MODELING CLIMATE WARMING FOR WATER MANAGEMENT IN CALIFORNIA

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ABSTRACT

Concern for climate change in California has increased in recent years and the potential effects of climate change have been widely discussed from a variety of perspectives. Unlike previous studies of California's water systems, which examined only one or few climate projections and focused on a few isolated river basins or one or two major water projects, this approach employed here used an integrated economic-engineering optimization model to examine the entire inter-tied California water supply system based on urban and agriculture water demand projections adjusted to land use changes and population growth at 2100 level as well as typical climate warming hydrologies from 12 climate warming scenarios for 2100. The results indicate California's water system can adapt to severe population growth and climate warming, although the costs in absolute terms can be high. Agricultural water users in the Central Valley are the most vulnerable to climate warming and, water use in Southern California is likely to become predominantly urban.

1 INTRODUCTION

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. An integrated economic-engineering optimization model (CALVIN) is employed to examine the performance of California's entire inter-tied 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 (Lund et al. 2003)

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 hydrologies were examined to develop integrated statewide hydrologies covering changes in all major inflows to California's water system. For each climate-warming scenario, permutations of historical flow changes were developed for six representative basins throughout California (Miller, et al. 2001). These changes were used as index basins to permute the 113 hydrologic inputs into the integrated economic-engineering optimization model (Figure 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 the comprehensive changes in California's water availability are then estimated, including effects of forecasted changes in 2100 urban and agricultural water demands.

CALVIN was developed for general water policy, planning, and operations studies (Jenkins et al. 2001; Newlin et al. 2002; Draper et al. 2003). This modeling approach illustrates 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).

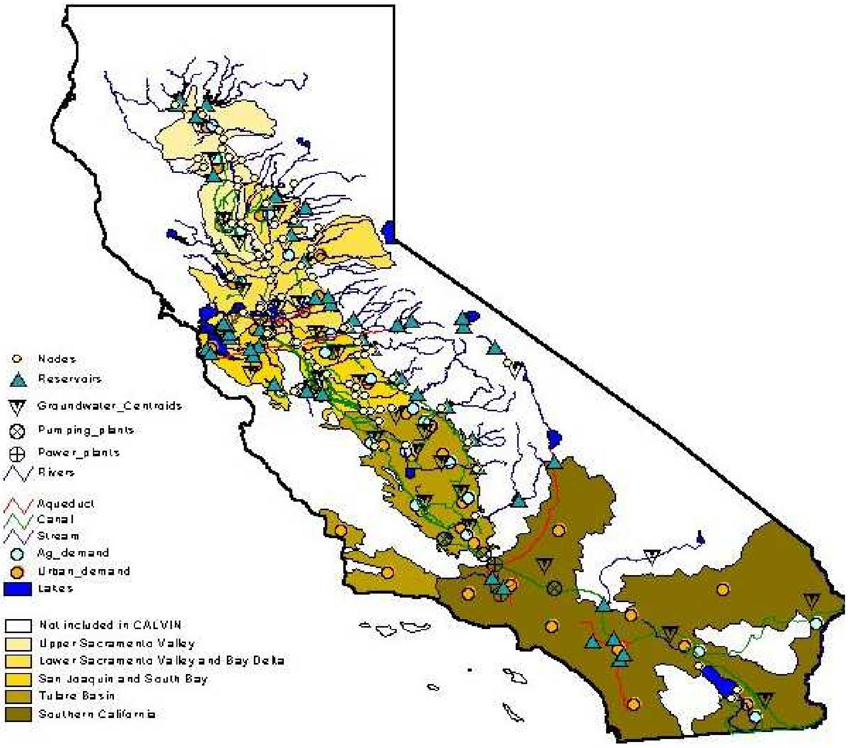

Figure 1. Demand Areas and Major Inflows and Facilities Represented in CALVIN

2 IMPROVEMENTS OVER PREVIOUS CLIMATE STUDIES

Previous explorations of climate change's implications for California have examined only a few isolated basins or one or two major surface water projects (Lettenmaier and Sheer 1991; Gleick and Chalecki 1999; Carpenter and Georgakakos 2001; Yao and Georgakakos 2001; Zhu et al. 2003). However, California has a very integrated and extensive water management system, which continues to be increasingly integrated in its planning and operations. Examination of the ability of this integrated system to respond to climate change is likely to require examination of the entire system. CALVIN is of much greater spatial scope and detail than other management models of water in California. It is the first model to represent explicitly the waters of the entire Central Valley, imports from the Trinity system, and Colorado and Eastern Sierra supplies to major water uses of California, with simultaneous optimization of surface and groundwater supplies and major water demands (Draper et al. 2003). This aids examination of conjunctive use alternatives and allows for the most economic adaptation to new facilities or changes in demands or regulations. In addition to statewide integration, the CALVIN model explicitly represents and integrates a wide variety of response options. 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. This variety of traditional and new water supply and management options are important to adaptation and impact studies. The use of optimization in this model allows rapid and impartial preliminary identification and screening of promising alternatives for more detailed consideration and analysis.

In CALVIN, systematic analytical overview of statewide water quantity and economic data was undertaken to support the model. Economic performance is the explicit objective of the model and economic values of agricultural and urban water use are estimated consistently for the entire inter-tied system. This facilitates economic evaluation of capacity alternatives, conjunctive operations, water conservation, and water transfers and estimation of user willingness-to-pay for additional supplies. 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. Data and model are well managed and documented in CALVIN.

The above innovations are crucial to support the search for technically workable, politically feasible, and socially desirable solutions to water problems in California. In addition, the approach employed for this study contributes several methodological 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:

- <u>Comprehensive hydrologic effects of climate warming</u>, including all major hydrologic inputs, including major streams, groundwater, and local streams, as well as reservoir evaporation. Groundwater, in particular, represents 30%-60% of California's water deliveries and 17% of natural inflows to the system.

- <u>Integrated consideration of groundwater storage</u>. Groundwater contributes about most of the storage used in California during major droughts.

- <u>Statewide impact assessment</u>. Previous explorations of climate change's implications for California have examined only a few isolated basins or one or two major water projects. However, California has a very integrated and extensive water management system. This system continues to be increasingly integrated in its planning and operations over time. Examination of the ability of this integrated system to respond to climate change is likely to require examination of the entire system.

- <u>Economic-engineering perspective</u>. The ability of water sources and a water management system to provide water for environmental, economic, and social purposes is the relevant measure of the effect of climate change and adaptations to climate change. An effective water management system depends to a large extent on the treatment of water as an economic and social good (Stakhiv 1998). Traditional "yield"-based estimates of climate change effects do not provide results as meaningful as economic and delivery-reliability indicators of performance.

- <u>Incorporation of multiple responses</u>. Adaptation to climate change will not be through a single option, but a concert of many traditional and new water supply and management options. The CALVIN model can explicitly represent and integrate a wide variety of response options, including operational changes, conjunctive use, water markets, transfers, and exchanges, wastewater reuse, water conservation, and desalination. All these options were included in the model.

- <u>Incorporation of future growth and change in water demands</u>. 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. Water demand estimates were made for a high 2100 population of 92 million (Landis and Reilly 2002).

- <u>Optimization of operations and management</u>. 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 more reasonable. Optimization approaches have limitations, 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.

3 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.

3.1 Changes in Water Demands

The demands included in CALVIN (Table 1 and Figure 1) represent about 90% of those in California. Population growth in California is expected to continue from today's 32 million, to as high as 92 million for 2100. Continuous population growth and urban areas expansion have implications for urban and agricultural water demands.

Table 1. Land and Applied Water Demands for California's Inter-tied Water System (millions of ha and billions of m^3/year)

Use	2020 Land	2100 Land	2020-2100 Decrease	2020 Water	2100 Water	2020-2100 Change
Urban				14.1	23.0	8.9
Agricultural	3.7	3.4	0.30	34.3	31.0	-3.3
Total	-	-	-	49.3	54.9	5.6

3.2 Changes in California's Water Supplies

The twelve climate warming scenarios examined, and their overall effects on water availability appear in Table 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. 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 2. Raw water availability (without operational adaptation, in billion m^3/yr)

Climate Scenario	Average Annual Water Availability Volume	Change		Climate Scenario	Average Annual Water Availability Volume	Change	
1) 1.5T 0%P	44.1	-2.6	-5.5%	7) HCM 2010-2039	51.7	5.1	10.8%
2) 1.5T 9%P	46.5	-0.1	-0.4%	8) HCM 2050-2079	50.0	3.3	7.2%
3) 3.0T 0%P	41.6	-5.1	-10.9%	9) HCM 2080-2099	52.3	5.7	12.1%
4) 3.0T 18%P	45.8	-1.0	-2.0%	10) PCM 2010-2039	44.1	-2.6	-5.6%
5) 5.0T 0%P	39.0	-7.7	-16.5%	11) PCM 2050-2079	40.6	-6.0	-13.0%
6) 5.0T 30%P	44.7	-2.0	-4.3%	12) PCM 2080-2099	35.2	-11.6	-24.8%
Historical	46.7	0.0	**0.0%**				

Among these climate warming scenarios, the PCM 2080-2099 is the driest with an annual average decrease in water availability of approximately 11.6 billion m^3/yr (24.8%). Conversely, the HCM 2080-2099 climate scenario is the wettest, with an annual average increase in water availability of 5.7 billion m^3/yr (12.1%). These two scenarios were selected to be modeled explicitly using CALVIN because they represent the two extreme conditions (extremely wet or extremely dry) relative to the historical hydrology.

3.3 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 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 (Jenkins et al, 2001; 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 (Jenkins et al, 2001; 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.

- **HCM 2100**: Using the same 2100 water demands as SWM 2100, this run employs the wet and warm HCM 2080-2099 climate warming hydrology

3.4 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 3 and Figures 2 and 3 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 3. Summary of Statewide Operating# and Scarcity Costs

Cost ($M/yr)	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 2.47 billion m^3/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.

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 (~1.23 billion m^3/yr), use of newer water reuse treatment (~1.85 billion m^3/yr) and sea water desalination technologies (~0.25 billion m^3 /yr), increased conjunctive use of ground and surface waters, and urbanization of agricultural land. For the dry PCM2100 scenario, several billion m^3/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).

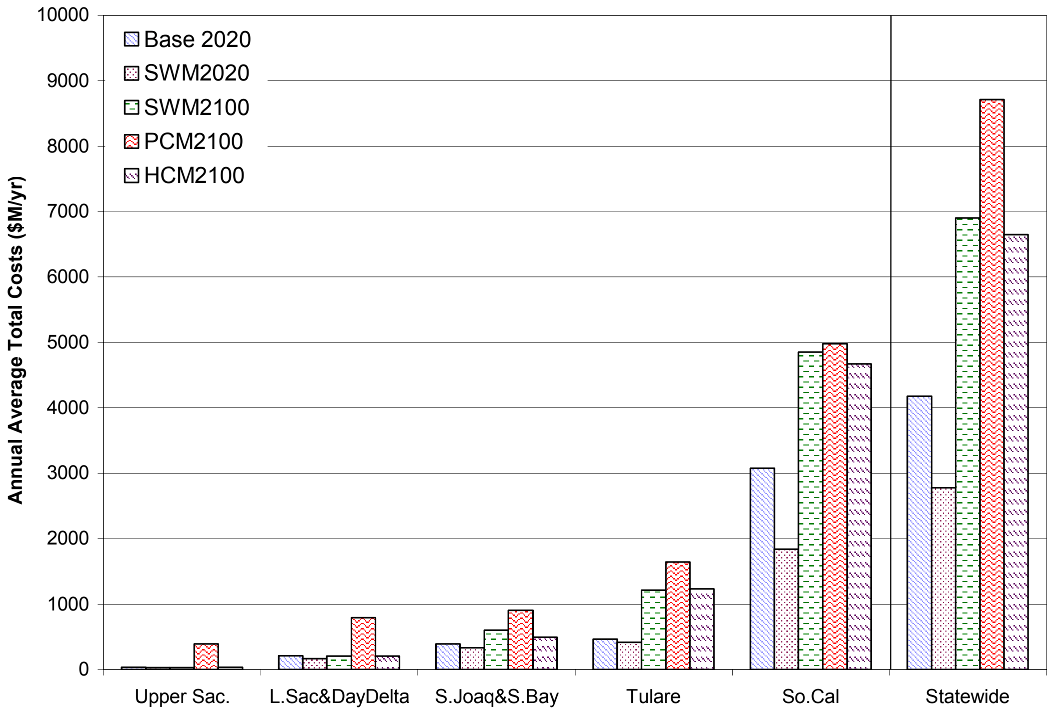

Figure 2. Total Scarcity and Operating Costs by Region and Statewide

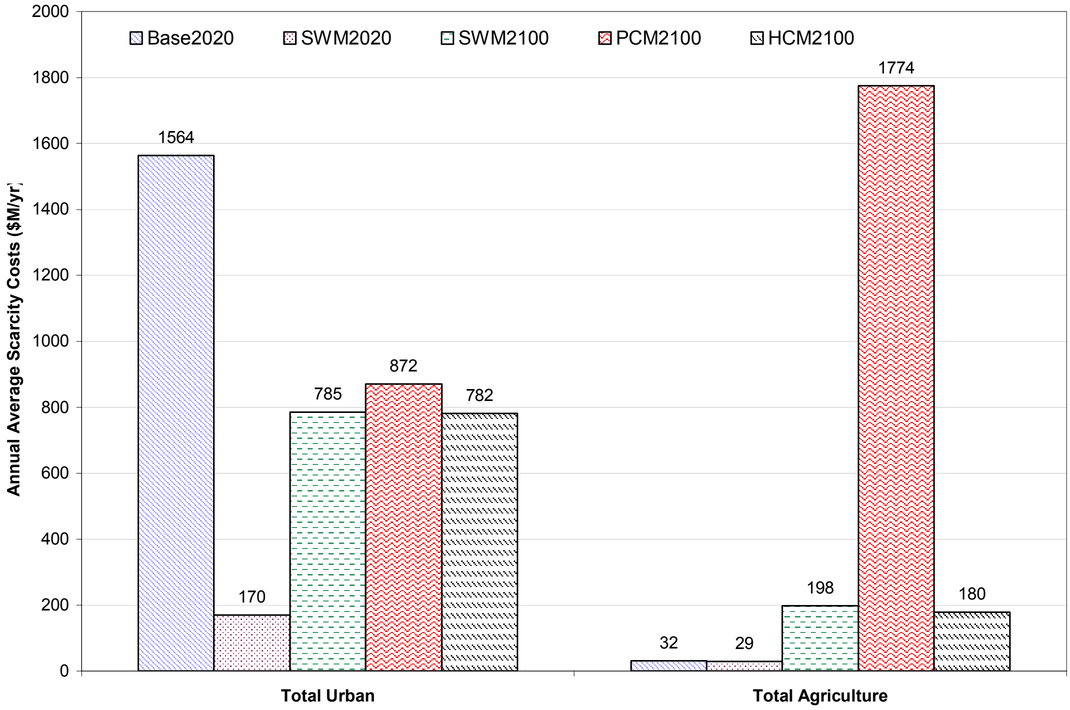

Figure 3. Average Annual Economic Scarcity Cost by Sector

Some operational results for overall groundwater storage in California appear in Figure 4. 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. Over two thirds of the storage used between wet and dry periods takes the form of groundwater. All optimized and future scenarios make greater use of groundwater storage for drought management than current policies (Base2020).

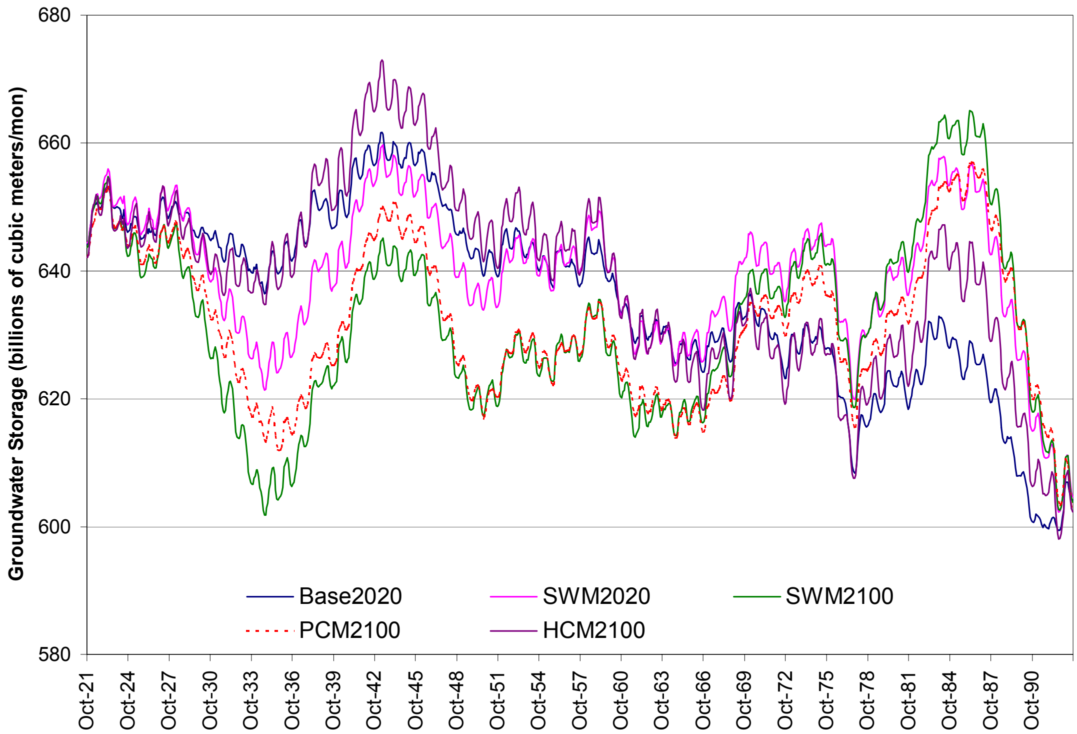

Figure 4. Groundwater Storage over the 72-year Period

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 substantially raise the costs of environmental requirements to urban, agricultural, and hydropower users. 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.

4 CONCLUSIONS

Methodologically, it is possible, reasonable, and desirable to include a wider range of hydrologic effects, changes in population and water demands, and adaptive 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.

In general, 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, while large in absolute terms, are a tiny proportion of California's current economy.

The wide range of climate warming scenarios for California show 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. 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. 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 the smaller 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 affected least by climate warming. Indeed, even in the dry scenario, with current conveyance infrastructure 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.

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.

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.

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