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Economic consequences of optimized water management for a prolonged, severe drought in California

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[1] If abrupt climate change has occurred in the past and may be more likely under human forcing, it is relevant to look at the adaptability of current infrastructure systems to severe conditions of the recent past. Geologic evidence suggests two extreme droughts in California during the last few thousand years, each 120–200 years long, with mean annual streamflows 40%–60% of the historical mean. This study synthesized a 72 year drought with half of mean historical inflows using random sampling of historical dry years. One synthetic hydrological record is used, and sensitivity to different interpretations of the paleorecord is not evaluated. Economic effects and potential adaptation of California's water supply system in 2020 to this drought is explored using a hydroeconomic optimization model. The model considers how California could respond to such an extreme drought using water trading and provides best-case estimates of economic costs and effects on water operations and demands. Results illustrate the ability of extensive, intertied, and flexible water systems with heterogeneous water demands to respond to severe stress. The study follows a different approach to climate change impact studies, focusing on past climate changes from the paleorecord rather than downscaled general circulation model results to provide plausible hydrologic scenarios. Adaptations suggested for the sustained drought are similar for dry forms of climate warming in California and are expensive but not catastrophic for the overall economy but would impose severe burdens on the agricultural sector and environmental water uses.

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1. Introduction

[2] Abrupt and widespread climate changes with major impacts have occurred repeatedly in the past and it is conceivable that human activity is increasing the probability of large-scale, rapid changes. Economic and ecological impacts of new climatic conditions on existing systems could be large and potentially serious. These impacts and the measures available to adapt current systems to severe conditions should be considered by policy makers [*Alley et al.*, 2003]. After abrupt change, it would be necessary to adapt existing infrastructure and management practices to new conditions. Although recent human-induced climate change may drastically change historical climate patterns, given the uncertainty of future climate water managers often rely on hydrologic conditions from the recent past to make decisions [*Loaiciga*, 2005]. Reconstructions of large paleodroughts (historical droughts deduced from geological records) provide an additional method of characterizing extreme climate periods to help evaluate existing system robustness under severe droughts, identify infrastructure and institutional adaptation measures, and take a long-term perspective on drought management policy.

[3] Climate varies over decades, even centuries, sometimes having precipitation rates and other climate characteristics well beyond historical scale variability. In the past decade future climate warming has raised concerns for how managed water systems could perform and adapt under very different climates. The development of hydrologic scenarios for such studies typically relies on general circulation models of climate (GCMs) with coarse results downscaled to local precipitation and temperatures, for use in basin rainfall-runoff models. These studies are rarely definitive because of the ever-evolving and multiplying nature of GCM models, the difficulties and uncertainties of downscaling, and the uncertainties of rainfall-runoff models

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applied to circumstances and climates likely to be very different from those under which rainfall-runoff models were calibrated. Furthermore, changes predicted by these models mostly occur at the decadal to century scale, giving societies ample time to adapt their infrastructure and management practices. This being said, most GCMs in North America have shown a reduction of snowpack which should increase vulnerability to drought [*Christensen et al.*, 2004; *Stewart et al.*, 2004].

[4] The geologic record has shown repeatedly that environmental change can come swiftly, with climate-driven hydrologic changes the main reason for shifts. This study takes a different and more extreme approach to examining water management under climatic change by focusing on severe and prolonged droughts from the paleorecord. Indications of severe and sustained mediaeval droughts in the past thousand years in California [*Stine*, 1994] are the basis in this study for developing a synthetic severe drought record for California. A synthetic drought of 72 years based on geologic observations is used in an economic engineering optimization model of water management in California. The results provide a preliminary indication of the ability of California's water management system to respond to such severe, but apparently not unprecedented droughts, and provide insights into the potential magnitude and management of drought disasters for the state.

[5] Use of the paleohydrologic record inscribed in historical, biological or geological memory is an accepted but infrequent approach in hydrologic engineering. One method is dendrohydrology, or tree ring research. *Loaiciga et al.* [1993] and *Loaiciga* [2005] describe how tree ring based hydrologic reconstructions can help discern patterns of long-term hydrologic variability and aid in storage infrastructure design; *Cook et al.* [1999] and *Meko et al.* [1995] use the technique to identify historical droughts in the United States. *Stedinger and Cohn* [1986] and others have found historical and paleohydrologic information beneficial in flood frequency analysis.

[6] Drought impacts on water resource and economic systems can be significant. *Harding et al.* [1995] simulate current system wide effects of a 38 year Colorado River paleodrought. They identify equity of allocation between states, loss of water quality, and loss of hydropower as major issues. *Sangoyomi and Harding* [1995] and *Booker* [1995] evaluate possible institutional responses to prolonged drought for the Colorado River System. Economic impacts of droughts can be considerable, particularly in agricultural economies where supply cannot be economically obtained by other means. Hydroeconomic models [*Harou et al.*, 2009] can help evaluate the economic costs of water scarcity during droughts and propose engineering and institutional responses [*Booker*, 1995; *Booker et al.*, 2005; *Ward et al.*, 2006]. Our study shares this economic engineering method [*Lund et al.*, 2006].

2. Extreme Paleodroughts in California

[7] Several geologic, dendrohydrologic (tree ring), and other studies of Holocene (geological epoch beginning 12,000 years ago) in California indicate severe and sustained droughts (up to 200 years) in the last millennium [*Brunelle and Anderson*, 2003; *Cook et al.*, 2004; *Ingram et al.*, 1996; *Starratt*, 2001; *Stine*, 1990a, 1990b, 1994]. According to *Stine* [1990a, 1994], two major droughts occurred in the last millennium, roughly from 930 to 1130 AD, and from 1250 to 1350. During these two droughts, levels of Mono Lake and other Sierra Nevada Lakes declined well below recent diversion-induced lows, as evidenced by in situ mature tree trunks dated from these periods. These tree ring records, with carbon dating, indicate prolonged droughts severe and sustained enough to reduce inflows to Mono Lake by 40%–60% during the drought, without any period of wet years sufficient to raise the lake level enough to inundate and drown these trees. These droughts were apparently not unique to the Mono Basin. Along the Sierra Nevada range, there are similar indications of sustained drought during these same periods [*Stine*, 1994]. For many large (Tahoe) and small (Tenaya) Sierra Nevada Lakes, inflow was reduced sufficiently to prevent many natural lakes from overtopping their current rims and contributing to Central Valley streamflows, as evidenced from tree stumps dated from this period lying below these lake outlet elevations.

[8] There is some evidence to dispute the spatial and temporal extent of these extreme droughts. *Meko et al.* [2001] develop a tree ring based hydrology from the Sacramento River from A.D. 869 to 2000 which shows several low-flow periods during the Stine droughts but does not support their uninterrupted nature. The Sacramento River is the largest single source of water for California's urban and agricultural water supply system. However, *Meko et al.* [2001, p. 1029] support that "the tree-ring record also suggests that persistently high or low flows over 50-year periods characterize some parts of the long-term flow history." Pollen-based reconstructions of climate by *Davis* [1999] generally match the Mono Lake fluctuations proposed by *Stine* [1990a], although fewer fluctuations are recorded. A sufficient number of studies identify periods of prolonged drought in the past to warrant the attention of current water managers and leads to the question whether such long-term fluctuations are observed more recently.

[9] Meko and colleagues identify a 20 year drought in the late 1500s with mean annual Colorado River flow at 80% of historical mean [*Meko et al.*, 1995; *Meko and Woodhouse*, 2005]. These studies and others like them show prolonged drought is not restricted only to the geologic past and naturally dry periods in addition to human-induced warming remain a possibility. Furthermore, these studies point to the possibility of abrupt climate change, which from a water management perspective is very different from the drying trends investigated in most GCM-led adaptation studies [*Hulme*, 2003]. Because larger, faster and less expected climate changes can cause more problems for economies and ecosystems, paleoclimatic data suggest the future may be more challenging than anticipated in current policy making [*Alley*, 2003].

3. Method

3.1. Synthetic Drought

[10] The character of the two droughts chosen for study in this work are of a sustained 100–200 year nature, with mean flows averaging 40%–60% of current mean flows, and devoid of single of multiple very wet years sufficient to

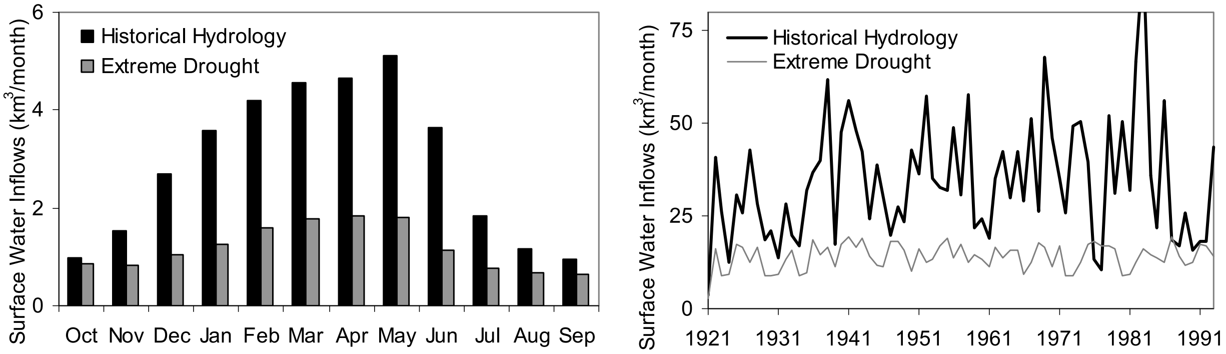

Figure 1. Monthly and annual average surface water inflows in km^3.

overtop these natural lake rims. A synthetic hydrologic record for a similar extreme drought covering all of California was developed by resampling surface flows from the historical record (1922–1993). The synthetic a set of hydrologic inflows averages 53% of the historical mean. This was done by random resampling from the 10 driest years of record, since no "wet" years seemed to have occurred in the extreme droughts in the geologic record [*Stine*, 1994]. The same ordering of dry years was used to establish time series of surface water inflows (Figure 1), groundwater inflows, local accretions (intrabasin runoff), seepage losses in rivers and environmental minimum flows for California's water resource system. Most hydrologic time series are taken from the CALSIM simulation model [*Draper et al.*, 2004]. Figure 1 shows how the persistent nature of the drought is captured by the synthetic record. Average total inflow to modeled areas is reduced from 48 km^3 (historical) to 25.6 km^3 for the synthetic drought (39 to 21 maf, million acre-feet (1 af = 1234 m^3)). Sensitivity of model results to the particular random sequence of dry years was not evaluated for several reasons including the time required to interpret the large quantity of results from a single run. Because the variability of inflows within the 10 driest years of record is low (Figure 1),

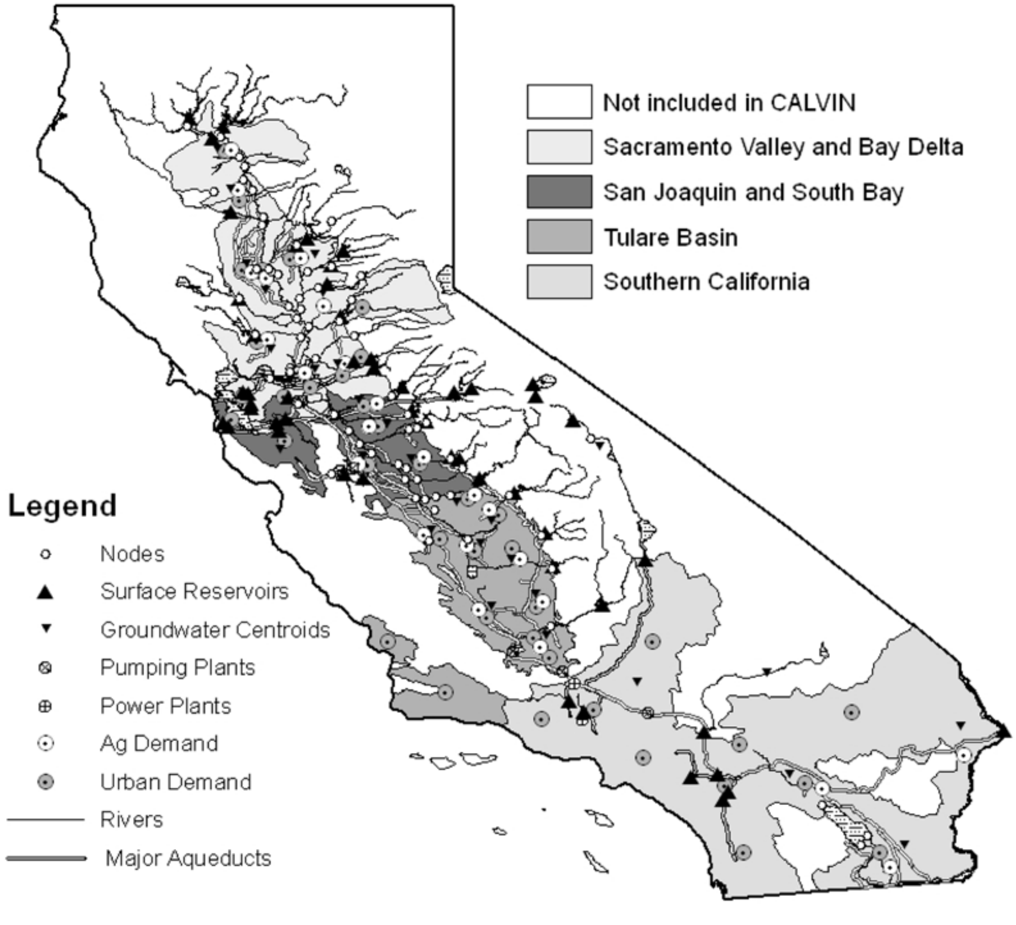

Figure 2. Hydrologic basins in California (125°W–113°W longitude, 32°N–42°N latitude), demand areas, major inflows, and facilities in CALVIN.

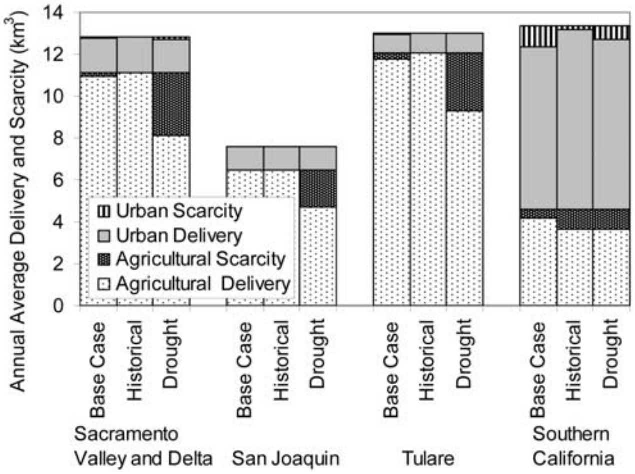

Figure 3. Average annual agricultural and urban water scarcity and deliveries. See Figure 2 for geographic outlines of four regions summarized here. Total water demands and delivery targets do not vary by scenario.

and because the multiperiod optimization model stores water optimally over time to avoid the worst shortfalls, the actual sequence of more or less "wet" dry years is relatively insignificant in the context of this study. Results aren't given for particular periods of the time horizon; rather we present only broad responses over the entire time horizon.

3.2. Hydroeconomic Model

[11] The CALVIN (California Value Integrated Network), hydroeconomic optimization model of water supply management covers the entire intertied water supply system of California (Figure 2) [*Draper et al.*, 2003]. It includes all major inflows, surface and groundwater reservoirs, conveyance infrastructure, pumping, water and wastewater reuse treatment, and potential desalination facilities. No hydrologic modeling is performed in CALVIN; it is a management model that uses preestablished monthly time series of flows produced by empirical data and/or simulation models.

[12] The model optimizes monthly water management over a 72 year historical hydrologic record (1921–1993) for a particular level of infrastructure, population and land use development (projected to the year 2020 in this case). The operating rule of the optimization model, i.e., the objective function, is to minimize statewide costs from water scarcity and water operations by allocating, storing and trading water throughout the network; sunk capital costs are not included. Water demands are represented by economic penalty functions derived from agricultural and urban economic demand curves for water. Penalty functions represent the economic value lost when a water demand receives less than their target water delivery. Target deliveries indicate where more water would not increase net benefits. Agricultural demand curves are estimated by the State-wide Agricultural Production (SWAP) model [*Howitt et al.*, 2001] and urban demand curves were taken from published sources [*Jenkins et al.*, 2003]. Examples of such functions are given by *Draper et al.* [2003]. Operating costs for pumping, artificial recharge, desalination and water treatment also are included.

[13] CALVIN employs the Prescriptive Reservoir Model (HEC-PRM) software [*U.S. Army Corps of Engineers*, 1999] as its computational and organizational core. HEC-PRM uses a computationally efficient generalized network flow linear optimization formulation that represents the system as a network of nodes and links. The model minimizes costs subject to flow continuity at nodes and capacity constraints on links; it can be written *Min* $\sum_i \sum_j c_{ij}X_{ij}$ subject to $\sum_i X_{ji} = \sum_i a_{ij}X_{ij} + b_j \; \forall j$, $X_{ij} \le u_{ij} \; \forall ij$, $X_{ij} \ge l_{ij} \; \forall ij$, where X_{ij} is flow from a node i toward node j (link ij) and X_{ji} is flow from node j to a node i (link ji), c_{ij} = costs of flow through link ij (scarcity costs or operational costs), b_j = external inflows to node j, a_{ij} = gain/loss coefficient on flows in link ij, u_{ij} = upper bound (capacity) on link ij, and l_{ij} = lower bound on link ij. This generalized network flow formulation precludes including constraints beyond flow continuity at nodes and capacity constraints on links. The number of links (1,617) multiplied by the number of time periods (864) gives the minimum number of X_{ij} decision variables (1,397,088) (can increase due to piecewise linearization). The model solves in approximately 12 h using an initial solution on a 2 GHz PC.

[14] Model results include time series of optimized monthly operations and water allocations to maximize statewide net economic benefits. This includes changing surface and groundwater operations and reallocating water to maximize net economic benefits (by minimizing net economic costs) within environmental flow, capacity, and mass balance constraints. Whenever and wherever optimal flow in the network is constrained, effect on the state's overall economic benefits are recorded as shadow values (Lagrange multipliers) providing valuable insights. Because of the monetary objective function, the network flow program's two constraint types have economically interpretable shadow values. Shadow values of capacity constraints (minimum or maximum storage or conveyance) provide the system-wide benefit that would result if the constraint were relaxed by 1 unit (e.g., if canal or reservoir capacity were increased). In the case of environmental flow constraints (minimum flows), shadow values provide the system-wide opportunity costs (foregone benefits) of the restrictions. Shadow values of mass

Table 1. Statewide Mean Annual Water Scarcity and Scarcity Cost Estimated by Model

	Water Scarcity (km^3/yr)			Water Scarcity Cost (million $/yr)		
Scenario	Agricultural Model	Urban Model	Total	Agricultural Model	Urban Model	Total
Base Case	0.9	1.1	2.0	26	1564	1590
Historical	1.0	0.2	1.1	33	89	123
Drought	8.5	0.8	9.3	1040	637	1677

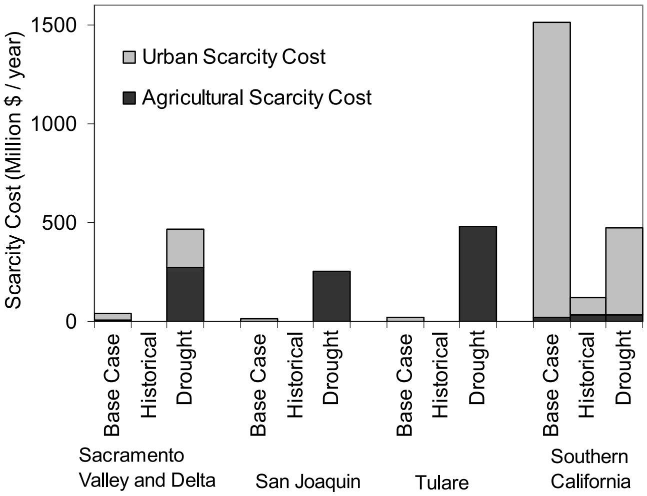

Figure 4. Costs due to agricultural and urban water scarcity.

balance constraints indicate for each time period and node how the objective function would change if an extra unit of water were available. This provides information on system-wide marginal value of increased local water deliveries.

3.3. Scenarios

[15] The model has been applied previously with perturbed historical hydrologic inflows derived from GCM models to represent climate warming [*Medellín-Azuara et al.*, 2008; *Tanaka et al.*, 2006]. Here, the perturbed hydrology is a synthetic time series designed to approximate one of California's major medieval droughts. We investigate economic and water management effects if a severe dry period would befall the current system, and compare it with operation under current climate and management.

[16] Three scenarios are modeled with water management infrastructure and water demands for the year 2020: (1) a "base case" constrains operations and allocation policies to emulate historical allocation policies, (2) a "historical" climate scenario optimizes assuming institutional flexibility and economically driven operation with historical hydrology, and (3) a "drought" scenario optimizes assuming institutional flexibility and economically driven operation with the extreme drought hydrology. The base case scenario reflects historical operating policies (e.g., water rights) and climate; its results are heavily constrained to emulate CALSIM simulation model results [*Draper et al.*, 2004]. CALSIM aims to reproduce historical allocations and reservoir operations. Optimized scenarios 2 and 3 involve best-case costs and operations that could occur under economically optimal and institutionally unconstrained management.

4. Results

4.1. Water Scarcity and Its Economic Cost

[17] Water scarcity is defined here as the difference between modeled water deliveries and the water that users would use at zero marginal cost (target demands). Urban scarcity is concentrated mostly in southern California (Figure 3) and changes little among the three scenarios (Table 1) due to high economic values for urban water use (a consequence of high willingness to pay for water). Agricultural scarcity increases greatly under the extreme drought (Table 1) in all regions except southern California (Figure 3). Southern California retains much agricultural water use under extreme drought because of relatively reliable Colorado River flows and limited conveyance capacity to urban coastal areas (limiting the ability to export Colorado River water there). These flows are secure because California has the first priority water right to flow of the Colorado River [*Norviel et al.*, 1922]; in addition, farmers in the southern Californian desert have senior water rights to much of the Colorado River flow. So flows from Colorado are fixed in the model and do not reflect potential drought in that area.

[18] Scarcity costs are calculated as the lost economic benefits to water demand areas if they receive less than their target demand. Urban scarcity costs are high in southern California due to infrastructure constraints, primarily the limited capacity of Colorado aqueduct (see Table 5). In the base case these costs are even higher due to additional water right constraints (Figure 4) such as the historical water rights of Imperial, Palo Verde and Coachella irrigation districts, together amounting to 86% of California's Colorado River allocation.

[19] Scarcity costs for the extreme drought under economically optimal operations are greatest for the agricultural sector except in southern California where urban scarcity costs dominate. Agricultural scarcity is low in the base case and historical scenarios, but increases greatly with the drought (Table 1). Scarcity costs are an order of magnitude larger in the drought than in the historical scenario. For the base case, permanent water rights transfers in southern California since 1997 are not taken into account; if they were, base case urban scarcity in southern California would decrease. The appearance of urban scarcity costs and high willingness to pay for more water in Northern California are also significant in the extreme drought.

Table 2. Average Annual Operating Costs and Unit Operating Costs Estimated by Model

	Operating Costs ($ million/yr)			Average Unit Operating Costs ($/10^3 m^3)		
Scenario	Base Case	Historical Model	Drought Model	Base Case	Historical Model	Drought Model
Sacramento	247	200	182	20	16	19
San Joaquin	394	375	378	52	49	65
Tulare	461	920	936	36	71	91
Southern California	3,074	1,974	1,901	257	161	162
Total[a]	4,176	3,468	3,396	93	76	91

[a] For average unit operating costs, the total shown is the average of all values.

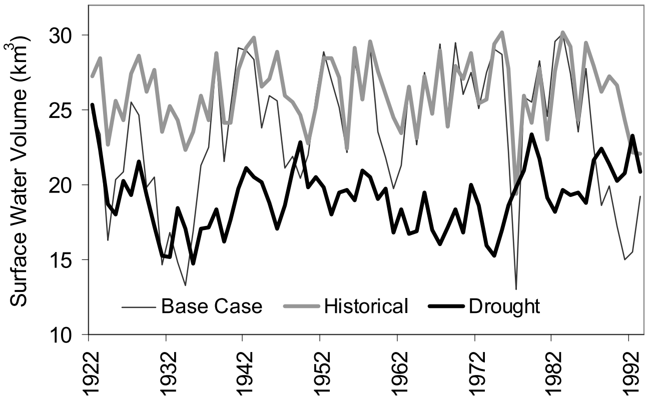

Figure 5. Statewide annual surface water storage.

4.2. Operating Costs

[20] Operating costs and average unit operating costs incurred in the modeled scenarios appear in Table 2. These are obtained by multiplying estimated unit costs (pumping, treatment) of conveyance through a link by the amount of water passing through that link. These describe variable operating costs incurred through activities such as pumping and treating water. Both optimized scenarios produce similar total operating costs because the drought scenario involves lower deliveries which reduces pumping costs. The unit costs are higher for the extreme drought as would be expected since existing resources are more actively managed. Operating costs are always at least twice the scarcity costs, implying rises in energy costs could significantly affect operations and total cost.

4.3. Adaptive Actions: Infrastructure and Trading

[21] California has a wide variety of options to adapt to the water supply effects of a severe and prolonged drought. These options include traditional water supply reservoir operations, conjunctive use of surface and groundwaters, urban and agricultural water use efficiency practices, desalination, water reuse and water markets. Optimization results suggest portfolios of actions that economically adapt to changes in climate and population, as discussed below.

[22] The need of surface and groundwater storage is lessened for the prolonged extreme drought due to greatly decreased inflow and decreased inflow variability. The value of additional surface storage capacity becomes zero under the major paleodrought as even existing reservoirs never fill (Figure 5).

[23] Figure 6 shows seasonal and over-year statewide groundwater storage. Initial and end estimates of state storage in 1921 and 1993 were estimated form regional groundwater models then set as start and end model constraints. Seasonal draw down and refill indicates annual wet and dry season refill and use of aquifers. The amplitude of these seasonal storage variations averages about 2–3 km^3. The much longer period variations in groundwater levels, about 10–20 years, indicate the use of groundwater for drought storage. This over-year storage use of groundwater has an amplitude of about 20–30 km^3 for the historical hydrology. Less aggressive use of groundwater is made with the prolonged drought because little wet year surface water is available to recharge groundwater basins; interannual variation in groundwater storage is greatly reduced for the extreme drought.

[24] Larger water scarcities give economic incentives for owners of high-priority water rights with low-valued water uses to sell water to more economically productive water uses. This water market is implicit in the objective function of the optimization model [*Jenkins et al.*, 2004] and is increasingly characteristic of California's water management. Water markets facilitate both reallocation of water from agriculture to growing urban uses, as well as more economical operation of water resources to improve technical operating efficiency [*Harou and Lund*, 2008; *Pulido-Velazquez et al.*, 2004]. This reallocation is evidenced in Figures 3 and 4 by the relative shift of water scarcity from urban to agricultural uses (limited in southern California by conveyance capacities).

[25] Water transfers are effective enough to preclude need for seawater desalination in either optimized scenarios at the conservative cost of \$1.14/m^3. Average annual wastewater reuse increases 40% from 91 × 10^6 m^3 in the optimized historical scenario to 128 × 10^6 m^3/yr with the extreme drought.

4.4. Marginal Economic Values

[26] Average and monthly willingness to pay for additional water deliveries are produced for each individual economic demand area (see Table A1). Willingness to pay is

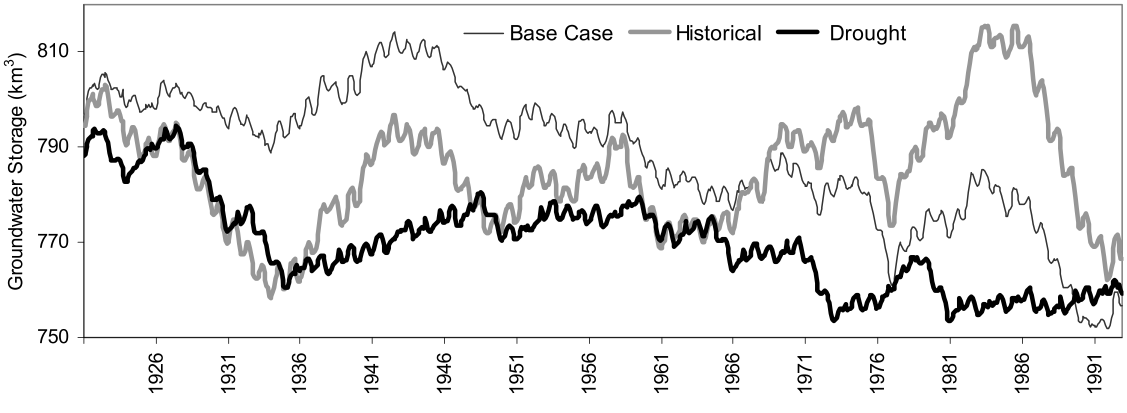

Figure 6. Statewide groundwater storage with base case and historical and drought scenarios.

Table 3. Average Annual Environmental Flows for the Historical and Drought Model Runs and Their Reduction Due to Infeasibilities

Environmental Flow Location	Historical Model[a]	Reduction for Synthetic Drought[a]	Reduction for Computational Feasibility[a]	Drought Model[a]	Percent Decrease in Environmental Flows
American River	191	73	0	118	38
Trinity River	62	20	0	41	33
Clear Creek	13	1.3	0	11	11
Upper Sacramento River	736	92	83	561	24
Lower Sacramento River	24447	615	166	23665	3
Mokelumne River	36	24	0	12	67
Calaveras River	7.1	0	2.9	3.9	45
Stanislaus River	568	200	0	368	35
Tuolomne River	799	330	0	468	41
Merced River	242	43	0	199	18
San Joaquin River	1272	687	0	585	54
San Joaquin Refuge	57	5	0	52	9
Mono Lake	7.6	0	1.5	6.1	20
Delta	6899	1933	0	4966	28
Total	35334	4024	254	31056	12

[a] Values are × 10^6 m^3.

estimated by looking up monthly model deliveries in the water demand functions and reporting the slope (in $/$10^3$ m^3). In the optimized historical scenario, the economic willingness to pay for additional water is very small in much of California. For the extreme drought, willingness to pay for additional water (or its equivalent from reuse or efficiency actions) greatly increases. Agricultural willingness to pay for additional water often exceeds $100/$10^3$ m^3, precluding lower-value crops for the extreme drought. Urban willingness to pay for additional water in Southern California commonly exceeds $700/$10^3$ m^3, reflecting physical capacity limits for importing water to southern California. In Northern California, urban willingness to pay for additional water is very low, since urban users can purchase supplies from lower-valued agricultural uses.

[27] Environmental flows in the model are represented with constraints for minimum streamflows and water deliveries to wetlands. Time series constraints were taking from existing operations models [*Draper et al.,* 2003]. The model does not recommend new environmental flow standards, but rather indicates (1) the physical unavailability of water to sustain current environmental flow levels with such a sustained drought and (2) the economic value of water used for noneconomic ecological purposes. To ensure computational feasibility of the severe drought model (i.e., not violate mass balance), environmental flow had to be reduced compared to those required for the historical model (Table 3). Environmental flows are reduced by various amounts (between 3% and 67%), some locations requiring large reductions. Most reductions occur through sampling environmental flow requirements of driest years as explained in the synthetic hydrology section; a few additional reductions had to be made for the solver to find a feasible solution (Table 3).

[28] Average marginal economic (opportunity) costs of environmental flow requirements are supplied by model

Table 4. Marginal Economic Opportunity Costs of Environmental Flow Requirements Estimated by Model[a]

	Average Opportunity Cost		Maximum Opportunity Cost	
	Historical Model	Drought Model	Historical Model	Drought Model
Minimum In-Stream Flows				
Trinity River	28	40,781	47	114,150
Clear Creek	13	40,143	28	114,044
Sacramento River	0.2	286	5	113,618
Sacramento River at Keswick	1	32,238	16	113,150
Feather River	0.2	44	7	162
American River	0.4	62	8	846
Mokelumne River	2	1,767	8	2,804
Calaveras River	0	5	0	241
Yuba River	0	68	6	3,322
Stanislaus River	7	106	37	272
Tuolumne River	6	122	32	369
Merced River	7	70	23	274
Mono Lake inflows	781	384	1158	1,931
Owens Lake dust mitigation	604	899	660	1,514
Refuges				
SacWest Refuge	2	140	7	745
SacEast Refuge	0.1	3	5	149
Volta refuges	19	146	25	267
San Joaquin/Mendota refuges	17	115	23	210
Pixley	26	256	39	328
Kern	31	165	37	231
Delta outflow	1.9	81	6.7	170

[a] Average monthly values are given in $/$10^3$ m^3.

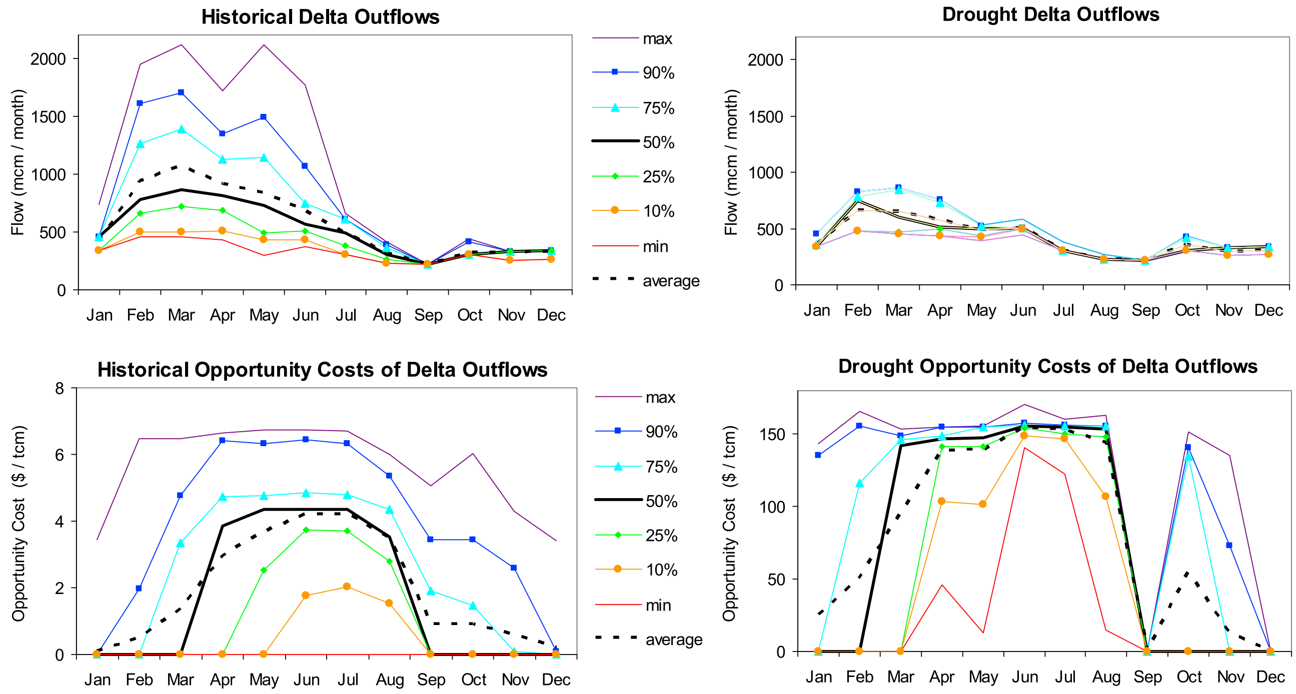

Figure 7. Sacramento River Delta outflows and their opportunity costs. Note that the bottom graphs have differing scale.

shadow values. Table 4 contains the monthly average marginal economic costs of selected environmental flow requirements in California as well as the monthly maximum over 72 years. These are the opportunity costs of environmental flows to urban, agricultural, and hydropower users of this water supply system. Even after a 12% total reduction in environmental flows to ensure feasibility, the opportunity cost of meeting environmental flow deliveries increase substantially with the extended drought; from hundreds to thousands of $\$/10^3$ m^3 for rivers and from tens to hundreds of $\$/10^3$ m^3 for ecological refuges. These opportunity costs of environmental flows illustrate the likelihood of increased water management controversy with such a drought.

[29] One location where opportunity costs are especially relevant is the Sacramento River Delta which flows into the Bay of San Francisco, due to the large flow volume involved, its importance for facilitating north-to-south water transfers during drought, and the fragility of its infrastructure [*Lund et al.*, 2008]. Opportunity costs are largest during the summer irrigation season; and lowest in September, when environmental flow requirement are at their lowest (Figure 7).

4.5. Changes in Infrastructure Value and Hydropower Production

[30] With the severe drought, economic values for expanding surface storage capacity become zero as even existing reservoirs never fill. However, because of the generalized increase in water transfers under drought, enlarged conveyance infrastructure makes sense at several locations in California. Table 5 provides monthly average and monthly maximum marginal values of increasing conveyance capacity at selected canals, diversions and pipelines. The Colorado aqueduct has the highest value for more infrastructure due to its ability in the model to bring more water to southern California. In a few cases, the marginal value of expanding conveyance capacity decreases due to reduced availability of water to convey.

Table 5. Monthly Average and Maximum Marginal Value of Conveyance Capacity Over 72 Years at Selected Sites Estimated by Model

Conveyance Infrastructure	Physical Capacity (10^3 m^3/month)	Average Marginal Value ($\$/10^3$ m^3)		Maximum Marginal Value ($\$/10^3$ m^3)	
		Historical Model	Drought Model	Historical Model	Drought Model
Colorado Aqueduct	134	118	224	283	962
Kings River Diversion	17	3	47	26	289
Sacramento River Diversion	13	0	41	0	808
American River Diversion	25	0	40	0	532
Cross Valley Canal	60	0	26	0	186
Kern Water Bank Canal	74	0	20	0	186
Auld Valley Pipeline	26	0	5	0	256
Arvin Edison intertie	15	0	5	0	170
SFPUC to Santa Clara Valley	17	0	3	0	99
Auld Valley Pipeline	26	1.2	0	6	0
San Diego Canal	127	0.3	0	77	0
Santa Ana Pipeline	35	0.2	0	77	0
MWD feeders	112	0	0.1	0	19

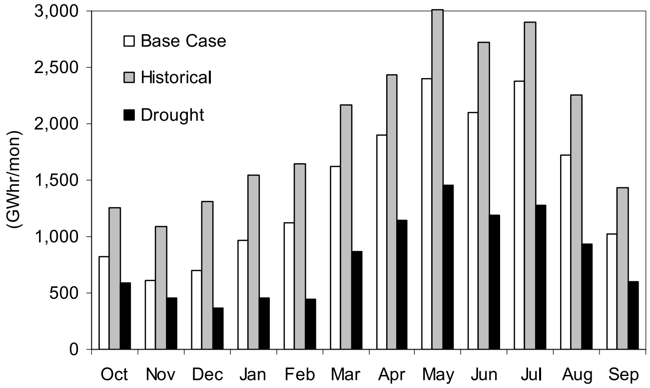

Figure 8. Monthly reservoir hydropower generation (GWh/month).

[31] Figure 8 shows monthly reservoir hydropower generation for the three scenarios. The paleodrought looses 60% of the state's hydropower production from water supply reservoirs when comparing both optimal scenarios, reflecting reductions in inflows.

5. Discussion

[32] Much of the great reduction in water available in the synthesized drought is from eliminating wet years when significant amounts of water are surplus to economic uses and "spill" from the system. This leads a 47% reduction in inflows to cause an order of magnitude increase in water scarcity and scarcity costs. The elimination of wet years especially tests the system's resiliency by not replenishing aquifer and reservoir storage. To understand the implications of this study it is important to understand the assumptions and limitations behind the approach, as summarized below.

[33] A disadvantage of the resampling approach is that the entire synthetic drought record contains no single year drier than the driest year on the historical record. For such a drought, it seems likely that some years would be drier than the driest year from the historical hydrologic record. California's Colorado River supplies were not reduced beyond current 5.4 km^3/yr (4.4 maf) supplies whereas this share might be reduced under such extreme circumstances. A further limitation is that sensitivity to the random ordering of dry years is not evaluated.

[34] Specific technical limitations of the CALVIN model are discussed elsewhere [*Draper et al.*, 2003; *Jenkins et al.*, 2004]. The most significant drawbacks relate to the (1) use of a network flow formulation that limits ability to represent important physical phenomena (e.g., stream-aquifer interaction, dynamic pumping costs, etc.) and grants perfect hydrologic foresight to the optimization, (2) nonconsideration of flood control and recreation benefits, and (3) use of imperfect and simplified data. Generally, the approach and results of this study assume California water management is institutionally flexible enough to allow it to economically optimize water operations. While many water management and policy decisions are driven by economics, perfect economic rationality is unlikely to prevail. The onset of an extreme prolonged drought would require a period of structural and expectation adjustment for the society, economy, institutions, and water managers. This study describes optimal management attainable during the latter years of the drought, after water managers have realized the onset and implications of prolonged drought. Environmental impacts of such an extreme, sustained drought would be severe, probably locally catastrophic, and merit a separate study with an appropriate methodology.

6. Conclusions

[35] A synthetic version of a geologically/dendrohydrologically inferred prolonged medieval drought is used to study potential water supply effects of abrupt climate change in California. A single set of synthetic drought hydrologic time series with half (53%) of historical inflows is built by resampling the driest years of the historical record. A hydroeconomic optimization model is used to quantify economic and water management implications of the drought. Three scenarios were modeled: a constrained base case to represent current practices, an optimized historical run and an optimized drought scenario. Optimized scenarios assume pure economic optimization and pose no institutional constraints outside of ecological low-flow limits.

[36] Results for California's current water supply system showed that the economic cost of water scarcity under optimized drought management is roughly 5 times worse than the base case and 10 times worse than the optimally managed historical scenario. Scarcity costs were similar for the base case and drought scenarios, but they were an order of magnitude more than the optimized historical scenario. This implies scarcity costs even under efficient water management rise 10 fold under an approximate 50% reduction in inflows. Operating costs are always at least twice scarcity costs, indicating that scarcity costs under efficient management are not catastrophic on a statewide scale. Other indicators confirm the systems robustness under economically efficient management: desalination is not triggered at any time or place during the 72 year drought and wastewater reuse only increases by 40% as compared to the optimized historical scenario. Lower inflows imply reduced use of surface water and groundwater storage and no value for expanding storage capacity. Conveyance capacities showed high value of expansion, particularly in southern California where low supplies are heavily managed (i.e., conveyed). Opportunity costs of environmental low flows rose by 1 or more orders of magnitude with the extreme drought, pointing toward the high stakes competition for water that is inevitable under a severe prolonged drought.

[37] California's current water storage, conveyance and treatment infrastructure allows adapting to severe prolonged drought despite severe economic and water supply effects to many regions. In the best case, optimal statewide trading allows the water supply system to function without a catastrophic disruption to the statewide economy. However, the agricultural sector and environmental uses would face severe disruptions, and might be catastrophic for local ecosystems and communities. Effective response to such a severe and prolonged drought would require considerable institutional flexibility and use of water markets or other forms of water reallocation.

Appendix A

[38] Table A1 shows full regional results on deliveries, scarcity, scarcity costs and willingness to pay. Water volumes

Table A1. Full Regional Results on Deliveries, Scarcity, Scarcity Costs, and Willingness to Pay

		Base Case					Unconstrained Historical Hydrology					Unconstrained Drought Hydrology				
	Target (× 10^6 m^3/yr)	Delivery (× 10^6 m^3/yr)	Scarcity (× 10^6 m^3/yr)	Scarcity Percent	Scarcity Cost ($M/yr)	WTP ($/$10^3$ m^3)	Delivery (× 10^6 m^3/yr)	Scarcity (× 10^6 m^3/yr)	Scarcity Percent	Scarcity Cost ($M/yr)	WTP ($/$10^3$ m^3)	Delivery (× 10^6 m^3/yr)	Scarcity (× 10^6 m^3/yr)	Scarcity Percent	Scarcity Cost ($M/yr)	WTP ($/$10^3$ m^3)
							Northern California									
Ag																
CVPM 1	189	189	0.4	0	0.01	0	189	0	0	0	0	40	149	79	17.4	77
CVPM 2	859	790	69.9	8	3.5	28	859	0	0	0	0	456	403	47	53.8	103
CVPM 3	2,009	1,903	105.7	5	3.2	16	2,009	0	0	0	0	1,337	672	33	65.1	78
CVPM 4	1,354	1,356	0	0	0	0	1,354	0	0	0	0	916	438	32	39.2	79
CVPM 5	2,142	2,144	0	0	0	0	2,142	0	0	0	0	1,681	461	22	30.1	57
CVPM 6	1,292	1,293	0	0	0	0	1,292	0	0	0	0	1,041	251	19	22.2	89
CVPM 7	697	697	0.4	0	0	0	697	0	0	0	0	544	153	22	10.7	58
CVPM 8	1,103	1,103	0	0	0	0	1,103	0	0	0	0	851	252	23	22.3	92
CVPM 9	1,461	1,451	9.6	1	0.1	16	1,461	0	0	0	0	1,262	199	14	11.0	44
Urb																
Napa-Solano	142	129	13.1	9	22.0	456	142	0	0	0	0	142	0	0	0	0
Contra Costa	166	166	0.5	0	0	15	166	0	0	0	0	166	0	0	0	0
East Bay Mud	367	358	9.2	3	12.0	231	366	0.8	0	0.6	22	257	109	30	196.6	1981
Stockton	117	117	0	0	0	5	117	0	0	0	0	117	0	0	0	4
Sacramento	837	838	0	0	0	0	837	0	0	0	0	836	0	0	0.3	2
Yuba	66	64	1.2	2	0.9	44	66	0	0	0	0	66	0	0	0	0
							San Joaquin									
Ag																
CVPM 10	2,095	2,095	0	0	0	0	2,095	0	0	0	0	1,888	207	10	14.5	56
CVPM 11	1,069	1,070	0	0	0	0	1,066	2.4	0	0.06	0.9	419	650	61	117.9	144
CVPM 12	990	990	0	0	0	0	989	1.4	0	0.04	0.3	593	397	40	56.0	162
CVPM 13	2,332	2,334	0	0	0	0	2,332	0	0	0	0	1,787	546	23	67.5	141
Urb																
San Francisco	294	286	7.6	3	5.0	191	294	0	0	0	0	294	0	0	0.05	6
Santa Clara V.	810	797	12.3	2	10.0	164	810	0	0	0	0	810	0	0	0	0
Tulare																
Ag																
CVPM 14	1,845	1,847	0	0	0	0	1,845	0	0	0	0	1,086	759	41	219.2	158
CVPM 15	2,457	2,446	10.5	0	0.4	26	2,457	0	0	0	0	1,989	468	19	45.5	100
CVPM 16	611	615	0	0	0	0	605	6	1	0.1	13	517	95	16	13.7	164
CVPM 17	1,030	1,032	0	0	0	0	1,012	17	2	0.4	15	809	221	21	29.7	178
CVPM 18	2,664	2,392	272.7	10	18.8	106	2,664	0	0	0	0	1,827	837	31	125.1	156
CVPM 19	1,180	1,181	0	0	0	0	1,180	0	0	0	0	1,042	138	12	14.0	80
CVPM 20	835	835	0	0	0	0	835	0	0	0	0	713	122	15	14.9	121
CVPM 21	1,433	1,433	0.1	0	0	0	1,433	0	0	0	0	1,287	146	10	18.0	95
Urb																
Fresno	469	417	51.9	11	18.0	311	469	0	0	0	0	468	1	0	0.4	53
Bakersfield	321	323	0	0	0	0	321	0	0	0	0	321	0	0	0	0
SB-SLO	171	172	0	0	0	0	171	0	0	0	0	171	0	0	0	0

Table A1. (continued)

		Base Case					Unconstrained Historical Hydrology					Unconstrained Drought Hydrology				
	Target (× 10^6 m^3/yr)	Delivery (× 10^6 m^3/yr)	Scarcity (× 10^6 m^3/yr)	Scarcity Percent	Scarcity Cost ($M/yr)	WTP ($/$10^3$ m^3)	Delivery (× 10^6 m^3/yr)	Scarcity (× 10^6 m^3/yr)	Scarcity Percent	Scarcity Cost ($M/yr)	WTP ($/$10^3$ m^3)	Delivery (× 10^6 m^3/yr)	Scarcity (× 10^6 m^3/yr)	Scarcity Percent	Scarcity Cost ($M/yr)	WTP ($/$10^3$ m^3)
							Southern California									
Ag																
Palo Verde	973	815	157.2	16	1.4	14	619	354	36	10.2	58	619	354	36	10.2	58
Coachella	241	240	0.6	0	0	0	223	18	7	1	50	223	18	7	0.9	50
Imperial	3,370	3,146	224.1	7	4.4	15	2,807	563	17	21.5	60	2,807	563	17	21.5	60
Urb																
San Bernardino	348	344	4.6	1	4.0	207	348	0	0	0	0	322	26	8	13.7	559
Mojave	434	277	157.3	36	181.0	1004	427	7	2	2.9	138	387	47	11	23.8	594
Central MWD	4,602	4,360	241.3	5	183.0	589	4,602	0	0	0	0	4,298	303	7	216.3	774
Castaic Lake	158	55	102.8	65	508.0	6901	147	11	7	5.4	537	134	24	15	15.0	749
Antelope Valley	342	230	112.2	33	185.0	1693	331	11	3	6.5	606	314	28	8	20.0	799
San Diego	1,219	1,178	41.2	3	35.0	409	1,219	0	0	0	0	1,162	57	5	44.1	769
Coachella	741	429	311.9	42	367.0	1000	618	123	17	73.8	827	630	111	15	63.7	739
E&W MWD	913	872	41.0	4	33.0	546	913	0	0	63.9	1	856	57	6	42.8	786
Total	46,749	44,809	1,959		1,596		45,635	1,114		186		37,487	9,262		1,677	
Average	1,087	1,042	46	6	37	325	1,061	26	2	4	54	872	215	18	39	238
Average ari regions	1,426	1,392	35	2	1	9	1,386	40	3	1	8	1,072	354	27	43	100
Average urban regions	659	601	58	12	82	724	651	8	1	8	112	619	40	5	34	411

are in million cubic meters (10^6 m^3) or thousand cubic meters (10^3 m^3) per year.

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References

Alley, R. B. (2003), Palaeoclimatic insights into future climate challenges, *Philos. Trans. R. Soc. London, Ser. A*, *361*, 1831–1848, doi:10.1098/rsta.2003.1236.

Alley, R. B., et al. (2003), Abrupt climate change, *Science*, *299*, 2005–2010, doi:10.1126/science.1081056.

Booker, J. F. (1995), Hydrologic and economic impacts of drought under alternative policy responses, *Water Resour. Bull.*, *31*, 889–906.

Booker, J. F., A. M. Michelsen, and F. A. Ward (2005), Economic impact of alternative policy responses to prolonged and severe drought in the Rio Grande Basin, *Water Resour. Res.*, *41*, W02026, doi:10.1029/2004WR003486.

Brunelle, A., and R. S. Anderson (2003), Sedimentary charcoal as an indicator of late-Holocene drought in the Sierra Nevada, California, and its relevance to the future, *Holocene*, *13*, 21–28, doi:10.1191/0959683603hl591rp.

Christensen, N. S., A. W. Wood, N. Voisin, D. P. Lettenmaier, and R. N. Palmer (2004), The effects of climate change on the hydrology and water resources of the Colorado River basin, *Clim. Change*, *62*, 337–363, doi:10.1023/B:CLIM.0000013684.13621.1f.

Cook, E. R., D. M. Meko, D. W. Stahle, and M. K. Cleaveland (1999), Drought reconstructions for the continental United States, *J. Clim.*, *12*, 1145–1162, doi:10.1175/1520-0442(1999)012<1145:DRFTCU>2.0.CO;2.

Cook, E. R., C. A. Woodhouse, C. M. Eakin, D. M. Meko, and D. W. Stahle (2004), Long-term aridity changes in the western United States, *Science*, *306*, 1015–1018, doi:10.1126/science.1102586.

Davis, O. K. (1999), Pollen analysis of a late-glacial and Holocene sediment core from Mono Lake, Mono County, California, *Quat. Res.*, *52*, 243–249, doi:10.1006/qres.1999.2063.

Draper, A. J., M. W. Jenkins, K. W. Kirby, J. R. Lund, and R. E. Howitt (2003), Economic-engineering optimization for California water management, *J. Water Resour. Plann. Manage.*, *129*, 155–164, doi:10.1061/(ASCE)0733-9496(2003)129:3(155).

Draper, A. J., A. Munevar, S. K. Arora, E. Reyes, N. L. Parker, F. I. Chung, and L. E. Peterson (2004), CalSim: Generalized model for reservoir system analysis, *J. Water Resour. Plann. Manage.*, *130*, 480–489, doi:10.1061/(ASCE)0733-9496(2004)130:6(480).

Harding, B. L., T. B. Sangoyomi, and E. A. Payton (1995), Impacts of a severe sustained drought on Colorado River water resources, *Water Resour. Bull.*, *31*, 815–824.

Harou, J. J., and J. R. Lund (2008), Ending groundwater overdraft in hydrologic-economic systems, *Hydrogeol. J.*, *16*, 1039–1055, doi:10.1007/s10040-008-0300-7.

Harou, J. J., M. Pulido-Velazquez, D. E. Rosenberg, J. Medellin, J. R. Lund, and R. E. Howitt (2009), Hydro-economic models: Concepts, design, applications, and future directions, *J. Hydrol.*, *375*, 627–643, doi:10.1016/j.jhydrol.2009.06.037.

Howitt, R. E., K. B. Ward, and S. M. Msangi (2001), Appendix A: Statewide water and agricultural production model, in *Improving California Water Management: Optimizing Value and Flexibility*, edited by M. W. Jenkins et al., pp. A-1–A-11, Cent. for Environ. and Water Resour. Eng., Univ. of Calif., Davis.

Hulme, M. (2003), Abrupt climate change: can society cope?, *Philos. Trans. R. Soc. London, Ser. A*, *361*, 2001–2019, doi:10.1098/rsta.2003.1239.

Ingram, B. L., J. C. Ingle, and M. E. Conrad (1996), A 2000 yr record of Sacramento San Joaquin river inflow to San Francisco Bay estuary, *Calif. Geol.*, *24*, 331–334.

Jenkins, M. W., J. R. Lund, and R. E. Howitt (2003), Using economic loss functions to value urban water scarcity in California, *J. Am. Water Works Assoc.*, *95*, 58.

Jenkins, M. W., J. R. Lund, R. E. Howitt, A. J. Draper, S. M. Msangi, S. K. Tanaka, R. S. Ritzema, and G. F. Marques (2004), Optimization of California's water supply system: Results and insights, *J. Water Resour. Plann. Manage.*, *130*, 271–280, doi:10.1061/(ASCE)0733-9496(2004)130:4(271).

Loaiciga, H. A. (2005), Drought, tree rings, and reservoir design, *J. Am. Water Resour. Assoc.*, *41*, 949–958.

Loaiciga, H. A., L. Haston, and J. Michaelsen (1993), Dendrohydrology and long-term hydrologic phenomena, *Rev. Geophys.*, *31*, 151–171, doi:10.1029/93RG00056.

Lund, J. R., X. Cai, and G. W. Characklis (2006), Economic engineering of environmental and water resource systems, *J. Water Resour. Plann. Manage.*, *132*, 399–402, doi:10.1061/(ASCE)0733-9496(2006)132:6(399).

Lund, J., E. Hanak, W. Fleenor, W. Bennett, R. Howitt, J. Mount, and P. Moyle (2008), *Comparing Futures for the Sacramento–San Joaquin Delta*, 184 pp., Public Policy Inst. of Calif., San Francisco.

Medellín-Azuara, J., J. J. Harou, M. A. Olivares, K. Madani, J. R. Lund, R. E. Howitt, S. K. Tanaka, and M. W. Jenkins (2008), Adaptability and adaptations of California's water supply system to dry climate warming, *Clim. Change*, *87*, suppl. 1, 75–90, doi:10.1007/s10584-007-9355-z.

Meko, D. M., and C. A. Woodhouse (2005), Tree-ring footprint of joint hydrologic drought in Sacramento and Upper Colorado river basins, western USA, *J. Hydrol.*, *308*, 196–213, doi:10.1016/j.jhydrol.2004.11.003.

Meko, D., C. W. Stockton, and W. R. Boggess (1995), The tree-ring record of severe sustained drought, *Water Resour. Bull.*, *31*, 789–801.

Meko, D. M., M. D. Therrell, C. H. Baisan, and M. K. Hughes (2001), Sacramento River flow reconstructed to AD 869 from tree rings, *J. Am. Water Resour. Assoc.*, *37*, 1029–1039, doi:10.1111/j.1752-1688.2001.tb05530.x.

Norviel, W. S., W. F. McClure, D. E. Carpenter, J. G. Scrugham, J. S. B. Davis, R. E. Caldwell, and F. E. Emerson (1922), *Water and the West: The Colorado River Compact and the Politics of Water in the American West*, Univ. of Calif. Press, Berkeley.

Pulido-Velazquez, M., M. W. Jenkins, and J. R. Lund (2004), Economic values for conjunctive use and water banking in southern California, *Water Resour. Res.*, *40*, W03401, doi:10.1029/2003WR002626.

Sangoyomi, T. B., and B. L. Harding (1995), Mitigating impacts of a severe sustained drought on Colorado River water resources, *Water Resour. Bull.*, *31*, 925–938.

Starratt, S. W. (2001), Diatoms as indicators of freshwater flow variation in central California, in *Proceedings of the Eighteenth Annual Pacific Climate Workshop*, edited by G. J. West and L. D. Buffaloe, pp. 129–144, Calif. Dep. of Water Resour., Sacramento. (Available at http://meteora.ucsd.edu/paclim/10Starratt.pdf)

Stedinger, J. R., and T. A. Cohn (1986), Flood frequency analysis with historical and paleoflood information, *Water Resour. Res.*, *22*, 785–793, doi:10.1029/WR022i005p00785.

Stewart, I. T., D. R. Cayan, and M. D. Dettinger (2004), Changes in snowmelt runoff timing in western North America under a 'business as usual' climate change scenario, *Clim. Change*, *62*, 217–232, doi:10.1023/B:CLIM.0000013702.22656.e8.

Stine, S. (1990a), Late Holocene fluctuations of Mono Lake, eastern California, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, *78*, 333, doi:10.1016/0031-0182(90)90221-R.

Stine, S. (1990b), Past climate at Mono Lake, *Nature*, *345*, 391, doi:10.1038/345391b0.

Stine, S. (1994), Extreme and persistent drought in California and Patagonia during medieval time, *Nature*, *369*, 546–549, doi:10.1038/369546a0.

Tanaka, S. K., T. J. Zhu, J. R. Lund, R. E. Howitt, M. W. Jenkins, M. A. Pulido, M. Tauber, R. S. Ritzema, and I. C. Ferreira (2006), Climate warming and water management adaptation for California, *Clim. Change*, *76*, 361–387, doi:10.1007/s10584-006-9079-5.

U.S. Army Corps of Engineers (1999), HEC-PRM package, Hydrol. Eng. Cent., Davis, Calif.

Ward, F. A., J. F. Booker, and A. M. Michelsen (2006), Integrated economic, hydrologic, and institutional analysis of policy responses to mitigate drought impacts in Rio Grande Basin, *J. Water Resour. Plann. Manage.*, *132*, 488–502, doi:10.1061/(ASCE)0733-9496(2006)132:6(488).

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