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Climate Change and Water Supply Adaptation in California 2050

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CLIMATE CHANGE AND WATER SUPPLY ADAPTATION IN CALIFORNIA 2050

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The cost and ability of California's water supply system to adapt to major changes in climate are assessed using the CALVIN economic-engineering model. A dry climate warming GCM scenario is used to create statewide hydrologic changes, which are combined with 2050 water demands in the model. Results indicate that dry climate warming could have significant economic effects on California's water supply, particularly for some agricultural areas. However, a portfolio of water management adaptations allows the magnitude of these economic impacts to be small compared with the overall state economy.

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CLIMATE WARMING AND WATER SUPPLY MANAGEMENT IN CALIFORNIA

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Abstract

This paper examines economic water management adaptations, effects, and other implications of a dry climate warming scenario (GCM GFDL-A2 year 2085) for California's water supply system with estimated year 2050 water demands and land use. Economic performance and adaptive water management activities for this climate scenario are compared with a similar modeling scenario with a continuation of the historical climate. Overall, such a dry climate warming scenario would impose large costs and challenges. While this scenario would severely affect the economies of some rural and agricultural regions of California, the state's overall predominantly urban economy would survive and remain largely unhindered by water supply limitations. The dry climate scenario reduces average annual water availability by 27%, which results in an average annual water scarcity of 17%. Statewide, average agricultural areas see water deliveries 24% lower than demand targets, and urban areas see an average of 1% less deliveries than their demand targets. However, there are great regional disparities. Southern California experiences almost all of the urban water scarcity.

Introduction

This study employs downscaled hydrologic results from the GFDL-A2 GCM model run for year 2085 in an economic-engineering optimization model of California's statewide water supply system (CALVIN) (Medellin *et al.* 2006). This climate warming scenario was chosen because it is likely to stimulate interesting adaptive water management actions in the optimization model. The CALVIN model has been used for several years for water policy and management studies and some previous climate change and climate warming adaptation studies (Draper *et al.*2003; Lund *et al.* 2003; Jenkins et al, 2004; Pulido *et al.* 2004; Null and Lund 2006; Tanaka *et al.* in press). In general, the approach used was that employed in Lund *et al.* (2003) and Tanaka *et al.* (in press) for examining implications of climate warming for water supply impacts and adaptations in California of a PCM2 climate warming scenario in the year 2100, including exogenous land use, population growth, and agronomic technology change effects on water demands as well as climate change. The hydrologic basins and spatial representation of California's water supply system employed in the CALVIN model appear in Figure 1. Overall, the model represents about 90% of California's urban and agricultural water demands and about two-thirds of all runoff in the state.

Changes from Earlier CALVIN Model

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

Hydrology for this dry-warm climate scenario was developed similarly to previous studies for other GCM scenarios (Zhu *et al.*2005, Medellin *et al.* 2006). For California overall, the GFDL-A2 scenario for the years 2070–2099 has 3.5% less precipitation and 2 degrees C greater temperature. This translated into 27% less overall water inflows to the system.

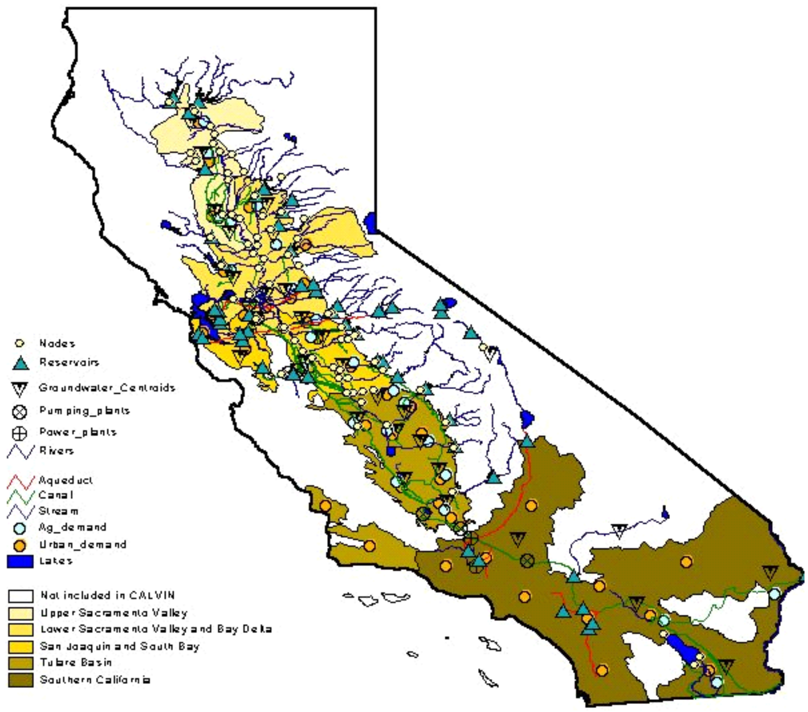

Figure 1. Hydrologic basins, demand areas, and major inflows and facilities represented in CALVIN

The model chosen for this study is the GFDL CM2.1 model (NOAA Geophysical Dynamics Laboratory, Princeton NJ) with the A2 (relatively high emissions) scenario. The GFDL model was chosen because it leads to both a warming and drying of California. The A2 emissions scenario was chosen because it decreased streamflows at selected locations by 27% for the year 2085, while the B1 scenario reduced flows by only 18%. GFD 2.1 A2 in the year 2085 thus provides the relatively dire scenario for negative effects of climate warming on California's water supply.

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

Total urban water demands (water use quantities where water scarcity is absent) are estimated to grow from 14,870 MCM/year for 2020 to 16,461 MCM/year for 2050 using the methods of Jenkins *et al.* (2003). Urban residential demands are estimated using empirical 1995 household economic water demand curves, modified for some increased availability of urban water conservation and increased or decreased housing density (depending on the location), scaled by the estimated population of households in 2050.

Improvements in representing water management infrastructure in the Tulare Basin also were made (Medellin, *et al.* 2006). This newer representation improves the accuracy of some groundwater inflows and representation of conjunctive use facilities and capabilities in the Tulare Basin.

Results

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

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

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

Water Scarcity

The dry climate warming scenario increases water scarcity substantially in some regions and very little for others (Tables 1a and b). For 2020 conditions, where optimization is allowed, water scarcities are relatively benign, at about 2% of statewide water demands. Scarcity is essentially zero in the Sacramento Valley, generally small for agriculture and zero for urban users in the San Joaquin and Tulare Basins. Scarcity is generally a few percent for Southern California urban users (except 17% for Coachella urban users), but greater, about 20%, for Southern California agricultural users who have sold water to Southern California urban users to the limit of the Colorado River Aqueduct's conveyance capacity.

With population growth to roughly 65 million in the year 2050, without climate change, statewide water scarcity increases to 9% (Table 1a). Agricultural water scarcities increase for agricultural areas north of the Tehachapi Mountains, to about 2% in the Sacramento Valley, 20% in the San Joaquin Basin, and 12% in the Tulare Basin. Southern California agricultural water scarcity increases to 29%, but is limited by the capacity limit on the Colorado River Aqueduct and recharge for use in a the Coachella urban area. California is assumed to retain 5,425 MCM/year of Colorado River flows, so water scarcity in Imperial, Palo Verde, and Coachella IDs is entirely due to water sales to urban areas in Southern California. Urban water scarcities remain almost entirely absent north of the Tehachapis. These statewide optimized results allow water to be shifted between large regions of the state to meet economic objectives, as they would in an economically ideal water market. When population growth to the year 2050 is not accompanied by policy flexibility to transfer water beyond 2020 conditions, water scarcities (and scarcity costs) increase slightly, by 247 MCM/year statewide (Table 1b).

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

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

Table 1a. Average Water Scarcities, Statewide Optimization

	2050 Demands								2020 Demands			
	Dry - Warm Hydrology				Historical Hydrology				Historical Hydrology			
	Target	Delivery	Scarcity		Target	Delivery	Scarcity		Target	Delivery	Scarcity	
	MCM	MCM	MCM	%	MCM	MCM	MCM	%	MCM	MCM	MCM	%
Total	**52,409**	**43,700**	**8,709**	**17**	**51,890**	**47,353**	**4,541**	**9**	**46,732**	**45,617**	**1,113**	**2**
Total Agriculture	36,615	28,008	8,608	24	36,096	31,634	4,467	12	34,221	33,259	961	3
Total Urban	15,792	15,692	100	1	15,792	15,720	74	0	12,511	12,358	153	1
Sacramento V. Ag.	11,938	9,095	2,843	24	11,420	11,208	211	2	11,103	11,103	0	0
San Joaquin V. Ag.	7,823	5,826	1,997	26	7,822	6,297	1,529	20	6,484	6,481	4	0
Tulare Basin Ag.	12,822	10,214	2,608	20	12,822	11,255	1,566	12	12,050	12,028	23	0
S. California Ag.	4,033	2,872	1,161	29	4,033	2,873	1,160	29	4,582	3,648	935	20
Sac. V. Urban	2,048	2,042	6	0	2,048	2,049	0	0	1,694	1,694	1	0
SJ Valley Urban	2,015	2,015	0	0	2,015	2,015	0	0	1,102	1,102	0	0
Tulare Basin Urb.	1,734	1,734	0	0	1,734	1,734	0	0	961	961	0	0
S. California Urb.	9,996	9,902	94	1	9,996	9,922	74	1	8,753	8,601	152	2

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

Table 1b. Average Water Scarcities, Regional Optimization, 2050 Water Demands*

	Dry - Warm Hydrology				Historical Hydrology			
	Target	Delivery	Scarcity		Target	Delivery	Scarcity	
	MCM	MCM	MCM	%	MCM	MCM	MCM	%
Total	**52,409**	**41,177**	**11,231**	**21%**	**51,806**	**47,011**	**4,795**	**9%**
Total Agriculture	36,615	25,637	10,979	30%	36,012	31,458	4,555	13%
Total Urban	15,793	15,542	252	2%	15,793	15,553	240	2%
Sacramento V. Ag.	11,938	9,379	2,557	21%	11,335	11,257	78	1%
San Joaquin V. Ag.	7,823	3,773	4,050	52%	7,822	6,239	1,583	20%
Tulare Basin Ag.	12,822	9,612	3,209	25%	12,822	11,090	1,732	14%
S. California Ag.	4,033	2,872	1,161	29%	4,033	2,873	1,161	29%
Sacramento V. Urb.	2,048	2,042	7	0%	2,048	2,049	0	0%
San Joaquin V. Urb.	2,015	2,015	0	0%	2,015	2,015	0	0%
Tulare Basin Urban	1,734	1,734	0	0%	1,734	1,734	0	0%
S. California Urban	9,996	9,751	245	2%	9,996	9,755	240	2%

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

Scarcity and Operating Costs

Water scarcity costs increase as water becomes scarcer with a dry form of climate warming. Local water users see these costs from receiving less water than their ideal economic water delivery. For instance, an agricultural water user receiving full economic water deliveries sees no marginal value for additional water deliveries, and no water scarcity or scarcity cost. Lesser water deliveries imply that water at that location is scarce, incurring a reduction in profits from agricultural production, termed a scarcity cost. This scarcity cost for the water demand area includes both reductions in agricultural production (and crop revenues) and increases in crop production costs (perhaps to increase irrigation efficiency). In some cases farmers reduce water deliveries to allow them to sell water to other water users, profiting more from water sales than their self-imposed scarcity costs.

Water scarcity costs are felt particularly by agricultural regions, which see a small rise in scarcity with population growth from 2020 to 2050 (with historical hydrology), and a large additional increase in scarcity cost with the advent of this dry form of climate warming (Table 2). For the Tulare Basin, a 66% increase in scarcity volume with dry-warm climate warming leads to a 168% increase in scarcity cost over 2050 conditions with historical inflows. Urban regions, with higher economic values for water use, purchase water from existing sources north of the Tehachapis. Climate warming imposes significant costs on agricultural production in the Sacramento, San Joaquin, and Tulare Basins. Some farmer losses from water scarcity would be compensated by revenues from water purchases by cities. In Southern California, the major economic impact of water scarcity is from population growth from 2020 to 2050, with relatively little additional cost from climate warming. If optimally managed, water scarcity costs increase from $123 million/year for 2020, to $240 million/year with 2050 water demands, to $360 million/year with 2050 water demands and dry-warm climate warming. The statewide economic effects of population growth and climate change are of similar magnitudes.

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

Average annual operating costs (Table 3) are much higher than water scarcity costs, as they occur in all years. Operating costs represented in the model include variable operating costs for pumping, water treatment, wastewater treatment, and salinity costs to urban areas. CALVIN does not consider fixed, capital investment costs. Growth in population could increase water operating costs by $413 million/year (or five times the $82 million/year increase in average water scarcity costs). The additional of dry-warm climate warming raises operating costs by $384 million/year above that for 2050 water demands and historical hydrologic conditions. These costs would arise from greater pumping and treatment costs for the acquisition and movement of water to provide water to the higher-valued water demands.

Table 2. Average Scarcity Costs ($K/yr)

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

Table 3. Average Operating Costs, 2050 Demands, Statewide Optimization ($K/year)

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

Environmental Water Shortages (and Reduced Fixed Diversions)

With the dry form of climate warming, some minimum instream flows and diversions are simply infeasible (Medellin, *et al.*2006). These reductions in environmental flow quantities average 1,370 MCM/year and are typically small. However, additional water-related environmental effects of climate warming would occur due to increases in water temperature, which, unfortunately, are not modeled here. The largest environmental flow reduction is for flows in the upper Sacramento River, below Keswick Dam, related to winter-run salmon flows and cold-water pool in the Shasta Reservoir. In addition, for the San Joaquin regional model run, an average of 269 MCM/year of reduced San Joaquin River exports via the Friant-Kern Canal was needed to make operations of Millerton Reservoir physically feasible with climate warming. This would raise water scarcity in the Tulare Basin for its regional model run by 10%–15%.

Delta outflows and exports are often of interest for water management in California. Figure 2 shows monthly average results from the statewide models. Delta exports do not change much (with possible exceptions for June and July) with water demand changes from 2020 to 2050. However, dry-warm climate warming increases Delta exports in winter months (when runoff would be more plentiful), decreases significantly during the present spring snowmelt season, and decreases a little during the summer. Surplus Delta outflows (Figure 2) do not change much with population change alone from 2020 to 2050, but decrease greatly with dry-warm climate change.

Table 4 contains the average marginal economic costs of additional environmental flow requirements for various locations and conditions. These are the opportunity costs of these environmental flows to urban, agricultural, and hydropower users of this water supply system. Many environmental requirements have low economic costs to other water supply users. However, environmental flows for the Trinity River, Clear Creek, and Mono Lake have high values, which increase substantially with dry climate warming. American River instream flow requirements, which have a low economic impact without climate change, rise substantially with climate warming.

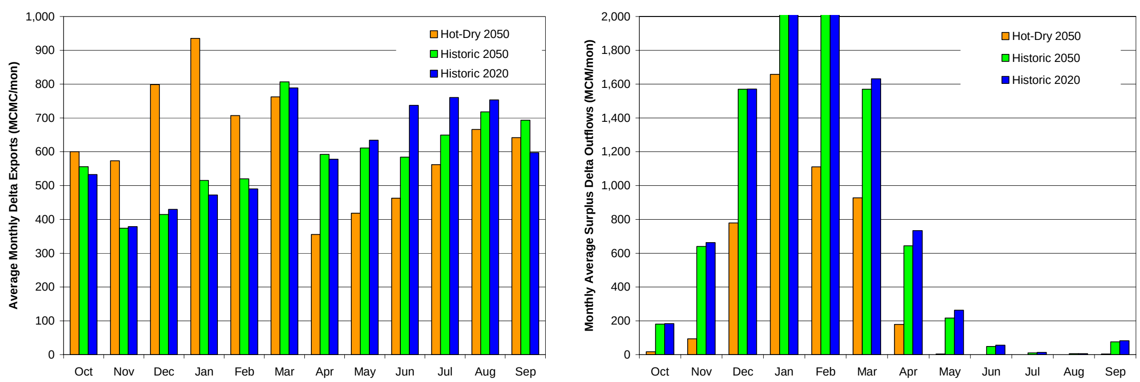

Figure 3. Monthly average delta exports and surplus delta outflows, (MCM/month)

Table 4. Marginal Values of Environmental Flows, 2050 Water Demands ($/1000 m^3)

Hydrology	Historical		Dry-Warm	
Optimization Area / Environmental Flow	Regional	Statewide	Regional	Statewide
Trinity River	41.63	42.76	79.31	89.37
Clear Creek	20.28	20.59	28.29	29.41
Sacramento River	0.22	0.15	1.06	0.86
Sacramento River at Keswick	2.02	2.27	8.22	9.28
Feather River	0.67	0.41	6.15	6.83
American River	0.67	0.62	337.19	331.89
Calaveras River	0.00	0.00	0.00	0.00
Delta Outflow	2.19	2.96	24.98	33.45
Mono Lake	1,552.85	1,186.06	2,289.85	1,821.52

Adaptive Actions

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

In both sets of results, seasonal draw-down and refill indicates annual wet and dry season refill and use of aquifers. The amplitude of these seasonal variations averages about 2,466–3,700 MCM of storage annually. The much longer period variations in groundwater levels, about 10–20 years, indicate the use of groundwater for long-term drought storage. This long period use of over-year storage has an amplitude of about 24,670–37,000 MCM.

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

Surface water storages for the two climate scenarios follow similar inter-annual patterns. However, the dry-warm climate scenario tends to result in more use of the reservoir's lower reaches. This would encroach more into what is now the drought storage pool for major reservoirs. The model's response is to use groundwater more for drought storage, making more storage capacity available in surface water reservoirs for the more variable seasonal flows.

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

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

Seawater desalination is made available to all coastal areas in unlimited amounts at $1,726/TCM. With the historical hydrology, no urban area finds seawater desalination economical. Under climate change dry-warm climate scenario seawater desalination is only used in Southern California, for a total annual average is 7.31 MCM/year. Except where limited by conveyance capacity constraints, urban coastal areas have sufficient access to less-expensive sources (or demand reductions) for water.

Major Limitations

Any model for future conditions will have significant limitations. The general limitations of this approach are well discussed elsewhere, but are not diminished for having already been discussed (Draper *et al.*2003; Tanaka *et al.*in press). These results and conclusions are at best an exploratory analysis, based on mostly reasonable assumptions from the present-day perspective. It is, of course, impossible to conduct an analysis of this situation that is entirely reasonable from all perspectives. Nevertheless, some qualitative conclusions seem reasonable.

Conclusions

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

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

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

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

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