IMPROVING CALIFORNIA WATER MANAGEMENT:

OPTIMIZING VALUE AND FLEXIBILITY

EXECUTIVE SUMMARY

October 2001

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A study funded by the CALFED Bay-Delta Program, State of California Resources Agency, the National Science Foundation, the US Environmental Protection Agency, and the University of California

http://cee.engr.ucdavis.edu/faculty/lund/CALVIN/

> "When the well's dry, we know the worth of water."
> Benjamin Franklin (1746), *Poor Richard's Almanac.*

INTRODUCTION

Water is scarce in California, and better options and frameworks are needed for water management. This project provides the foundation for a different approach to water management in California, combining powerful ideas from economics and engineering optimization with advances in software and data to suggest more integrated management of water supplies regionally and throughout California. While these newer ideas and methods cannot by themselves "solve" California's water problems, they can help us move beyond approaches that might have been more appropriate in the past and they illustrate what is possible and economically desirable for water management. There are better ways to think about solving California's water problems.

The key ideas illustrated by this project are:

1) "Shortage" is an imprecise and outmoded concept for water management in California. Economic scarcity is the difference between deliveries (actual use) and what users would use if water were free (price is trivial) and had unrestricted availability. Scarcity cost is the economic value that users would gain if deliveries were increased at no additional price, to a level where no scarcity exists. Measured either as volume or as economic value for water users, scarcity is a far

more precise, measurable, and informative indicator of the balance between supplies and demands. Scarcity costs can be compared with the costs and other effects of alternative supply and demand management options, and allocation of scarcity costs typically has greater social and economic impact than volumes of water. Some scarcity may be preferable to paying the costs of additional supplies or demand management.

2) California's diverse mix of water sources and demands often can be managed better together rather than separately. Many options are available for integrating the management of these supplies and demands to provide greater overall benefits at local, regional, and statewide levels. Combining traditional storage, conveyance, and water conservation options with water exchanges, conjunctive use, water markets, recycling, shared facilities, and other forms of cooperative operation provides substantially greater planning and operating flexibility, with substantial potential economic benefits to all water users. Options can be more valuable when employed together, rather than separately.

3) The range of hydrologic events, not just "average" and "drought" years, are important for understanding and managing water in California. California's hydrology is too variable to plan exclusively for an "average" year, and planning for a "drought" year is too conservative and fragile (since droughts can take many forms). Better planning should address management over the range of wet and dry conditions.

4) Recent developments in software, data, and water management theory and methods allow us to explicitly explore opportunities for joint management of all major water supplies and demands, using a wide variety of options, and over a wide range of hydrologic conditions. These newer methods also allow us to place economic values on proposed changes in management, regulation, and facilities and provide estimates of the volumes and economic costs of scarcity to major water users over the range of water conditions.

This report presents an economic-engineering optimization model of California's water supply system (CALVIN) that suggests potential improvements in water operations, facilities, and allocations for projected 2020 conditions. The optimization offers a variety of advantages that complement traditional simulation modeling. In particular, mathematical optimization offers relatively independent guidance in suggesting or supporting ideas for managing large and complex systems.

"Optimizing" California's water supply system is an ambitious undertaking, so it has been necessary to apply some innovative and sophisticated strategies. A variety of solver, database, and interface software has been employed or developed for this project, reflecting recent advances in these fields. Data of many types and origins have been brought together and documented for most of the state, at considerable effort. The results of the model offer insights into improved regional and statewide water management for California. And the modeling framework used suggests considerable potential for improving the consistency, quality, and utility of water data and analysis statewide and regionally.

APPROACH

The CALVIN model explicitly integrates the operation of water facilities, resources, and demands for California's great inter-tied system. It is the first model of California water where surface waters, groundwater, and water demands are managed simultaneously statewide. The CALVIN model covers 92% of California's population and 88% of its irrigated acreage (Figure ES-1), with roughly 1,200 spatial elements, including 51 surface reservoirs, 28 groundwater basins, 18 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. (See http://cee.engr.ucdavis.edu/faculty/lund/CALVIN/ for the model's detailed schematic.) This detailed and extensive model has necessitated the assembly and digestion of a wide variety of data within a consistent framework.

The second major aspect of the CALVIN model is that it is an economically-driven engineering "optimization" model. The model, unless otherwise constrained, operates facilities and allocates water so as 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, as is done for the Base Case.

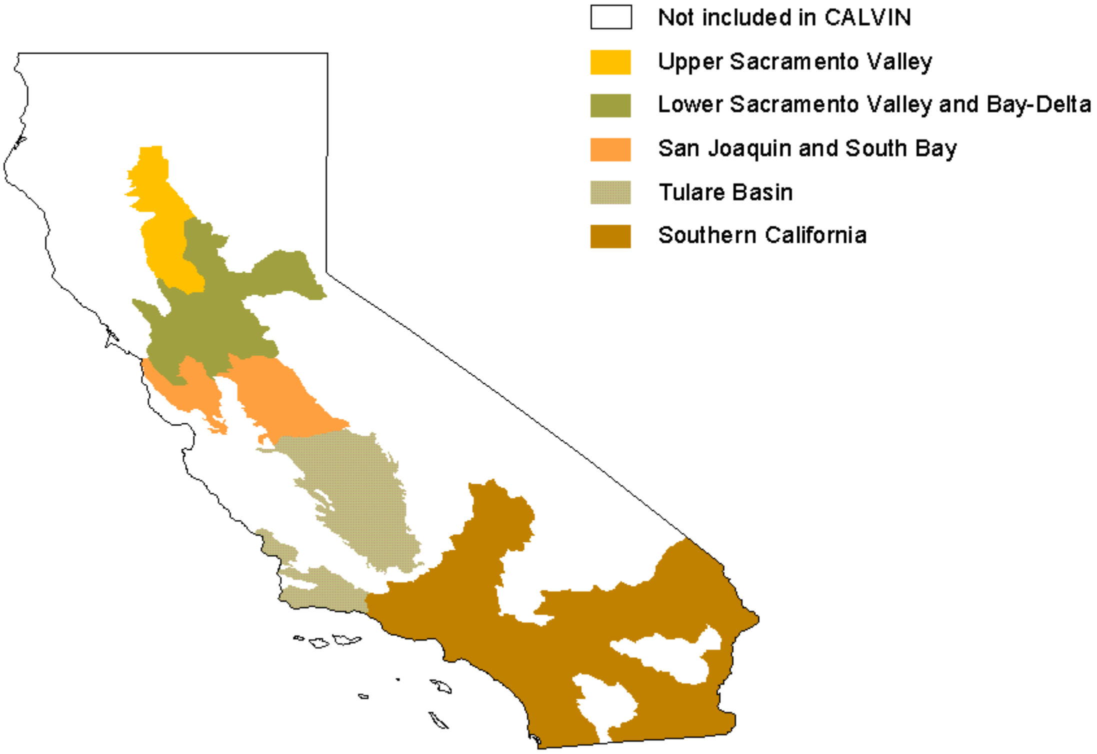

Figure ES-1. Demand Areas Represented in CALVIN Model of California's Water System

The diagram below (Figure ES-2) illustrates the assembly of a wide variety of relevant data on California's water supply, its systematic organization and documentation in large databases for input to a computer code (HEC-PRM) which finds the "best" water operations and allocations for maximizing regional or statewide economic benefits, and the variety of outputs and uses of outputs which can be gained from the models results.

Over a million flow, storage, and allocation decisions are suggested by the model over a 72-year statewide run, making it among the most sophisticated water optimization models constructed to date. A range of water management and economic outputs are produced.

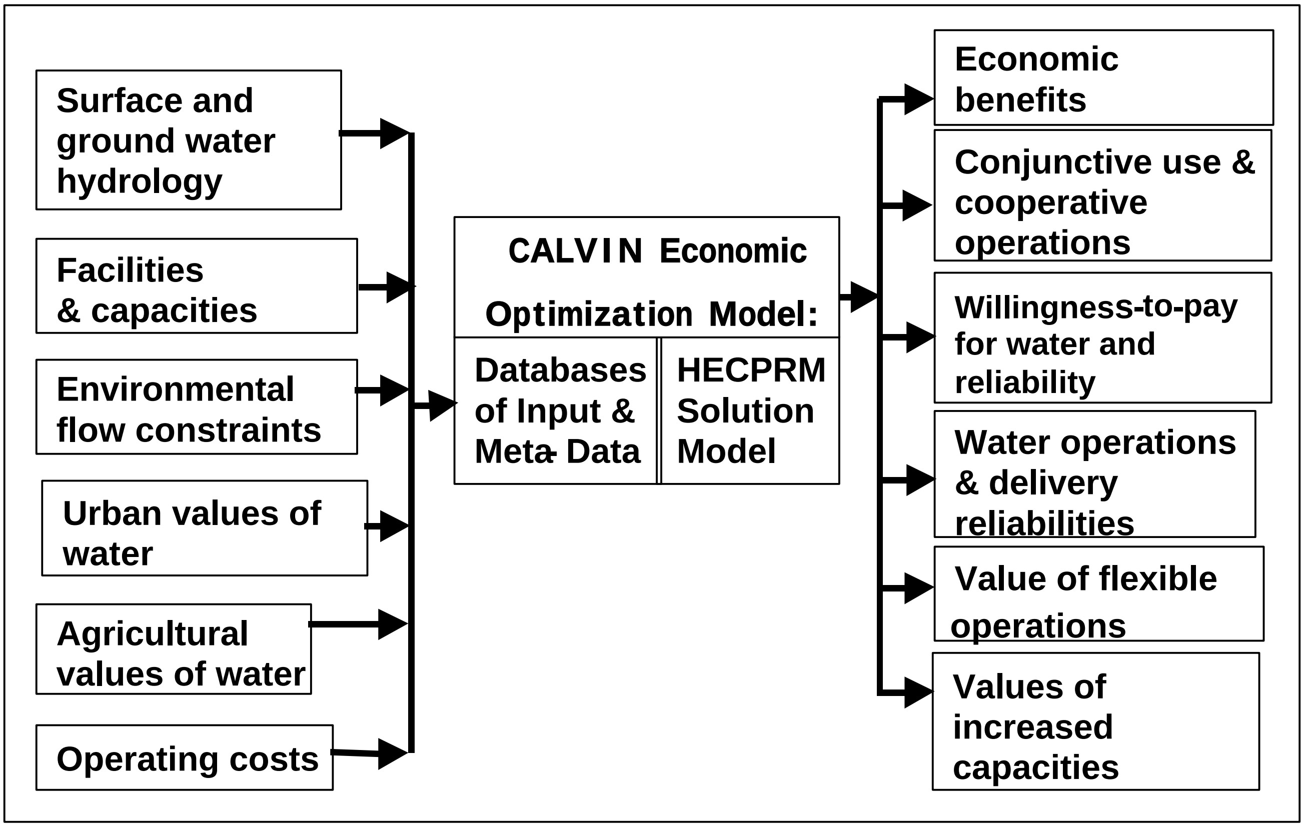

Figure ES-2. Data flow schematic for CALVIN

USES

Results from the CALVIN model can be used for a wide variety of policy, planning, and operations planning purposes. These uses include:

- Identification of economically promising changes in reservoir, conveyance, recharge, and recycling facility capacities at the local, regional and statewide levels
- Identification of promising operational opportunities, such as:
    - conjunctive use of surface water and groundwater
    - cooperative operations of supplies
    - water exchanges and transfers
    - water conservation and recycling
    - improved reservoir operations
- Assessing user economic benefits or willingness-to-pay for additional water

- Independent and relatively rigorous presentation of physically possible and economically desirable water management
- Providing promising solutions for refinement and testing by simulation studies
- Preliminary economic evaluations of proposed changes in facilities, operations, and allocations.

In addition, the project demonstrates several improvements in analytical methods that should be of long-term value to the state. These technical improvements include:

- Feasibility of economic-engineering optimization of California's water supplies
- Data assessment, documentation, and partial reconciliation for surface water, groundwater, and water demand data statewide
- Demonstrating advances in modeling technique, documentation, and transparency.

These improvements in data management, methods, and concepts offer potential for significant and sustained long-term improvements in California water management.

INNOVATIONS

The CALVIN model and approach differs from current large-scale simulation models of California and from other optimization models of parts of California. The major innovations of CALVIN include:

1) Statewide modeling with all major parts of California's inter-tied system from Shasta-Trinity to Mexico, allowing for more explicit statewide examination of water supply issues.
2) Groundwater is explicitly included and operated in all regions represented in the model, allowing more explicit examination of conjunctive use alternatives.
3) Economic performance is the explicit objective of the model, facilitating economic evaluation of capacity alternatives, conjunctive operations, and water transfers and estimation of user willingness-to-pay for additional supplies.
4) Surface and groundwater supplies and water demands are operated in an integrated manner, allowing for the most economic system adaptation to new facilities or changes in demands or regulations.
5) Economic values of agricultural and urban water use are estimated consistently for the entire inter-tied system.
6) Data and model management have been fundamental to model development with all major model components in the public domain and extensive documentation of model assumptions.
7) Systematic analytical overview of statewide water quantity and economic data was undertaken to support the model.
8) New management options for water exchanges and marketing, cooperative operations, conjunctive use, and capacity expansion are suggested by the model.
9) Use of optimization allows rapid and impartial preliminary identification and screening of promising alternatives for more detailed consideration and analysis.

Such innovations are crucial to support the search for technically workable, politically feasible, and socially desirable solutions to water problems in California.

RESULTS

CALVIN models were developed and run for three alternatives: 1) a Base Case representing 2020 conditions with current operating and allocation policies (based on CVPIA PEIS No Action Alternative and DWRSIM run 514a), 2) independent Regional, economically-driven operations and allocations for each of five hydrologic regions of California, and 3) Statewide economically-driven operations and allocations. For simplicity, the latter alternatives can be thought of as ideal regional water markets and an ideal statewide water market. Some results of these models appear below to summarize overall scarcity, scarcity cost, and total cost results, examine the 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.

Scarcity, Scarcity Cost, and Total Cost Results

Table ES-1 presents regional and statewide water scarcities, scarcity costs, and total costs for the three management alternatives. Under Base Case 2020 conditions, average annual water scarcity amounts to almost 1.6 maf statewide, mostly for urban water users, resulting in average annual scarcity costs of almost $1.6 billion, almost entirely to urban water users. Scarcity is defined as the difference between water deliveries and the maximum economic demand of water users (the quantity of water they would desire if the price were trivial and availability were unlimited). Most of this scarcity and more of the scarcity cost 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 regions, although scarcity costs decrease in all regions and decrease for agriculture except for Southern California. Statewide water scarcity costs with idealized regional water markets are reduced more than 80% ($1.32 billion/year) from those in the Base Case, with total costs (including changes in operating costs) reduced by $1.33 billion/year. Shifts in Southern California from Colorado River-based agriculture to Southern California urban users and some re-operation and internal reallocations of water in coastal Southern California, are responsible for 95% ($1.25 billion/yr) of reduced scarcity costs. Other interesting changes occur elsewhere in the state.

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

Regional water markets, or other forms of regional economically-based water management, have significant potential to reduce both scarcity and scarcity costs in all regions and statewide. Movement to a statewide water market produces slightly more economic benefits and further scarcity reductions.

Table ES-1. Regional and Statewide Scarcity, Scarcity Cost, and Total Cost Performance

	Average Scarcity (taf/yr)			Average Scarcity Cost ($M/yr)			Average Total Cost# ($M/yr)		
Region	**BC***	**RWM***	**SWM***	**BC**	**RWM**	**SWM**	**BC**	**RWM**	**SWM**
Upper Sacramento Valley	144	157	0	7	5	0	35	34	29
Lower Sacramento & Delta	27	1	1	36	1	1	212	166	166
San Joaquin and Bay Area	16	0	0	15	0	0	394	358	333
Tulare Lake Basin	274	322	33	37	19	2	461	434	415
Southern California	1132	929	857	1501	255	197	3074	1855	1838
TOTAL	1594	1409	890	1596	279	200	4176	2847	2780
Agriculture Only									
Upper Sacramento Valley	144	157	0	7	5	0			
Lower Sacramento & Delta	8	0	0	0	0	0			
San Joaquin and Bay Area	0	0	0	0	0	0			
Tulare Lake Basin	232	322	30	19	18	1			
Southern California	309	703	703	6	28	28			
Total Agriculture	693	1182	733	32	51	29			
Urban Only									
Upper Sacramento Valley	0	0	0	0	0	0			
Lower Sacramento & Delta	19	1	1	36	1	1			
San Joaquin and Bay Area	16	0	0	15	0	0			
Tulare Lake Basin	42	0	2	18	0	1			
Southern California	823	227	154	1495	227	169			
Total Urban	901	227	157	1564	227	170			

* **-** BC = Base Case, RWM = Regional Water Markets, SWM = Statewide Water Market

\# **-** Total Cost = Scarcity Cost + Operating Costs

Note: Totals might not sum due to rounding of significant figures.

Reservoir, Conveyance, Recharge, and Recycling Expansion

Table ES-2 presents the marginal economic values to agricultural and urban users of expansions in various surface reservoir, conveyance, and other facilities. These results apply to only small changes in capacity (and thus might overestimate economic values for large capacity changes). 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 a statewide water market.

Table ES-2. Marginal Economic Values of Selected Facility* Expansion Options

		Annual Marginal Expansion Value ($/yr/af or $/af)	
Facility*	Physical Capacity	RWM	SWM
Surface Reservoirs	(taf)		
Pardee	210	14.5	14.5
East Bay Local	153	13.7	13.7
South Bay Local	170	12.5	12.4
Kaweah	143	55.6	31.7
Success	82	48.2	26.4
Grant	47	42.5	38.3
S. Cal. SWP Storage	694	12.1	2.8
Conveyance	(taf/yr)		
Colorado River Aqueduct	1303	351	209
Hetch Hetchy Aqueduct	336	268	280
East Bay/South Bay Connector	0	237	253
EBMUD/CCWD Cross Canal	0	146	145
Folsom South Canal Extension	0	26.0	26.0
Los Angeles Aqueduct	565	15.2	13.0
Other Facilities	(taf/yr)		
Coachella Artificial Recharge	120	2,654	2,796
SCV Groundwater Pumping	366	230	178
SFPUC Recycling	0	55.0	71.5
SCV Recycling Facility	16	30.4	46.5
EBMUD Recycled Water Facility	25	20.2	20.2

* - Facilities reported with greater than $10/yr/af annual average value to expansion

Conjunctive Use

Figure ES-3 shows the frequency of different levels of groundwater use statewide. Statewide, the median groundwater use is about 33% of total water deliveries for all cases. In wet years, this can drop to as low as about 16-22%, 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 Base Case, with greater variation in groundwater use between years. With a statewide water market, conjunctive use appears to be used somewhat more still.

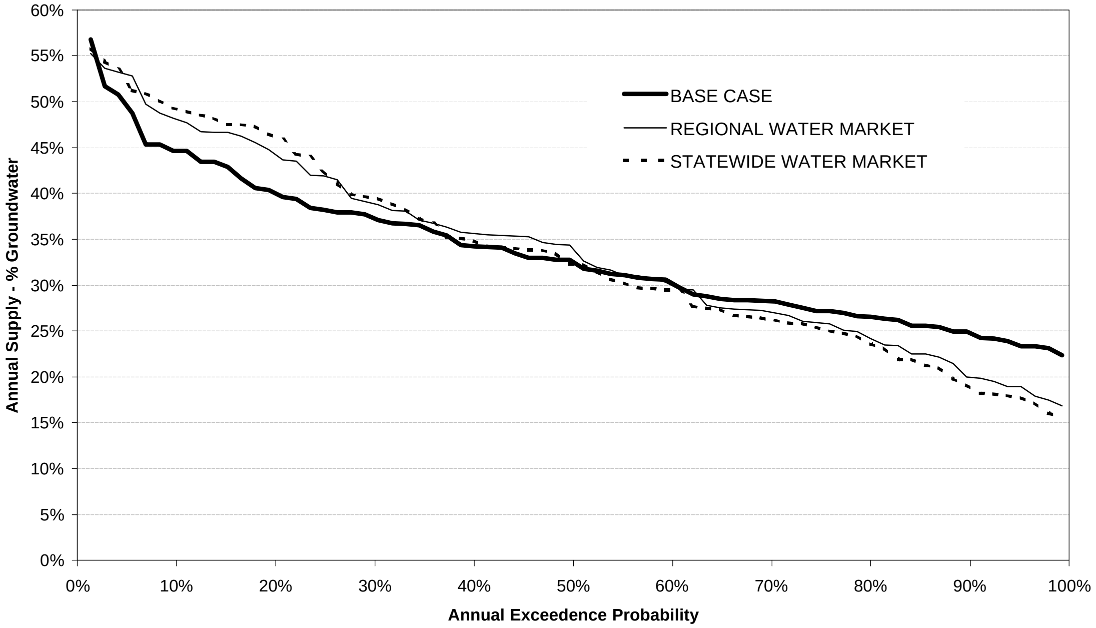

Figure ES-3. Reliance on Groundwater and Conjunctive Use

Water Transfers

Table ES-3 shows changes in deliveries and scarcity costs for all economic regions represented in the CALVIN model with regional and statewide water markets. With regional water markets, from the summing of these figures, on average 606 taf/yr of water "sold" in the markets is from agriculture and 184 taf/yr is from improved operational efficiencies. Of the water "bought," 116 taf/yr goes to agricultural users and 674 taf/yr to urban users. With a statewide water market, agricultural users "sell" less water (414 taf/yr) and 703 taf/yr becomes available from operational improvements. Agricultural users "buy" 373 taf/yr and urban users 744 taf/yr. The bulk of water transfers occur in Southern California, then in the Tulare Basin, with some transfers elsewhere. User participation in water markets often varies with hydrologic circumstances.

Finance and Economic Willingness-to-Pay

Table ES-4 summarizes the willingness of water users to pay for additional water beyond that allocated in each model run. Demand regions without water scarcity are unwilling to pay for additional water. In the Base Case, water users show a wide range of willingness-to-pay for additional water, from nothing to over $10,000/acre-ft. Within the agricultural sector, willingness-to-pay averages between zero and $161/acre-ft. 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 rises (as can be seen for Colorado River agricultural users). 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 sometimes regions would import additional water and export more water at other times.

Table ES-3. Average Water Reallocations and Scarcity Costs by Demand Area

	Deliveries (taf/yr)	∆Deliveries (taf/yr)		Scarcity Costs ($M/yr)			∆Scarcity Costs ($M/yr)	
Demand Region	BC	RWM-BC	SWM-BC	BC	RWM	SWM	RWM-BC	SWM-BC
CVPM 1	153	-1	0	0.01	0.02	0	0.01	-0.01
CVPM 2	640	47	57	3.46	0.22	0	-3.23	-3.46
CVPM 3	1543	7	86	3.15	2.94	0	-0.21	-3.15
CVPM 4	1098	-66	0	0	2.11	0	2.11	0
CVPM 5	1737	0	0	0	0	0	0	0
CVPM 6	1048	0	0	0	0	0	0	0
CVPM 7	565	0	0	0	0	0	0	0
CVPM 8	894	0	0	0	0	0	0	0
CVPM 9	1176	8	8	0.11	0	0	-0.11	-0.11
CVPM 10	1698	0	0	0	0	0	0	0
CVPM 11	867	0	0	0	0	0	0	0
CVPM 12	803	0	0	0	0	0	0	0
CVPM 13	1891	0	0	0	0	0	0	0
CVPM 14	1497	0	0	0	0	0	0	0
CVPM 15	1983	-65	-11	0.35	2.90	0.80	2.55	0.45
CVPM 16	498	-5	-2	0	0.12	0.05	0.12	0.05
CVPM 17	836	-14	-8	0	0.36	0.21	0.36	0.21
CVPM 18	1938	54	222	18.8	10.4	0	-8.41	-18.8
CVPM 19	957	-38	0	0	2.51	0	2.51	0
CVPM 20	677	0	0	0	3	0	3	0
CVPM 21	1162	-23	0	0	1.43	0	1.43	0
Palo Verde	661	-114	-113	1.43	6.91	6.89	5.47	5.46
Coachella	195	-14	-14	0	0.87	0.87	0.87	0.87
Imperial	2550	-266	-266	4.35	20.5	20.5	16.2	16.2
Total Agriculture	**27067**	**-490**	**-41**	**32**	**51**	**29**	**20**	**-2**
Yuba	52	1	1	1	0	0	-1	-1
Napa-Solano	105	10	10	22	0	0	-22	-22
Contra Costa	135	0	0	0	0	0	0	0
East Bay MUD	290	7	7	12	1	1	-12	-12
Sacramento	679	0	0	0	0	0	0	0
Stockton	95	0	0	0	0	0	0	0
San Francisco	232	6	6	5	0	0	-5	-5
Santa Clara Valley	646	10	10	10	0	0	-10	-10
SB-SLO	139	0	0	0	0	1	0	0
Fresno	338	42	40	18	0	0	-18	-17
Bakersfield	261	0	0	0	0	0	0	0
Castaic Lake	44	75	79	508	5	3	-503	-505
Antelope Valley	186	87	91	185	3	0	-182	-185
Coachella	348	104	103	367	365	166	-202	-201
Mojave*	225	127	127	181	0	0	-181	-181
San Bernardino	279	0	4	4	2	0	-2	-4
Central MWD	3534	152	197	183	37	0	-146	-183
E & W MWD	706	26	34	33	7	0	-26	-33
San Diego	954	26	34	35	7	0	-28	-35
Total Urban	**9246**	**674**	**744**	**1564**	**227**	**170**	**-1337**	**-1394**

* - neglects conveyance capacity constraint entering Mojave region

Table ES-4. Marginal Willingness-to-Pay (WTP) for Additional Water

	Average WTP ($/af)			Maximum WTP ($/af)	
	BC	RWM	SWM	RWM	SWM
Agricultural					
CVPM 1	0	11.9	0	19.0	0
CVPM 2	42.2	14.6	0	21.7	0
CVPM 3	25.2	26.7	0	37.2	0
CVPM 4	0	23.5	0	34.7	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	24.8	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	39.5	26.2	14.3	39.5	39.5
CVPM 16	0	16.6	9.9	25.7	25.5
CVPM 17	0	17.6	11.0	32.0	32.0
CVPM 18	162	40.0	0	61.6	0
CVPM 19	0	31.8	0	65.5	0
CVPM 20	0	4.6	0	67.2	0
CVPM 21	0	41.1	0	61.6	0
Palo Verde	20.9	56.8	57.1	71.1	71.1
Coachella	0	61.4	61.4	61.8	61.8
Imperial	23.9	67.7	67.7	67.7	67.7
Urban					
Yuba	66.1	0	0	0	0
Napa-Solano	694	0	0	0	0
Contra Costa	23.4	0	0	0	0
East Bay MUD	351	27.6	27.6	1,130	1,130
Sacramento	0	0	0	0	0
Stockton	7.5	0	0	0	0
San Francisco	291	0	0	0	0
Santa Clara Valley	249	0	0	0	0
SB-SLO	0	0	0	0	0
Fresno	472	0	42.4	0	343
Bakersfield	0	0	0	0	0
Castaic Lake	10,495	645	519	1,039	585
Antelope Valley	2,574	238	0	896	0
Coachella	1,520	1,358	1359	1,952	1,952
Mojave*	1,527	0	0	0	0
San Bernardino	315	145	0	753	0
Central MWD	897	218	0	1,095	0
E & W MWD	831	219	1.8	1,020	800
San Diego	622	194	0	1,060	0

* - neglects conveyance capacity constraint entering Mojave region

Environmental Regulation

Table ES-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 $1,700/af in the Mono and Owens basins (due mostly to the value of hydropower there – the only locations with hydropower currently modeled), but with frequent average costs on the order of $45/af. However, many environmental flow requirements appear to have no consequence to agricultural and urban water users under regional water market conditions. Moving from regional to statewide water markets tends to reduce the economic impacts of riparian flow requirements.

All forms of analysis involve errors, and something should be said about the likely effects of such errors on these results. Many errors in the current model arise from data and representations taken from other recent modeling and analysis efforts. These errors are particularly troublesome in the Tulare Basin. We are sure there are errors that affect results at the local level (such as a missing conveyance capacity constraint into the Mojave Basin). However, based on our experience with this and other models and with California water operations, we believe the major policy conclusions of this report (presented below) are insensitive to likely modeling errors. A fuller discussion of limitations appears in Chapter 5.

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

	Annual Req. (taf/yr)	Avg Opportunity Cost ($/af)		Max Opportunity Cost ($/af)	
		RWM	SWM	RWM	SWM
River					
Trinity River	357	45.6	0.7	49.6	6.3
Clear Creek	42	0.5	0.4	46.4	5.1
Sacramento River (Nav. Control Point)	3117	0.7	0.2	48.0	3.7
Feather River	936	0	0.1	0	0.8
American River	1076	0	0	0.2	1.1
Mokelumne River	88	0.1	0.1	0.9	1.4
Calaveras River	1	0	0	0	0
Yuba River	170	0	0	0.2	0.5
Sacramento River	3619	0	0	0	0.8
Stanislaus River	196	4.4	1.3	13.7	24.5
Tuolumne River	119	2.4	0.6	13.6	23.7
Merced River	79	3.1	2.0	13.5	22.3
Mono Lake Inflows*	74	963	818	1,716	1,215
Owens Lake Dust Mitigation*	40	750	611	1,171	666
Refuge					
Sacramento West Refuge	106	41.8	0.3	45.4	3.9
Sacramento East Refuge	62	0	0.2	1.0	1.0
Volta Refuges	36	8.3	19.9	20.5	22.8
San Joaquin/Mendota Refuges	237	6.6	15.9	17.7	21.8
Pixley	1	46.3	26.0	72.1	41.1
Kern	11	43.2	34.4	85.7	37.5
Delta Outflow					
Bay Delta	5593	0	0	0	0

* - includes hydropower costs

CONCLUSIONS

Several methodological and policy conclusions are presented below.

1. Optimization based on fundamental economic and engineering principles is feasible and available for water management in California. Recent advances in computing software have made it possible to solve optimization problems as large as California and to store, present, and document data for such large-scale models. Advances in local and regional modeling, data gathering, and data reconciliation also have provided sufficient data to calibrate and run useful large-scale economic-engineering optimization models of California's water system. These advances complement advances in simulation modeling for California's water supply system.

2. Optimization results provide considerable information and insight for policy and operations planning. Examples of these results are presented in the chapters and appendices of this report, with some more related policy conclusions itemized below. These kinds of 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 have direct usefulness for policy, planning, finance, and operations planning problems regarding projected water scarcity at State, regional, and local levels.

3. Some qualitative policy conclusions emerge from model results. These include:

a) Regional or statewide water markets have considerable potential to reduce water 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 on the order of $1 billion per year, with differences in the economic value of water between buyers and sellers sometimes being more than an order of magnitude. Statewide markets provide some additional benefits.

b) 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 the demand for importing additional water from other regions. This is true for all regions. For example, Bay Area results suggest that regional water markets or other forms of flexible and coordinated operations among urban agencies have potential to substantially reduce or eliminate urban water scarcity with existing infrastructure and water resources.

c) Environmental flows have economic opportunity costs for agricultural, urban, and other activities. Environmental water requirements often come with significant opportunity costs to agricultural, urban, and other water users. However, there are many cases where these costs to non-environmental water users are very small, or zero. The opportunity costs of environmental flows are often greatly reduced when more economic operations and allocations are employed.

d) Economic values exist for expanding facilities. There is considerable economic value to expanding some storage, conveyance, recharge, and recycling facilities in California. This is especially true for surface storage on smaller rivers in the Tulare Basin and in Southern California for groundwater storage, recharge facilities, and the Colorado River Aqueduct.

e) Some scarcity is optimal. It is neither economically feasible nor desirable to eliminate all water scarcity and scarcity costs within California. In many cases, the scarcity costs are smaller than the costs of providing additional water either from new sources, efficiency improvements, water conservation, or reallocations by whatever means from other water uses.

f) Economically optimal water reallocations are very limited, but reduce scarcity and scarcity costs considerably. Under ideal market conditions, a very small amount of water is redistributed for 2020 water demands. Statewide, with regional water markets, all reallocations (both increases and reductions) amount to less than 3.9% of total Base Case 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 system-wide increases slightly to 4.2%, with reallocations in Southern California amounting to 11% of Base Case deliveries there. Colorado River deliveries to agriculture are diminished by less than 12% for both Regional and Statewide water markets; for the entire state, these are the greatest local reductions in deliveries. 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 more extensive in some regions. Some of these exchanges also support urban water quality benefits for the Solano-Napa, Sacramento, Tulare, and Bay areas, as elaborated further in Chapter 4 and the appendices.

g) *Greater conjunctive operation of local, regional, and statewide water resources decreases competition with environmental uses for limited streamflows*. This is especially true under critical dry conditions when agricultural and urban reliance on surface flows is significantly reduced from Base Case levels. Under the statewide water market, total diversions from the Sacramento River are reduced on average by 429 taf during drought years with supplies made up by greater use of groundwater. Similarly, American River diversions during droughts are reduced by 228 taf/yr.

4. As with all modeling, there are limitations to the results. Limitations of this effort are presented extensively in Chapter 5 of this report and elsewhere in related reports and appendices. Recommendations are made to pursue some of the major limitations. Nevertheless, the results from this type of optimization model are best seen as offering promising suggestions for improvements in water management, worthy perhaps of further testing and refinement with simulation-based analysis. The optimization model also is adept at identifying particularly costly constraints. The CALVIN model does not diminish the importance of other planning and analysis efforts, but rather provides an aid to placing local and other statewide planning efforts in context and giving them greater focus.

5. Development of the optimization model has highlighted some areas where additional data refinement and development are needed. While the current CALVIN model is useful, its limitations would be less and its results more accurate and reliable with additional refinement and reconciliation of input data and other improvements in the model. These are discussed in Chapters 3 and 5. Problems are particularly common in the Tulare Basin. A broadly useful side benefit of large-scale optimization is that, if properly used, it provides a framework for analysis that insists that all water availability and demand data be consistent and transparent. This makes large-scale optimization useful for identifying important data gaps and inconsistencies. The model becomes a framework to see if the data pieces make sense together.

RECOMMENDATIONS

Several recommendations for additional technical work are made.

Comprehensive Central Valley Groundwater, Surface Water, and Agricultural Hydrology

A major comprehensive effort is needed to better represent the groundwater hydrology, recharge, local runoff and accretions, and agricultural return flows in the Central Valley. This effort needs to pay particular attention to the representation of groundwater Central Valley-wide, the separation of surface and groundwater resources, as well as all aspects of surface water hydrology in the Tulare Basin. The calibration of CALVIN and the CVPIA-PEIS models both demonstrate the limited and inconsistent understanding afforded by CVGSM and other sources.

A consistent statewide groundwater modeling effort is needed. A more physically-based approach is needed which is explicitly consistent with statewide modeling and analysis requirements and the representations of surface water and water demands.

Comprehensive Agricultural and Urban Water Use Study

Better reconciliation of water use data and water demand models is needed. In many cases, discrepancies have arisen in the representation and reality of agricultural water demands. These discrepancies account for roughly 10% of agricultural demand in the Central Valley (2 maf/yr). In addition, the variability of both agricultural and urban water uses between different types of water years also needs to be better represented in the optimization model. This requires the refinement of the SWAP agricultural water demand model and urban water demand representations in the context of field understandings of how these demands operate and vary seasonally and across water years. This effort should be undertaken systematically, statewide.

The utility of developing a more comprehensive and systematic understanding and representation of water demands in California extends well beyond its value for optimization modeling. Such an effort is essential for providing more reliable and convincing analysis of supplies and demands for any local, regional, or statewide effort, including further Bulletin 160, CALFED, CVPIA, and other planning efforts. Such consistency also provides a better ability to compare local or regional projects and proposals. A concerted scrutiny and modernization of data collection, storage, documentation, and access is essential as part of this work.

Tulare Basin

The Tulare Basin is central operationally and geographically to California's statewide water system (as recognized in the 1930 California Water Plan). Moreover, the Tulare Basin accounts for roughly 40% of water demands and more than half the value of agricultural production in the

Central Valley. However, the Tulare Basin is by far the weakest link of regional and statewide modeling, in terms of inconsistent data and underdeveloped analytical capability. While some insights can be gained with current capabilities and data, a broad concerted technical effort is needed to improve the data, modeling, and analytical understanding of this basin in the context of statewide water management. We are acutely aware of problems in the Westlands and Kern County areas that seem poorly represented in this or other major planning and operations models.

Institutional Home for CALVIN

The CALVIN model has gone on well beyond the normal development of a University research effort. Most of its remaining limitations and its general use are ill suited to being addressed in a University environment. It is time for CALVIN to graduate from college. Several alternative homes for CALVIN-types of modeling can be envisioned.

Overall, further development of CALVIN (or a successor) and its general use seems best undertaken by the California Department of Water Resources, with ancillary support from other agencies (particularly USBR) and university staff. A technical advisory committee might prove worthwhile and useful in this effort. DWR has most of the in-house expertise needed to use and develop such models, is the home of most of the data collection and reconciliation activities needed to support such models, and has clear institutional missions for which a large-scale optimization model would be useful. Nevertheless, others involved and interested in California water also have a considerable stake in the success of such models and often have complementary expertise and data for model development and use.

Further Model Development

The CALVIN model serves as a usable first cut at a unified framework for data and analytical modeling capability. CALVIN provides approximate optimization insights that can be refined and tested using more detailed analysis tools, such as a geographically extended CALSIM. As detailed in Chapter 5 and elsewhere, there are many areas where CALVIN (or a successor) could be further developed to yield more accurate, reliable, and precise results, which would be useful for policy, planning, and operational purposes.

Following this project, the State Energy Commission and Electric Power Research Institute have funded UC Davis to add some hydropower and flood control values to the current CALVIN model. They have interests in using the model for hydropower and climate change studies. These expanded capabilities and data will become available in due time.

California water management is one of modern civilization's great accomplishments. Yet, just as ancient Rome's water supply was subject to constant evolution and change over hundreds of years, the management and infrastructure of California's water system must change to respond to the state's changing economy, population, and societal goals as well as improvements in our understanding of this vast natural and human system. For California, water management is an evolving process. We believe this process will be less painful and more productive if it incorporates optimization and advanced data management techniques that provide a wider variety of options for water operations and water policy.