CLIMATE WARMING AND WATER MANAGEMENT ADAPTATION FOR CALIFORNIA

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Abstract. The ability of California's water supply system to adapt to long-term climatic and demographic changes is examined. Two climate warming and a historical climate scenario are examined with population and land use estimates for the year 2100 using a statewide economic-engineering optimization model of water supply management. Methodologically, the results of this analysis indicate that for long-term climate change studies of complex systems, there is considerable value in including other major changes expected during a long-term time-frame (such as population changes), allowing the system to adapt to changes in conditions (a common feature of human societies), and representing the system in sufficient hydrologic and operational detail and breadth to allow significant adaptation. While the policy results of this study are preliminary, they point to a considerable engineering and economic ability of complex, diverse, and inter-tied systems to adapt to significant changes in climate and population. More specifically, California's water supply system appears physically capable of adapting to significant changes in climate and population, albeit at a significant cost. Such adaptation would entail large changes in the operation of California's large groundwater storage capacity, significant transfers of water among water users, and some adoption of new technologies.

1. Introduction

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, energy and budget crises, population growth, and climatic change.

In California, concern for climate change has increased in recent years with research on global climate change applied to California and studies of how California's climate has changed recently (Dettinger and Cayan, 1995; Gleick and Chalecki, 1999; NRC, 1999) and in recent millennia (Stine, 1994, 1996; Haston and Michaelson, 1997; Meko et al., 2001). 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 (Gleick, 1987; Roos, 1987; Lettenmaier and Gan, 1990; Snyder

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et al., 2002). The potential effects of climate change on California have been widely discussed from a variety of perspectives (Lettenmaier and Sheer, 1991; Gleick and Chalecki, 1999; Gleick, 2000; Wilkinson, 2002; VanRheenen et al., 2004). Forests, marine ecosystems, energy use, coastal erosion, water availability, flood control, and general water management issues have all been raised. Climate changes for the future include continued sea level rise (Logan, 1990; IPCC, 2001; Roos, 2002), continued long-cycle variations such as ENSO and Pacific Decadal Oscillations (Haston and Michaelson, 1997; Cayan et al., 1999; Biondi et al., 2001), climate warming (Dettinger and Cayan, 1995; Huber and Caballero, 2003), and perhaps other forms of climate change (Hulme et al., 1999; Arnell, 1999).

Over the next 100 years, much will happen in California. While this time-frame is distant, 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 often 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 that evolved 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 also increase. While, no one can be sure exactly what will happen in the next 100 years, prudence asks that we examine a range of reasonable long-term scenarios.

This paper focuses on the likely effects of a range of climate warming estimates on the long-term performance and management of California's water system. A relatively comprehensive approach is taken, which considers the entire inter-tied California water supply system, including ground and surface waters, agricultural and urban water users, environmental flows, hydropower, and potential for changing water supply infrastructure and management. A large-scale economic-engineering optimization model of California's water supply, CALVIN (CALifornia Value Integrated Network), is employed to examine the ability of this complex, extensive, and diverse system to adapt to significant changes in climate and population (Draper et al., 2003). The results are examined both for their implications for climate change research and for California water policy in the face of major long-term population and climate changes (Lund et al., 2003).

2. Project Approach

Many types of climate change can affect water and water management in California. This paper examines climate warming, and neglects, for the time being climate variability, sea level rise, and other forms of climate change. Twelve distinct climate-warming scenarios were examined to develop integrated statewide hydrologies covering changes in all major inflows to the California inter-tied water system. For

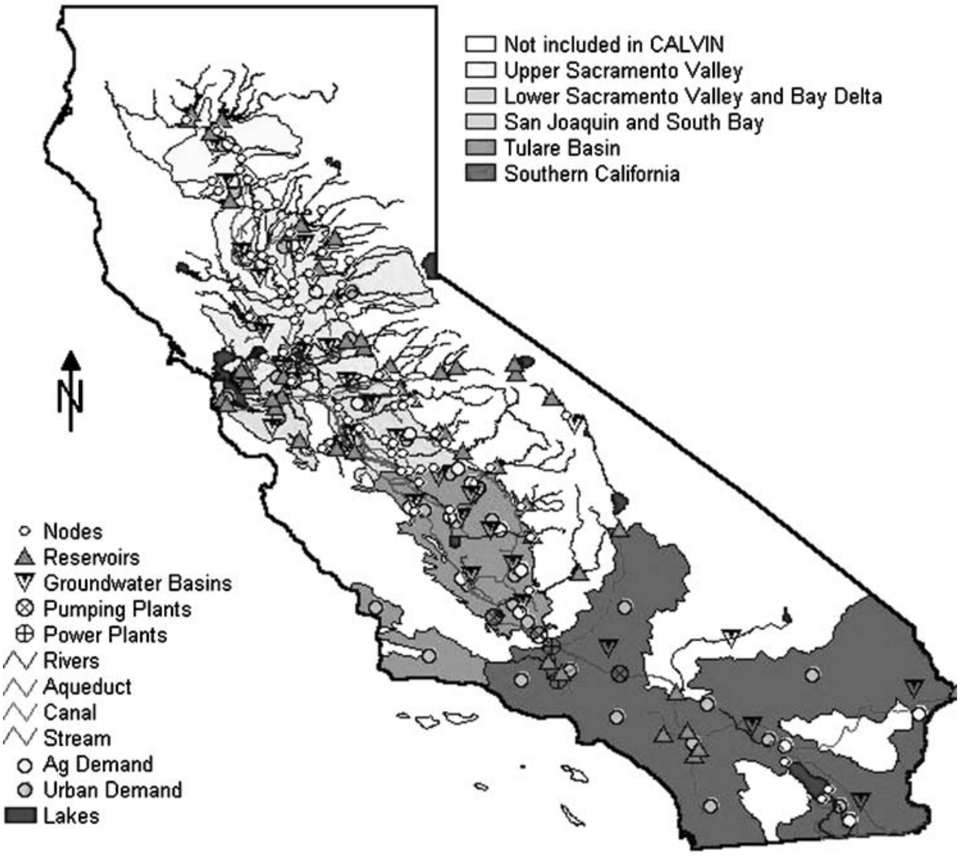

Figure 1. Demand areas and major inflows and facilities represented in CALVIN.

each climate-warming scenario, permutations of historical flow changes were developed for six representative basins throughout California by researchers at Lawrence Berkeley National Laboratories (Miller et al., 2003). These six index basin streamflow changes and distributed statewide temperature and precipitation changes were used to permute the 113 hydrologic inputs into the integrated economic-engineering optimization model (Figure 1) based on the historical hydrologies represented by monthly time series from 1922 through1993 (Zhu et al., 2005). This comprehensive hydrology includes inflows from mountain streams, groundwater, and local streams, as well as reservoir evaporation. A historical scenario and two of the twelve hydrologic scenarios are explored in this paper: 1) historical hydrology, represented by monthly 1922–1993 time series, 2) Parallel Climate Model (PCM) run B06.06, a dry form of climate warming for California, for the period 2080 to 2099 and 3) Hadley Centre Climate Model 2 (HCM) run 1, a wet form of climate warming, also for the period 2080 to 2099 (Miller et al., 2003; Zhu et al., 2005). The PCM run B06.06 and HCM run 1 were selected because they represent extreme dry and extreme wet conditions, respectively, and bracket a range of conditions that climate change may cause. Additional details on the hydrologic scenarios are presented later and in Miller et al. (2003) and Zhu et al. (2005). Water demands also are likely to change substantially in the coming century, with significant implications for water management and climate change impacts and adaptations (Vörösmarty et al., 2000). Year 2100 urban and agricultural economic water demands were estimated for a high forecast of 92 million people in California (Landis and Reilley, 2002; Lund et al., 2003). Year 2020 forecasted urban economic water demands were scaled by 2100 population, correcting for forecast changes in local population densities in 41 separate areas in the state. Initially, gross changes in water availability and demands were compared, without the aid of detailed models. The economic urban water demands in this model implicitly include per-capita water conservation and behavior as commonly practiced in 2000 (Jenkins et al., 2003), scaled up for a high 2100 population forecast. In effect the demands represent a future where conservation measures are not significantly increased over present amounts. While the future is likely to see increased conservation (Gleick et al., 2003), the chosen representation, coupled with the chosen hydrology, present an extreme case.

CALVIN (California Value Integrated Network), the integrated economic-engineering optimization model of California's inter-tied water system, was developed for water policy, planning, and operations studies (Jenkins et al., 2001; Draper et al., 2003). The generalized network flow-based optimization model minimizes the economic operating and scarcity costs of water supply, subject to water balance, capacity, and environmental constraints for a range of hydrologic and operational conditions represented by a monthly 72 year time series of inflows. The CALVIN model is an enhancement of the HEC-PRM (Hydrological Engineering Center Prescriptive Reservoir Model) code developed by the U.S. Army Corps of Engineers (HEC, 1991). As a combined economically driven engineering and optimization model it produces traditional engineering outputs as well as useful economic results and shadow values for infrastructure capacities and environmental and policy constraints. This modeling approach is used to illustrate how the infrastructure and management of California's water might economically adapt and respond to changes in climate, in the context of higher future populations and changes in land use and technology. Unlike traditional simulation modeling approaches, this economically optimized re-operation of the system is not limited by present-day water system operating rules and water allocation policies.

3. Methological Contributions

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

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

Population-induced changes in water demands are integrated into the analysis. Because climate change will have its greatest effects some decades from now, this study incorporated future growth and changes in water demands for 2100. A statewide population of 92 million, a high estimate, was assumed and distributed across the state (Landis and Reilly, 2002). Others have found population effects on water resources to be significant for understanding climate change effects (Vörösmarty et al., 2000). As noted earlier, urban water demands were not modified for additional conservation or efficiency (Gleick et al., 2003).

Water supply impacts and adaptation are essentially statewide, covering the entire California inter-tied water system (Figure 1). For 2020, this represents roughly 90% of statewide urban and irrigation water demands. Previous explorations of climate change's implications for California have examined only a few isolated basins or one or two major water projects. However, California has a very integrated and extensive water management system, which continues to be increasingly interdependent in its planning and operations over time and across scales from statewide down to household-level operations. Quantification of the ability of this integrated system to respond to climate change is likely to require examination of dynamic integration of the entire system and its adaptive potential.

Economically-driven adaptation is assumed with multiple types and scales of responses. In addition to being integrated statewide, adaptation to climate change will not be through a single response (such as reservoir re-operation alone), but will involve a concert of many traditional and new water supply and management activities. The CALVIN economic-engineering optimization model explicitly represents and integrates a wide variety of responses, summarized in Table I. Most option costs and details regarding CALVIN methodology are presented in Jenkins et al. (2001), Draper et al. (2003). For this study additional technologies for wastewater reuse (up to 50% of urban demands) were available to all urban demand areas at \$1,000/acre-ft, and seawater desalination was available in unlimited quantities to coastal communities for \$1,400/acre-ft (all costs are in 1995 dollars). Other studies (Gleick et al., 2003) indicate that water conservation and efficiency improvement efforts could provide an additional 2 million acre-feet per year (maf/yr) to the urban sector at a cost of roughly \$600/acre-feet. This is less

TABLE I
Summary of available climate change responses (* – represented in CALVIN)

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

than the cost of wastewater reuse or desalination used in CALVIN, indicating that urban water scarcities might actually be much less than those modeled.

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

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

4. Limitations

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

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

5. Results

First, we present estimates of the overall water supply and demand volumes, and base case climate and population changes assumed for this study. We then show results from the CALVIN economic-engineering model for the impacts of climate and population change on the physical and economic performance of California's inter-tied water supply system.

5.1. CHANGES IN WATER DEMAND VOLUMES

Projections of future water demands are an important aspect of future water management. 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 as high as 92 million in 2100 (Landis and Reilly, 2002). The demands included in CALVIN are those on the inter-tied water system (Table II and Figure 1), about 90% of California's agricultural and urban water demands. For all scenarios, about 26.9 million acre-ft/year of instream and wetland environmental demands are assumed to occur over 31 locations.

5.2. CHANGES IN CALIFORNIA'S WATER SUPPLIES

The twelve climate warming scenarios examined, and their overall effects on basic water availability appear in Table III (Zhu et al., 2005). Initially, increases in wet season (November–March) flows are assumed to spill since current surface storage facilities are not able to catch them, except for those flows that can be used due to changes in groundwater infiltration. Changes in dry season (April–October) flows are assumed to directly affect water availability. While these are raw hydrologic results, adjusted for groundwater storage effects, they indicate a

TABLE II

Land Use and Applied Water Demands for California's Inter-tied Water System (millions of acres and millions of acre-ft/year)[a]

Use	2020 Land	2100 Land	2020–2100 Decrease	2020 Water	2100 Water	2020–2100 Change
Urban	–	–	−0.75	11.4	19.5	+8.0
Agricultural	9.2	8.4	0.75	27.8	25.1	−2.7
Total	–	–	–	39.2	44.5	+5.3 maf/yr

[a]Numbers may not add up due to rounding.

TABLE III
Raw water availability (without operational adaptation, in maf/yr)

	Average annual water availability		
		Change	
Climate scenario	Volume (maf)	(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 (1.4 T; 26% P)	41.9	4.1	10.8%
(8) HCM 2050–2079 (2.4 T; 32% P)	40.5	2.7	7.2%
(9) HCM 2080–2099 (3.3 T; 62% P)	42.4	4.6	12.1%
(10) PCM 2010–2039 (0.4 T; −2% P)	35.7	−2.1	−5.6%
(11) PCM 2050–2079 (1.5 T; −12% P)	32.9	−4.9	−13.0%
(12) PCM 2080–2099 (2.3 T; −26% P)	28.5	−9.4	−24.8%
Historical	37.8	0.0	0.0%

wide range of potential water supply impacts on California's water supply system. These effects range from an increase of 4.6 million acre-feet (maf)/yr to a decrease of 9.4 maf/yr. Figure 2 shows the total seasonal flow results for the HCM 2080–2099 and PCM 2080–2099 warming scenarios for mountain rim inflows, currently about 72% of California system inflows. These two warming scenarios bracket all other warming scenarios among the twelve examined (Zhu et al., 2005). In all cases spring snowmelt is greatly decreased with climate warming, and winter flows are generally increased (except for some PCM scenarios). This pattern of changes in runoff has long been identified based on studies of individual or a few basins (Gleick, 1987; Roos, 1987; Lettenmaier and Gan, 1990).

The PCM 2080–2099 is the driest climate scenario with an annual average decrease in pre-operated water availability of approximately 9.4 maf/yr (24.8%). Conversely, the HCM 2080–2099 climate scenario is the wettest, with an annual average increase in pre-operated water availability of 4.6 maf/yr (12.1%). These two scenarios were selected to be modeled explicitly using CALVIN because they represent the two extreme conditions (extremely dry or extremely wet) relative to the historical hydrology. This allows a comparison between very rough estimates of unmanaged changes in water availability and more highly managed operations, modeled using CALVIN.

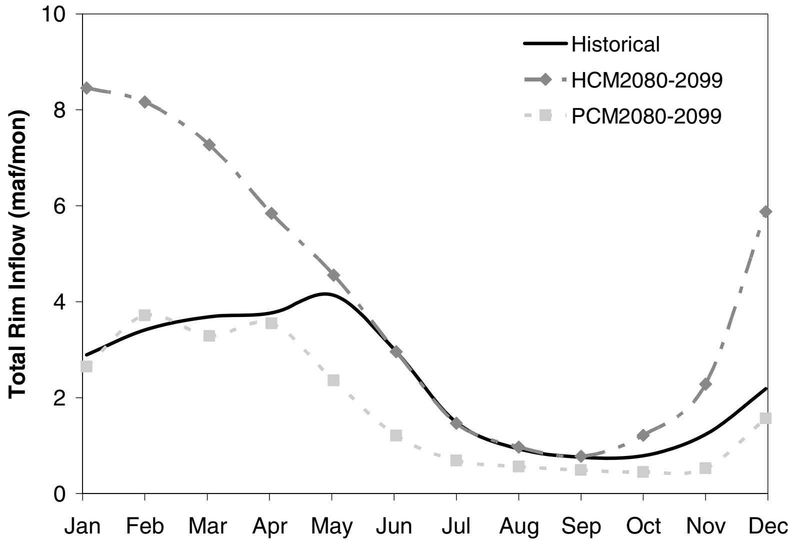

Figure 2. Monthly mean rim inflows for the climate scenarios and historical data.

5.3. ADAPTIVE CHANGES FOR WATER MANAGEMENT

Five statewide scenarios were run using the CALVIN 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 is documented extensively elsewhere (Jenkins et al., 2001, 2004; Draper et al., 2003).
- SWM 2020: This run represents operations, allocations, and performance in the year 2020 assuming flexible and economically-driven operation and allocation policies. This run also is documented extensively elsewhere (Jenkins et al., 2001, 2004; Draper et al., 2003).
- 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 2080–2099 climate warming hydrology (scenario 12, Table III).
- HCM 2100: Using the same 2100 water demands as SWM 2100, this run employs the wet and warm HCM 2080–2099 climate warming hydrology (scenario 9, Table III).

TABLE IV
Summary of statewide operating# and scarcity costs

Cost ($M/yr)	Base 2020	SWM2020	SWM2100[a]	PCM2100[a]	HCM2100[a]
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

[a]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.
[b]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.

5.4. PERFORMANCE WITH CLIMATE WARMING AND POPULATION GROWTH

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 IV and Figures 3 and 4 which contain CALVIN economic, delivery, and scarcity results for urban and agricultural water users under each scenario modeled.

Overall, population growth alone raises economic operating and scarcity costs of water deliveries by $4.1 billion/year (SWM2100 compared to SWM2020), with the driest climate warming hydrology (PCM 2100) increasing these costs a further $1.2 billion/year. The wet climate warming hydrology (HCM 2100) decreases total water supply costs by about $0.3 billion/year from the case of historical hydrology with population growth. However, as discussed later, despite inclusion of current flood storage capacities in reservoirs, flood damages are not included in this analysis. The driest climate-warming scenario severely affects agricultural water users in 2100. Given optimized water allocations and operations, water scarcity costs for 2100 without climate changes (SWM 2100) are less than in year 2020 without changes in current water allocation policies (Base 2020), although operating costs are much greater ($5.1B/yr versus $2.6B/yr, respectively). Most of the decreased scarcity cost is due to water transfers from Colorado River agricultural users to Southern California urban users; many of these transfers have been implemented since these model runs.

Figures 3 and 4 show the regional water delivery and scarcity cost effects of the five scenarios. For all three 2100 scenarios, the southern California region (Figure 1) has significant shifts of water from agriculture to urban users, both from

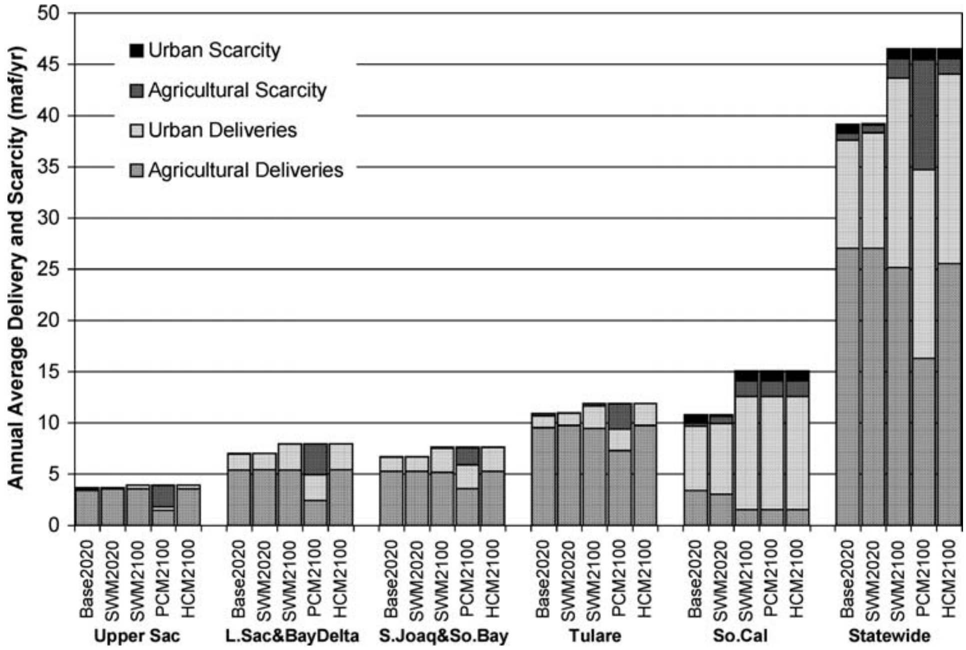

Figure 3. Water deliveries and scarcities by region and statewide.

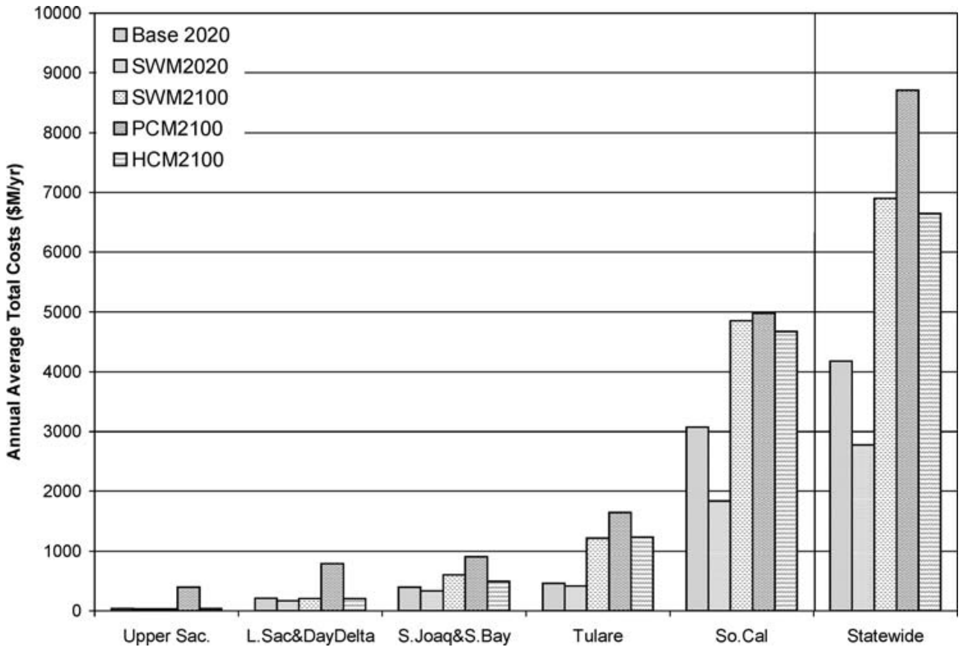

Figure 4. Total scarcity and operating costs by region and statewide.

urbanization of agricultural land and from water transfers to urban users. Water scarcity for southern California is relatively unaffected by the climate scenarios because the region's extensive capacity to import water and its high economic values for water use allow it to purchase and import water from water users elsewhere. Also, these particular climate scenarios have little direct effect on water available locally in southern California. Central Valley (Sacramento, S. Joaquin & So. Bay and Tulare) water users are much more sensitive to climate change, particularly the dry PCM2100 scenario, which reduces Valley agricultural water deliveries by 37% from current deliveries (and 24% from 2100 urbanization-corrected agricultural demands) and raises Valley water scarcity costs by $1.7 billion.

CALVIN model results indicate several promising and economically efficient adaptations to population growth and climate change. For all 2100 scenarios, model results show increased market water transfers from agricultural to urban users, additional urban water conservation (~1 maf/yr), use of newer wastewater 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, reducing statewide agricultural water use by about 2.7 maf/year. Land fallowing due to additional water scarcity under the dry climate scenario is about 15% (Howitt et al., 2003). For the dry PCM2100 scenario, several million acre-feet/year of reductions in agricultural water use occur due to land fallowing. 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 California water district (Metropolitan Water District of Southern California, $900 million/year), but are small compared with the current size of California's economy (currently $1.5 trillion/year) or the current State government budget (~$120 billion/year).

5.5. GROUNDWATER

Some operational results for total groundwater storage in California appear in Figure 5. The model operates using a 72-year sequence of historical monthly inflows to represent hydrologic variability and various complex combinations of wet and dry year sequences in the historical record that are important for actual operations and water allocations, and the evaluation of system performance. Most water storage in California is underground; over two thirds of the storage used during dry periods is groundwater. All optimized and future scenarios make greater use of groundwater storage for drought management than current policies (Base 2020). This is well illustrated by Figure 6, which shows the proportion of water deliveries coming from groundwater over the range of wet and dry years. The dry climate warming and historical climate scenarios show (both with population growth) increased

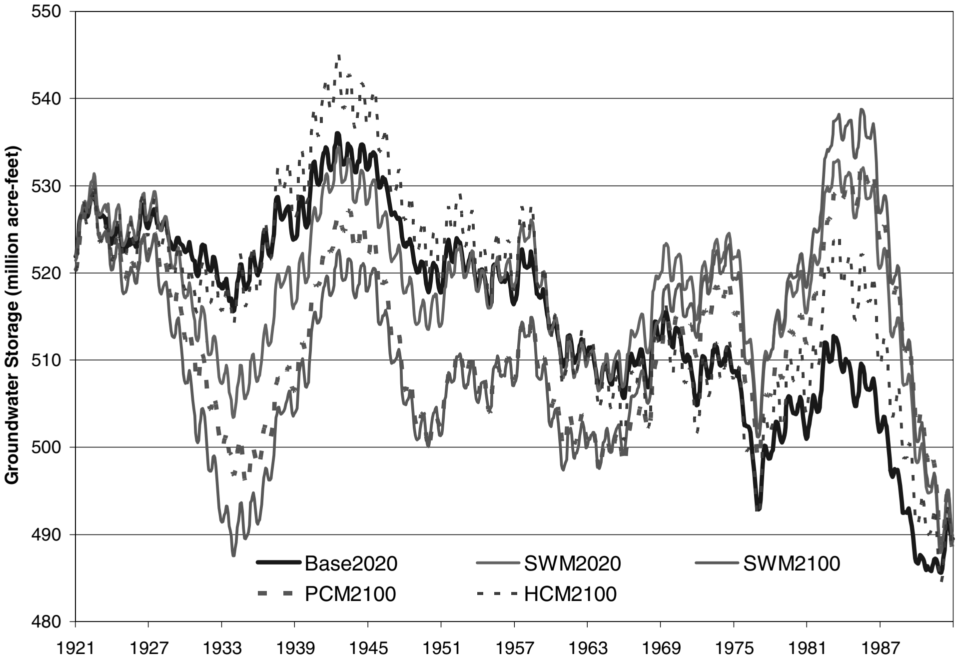

Figure 5. Groundwater storage over the 72-year period at 2100 water demand levels.

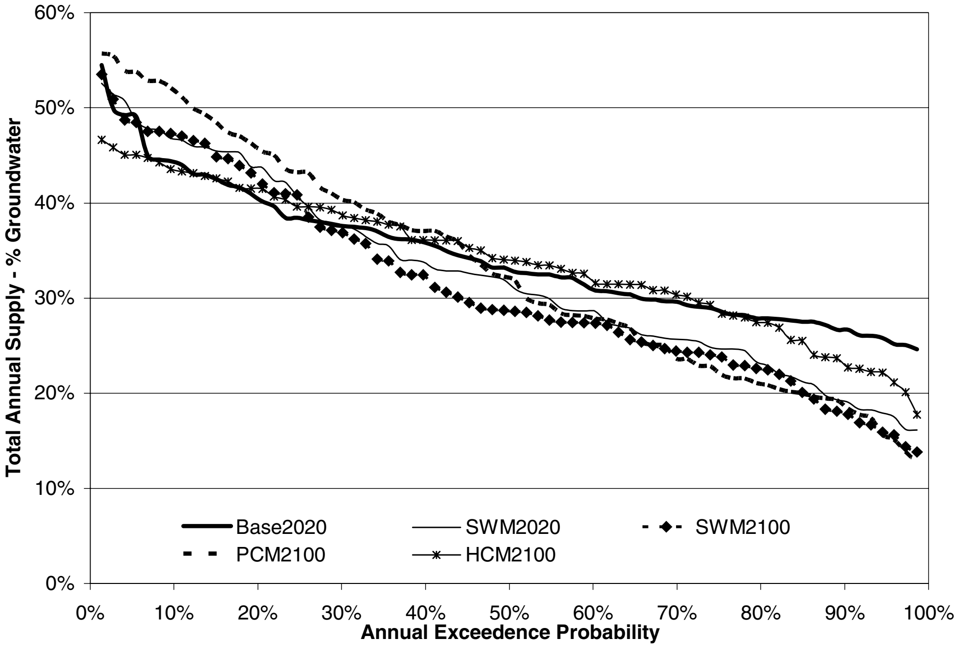

Figure 6. Annual variability in statewide use of groundwater.

groundwater use in dry years and decreased groundwater use in wet years. The steeper slopes and wide amplitudes of groundwater storage shown in Figure 5 reflect the strong interplay of conjunctive surface and groundwater use. The decadal and longer drawdown periods, most noticeable in SWM2100 and PCM2100, are typical of "cyclic storage" (Lettenmaier and Burges, 1982). The aquifer would be recharged and discharged at much greater rates with consequent possible changes in aquifer geochemistry. Only under the wet climate warming scenario, where surface water become much more available, does conjunctive use remain similar to Base 2020.

5.6. SURFACE WATER

Surface water operations change significantly with climate. As expected, the wetter scenario tends to have greater amounts of surface storage, and under the drier scenario less surface water storage amounts is used, with relatively few shifts in seasonal surface storage (Figure 7). All optimized operations, except the wet HCM2100, tend to store less water in surface reservoirs, relative to Base 2020. Changes in conveyance operations are more important. For 2100, all conveyance into southern California's urban area operates at capacity in all periods, isolating this region somewhat from climate change elsewhere. This inability of southern California to import additional water in dry periods leads to increases in local water management options (conservation, reuse, and desalination) for the drier climate scenario. Lower costs for conservation and desalination, which seem likely, would provide further ability for California's water system to adapt economically to climate change.

5.7. NEW WATER SUPPLY TECHNOLOGIES

The inability to access additional, less expensive, water supplies for southern California (for example, from purchased agricultural water in the Colorado or Central Valley basins) leads to significant use of wastewater reuse, seawater desalination, and water conservation in southern California in all 2100 scenarios. Figure 8 illustrates the additional use of wastewater reuse and sea water desalination technologies. With the drier climate scenario, about 1.35 maf/year of wastewater reuse is employed and about 0.24 maf/year of seawater desalination. Seawater desalination is identical for SWM2100 and HCM2100 scenarios. These quantities are large by current standards, and make a significant contribution to water supplies, but are not dominant water sources. At lower costs, these new technologies might see greater adoption; seawater desalination costs used here were $1,400/af. Again, increased water conservation capacity (above current levels) was not explicitly included in the analysis.

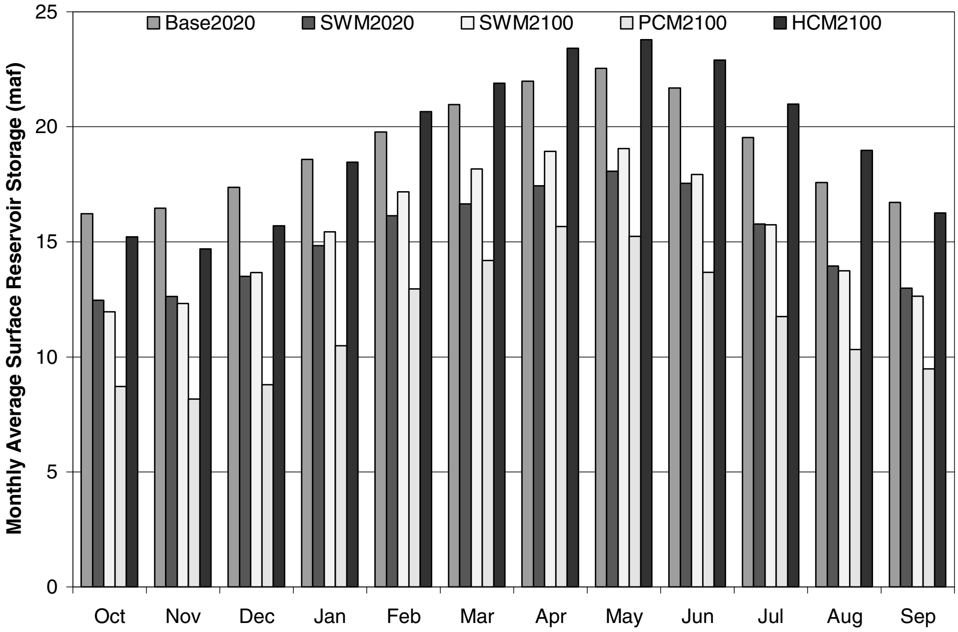

Figure 7. Average seasonal pattern of surface water storage.

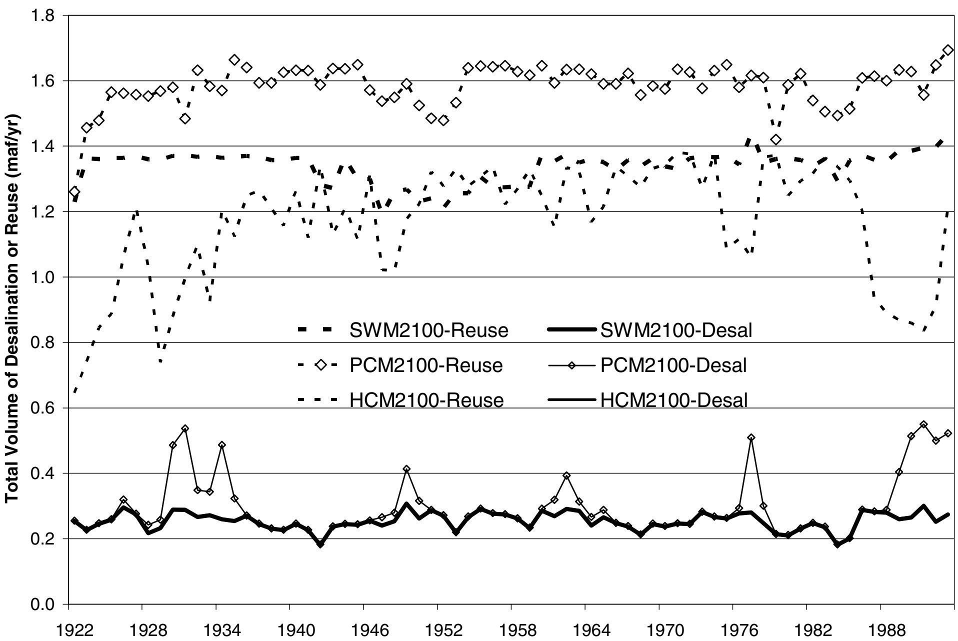

Figure 8. Use of seawater desalination and urban wastewater recycling at 2100 water demand levels.

5.8. INTERACTION OF RESPONSES

Responses to population growth and climate change are highly interdependent. Water transfers require changes in conveyance and storage operations, and additional water conservation or use efficiencies from the transferring party. Much of the water scarcity in agriculture with the PCM2100 scenario would, under current water rights, arise from sales of water to higher-valued urban uses, with changes in agricultural irrigation technologies and crop mix, as well as changes in both surface and groundwater water storage and conveyance operations.

5.9. ENVIRONMENTAL CHALLENGES

Population growth and climate warming also impose serious environmental challenges. While in 2020, or with 2100 population growth alone, it appears possible to comply with environmental flow and delivery requirements under climate change, though some reductions in deliveries for environmental flows are required for the PCM2100 scenario. However, increased water demands and decreased water availability substantially raise the costs of environmental requirements to urban, agricultural, and hydropower users, as shown in Table V. Higher increases in costs result when the environmental use is “consumptive”, in that it requires that water leave the managed system. This occurs with required outflows (Trinity and Delta flows) or delivery to consumptive uses, such as wetlands, with little return flow. Increased economic costs of complying with environmental requirements could raise incentives to dispute and evade such requirements, as well as incentives to address environmental demands creatively.

In many cases, the costs imposed on other water users by environmental requirements are episodic, and restricted to drought periods. Figure 9 shows shadow costs for the Trinity River instream flow requirement. When water is relatively abundant (HCM2100), the instream flow requirement’s costs are mostly due to hydropower losses (about \$35/acre-ft) through the diversion tunnel (which are zero when the tunnel is at the turbine capacity). When water becomes very scarce (PCM2100), shadow costs are very high in all but the wettest years due to the high economic values of unmet agricultural and urban demands downstream. These values are especially high for the Trinity River, because it supplies the northern end of the Sacramento River, with repeated usage of return flows possible as the water flows south. During droughts under the dry PCM2100 scenario, shadow costs of Trinity River instream flows become extraordinary, when higher-valued urban water uses are shorted.

5.10. FLOODING

The potential for climate warming to deprive California’s hydrology of the storage capacity of snowpacks, both for buffering floods and providing seasonal water

TABLE V
Shadow costs of selected environmental requirements[b]

	Average willingness to pay ($/af)			
Minimum instream flows	SWM2020[a]	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	0.1	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
Tuolumne River	0.5	5.6	55.4	0.0
Mono Lake Inflows	819.0	1254.5	1301.0	63.9
Owens Lake Dust Mitigation	610.4	1019.1	1046.1	2.5
Refuges				
Sacramento Refuges	0.3	1.1	231.0	0.1
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
Average Infeasibilities (taf/yr)	0	0	328.7	8.4

[a]SWM2100 results do not include hydropower values (except for Mono and Owens flows).
[b]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 an increase in the minimum environmental flow requirements.

supply storage, has long been a concern. While flood damages of water management have not been explicitly represented in this analysis, changes in flood flows and flood frequencies in the results are apparent (Miller et al., 2003). The dry warming PCM2100 hydrology does not show a substantially greater flooding threat (a somewhat tentative conclusion given the monthly basis of the model and the lack of explicit flood penalties in the model). However, for wet forms of climate warming (HCM2100) monthly flood flows are much greater than anything experienced historically.

These flooding results might be an artifact of the hydrology developed; 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, peak flows might be over-estimated (or underestimated). This merits further hydrologic and operational research. Flood flow frequency and adaptation studies for the Lower American River

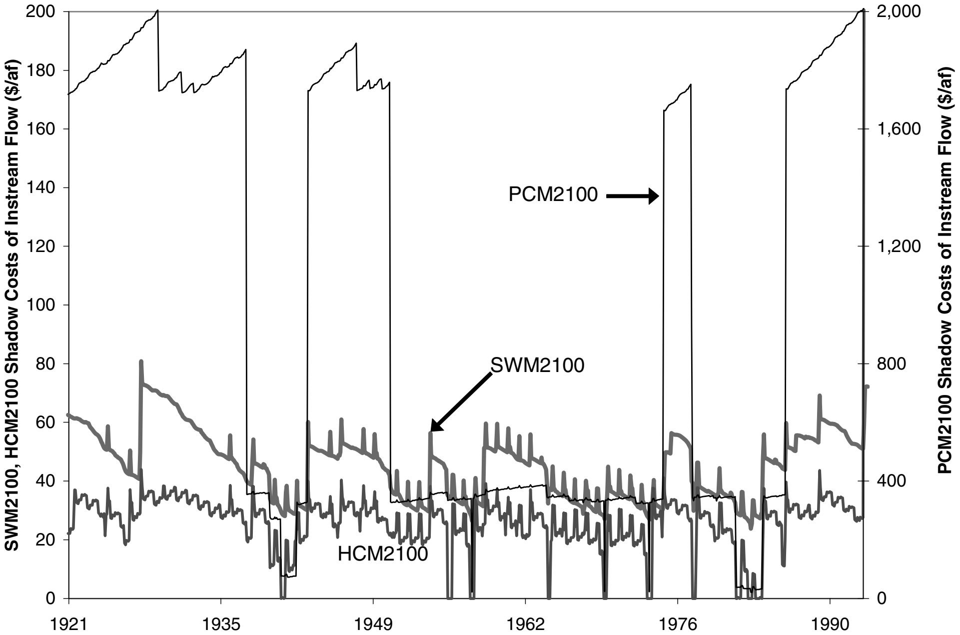

Figure 9. Time series of shadow costs for trinity river instream flow requirement.

(Zhu, 2003), based on the same HCM hydrology, show serious flooding results. Yao and Georgakakos (2001) demonstrated the value of forecasting and flexible reservoir operations for reducing the risk of flooding due to climate change. 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.

5.11. VALUE OF NEW FACILITIES

Table VI contains the average value that one additional unit of increased capacity for selected storage and conveyance capacities in California's water system for the 2100 scenarios. All of these values exceed those for year 2020 populations (Jenkins et al., 2004), 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. For example, under historic conditions increasing the capacity of the Colorado River Aqueduct would be worth $1,063/acre-foot in any given month, whereas increasing the capacity of Turlock Reservoir by one unit would be worth $69/acre-foot. Expansions of conveyance capacity would typically be used more frequently than expansions in storage. Whereas expanded storage would be useful mostly just before droughts (when water could be

TABLE VI
Average annual marginal value of expanding selected facilities (Shadow Values)

Facility	Average marginal value		
	SWM2100	PCM 2100	HCM 2100
Surface Reservoir ($/acre-foot per year)			
Turlock Reservoir	69	202	56
Santa Clara Aggregate	69	202	56
Pardee Reservoir	68	202	56
Pine Flat Reservoir	66	198	56
New Hogan Lake	66	198	56
New Bullards Bar Reservoir	65	196	56
Los Vaqueros Reservoir	64	186	53
Lake Success	32	150	22
Lake Eleanor	28	125	21
Lake Mathews (MWDSC)	28	125	21
Lake Kaweah	28	124	21
Conveyance ($/(acre-foot per month) per year)			
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

stored in available capacity), conveyance expansions often would provide benefits every year, and sometimes in every month of every year.

5.12. HYDROPOWER

Hydropower generation and its 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.

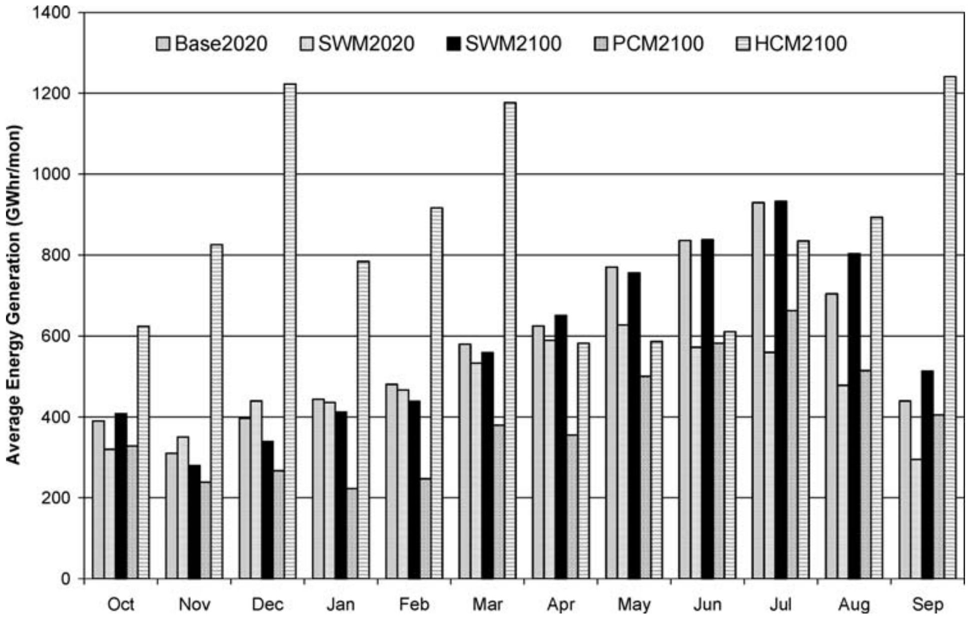

Figure 10. Average seasonal hydropower generation from major reservoirs.

Hydropower production from the major water supply reservoirs 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 probably indicates the overall effect, and is similar to the change in streamflow. With the wet HCM2100 hydrology, hydropower production of $248 million/year greatly exceeds current levels. Seasonal variability in hydropower generation is depicted in Figures 10.

5.13. CHANGES IN AGRICULTURAL LAND USE AND INCOME

Figure 11 shows changes in water use, irrigated acreage, and farm income between SWM2100 and PCM 2100 for 21 agricultural regions in the Central Valley, arranged roughly from north (v01) to south (v21). These results come from post-processing the agricultural water deliveries from the CALVIN model runs through the more detailed Statewide Water and Agricultural Production (SWAP) model of Central Valley agricultural production and economic value. SWAP is an agricultural production model which makes irrigation, cropping, and land use decisions based on farm profit maximization (Howitt et al., 2003).

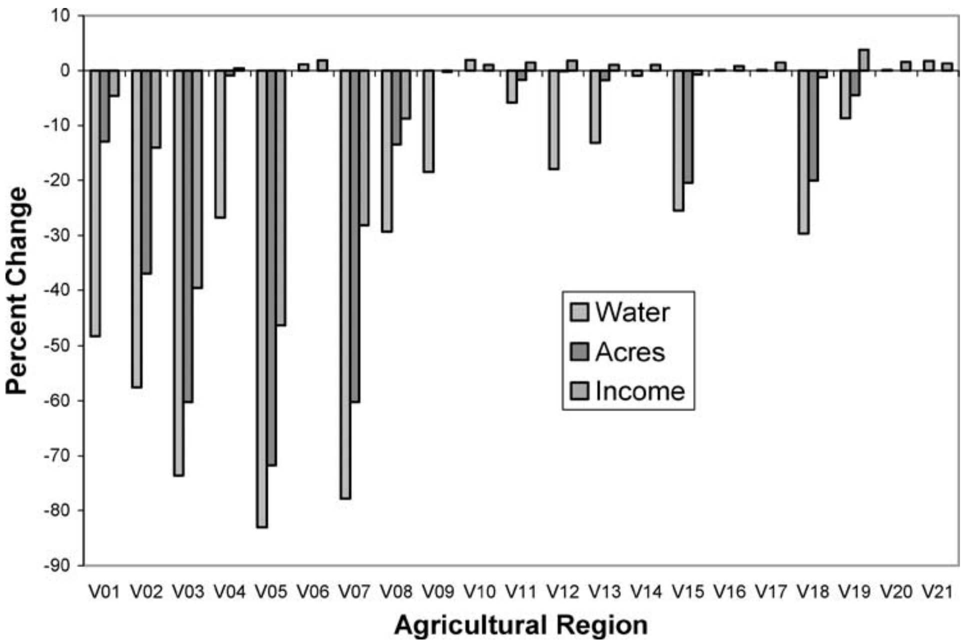

Figure 11. SWM2100 – PCM2100 changes in agricultural water, acreage, and income by central valley agricultural region ("V##" refers to the Central Valley Production Model region ID) (Howitt et al., 2003).

These SWAP 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, irrigated area is reduced much less, as farmers change irrigation technologies and crop mix. Since farmers preserve higher valued crops, agricultural income reductions are much less, averaging about 6% statewide despite about 24% reductions in agricultural water deliveries from 2100 urbanization-adjusted agricultural water demands, with an average 15% reduction in irrigated land.

Large complex systems often have many layers (or scales) of potential adaptation. In the case of California water, layers of adaptation at statewide, regional, local, and user levels combine to provide a substantial degree of buffering of climate warming impacts. However, for these layers of adaptation to be effective, they must be allowed and encouraged institutionally to function appropriately.

6. Conclusions

Several conclusions are supported by this study.

This method of studying the impact and adaptation to climate change incorporates a wider range of hydrologic effects and resources (particularly groundwater), as well as changes in population, water demands, and system operations than has been customary. Including more varied aspects in climate change studies provides more useful, realistic, and insightful results for purposes of policy, planning, and public education.

The use of optimization for such a large complex system is necessary, given the complexity and dynamic interdependencies of this system at multiple scales, but is likely to provide results which are somewhat more optimistic than what would be possible institutionally. Nevertheless, even complex integrated models such as CALVIN are unlikely to be able to represent the full range of adaptation possibilities and options, and so might be pessimistic in some regards.

For California, a wide range of climate warming scenarios shows significant increases in wet season flows and significant decreases in spring snowmelt. This provides more general and quantitative confirmation of many earlier studies of climate warming effects for California's water resources. The magnitude of climate warming's effect on water supplies can be comparable to population-driven water demand growth in the coming century. Other forms of climate change, such as sea level rise, were not examined.

California's water system can adapt to the fairly severe representations of population growth and climate warming. This adaptation will be costly in absolute terms and include transaction, institutional, and fixed costs not quantified in the model, 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 and environmental sectors.

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

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 urban uses. This diversion is limited primarily by the conveyance capacities of the Colorado River Aqueduct (for Colorado River water) and the California Aqueduct (delivering water from the Central Valley). Given the 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 less affected by climate warming. 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 levels of wastewater reuse and lesser, but substantial, use of seawater desalination.

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 significant 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 increase, raising the intensity of water conflicts, unless management institutions can devise more efficient and flexible means for managing water in the coming century.

The limitations of this kind of study are considerable, but the qualitative implications seem clear. It behooves us to consider and develop a variety of promising infrastructure, management, and governance options to allow California and other regions to respond more effectively to the twin challenges of climate change and population increase in the future.

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 Lund et al. (2003). Other general improvements in the modeling tool, particularly representations of the Tulare basin, Central Valley groundwater, agricultural water demands, and limitation of model hydrologic foresight also are desirable.

Extensive, complex, highly-intertied water systems can have a great deal of physical and economic flexibility in how they can respond to major exogenous changes, such as climate change and population growth. This flexibility occurs at the system scale of water supply management, the regional scale of water utilities, and the local scale of individual water users. However, this flexibility is not costless, and may be limited by legal, regulatory, or other institutional constraints, which historically have often taken longer to modify than constructed physical infrastructure.

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