate 2100 economic (price-sensitive) demands for water by urban areas throughout California's inter-tied water supply system. Table 3-1 summarizes these projections. Table 3-2 shows details of these projections for different urban areas, and urban-areas-to-be, around California. Land use aspects of these changes are discussed in the next section.

Table 3-1. Total CALVIN 2020 and 2100 Population

	2020 Projection	2100 Projection	% Increase
Population CALVIN	44,881,273	85,560,323	91
Population California	47,507,399	92,081,030	94
CALVIN Urban Water Demand (maf/yr)	10.06	19.38	61

Tables 3-3a and 3-3b detail 2020 and 2100 projections of total urban economic water demands in the CALVIN model. These economic water demands are estimated as detailed in Appendix B, incorporating consideration of urban water use efficiency practices, changes in land use density for various areas of the state, current local water prices, and current local water use rates. In all cases, these demands are represented in CALVIN as true, price-varying economic demands for water, with appropriate return flow rates back into the supply system. The large growth in population expected between 2020 and 2100 required that many of the small urban demands scattered throughout the Central Valley, which had been represented as fixed urban water uses. These urban areas were updated to more complete economic representations of urban water demands, with price-sensitive water use. These new urban economic demand areas are detailed in Table 3-3b. Table 3-3b also includes Blythe, a new urban area that had not previously been represented in the CALVIN model at all, but is forecast to have a population of almost 900,000 by the year 2100 and accompanying water demands of 240 taf/year.

An interesting aspect of these projections is the rates of population growth compared to growth in water demands. From 2020 to 2100, population is estimated to increase by over 90%. But during this time, urban water demand might increase by only 61%. This implies a 16% decrease in per-capita water use from 240 gpcd in 2020 to 202 gpcd in 2100. Given the spread of urban populations in the drier, hotter parts of California and substantial expected sprawl development, this decrease in per capita applied water use is remarkable.

Table 3-2. Percent Population Increase from DWR 2020 Projection to 2100 Projection

Urban Area	DWR 2020 Population	2100 Population	% Population Increase
Redding Area	231,495	421,786	82
Yuba et al.	210,450	442,266	110
Sac Area	2,181,605	4,201,943	93
Napa-Solano	711,324	1,334,834	88
Contra Costa	565,353	896,486	59
EBMUD	1,326,460	1,961,825	48
SFPUC	1,501,900	1,987,120	32
Santa Clara V. (SCV)	2,971,513	5,690,081	91
SBarbara-S Luis Obispo (SB-SLO)	713,675	1,534,167	115
Ventura	1,022,850	1,956,007	91
Castaic	688,500	1,156,443	68
San Bernardino VWD (SBV)	878,944	1,016,582	16
Central MWD	15,645,756	25,321,581	62
E/W MWD	2,251,030	5,381,640	139
Antelope Valley	1,079,650	1,821,155	69
Mojave R	1,075,775	4,395,538	309
Coachella	628,820	2,477,594	294
San Diego	3,839,800	8,078,707	110
Stockton	421,575	904,601	115
Fresno	1,142,125	1,429,670	25
Bakersfield	612,100	987,108	61
El Centro et al.	214,250	977,078	356
Blythe	58,800	889,500	1413
CVPM 2	190,110	461,137	143
CVPM 3	42,275	125,008	196
CVPM 4	17,565	121,927	594
CVPM 5	358,800	371,471*	4
CVPM 6	894,299	368,680 *	-59
CVPM 8	92,445	514,633	457
CVPM 9	391,700	753,932	92
CVPM 10	150,580	350,271	133
CVPM 11	653,980	1,277,364	95
CVPM 12	297,770	727,016	144
CVPM 13	422,150	1,263,670	199
CVPM 14	69,375	97,531	41
CVPM 15	216,200	349,507	62
CVPM 17	294,210	1,060,199	260
CVPM 18	534,140	1,369,290	156
CVPM 19	41,100	95,210	132
CVPM 20	156,675	823,226	425
CVPM 21	84,150	166,539	98
Subtotal	44,881,273	85,560,323	91
Total California	47,507,399	92,081,030	94

*: Changed with regard to CALVIN 2020 model (DAU originally shared with Yuba and Napa-Solano are transferred fully from CVPM 5 and CVPM 6 demands to Yuba and Napa-Solano, respectively)

Table 3-3a. CALVIN 2020 and 2100 Urban Water Demands: Existing Economically Represented Urban Demand Areas in CALVIN

#	CALVIN Node Name	DAUs Included	2020 Demand TAF/year	2100 Demand TAF/year	Description of Major Cities, Agencies, or Associations
20	Yuba City et al	159, 168	64	116	Oroville, Yuba City
30	Sacramento Area	172, 173, 158, 161, 186	678	1,061	Sacramento Water Forum, Isleton, Rio Vista, PCWA, EID, W. Sacramento, N. Auburn
50	Napa-Solano	191, 40, 41	149	260	Cities of Napa and Solano Counties
60	Contra Costa WD	192, 70% of 46	135	146	Contra Costa Water District
70	EBMUD	70% of 47, 30% of 46	297	352	East Bay Municipal Utility District
80	SFPUC	43	238	264	San Francisco PUC City and County and San Mateo County service areas not in node 90
90	SCV	44, 45, 62, 30% of 47	658	928	Santa Clara Valley, Alameda County and Alameda Zone 7 WD
110	Santa Barbara-San Luis Obispo	67, 68, 71, 74, 75	139	269	Central Coast Water Authority
130	Castaic Lake	83	177	263	Castaic Lake Water Agency
140	SBV	44% of 100	282	285	San Bernardino Valley Water District
150	Central MWD	87, 89, 90, 92, 96, 114, 56% of 100	3,731	3,899	Mainly Los Angeles and Orange County portions of Metropolitan Water District of Southern California (MWD)
170	Eastern & Western MWD	98, 104, 110	740	1,245	Mainly Riverside County portion of MWD
190	Antelope Valley Area	SL3, SL4	283	420	AVEKWA, Palmdale, Littlerock Creek
200	Mojave River	SL5, CR1	355	1,397	Mojave Water Agency and Hi Desert Water Agency
210	Coachella Valley	CR4 (348, 349)	601	2,079	Dessert Water Agency, Coachella Valley Water Agency
230	San Diego MWD*	120 + CR5	988	1,660	all of San Diego County
240	Stockton	182	95	176	City of Stockton
250	Fresno	233	384	447	Cities of Fresno and Clovis
260	Bakersfield	254	260	382	City of Bakersfield
Total			10,254	15,535	
*: Area expanded from 2020 CALVIN representation to include CR5					

Table 3-3b. CALVIN 2020 and 2100 Urban Water Demands: New 2100 Economically Represented Urban Demand Areas in CALVIN

#	CALVIN Node Name	DAUs Included	2020 Demand TAF/year	2100 Demand TAF/year	Description of Major Cities, Agencies, or Associations
10	Redding	141, 143	80	146	Redding
120	Ventura	81	219	368	Oxnard (Camarillo, Ventura)
270	El Centro et al.	all CR6	52	205	El Centro, Calexico, Brawley
280	Blythe et al.*	CR2, CR3	-	240	Blythe, Needles
308	CVPM 8 Urban	180, 181,184	26	134	Galt
311	CVPM 11 Urban	205,206,207	232	379	Modesto, Manteca
312	CVPM 12 Urban	208, 209	110	292	Turlock, Ceres
313	CVPM 13 Urban	210-215	161	412	Merced, Madera
317	CVPM 17 Urban	236, 239,240	85	256	Sanger, Selma, Reedley, Dinuba
318	CVPM 18 Urban	242, 243	147	347	Visalia, Tulare
320	CVPM 20 Urban	256, 257	54	270	Delano, Wasco
Total			1,165	3,049	

* Entirely new urban demand in 2100 CALVIN model

LAND USE

Population growth will be accompanied by major changes in land use. Such land use changes have large implications for water use.

Expansion of Urban Land

As detailed in Appendix C and Landis and Reilly (2002), urban development from the year 2020 until 2100 may cover an additional 1,350,000 additional acres of land, Figure 3-1. Approximately 750,000 acres of this urbanization is likely to come from land currently in agricultural uses. In parts of the Central Valley, most urban growth is expected to be at lower than current average densities, because more of it will be in the form of lower-density suburban development and there is less opportunity for in-fill development. In other parts of California, greater densities of new urban growth are expected (Landis and Reilly 2002).

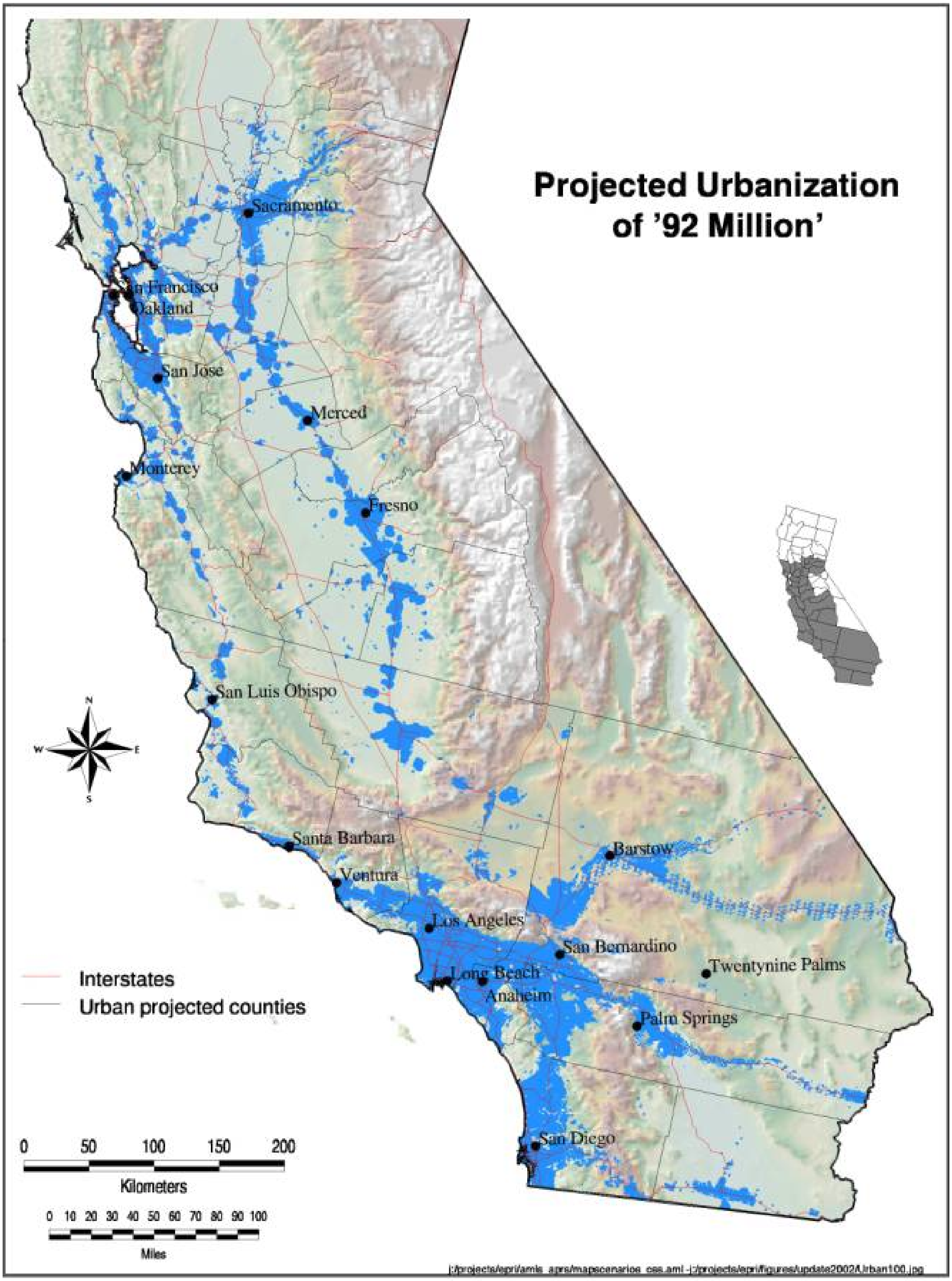

Figure 3-1. Urban Land Use 2100 (from Landis and Reilly 2002)

Conversion of Land from Agricultural to Urban Uses

The conversion of 750,000 acres of land from agricultural to urban uses between 2020 and 2100 would reduce agricultural applied water use by roughly 2.7 million acre-ft (Appendix C). This compares to estimated reductions in irrigated land of 325,000 acres from 1995 to 2020 from all causes (urbanization, agricultural drainage problems in the San Joaquin Valley, and increased competition in agricultural commodity markets) (DWR 1998). While this conversion of what is now agricultural land is extensive, it will reduce total land in irrigated agriculture in California (now 9.5 million acres) by only about 11%. Agricultural use of land and water will remain the dominant human uses of land and water in California through 2100.

WEALTH

The history of California has been one of mostly rising wealth, income, and living standards for the vast majority of the population. For this reason, as well as native optimism, this trend seems likely to continue.

Water use and wealth seem to be significantly correlated. Historically and currently, rising wealth correlates well with larger homes, larger yards, more use of water-intensive home appliances, including spas, and total water use. Studies in California often find that a 10% increase in household income raises water use by between two and seven percent (Baumann et al. 1998).

While increasing wealth could easily justify estimates of greater per-household economic water demands in the future, we have not done so in this study. There are several reasons for this.

First, we are particularly distrustful of estimates of wealth of Californians for the year 2100. An assumed small annual rate of growth in real income leads to average wealth beyond our dreams in the year 2100. A 1% annual average increase in wealth leads to an average wealth 2.7 times current levels in 2100. A 2% annual increase in wealth grows to 7.4 times current household wealth in 2100.

Second, improvements in residential and commercial water use efficiency are expected to continue, perhaps fundamentally changing how wealth affects urban water use. In recent decades growth in aggregate wealth has not led to growth in aggregate urban water use. Thus, we expect the effects of wealth increases on water use to decrease over time (Gleick, et al. 1995).

We have some difficulty imagining the havoc on water demands that would be wrought from even modest projections of increased wealth of Californians, assuming that recent historical correlations between wealth and urban water use continue. Multiplying exponential increases in income growth (even at low levels) by a significant correlation between income and water use over a very long period of time could lead to incredible quantities of average household water use.

Recoiling from this, and perhaps holding to “the sunnier side of doubt,” we have neglected potential wealth effects on household and commercial water use for the year 2100. In this way, we expect to have underestimated urban water demands for 2100. This one of many areas where long-term non-climate changes will affect future water system performance and management.

TECHNOLOGY IMPROVEMENTS

Crop Yields

In the last 100 years, technological improvements have increased crop yields for many major crops have risen steadily at significant rates. This has the long-term effect of increasing the water use efficiency of agriculture, in terms of crop yield per unit of water consumed, and the land area needed. For the post-processed analysis, we extrapolated these trends until 2020, then extended the crop yield series at a low constant growth rate. Because of inadequate time, crop yields in the CALVIN agricultural penalty functions remain at 2020 levels.

Urban Water Demand

In the first half of the last century, urban per-capita water use increased perhaps ten-fold with increased wealth, water availability, and new water-using appliances (such as toilets), and lower real prices. Urban water use (per-capita) is now decreasing, with vastly lower rates of industrial water use and more efficient water use technologies. There is reason to believe that improvements in technology and a maturing economy have fundamentally changed the role and importance of water use for urban growth and prosperity. Urban and domestic activities are no longer as dependent on the use of large quantities of water as they have been historically (Lund 1988).

Water Supply and Treatment

Advances in water treatment technology may provide substantial improvements in the cost-effectiveness of additional water supplies from non-traditional sources. In particular, wastewater treatment for reuse has now become a significant minor supply for several areas of California, and is expected to increase in the future. Seawater desalination, with total capital and operating costs of a bit under $2,000/acre-ft today, may become cost-effective in the future.

To be effective for growing urban water demands, a new technology must offer 1) publicly acceptable assurances of water quality, 2) cost-effectiveness compared with next best supply or demand alternatives, and 3) reliability. Currently, wastewater reuse has achieved this to only a limited degree, for only some urban uses, and often at a barely acceptable cost. For California, seawater desalination, is only experimental, but shows some promise if costs continue to decline and the costs of alternative options continue to increase.

SHIFTS IN WORLD AGRICULTURAL COMMODITY AND LAND MARKETS

Much of California's agricultural sector and water use responds to national and international agricultural commodity markets and prices. These world prices are likely to change in the future, but there is considerable uncertainty in how they might change. For post-processing through SWAP, we assumed that the demand for California products would grow at past levels until 2020, and then expand as a function of US population and income growth. (For the CALVIN model runs, agricultural economic penalty functions remain at 2020 levels.)

Changes in commodity prices and markets for agricultural products can directly affect the profitability of agricultural enterprises and thus the market price of agricultural land. If the world becomes more productive agriculturally and agricultural commodity process drop, it becomes less profitable to farm as a commercial enterprise and agricultural land values would thus fall. Reductions in agricultural land prices make the use of such land for other uses more attractive. As for water, most urban land uses can already out-bid agricultural uses for land, and so diminished agricultural land values would not likely increase urban sprawl greatly. However, lower agricultural land values would make acquisition of agricultural land for environmental restoration or other public purposes more attractive. Agricultural land would also become more attractive for less commercial forms of agriculture, such as "hobby farms."

CHANGES IN CALIFORNIA WATER DEMANDS

Overall changes in California water demand volumes are summarized in Table 3-4 below. Overall demands for water can be expected to increase, even accounting for decreases in agricultural water use driven in part by urbanization of agricultural land.

Table 3-4. Summary of Land and Applied Water Demands for California's Inter-tied Water System (millions of acres and millions of acre-ft/year)

Use	2020 Land	2100 Land	2020-2100 Change	2020 Water	2100 Water	2020-2100 Change
Urban				11.4	18.6	+7.2
Agricultural	9.2	8.4	0.75	27.8	25.1	-2.7
Environmental	-	-	-	-	-	-
Total	**-**	**-**	**-**	**39.9**	**44.5**	**+4.5 maf/yr**

Comparison of these changes in applied water demands with changes in water availability from Chapter 2, Table 2-7, indicate that increases in water demands, even when mitigated somewhat by reductions in agricultural land and water use, might pose greater challenges for water management than climate warming. It is also plausible that climate warming could have a larger effect than net population growth changes. In any event, there will be new challenges for water management in California's future.

CHAPTER 4

ADAPTATIONS TO CLIMATE CHANGE

People do not accept the weather or climate passively. Humans have found ways to survive sustainably in some of the most extreme climates on earth, from the Arctic to deserts to hurricane-pummeled coastlines to pestilential tropical forests and wetlands. Given the right political and economic conditions, civilizations have even thrived in a wide variety of climates. With substantially the same climate as today, rainfall-based commercial agriculture existed in the Negev Desert (Israel) during Roman and Byzantine times (Evenari, et al. 1982). Human systems have an incredible array of means to respond and prosper to climatic and other changes (Stakhiv 1998). How well could our modern civilization in California adapt to major changes in climate?

California's complex water management system affords many opportunities to respond and adapt to challenges, be they from climate change, or less exotic challenges such as earthquakes, population growth, changes in water quality regulations, or other stimuli. These water management responses are common for most types of water supply challenges, and are summarized in Table 4-1 below.

Table 4-1. Summary of Responses Available

Response Category	Response	Remarks or Sources
Facilities	On-stream surface Reservoirs	
	Off-stream surface reservoirs	
	Groundwater recharge	
	Well-field expansion	
	Water treatment	includes desalting
	Water reuse treatment and redistribution	
	Water conveyance	Canals, pipelines, etc.
	Rainwater harvesting	Evenari, et al. 1982
Operations	Seasonal changes	Seasonal flood control rules, hedging, conjunctive use
	Over-year changes	Hedging, conjunctive use
	Improved forecasts	Yao and Georgakakos 2001
Water Allocation	Contract changes	
	Markets	Israel and Lund 1995
	Exchanges	Lund and Israel 1995
	Water rights	
	Pricing	
	Water Scarcity	Reductions of water use functions for economic, social, environmental purposes
Water Use Efficiency	Urban	
	Industrial	
	Agricultural	
	Environmental	Improved fish passage and habitat
Institutions	Governance and finance	Essential to implementing other responses

FACILITIES

Perhaps because we have used facilities historically to adapt our hydrologic environment to our desires for water use, we typically think of modifying water management facilities to respond to climate change. Indeed, it is almost inevitable that facilities of some sort would change in response to significant climate change. Facility changes can include those that readily come to mind, such as reservoir or conveyance expansion, those that are more novel, such as expansions of groundwater infiltration and pumping capacity to allow for greater conjunctive use of surface and ground waters, to ideas that would merely be new for California such as rainwater harvesting from hill-slopes or water treatment technologies (including perhaps desalting) which make useless or even problematic waters useful (at some cost).

Each type of facility in Table 4-1 interacts with others based on their geometric configuration capacities, and operations. It is not always obvious which type of facility, or combination of facilities, would be the most effective for a given region of particular form of climate change. Such questions typically require insights from detailed computer modeling studies.

OPERATIONS

The operation of a set of facilities in a hydrologic environment to accomplish a set of water management objectives is a complex business, especially in an extensive and heterogeneous system such as California's. The operation of a given set of infrastructure has several effects on water deliveries, quality, costs, and environmental performance.

Delivery Quantities and Reliability

Conveyance operations have important implications for water supply reliability. By better coordinating the use of water conveyed from different sources, more effective and complete use can be made of a region's or a state's water resources, losses or costs can be reduced, and reliability increased. These operations also have water quality and cost implications.

Hedging allows system operators to reduce the probability of severe water shortages, by withholding water in reservoirs when it is otherwise available. Hedging keeps more water in reservoirs, but also induces small amounts of scarcity in more average and dry years when there is physically sufficient water to supply all normal demands. This creates a trade-off, less water more reliably, or more water on average with greater variability.

Storage allocation allows system operators to place water in locations that reduce loss of water to evaporation or seepage, and to minimize the amount of "spilled" water during wet periods. This increases total water availability, though it might increase conveyance costs or change water quality. Conjunctive use of surface and ground water is an important aspect of allocating and using water storage.

Water Quality

Especially in California, the mixing of water sources has important water quality effects on all types of water users. These effects affect environmental performance, agricultural productivity and sustainability, and urban costs and consumer satisfaction. The operation of storage, conveyance, and treatment facilities of all sorts often have important water quality roles.

Water Cost

The operating costs of a system include pumping, water treatment, wastewater treatment, and maintenance that can vary with operations, as well as fixed administrative and maintenance costs. In addition, there are negative costs on water systems, such as hydropower and recreation benefits and revenues.

Environmental Performance

The operation of reservoirs, pumps, and diversions can have well-known effects on environmental species and ecosystems. These effects can be interactive and cumulative.

WATER ALLOCATIONS AND SCARCITY

The allocation of water between users is always controversial but unavoidable when water is scarce or threatens to become scarce. A variety of water allocation approaches are available. Current water rights, contracts, and regulations constitute a system of water allocation. We supplement this system with contract changes, water markets, and water exchanges, as well as by using water prices (in a market or banking setting) to encourage the movement of water to higher-valued uses with economic compensation to right-holders.

Water allocation options often imply scarcities for some water users. Water scarcity is the deliberate curtailment of water deliveries to some users, so as to maximize the benefits system-wide, given limited supplies. Akin to water rationing or cutbacks to agricultural water allocations during drought, this is a conscious decision to limit water use for some or all water users. All water use sectors can suffer from such scarcities.

WATER USE EFFICIENCY

The intent of water use efficiency options is to attain similar levels of economic, social, or environmental performance with less water. Water use efficiency options exist for all sectors of water use. For urban uses, use efficiency options include toilet retrofits, reducing water use per flush or xeriscape landscaping for attaining similar garden desirability with less water use. Agricultural water use efficiency options would include irrigation or drainage technology or improvements in cultivars that reduces water consumption per unit of crop output. Consumed water per unit of crop yield is a better indicator of efficiency than water applied per unit of crop output, due to reuse of crop return flows to surface and ground waters. Environmental water use efficiency might include fish ladders that require less by-pass flow, or improvements in channel morphology to provide similar habitat with less streamflow.

INSTITUTIONS

Physical, operational, and technical water management activities are implemented and financed in an environment of institutions. These institutions begin with millions of households and thousands of businesses (farms, other industries, and commercial users) that make water use decisions with various personal, social, and economic objectives in mind. Many hundreds of local water suppliers, city water departments, irrigation districts, and suburban water purveyors, influence these decisions through their conditions of water supply such as prices, rationing policies, and regulations and incentives of water use. Many local water suppliers receive water from larger water projects or agencies, or must otherwise interact at regional levels to receive water supplies. These larger projects and water sources have a host of financial, regulatory, and other institutional aspects which affect how they operate and respond. Finally, at the statewide level (and to a lesser degree the national level), water management decisions are affected by State water rights, regulatory policies, plumbing codes, financing arrangements, and provision of technical information.

Unlike the society and pyramids of ancient Egypt, the pyramid of California water management is led primarily from its broad base. Most leadership, authority, and funding for water management in California are based at local levels, with implementation authority and funding capabilities diminishing towards the "summit" of state authority. The days of State and Federal water projects developing large statewide systems seem to be over, for very practical technical, economic, and political reasons. Historically, in the U.S. and most of the developed world, water supply is a local responsibility, predominantly funded locally, with occasional regional cooperation and coordination.

However, State and Federal activities are not unimportant. State and Federal governments are likely to continue to be involved in their respective large-scale water projects, providing wholesale water to much of California, either as project owners and operators or as regulators of these projects. State and Federal governments also provide a legal context for local actions and activities, regarding contract law, environmental regulations, and administrative law. State government is especially important here, since it governs the system of water rights, ownership, and environmental regulation. Early California water development was hampered significantly for about 50 years by legal disputes over water right systems (Hundley 2000). Local and regional entities cannot make good decisions in a context of uncertainties in water rights. Such political and legal outcomes for the future are not subject to the results of computer models.

INTERACTION OF RESPONSES

The responses outlined above are each part of a very complex water system. It is highly unlikely that the most effective response to any catastrophe or change in the system would be in the form of a single response. A concerted combination of responses is likely to be required and desirable. To identify and explore promising combinations of responses for a complex system to a major change in its operating environment typically requires the use of computer modeling. The following chapter discusses the application of the CALVIN economic-engineering optimization model to estimate impacts and promising adaptive responses to climate change in California's water supply system.

CHAPTER 5

MODELING ADAPTATION WITH CALVIN

The method applied here uses a system optimization model (CALVIN) to estimate system-wide changes in both performance and desirable management (Jenkins, et al. 2001; Draper, et al, in press). This approach is unique for climate change studies of California. Some limitations of this approach are detailed by Jenkins, et al. (2001) and explored by Draper et al (in press). The approach taken in this study advances the climate warming simulation studies of Lettenmaier and Sheer (1991), VanRheenen et al (2001), and others in several ways: 1) the spatial analysis is more extensive and integrated, covering more of California and including groundwater, 2) the spatial hydrology is more extensive and detailed, 3) the optimization model employed is far more adaptable than simulation modeling, 4) economic performance results are generated and reported explicitly, and 5) future water demands are incorporated into the results, since climate change will occur under different water demand circumstances than today.

WHAT IS CALVIN?

The CALVIN model explicitly integrates the operation of water facilities, resources, and demands for California's great inter-tied water system. It is the first model of California water where surface waters, groundwater, and water demands are managed simultaneously statewide. The CALVIN model covers 92% of California's population and 88% of its irrigated acreage (Figure 5-1), with roughly 1,200 spatial elements, including 51 surface reservoirs, 28 groundwater basins, 18 current urban economic demand areas, 24 agricultural economic demand areas, 39 environmental flow locations, 113 surface and groundwater inflows, and numerous conveyance and other links representing the vast majority of California's water management infrastructure. This detailed and extensive model has necessitated the assembly and digestion of a wide variety of data within a consistent framework. The model's detailed schematic and documentation can be found at cee.engr.ucdavis.edu/faculty/lund/CALVIN/.

The second major aspect of the CALVIN model is that it is an economically-driven engineering "optimization" model. The model, unless otherwise constrained, operates facilities and allocates water to maximize statewide agricultural and urban economic value from water use. This pursuit of economic objectives is initially limited only by water availability, facility capacities, and environmental and flood control restrictions. The model can be further constrained to meet operating or allocation policies, as is done for the Base Case.

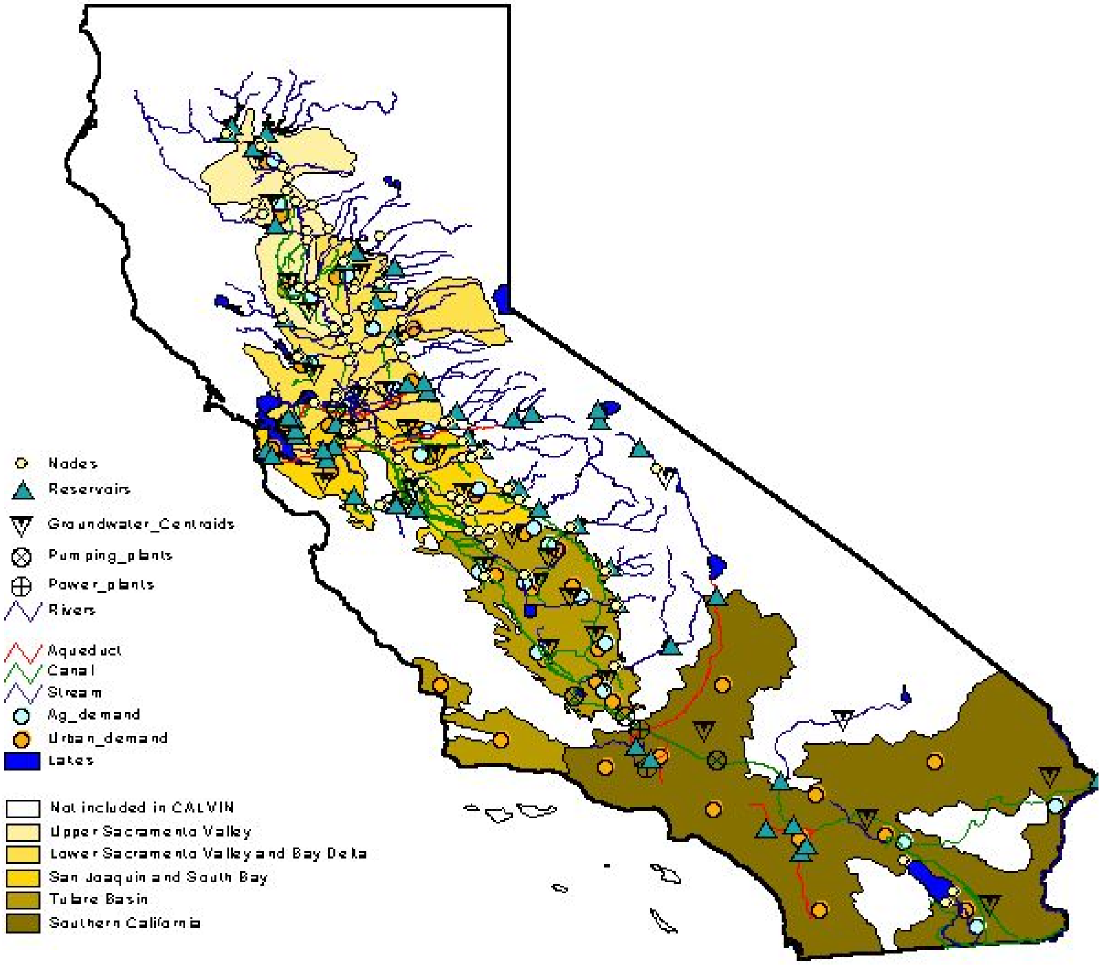

Figure 5-1. Demand Areas and Major Inflows and Facilities Represented in CALVIN

The diagram below (Figure 5-2) 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.

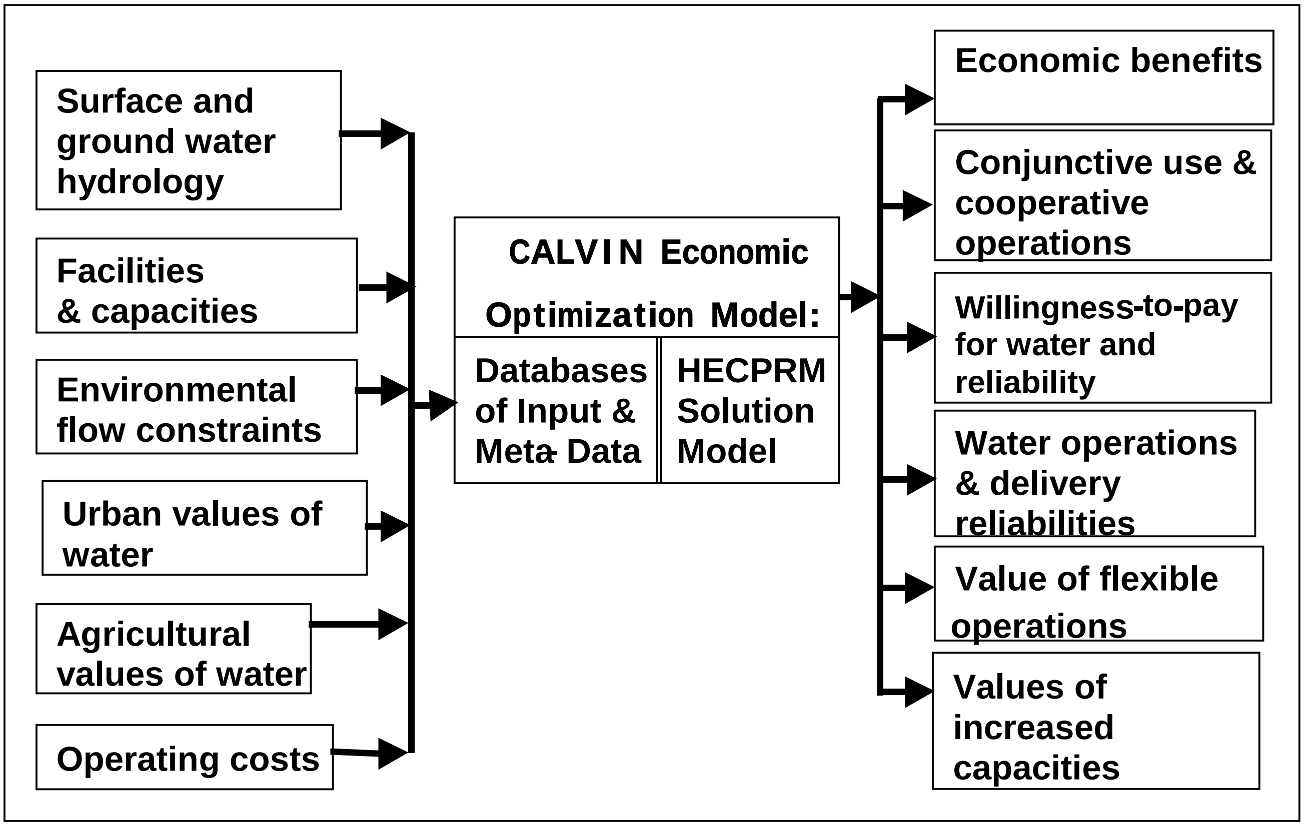

Figure 5-2. Data flow schematic for CALVIN

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:

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 5-1 below. While CALVIN is the largest such application, other applications include some of the largest water resource systems in the nation.

Table 5-1. 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, & Multi-Purpose Operations Seasonal Operations	USACE, 1991b, 1993, 1995, 1996
1997	Carson-Truckee System (5)	Prioritization of Uses & 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 & Multi-objective performance	USACE 1998a; Watkins et al, 2003
1999	Panama Canal System (5)	Drought Performance & 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, & 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:

- Comprehensive hydrologic effects of climate warming, 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.

- Integrated consideration of groundwater storage. Groundwater contributes about 75% of the storage used in California during major droughts.

- Statewide impact assessment. 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.

- Economic-engineering perspective. 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.

- Incorporation of multiple responses. 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. The limitations of the CALVIN model arise from three main sources, as detailed in Chapter 5 of Jenkins et al. (2001) and Draper, et al. (in press):

1) The input data used to characterize surface and groundwater supplies, water demands, and base case operations in the CALVIN model are limited by the quality of existing data sets, by weak or unavailable information for some parts of the state, as well as by our own project time constraints. The CALVIN calibration, with its own limitations, attempts to rectify and resolve inconsistencies in data sets to achieve an integrated surface and groundwater hydrologic balance for the Central Valley. Similarly, for climate studies, characterization of climate inputs is a source of potential limitations.

2) Choice of a network flow with gains optimization solver (HEC-PRM) imposes several restrictions on the model's ability to represent the system accurately. In particular, flow relationship constraints such as those involved in environmental regulation, water quality, and stream-aquifer and other groundwater behavior, must be simplified. In addition, water allocation and storage decisions are biased somewhat by perfect foresight in the deterministic optimization solution. This last issue has been examined in some detail (Draper 2001; Newlin et al, 2001), but merits consideration when interpreting results and further work.

3) Exclusion of flood control and recreation benefits from reservoir operations in this initial model development may distort operations of some parts of the model and limit the identification of opportunities for storage re-operation. It does, however, make interpretation of CALVIN results somewhat easier. This limitation reflects mainly a time constraint model development. This project added hydropower representation to the earlier version of CALVIN.

MODEL MODIFICATIONS FOR CLIMATE CHANGE STUDY

A major modification to the CALVIN model for this study was the addition of hydropower on many of the systems surface reservoirs. Hydropower impacts of climate change are likely to be extensive, and hydropower benefits are an important aspect of the operation of California's water system. Details of hydropower representation in CALVIN appear in Appendix D (Hydropower Demands).

More minor permanent modifications to the model include, updating environmental flow and operations constraints (Appendix E – Revised Environmental Demands), and correction of some small errors in the earlier model version.

For this particular climate change study, for the year 2100 time horizon with 2100 demands, several additional modifications were made:

- Changes in hydrology and water availability were made for surface and groundwater sources throughout the system to represent different climate warming scenarios.
- Estimates of year 2100 urban and agricultural economic water demands were used.
- Coastal areas were given unlimited access to sea water desalination at a constant unit cost of $1,400/acre-ft,
- Urban wastewater reuse was made available above 2020 levels at $1,000/acre-ft, up to 50% of urban return flows,
- Local well, pumping, and surface water diversion and connection and treatment facilities were expanded to allow access to purely local water bodies at appropriate costs.

MODEL RUNS

Several statewide model runs were used to evaluate the potential impact of climate change on California with and without population growth and adaptation. These runs are summarized as:

- **Base 2020**: This run represents projected water supply operations and allocations in the year 2020, assuming continuation of current operation and allocation policies. This run was prepared for CALFED and extensively documented elsewhere (Jenkins et al, 2001; Draper, et al. in press).
- **SWM 2020**: This run represents operations, allocations, and performance in the year 2020, assuming flexible and economically-driven operation and allocation policies. This optimized operation can be understood as representing the operation of a statewide water market, or equivalent economically-driven operations. This run also was prepared for CALFED and extensively documented elsewhere (Jenkins et al, 2001; Draper, et al. in press).

- **SWM 2100**: This run extends the SWM 2020 model and concept for 2100 water demands, but retains the same (historical) climate used in Base 2020 and SWM 2020.

- **PCM 2100**: Using the same 2100 water demands as SWM 2100, this run employs the PCM 2100 climate warming hydrology described in Chapter 2.

- **HCM 2100**: Using the same 2100 water demands as SWM 2100, this run employs the HCM 2100 climate warming hydrology described in Chapter 2.

For the SWM 2100 and PCM 2100 runs, two optimization runs were performed, with and without a more sophisticated representation of hydropower operations (explicitly modeling variable hydropower heads versus the simpler and more approximate implicit representation of hydropower head). For the purposes of this report, no significant differences were found in the results from these two representations of hydropower. This subtlety is discussed in more detail in Appendix D (Hydropower).

ECONOMIC IMPACTS AND ADAPTATION FOR CLIMATE CHANGES

Figure 5-3 summarizes the average water availability to each region of California under the historical hydrology and the two climate warming scenarios. Compared with the historical hydrology, PCM2100 is much drier and HCM2100 is much wetter. Note also that the Southern California region is not greatly affected hydrologically by these changes.

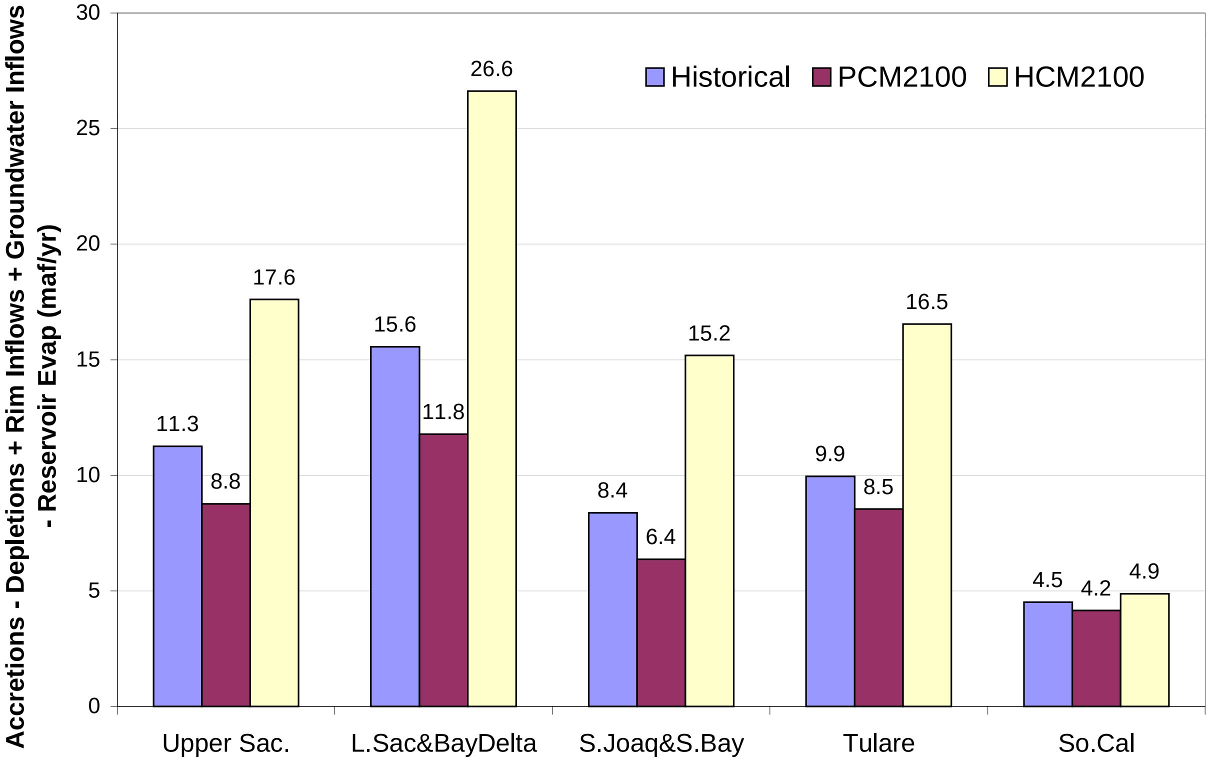

Figure 5-3. Water Availability in each Region for Three Climate Scenarios

Economic Costs of Water Scarcity and Operations

As shown in Figure 5-5, water scarcity is the difference between the amount of water delivered and that water user's desired delivery if water were free and unfettered in its availability. Scarcity cost is a water user's economic loss from this scarcity of water supply or their willingness to pay to have deliveries to the maximum level.

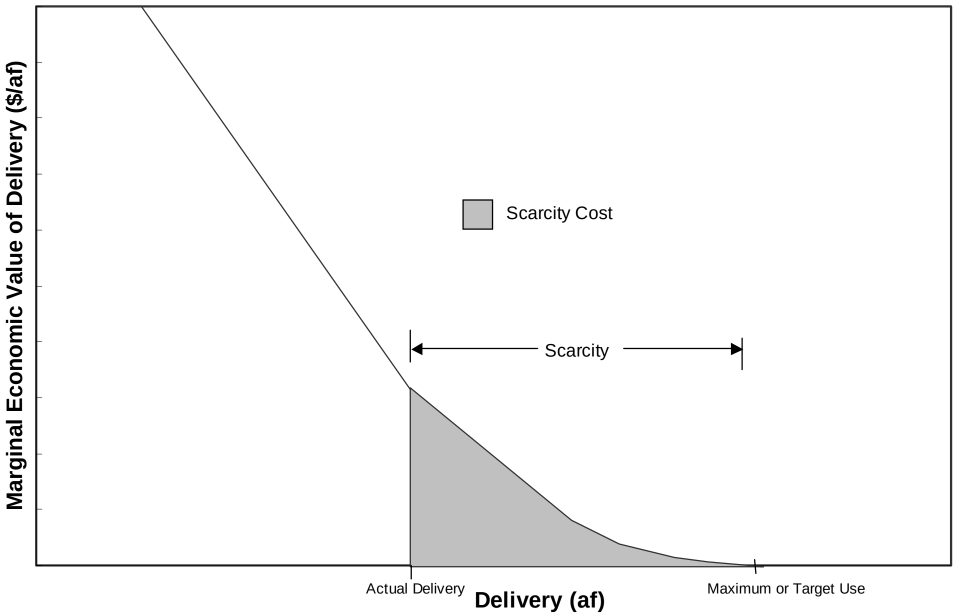

Figure 5-5. Definition of Scarcity and Scarcity Cost for a Water User

Table 5-2 summarizes the economic performance of California's water system under the five scenarios modeled. In all cases, operating costs greatly exceed scarcity costs seen by water users, although operating costs vary less among climate change scenarios than scarcity costs. Population growth alone leads to a $4.1 billion/year increase in water operations and scarcity costs to California, including almost a five-fold increase in water scarcity costs over a similarly optimized SWM2020. The further addition of a dry climate warming hydrology (PCM2100) further increases total costs by $1.8 billion/year, most which is scarcity costs in the agricultural sector. The wet climate warming scenario (HCM2100) reduces scarcity and operating costs to all sectors by $250 million/year overall, most of which is reduced operating costs.

Table 5-2. Summary of Statewide Operating# and Scarcity Costs

Cost	Base 2020	SWM2020	SWM2100*	PCM2100*	HCM2100*
Urban Scarcity Costs	1,564	170	785	872	782
Agric. Scarcity Costs	32	29	198	1,774	180
Operating Costs	2,581	2,580	5,918	6,065	5,681
Total Costs	**4,176**	**2,780**	**6,902**	**8,711**	**6,643**

* - Agricultural scarcity costs are somewhat overestimated because about 2 maf/year of reductions in Central Valley agricultural water demands due to urbanization of agricultural land are not included.

- Operating costs include pumping, treatment, urban water quality, recharge, reuse, desalination, and other variable operating costs. Scarcity costs represent how much users would be willing to pay for additional water deliveries.

Total water deliveries and scarcities are shown in Figure 5-6 for the five scenarios, statewide and for each of five major regions. Water demands statewide and for each region increase, due to urbanization. Southern California surpasses Tulare Basin as the major water-consuming region of California. With the exception of Southern California, all regions have small-but manageable water scarcities in 2100 with historical and HCM2100 hydrologies. With PCM2100's dry hydrology, significant scarcities exist in all regions, although Southern California's scarcity amounts are not greatly changed.

Figure 5-7 shows water deliveries and scarcities by region and statewide for just agricultural users. These estimates are overestimated perhaps 2 maf/year because Central Valley agricultural water demands were not reduced to correct for urbanization of agricultural land. This correction should be approximately 2 maf/year Central Valley-wide. Nevertheless, in 2100, agriculture remains the largest user of water in California. In Southern California, agricultural water use drops substantially due to urbanization of agricultural land and the sale of agricultural water to urban users, via the Colorado River Aqueduct, the Coachella canal, and other canals serving major urban areas within the Colorado River watershed. Under the dry PCM2100 hydrology, there are major agricultural scarcities in Central Valley agriculture, amounting to about 50% of agricultural water demands in some regions. Except for Southern California, these problems disappear with the wetter HCM2100 hydrology.

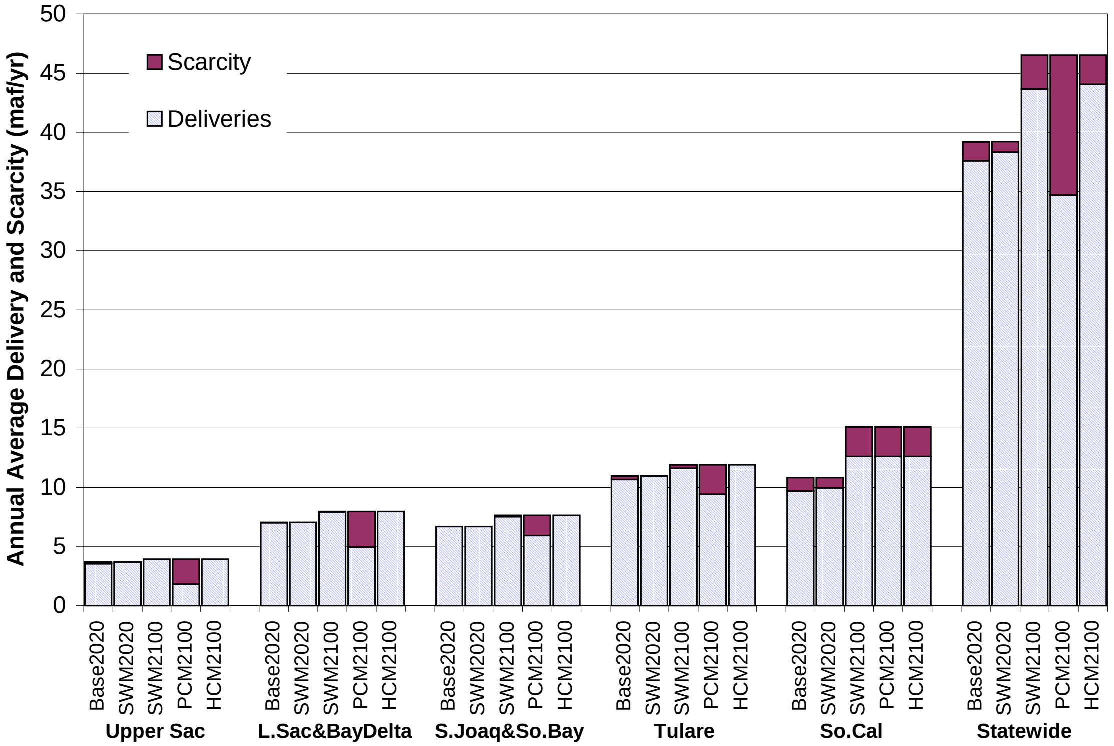

Figure 5-6. Total Water Deliveries and Scarcities by Region and Statewide

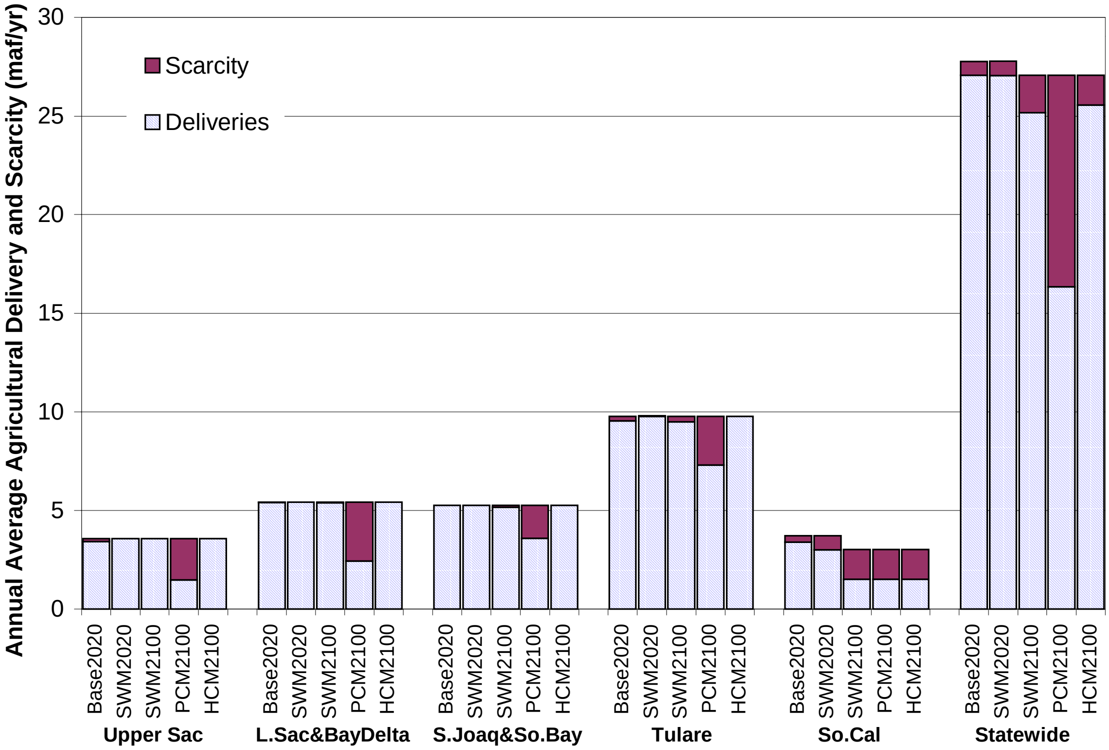

Figure 5-7. Agricultural Water Deliveries and Scarcity by Region and Statewide

As seen in Figure 5-8, urban water deliveries are much less affected by growth and climate warming. This insensitivity has several causes. First, urban water use has higher marginal economic values. In the optimization model, this allows urban areas to purchase water from other users and bear expenses for wastewater reuse and desalination that would be unacceptable for agricultural users. Second, despite significant growth, urban users remain a lesser proportion of water demands in most of California, so that for non-Southern California regions, agricultural water users exist from which to purchase water. Third, Southern California, where urban water use becomes the major use, is both hydraulically isolated by already limiting conveyance capacity on the California Aqueduct and Colorado River Aqueduct and is relatively less affected by climate warming hydrologic changes.

The overall effect, seen in Figures 5-9 and 5-10, is for 2100 urban water scarcity and scarcity costs to be relatively insensitive to climate change. Urban areas implement roughly a million acre-ft/year of additional water conservation, which this model sees as scarcity (with an associated urban scarcity/conservation cost). This urban conservation/scarcity changes relatively little with climate scenario. Agricultural water users are economically much more sensitive to climate changes, since it is assumed that urban areas can purchase much of the water they need from agricultural areas under unfavorable climates. Arguably, much of Central Valley agriculture would likely disappear or change to less productive dryland farming given very dry forms of climate warming, such as PCM2100, leaving the larger urban water economy relatively unaffected.

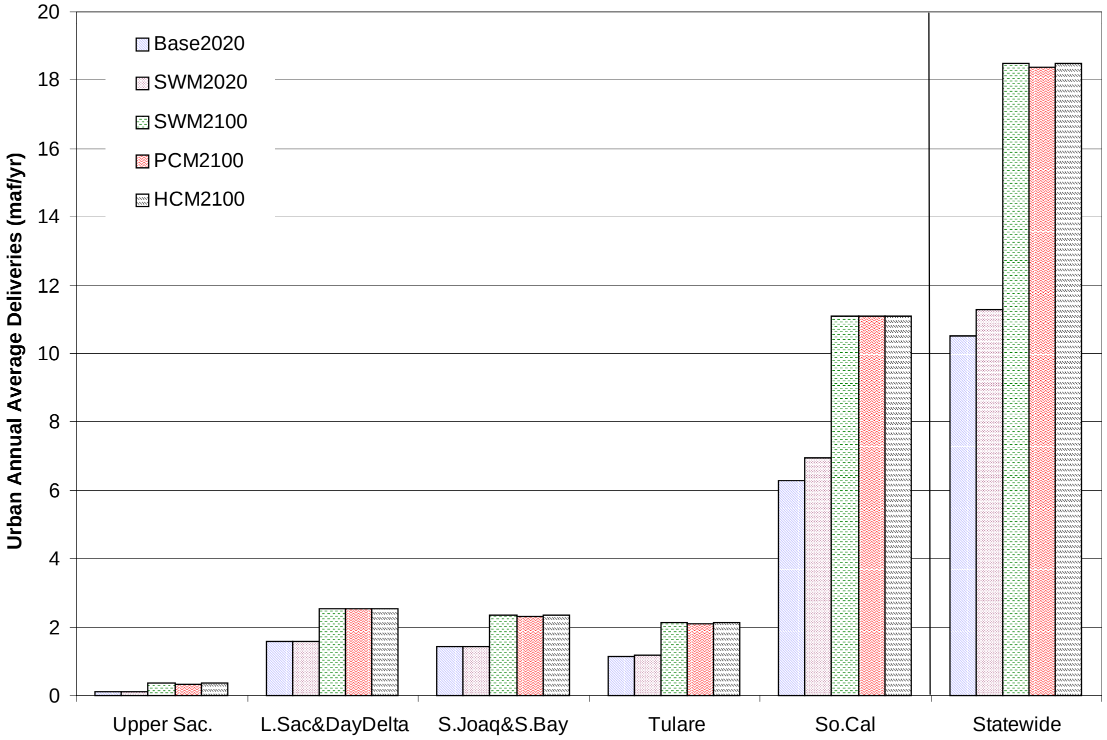

Figure 5-8. Total Urban Water Deliveries by Region and Statewide

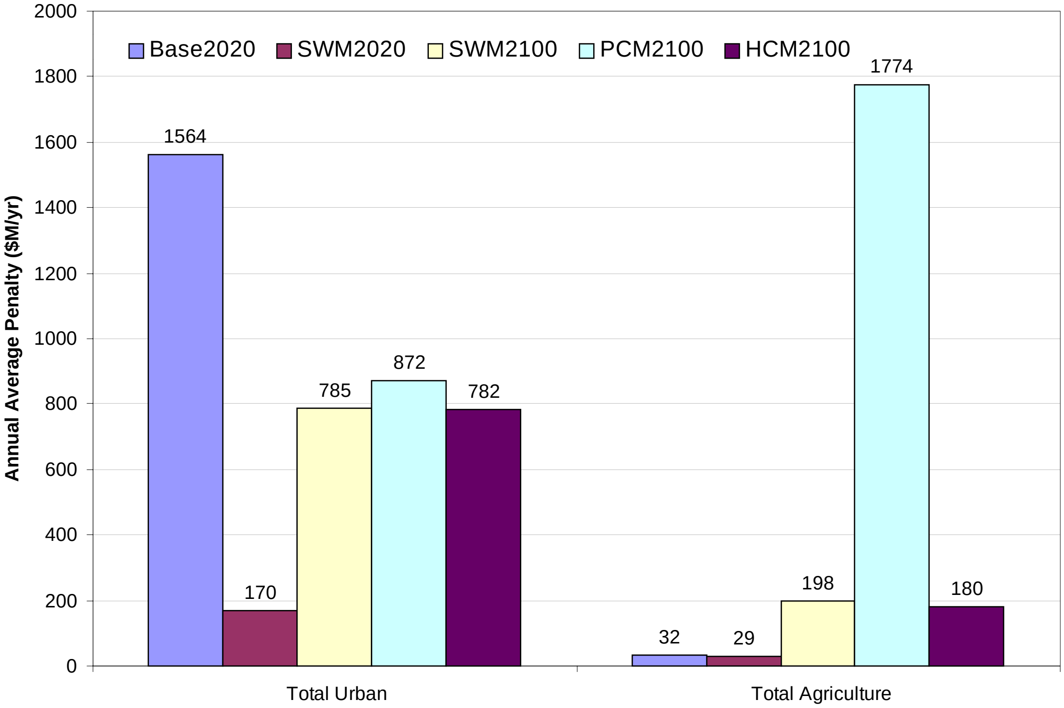

Figure 5-9. Average Annual Economic Scarcity Cost by Sector

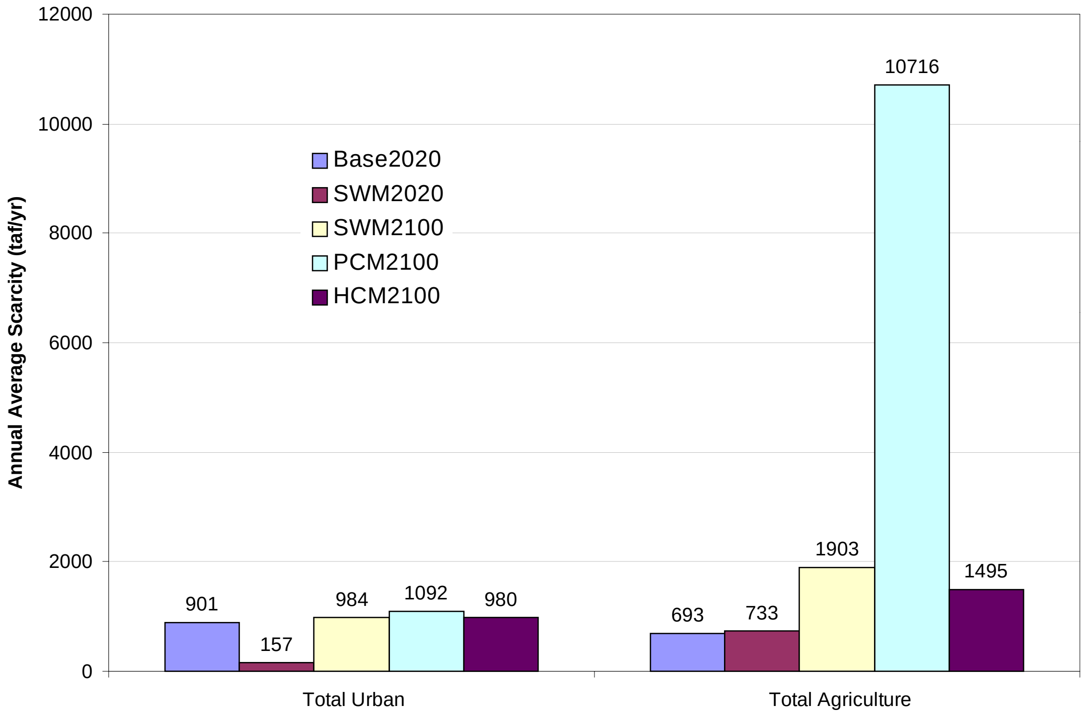

Figure 5-10. Total Volumetric Scarcity

The varying regional and sectoral character of these scarcities and scarcity costs and sensitivities to population growth and climate warming are shown in greater detail in Figures 5-11 and 5-12 and Table 5-3. The sensitivity of a region and sector are driven by competitive forces such as the relative values of water uses in the context of relative water availabilities and the availability of conveyance capacity to move water between regions.

For the urban areas, water scarcities generally imply water conservation measures. The demand curves used to estimate water scarcity costs represent consumers' willingness to use less water in exchange for lower water costs. Much of urban customer response to water scarcity therefore takes the form of installation of water-conserving plumbing fixtures, landscaping which requires less water, and various other water conservation actions, which often create financial and inconvenience costs to consumers.

As seen later, having "backstop" water source technologies available, such as wastewater reuse and seawater desalination, dampens the economic demands of water-short urban regions to import additional water. Willingness of urban coastal users to pay for additional imports would be limited by the availability of seawater desalination (at unlimited capacity) at $1,400/acre-ft.

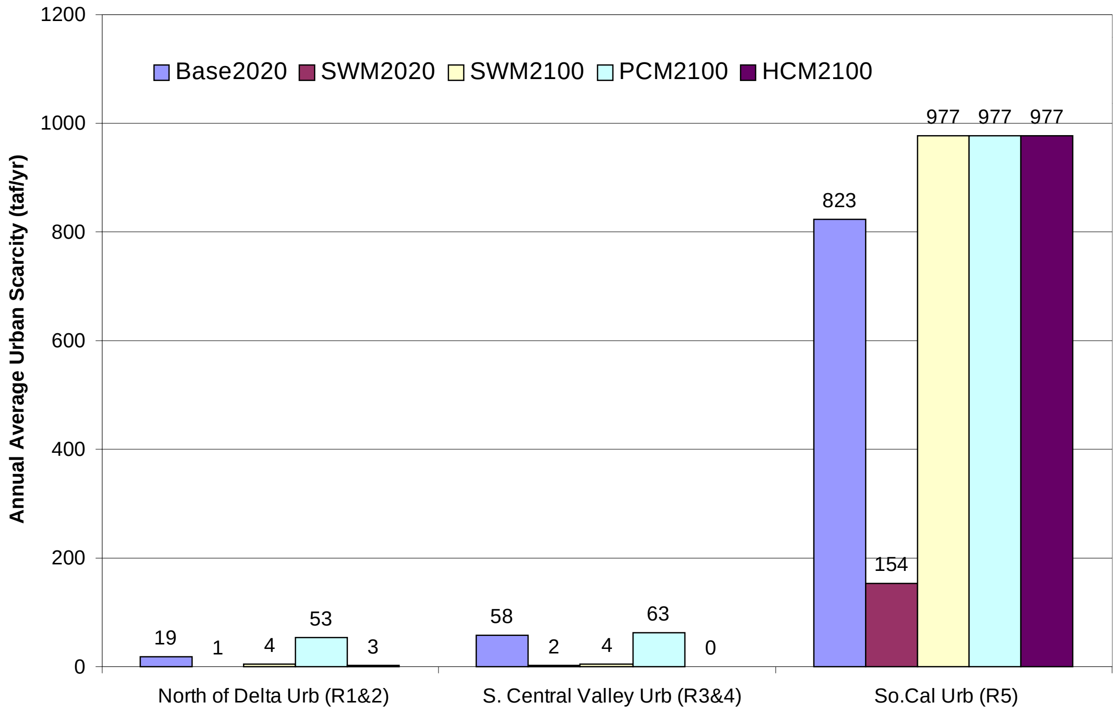

Figure 5-11. Urban Scarcity Cost by Region

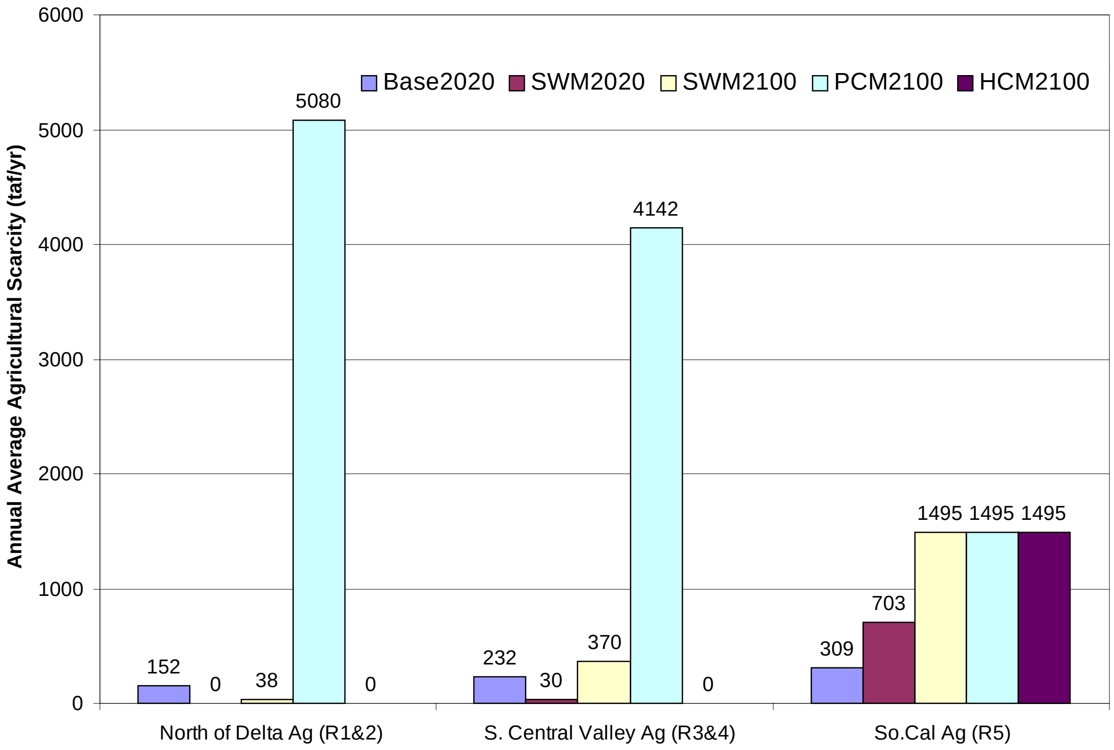

Figure 5-12. Agricultural Scarcity Cost by Region

Table 5-3a. Water Scarcity Costs for Agricultural Economic Demand Areas ($million/year)

Demand Area	Base2020	SWM2020	SWM2100	PCM2100	HCM2100
CVPM 1	0.0	0.0	0.0	11.5	0.0
CVPM 2	3.5	0.0	0.2	72.8	0.0
CVPM 3	3.1	0.0	0.0	215.5	0.0
CVPM 4	0.0	0.0	0.0	48.4	0.0
CVPM 5	0.0	0.0	0.2	240.4	0.0
CVPM 6	0.0	0.0	0.3	30.9	0.0
CVPM 7	0.0	0.0	0.0	74.9	0.0
CVPM 8	0.0	0.0	0.0	86.9	0.0
CVPM 9	0.2	0.0	0.0	42.9	0.0
CVPM 10	0.0	0.0	1.6	52.9	0.0
CVPM 11	0.0	0.0	0.0	68.6	0.0
CVPM 12	0.0	0.0	0.0	53.0	0.0
CVPM 13	0.0	0.0	1.3	139.9	0.0
CVPM 14	0.0	0.0	0.0	41.4	0.0
CVPM 15	0.4	0.8	2.9	85.6	0.0
CVPM 16	0.0	0.1	0.1	16.2	0.0
CVPM 17	0.0	0.2	0.4	49.4	0.0
CVPM 18	18.8	0.0	10.0	149.2	0.0
CVPM 19	0.0	0.0	0.0	36.7	0.0
CVPM 20	0.0	0.0	0.0	33.5	0.0
CVPM 21	0.0	0.0	1.4	44.2	0.0
Palo Verde	1.4	6.9	66.1	66.1	66.1
Coachella	0.0	0.9	8.4	8.4	8.4
Imperial	4.3	20.5	105.2	105.2	105.2
North of Delta Ag (R1&2)	6.8	0.0	0.8	824.2	0.0
S. Central Valley Ag (R3&4)	19.1	1.1	17.8	770.5	0.0
So.Cal Ag (R5)	5.8	28.3	179.7	179.7	179.7
Total Agriculture	**31.7**	**29.3**	**198.3**	**1774.4**	**179.7**

Table 5-3b. Water Scarcity Costs for Urban Economic Demand Areas ($million/year)

Urban Demand Area	Base2020	SWM2020	SWM2100	PCM2100	HCM2100
Redding	0.0	0.0	0.0	31.6	0.0
Napa-Solano	22.0	0.0	0.0	0.0	0.0
CCWD	0.1	0.0	0.0	0.0	0.0
East Bay MUD	12.5	0.6	3.7	24.1	2.8
Stockton	0.1	0.0	0.0	0.0	0.0
Sacramento	0.0	0.0	0.0	0.0	0.0
Yuba	0.9	0.0	0.0	0.0	0.0
Galt	0.0	0.0	0.0	0.0	0.0
San Francisco	5.1	0.0	2.4	8.8	0.0
Santa Clara Valley	10.2	0.0	0.0	16.0	0.0
Modesto	0.0	0.0	0.0	0.4	0.0
Turlock	0.0	0.0	0.0	1.7	0.0
Merced	0.0	0.0	0.0	0.5	0.0
SB-SLO	0.0	0.0	0.0	0.0	0.0
Fresno	17.7	0.7	0.0	0.2	0.0
Bakersfield	0.0	0.0	0.0	0.0	0.0
Sanger	0.0	0.0	0.0	0.0	0.0
Visalia	0.0	0.0	0.0	5.2	0.0
Delano	0.0	0.0	0.0	3.8	0.0
SBV	3.5	0.0	8.8	8.8	8.8
San Diego	34.7	0.0	150.7	150.7	150.7
East MWD	32.7	0.1	117.9	117.9	117.9
Central MWD	183.4	0.0	170.3	170.3	170.3
Castaic	507.8	2.7	18.9	18.9	18.9
Coachella	367.4	166.2	222.3	222.3	222.3
Mojave	180.7	0.0	45.8	45.8	45.8
Antelope Valley	185.2	0.0	21.1	21.1	21.1
Ventura	0.0	0.0	15.6	15.6	15.6
El Centro	0.0	0.0	4.5	4.5	4.5
Blythe	0.0	0.0	3.5	3.5	3.5
North of Delta Urb (R1&2)	35.5	0.6	3.7	55.7	2.8
S. Central Valley Urb (R3&4)	32.9	0.7	2.4	36.5	0.0
So.Cal Urb (R5)	1495.6	168.9	779.2	779.3	779.3
Total Urban	**1564.0**	**170.3**	**785.3**	**871.5**	**782.1**

Note: CCWD – Contra Costa Water District; SB-SLO – Santa Barbara and San Luis Obispo; SBV – San Bernardino Valley

Operations

Figures 5-13 and 5-14 show that surface water storage operations vary somewhat among the different model runs, with Base 2020 and HCM2100 runs generally having higher storages and PCM2100 surface storages generally being lower. In Figure 5-13, the same drought drawdown pattern can be seen for all scenarios (except HCM2100), with a similar seasonal drawdown-refill cycle for all scenarios. As seen in these figures, the model operates using a 72-year sequence of inflows, based on the historical record, to represent hydrologic variability and various complex expressions of wet and dry years, which is quite important for actual operations and water allocations, and the evaluation of system performance.

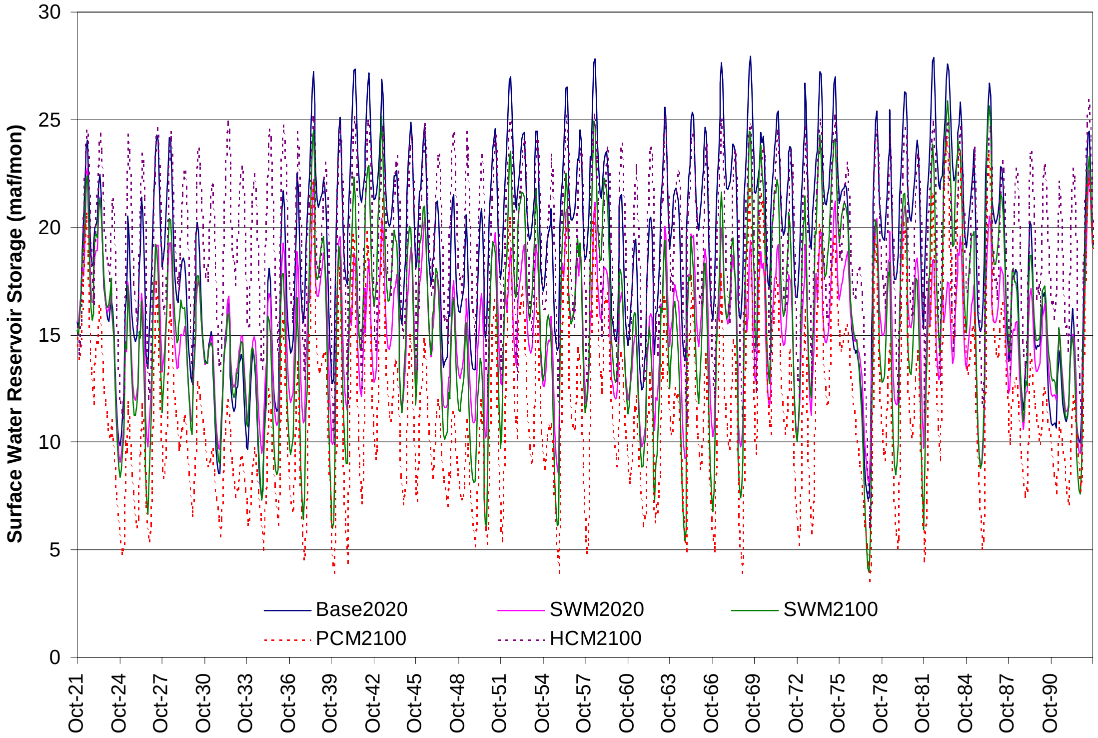

Figure 5-13. Statewide Surface Water Storage over 72-year Period

The most limiting type of facility for the year 2100 is conveyance capacity. This is especially true for Southern California, where present Colorado River Aqueduct and California Aqueduct capacities to deliver water to Los Angeles, San Diego, and other parts of metropolitan Southern California are used to their limits in all 2100 scenarios. This implies that urban users in these regions must be creative about new water supply technologies and the employment of water conservation/use efficiency. For 2100, Southern California employs considerable quantities of new water supply technology, averaging 1.4 maf/yr of additional wastewater recycling and 0.2 maf/yr of sea waster desalination. While these are large contributions by present-day standards, they represent only a modest proportion of Southern California's 2100 urban water demands. Increases in water use efficiency and water conservation are together represented as water scarcity and scarcity cost. While these are considerable in 2100 compared with SWM 2100, these scarcity costs are comparable to Base 2020, or what would be expected if current operation and allocation policies were continued until 2020. In the absence of climate change, flexible operations and allocations provide reasonable water supplies until 2100 for most of California.

Conveyance facilities are among the most binding constraints in the system in the year 2100. Figure 5-15 shows flows from the State Water Project's California Aqueduct to Southern California, over the Tehachapi Mountains. For both 2020 model runs, considerable conveyance capacity remains in this facility to provide additional water. For year 2100 demands, this facility is always at its capacity for every month of the 72-year period.

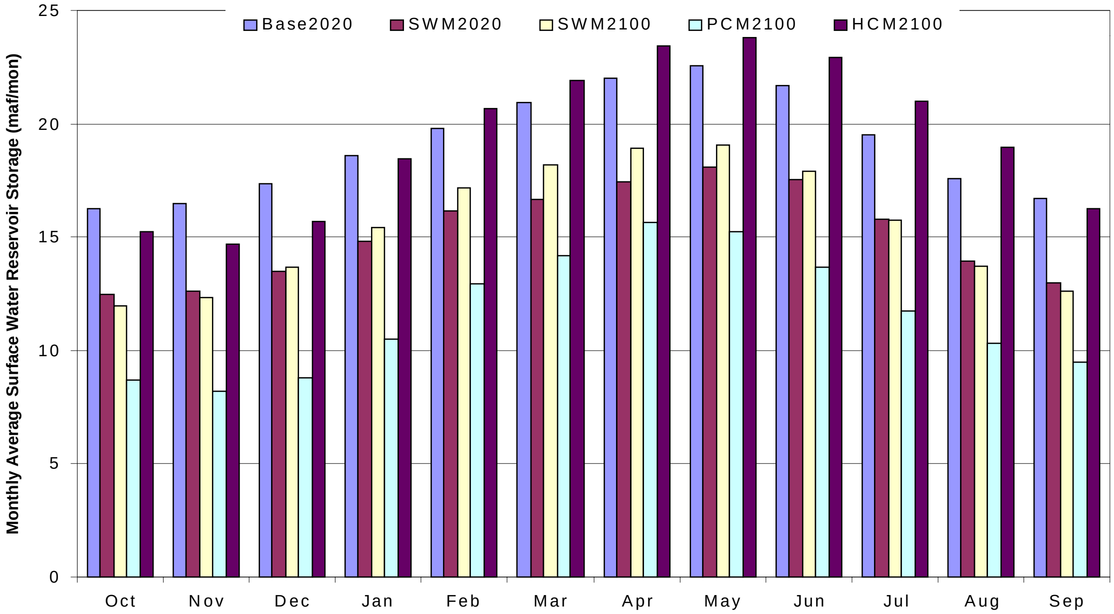

Figure 5-14. Average Seasonal Pattern of Surface Water Storage

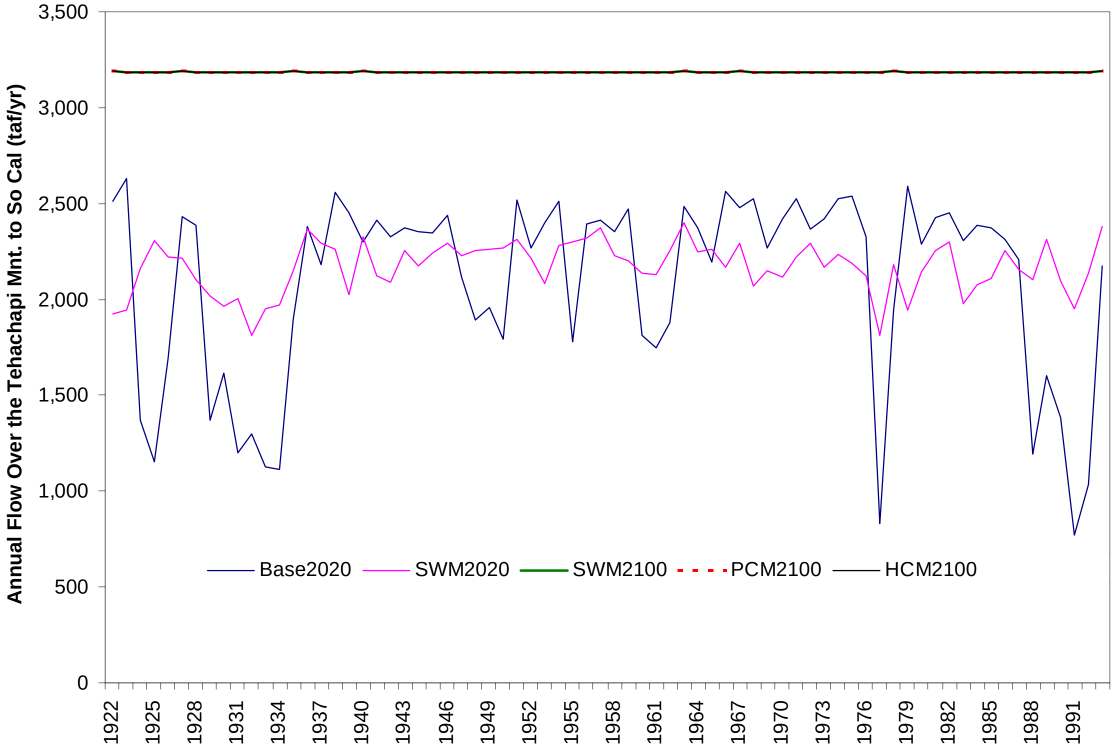

Figure 5-15. Annual Central Valley Imports to Southern California

Groundwater Use

Most water storage capacity in California is underground. This can be seen from comparing the scales of surface water storages and fluctuations in Figure 5-13 with those for groundwater storage in Figure 5-16. Increasing statewide water demands lead to increased use of groundwater storage to even out hydrologic variability. For some decades, most drought storage of water for California users has been underground. In the future, this will increase. Even with current operating policies, drought storage of water underground amounts to 27 maf in 2020. With optimized operations in 2020 (SWM2020), this amount increases to only slightly to 45 maf but is used more aggressively. With continued increases in urban water demands, use of groundwater for drought storage increases to about 51 maf in 2100 (SWM2100). This represents an expansion in storage far greater than any storage expansions contemplated for surface water storage.

While the volumetric use of groundwater for drought storage increases with time and urban water demands, the pattern of use remains similar with time, as seen in Figure 5-17 below. There is some slight increase in dependence on groundwater with time, but the major change is the change of operating policies from current policies (Base2020) to economic operations (SWM2020). Thereafter, the pattern of more explicit use of groundwater for drought storage remains clear and relatively constant.

While the qualitative nature of these groundwater findings are thought to be fairly secure, precise results are less certain, given the poor data available for representing groundwater And groundwater operations in models of California water (Jenkins et al. 2001).

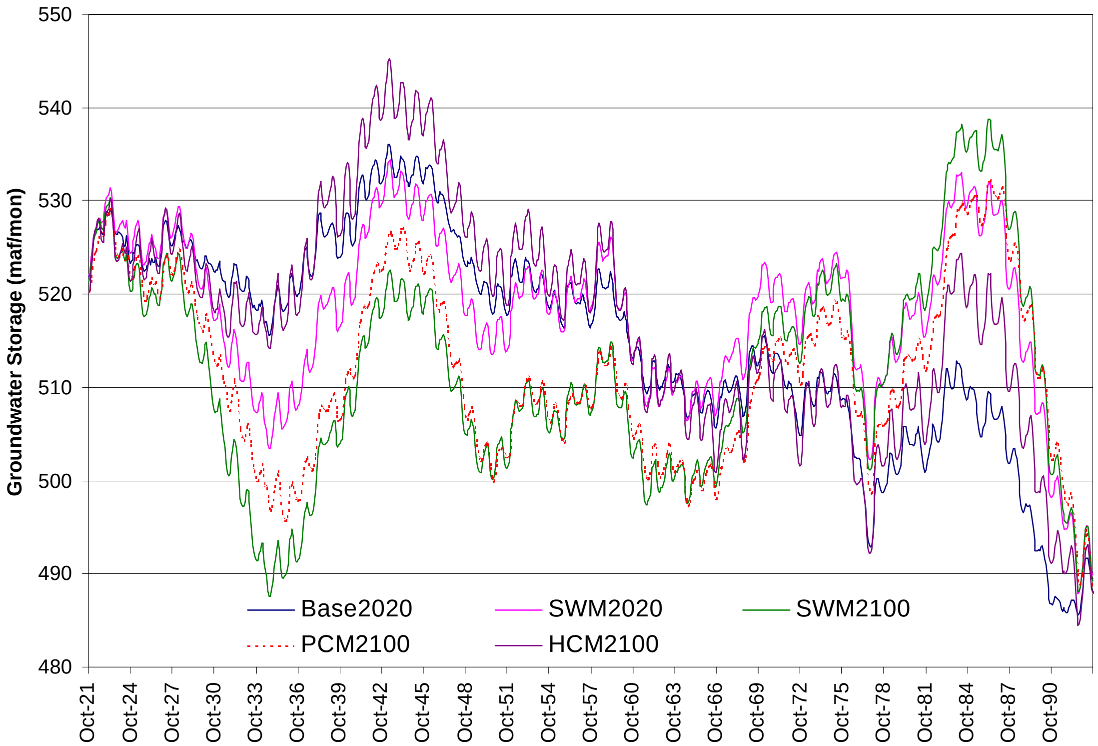

Figure 5-16. Groundwater Storage over the 72-year Period

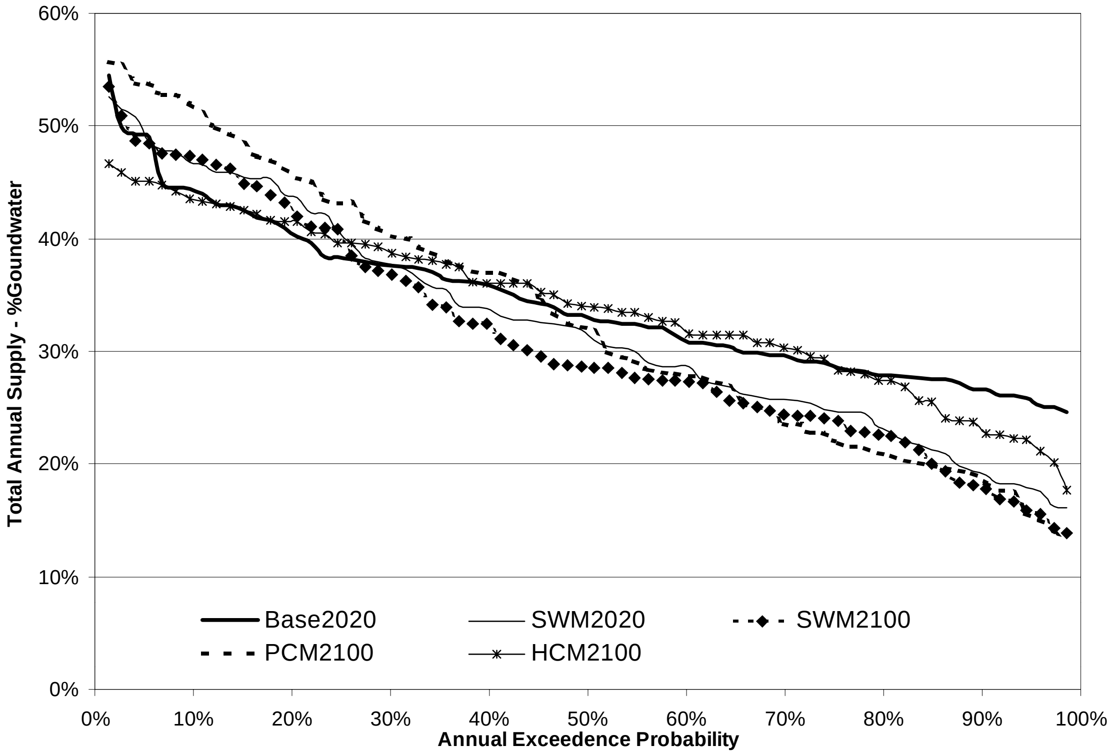

Figure 5-17. Annual Variability in Statewide Use of Groundwater

New Water Management Technologies

For any climate warming scenario, increasing urban water demands and non-expansion of conveyance capacity lead to increased use of new water supply technologies for the year 2100. This is particularly true for Southern California, which in our model runs is limited to existing conveyance capacity for importing additional water from outside its urban areas.

Figure 5-18 illustrates the increased use of wastewater reuse and seawater desalination for the three 2100 climate scenarios. Use of both new water supply technologies increases greatly, with somewhat greater use of both technologies occurring under the PCM2100 hydrology. About 240 taf/year of seawater desalination is employed, somewhat more with PCM2100 hydrology (at $1,400/acre-ft or $1.15/cubic meter). Urban wastewater reuse is employed at about 1,350 taf/year (1,600 taf/yr for PCM2100) above 2020 reuse levels (at $1,000/af).

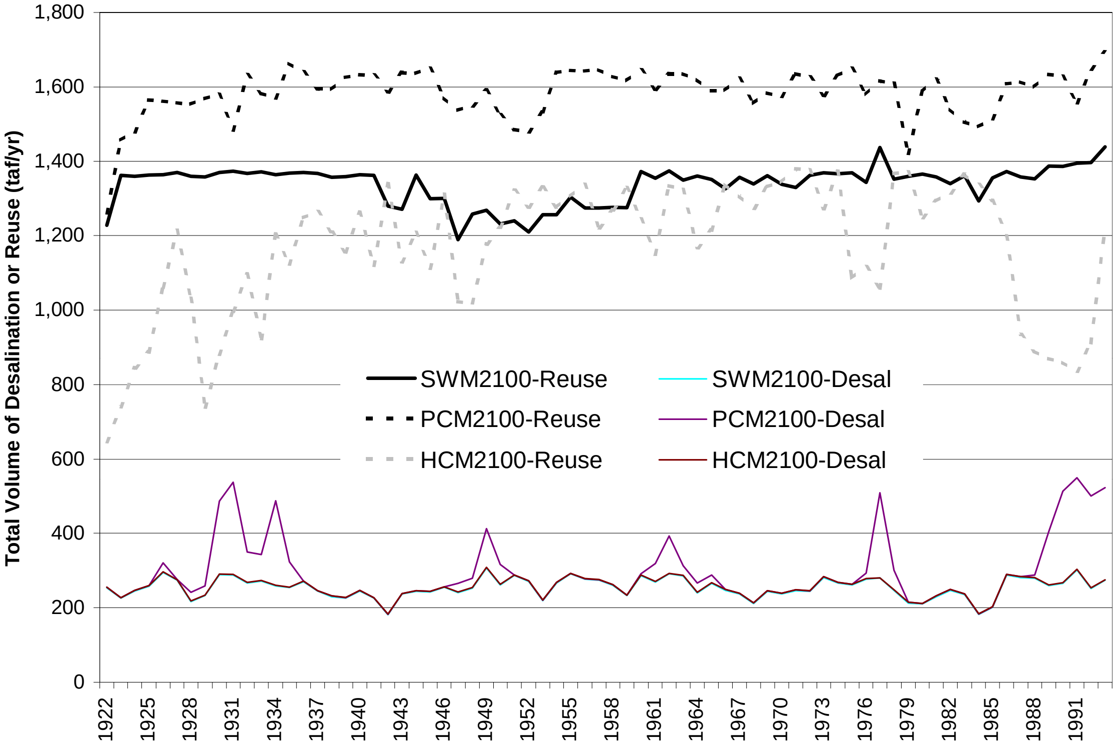

Figure 5-18. Use of Seawater Desalination and Urban Wastewater Recycling in 2100

Environmental Performance and Opportunity Costs

The shadow costs of various environmental flows to agricultural, urban, and hydropower users appear in Table 5-4 for the four optimized scenarios. The effects of population increase (and the addition of hydropower) are substantial, and would somewhat increase the economic basis for controversy over environmental flows. The increase in shadow costs from SWM2020 to SWM2100 is not overwhelming (especially considering that including hydropower in SWM2020 would raise some costs for that scenario).

The addition of the dry PCM2100 hydrology to the high population in SWM2100 creates a very substantial increase in the agricultural, urban, and hydropower costs of environmental flows. In most cases, the shadow costs of environmental flows are increased by at least an order of magnitude to very substantial absolute amounts. The dry PCM2100 form of climate warming would add substantial additional stress and controversy to environmental flows.

In some cases, the PCM2100 hydrology is infeasibly dry for some environmental flows. This hydrology simply does not have enough water in some parts of the system at some times to satisfy current environmental requirements, even if all water were allocated for environmental uses. These infeasibilities are noted in Table 5-5 and required modest reductions in some environmental flows. In the case of Mono Lake, for the dry PCM2100 scenario, the minimum storage constraint was eliminated; SWM2100 Mono Lake storage was 3.2 maf, while for PCM2100 is was 2.7 maf. In contrast, the wet HCM2100 hydrology is more benign than the historical hydrology in terms of the economic effects of environmental flows. For this scenario, many shadow costs disappear or are greatly diminished in importance.

Table 5-4. Shadow Costs of Environmental Requirements

	Average WTP ($/af)			
	SWM2020*	SWM2100	PCM2100	HCM2100
Minimum Instream Flows				
Trinity River	0.6	45.4	1010.9	28.9
Clear Creek	0.4	18.7	692.0	15.1
Sacramento River	0.2	1.2	25.3	0.0
Sacramento River at Keswick	0.1	3.9	665.2	3.2
Feather River	0.1	1.6	35.5	0.5
American River	0.0	4.1	42.3	1.0
Mokelumne River	0.1	20.7	332.0	0.0
Calaveras River	0.0	0.0	0.0	0.0
Yuba River	0.0	0.0	1.6	1.0
Stanislaus River	1.1	6.1	64.1	0.0
Tuolumne River	0.5	5.6	55.4	0.0
Merced River	0.7	16.9	70.0	1.2
Mono Lake Inflows	819.0	1254.5	1301.0	63.9
Owens Lake Dust Mitigation	610.4	1019.1	1046.1	2.5
Refuges				
Sac West Refuge	0.3	11.1	231.0	0.1
Sac East Refuge	0.1	0.8	4.4	0.5
Volta Refuges	18.6	38.2	310.9	20.6
San Joaquin/Mendota Refuges	14.7	32.6	249.7	10.6
Pixley	24.8	50.6	339.5	12.3
Kern	33.4	57.0	376.9	35.9
Delta Outflow				
Delta	0.1	9.7	228.9	0.0

*- SWM2100 results do not include hydropower values (except for Mono and Owens flows). #Shadow costs are the cost to the economic values of the system (urban, agricultural, hydropower, and operations) of a unit change in a constraint, in this case environmental flow requirements.

Table 5-5. Infeasible Environmental Requirements under PCM2100 Hydrology

Flow Location	Current Req.(taf/yr)	Average Reduction (taf/yr)		
		SWM2100	PCM2100	HCM2100
Trinity River	599	No change	1.1	No change
Sac. R. at Keswick	4,069	No change	112.3	8.43
Clear Creek	122	No change	11.1	No change
Sacramento R. (Various locations)	2,000-3,000	No change	36.9	No change
Sac. Nav. Control Pt.	3,293	No change	20.3	No change
Amer. d/s Nimbus	1,398	No change	0.6	No change
Mono Lake Inflow	74	No change	10.6	No change
Mono Lake min storage	-	No change	removed	No change
Total		No change	**328.7**	**8.4**

The average shadow costs in Table 5-4 often vary considerably by month and between wet and dry years. This is illustrated dramatically in Figure 5-19, a plot of the shadow costs of Trinity River instream flow requirements over time. Here, the differences in the average shadow costs for the different scenarios is very evident, but considerable seasonal and inter-annual variability is also evident. In wet years, environmental requirements can incur far lower than average costs, and in dry years these shadow costs can be considerably higher. This hints that there might be opportunities for more flexible forms of environmental regulation that could be mutually beneficial to both environmental and economic water users. The high costs of Trinity River environmental flows in the PCM2100 run arise from high economic costs of scarcity in the Redding metropolitan area.

Figure 5-20 offers similar insights from seasonal variability on shadow costs for Delta outflow requirements. In the case of Delta outflows, PCM2100 greatly reduces surplus delta outflows, Figures 5-21 and 5-22, both in magnitude and frequency, as well as increasing the shadow costs of minimum flows.

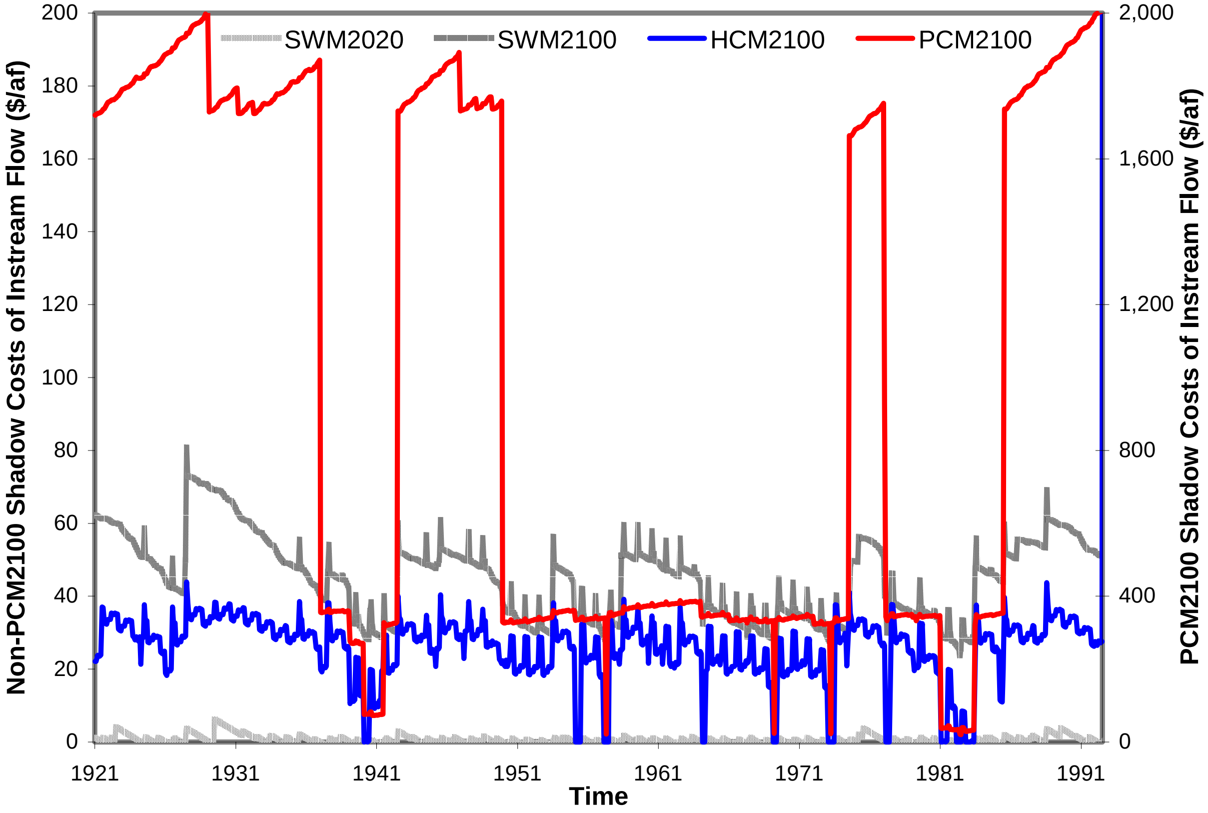

Figure 5-19. Time Series of Shadow Costs for Trinity River Outflow Requirement

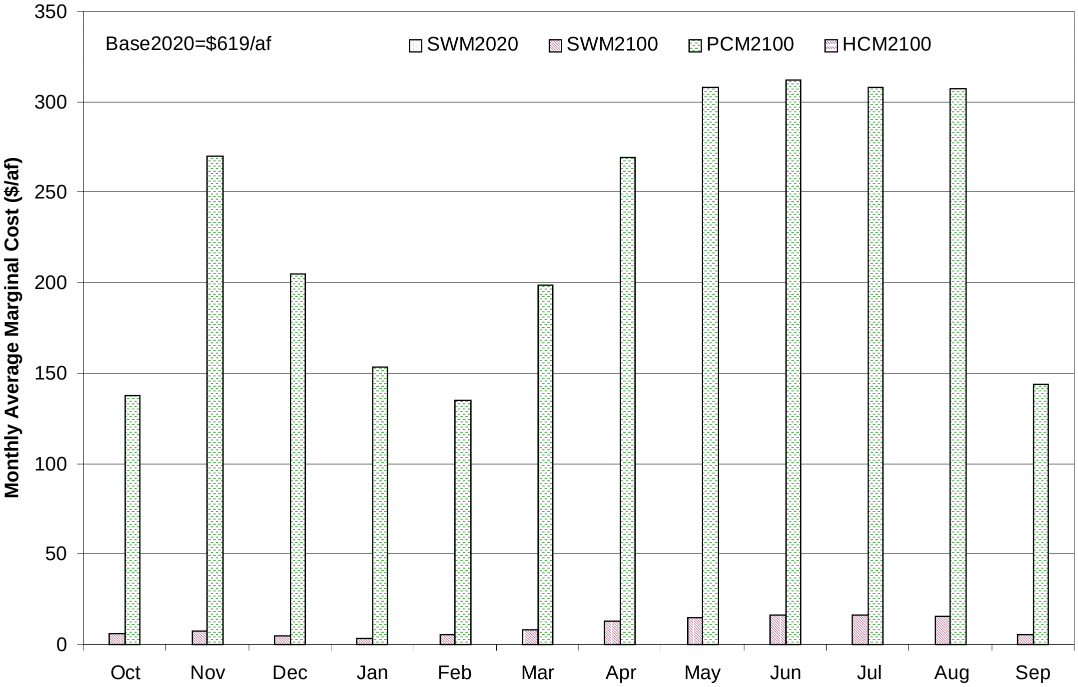

Figure 5-20. Opportunity (Shadow) Costs of Delta Outflow Requirements for Agricultural and Urban Users: Monthly Averages

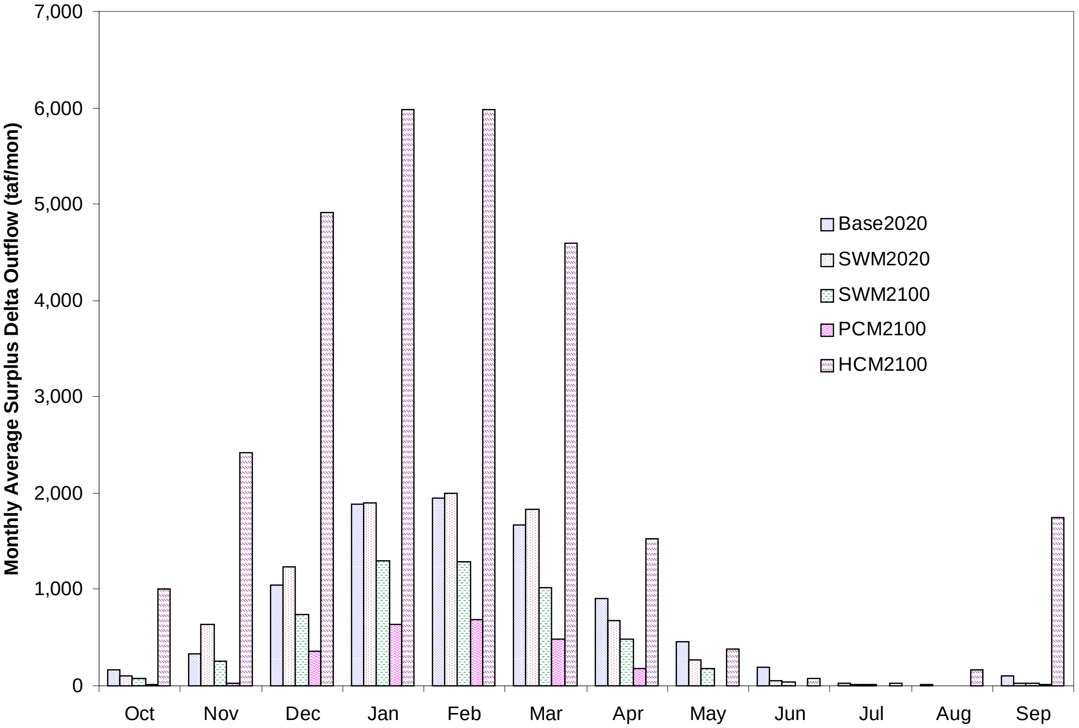

Figure 5-21. Monthly Average Surplus Delta Outflows

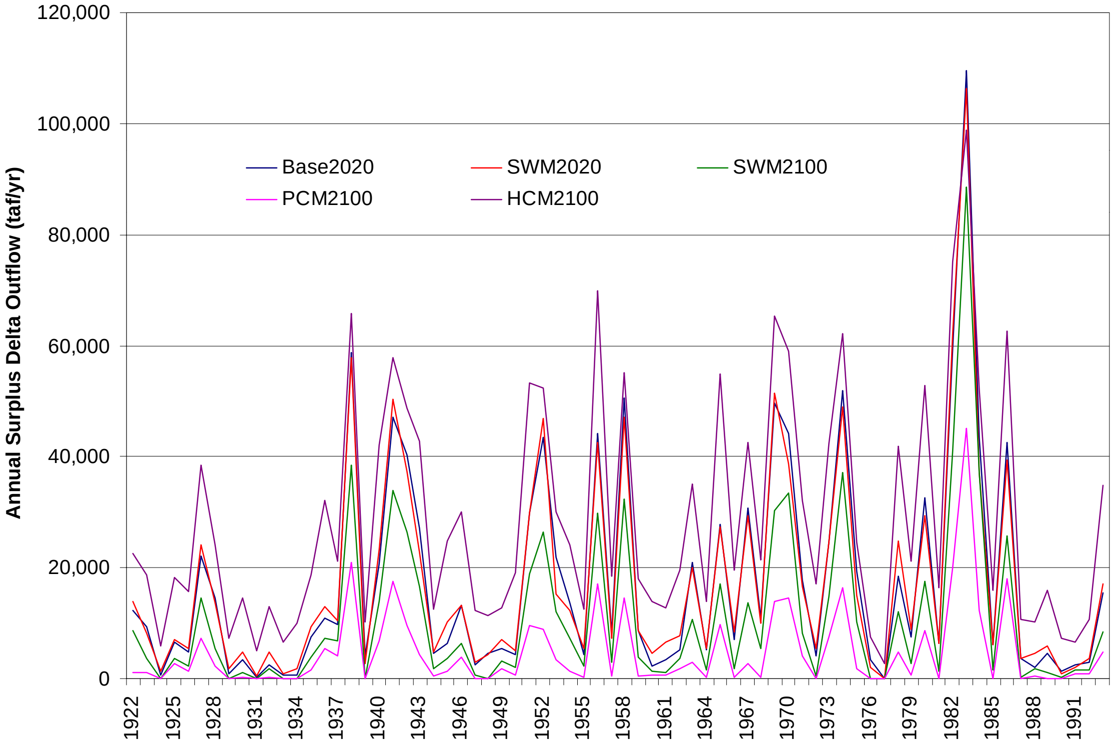

Figure 5-22. Annual Surplus Delta Outflow

Flood Flows

Climate warming's effects of depriving California's hydrology of the storage capacity of snowpacks, both for buffering floods and providing seasonal water supply storage, has long been a concern. While flood damages of water management have not been explicitly represented in this model, flood flows and flood frequencies in model results are apparent. Two examples of flood results from the three modeled hydrologies appear in Figures 5-23 and 5-24. In both cases, the dry warming PCM hydrology does not show a substantially greater flooding threat. This conclusion is somewhat tentative given the monthly basis of the model and the lack of explicit flood penalties in the model, but the curves demonstrate that for the PCM2100 hydrology, monthly flows at several especially vulnerable geographic locations do not seem greater, and are often much less than managed flows with the historical hydrology.

However, wet forms of climate warming could be devastating, as shown for the HCM2100 hydrology at these two critical locations. Monthly flood flows are tremendously greater than anything experienced historically. Given the magnitude of these flood flows relative to current or even imaginable flood storage capacity on these rivers, it is unlikely that flood storage in surface reservoirs would contain flood peaks. Monthly flows for many events on the American River are well above current levels. For the Sacramento River above the confluence with the American River, increases in flood flows could be greater still. In both cases, increased flood volumes could easily be above that controllable by current or potential surface water reservoirs.

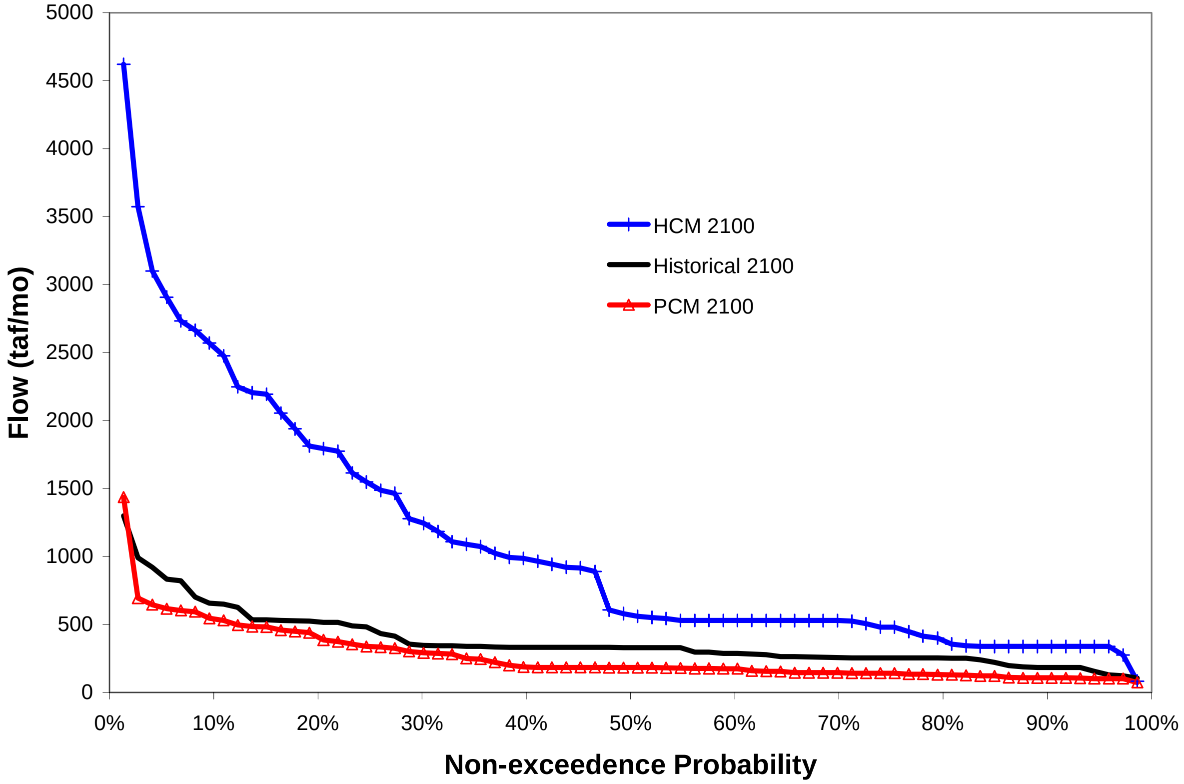

Figure 5-23. Annual Flood Probabilities: American River

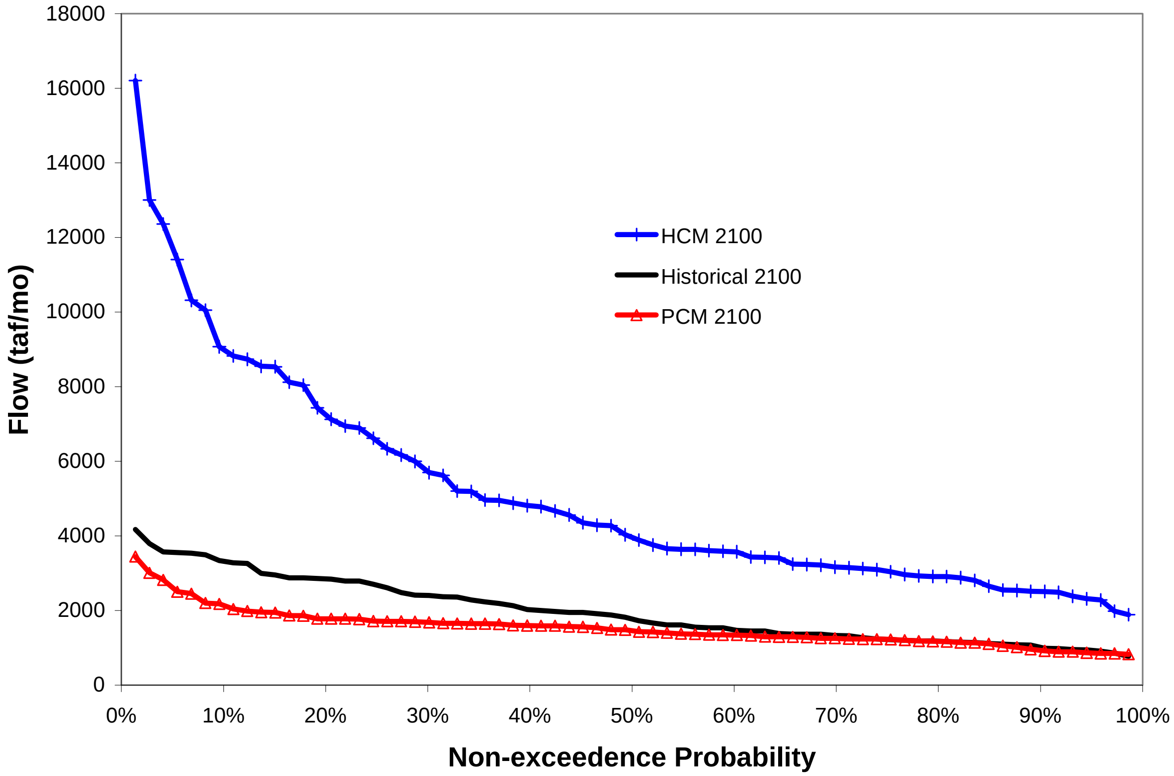

Figure 5-24. Annual Flood Probabilities: Sacramento River Upstream of Confluence with American River

These startling flooding results might be something of an artifact of the hydrology used for this and most other climate change projects; by changing each flow in the historic record by a constant monthly percent to represent climate warming seen in a short record of CGM results on a few basins, peak flows might be over-estimated (or underestimated). This merits further hydrologic and operational research, perhaps using a different set of permutations for different year-types for the GCM scenarios. The general magnitude of flood flow frequency changes after reservoir operation is not greatly different from that found for inflows before reservoir operations (Miller et al. 2002). Flood flow frequency and adaptation studies for the Lower American River (Zhu et al. 2003), based on the same HCM2100 hydrology (Miller et al. 2001), show serious, but not so overwhelming results. It is likely that additional flood studies for long-term urbanization and climate change are desirable, given the long-term nature of land use changes and flood control infrastructure decisions.

Value of Expanded Storage and Conveyance Facilities

Table 5-6 contains the average marginal values of increased capacity for various selected storage and conveyance capacities in California's water system for the year 2100 scenarios. All of these values are greater than those for year 2020 populations (Jenkins et al. 2001), reflecting increasing water demands over the intervening 80 years. For all scenarios expanding conveyance facilities typically has much greater value than expanding reservoir storage capacity.

Table 5-6. Average Marginal Value of Expanding Selected Facilities (Shadow Values)

	Average Marginal Value ($/unit-yr)		
Facility	**SWM2100**	**PCM 2100**	**HCM 2100**
Surface Reservoir (taf)			
Turlock Reservoir	69	202	56
Santa Clara Aggregate	69	202	56
Pardee Reservoir	68	202	56
Pine Flat Reservoir	66	198	56
New Hogan Lake	66	198	56
New Bullards Bar Reservoir	65	196	56
Los Vaqueros Reservoir	64	186	53
Lake Success	32	150	22
Lake Eleanor	28	125	21
Lake Mathews (MWDSC)	28	125	21
Lake Kaweah	28	124	21
Conveyance (taf/month)			
Lower Cherry Creek Aqueduct	7886	8144	7025
All American Canal	7379	7613	6528
Los Vaqueros delivery to Contra Costa Canal	7379	7613	6528
Putah S. Canal	7378	7611	6528
Mokelumne Aqueduct	7180	7609	6301
Coachella Canal	3804	3487	3618
Friant Kern Canal	1733	1960	3585
San Diego Canal	1289	1196	985
Colorado Aqueduct	1063	970	759
California Aqueduct	669	1823	452
Contra Costa Canal	519	543	373
Hetch Hetchy Aqueduct	489	410	452

Hydropower Performance

Hydropower generation and economic value were produced from the model for the major water supply reservoirs in the California system. While these do not include all the reservoirs in the system of importance to hydropower, they do include the major reservoirs where trade-offs exist between hydropower and water supply operations and are a significant proportion of statewide hydropower generation.

Hydropower production from the major water supply reservoirs in the California system would not be greatly affected by population growth, but would be reduced by the PCM2100 climate warming scenario. Base2020 hydropower revenues average $161 million/year from the major water supply reservoirs, compared with $163 million/year for SWM2100. However, the dry PCM2100 scenario reduces hydropower revenue 30% to $112 million/year. While this does not include the hydropower impacts of climate change on other hydropower plants in California, the percentage reduction is probably reasonable overall. With the wet HCM2100 hydrology, hydropower production greatly exceeds current levels ($248 million/year). Seasonal and inter-annual variability in hydropower generation and economic value is depicted in Figures 5-25 through 5-27.

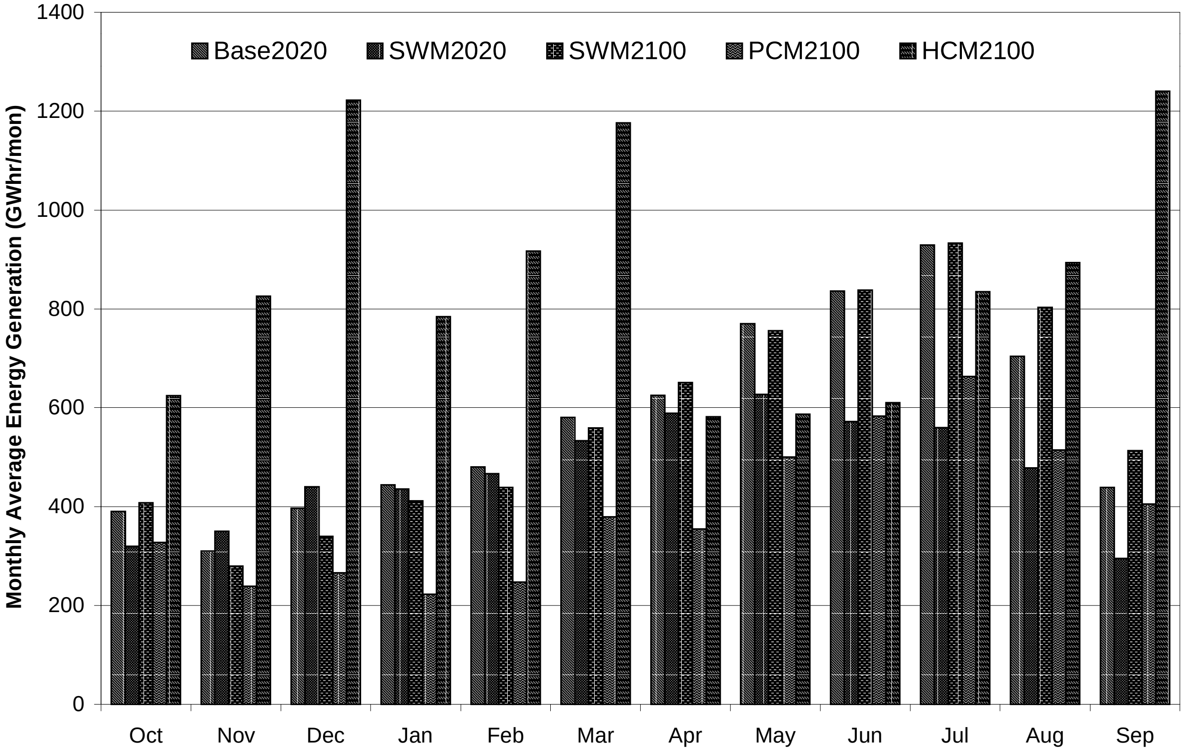

Figure 5-25. Monthly Hydropower Generation from Major Reservoirs

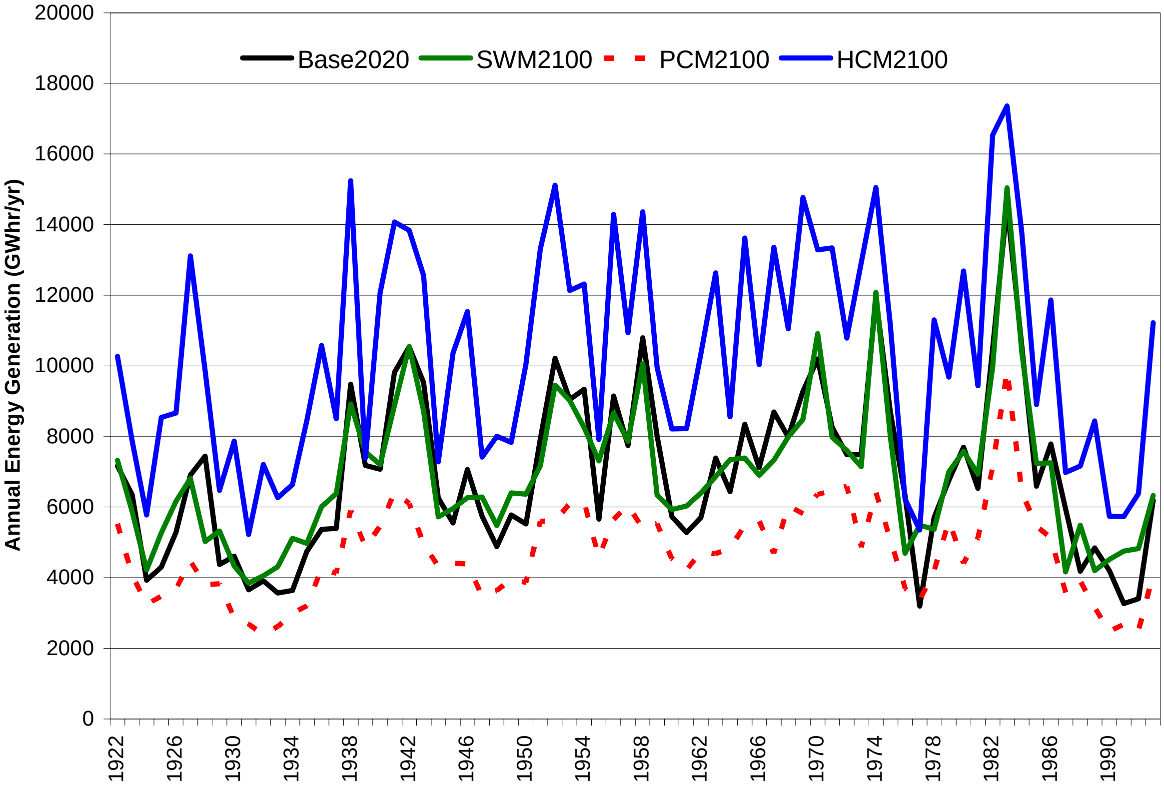

Figure 5-26. Annual Hydropower Generation from Major Reservoirs

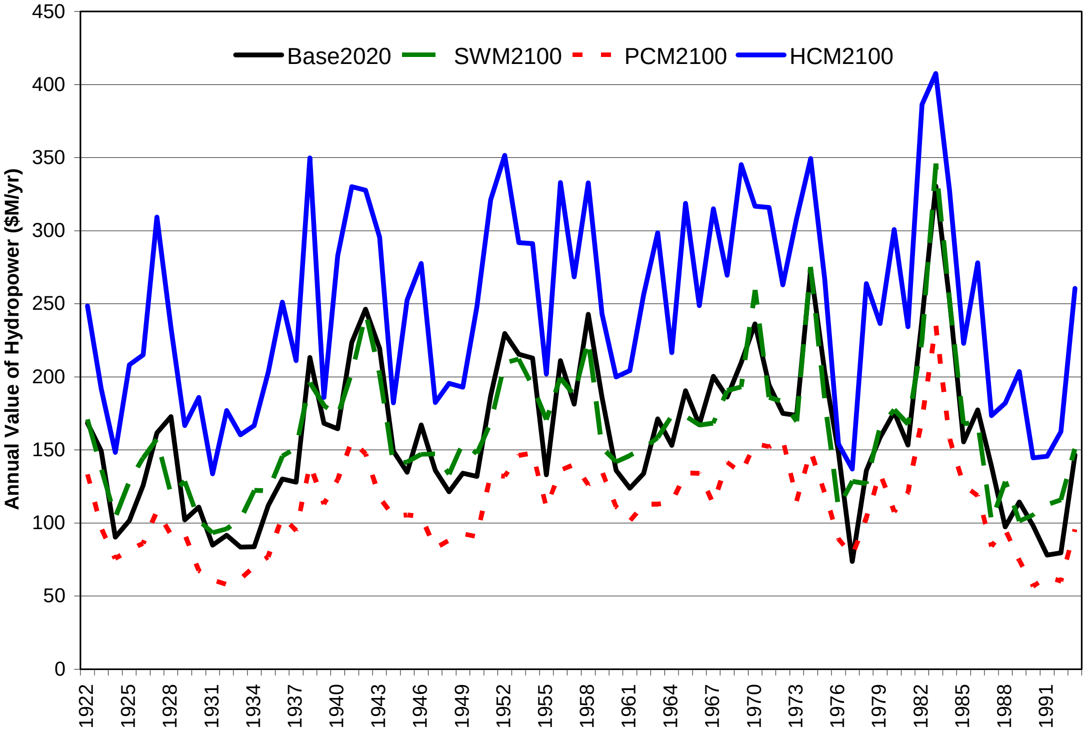

Figure 5-27. Annual Hydropower Value for Major Reservoirs

Changes in Agricultural Acreage and Income

Figure 5-28 shows changes in water use, irrigated acreage, and farm income between SWM2100 and PCM 2100 for 21 agricultural regions in the Central Valley. These results come from post-processing the agricultural water deliveries from the CALVIN model runs through the more detailed SWAP model of Central Valley agricultural production and economic value.

These model results illustrate the additional adaptive responses that farmers can take to climate changes and changes in water deliveries. While water deliveries are greatly reduced in many cases for the PCM2100 scenario, acres irrigated are reduced much less. And since farmers shift to higher valued crops, agricultural income reductions are much less still, averaging about 6% statewide despite about 24% reductions in agricultural water deliveries, with about 15% reductions in irrigated land.

Large complex systems tend to have many layers of potential adaptation. In the case of California water, the are layers of adaptation at state-wide, regional, local, and user levels that can provide a substantial level of buffering of climate warming impacts. However, for these layers of adaptation to be effective, they must be allowed and encouraged to function appropriately.

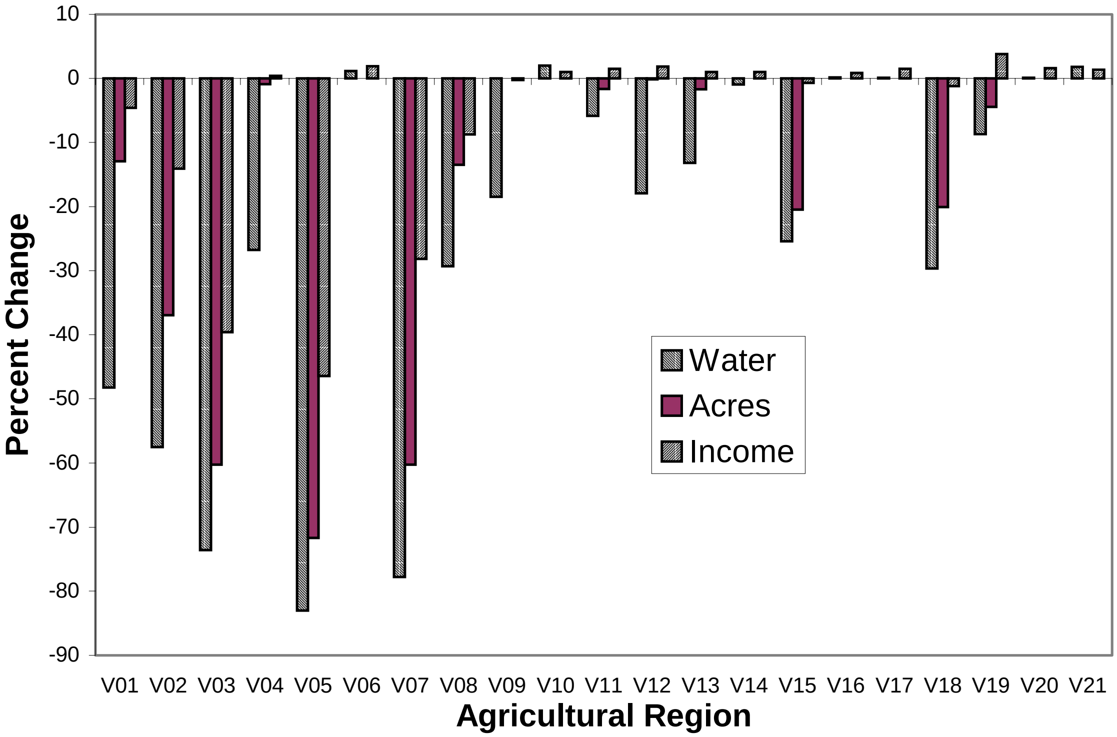

Figure 5-28. SWM2100 – PCM2100 Changes in Agricultural Water, Acreage, and Income by Central Valley Agricultural Region

CHAPTER 6

CONCLUSIONS

Many things could happen in the future. California has always changed, and change will continue. California's water management system has always been both a cause and result of other changes in California.

SOME QUESTIONS ANSWERED

What are some major changes that can be expected in California by 2100?

- Climate warming could easily be significant in the future. There are some hydrologic indications of climate warming recently in California (Aguado, et al. 1992; Dettinger and Cayan 1995).
- Sea level rise is fairly certain.
- Other changes in climate, including changes in climate variability, are possible, although we know less about them. Several types of climate variability seem present in the historic record and in contemporary climate processes.
- Population growth and technological changes are more certain, with implications for urban and agricultural land uses and water demands. Increases in household wealth may further increase water demands.
- Water use, reuse, and management technologies will improve, and show increased promise for the future, particularly in the absence of major conveyance facility expansions.
- Changes in water quality regulations are likely to be important.
- There will be incentives for change in management and institutions governing California water.

What would be the major hydrologic effects of climate warming?

- Winter streamflows generally will increase, with prospects for increased flooding. For wetter forms of climate warming, these effects might be large enough to overcome regulation by current or plausibly sized proposed reservoirs.
- Spring snowmelt runoff will decrease, challenging water supply operations.
- Continued or accelerated sea level rise will threaten islands and water quality in the San Francisco and San Joaquin Delta.
- Higher precipitation rates could substantially reduce or overcome effects of reduced snowpack on water supply.

- It is unclear if climate warming will increase or decrease total water availability for California.

Overall, climate warming could have either negative or positive effects on the ability of California to supply water for urban, agricultural, and environmental purposes. However, it appears most likely that the depletion of snowpack and spring runoff would lessen the performance of California's water supply system, at a time of major growth in high-valued urban water demands.

How could California's water system adapt to expected changes in 2100, including climate warming and 200% population growth?

California has a tremendously versatile natural and man-made water management system. It has a large capacity to adapt, including improvements in conjunctive use of ground and surface waters, water markets, transfers, and exchanges, urban wastewater reuse, seawater desalination, and water use efficiency improvements. While this capacity to adapt is large, it is not an infinite or perfect ability to adapt to huge changes. Scarcities of water are likely to occur at some locations and times, and it is sometimes more expensive to supply additional water than the cost of accepting some water scarcity. While some scarcity can be optimal, there is also considerable value for expansion of some facilities, particularly conveyance. Most of these changes are desirable with or without changes in climate, and are driven solely by growth in water demands.

Could California's water system adapt to these anticipated growth and climate warming changes?

California's water system could economically adapt to the range of climate warming scenarios examined. In the most extreme dry scenarios for climate warming, the Central Valley's agricultural sector would be severely affected. The costs and damages from severely dry climate warming would be significant, on the order of the current revenues for California's largest water district (about $1 billion currently). But on a statewide and economy-wide basis, these water supply and hydropower costs are not large. California's current State budget is almost $100 billion/year and its gross domestic product is about $1.3 trillion/year.

What are the most promising adaptations for California's water management system to respond to severe dry forms of climate warming?

In responding to the severely dry PCM2100 climate warming scenario, the optimization model results suggest:

- Conjunctive use of ground and surface waters to cover storage is very promising economically.

- Sales of water from agriculture to urban areas could compensate economically for lesser amounts of available water.

- Fallowing of agricultural land results from lesser water availability and water sales.

- Some facility expansions, particularly conveyance and wastewater reuse, appear economically promising.

These same responses are also promising, though to lesser degrees for historical hydrology and the warm wet HCM hydrology. These actions, and the required institutional changes needed to support then, would constitute a potential “no regrets” strategy (Stakhiv 1998).

What would be the greatest problems for California from severely dry climate warming?

- Central Valley agriculture could be devastated by severely dry forms of climate warming. Some Central Valley regions would lose or sell on the order of half their desired water use.

- Environmental water uses become vastly more expensive in terms of their effects on agricultural, urban, and hydropower economic performance. This would tend to greatly increase the controversy of water management in California.

- Southern California urban users, being largely isolated from the system by limited conveyance capacity and having very high willingness-to-pay for water, would be much less affected by climate change. However, Southern California users are acutely affected by population growth.

How would climate warming affect the lives of future Californians?

Who knows, really? Here are some speculations. …

- Urban water users would see much higher costs for water supply. While expensive, these costs would provide fairly reliable supplies and involve more use of newer wastewater reuse, desalination, and water use efficiency technologies.

- Central Valley agriculture is rather un-sheltered from positive or negative effects of climate warming on water supplies. Some financial buffering for farm owners exists from potentially lucrative sales of water to cities, particularly in dry climate warming scenarios.

- Flooding effects could be very substantial with wet forms of climate warming. These flooding effects could be beyond the management capabilities of plausible reservoirs. In such a case, expansion of floodways with large changes in floodplain land use might become desirable.

- Drier climate warming scenarios greatly increase the likelihood and severity of economically motivated conflicts over environmental water allocations. Under drier scenarios, the system as a whole must be more tightly managed with greater consequences for all users, but especially agricultural and environmental uses. Conversely, wetter climate warming greatly reduces the frequency and severity of trade-offs and potential conflicts among water supply uses.

- Climate warming, of any form, would create incentives for changes in the management of California’s water.

What potentially big effects were not considered in this study?

Many factors cannot be considered in any real and finite analysis, some missing things that are likely to be important include:

- Flood damages and adaptation to floods were not explicitly considered in these model results. For wet forms of warming, these effects are likely to be considerable. Zhu et al. (2003) provide some very preliminary results for the Lower American River, based on the HCM hydrology used in this study.

- Since urbanization of agricultural land in the Central Valley was not accounted for in the model runs, modeled Central Valley agricultural water demands are about two million acre-feet/year too high. While this is a large quantity of water, it is not enough to change the reports qualitative conclusions; Central Valley agriculture would remain tremendously affected under the PCM2100 hydrology and relatively unaffected for the historical and HCM2100 hydrologies.

- Non-population effects on water demands were largely omitted from this study. Urban demands could be larger due to increased wealth or smaller due to improvements in water use efficiency. Agricultural water demands could be larger or smaller due to changes in prices and demands for agricultural products and technological or climatic changes in agricultural yields, and could be smaller due to increased real costs of agricultural production due to the environmental impacts of agriculture.

- Delta salinity and other water quality requirements are taken from 2020 modeling studies by the California Department of Water Resources (DWR). Recent preliminary post-processing of the CALVIN PCM2100 results through the DWR hydrodynamic model of Delta salinity indicates problems with salinity intrusion in winter months, although this might also be an artifact of assumed in-Delta operations. Mode examination of this issue is desirable, perhaps in conjunction with sea level rise.

- Sensitivity of results to large reductions in costs for seawater desalination or wastewater reuse. Based on the costs of alternative sources of water, if costs of desalination or reuse were reduced to $500-$800/acre-foot, these newer technologies could economically displace some traditional supplies for coastal and urban areas. Some results are also likely to be sensitive to the availability of conveyance and groundwater recharge capacity, as indicated by shadow values on facility capacities.

- Climate changes other than warming might have significance. Sea level rise effects on Delta exports and agriculture is likely to be important. Climate variability and changes in this variability, while currently difficult to represent for analytical purposes, could be quite important.

- The ability of California’s water management institutions to adopt adaptations to population growth and climate changes is assumed here to be graceful and very effective. While water management institutions certainly adapt to changes in conditions, they do so sometimes slowly and often imperfectly.

OVERALL STUDY CONCLUSIONS

The main conclusions of this work are:

1) Methodologically, it is possible, reasonable, and desirable to include a wider range of hydrologic effects, changes in population and water demands, and changes in system operations and management in impact and adaptation studies of climate change than has been customary. Overall, including such aspects in climate change studies provides more useful and realistic results for policy, planning, and public education purposes.

2) A wide range of climate warming scenarios for California shows significant increases in wet season flows and significant decreases in spring snowmelt. This conclusion, confirming many earlier studies, is made more generally and quantitatively for California’s major water sources. The magnitude of climate warming’s effect on water supplies can be comparable to water demand increases from population growth in the coming century. Other forms of climate change, such as sea level rise, were not examined.

3) California’s water system can adapt to the population growth and climate changes modeled, which are fairly severe. This adaptation will be costly in absolute terms, but, if properly managed, should not threaten the fundamental prosperity of California’s economy or society, although it can have major effects on the agricultural sector. The water management costs are a tiny proportion of California’s current economy.

4) Agricultural water users in the Central Valley are the most vulnerable to climate warming. While wetter hydrologies could increase water availability for these users, the driest climate warming hydrology would reduce agricultural water deliveries in the Central Valley by about a third. Some losses to the agricultural community in the dry scenario would be compensated by water sales to urban areas, but much of this loss would be an uncompensated structural change in the agricultural sector.

   The balance of climate warming effects on agricultural yield and water use in unclear. While higher temperatures can be expected to increase evapotranspiration, longer growing seasons and higher carbon-dioxide concentrations can be expected to increase crop yield. The net effect is likely to be an increase in crop yields per unit water.

5) Water use in Southern California is likely to become predominantly urban in this century, with Colorado River agricultural water use being displaced by urban growth and diverted to serve urban uses. This diversion is limited only by conveyance capacity constraints on the Colorado River Aqueduct deliveries of Colorado River water and California Aqueduct deliveries of water from the Central Valley. Given small proportion of local supplies in southern California, the high willingness-to-pay of urban users for water, and the conveyance-limited nature of water imports, this region is little affected by climate warming. Indeed, even in the dry scenario, Southern California cannot seek additional water imports. Population growth, conveyance limits on imports, and high economic values lead to high use of wastewater reuse and lesser but substantial use of seawater desalination along the coast.

6) Flooding problems could be formidable under some wet warming climate scenarios. Flood flows indicated by the HCM2100 scenario would be well beyond the control capability of existing, proposed, and probably even plausible reservoir capacities. In such cases, major expansions of downstream floodways and changes in floodplain land uses might become desirable.

7) While adaptation can be successful overall, the challenges are formidable. Even with new technologies for water supply, treatment, and water use efficiency, widespread implementation of water transfers and conjunctive use, coordinated operation of reservoirs, improved flow forecasting, and the close cooperation of local, regional, state, and federal government, the costs will be high and there will be much less "slack" in the system compared to current operations and expectations. The economic implications of water management controversies will be greater, motivating greater intensity in water conflicts, unless management institutions can devise more efficient and flexible mechanisms and configurations for managing water in the coming century.

8) The limitations of this kind of study are considerable, but the qualitative implications seem clear. It behooves us to carefully consider and develop a variety of promising infrastructure, management, and governance options to allow California's local, regional, and statewide water systems to respond more effectively to major challenges of all sorts in the future.

FURTHER RESEARCH

1) Improvements to the base CALVIN model are desirable for many purposes. Desirable improvements are detailed in Chapter 5 of Jenkins et al. (2001). Especially desirable improvements include representation and hydrology in the Tulare Basin and ability to operate with lesser levels of hydrologic foresight. Improved representation of groundwater recharge, operations, and quality in many parts of California are also desirable.

2) Effects of sea level rise on water availability through the Sacramento-San Joaquin Delta are of potentially great importance. These could not be included in this study, but merit further examination. As part of such work, improved Delta outflow water quality requirements for 2100 conditions and hydrologies should be developed.

3) For climate change studies in particular, inclusion of flood damages and explicit incorporation of agronomic and land use effects on economic values of water deliveries for agriculture would be useful. This study collected data for such improvements, but was unable to incorporate them into the model in time for this study's completion.

4) Modeling of flood flow impacts, responses, and adaptations are likely to be very important for wet climate warming scenarios. Given the potential magnitude of these flooding impacts, land use changes and adaptations and their economics should be incorporated explicitly. Some other non-CALVIN modeling results for climate warming and flooding on the Lower American River (Zhu et al. 2003), give a more refined, but still preliminary look at this problem.

5) This study examined only some forms of climate warming and their effects on long-term management of California water. In addition to sea level rise, there is evidence of significant long-term variability in California's climate, not necessarily related to climate warming. These and other reasonable climate change scenarios should be considered for additional operational studies.

6) Hydrology development for this work was based on monthly-varying permutation ratios for each stream in the modeled system. For the GCM scenarios, it might be valuable to develop more complex hydrologies, where these permutation ratios vary with year-type (e.g., wet, dry, and intermediate years). This might show some effects on drought and flood behavior. Running additional hydrologies through the management model would allow assessment of intermediate and perhaps more extreme climate change scenarios.

7) Additional post-processing of results would reveal impacts and promising adaptations in more detail.

8) Additional index basins and improvements in deep percolation and reservoir evaporation representations would help refine hydrologic estimates of climate warming. In doing so, consideration should be given to altering flows by year-types, rather than having all years altered by the same monthly factors. If wet and dry years are changed differently with a climate change scenario, it is important to try to preserve such changes when going from GCM results to hydrologic inputs for distributed operations models.

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APPENDICES

A - Hydrology

B - Urban Water Demands

C - Agricultural Water Demands

D - Hydropower Demands

E - Revised Environmental Constraints

F – Miscellaneous Revisions for CEC Climate Change Study

APPENDIX F

MISCELLANEOUS REVISIONS FOR CEC CLIMATE CHANGE STUDY

Table F-1: List of Local Supply Modifications to CALVIN for 2100 Demands and Perturbed Hydrologies

(These are further modifications in addition to creating an initial set of new supply links for each of the new urban economic demands created for 2100).

New Links with UPPER BOUNDS = 0:

C173_T43 UB=0, cost $50

New and old links with modified UPPER BOUNDS:

a. Mallard PMP_C71 set back to UBMonthly of about 3 taf/mo. cost 299

b. GW-SCV_T7, from previous 30.5 to 45.7 (raised 50% for 2100 demands)

c. D662_T66 set to Ag capacity for D662 to CVPM 12 ($50 cost) (UB=107.1)

d. C65_T53, Delano (CVPM 20 urb) set to ag capacity for C65 to CVPM 20 ($50 cost) UB=79.2

e. FKC C688_T51 and C56_T51 Kaweah (urban CVPM 18 Visalia) set to ag link upper bound and $50 cost

Existing links with unconstrained Upperbounds (change constraint method to "none" for upper bound):

a. GW-21_T28 & D850_T28 (Bakersfield)

b. D16_T45 & D662_T45 (Modesto)

c. C74_C97 & C74_HSU20C74 (Cross Valley canal deliveries to CVPM 19 and 20)

d. C689_C65 (FKC wasteway to Kern River)

e. D689_HSU11, D664_HSU11, & D672_HSU11 (SW supplies for CVPM 11 from San Joaquin, lower Tuolemne and lower Stanislaus)

f. C49_T24 (Fresno Urban supply from FKC)

g. D606_HSU16 (San Joaquin R supply to CVPM 16 AG)

h. D645_T66 (Merced to Turlock CVPM 12 Urb)

i. D848_D849 (Coastal Aqueduct ending capacity of 71 cfs or 3.94-4.3 taf/mo turned off)

j. T11_C158, wastewater recharge to lower Coachella valley, set to unconstrained (constraint on total recharge capacity C158_GW-CH)

k. SR-28_C106 and SR-29_C106

New Links with unconstrained capacity:

a. D871_T3 (Mojave SWP direct use); cost would be $349 unconstrained

b. C136_T31 (CRA to Coachella direct use) unconstrained, cost = 251

c. Add new node HWTC147, and links C147_HWTC147, HWTC147_T31 (Coach Canal direct to Coachella Urban) unconstrained, cost = 372