Optimization of California's Water Supply System: Results and Insights

Marion W. Jenkins[1]; Jay R. Lund[2]; Richard E. Howitt[3]; Andrew J. Draper[4]; Siwa M. Msangi[5]; Stacy K. Tanaka[6]; Randall S. Ritzema[7]; and Guilherme F. Marques[8]

Abstract: This paper presents results of a large-scale economic-engineering optimization model of California's water supply system. The results of this 4-year effort illustrate the value of optimization modeling for providing integrated information needed to manage a complex multipurpose water system. This information includes economic benefits of flexible operations, economic valuation of capacity expansion opportunities, estimating user willingness to pay for additional water, economic opportunity costs of environmental flows, and identification of promising conjunctive use and water transfer opportunities. The limitations of such modeling also are discussed. Overall, the results suggest improvements to system operation and water allocations with a statewide expected value potentially as high as $1.3 billion/year. Significant improvements in performance appear possible through water transfers and exchanges, conjunctive use, and various operational changes to increase flexibility. These changes also greatly reduce costs to agricultural and urban users of accommodating environmental requirements. Model results also suggest benefits for expanding selected conveyance and storage facilities.

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Introduction

Water is scarce in California. Significant spatial and temporal variability of water supplies has led to construction of a vast intertied network of reservoirs, aqueducts, wells, and recharge and reuse facilities throughout the state. Competition between agricultural, urban, and environmental demands has intensified with population growth and increasing environmental allocations. The complexity of selecting efficient water management alternatives at both state and regional levels suggests that perhaps a different, more integrated approach is needed to complement existing simulation-based planning approaches. This paper outlines results from a study utilizing CALVIN, a model combining ideas from economics and engineering optimization with advances in software and data to suggest more integrated management of water supplies regionally and throughout California (Jenkins et al. 2001; Draper et al. 2003). The results presented here have implications for long-term water policy, planning, and management in California.

[1]Professional Researcher, Dept. of Civil and Environmental Engineering, Univ. of California, Davis, Davis, CA 95616. E-mail: mwjenkins@ucdavis.edu

[2]Professor, Dept. of Civil and Environmental Engineering, Univ. of California, Davis, Davis, CA 95616. E-mail: jrlund@ucdavis.edu

[3]Professor, Agricultural and Resource Economics, Univ. of California, Davis, Davis, CA 95616. E-mail: rehowitt@ucdavis.edu

[4]Senior Engineer, Montgomery-Watson-Harza, San Francisco, CA.

[5]PhD Candidate, Agricultural and Resource Economics, Univ. of California, Davis, Davis, CA 95616.

[6]Doctoral Student, Dept. of Civil and Environmental Engineering, Univ. of California, Davis, Davis, CA 95616.

[7]Engineer, CH2M-Hill, Sacramento, CA 95833.

[8]Post-Doctoral Researcher, Dept. of Civil and Environmental Engineering, Univ. of California, Davis, Davis, CA 95616.

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Water Management in California

California's intertied water system serves almost 30 million people and over 2.3 million ha of irrigated farmland and supports substantial environmental resources (CDWR 1998). Over 50 billion cubic meters (bcm) of water are managed in this system in an average year. It is one of the world's largest, most productive, and most controversial managed water systems (Bain et al. 1966; Hundley 2001). Like most large water systems, its governance is largely decentralized, involving a few dozen federal and state agencies, roughly 3,000 local agencies and special districts, and the water demand decisions of thousands of farmers and millions of urban users.

The geographic and seasonal mismatch between the availability of water in the north and east of California in wet winter months and major agricultural and urban water demands in the center, south, and west of the state in the dry spring and summer has led to the development of extensive surface-water and groundwater storage and conveyance facilities. These developments occur at a statewide scale under the auspices of federal, state, and local governments. The intertying of watersheds in California, first proposed in the 1870s, planned in the 1920s and 1950s, and implemented between 1930 and 1980, allows major regions of the state to import and/or export large amounts of water. These major imports and exports are shown in Fig. 1.

Aside from the water management and economic benefits of these statewide interties, these connections have also generated

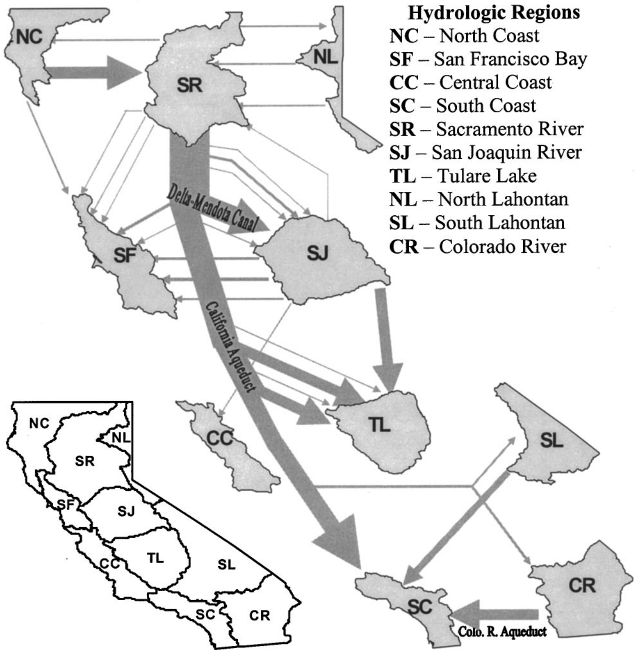

Fig. 1. 1990 interregional water flows in California (CDWR 1993)

controversies regarding water allocation, environmental impacts, and management of water within regions of California (Hundley 2001). The decentralized administration of this system, while ensuring local accountability and responsiveness, has hindered somewhat the technical understanding of the system and broader technical possibilities for its management. The CALVIN model (Draper et al. 2003) is an attempt to provide a more unified technical and economic understanding of California's water system and possibilities for improving its economic performance.

Optimization in Water Resources Management

An optimization or ''what's best?'' approach is appealing in cases where problems (1) are clearly defined with quantifiable objectives; (2) are describable by a reasonably tractable mathematical model; (3) have a sufficient amount of available data to characterize the effects of alternative solutions; and (4) are without an obvious best alternative (Haith 1982). Although the last criterion clearly applies to California water management, the first three criteria have historically been either prohibitive or intractable in the development of large-scale water optimization models. In the implementation of the CALVIN model, several innovative strategies have successfully satisfied the requirements needed for developing an effective optimization model.

First, economic performance is used in the objective function as an effective, quantifiable way to capture the balance between supply and demand. Here, scarcity quantity represents the difference between deliveries and beneficial use if supplies were unrestricted and free, and scarcity cost represents the economic value to users of increasing deliveries to eliminate scarcity. Scarcity and scarcity cost serve as rigorous and measurable indicators of system performance (Draper et al. 2003; Jenkins et al. 2003). CALVIN optimizes by minimizing the sum of water scarcity costs and operating costs associated with water operations and allocations to maximize net economic benefit to the entire state.

Second, until recently, large-scale computational tools needed to model California's water system have been unavailable. Recent advances in software, data, computational speed, and economic water management theory have removed some barriers to model tractability. CALVIN incorporates a variety of solver, database, and interface software that reflects these advances (Draper et al. 2003).

Third, with considerable effort, data of many types and origins were gathered, documented, and incorporated into a coherent framework. This was not only a necessary modeling exercise, but also highlighted areas where data quality was problematic (Jenkins et al. 2001; Draper et al. 2003).

Within this framework, an optimization model such as CALVIN offers relatively independent guidance in suggesting or supporting ideas for managing large and complex systems. In its search for the ''best'' management alternatives, it suggests opportunities for joint management of complex systems of interrelated water supplies and demands, using a wide variety of options over a wide range of hydrologic conditions. Furthermore, the model estimates economic values for proposed changes in management, regulation, and facilities and estimates the volumes and economic costs of scarcity to major water users.

CALVIN Model

CALVIN is an economic-engineering optimization model that explicitly integrates the operation of water facilities, resources, and demands for California's intertied system. It is the first model of California where surface waters, groundwater, and water demands are managed simultaneously statewide (Draper et al. 2003).

The CALVIN model covers 92% of California's population and 88% of its irrigated acreage with roughly 1,200 spatial elements, including 51 surface reservoirs, 28 groundwater basins, 19 urban economic demand areas, 24 agricultural economic demand areas, 39 environmental flow locations, 113 surface and groundwater inflows, and numerous conveyance and other links representing the vast majority of California's water management infrastructure (Fig. 2).

The model, unless otherwise constrained, operates facilities and allocates water to maximize statewide agricultural and urban economic value from water use. This pursuit of economic objectives is initially limited only by water availability, facility capacity, and environmental and flood control restrictions. The model can be further constrained to meet operating or allocation policies. CALVIN consists of two parts: first, an extensive set of connectivity, inflow, economic cost, constraint, parameter, and metadata databases, and second, the HEC-PRM optimization code with its generalized network flow optimization solver. Typically, the model is run for an entire 72-year historical record of inflows for the entire intertied system, but can be run for different inflow periods or synthetic inflows and is often run for smaller regional models.

Fig. 3 illustrates the assembly of a wide variety of data on California's water supply, its systematic organization and documentation in large databases for input to a computer code (HEC-PRM). The HEC-PRM code finds the ''best'' water operations and allocations for maximizing regional or statewide economic benefits. A variety of outputs and uses of outputs can be gained from the model's results. Over a million monthly flow, storage, and allocation decisions are suggested by the model over a 72-year statewide run. Jenkins et al. (2001) and associated appendices provide details of the CALVIN model and its results.

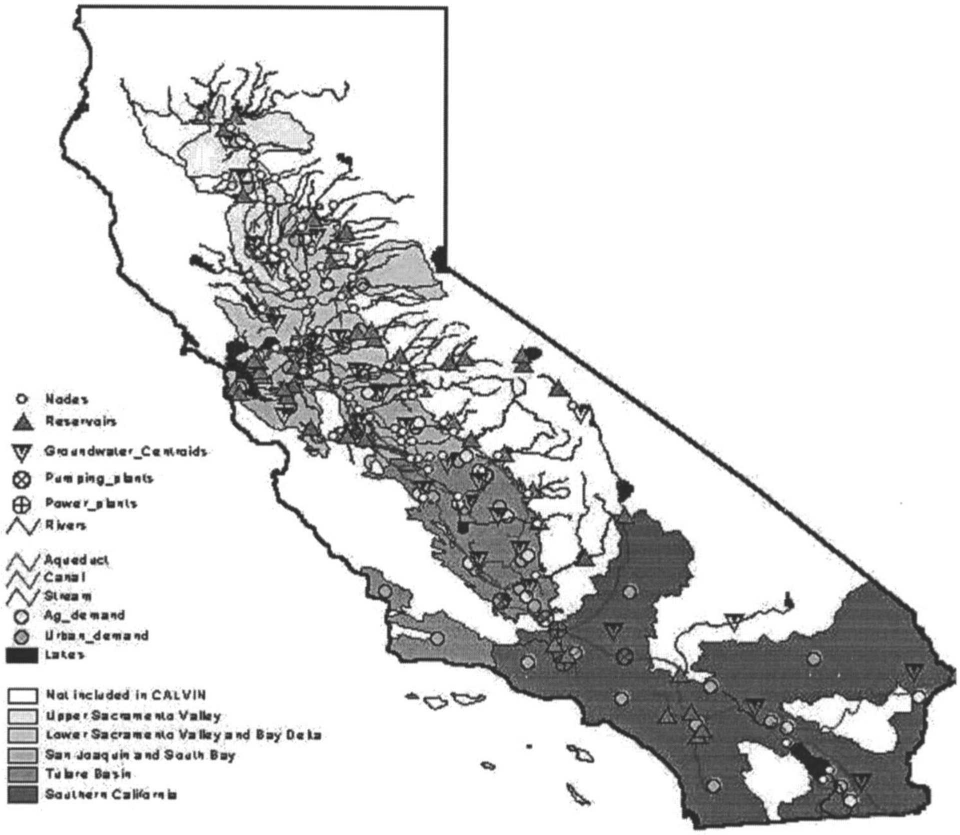

Fig. 2. Regions, reservoirs, other major inflows, and agricultural and urban water demands in CALVIN model

Results

The CALVIN model was developed and run for three alternatives: (1) a base case (BC) representing year 2020 conditions with current operating and allocation policies; (2) independent regional, economically driven operations and allocations for each of five hydrologic regions of California; and (3) statewide economically driven operations and allocations. The BC represents combined results of simulation models for surface water (DWRSIM) and groundwater (CVGSM) operations and deliveries for 2020 using current operating rules and policies as described in Draper et al. (2003). For simplicity, the other two alternatives can be thought of as ideal regional water markets (RWM) (with interregional flows kept at BC levels) and an ideal statewide water market (SWM). Some results of these model runs are presented to summarize overall scarcity, scarcity cost, and total cost results, as well as estimate economic values of reservoir, conveyance, recharge, and recycling facility expansions, conjunctive use, water transfers, finance and economic willingness to pay for water, and the economic impact of environmental regulations. Additional results

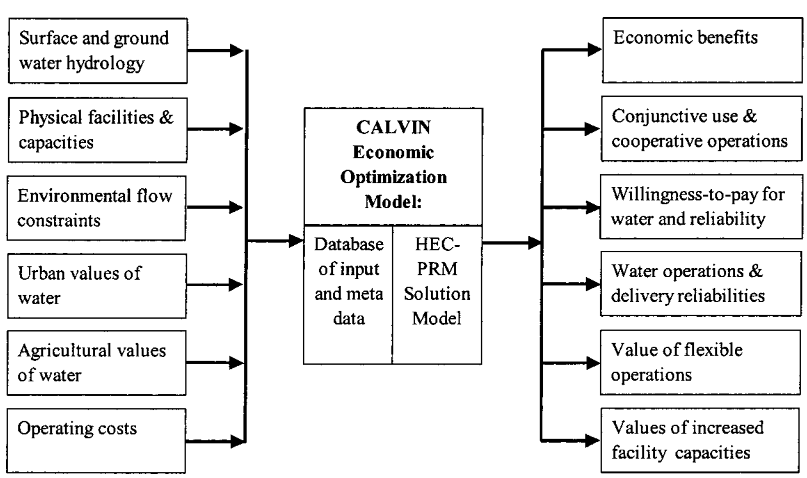

Fig. 3. Data flow for CALVIN

Table 1. Regional and Statewide Total Cost Performance

Region	Average total cost ($M/year)		
	BC	RWM	SWM
Upper Sacramento Valley	35	34	29
Lower Sacramento and Delta	212	166	166
San Joaquin and Bay Area	394	358	333
Tulare Lake Basin	461	434	415
Southern California	3,074	1,855	1,838
Total	4,176	2,847	2,780

Note: BC=base case; RWM=regional water market; and SWM=statewide water market.

and discussion appear in Jenkins et al. (2001) and associated appendices.

Scarcity, Scarcity Cost, and Total Cost Results

Tables 1 and 2 present regional and statewide water scarcities, scarcity costs, and total costs for the three management alternatives. Under BC 2020 conditions, average annual water scarcity amounts to almost 2 bcm statewide, mostly for urban water users, resulting in average scarcity costs of almost $1.6 billion/year, imposed almost entirely on urban users. Most of the water scarcity and scarcity costs occur in Southern California, although other regions also have significant scarcity volumes and costs.

With unconstrained regional water markets within each of the five hydrologic regions, scarcity decreases slightly statewide but increases in some areas ‘‘selling’’ water. Nevertheless, scarcity costs decrease in all regions and decrease for agriculture except in Southern California. Statewide water scarcity costs with idealized regional water markets are reduced more than 80% ($1.32 billion/year) from those in the BC, with total costs (including operating costs) reduced by $1.33 billion/year. Water transfers in Southern California from Colorado River-based agriculture to southern Californian urban users and some reoperation and internal reallocations of water in coastal Southern California are responsible for 95% ($1.25 billion/year) of reduced scarcity costs (Newlin et al. 2002). These particular Southern California transfers are very steady and require none of the deterministic model’s hydrologic foresight.

With an unconstrained statewide water market, scarcity further decreases in the Upper Sacramento Valley, the Tulare Basin, and Southern California. This occurs largely because of changes in the use of surface and groundwater through increased conjunctive operation. Remaining agricultural scarcity costs outside of Southern California are reduced significantly, and statewide total costs (including operating and scarcity costs) decrease by only an additional $67 million/year.

Regional water markets or other forms of regional, economically based water management have potential to reduce both scarcity and scarcity costs in all regions and statewide. Roughly 95% of the benefits of economically ideal statewide water management are obtained with regional optimization, holding interregional flows of water at BC levels. Movement to a statewide water market produces slight additional economic benefits and further scarcity reductions.

Reservoir, Conveyance, Recharge, and Recycling Expansion

Table 3 presents the average marginal economic values to agricultural and urban users of expansions in various surface reservoir, conveyance, and other facilities over the 72-year historical hydrology. These results apply only to small changes in capacity and thus might overestimate economic values for large capacity changes. However, the deterministic model’s perfect foresight (or omniscience) leads to overoptimistic operations, decreasing some shadow values for facility expansion, although this problem does

Table 2. Regional and Statewide Scarcity and Scarcity Costs

Region	Average scarcity (mcm/year)			Average scarcity cost ($M/year)		
	BC	RWM	SWM	BC	RWM	SWM
Upper Sacramento Valley	178	194	0	7	5	0
Lower Sacramento and Delta	33	1	1	36	1	1
San Joaquin and Bay Area	20	0	0	15	0	0
Tulare Lake Basin	338	397	41	37	19	2
Southern California	1,396	1,145	1,057	1,501	255	197
Total	1,965	1,737	1,097	1,596	279	200
Agriculture only						
Upper Sacramento Valley	178	194	0	7	5	0
Lower Sacramento and Delta	10	0	0	0	0	0
San Joaquin and Bay Area	0	0	0	0	0	0
Tulare Lake Basin	286	397	37	19	18	1
Southern California	381	867	867	6	28	28
Total agriculture	854	1,457	904	32	51	29
Urban only						
Upper Sacramento Valley	0	0	0	0	0	0
Lower Sacramento and Delta	23	1	1	36	1	1
San Joaquin and Bay Area	20	0	0	15	0	0
Tulare Lake Basin	52	0	2	18	0	1
Southern California	1,015	280	190	1,495	227	169
Total urban	1,111	280	194	1,564	227	170

Note: BC=base case; RWM=regional water market; and SWM=statewide water market.

Table 3. Average Marginal Economic Values of Selected Facility Expansion Options

Facility	Physical capacity (mcm/year)	Annual marginal expansion value ($/year/tcm or $/tcm)	
		Regional water market	Statewide water market
Surface reservoirs			
Pardee	259	11.8	11.8
East Bay Local	189	11.1	11.1
South Bay Local	210	10.1	10.1
Kaweah	176	45.1	25.7
Success	101	39.1	21.4
Grant	58	34.5	31.1
Southern California SWP storage	856	9.8	2.3
Conveyance			
Colorado River Aqueduct	1,607	285	170
Hetch Hetchy Aqueduct	414	217	227
East Bay/South Bay Connector	0	192	205
EBMUD/CCWD Cross Canal	0	118	118
Folsom South Canal Extension	0	21	21
Los Angeles Aqueduct	697	12	11
Other facilities			
Coachella Artificial Recharge	148	2,152	2,268
SCV Groundwater Pumping	451	187	144
SFPUC Recycling	0	45	58
SCV Recycling Facility	20	25	38
EBMUD Recycled Water Facility	31	16	16

not often overwhelm results (Draper 2001; Newlin et al. 2002). Capacity expansion values are particularly great for some conveyance and groundwater management facilities. The value of expanding most reservoirs decreases with the increased flexibility of statewide operations. Conveyance facility expansions tend to have greater economic value than surface storage expansions, given the availability of groundwater storage for conjunctive use. Some wastewater recycling facilities also show economic value for water supply. These potential economic values for facilities only indicate economic promise and should be considered in the context of detailed implementation aspects and compared with construction and other implementation costs.

Economic Willingness to Pay

Table 4 summarizes the willingness of users to pay for additional water beyond that delivered in each model run. These estimates come from the time series of shadow values for conservation of mass constraints at each agricultural and urban water demand location. [Demand areas in Table 4 are arranged geographically from north to south; CVPM regions come from the Central Valley Production Model representation of Central Valley agriculture (Jenkins et al. 2001).] Demand regions without water scarcity are unwilling to pay for additional water. In the BC, water users show a wide range of willingness to pay for additional water, from nothing to over $8,000/thousand cubic meters (tcm). Within the agricultural sector, willingness to pay averages between zero and $130/tcm. Regional water markets considerably reduce the variability in the value of additional supplies, but when water is sold from some agricultural users, their willingness to pay for additional water increases.

The willingness to pay for additional water imports to demand regions decreases considerably with regional water markets. With a statewide water market, willingness to pay for additional water typically decreases further, often considerably. Differences between average and maximum willingness to pay illustrate the variability of willingness to pay with hydrologic and demand conditions. Economically, there are cases where regions would sometimes import additional water and export more water at other times.

Environmental Regulation

Table 5 presents the cost to agricultural and urban water users of unit changes in the environmental flow constraints included in the CALVIN model. With regional water markets, these costs are as high as $1,400/tcm in the Mono and Owens basins (due mostly to the value of hydropower there—the only locations with hydropower modeled), but with frequent average costs on the order of $35/tcm. However, many environmental flow requirements appear to have no consequence to agricultural and urban water users under regional water market conditions. This is especially true for instream flows, which can often be reused downstream. Consumptive wildlife refuge deliveries often have higher opportunity costs. Moving from regional to statewide water markets tends to reduce the economic impacts of riparian flow requirements, perhaps the greatest potential benefit of statewide management.

Conjunctive Use

Conjunctive use of ground and surface waters is already common in many parts of California. California's intertied water system has about 50 bcm of surface water storage and over 170 bcm of available groundwater storage. With current operations, for a repeat of the historical hydrology, roughly 71 bcm of groundwater storage capacity is used over the longest drought period, so drought storage in California is mostly groundwater based. With statewide economic optimization, groundwater storage capacity use increased to roughly 90 bcm. For both the BC and optimized cases, although there is typically some seasonal drawdown and

Table 4. Marginal Demand Area Willingness to Pay for Additional Water

	Average WTP ($/tcm)			Maximum WTP ($/tcm)	
	BC	RWM	SWM	RWM	SWM
Agricultural					
CVPM 1	0	10	0	15	0
CVPM 2	34	12	0	18	0
CVPM 3	20	22	0	30	0
CVPM 4	0	19	0	28	0
CVPM 5	0	0	0	0	0
CVPM 6	0	0	0	0	0
CVPM 7	0	0	0	0	0
CVPM 8	0	0	0	0	0
CVPM 9	20	0	0	0	0
CVPM 10	0	0	0	0	0
CVPM 11	0	0	0	0	0
CVPM 12	0	0	0	0	0
CVPM 13	0	0	0	0	0
CVPM 14	0	0	0	0	0
CVPM 15	32	21	12	32	32
CVPM 16	0	13	8	21	21
CVPM 17	0	14	9	26	26
CVPM 18	131	32	0	50	0
CVPM 19	0	26	0	53	0
CVPM 20	0	4	0	55	0
CVPM 21	0	33	0	50	0
Palo Verde	17	46	46	58	58
Coachella	0	50	50	50	50
Imperial	19	55	55	55	55
Urban					
Yuba	54	0	0	0	0
Napa-Solano	563	0	0	0	0
Contra Costa	19	0	0	0	0
East Bay MUD	285	22	22	916	916
Sacramento	0	0	0	0	0
Stockton	6	0	0	0	0
San Francisco	236	0	0	0	0
Santa Clara Valley	202	0	0	0	0
SB-SLO	0	0	0	0	0
Fresno	383	0	34	0	278
Bakersfield	0	0	0	0	0
Castaic Lake	8,512	523	421	843	474
Antelope Valley	2,088	193	0	727	0
Coachella	1,233	1,101	1,102	1,583	1,583
Mojave[a]	1,238	0	0	0	0
San Bernardino	255	118	0	611	0
Central MWD	727	177	0	888	0
E & W MWD	674	178	1	827	649
San Diego	504	157	0	860	0

[a]Neglects conveyance capacity constraint entering Mojave region. WTP = willingness to pay; BC = base case; RWM = regional water market; and SWM = statewide water market.

refill, drought drawdown and refill of groundwater storage is often a decadal process across wet and dry hydrologic periods (Jenkins et al. 2001).

Optimized groundwater operations tend to be more aggressive, however, allowing water transfers and other operational changes to be more economically effective. Fig. 4 shows the frequency of different levels of groundwater use. Statewide, the median groundwater use is about 33% of total water deliveries for all cases. In wet years, this use can decline to as low as about 16 to 22%, and in dry years it can increase to as high as about 56%. Regional water markets, or other economically based operations and allocations, would tend to use groundwater far more conjunctively than in the BC, with greater variation in groundwater use between years. With a statewide water market, conjunctive use appears to be somewhat greater still. While this use represents an extreme of efficiency and coordination for groundwater operations, it also indicates significant additional potential for conjunctive use operations in California.

Water Transfers

Table 6 shows changes in deliveries and scarcity costs for all economic regions represented in the CALVIN model with regional and statewide water markets (values reported in the table represent individual demand areas within the hydrologic region). With the more restricted regional water markets, and summing the regional totals, on average 747 million cubic meters (mcm)/year of water "sold" in the markets is from agriculture and 227 mcm/year is from improved operational efficiencies. Of the water "bought," 143 mcm/year goes to agricultural users and 831 mcm/year to urban users. With a statewide water market, agricultural users sell less water (510 mcm/year) and 867 mcm/year becomes available from operational improvements. Agricultural users buy 460 mcm/year and urban users 917 mcm/year.

The bulk of water transfers occur in Southern California and in the Tulare Basin, with some additional transfers elsewhere. The water transfers in Southern California from agricultural to urban users alone account for over $900 million of the $1.6 billion/year of average year benefits. These transfers are steady each year and month and require no operational foresight (Newlin et al. 2002). Otherwise, user participation in water markets sometimes varies with hydrologic circumstances, with buyers and sellers sometimes switching in different years.

With regional water markets statewide, all increases and reductions in deliveries amount to less than 4% of total BC deliveries. In Southern California, the region with the most extensive water transfers, slightly more than 10% of water is reallocated (including both increases and decreases in deliveries). With a statewide water market, the proportion of water reallocated systemwide increases slightly to 4.2%, with reallocations in Southern California amounting to 11% of BC deliveries. Colorado River deliveries to agriculture are diminished by less than 12% for both regional and statewide water markets; these are the greatest local reductions in deliveries for the entire state. Small changes in water allocations, along with more flexible operations and conjunctive use, are responsible for the vast majority of economic improvements suggested by the model. Exchanges of water sources to support the greater conjunctive use suggested by CALVIN are somewhat greater in some regions. Some exchanges also support urban water quality benefits for the Solano-Napa, Sacramento, Tulare, and San Francisco Bay areas.

Limitations

All models require simplification of the true conditions, processes, and operations occurring in a given system and rely heavily on the ability to quantify these as a solvable set of equations with appropriately specified parameters and input data. Model simplifications and the quality of data can impose limitations on the interpretation of model results and the appropriate-

Table 5. Opportunity Costs of Environmental Flows to Agricultural and Urban Users

	Annual requirement (mcm/year)	Average opportunity cost ($/tcm)		Maximum opportunity cost ($/tcm)	
		RWM	SWM	RWM	SWM
River					
Trinity River	290	37.0	0.6	40.2	5.1
Clear Creek	34	0.4	0.3	37.6	4.1
Sacramento River (upper)	2,528	0.6	0.2	38.9	3.0
Feather River	759	0	0.1	0	0.6
American River	873	0	0	0.2	0.9
Mokelumne River	71	0.1	0.1	0.7	1.1
Calaveras River	1	0	0	0	0
Yuba River	138	0	0	0.2	0.4
Sacramento River (lower)	2,935	0	0	0	0.6
Stanislaus River	159	3.6	1.1	11.1	19.9
Tuolumne River	97	1.9	0.5	11.0	19.2
Merced River	64	2.5	1.6	10.9	18.1
Mono Lake inflows	60	781	663	1,392	985
Owens Lake dust mitigation	32	608	496	950	540
Wildlife refuge					
Sacramento West Refuge	86	33.9	0.2	36.8	3.2
Sacramento East Refuge	50	0	0.2	1	1
Volta Refuges	29	6.7	16.1	16.6	18.5
San Joaquin/Mendota Refuges	192	5.4	12.9	14.4	17.7
Pixley	1	37.6	21.1	58.5	33.3
Kern	9	35.0	27.9	69.5	30.4
Delta outflow					
Bay Delta	4,536	0	0	0	0

Note: RWM=regional water market and SWM=statewide water market.

ness of some model applications. This is no less true for CALVIN, representing the diverse and complex nature of the state's intertied surface and groundwater systems and water uses in an optimization modeling approach (Jenkins et al. 2001). Limitations of the CALVIN model, indicative of those faced by large-scale water resource optimization modeling, arise from three main sources.

Data Quality

First, the input data used to characterize surface and groundwater supplies, water demands, and BC operations in the CALVIN model are limited by the quality of existing data sets, tenuous or unavailable information for some parts of the state (especially the Tulare Basin), and project time constraints. The CALVIN calibra-

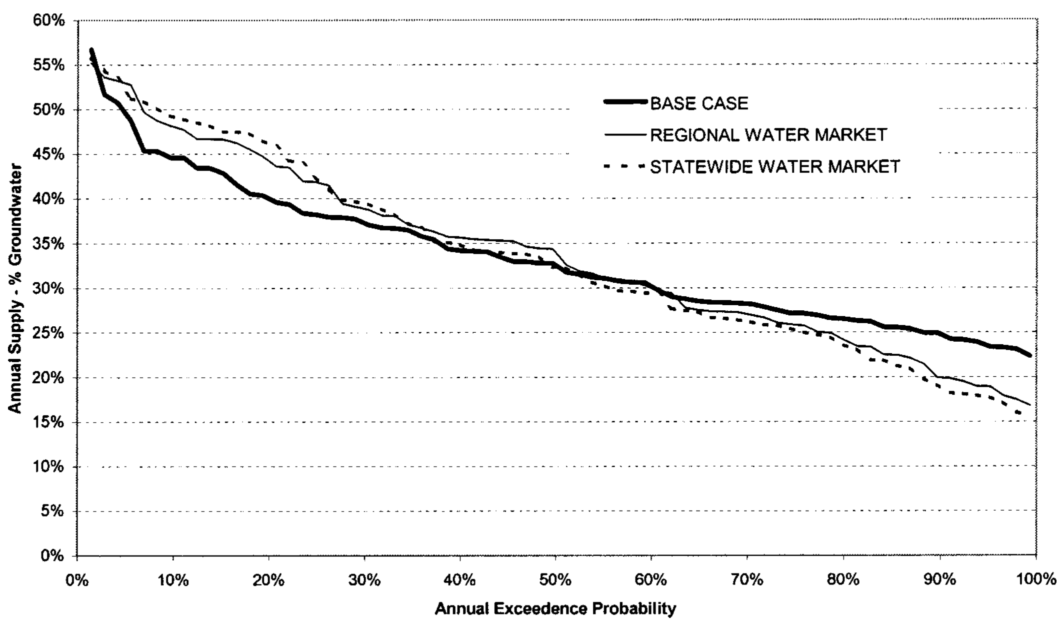

Fig. 4. Reliance on groundwater and conjunctive use

Table 6. Average Water Deliveries and Scarcity Costs (from Demand Areas)

Demand region	Deliveries (mcm/year)		ΔDeliveries (mcm/year)		Scarcity costs ($M/year)			ΔScarcity costs ($M/year)	
	Maximum[a]	BC	RWM-BC	SWM-BC	BC	RWM	SWM	RWM-BC	SWM-BC
CVPM 1	124	124	−1	0	0.01	0.02	0	0.01	−0.01
CVPM 2	565	519	38	46	3.46	0.22	0	−3.23	−3.46
CVPM 3	1,321	1,251	6	70	3.15	2.94	0	−0.21	−3.15
CVPM 4	891	891	−54	0	0	2.11	0	2.11	0
CVPM 5	1,409	1,409	0	0	0	0	0	0	0
CVPM 6	850	850	0	0	0	0	0	0	0
CVPM 7	458	458	0	0	0	0	0	0	0
CVPM 8	725	725	0	0	0	0	0	0	0
CVPM 9	960	954	6	6	0.11	0	0	−0.11	−0.11
CVPM 10	1,377	1,377	0	0	0	0	0	0	0
CVPM 11	703	703	0	0	0	0	0	0	0
CVPM 12	651	651	0	0	0	0	0	0	0
CVPM 13	1,534	1,534	0	0	0	0	0	0	0
CVPM 14	1,213	1,214	0	0	0	0	0	0	0
CVPM 15	1,616	1,608	−53	−9	0.35	2.90	0.80	2.55	0.45
CVPM 16	402	404	−4	−2	0	0.12	0.05	0.12	0.05
CVPM 17	677	678	−11	−6	0	0.36	0.21	0.36	0.21
CVPM 18	1,752	1,572	44	180	18.8	10.4	0	−8.41	−18.8
CVPM 19	776	776	−31	0	0	2.51	0	2.51	0
CVPM 20	549	549	0	0	0	3	0	3	0
CVPM 21	942	942	−19	0	0	1.43	0	1.43	0
Palo Verde	640	536	−92	−92	1.43	6.91	6.89	5.47	5.46
Coachella	158	158	−11	−11	0	0.87	0.87	0.87	0.87
Imperial	2,216	2,068	−216	−216	4.35	20.5	20.5	16.2	16.2
Total agriculture	22,509	21,952	−397	−33	32	51	29	20	−2
Napa-Solano	93	85	8	8	22	0	0	−22	−22
Contra Costa	109	109	0	0	0	0	0	0	0
East Bay MUD	241	235	6	6	12	1	1	−12	−12
Sacramento	551	551	0	0	0	0	0	0	0
Stockton	77	77	0	0	0	0	0	0	0
San Francisco	193	188	5	5	5	0	0	−5	−5
Santa Clara Valley	532	524	8	8	10	0	0	−10	−10
SB-SLO	113	113	0	0	0	0	1	0	0
Fresno	308	274	34	32	18	0	0	−18	−17
Bakersfield	212	212	0	0	0	0	0	0	0
Castaic Lake	104	36	61	64	508	5	3	−503	−505
Antelope Valley	225	151	71	74	185	3	0	−182	−185
Coachella	487	282	84	84	367	365	166	−202	−201
Mojave[b]	285	182	103	103	181	0	0	−181	−181
San Bernardino	230	226	0	3	4	2	0	−2	−4
Central MWD	3,026	2,866	123	160	183	37	0	−146	−183
E & W MWD	600	573	21	28	33	7	0	−26	−33
San Diego	801	774	21	28	35	7	0	−28	−35
Total urban	8,230	7,499	547	603	1,564	227	170	−1,337	−1,394

Note: BC=base case; RWM=regional water market; and SWM=statewide water market.

[a]Delivery volume without economic scarcity.

[b]Neglects conveyance capacity constraint entering Mojave region.

tion process, with its own limitations, attempts to rectify and resolve inconsistencies in data sets to achieve an integrated surface and groundwater hydrologic balance for the Central Valley. Because of poor data quality in some areas of the state, overall trends in results, rather than specific local reoperations and reallocations, are the most useful information.

System Simplification

Second, choice of a network flow with a gains optimization solver (HEC-PRM) imposes several restrictions on the model's ability to represent the system accurately. In particular, flow relationship constraints, such as those involved in environmental regulation, water quality, and stream-aquifer and other groundwater behavior, must be simplified. In addition, water allocation and storage decisions are biased somewhat by perfect foresight in the deterministic optimization solution (Draper 2001; Newlin et al. 2002). However, in many cases changes in operations suggested by the model are so consistent that hydrologic foresight is not needed to achieve these benefits. The model also assumes that operational and allocation changes suggested by the model are possible institutionally. This might not be possible given California's complex set of management institutions. Nevertheless, as seen with water transfers, large benefits can occur when implementing a few changes.

Nonexhaustive Economic Representation

Third, hydropower, flood control, and recreation benefit functions were generally not included in this initial model due to time constraints (seasonal flood storage constraints were included, however). The absence of these purposes will distort operations of some parts of the model, limit the identification of opportunities for storage reoperation, and somewhat reduce the value of instream storage options. While major water quality differences for urban uses are represented in terms of their treatment and consumer costs, smaller economic differences between surface and groundwater for agricultural production are not yet represented. Repayment and financing of existing facilities, which affect some decisions, have been regarded as sunk costs and neglected.

Conclusions

The limitations above can be significant and lead one to look for qualitative insights and guidance, rather than precise quantification, from model results. Considering these limitations, the following qualitative conclusions are supported by model results and point to promising directions for practical water management.

Optimization results provide considerable information and insight for policy and operations planning. These results illustrate the ability of economic and engineering-based optimization modeling to assemble and digest large quantities of information to make useful and insightful conclusions for regional and statewide water management. The results of these models identify economically promising facility locations for expansion, changes in operation and water allocations, opportunity costs of environmental and other institutional regulations, and a general quantitative context for understanding the engineering and economic potential of system operations and policies. CALVIN or similar economic-engineering optimization models could be applied to integrated long-term regional and statewide planning, integrated supply and demand data management, preliminary economic and financial evaluation, and planning and operations studies. In addition, the model can be used for integrated system studies regarding such issues as facility expansion, joint operations, conjunctive use, catastrophe response, climate change, and water transfers. Nevertheless, the limitations of such optimization models indicate that their results should not be interpreted with undue precision. Commonly, precise applications of optimization insights will require testing and refinement by more detailed simulation studies.

Nevertheless, some policy conclusions emerge from model results:

Regional and statewide water markets, transfers, and exchanges have great potential to improve the flexibility and economic performance of California's water system, considerably reducing both water scarcity and scarcity costs. Within some regions, particularly Southern California, water markets or other forms of economic reallocation with existing facilities have the potential to greatly reduce regional water scarcity costs, perhaps by as much as 80%. Results also indicate that the potential overall gains from regional water markets to California average as high as $1 billion per year. The large majority of economic and delivery improvement benefits occur with regional markets, with only a small additional improvement from a theoretically perfect statewide market. In some cases, a series of water exchanges could allow environmental flows to be more easily accommodated. Exchanges and transfers improve operational efficiency and increase overall deliveries.

Economically efficient improvements in local and regional water management reduce demands for imports. Economically efficient operation and allocation of water within each region greatly reduce economic demands for importing additional water from other regions. This is true for all regions (Table 4). For example, Bay Area results suggest that regional water markets or other forms of flexible and coordinated operations among urban agencies could substantially reduce or eliminate urban water scarcity with existing infrastructure and water resources, if institutionally feasible.

Ideal water markets never reduced deliveries to any major user more than 15%. Although important changes often were suggested for how water could be delivered and for the sources of water for users, overall it appears that if about 20% of California's water were allocated by markets or other flexible mechanisms, most water scarcity would disappear statewide.

There is economic value to expanding some storage, conveyance, recharge, and recycling facilities in California at some locations and times. By far the greatest benefits appear to come from select interties, recharge, and other conveyance expansions, particularly in Southern California and in the San Francisco Bay Area. Assuming conjunctive use is available, surface storage expansion typically has much less value.

Expanded conjunctive use, particularly over interannual or drought periods, could result in economic and operational benefits for every region. Most of these benefits occur with regional optimization, but some additional statewide benefits also exist. The availability of conjunctive use operations in CALVIN reduces the value of increasing surface storage at most locations. Greater conjunctive operation of local, regional, and statewide water resources decreases competition with environmental uses, especially in dry years when agricultural and urban reliance on surface flows is significantly reduced from BC levels. For example, under the statewide water market, total diversions from the Sacramento River are reduced on average by 529 mcm during drought years, with supplies made up by greater use of groundwater.

Optimized operations and allocations can satisfy most agricultural and urban water demands for the California intertied system at 2020 levels. Most unsatisfied demands could be well compensated with revenues from market transactions (Table 6). However, satisfying all demands is not always economically worthwhile. It is neither economically feasible nor desirable to eliminate all water scarcity and scarcity costs in California. The costs of providing additional water from new sources, efficiency improvements, or reallocations from other water users sometimes exceed scarcity costs associated with conservation or rationing. In such cases, some scarcity is optimal, indicating economically efficient opportunities for increasing local water conservation.

Some environmental flows impose costs on agricultural and urban users under economically optimized operations, but many flow requirements need not impose any significant costs.

Flexible operations greatly reduce the costs of environmental flows to other users. This is especially true of statewide optimization. Consumptive wildlife refuge deliveries tend to impose greater costs upon agricultural and urban water users than instream flows.

CALVIN model results indicate the vast majority of potential economic improvements in California's water system are from local and regional changes. These local and regional improvements greatly reduce demands for additional imported water, often by 70 to 90%. Statewide management has some additional benefits, especially for mitigating economic impacts of environmental requirements.

As a concluding thought, the purposes of computer models are to (1) make better sense of complex systems; (2) suggest promising operations and infrastructure; and (3) develop ideas for better management. The application of large-scale economic-engineering optimization to California's intertied water supply system appears to offer benefits in all these areas.

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