IMPROVING CALIFORNIA WATER MANAGEMENT:

OPTIMIZING VALUE AND FLEXIBILITY

Marion W. Jenkins
Andrew J. Draper
Jay R. Lund
Richard E. Howitt
Stacy Tanaka
Randy Ritzema
Guilherme Marques
Siwa M. Msangi
Brad D. Newlin
Brian J. Van Lienden
Matthew D. Davis
Kristen B. Ward

Department of Civil and Environmental Engineering
Department of Agricultural and Resource Economics
University of California, Davis 95616

a report for the

CALFED Bay-Delta Program
Sacramento, California

October 2001

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

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PREFACE

"There is a terrible shortage of sports cars. I don't have one."

Water is scarce in California. Water often is less available than we would like at the times, locations, and prices that people would like it. The same is true for energy, housing, education, transportation, or a good wine. Traditional water supply analysis, confused by such concepts as "firm yield" and "shortage," provides little insight as to how supplies and demands can be managed when a resource is scarce and has variable availability.

This study presents an alternative approach to understanding water scarcity in California, combining economic and engineering analysis in the form of an optimization computer model, CALVIN. We consider not only the difference between deliveries and the amount of water users would like at zero price (scarcity), but also the economic losses of scarcity, how scarcities vary seasonally and between dry and wet years, and the operating costs of reducing scarcity. (Indeed, some scarcity is often desirable, given operating costs for providing water.) This more economic approach may be difficult for some to grasp, but it is very similar to the way the larger economy operates. We would all like water, and sports cars, to not be scarce, but most of us are unwilling to pay to eliminate such scarcities.

Water is different than most goods, however. After use, some of it is available for reuse. But reuse and repeated reuse can create water quality problems. Water, despite evaporative losses, also can be stored indefinitely. Water, in small amounts, is also vital to all human and environmental activities. These differences do not pose great problems for our approach. Indeed, a combined economic and engineering approach to water management provides a way to trace and manage these effects throughout the water system to better ensure that water is allocated to its highest and best uses with reduced economic losses statewide.

This project has unusually broad scale, scope, and importance for University researchers. We have had to assemble, attempt to reconcile, and consistently integrate an incredible variety of hydrologic, water demand, and water management information from across the state into a single economic-engineering optimization model. This has never been done in California, particularly with any detail. Thus, the resulting analysis provides unusually insightful and useful results. Perhaps more importantly, the process of developing the model has forced us to examine, often quite painfully, the data available for statewide modeling in California. A consistent understanding of data gaps and uncertainties thus also results from this project. Any statewide or regional water planning analysis, either simulation of optimization, relies on having such data.

Like many large projects, this one has a curious history. The project began with discussions between Doug Wheeler, then Secretary of the California Resources Agency, and Henry Vaux, University of California Associate Vice President for Programs, DANR, regarding long-term financing of water supplies. Financial support for the initial 1 1/2 year project came primarily from the California Resources Agency, with additional support from the National Science Foundation and US Environmental Protection Agency's Water and Watersheds program. A "running" model, not calibrated to actual flow data, resulted from this phase (Howitt, et al. 1999). The interest generated by this work, and the practical limits of alternative approaches, led to continued funding by the CALFED Bay-Delta Program. In this second 1 1/2 years, the "running" model has evolved into a more reliable, but still imperfect, "

better matches the California water community's understanding of water availability, hydrologic process, and water demands in the state.

Great thanks are due to the Advisory Committee originally established by the Resources Agency for this project. They have given freely of their time to attend meetings, provided sage and useful advice, and asked questions when our work and presentations were unclear. This committee and overall coordination with the Resources Agency and CALFED were overseen most capably by Anthony Saracino. Members of the Advisory Committee were: Anthony Saracino, Private Consultant (Chair); Fred Cannon, California Federal Bank; Duane Georgeson, Metropolitan Water District of Southern California; Jerry Gilbert, Private Consultant; Carl Hauge, California Department of Water Resources; Steve Macaulay, State Water Contractors and then California Department of Water Resources; Dennis O'Connor, California Research Bureau; Stu Pyle, Kern County Water Agency; Maureen Stapleton, San Diego County Water Authority; and David Yardas, Environmental Defense Fund.

Ken Kirby, now of Saracino-Kirby-Snow, was very involved in the development of the earlier uncalibrated physically based model, especially the data architecture which has carried over into this work, and has continued to be central in the development of the database and model software essential to making CALVIN work in a relatively transparent and efficient way. Pia Grimes provided programming, documentation, and editorial support to the project.

This project involved an unusual amount of data gathering from many agencies from all over California. Particular thanks go to: Tariq Kadir, Scott Matyac, Ray Hoagland, Armin Munevar, Pal Sandhu, and Saied Batmanghilich (DWR); Tim Blair and Devendra Upadyhyay (MWDSC); Lenore Thomas, David Moore, and Peggy Manza (USBR); Roger Putty and Bill Swanson (Montgomery-Watson); Terry Erlewine (SWC); Judith Garland (EBMUD); Rolf Ohlemutz and Bill Hasencamp (CCWD); Ralph Johonnot (USACE); Chris Barton (YCFCWCD); Ken Weinberg (SDCWA); Melinda Rho (LADWP); Richard McCann (M-Cubed). The US Army Corps of Engineers Hydrologic Engineering Center's Bob Carl, David Watkins (now with Michigan Technical University), and Mike Burnham (now a private consultant), with assistance from Paul Jensen of the University of Texas, Austin, provided technical support and technical extensions for the HEC-PRM code. Our apologies to others we have certainly missed.

Rarely are University researchers privileged to work with real systems at all, let alone systems as extensive and complex as California's water supply system. We are simultaneously grateful to have had this opportunity, excited by the interest shown in this work and its continuation, and much more appreciative of the difficulties of working at this scale than we were before. We hope that this effort helps others become comfortable with more modern approaches to water management, particularly the potential of economics and optimization for improving management of California's water resources. All parties to California's common resource problem are likely to find both good and disturbing aspects to the approach, model results, and implications. We do not underestimate the difficulties of managing water under this different economic-engineering approach, but we do feel this more modern approach has more promise under current conditions than continuation of some traditional concepts of water management, which were effective in the now distant past.

This report and appendices are on the web: http://cee.engr.ucdavis.edu/faculty/lund/CALVIN/

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EXECUTIVE SUMMARY

October 2001

Principal Investigators
Jay R. Lund, Professor of Civil and Environmental Engineering, jrlund@ucdavis.edu
Richard Howitt, Professor of Agricultural and Resource Economics, rehowitt@ucdavis.edu
University of California, Davis

Report Authors: Marion W. Jenkins, Andrew J. Draper, Jay R. Lund, Richard E. Howitt, Stacy Tanaka, Randy Ritzema, Guilherme Marques, Siwa M. Msangi, Brad D. Newlin, Brian J. Van Lienden, Matthew D. Davis, Kristen B. Ward

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

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"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.

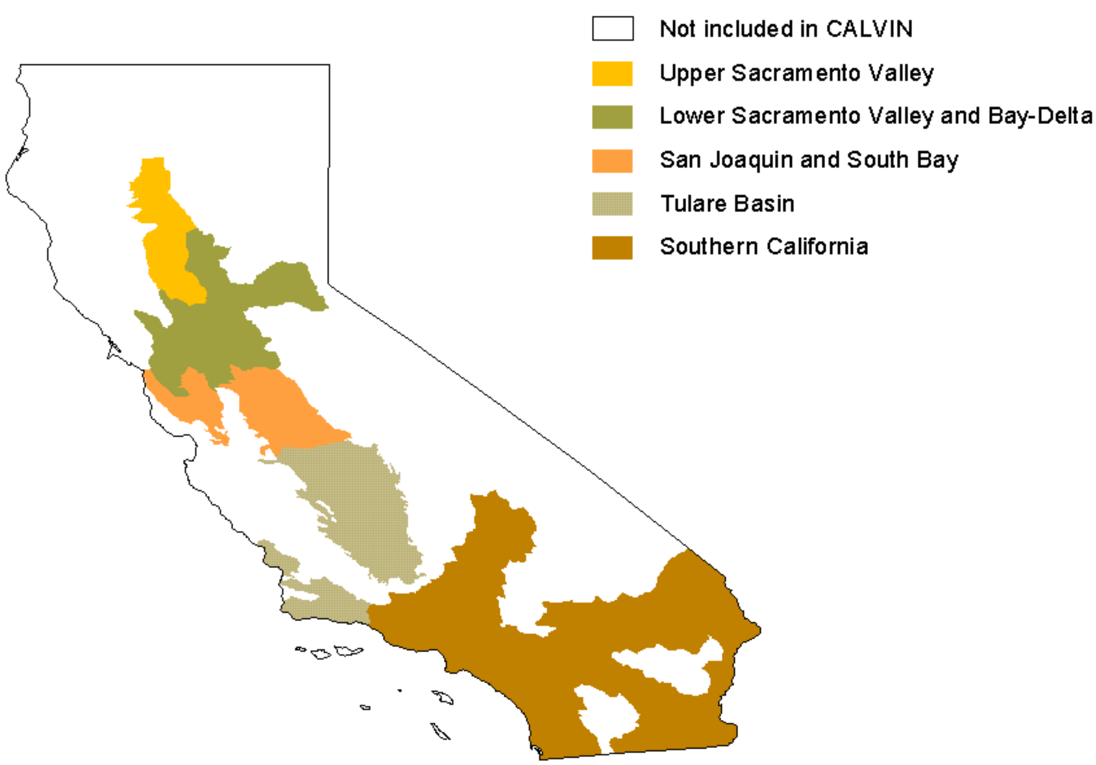


Figure ES-1. Demand Areas Represented in CALVIN Model of California's Water System

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.

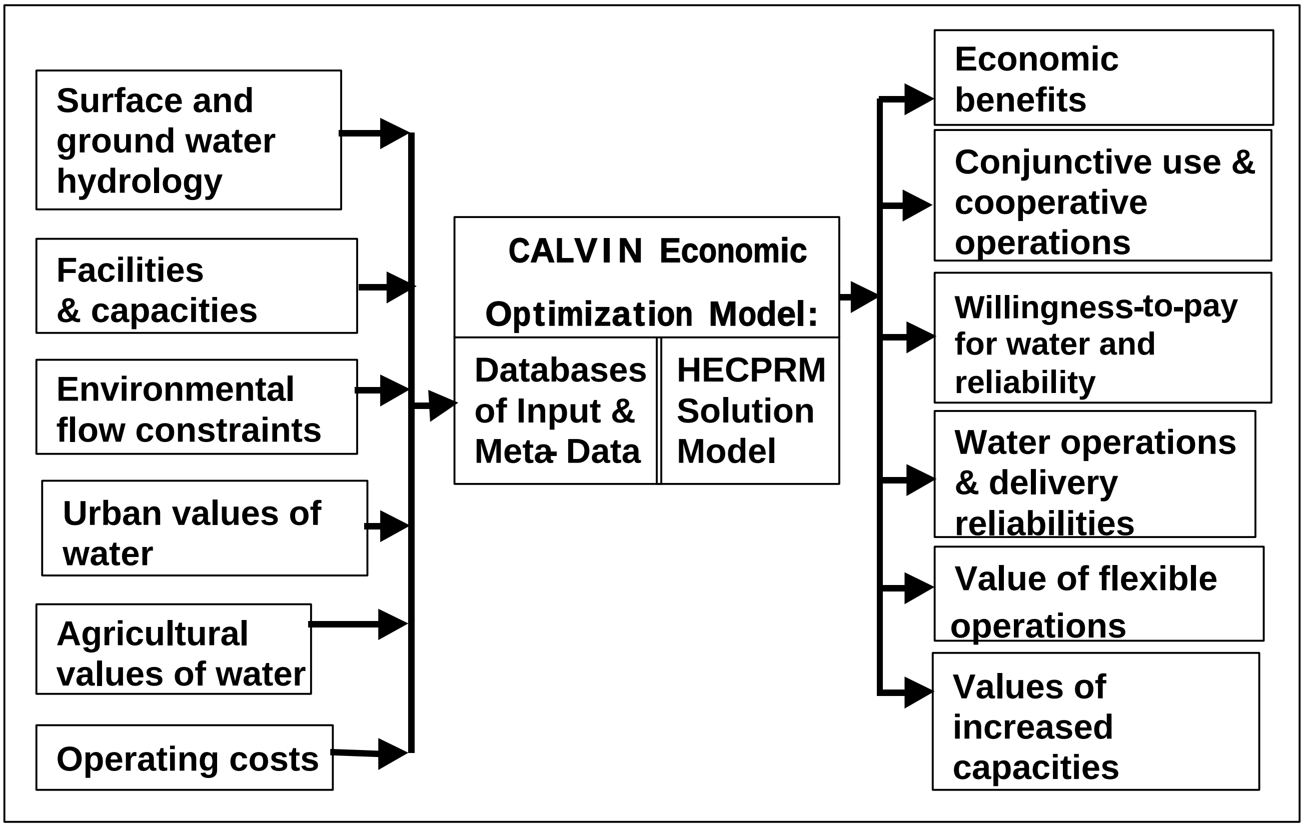


Figure ES-2. Data flow schematic for CALVIN

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

Facility*	Physical Capacity	Annual Marginal Expansion Value ($/yr/af or $/af)	
		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.

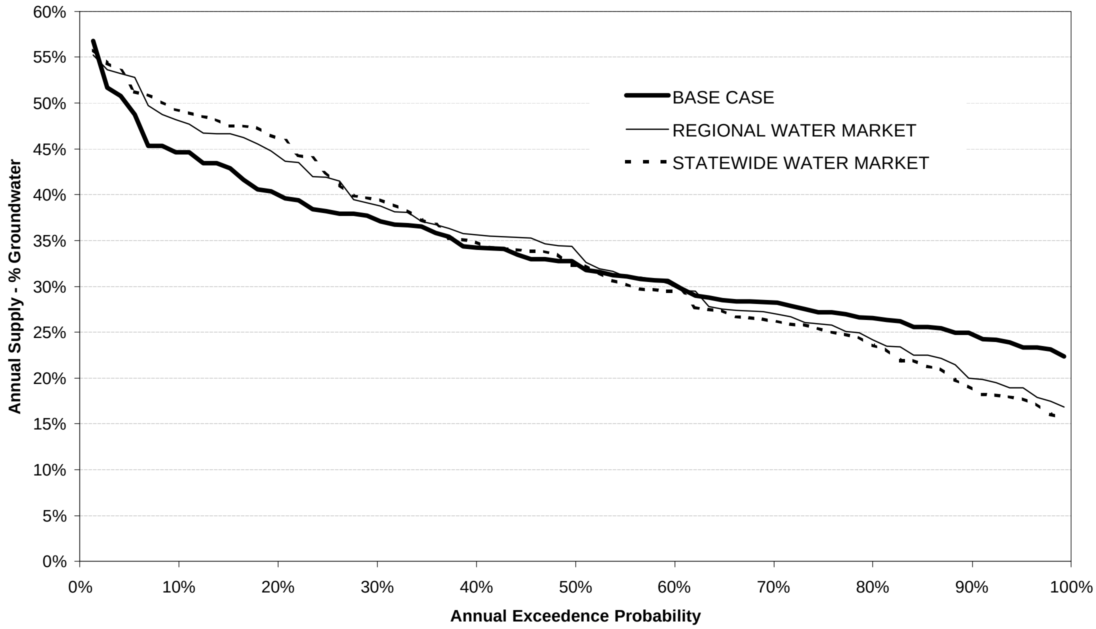


Figure ES-3. Reliance on Groundwater and Conjunctive Use

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.	Avg Opportunity Cost ($/af)		Max Opportunity Cost ($/af)	
	(taf/yr)	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.

CHAPTER 1

INTRODUCTION

"It has been well said that 'water is the wealth of California.' If it has been so in the past, it will be more so in the future." *Report of the Board of Commissioners on the Irrigation of the San Joaquin, Tulare, and Sacramento Valleys of the State of California* (1873), Chapter III

The management of California's water has long been recognized as a key to the state's wealth and economic well-being. Much of the historical analysis and planning of the state's water resources has assumed that the provision of additional water supplies, at almost any cost, was economically worthwhile. And in the early days, when water development was inexpensive on abundant streams with more economically developable reservoir and aqueduct sites, this was largely true. Thus, California is blessed with a water storage and conveyance infrastructure that is the envy of much of the world.

In recent times, the economic and social value of additional water development and other water management activities has come under additional scrutiny, in environmental, economic, social, and political terms. A wide variety of water management and development options are being considered, ranging from new surface reservoir sites, more conjunctive use of groundwater storage, additional water conveyance capacity, more expensive and effective forms of water treatment and wastewater recycling, water transfers among water users, as well as experimental forms of environmental restoration. The integration of such a variety of new measures into an already complex water management system is a difficult task. This task can be made somewhat easier by the judicious use of optimization modeling.

This report presents the calibration and preliminary results of an economic-engineering optimization model of California's main inter-tied water system, including the Central Valley, most of the San Francisco Bay metropolitan area, and southern California. The model, CALVIN, operates water facilities and allocates water over the historical hydrologic record to maximize the economic values of agricultural and urban water use statewide. CALVIN is based on data from existing large-scale simulation models, with the addition of economic values for agricultural and urban water use at different locations throughout the system and a network flow optimization solver provided by the US Army Corps of Engineers (HEC-PRM). This relatively simple, if large-scale, optimization model supports several technical and policy conclusions with long-term significance for management of California's water.

EARLIER OPTIMIZATION IN CALIFORNIA AND ELSEWHERE

Simulation modeling has been applied practically to water resource systems since the early 1950s, and remains the analysis main-stay for water systems. Optimization models have been applied to water resource systems from the late 1950s up to the present, mostly as experiments and academic exercises. During the 1980s there was much discussion among academic water resource modelers regarding why optimization models had been so little-used in practice (Rogers and Fiering 1986; etc). However, during the 1990s, a combination of improved availability of optimization software (e.g., in Microsoft Excel), improved data availability, increased confidence in economic valuation, and increasing acceptance of computer modeling for operations has seen the common application of optimization methods for hydropower purposes and more frequent practical application of optimization for more general water resources planning and analysis. Large-scale multipurpose water resource systems optimization has been applied recently to the Missouri River system (USACE 1992a, b; Lund and Ferreira 1996), the Columbia River system (USACE 1993, 1996), South Florida (USACE 1998a), and the Panama Canal (USACE 1998b), all using the HEC-PRM software provided by the US Army Corps of Engineers. The World Bank applied similar analyses to China's Yellow River Basin (World Bank 1993). Flood control optimization results have also found use in Iowa (Needham et al. 2000) and California (USACE 2000). Optimization methods also have become a common engine for simulation models using goal programming approaches (MODSIM, Acres, CALSIM, OASIS, and others) (TWDB 1970; Sigvaldison 1976; Kuczera 1993; Labadie et al. 1986), including recent applications of CALSIM, OASIS, MODSIM, and other software to systems within California (Chung et al. 1989; Sabet and Creel 1991; Andrews et al. 1992; DWR 2000; Randall, et al. 1997; Leu 2001).

Most of California's current water supply infrastructure was planned and designed before the 1960s, without the use of computer models. In recent decades, simulation models have been used extensively to examine water management alternatives and policies. These simulation models typically derive the operations and water allocations of the system over a repeat of an adjusted historical hydrologic record for a given set of system operating and water allocation rules or priorities. In recent years, optimization algorithms have increasingly been used as the engines for these simulation models using goal programming approaches to minimize the deviations of operations from operating priorities, making the simulation models more data-driven, flexible, and transparent (OASIS, DWRSIM south of the Delta, and CALSIM). True optimization models, with performance-based objective functions, have been employed, mostly experimentally, for parts of the system for various operating purposes, but have not yet played a major role in California's water management. Some earlier applications of optimization to parts of California's system include several generations of efforts applied to the Central Valley Project hydropower and water operations (Becker et al. 1976; Marino and Loaiciga 1985a, b; Tejada-Guibert et al. 1993, 1995). Lefkoff and Kendall (1996) apply optimization to maximize water supply yield from the Central Valley. Pacific Gas and Electric (PG&E) and Southern California Edison regularly use optimization models for hydropower scheduling (Jacobs et al. 1995). Metropolitan Water District of Southern California uses optimization as part of its Integrated Resources Planning (IRP) model (MWD 1997; Sun et al. 1995), as does the San Diego County Water Authority (SDCWA 1997). Vaux and Howitt (1984) used an optimization model of a simplified and hydrologically static representation of California to estimate the economic values of inter-regional water transfers. While optimization models have been used for actual planning and management of some local and regional systems, they have not been applied in great detail for California's broader water supply system.

The work here is the largest attempt to apply economically-based optimization to California's entire inter-tied water supply system. This report presents refinement and calibration of the California Value Integrated Network (CALVIN) model, whose conceptual formulation and general approach are described in detail by Howitt et al (1999), particularly in their appendices.

Some policy results from the calibrated model also are presented. The intended uses and some limitations of this current model (CALVIN) are summarized below and detailed later in the report. A variety of appendices examine the assumptions and results from various regional and thematic perspectives.

USES FOR OPTIMIZATION MODELS OF CALIFORNIA WATER

Optimization models cannot answer all water planning questions, and answers from optimization models will often be only approximate. However, economically-based optimization can provide some useful information more rigorously and expeditiously than other currently available approaches.

Identify Promising Solutions

Optimization models suggest promising solutions based on identified decision options, explicitly stated objectives, and explicitly stated constraints. For California's already complex water resource system, optimization model results can rapidly suggest how the operation of new facilities can best be integrated into the large existing system as well as locations in the system where expansion of capacity would have the greatest value.

A simple but extensive optimization model, such as CALVIN, can identify economically promising:

- locations for expanded capacity of reservoir, conveyance, pumping, recycling, and recharge facilities
- water transfers (permanent and short term)
- water quality exchanges
- conjunctive use opportunities for groundwater
- cooperative operation opportunities for reservoirs and conveyance facilities currently under independent operations.

An optimization model used in this screening sense can greatly reduce the number of simulation model runs needed to conduct a complete analysis. Many thousands of simulation model runs would need to be formulated, run, and interpreted to provide the type of broad evaluation and direction provided by a few (in this case three) optimization model runs. However, while highly efficient at identify promising solutions, an optimization model is typically simpler than a simulation model. Thus, it is often necessary to test and refine the "solutions" suggested by an optimization model using more detailed simulation models (Lund and Ferreira 1996). This general approach employs simulation and optimization models in the areas that each excels.

Preliminary Economic Valuation

As an economic-engineering optimization model, CALVIN provides considerable economic information on base and alternative cases. This allows for economic evaluation and comparison of the desirability of alternatives, as well as providing suggestions of the economic value of small changes in capacities and constraints, and contributing some information useful for project finance.

Some particular economic information from the CALVIN model includes preliminary economic values for:

- changes in individual facility capacities (from Lagrange multipliers)
- changes in operating and allocation policies
- changes in environmental constraints
- willingness-to-pay of water users for additional supplies or reliability
- water scarcity to agricultural and urban users.

Economic information from the model also can be used to estimate regional economic impacts of proposed changes in water deliveries, as illustrated in Appendix 2J.

In many cases, even preliminary economic results will allow an alternative to be screened out without need for further study and provides some basis for prioritizing analysis of promising alternatives.

Systematic Thinking

By forcing a systematic description of the system and its performance objectives, an optimization model requires that data describing the system, its management options, and objectives be reconciled and systematized. This frequently leads one to think of solutions and alternatives in a new and more flexible light. For optimization, alternatives are suggested flexibly by the model, provided that the objectives, constraints, and decision options are clear and reasonable. In understanding that the model is merely trying to maximize performance within physical and policy limits, one can often see new opportunities or the value of particular alternatives derived by the model. CALVIN, for example, will suggest a mix of water transfers, new facilities, conjunctive use, and changes in existing facility operations. Such a mix is difficult to conceive of in detail without a model and is tedious to explore by simulation modeling.

Beyond thinking more broadly about solutions to the problem, large-scale modeling also facilitates reconciliation of hydrologic, capacity, demand, and other operating data needed to coherently represent a system. Such reconciliation is needed for the optimization results to make sense. And an optimization model that has gone astray often is more easily detected than a simulation model, which usually is bound more closely to conventional historical operations. This reconciliation of data and assumptions is needed for any large-scale analysis, either simulation or optimization.

LIMITATIONS OF CALVIN

No computer model can provide all the answers. While optimization models can provide some things that are difficult to achieve with simulation models, optimization models, like models of any type, also have significant limitations. These limitations are detailed in Chapter 5, but are outlined here for clarity.

Hydrology

The hydrologic representation of the Central Valley is the subject of some uncertainty and controversy. This project has not been in a position to resolve these issues, but we have tried, where we can, to illustrate their importance. In this project, our general approach is to use the historical record of streamflows and groundwater as refined and interpreted by the California Department of Water Resources and US Bureau of Reclamation. These interpretations are not consistent, however, and we have made some efforts to provide a consistent, though not necessarily correct, version of the hydrology of the Central Valley and Southern California. The approach we have taken has all the benefits and limitations of the use of historical hydrologic data, as sifted through a long history of technical studies.

Water Demands and Deliveries

Water demand levels are assumed for 2020 conditions, based on Department of Water Resources Bulletin 160-98 population and land use estimates. These economic water demands have quantity varying with price according to an economic model of agricultural production (Appendices A and 2L) or elasticity estimates of urban water demand (Appendix B). The urban demands' limitations are described extensively in Appendix B. For our purposes, we believe the major limitation here is the lack of inter-annual variability in the economic value of water for agricultural and urban purposes. This variability is included for Southern California urban uses with data from MWDSC, where they see roughly 17 percent variability in urban demand between high and low water use years. Other urban water demands in CALVIN do not vary between years. Agricultural water demands, which appear to vary as much as 16% between years (Ray Hoagland, personal communication), are represented as constant average year quantities. These are limitations that can be overcome in future years if this modeling approach is found to be valuable to the state.

Water Quality

The network flow formulation that is at the heart of the CALVIN model has little ability to explicitly represent water quality. Water quality has been represented with some flow constraints and the elimination of some water sources (saline aquifers and surface water bodies) as potential water supplies. For urban demands, water quality costs have been added to sources with higher salinity, greater treatment costs, or otherwise poorer water quality (MWD and USBR 1998). For agriculture, water quality costs have not been represented, but appear to be smaller.

Environmental Regulation

Environmental water uses are represented in the model as minimum instream flow constraints. Ideally, for economically-based optimization, environmental flows would be given economic values as was done for agricultural and urban water uses. However, monetization of environmental purposes was avoided due to the controversy and uncertainty involved in economically valuing environmental flows and the practical regulatory nature of environmental flow regulations. Nevertheless, while the value of environmental flows is unknown, the model does provide the cost or benefits to agricultural and urban water users of changes in environmental flow requirements.

A second environmental limitation of the CALVIN model is the approximate nature of its representation of some environmental flow requirements. The particular network flow formulation used for this model, which provides relatively fast run times and a public domain solver, also restricts the types of constraints that can be explicitly represented in the model.

Complex Delta flow requirements and pumping limitations are therefore represented approximately.

Perfect Foresight

As a deterministic optimization model, CALVIN has a potentially major limitation of enjoying perfect hydrologic foresight. This allows the model to perfectly fill and drain reservoirs in ideal anticipation of wet and dry periods. This tends to depress the economic values of expanded facilities, compared with realistic operations, since operations with more realistic imperfect foresight tend to be more conservative. Experiments presented in Appendix 2K indicate that for this model, the economic values of new facilities might be somewhat larger than that indicated by the model, although this effect diminishes greatly with the presence of large amounts of groundwater storage, as is common in California. In many cases economic values provided by the "perfect foresight" model results are useful for preliminary planning purposes. Deterministic optimization often produces useful results for real reservoir systems (Lund and Ferreira 1996). In some important cases, such as the Southern California region of the model, perfect foresight seems to only improve modeled system performance by as little as five percent (Newlin et al in press; Appendix 2F).

Appendix 2K presents two approaches for reducing the perfect foresight of CALVIN to within each water year by running CALVIN sequentially for one-year periods over the historical record with carryover storage value functions. Optimization of the carryover storage value functions is attempted by stochastic dynamic programming and by non-linear search. These carryover storage value functions alone should have some utility for operators making decisions to allocate water to carryover storage versus current water allocations.

Flood Control and Hydropower

CALVIN is a model mostly of water supply for agricultural, urban, and environmental purposes. But California's water resource system is operated for other purposes, with flood control, hydropower, and recreation having some prominence. Flood control operations are represented somewhat in CALVIN by restricting winter reservoir storage to the water supply "pool" of each reservoir, eliminating from the model seasonal storage capacity commonly held in reserve for flood control. For a monthly model, this prevents some unreasonable flood control operations. In other similar optimization models for other parts of the country, flood damage functions have been included, but this has not yet been done for CALVIN. The Lagrange multipliers on these flood storage capacity constraints represent a lower bound of the water supply costs of flood control storage capacity.

Hydropower is represented only at a few locations with fixed-head hydropower, such as on the Los Angeles Aqueduct. The solver for CALVIN, HEC-PRM, includes a hydropower solution algorithm for representing the storage-head-release nature of hydropower production. On the Columbia River system, this feature was employed successfully (USACE 1993, 1995, 1996). In the future, hydropower can be added to the model, although the iterative hydropower solution algorithm might restrict the addition of hydropower in terms of model run time.

Recreation, navigation, and other operating purposes for California's water system are not included in the model. Most such purposes could be included in the future with the addition of appropriate economic value functions.

STRUCTURE OF THE REPORT

Following this Introduction, Chapter 2 provides an overview of the CALVIN Model. This is a large and complex model, so many details of the model appear in appendices, both of this report and the previous report (Howitt et al. 1999). Chapter 3 describes the hydrologic and agricultural water demand calibration of the CALVIN model, the calibration process, results, and some implications. Selected policy results are summarized in Chapter 4, both for the five regional models developed and the combined statewide model. Chapter 5 includes an extensive discussion of the limitations of the model. As the first model of its type intended to stimulate continuing use of economic optimization for California water, the model's limitations are important both for practical use of the current model and future development of optimization and simulation models for the state. Chapter 6 presents some water planning and policy implications of current results and methods. Conclusions and recommendations are summarized in Chapter 7.

The appendices of this and the previous report (Howitt et al. 1999) are vital to understanding the development, results, and future potential of the CALVIN model. While the appendices of the previous report, with updated versions available on the internet, focus on the model's development and data details, the appendices of the present report focus on the regional and statewide calibration and results of the model. Thus appendices A through L are updated appendices from Howitt, et al (1999), but are included as appendices to this report. New appendices for this report are distinguished from those of the previous report by the prefix 2. Appendices 2A, 2B, 2C, 2D, and 2E present the calibrated results of five regional CALVIN sub-models. Model calibration and testing was conducted for five sub-areas of the state, with the statewide model merging calibrated data from these five regional models. These five sub-areas are Upper Sacramento Valley, Lower Sacramento Valley and Delta, San Joaquin Valley, Tulare Basin, and Southern California. A copy of a refereed journal paper on the Southern California model and results appears in Appendix 2F, with some additional analysis on the lack of importance of perfect foresight for results in this region. These five regional models are followed by a presentation of CALVIN statewide model results, Appendix 2G.

The calibration process for the regional models is presented in Appendix 2H. Base case details are summarized in Appendix 2I. Appendix 2J presents extension of some model results to develop regional economic impacts, including secondary economic impacts of changes in water deliveries.

Appendix 2K presents results of efforts to reduce the hydrologic foresight inherent in the basic CALVIN model. Part of this includes estimates of the effects of perfect foresight on some model results. Appendix 2L presents some extensions to the SWAP model originally presented in Appendix A of Howitt et al 1999. Appendix 2M is a study of the effects of spatial representation and aggregation on the accuracy of CALVIN results.

CHAPTER 2

CALVIN MODEL OVERVIEW

"Even today few businessmen understand that research, to be productive, has to be the "disorganizer," the creator of a different future and the enemy of today. In most industrial laboratories, "defensive research" aimed at perpetuating today, predominates." Peter F. Drucker (1967), *The Effective Executive*, p. 117

INTRODUCTION

Analysis of California's water problems is currently undertaken with a variety of models, each with a limited extent, often utilizing data from different sources, and developed with sometimes incompatible intents. CALVIN is an economic-engineering optimization model of California's water supply system. The CALVIN model is an attempt to represent the major storage and conveyance facilities of the entire inter-tied California water supply system, its major surface and groundwater supplies, environmental water requirements, and agricultural and urban economic demands for water. As an optimization model, CALVIN suggests how this system might be operated and its water allocated to provide the greatest economic benefit to the state, while meeting physical and environmental requirements. This chapter provides an overview of this modeling effort. For details on data and methods, please refer to the appendices of this report. Additional conceptual background is presented in Howitt et al (1999). Specifics of the model's calibration are presented later in this report and in its appendices. Model results for the statewide and regional models appear later in this report and in its appendices.

This chapter presents model objectives in greater detail, followed by the conceptual approach used, an overview of the approaches used for developing economic objective functions, environmental constraints, hydrologic inputs, and facility capacities. Data management efforts are reviewed, as they are particularly important for such a large-scale analysis. The limitations of this model are summarized, followed by its innovations and a comparison of CALVIN with other models currently used in California.

MODELING OBJECTIVES

No model solves all problems. And most models, like most oracles and many experts, provide only imperfect answers. The CALVIN project is intended to pursue the objectives of:

- Identification of Economically Promising Facility Changes
- Assessment of User Willingness-to-Pay for Water
- Identification of Promising Water Transfers and Exchanges
- Integration of Facility Operations
- Feasibility of Economic-Engineering Optimization of California's Water Supplies
- Data Assessment and Reconciliation
- Demonstration of Advances in Modeling Technique and Documentation
- Identification of Promising Solutions for Refinement and Testing by Simulation Studies

Each of these objectives is described briefly below.

Identification of Economically Promising Facility Changes

One output of an economic optimization model run is the economic value of small changes that could be made in each facility capacity in the system (called the shadow values or Lagrange multipliers of facility constraints). These results allow the relative economic value of changes in all facility capacities in the system to be quickly, if approximately, assessed with a single model run. This allows for the detection of bottlenecks and promising "hot spots" for facility expansion. Conversely, these shadow price results also show the economic costs of small reductions in facility capacity, for cases where reductions in capacity might be under consideration.

Where larger changes in capacity are being considered, including new facilities, separate model runs can be compared to assess their potential economic values to the system. In these new model runs, the optimization model can automatically adjust the operation of the system to try to make the best use of the new or expanded facilities, in terms of economic performance.

Assessment of User Willingness-to-Pay for Water

If water is economically valuable, it is valuable to someone. The results of CALVIN include the economic value or cost of small changes in water delivery to specific agricultural and urban users. This provides a consistent preliminary estimate of each user's willingness-to-pay (WTP) for additional water. These user economic values are provided for each month of the model run, allowing also some idea of the variability of each water user's willingness-to-pay for water.

To assess the financial willingness of users to pay for a particular facility, the WTP during relevant wet or dry time periods can be multiplied by the quantities of additional water delivery each user would receive with a new facility. Where a facility greatly changes water deliveries, comparative model runs are required.

Identification of Promising Water Transfers and Exchanges

Unless otherwise constrained, CALVIN will re-allocate water deliveries to the economically highest and best use. In effect, CALVIN typically runs as an ideal water market. This allows estimation of the changes in flows and economic values that would accompany potential water market opportunities. The maximum extent of water transfers and their frequency can also be estimated. The optimized operations implied by CALVIN results also adjust the operation of facilities to make such transfers possible.

Lesser degrees of water marketing also can be explored using the economic-engineering optimization model. By constraining deliveries to be greater or equal to current allocations, improvements in deliveries can be explored or potential water sales from particular water users. With many simulation models, modeling of water transfers is limited by the rigidity of system operating rules that must be changed to allow temporary or permanent reallocations of water. In the CALVIN model calibration, one run is made which allows no water transfers, requiring that deliveries match estimated year-2020 deliveries under current policies for 1922-1993 hydrology.

Integration of Facility Operations

As an optimization model, CALVIN automatically integrates the facilities represented in the model to best achieve economic objectives. This means that facilities owned and operated by different entities for different purposes are re-operated to achieve economic purposes. In principle, it is as if the users that gain from such improved operations compensated any disadvantaged users or operators for such changes. There are several practical implications of this ability for California:

- Coordinated operation of surface water facilities can be explored
- Conjunctive use of surface and groundwater storage and conveyance facilities can be explored
- Desirable changes in operations to accompany water transfers can be examined
- Desirable changes in operations system-wide can be identified to accompany any major changes in system facilities.

As with water transfers, CALVIN can also be constrained to limit the flexibility of operations to meet various institutional or facility constraints. For example, if one facility operator prefers to maintain current operating policies, operational constraints representing these policies can be imposed on the model. The costs to the system of these constraints can then be evaluated, and the ability of the system to work around these constraints can be assessed. In model calibration, one run is made which constrains the operations of most facilities to current policies.

Feasibility of Economic-Engineering Optimization of California's Water Supplies

Aside from the practical benefits of CALVIN optimization model results, there are several methodological and data-related objectives of this work. The first is to test, and hopefully establish, the feasibility of large-scale economic-engineering modeling for practical regional water management. An economic-engineering optimization model, such as CALVIN, requires integration of a host of aspects of the system including surface hydrology, groundwater hydrology, return flows, water demands, and economic valuation. Many aspects of the system are problematic and controversial in themselves, but optimization of this system requires some specification of all these elements. Beyond specification of each element individually, a greater problem is a coherent joint specification of all such elements on the same water accounting basis. Can such an integration be achieved for a very real and large system? Such an achievement is a tall order, and in a completely pure sense is unlikely to be achieved.

Some have reacted to this project that California water is simply too large, diverse, and complex to represent and optimize. This is a reasonable reaction considering data, computing, and methodological limitations for the state ten or even five years ago. Is this still the case? Our results show that there remain significant limits to performing integrated water modeling for California water supplies. However, a great deal of practical value can be learned from these efforts, despite their limitations. Furthermore, these initial efforts (and those of others) can identify improvements in data collection, processing, storage, and management required to support any analytical effort for improving water management in California, via optimization modeling or otherwise.

This question of whether such analysis is feasible is of more than academic interest. If integrated modeling cannot be done, then there are serious rational limits on our ability to understand and manage California's water, as well as other large environmental, social, and economic systems. Fortunately, we know more about water systems than we do about many of these other systems.

Data Assessment and Reconciliation

As this project began, we were pleasantly surprised by advances in data availability. Recent USBR CVPIA-PEIS, Department of Water Resources, CALFED, and local studies provide a wealth of data on many aspects of the system. The availability of these data and studies allowed (or perhaps seduced) this project to be much more extensive, detailed, and explicit in its representation and optimization of the system than previous work. However, were these data adequate for large-scale integrated modeling, particularly optimization modeling?

Most of the effort of this project went into trying to adapt and reconcile these data for the CALVIN model. While the calibration effort shows that it has not always been possible to perfectly reconcile these data sets, the model inputs and results typically do make reasonable sense. Nevertheless, while much can be learned using the current calibration, significant uncertainties remain and additional effort is needed to reconcile data for different aspects of the system.

Demonstrating Advances in Modeling Technique and Documentation

A major objective of this project is to further advance modeling and documentation techniques for water modeling in California. Large-scale modeling places greater demands on model and data management, documentation, and transparency than most other forms of analysis. Most models ultimately rely on trust. Aside from the fallible authority of the model developer, trust develops as a result of rational examination (which requires transparency) and experience (which requires time). To increase the transparency of the model and the ability to quickly gain experience with it, several techniques were adopted. These techniques are not necessarily new in an academic sense, but they are new to California water management.

Among the innovations for California water modeling is providing meta-data (or documentation of data) within the model input database. This allows rapid examination of data used in the model, better (but, alas, still imperfect) tracking down of errors, and the basis for more automatic and complete documentation for each model run.

Like other recent simulation modeling efforts, the model is essentially run from a database. The model computation software (HEC-PRM) is “data-driven.” Representation of policies, facilities, demands, and hydrology appear in databases, where they can be more easily understood.

Model documentation has also been unusual, particularly for a university modeling effort. This and the previous (Howitt, et al. 1999) report on the CALVIN model, with their numerous appendices, provide conceptual and methodological details of the model and its results. These are of course available on the web (http://cee.engr.ucdavis.edu/faculty/lund/CALVIN/).

Identification of Promising Solutions for Refinement and Testing by Simulation Studies

The ultimate objective of CALVIN is to provide promising solutions to California water supply problems that can be refined and tested with more detailed analysis, usually simulation studies. Using CALVIN as a screening model to identify promising solutions avoids the need to make thousands of simulation models over as wide a range of alternatives as exists for a system as large and complex as California’s. Optimization and simulation models each have their places, and they are quite complementary (Lund and Ferreira 1996).

CONCEPTUAL APPROACH

The general conceptual approach of the CALVIN model is to use optimization methods to suggest water facility operations and allocations that maximize the economic value of agricultural and urban water use in California's main inter-tied water supply system. Agricultural and urban water demands are represented by economic value functions for year-2020 conditions. Operation and allocation decisions are made monthly over the 1922-1993 range of hydrologic events and are limited by environmental flow requirements as well as facility capacities. All sources of water and storage are considered, including surface water, groundwater, and incidental and artificial reuse. The sections below provide some details. Data flows to and from the model are depicted in Figure 2-1 below.

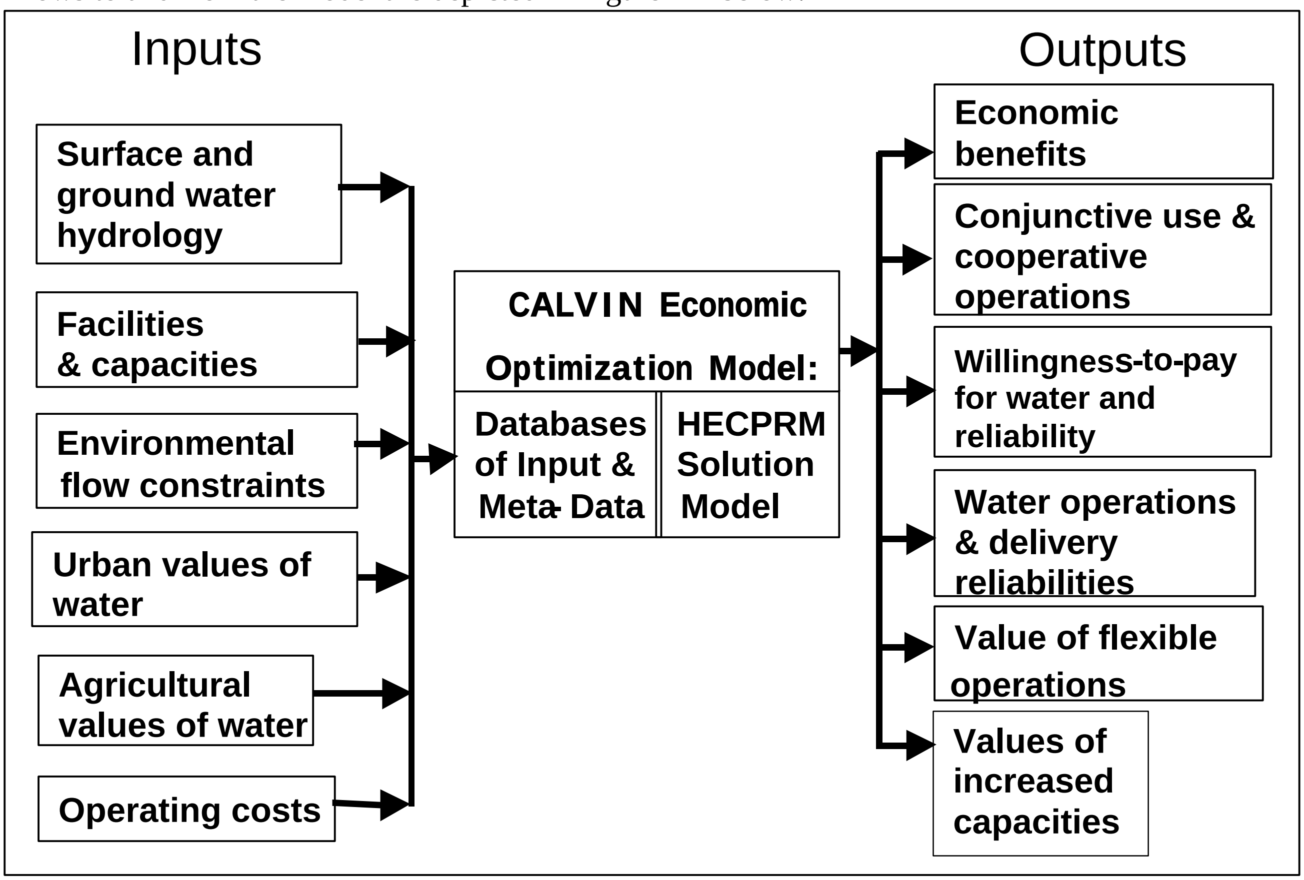


Figure 2-1. Data flow schematic for CALVIN

Network Flow Optimization with Gains/Losses

The fundamental optimization framework for CALVIN is network flow optimization with gains and losses (sometimes called generalized network flow optimization). The general mathematical form appears below (Jensen and Barnes 1980).

Minimize: $$Z = \sum_{i} \sum_{j} c_{ij} X_{ij} \,, \qquad (1)$$

Subject to: $$\sum_{i} X_{ji} = \sum_{i} a_{ij} X_{ij} + b_{j} \text{, for all nodes j,} \qquad (2)$$

$$X_{ij} \leq u_{ij} \qquad \text{for all arcs,} \qquad (3)$$

$$X_{ij} \geq l_{ij} \qquad \text{for all arcs,} \qquad (4)$$

where Z is the total cost of flows throughout the network, X_{ij} is flow leaving node i towards node j, c_{ij} = economic costs (ag. or urban), b_j = external inflows to node j, a_{ij} = gains/losses on flows in arc ij, u_{ij} = upper bound on arc ij, and l_{ij} = lower bound on arc ij.

The objective function, Equation 1, represents the minimum costs of all flows in the network each weighted by a unit cost that can vary between arcs. Equation 2 represents conservation of mass at each node in the network, the sum of all flows from a node must equal the sum of all flows to that node. Flows leaving other nodes for node j are weighted by the loss factor (1=no loss). The numerical solution of these problems is fairly fast and such algorithms are in the public domain (Jensen and Barnes 1980; USACE 1994a).

This simple formulation can be adapted to solve a wide variety of problems. If the arcs are seen as flows not only in space, but also in time, the optimization can occur over an optimization period as well as a spatial network. This allows for surface and groundwater reservoir storage. For CALVIN, the network is the model's spatial schematic in many layers, with one layer for each time-step. Each time layer is connected with arcs for each surface reservoir and aquifer, going forward in time with upper bounds of the reservoir's storage capacity. Storage is just a flow forward in time.

Some other extensions to the simple model can be achieved. Convex piece-wise linear cost functions on single arcs can be represented by using several arcs to represent one physical arc, with each sub-arc having an appropriate upper bound and unit cost. The losses a_{ij} in equation 2 can be used to represent reservoir evaporation, conveyance losses, consumptive use, and reuse, for example.

Software for solving fairly general large-scale water resource problems using this formulation has been developed by the US Army Corps of Engineers Hydrologic Engineering Center in their HEC-PRM software. This code uses a network solver developed by Paul Jensen of the University of Texas. This code has been applied to many water systems in the Western Hemisphere in the last decade and is the numerical core of the CALVIN model.

The use of pure network flow optimization (without gains and losses) has long been used to model water problems and remains quite common (Labadie 1997). The additional ability to use gains and losses allows for a more explicit representation of return flows, system losses, and differences between applied and consumptive water use. While there is little new in this problem formulation, its speed and simplicity allows for the solution of larger and more detailed problems than would otherwise be possible. As discussed in the introduction and Chapter 5, however, there are some aspects of California's water problems that can be only approximated in this formulation.

Statewide Inter-tied System

The model includes agricultural and urban water demands for the most populous and irrigated parts of California, including 92% of the population and 88% of the irrigated acreage, as shown in Figure 2-2. The infrastructure, flows, and demands are represented as a network. The network schematic for CALVIN appears in reduced form in Figure 2-3. (A larger schematic is available from the project's web site http://cee.engr.ucdavis.edu/faculty/lund/CALVIN) The schematic includes the entire Central Valley, including the Trinity River system reservoirs and flows which supply the Central Valley Project, the parts of the San Francisco Bay area which use water which originates in the Central Valley (San Francisco, East Bay, Contra Costa, Napa/Solano, Santa Clara Valley, etc.), Metropolitan Water District of Southern California and other major contractors receiving water from the State Water Project, and agricultural and urban users of California's portion of the Colorado River. The Owens Valley and Mono Basin sources of water and water facilities also are included. Groundwater and surface waters are represented for all these regions.

The network has been cut in several places to avoid modeling the details of secondary or tertiary portions of the overall system. At these locations, demands have been estimated and valued. The Coastal Aqueduct of the SWP is the largest example of such a cut. Here, the CALVIN model represents this part of the system as a time series of demands for SWP water, valued for urban water use. The details of modeling water operations and use in the Santa Barbara and San Luis Obispo regions is thus avoided. Since maximum demand through the Coastal Aqueduct is approximately 50 TAF/yr, the details of local water operations were not seen as having great implications for statewide water operations.

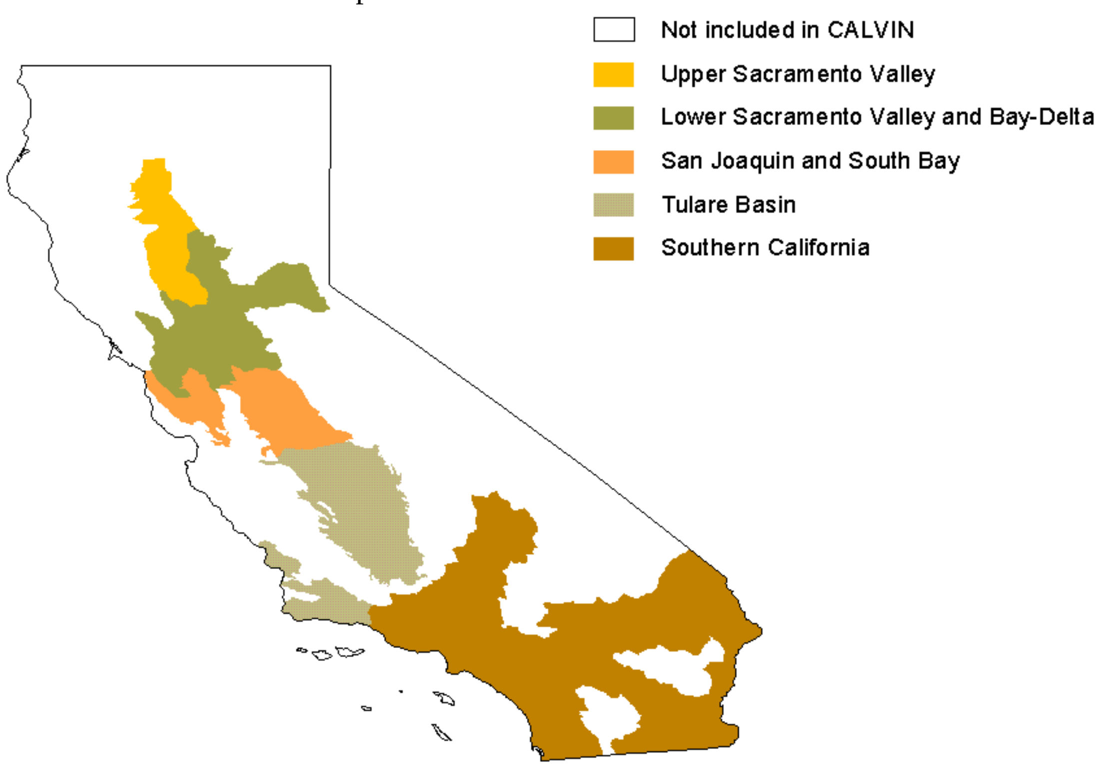
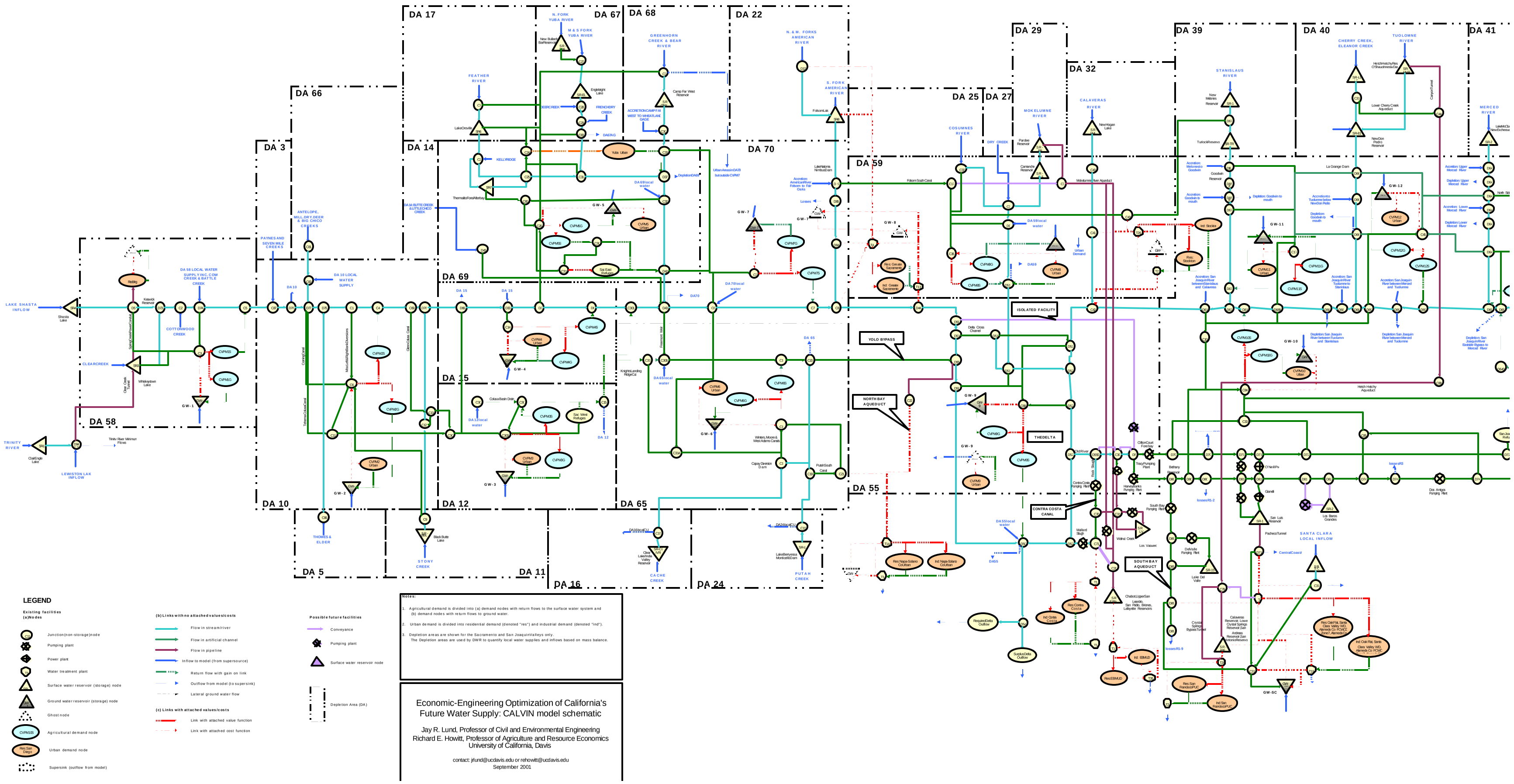


Figure 2-2. Demand Areas Represented in CALVIN Model of California's Water System


Economic-Engineering Optimization of California's Future Water Supply: CALVIN model schematic
Jay R. Lund, Professor of Civil and Environmental Engineering
Richard E. Howitt, Professor of Agriculture and Resource Economics
University of California, Davis
contact: jrlund@ucdavis.edu or rehowitt@ucdavis.edu
September 2001
LEGEND
Existing facilities
(a)Nodes
Junction(non-storage)node
Pumping plant
Power plant
Water treatment plant
Surface water reservoir (storage) node
Ground water reservoir (storage) node
Ghost node
Agricultural demand node
Urban demand node
Supersink (outflow from model)
(b) Links with no attached values/costs
Flow in stream/river
Flow in artificial channel
Flow in pipeline
Inflow to model (from supersource)
Return flow with gain on link
Outflow from model (to supersink)
Lateral ground water flow
(c) Links with attached values/costs
Link with attached value function
Link with attached cost function
Possible future facilities
Conveyance
Pumping plant
Surface water reservoir node
Depletion Area (DA)
Notes:
1. Agricultural demand is divided into (a) demand nodes with return flows to the surface water system and (b) demand nodes with return flows to ground water.
2. Urban demand is divided into residential demand (denoted "res") and industrial demand (denoted "ind").
3. Depletion areas are shown for the Sacramento and San JoaquinValleys only. The Depletion areas are used by DWR to quantify local water supplies and inflows based on mass balance.
DA 17
DA 67
DA 68
DA 22
DA 66
DA 3
DA 14
DA 70
DA 69
DA 15
DA 58
DA 10
DA 12
DA 65
DA 5
DA 11
DA 16
DA 24
DA 29
DA 32
DA 25
DA 27
DA 59
DA 55
DA 39
DA 40
DA 41
LAKE SHASTA INFLOW
TRINITY RIVER
FEATHER RIVER
STONY CREEK
THOMES & ELDER
ISOLATED FACILITY
YOLO BYPASS
NORTH BAY AQUEDUCT
THE DELTA
CONTRA COSTA CANAL
SOUTH BAY AQUEDUCT

California's Water Infrastructure
Network Configuration for CALVIN

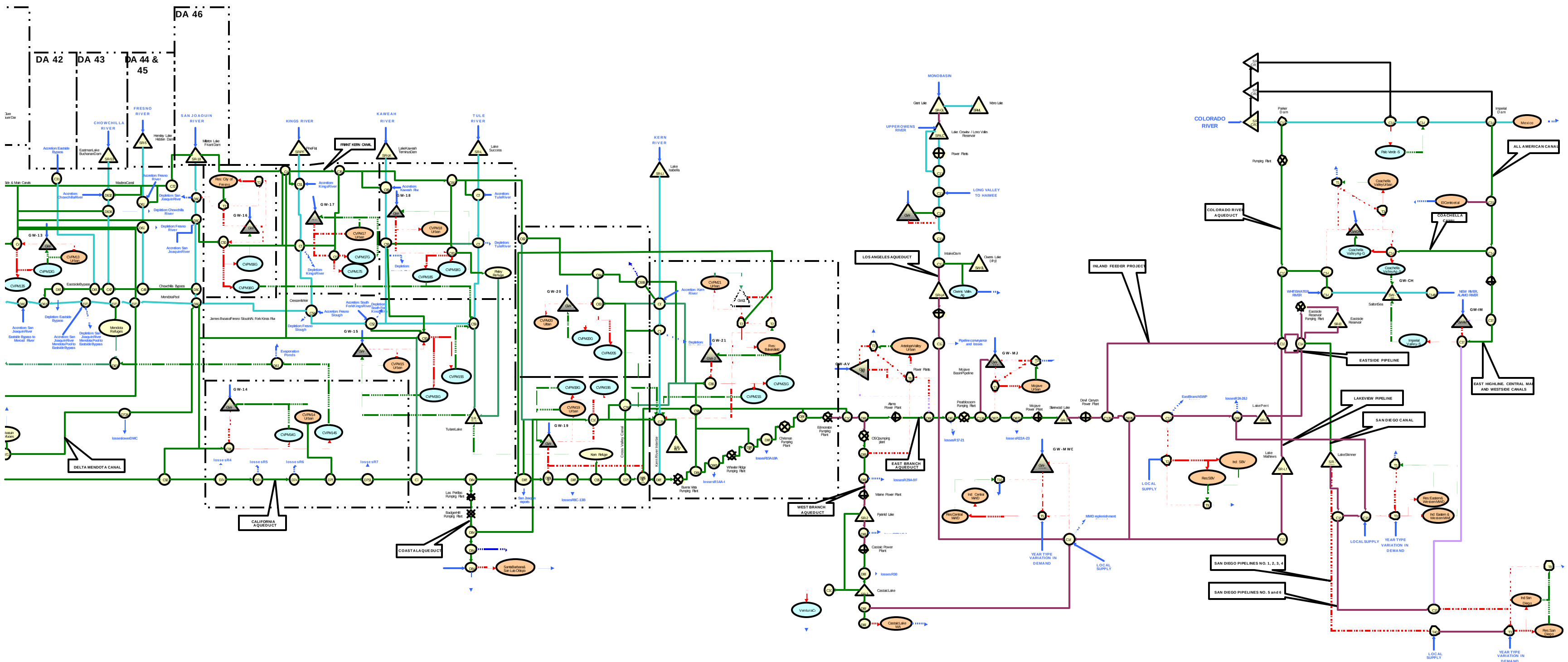
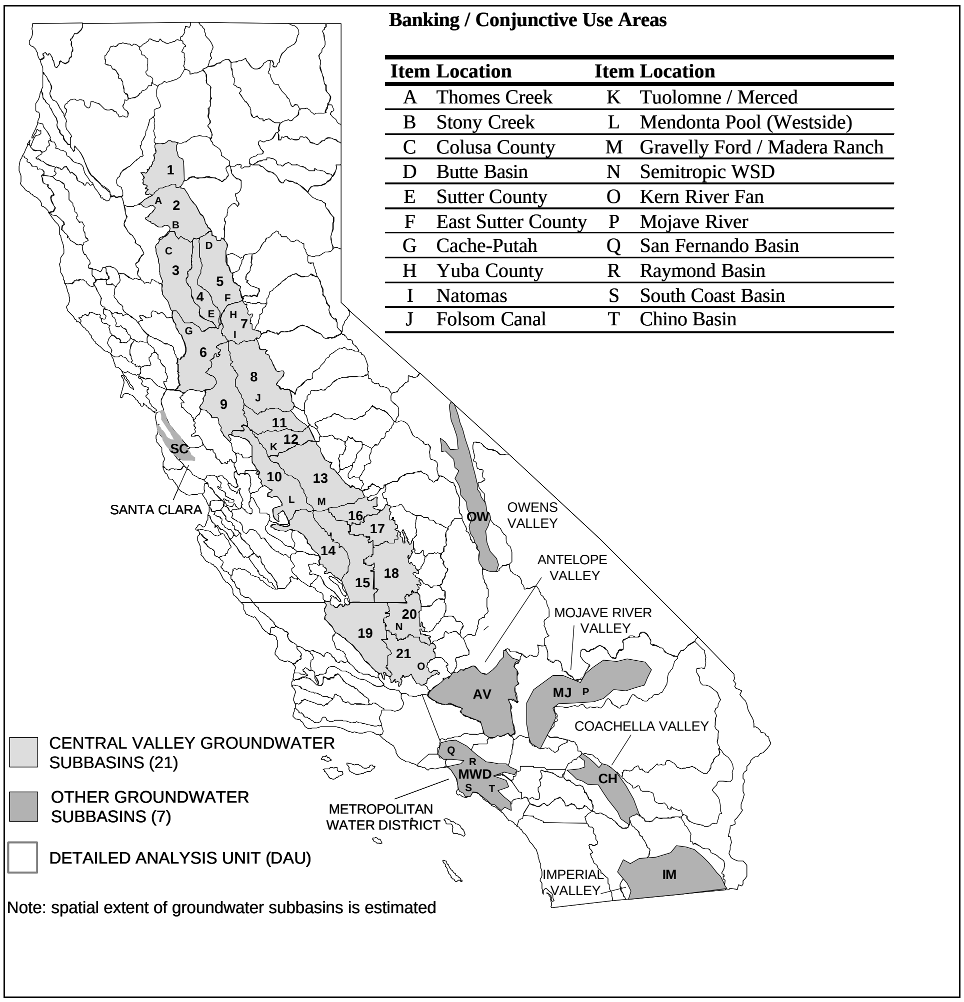


Figure 2-3. Reduced Schematic of CALVIN Model (previous two pages)

CALVIN is the first model to represent explicitly the surface and ground waters of the Central Valley, imports from the Trinity system, and Colorado and Eastern Sierra supplies to major water uses of California. This represents the major inter-tied water system of California, stretching from the Shasta-Trinity system to the Mexican border. The network has over 1,200 spatial elements including 51 surface reservoirs, 28 groundwater basins, 24 agricultural demand regions, 19 urban demand regions, 39 environmental flows, 112 inflows, and numerous conveyance flows (river channels, pipelines, canals, diversions, and recharge and recycling facilities). The groundwater basins represented in CALVIN appear in Figure 2-4. Solution of the statewide network for the historical record involves solving for over a million flow and storage decisions.



Item	Location	Item	Location
A	Thomes Creek	K	Tuolomne / Merced
B	Stony Creek	L	Mendonta Pool (Westside)
C	Colusa County	M	Gravelly Ford / Madera Ranch
D	Butte Basin	N	Semitropic WSD
E	Sutter County	O	Kern River Fan
F	East Sutter County	P	Mojave River
G	Cache-Putah	Q	San Fernando Basin
H	Yuba County	R	Raymond Basin
I	Natomas	S	South Coast Basin
J	Folsom Canal	T	Chino Basin

Figure 2-4. Groundwater Basins Represented in the CALVIN Model

Economic Performance Objective

The objective of the optimization is to maximize the year 2020 economic benefits of water operations and use to agricultural and urban water users throughout the statewide inter-tied system over the range of hydrologic conditions represented by the 1922-1993 historical hydrology. Water is valued according to the standard economic principle of willingness-to-pay, that water is worth what the users are willing to pay for it. The details of these valuation methods are discussed below and detailed in Appendices A, B, and 2L. Costs of pumping and other variable costs of water supply operations also are included in the economic objective of the model.

Environmental Constraints

Environmental objectives are represented by a series of minimum and fixed flow constraints at selected stream and wetland locations. Where possible, these environmental constraints are made to vary according to projected 2020 environmental regulations. Environmental flows are generally taken from the DWRSIM and PROSIM models. These constraints are detailed in Appendix F.

Monthly Model over Historical Hydrology

The hydrologic representation in the model consists of surface water inflows, groundwater inflows, and return flows to surface and groundwater resulting from urban and agricultural water uses. These are taken to represent year 1922-1993 monthly hydrologies under year 2020 development conditions. Major surface flows into the rim of the Central Valley are taken from inputs to DWRSIM and PROSIM. Groundwater hydrology and local accretions in the Central Valley are adapted from the CVGSM model run used for the CVPIA-PEIS no-action alternative (USBR 1997). A total of 4.4 million acre-ft of Colorado River water is assumed to be available each year. Other local inflows and return flows have been compiled from a variety of sources (see Appendices I and J).

Model Transparency

For any model of the scope and complexity of California's water system, model and data documentation is essential. Such transparency is essential from a practical point of view for those working with the model to understand what they are doing and for those inspecting model results to try to understand their limitations and see if they are reasonable. This modeling effort is based on a database of flows and facilities that includes documentation of the data ("metadata") and includes extensive and critical documentation of the methods, data, and sources used in the model and model data. As described in later chapters and appendices, the statewide model also has been calibrated and documented on a regional basis for more effective calibration, but also to make the model and model results more understandable.

ECONOMIC VALUE FUNCTIONS

Economic value and cost functions drive the results of this optimization model. Agricultural and urban economic uses of water are explicitly represented in CALVIN, as are various variable operating costs.

Agricultural Economic Values for Water Use

Agricultural economic values for water use are estimated for the 21 CVPM regions of the Central Valley and 3 regions of southern California. These regions are mapped in Figure 2-4 and with Central Valley CVPM agricultural regions described in Table 2-1 below. Values are estimated for each month of the year, but do not vary from year to year. For each region, an economic loss function is derived which decreases with water delivery to the agricultural region.

This economic loss represents the reduction in farm net revenues that result from limited water deliveries, compared to ideal farm profits if water were not a limiting factor.

The economic value of water for farmers is derived from the Statewide Agricultural Production model (SWAP). SWAP is a separate optimization model that maximizes farm profit, given a quadratic crop production function with water, land, technology, and capital inputs, and constraints on water, land, technology, and capital availability. Year 2020 acreages for agricultural land availability are assumed. The model is similar to the Central Valley Production Model (CVPM) commonly used in California water studies, but provides monthly (as opposed to annual) results and estimates its production function differently. See Appendices A, K, and 2L. An example set of economic value functions appear in Figure 2-5. Marginal values of water range from zero, where water no longer limits farm profits, to over $300 for high valued crops.

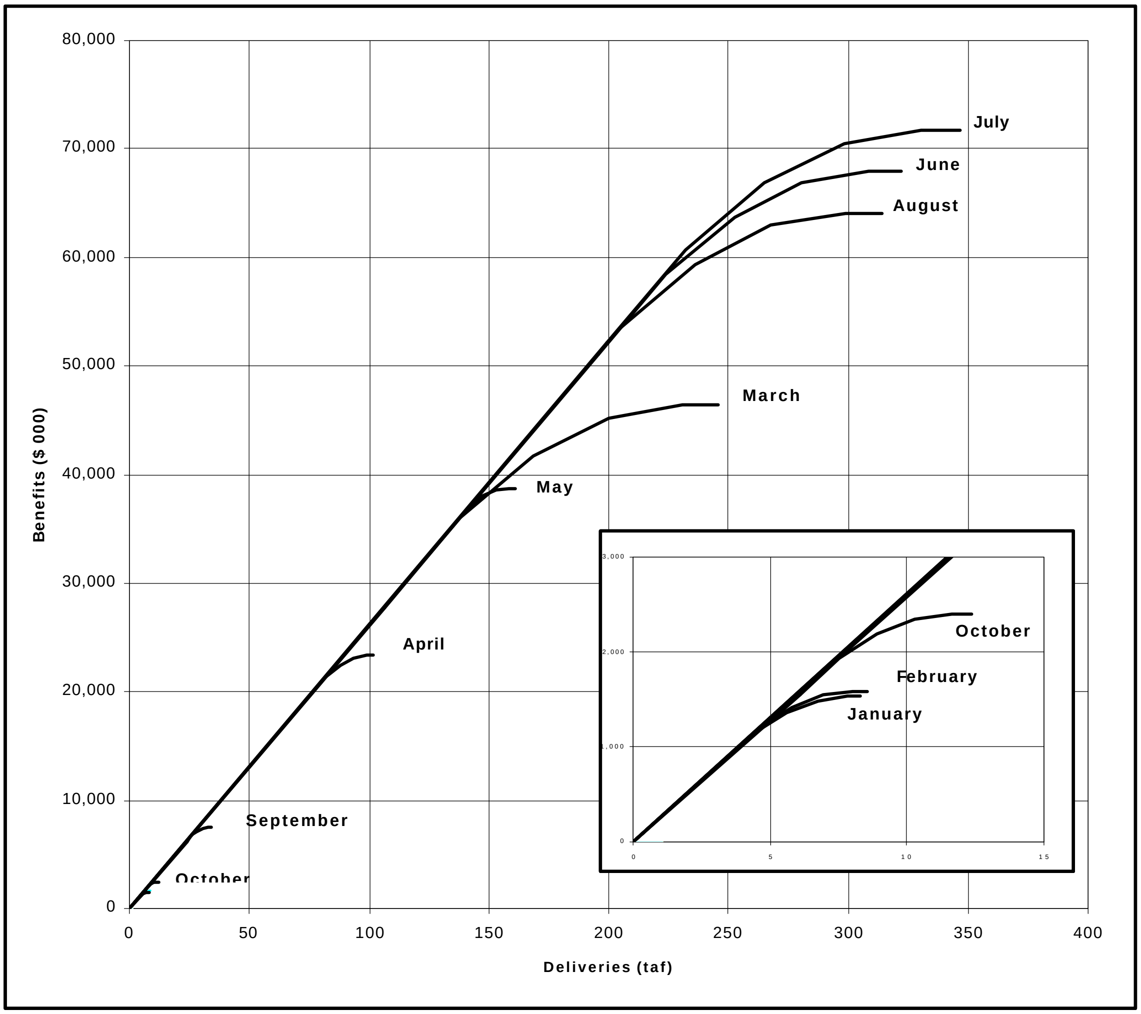


Figure 2-5. Example Economic Value Function

Table 2-1. Descriptions of CVPM Central Valley Agricultural Demand Regions

CVPM Region	Location	DWR Groundwater Sub-basins (Bull. 118-80)
1	Redding Basin	Redding Basin
2	Chico Landing to Red Bluff	North portion of Sacramento Valley
3	Colusa Trough	Midwest portion of Sacramento Valley
4	Chico Landing to Knight's Landing	Central portion of Sacramento Valley
5	Lower Feather R. and Yuba R.	Midwest portion of Sacramento Valley
6	Sacramento Valley Floor, Cache Cr., Putah Cr., and Yolo Bypass	Southwest portion of Sacramento Valley
7	Lower Sacramento R. below Verona	Mideast portion of Sacramento Valley
8	Valley Floor east of Delta	Southeast portion of Sacramento Valley, Sacramento County Basin, and north portion of Eastern San Joaquin County Basin
9	Sacramento-San Joaquin Delta	Tracy Basin and west portion of Sacramento County Basin
10	Valley Floor west of San Joaquin R.	Delta-Mendota Basin
11	Eastern San Joaquin Valley above Toulumne R.	Modesto Basin and south portion of Eastern San Joaquin County Basin
12	Eastern Valley Floor between San Joaquin R. and Tuolumne R.	Turlock Basin
13	Eastern Valley Floor between San Joaquin R. and Merced R.	Merced Basin, Chowchilla Basin, and Madera Basin
14	Westlands	Westside Basin
15	Mid-Valley Area	Tulare Lake Basin and east portion of Kings Basin
16	Fresno Area	Northeast portion of Kings Basin
17	Kings R. Area	Southeast portion of Kings Basin
18	Kaweah R. and Tule R. Area	Kaweah Basin and Tule Basin
19	Western Kern County	West portion of Kern County Basin
20	Eastern Kern County	Northeast portion of Kern County Basin
21	Kern R. Area	South portion of Kern County Basin

Urban Economic Values for Water Use

Economic losses from urban residential water shortages are estimated based on economic demand curves for urban water use (Appendix B; Jenkins and Lund 1999). The shape of the demand curves are assumed to have constant seasonal elasticity, which varies between summer, winter, and intermediate months. Demand curves are based on 1995 estimates of elasticity (Renwick et al. 1998) and are scaled for each of the 19 urban regions by the 2020 forecast populations. Industrial water shortage costs are taken from a 1991 CUWA study and scaled for each urban region where there is data. Commercial and institutional water demands are taken from 2020 estimates and are assumed to be fixed, mostly because no information on the costs of commercial shortages could be found in the literature. An example set of urban loss functions appear in Figure 2-6. More details on urban shortage cost method and data can be found in Appendix B. These cost functions vary by month, but not between years, except for the MWDSC region, where estimates were available for the inter-annual variability of urban demands.

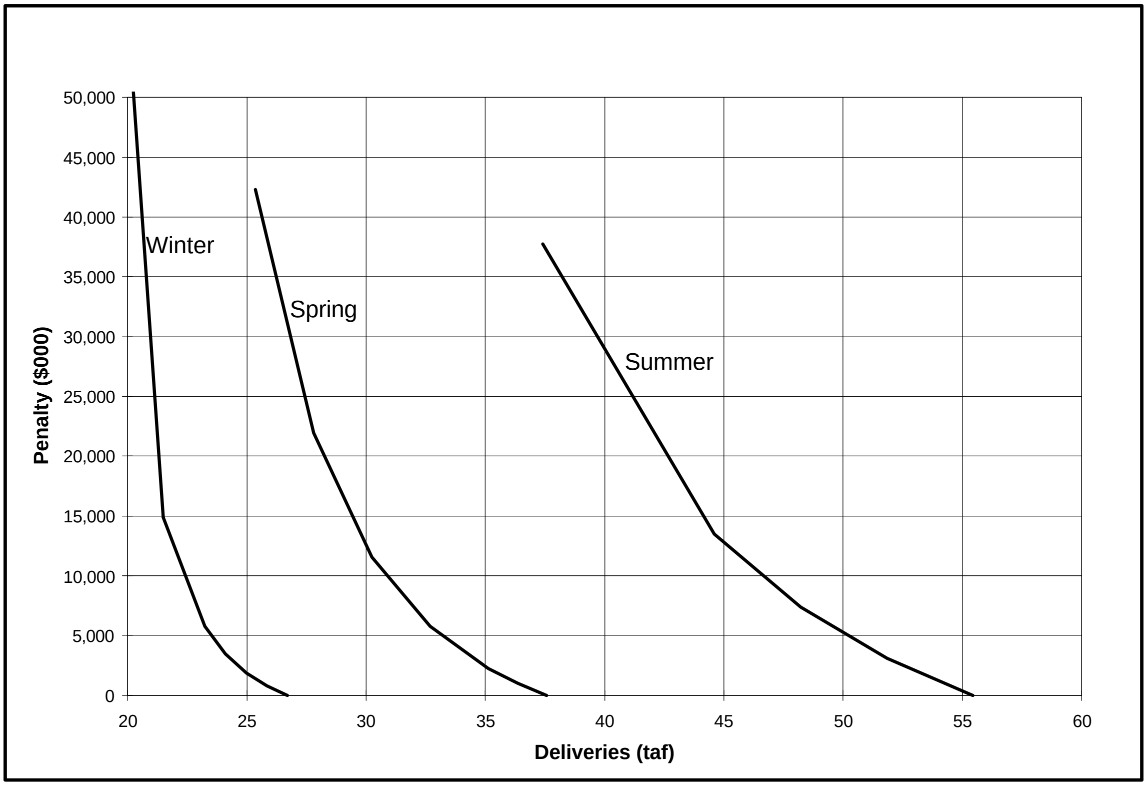


Figure 2-6. Example Monthly Urban Residential Loss Functions

Operating Costs

Variable operating costs and benefits are also included in CALVIN's objective function. These are detailed in Appendix G. Pumping costs include both energy costs and additional "wear and tear" variable maintenance costs. Energy costs in this version of the model assume fixed heads. Hydropower benefits occur at major fixed-head hydropower locations, but are otherwise excluded at this time. Costs of recharge facilities also are estimated as variable costs, since they typically involve taking land from agricultural production for their development. Variable urban water treatment (which vary with source quality), local distribution, recharge, and wastewater recycling costs are included, as are water quality costs for salinity reflecting consumer costs.

In some cases, tiny penalties are used to "persuade" the system to operate more as water managers would, when there is no economic (urban or agricultural water supply) reason to behave otherwise. For example, most reservoirs have a very small penalty (about $0.02/acre-ft) to keep water stored in reservoirs. Similarly, a small value is given to "persuade" the model to increase Delta outflows when there is no other economic use for that water. These "persuasion" penalties are a common technique to help the model better represent real operations without affecting economic operations.

ENVIRONMENTAL REPRESENTATION

Economic valuation of environmental flows remains controversial (Shabman and Staphenson 2000). Therefore, environmental objectives are represented as minimum instream flows at various locations in the Trinity, Sacramento, San Joaquin, Delta, and Mono and Owens regions. Some additional flows for wetlands are represented as fixed constrained deliveries. Table 2-2 lists most of the environmental objectives represented in the model as constraints. Minimum instream flows occur on 32 stream reaches (on 14 different rivers and streams). Required environmental deliveries occur at Owens Lake, five wetland locations, and as Delta outflow. The details of these environmental constraints appear in Appendix F.

Table 2-2a. Major Environmental Flow Constraint Locations - CALVIN River Reaches

River	CALVIN Links	Location	Flow Values (cfs)		
			min	max	avg
American	D64_C8	From urban diversions to mouth	188	500	315
American	D9 to D64	Below Nimbus Dam to urban diversions	250	3000	1624
Calaveras	SR-NHL to C41	Release from New Hogan Dam down to mouth	2	2	2
Clear Creek	SR-3_D73	Below Whiskeytown Lake	50	100	58
Delta Outflow	Required Delta Outflow_Sink	Delta outflow into S.F. Bay	3000	28468	7771
Feather	C25 to C32	Below Thermolito outflow to confluence with Bear River	1000	1700	1294
Feather	C32 to D43	From Bear River confluence to mouth	1000	1700	1294
Merced	D645_D646	Above confluence with San Joaquin R.	16	228	109
Merced	D649_D695	Above confluence with San Joaquin R.	16	228	109
Mokelumne	SR-CR to D98	Releases from Camanche Reservoir to CVPM 8 diversions	0	467	121
Mokelumne	D98 to D515	From CVPM 8 diversions to confluence with Delta	0	467	121
Mono basin	SR-GL_ SR-ML	Aggregate of Rush, Parker, Walker, and Lee Vining Creeks	72	137	102
Owens Lake	C120_SR-OL	Owens Lake Dust Mitigation requirements	15	146	55
Sacramento	D5_D73	Below Keswick Reservoir	3250	6000	3464
Sacramento	D76a to C69	Below Red Bluff	3250	3900	3298
Sacramento	D61_C301	Navigation control point	4000	5000	4306
Sacramento	D503_D511	At Hood	4999	5000	5000
Sacramento	D507_D509	Rio Vista requirements	0	4500	1327
San Joaquin	D676_D616	Below confluence with Stanislaus at Vernalis	0	6201	1434
Stanislaus	D653a_D653b	Below Goodwin	65	2921	270
Trinity	D94&D40_SinkD94	Trinity Below Lewiston Dam	300	1591	468
Tuolumne	D662_D663	Above confluence with San Joaquin R.	10	387	164
Yuba	C83_C31	Above confluence with American River	72	409	235

Table 2-2b. CALVIN Deliveries to Fish and Wildlife Refuges

Aggregate Refuge	Refuges Included	Deliveries (taf/month)		
		Min	Max	Avg
Kern	Kern NWR	0.7	5.6	3.0
Pixley	Pixley NWR	0	0	0
Sac West Refuges[a]	Sacramento, Delevan, and Colusa NWR	0.6	17.5	6.9
Sac East Refuges[a]	Sutter and Gray Lodge NWR	1.0	11.6	4.6
San Joaquin[b]	Volta WMA, Freitas SJBAP, Salt Slough SJBAP, China Island SJBAP	0.7	7.2	3.0
Mendota Pool[b]	Grassland WD, Los Banos WMA, Kesterson NWR, San Luis SWR, Mendota WMA, Merced NWR, West Gallo SJBAP	2.9	63.9	20.1

Notes:
[a] Sacramento West and East Refuge deliveries are reported as volumes of water delivered into the refuge. Conveyance losses have already been accounted for.
[b] DWRSIM aggregates these values but does not explain which refuges are included.
SJBAP = San Joaquin Basin Action Plan; NWR = National Wildlife Refuge; SWR = State Wildlife Refuge
WMA = Wildlife Management Area

FACILITY CAPACITIES

CALVIN includes representations of most of California's major water management facilities. These facilities are represented in terms of their storage and flow capacities. In the case of major reservoirs, their storage capacities vary seasonally to reflect flood control storage limits in the winter and spring. Facilities are also subject to losses of water, evaporation from reservoirs and seepage and evaporation from canals. Reservoir evaporation is represented as a simple linear function of storage, a somewhat simpler representation than DWRSIM or the other major simulation models. Flow losses in canals are represented as a simple proportion of flows in most cases. Most capacities and losses are taken from their DWRSIM or PROSIM representations or from local project-specific documents. Details are given in Appendix H.

The facilities included are those existing or presumed to exist in the year 2020. Reservoirs larger than 50,000 acre-ft generally are included in the model. In some cases, smaller proximate facilities are aggregated to form a single larger facility. However, many high Sierra reservoirs are excluded owing to lack of data availability and their nearly exclusive use for hydropower. Minimum storage levels are taken from reservoir operation guidelines and maximum water storage levels are varied seasonally with current flood control operation guidelines.

Representation of conveyance and pumping facilities is more extensive. In addition to the major conveyance facilities, pumping capacities for groundwater were estimated from groundwater use estimates throughout the Central Valley and elsewhere. Since each of the CVPM regions is an aggregation of irrigation districts and farms, there are internal conveyance limits within these CVPM regions. This necessitated the imposition of turn-out capacity constraints on each flow entering each agricultural region. These limits were generally set as the maximum monthly delivery seen in the results of other simulation models for this location over the 1922-1993 hydrologic period.

Studies were undertaken to assess the error likely to result from aggregation of capacity and demand elements of the system (Van Lienden 2000). These studies indicated that relatively little error would result from some minor aggregation of elements in the current schematic, but large-scale aggregation would greatly overestimate system performance, especially in terms of scarcity estimates. This study is included as Appendix 2M.

HISTORICAL HYDROLOGY

California has a very complex hydrology, with both surface and groundwater being important, the considerable role of snowpack and snowmelt, large but variable evaporation and evapotranspiration rates, and considerable local and temporal variability. The historical hydrology of 1922-1993, modified for 2020 land development, has been assumed as the basis for CALVIN's surface and groundwater inflows.

Surface Water

Where possible, surface inflows have been taken from those of other common simulation models of the system. This is particularly true for the rim flows into the major reservoirs around the rim of the Central Valley. These have come largely from DWRSIM, PROSIM, and SANJASM. Local inflows, for which there is much less agreement between models and modeling approaches, are much more affected by groundwater use and local water deliveries. In many cases, local or valley floor inflows have been recalculated in an attempt to reconcile surface, groundwater, and water use activities and data. Colorado River water supplies have been limited to California's 4.4 million acre-ft. annual share of that river. Other southern California supplies have been taken from local sources. Surface hydrology assumptions and methods are detailed in Appendix I and the model database.

Groundwater

Groundwater inflows, storage capacities, and initial conditions for the Central Valley have been taken from the No Action Alternative run of CVGSM for the CVPIA-PEIS. One groundwater basin is assumed for each CVPM region. Interflows between these CVPM regions are assumed to be those from this CVGSM model run and are fixed in the CALVIN model. Thus, while groundwater storage is dynamic in the CALVIN model, groundwater flow is not, since dynamic groundwater flow is incompatible with the required network flow formulation. Groundwater flows, storage capacities, and initial conditions elsewhere in the model are taken from local studies. These are detailed in Appendix J.

Return Flows

A major aspect of California's hydrology is return flows from agricultural and urban activities. For agriculture, these return flows are extensively addressed in Appendix K. For each agricultural region, return flows to groundwater and surface waters are estimated separately. The calibration of these return flows is presented in Appendix 2H.

SOFTWARE, META-DATA, AND DATABASES

CALVIN is a large-scale model that integrates many diverse aspects of California's water supply system. To be practical, and indeed to survive years of model development, the model required the development and use of model, database, and documentation software as described below.

Solution Software

A typical HEC-PRM application is run using a HEC-DSS data file for hydrologic inflow time-series and paired-data including economic penalty functions. The network configuration and capacities, fixed costs, and most other parameters in the model are represented in an ASCII text file (.PRI file). For most applications, this text file could be several to a dozen pages long. For the California system, this text input file is hundreds of pages long, with a vast potential for typographical errors and confusion on data entry and configuration.

For CALVIN, custom software was developed using Visual BASIC® to write the appropriate text input file for HEC-PRM from a database of the CALVIN schematic. This saving of network parameters in a relational database allowed for more systematic modifications and the documentation of these parameters within a single database. This also reduces confusion in the development and testing of the model and provides an efficient means of detailed model assumptions and their documentation. Without this type of software, such an extensive network would be very difficult to implement and modify for practical model runs.

Databases and Meta-Data

Model data and meta-data are stored in three types of databases. A relational database, currently in MS-ACCESS, is used to store basic information on all network elements (links and nodes). These data include the connectivity of elements, capacities, costs, and gains/losses. For each piece of data related to each spatial element, there are meta-data fields for the source, source contact information, citation of data-related documents, commentary on the data, an indicator of the perceived reliability of the data, and the project staff who entered and subsequently modified the data. Thus, most fields in the database deal with documentation of the model's data (meta-data). All time-series data and final penalty data are stored in HEC-DSS, as required by HEC-PRM. These are referenced and documented in the database, but are much more efficiently stored and accessed in HEC-DSS form. The model schematic is stored in an Excel spreadsheet. This model schematic and MS-ACCESS database have been designed to interact eventually. A graphical user interface provides access to the model databases and protects data integrity when making changes to the inputs.

Model Runs

For such a large-scale model, each model run has the potential to overwhelm the model users with information. Indeed the time required to comprehend the results of such a model run are much longer than model run times. Run times for CALVIN can vary between hours and days, while analysis can require several days to several weeks. Post-processors using MS-EXCEL have been developed to standardize much data analysis and presentation. The data processing plan for CALVIN includes further development of these data post-processors. The automated maintenance and detailed documentation of model runs for various alternatives is also anticipated in future work.

GUIDE TO MODEL DETAILS AND LIMITATIONS

The details of the CALVIN model are mostly described in the methodological appendices to Howitt, et al. (1999), which have been updated and included in this report. Additional discussion of hydrology, calibration, and base case details are included in new appendices to this report. Table 2-3 below lists the appendices to this report.

Table 2-3. Technical Appendices

Updated Appendices	**New Appendices**
A. Statewide Water and Agricultural Production Model	2A. Upper Sacramento Valley CALVIN Model Results
B. Urban Value Function Documentation	2B. Lower Sacramento Valley and Delta CALVIN Model Results
C. HEC-PRM Application Documentation	2C. San Joaquin Valley CALVIN Model Results
D. CALVIN Data Management	2D. Tulare Basin CALVIN Model Results
E. Post-Processor Object-Oriented Design	2E. Southern California CALVIN Model Results
F. Environmental Constraints	2F. Southern California Journal Paper
G. CALVIN Operating Costs	2G. Statewide CALVIN Model Results
H. Surface Water Facilities	2H. Calibration Process Details
I. Surface Water Hydrology	2I. Base Case Details
J. Groundwater Hydrology	2J. Regional Economic Impact Estimation
K. Irrigation Water Requirements	2K. Perfect Foresight
L. Glossary	2L. SWAP Revisions
	2M. Spatial Complexity and Reservoir Optimization Results

The calibration of the CALVIN model is a major contribution of this report, along with documentation of other areas of progress on the model. The model calibration process is done to assure that the model's demands and hydrology correspond to those commonly represented in other major models and technical studies of California's water supply system. The next chapter presents a summary of the model calibration exercise and its results. More details and detailed results appear in appendices to this report.

The limitations of particular aspects of the CALVIN model also are documented in these appendices. The most important of these limitations are reported in Chapter 5 of this report. While CALVIN is able to provide some results that are unavailable from other analytical tools and probably provides better results than many models, it must be realized that CALVIN is the first attempt to provide a nearly statewide model of California water supply and thus suffers some gaps and shortcomings.

COMPARISON WITH OTHER AVAILABLE MODELS

There are currently four major simulation models of California water supply operations. Each of these has different origins, somewhat different coverage, and a somewhat different approach.

First developed in the 1970s, DWRSIM is the simulation model most commonly used for California water management studies. It simulates the operation of most of the major reservoirs of the Sacramento and San Joaquin valleys as well as the State Water Project's California Aqueduct deliveries and operations to southern California. It is the closest to a widely used statewide simulation model, but does not include explicit representation of the Tulare Basin or non-SWP deliveries to southern California. As a simulation model, it is driven by hard-coded operating and allocation rules. The Department of Water Resources recently replaced DWRSIM with CALSIM, a more data-driven simulation model with an optimization engine.

PROSIM is the US Bureau of Reclamation's simulation model for the Central Valley Project, particularly the Sacramento Valley, Delta, and San Joaquin Valley deliveries of Delta water. SANJASM is a companion model of the San Joaquin River system and its tributaries. These models have been used extensively for federal studies. They use technology similar to that of DWRSIM.

CALSIM is a modern replacement for DWRSIM, PROSIM, and SANJASM. The software and approach of CALSIM are data-driven, resulting in a much more flexible modeling form and structure. The basic approach of CALSIM is to sequentially solve an optimization model for each monthly time-step that minimizes the sum of penalties associated with missing target deliveries and reservoir capacities. The end-of-period storages from each optimization are used as the initial conditions for the next monthly optimization. Integer linear programming optimization is used. Between months, non-linear simulation-style adjustments can be made to reflect more complex environmental regulations, groundwater dynamics, etc. The hydrologic inputs for CALSIM are being improved and extended. The CALSIM model shows great potential to allow more flexible and rapid simulation modeling of California water problems. As such, it is likely to be the major test bed for operational suggestions provided by optimization models such as CALVIN.

CVGSM is a simulation model of Central Valley groundwater supported by the US Bureau of Reclamation. The model was extensively used for the recent CVPIA-PEIS studies and provides the basis for CALVIN's representation of Central Valley groundwater and local urban and agricultural water deliveries for the Central Valley.

Table 2-4 provides a summary description and comparison of these different models of major parts of California's water system. While each of these models are intended for somewhat different purposes, they do have other fundamental differences.

The HEC-PRM network flow solution software and the general approach of the CALVIN model have been applied to numerous other locations over the past decade. These are listed in Table 2-5 below. While CALVIN is the largest such application, other applications include some of the largest water resource systems in the nation.

Table 2-4. Comparison of Selected California System Models

	DWRSIM/ CALSIM	PROSIM/ SANJASM	CVGSM	CALVIN
Operation				
Rule-based	✓	✓	✓	
Economically based				✓
Legal/contractual	✓	✓	✓	sometimes
Projects/regions represented				
CVP	✓	✓	✓	✓
SWP	✓	✓	✓	✓
Tulare Basin				✓
S. California				✓
Outputs				
Time-series of deliveries	✓	✓	✓	✓
Quantified benefits				✓
"Best" operation	CALSIM?			✓
Data-driven	CALSIM			✓

Table 2-5. Previous Optimization Studies Using HEC-PRM

Year(s)	Basin (No of Reservoirs)	Study Purpose(s)	Citation(s)
1990-1994	Missouri River (6)	Economic-based Reservoir System Operating Rules	USACE 1991a, 1991c, 1992a, 1992b, 1994b; Lund and Ferreira 1996
1991-1996	Columbia River System (14)	Economic-based Reservoir Operating Rules, Capacity, Expansion, & Multi-Purpose Operations Seasonal Operations	USACE, 1991b, 1993, 1995, 1996
1997	Carson-Truckee System (5)	Prioritization of Uses & Performance Assessment	Israel 1996; Israel and Lund 1999
1997	Alamo Reservoir (1)	Multi-objective reservoir operation	Kirby 1994; USACE 1998b,c
1998	South Florida System (5)	Capacity Expansion & Multi-objective performance	USACE 1998a
1999	Panama Canal System (5)	Drought Performance & Economic Reservoir Operations	USACE 1999
1999 - present	Models of 5 California Regions	Calibration of Statewide Model and study of regional market potentials	Appendices A, B, C, D, and E to this report, Newlin et al in press
1999 - present	California Inter-tied System (79)	Economic Capacity Expansion, Water Markets, & Financing	Howitt, et al. 1999 Present report

INNOVATIONS

The major innovations of the CALVIN model over previous large-scale simulation models of California are:

1) Use of performance-based optimization to examine the potential for more flexible operations and allocations, explicitly pursue economic objectives, and provide rapid preliminary identification of promising alternatives.
2) Statewide model including all major parts of California's inter-tied system from Shasta-Trinity to Mexico, allowing for explicit statewide examination of water supply issues.
3) Groundwater is explicitly included and operated in all regions represented by the model, allowing more explicit examination of conjunctive use alternatives.
4) 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.
5) Data and model management have been fundamental to model development with all major components in the public domain and extensive documentation of assumptions.
6) Economic values of agricultural and urban water use are estimated consistently for the entire inter-tied system.
7) New management options for water marketing, cooperative operations, conjunctive use, and capacity expansion are suggested by the model.
8) Systematic analytical overview of statewide water quantity and economic data was undertaken to support the model.

DESCRIPTION OF THE FIVE REGIONS WITHIN THE STATEWIDE MODEL

The CALVIN model is divided into five regional sub-models for model calibration (described in Chapter 3), formulating the first sets of alternatives examined which look at regionally-restricted water markets, and presenting regional and statewide model results (Chapter 4). This section provides summary descriptions of these five hydrologic regions. These regions appear in Figure 2-2 and are described in more detail in Appendices 2A-2F.

Region 1. The Upper Sacramento Valley

The Upper Sacramento Valley is the northern-most region. Inflows to Lake Shasta and Clair Engle Lake form the northern boundary. It covers Department of Water Resources depletion areas DA58, DA10, DA12 and DA15, corresponding to Central Valley Production Model (CVPM) agricultural regions 1 through 4. Outflows from the Colusa Basin Drain at Knight's Landing and the Sacramento River near Ord Ferry form the southern boundary of Region 1.

The Sacramento River is the main river in the region, fed by releases from Lake Shasta and diversions from Clair Engle Lake via the Clear Creek Tunnel and Whiskeytown Lake. The region also includes the Trinity River, as well as 14 major tributaries to the Sacramento River. Regional water demands are primarily agricultural, but there are small fixed urban demands. The largest urban water demands occur at Redding. Region 1 includes the Sacramento, Delevan and Colusa National Wildlife Refuges (NWR). There are also environmental minimum instream flow requirements along the Sacramento and Trinity Rivers, and on Clear Creek.

Region 2. The Lower Sacramento Valley and Bay-Delta

The Lower Sacramento Valley and Bay-Delta region covers DWR depletion areas 16, 17, 22, 24, 29, 32, 59, 55, 65, 67, 68, 69, and 70, which correspond to Central Valley Production Model (CVPM) agricultural regions 5 through 9. In addition to small fixed urban demands, economically modeled urban areas include Yuba, Greater Sacramento, Stockton, Napa-Solano County, Contra Costa, and East Bay Municipal Utilities District (EBMUD).

Flows in the Sacramento River before the confluence with the Feather River and flows from Colusa Basin Drain via Knight's Landing Ridge Cut (KLRC) form the northern boundary. The southern boundary just includes the Calaveras River across the San Joaquin River at Vernalis to the Tracy and Harvey Banks Pumping Plants. Excess flows in the Lower Sacramento Valley and Bay-Delta travel out the Delta as unconstrained surplus outflow.

The Sacramento River is the region's main river. Several other significant rivers enter the region, such as the Feather, Yuba, American, and Mokelumne Rivers. The region contains thirteen reservoirs, including Lake Folsom on the American River and Lake Oroville on the Feather River. Major infrastructure includes the North Bay and Mokelumne River Aqueducts, along with the Yolo Bypass and Delta pumping plants (Tracy and Harvey Banks).

Regional water demands are both agricultural and urban, with significant environmental requirements for the Sacramento-San Joaquin Delta, the Sutter National Wildlife Refuge and the Gray Lodge Wildlife Area. There are also minimum instream flow requirements along the Feather, American, Mokelumne, Calaveras, Yuba and Sacramento Rivers.

Region 3. The San Joaquin and South Bay Area

The San Joaquin and South Bay Area covers DWR detailed analysis units 205 through 216, corresponding to CVPM agricultural areas 10 through 13. Urban demand areas include those served by the San Francisco Public Utilities Commission (City and County of San Francisco and most of San Mateo County) and Santa Clara Valley (Santa Clara Valley Water District, Alameda County Water District, and Alameda County Zone 7).

The Stanislaus River from the east to the South Bay Aqueduct toward the west are just inside the northern boundary, while the Upper San Joaquin River defines the southern boundary of the region. The dominant hydrologic feature of the region is the San Joaquin River and its tributaries: the Fresno, Chowchilla, Merced, Tuolumne, and Stanislaus Rivers. There are fourteen surface water reservoirs, including New Melones Reservoir on the Stanislaus River and San Luis Reservoir. Major conveyance infrastructure includes the Delta Mendota Canal (DMC) and Mendota Pool, the California Aqueduct, and the Hetch-Hetchy Aqueduct.

Regional water demands include agricultural and urban areas, as well as environmental requirements for the Volta Refuges (Volta Wildlife Management Area (WMA), Freitas San Joaquin Basin Action Plan (SJBAP), Salt Slough SJBAP, and China Island (SJBAP) and the San Joaquin/Mendota Refuges (Grassland WA, Los Banos WMA, Kesterson NWR, San Luis State Wildlife Refuge (SWR), Mendota WMA, Merced NWR and West Gallo SJBAP). Minimum instream flow requirements exist on the Stanislaus, Tuolumne, Merced and San Joaquin Rivers.

Region 4. Tulare Basin Region

The Tulare Basin Region covers DWR detailed analysis units (DAUs) 233-244, 246, and 254-261, which correspond to CVPM agricultural areas 14 through 21. Economically represented urban areas include Fresno, Bakersfield, Santa Barbara, and San Luis Obispo. This region is an internally draining basin that stretches from the San Joaquin watershed south to the Tehachapi Mountains. It is enclosed by the Coastal Mountain range and the Sierra Nevada range.

The major rivers in this region are the Kings, Kaweah, Tule, and Kern Rivers, with the Kings and the Kern being the two most dominant hydrologic features. Pine Flat on the Kings River is the largest of the four surface water reservoirs in the region. Major infrastructure includes the Friant-Kern Canal, the joint SWP-CVP San Luis Canal, and the California Aqueduct. Regional water demands are both agricultural and urban, though primarily agricultural. Environmental requirements in the region include the Kern NWR and the Pixley NWR. There are no minimum instream flows in the Tulare Basin.

Region 5. Southern California

Southern California is the southern-most region. It is bounded in the north by the Tehachapi Mountains and by the United States-Mexico border in the south. Major economically represented urban areas include Antelope Valley, Castaic Valley, Metropolitan Water District (Central, Western and Eastern), Mojave, Coachella Valley, San Diego County Water Authority, and San Bernardino Valley.

The major river is the Lower Colorado River. There are eleven surface water reservoirs in the region. The major water demands are both urban and agricultural. Major infrastructure includes the Colorado River Aqueduct, All American Canal, Los Angeles Aqueduct, Coachella Artificial groundwater recharge facility, and the proposed Tijuana Canal. Environmental demands include the Mono Lake minimum inflows and the Lake Owens Dust Mitigation requirements.

Description of the Statewide Model

The statewide model represents the entire inter-tied California water system. It is composed of the five regional models presented previously. Required regional boundary flows between regions have been removed allowing for complete optimization of the state's water supply, while continuing to enforce environmental flow requirements, physical capacity constraints, flood operations, and ending groundwater storages.

CONCLUSIONS

CALVIN is an economic-engineering optimization model of California's inter-tied water supply system. The model is intended to provide preliminary planning information currently unavailable or very difficult to obtain. CALVIN's representation of the system is an assemblage of data from other more geographically and thematically restricted studies of water demands, hydrology, and operations conducted over several decades by many different agencies. While attempts have been made in the development of CALVIN to do quality control and reconciliation of these data, gaps and disagreements among sources do exist. In all these cases, documentation of the data (good, bad, and ugly) has been attempted. An extensive calibration and data reconciliation exercise is presented next.

CHAPTER 3

HYDROLOGIC AND AGRICULTURAL DEMAND CALIBRATION

"A Pigeon, oppressed by excessive thirst, saw a goblet of water painted on a signboard. Not supposing it to be only a picture, she flew towards it with a loud whir, and unwittingly dashed against the signboard and jarred herself terribly. Having broken her wings by the blow, she fell to the ground, and was caught by one of the bystanders. Zeal should not outrun discretion." *Aesop Fable*

INTRODUCTION

Large integrated water resource system models such as CALVIN entail enormous data requirements. Data from earlier project studies and diverse state, regional, and local sources have been assembled into the necessary hydrologic, water demand, and other parameter inputs for the CALVIN model. These collections of data, arising from various studies conducted at different times, by different agencies, and for different purposes, were generally not developed jointly or intended to be integrated. It is inevitable that they contain conflicting assumptions (despite efforts to correct for these) and methodological disparities. As collected, they are far from producing a consistent data set for the entire state that integrates surface and ground waters, supplies of water with demands, institutions of local and regional scales, and individual water use decisions with regional water management operations. Hydrologic and agricultural demand calibration becomes a necessary step to reconcile and integrate these data into a coherent model with meaningful results.

This chapter reviews the data reconciliation approach, focused on calibrating statewide hydrologic inflows, agricultural return flows, and agricultural water demands in CALVIN. The reference data sets to which CALVIN is calibrated (made to match) are the CVGSM No Action Alternative (NAA) from the CVPIA PEIS (USBR 1997) for groundwater, local supplies (Central Valley floor accretions), and deliveries, and DWRSIM Run 514a for surface water reservoir operations and main stem streamflows throughout the 1922-1993 period. Results from the calibration are presented and remaining inconsistencies and problems requiring additional data reconciliation efforts are identified. A more complete and detailed presentation of the calibration approach and results is provided in Appendix 2H.

CALIBRATION APPROACH

The objective of CALVIN's calibration is to integrate surface and groundwater hydrologies developed for DWRSIM and CVGSM and reconcile agricultural water demand assumptions (from Bulletin 160-98) with water deliveries in the CVPIA-PEIS (USBR 1997). This is essentially a spatially disaggregated physical calibration of the mass of water in the Central Valley's interconnected surface and groundwater system.

Outcomes of CALVIN's calibration include: 1) a workable model consistent with established representations of California's hydrology and water demands, and 2) identification of problems and regions where additional data reconciliation may be needed. In performing the calibration, we have tried to isolate calibration parameters from more physically-based parameters in the CALVIN model to better identify parameters and regions which appear to need further attention.

Overview of Calibration Steps

Two CALVIN modeling sets are used in the calibration process: the Unconstrained and Base Case alternatives. These data sets are revised systematically from an initial physically-based, but uncalibrated model (Howitt, et al. 1999) to the calibrated model needed to represent water quantities as they are commonly understood and modeled in California. The following steps outline the calibration approach.

Step 1. Uncalibrated Physical CALVIN Model

Flows, demands, and return flows represent available physical understanding of the system in this uncalibrated physical model, as documented in Appendices of this report and Howitt et al. (1999). When this model is run, its results do not accord with conventional understanding of how the system operates nor with the distribution of water scarcity across the state. Notable are a nearly complete absence of water scarcity throughout the 1922-1993 hydrologic record, conservation of mass infeasibilities in some locations, and distorted reservoir and Delta operations. Fundamental problems appear to be difficulties reconciling a) DWRSIM surface hydrology, b) CVGSM groundwater hydrology, and c) water demands based on Bulletin 160-98 land and water use assumptions.

Step 2. Adjustment of Agricultural Demands, Return Flows, and Reuse

SWAP agricultural water demands used in CALVIN are adjusted (usually increased) to reflect the greater amounts of water deliveries seen in CVPIA-PEIS NAA (USBR 1997). Return flow coefficients to split surface and groundwater portions of agricultural return flow are established and water reuse factors for agricultural demand regions are adjusted (usually decreased) so groundwater storages match CVGSM-PEIS NAA under the CALVIN Base Case Alternative (see details of Base Case in Appendix 2I).

Step 3. Adjustment of Surface Water Flows

Time series of surface inflows (positive and negative) are added to CALVIN to correct infeasibilities (typically at reservoirs) and to match streamflows in the CALVIN Base Case to those in DWRSIM (Run 514a) at 15 matching control point locations (see Table 2H-2 in Appendix 2H).

Step 4. Hydrologically Calibrated CALVIN Model

The resulting physically-based CALVIN, with adjustments to demands, reuse, return flows, and streamflows, matches demands and hydrologies to those accepted for the Central Valley, as represented by DWRSIM and CVGSM.

Uncalibrated Model Description

The two CALVIN model data sets used in the calibration process are the Unconstrained and Base Case Alternatives, both initially uncalibrated, representing a physically-based understanding of California's hydrologies and water demands. The essential assumptions represented by these two alternatives are summarized below. More detailed descriptions can be found in the Appendix 2H: Calibration Process Details and in Appendix 2I: Base Case Details.

Unconstrained Model

In step 1 above, the Unconstrained Alternative is used. Only conservation of mass, inflows, environmental minimum instream and refuge flows (current or "no action" policy levels, see Appendix F: Environmental Constraints), capacity and flood storage constraints on reservoirs, and capacity constraints on conveyance facilities (see Appendix H: Surface Water Facilities) are imposed on the model. All hydrologic inputs and coefficients (such as agricultural reuse rates, farm efficiencies, and return flow rates) are based to the greatest degree possible on a physically explicit understanding of the system, as described in the various appendices. Agricultural demands are represented by the SWAP water value functions representing Bulletin 160-98 planning data. Initially, none of these data are calibrated to "fit" other model results. Table 2H-1 of Appendix 2H identifies the sources for the physical data and coefficients used in CALVIN. It also notes inconsistencies, limitations, or other problems with differing sets of these data where known.

Base Case Model

CALVIN's Base Case model is considered the "base case" or "no action" alternative. It applies constraints to reservoir storages, diversions, and pumping, to replicate current (existing) operating policies and water allocation rules at the projected 2020 level of demand as they are modeled in the CVGSM NAA run (based in turn on the PROSIM and SANJASM NAA runs) and the DWRSIM 514a run (see Appendix 2I: Base Case Details). Base Case includes all the same physical, environmental, and agricultural demand assumptions as the Unconstrained model scenario along with these added operational constraints to represent a "base case" scenario equivalent to the two reference "base case" modeling data sets. The Base Case CALVIN model is used in step 3 above to determine time series of streamflow adjustments at various locations throughout the system and verify the calibration of groundwater.

Problems with Uncalibrated Physically-Based CALVIN Model

The problems with the physically-based modeling results, noted above, arise from several parameter estimates in the CALVIN model. These included:

1) assumptions about agricultural return flows and their destinations;
2) estimates of groundwater pumping and recharge;
3) estimates of agricultural on-farm efficiency, reuse rates, and CVPM regional efficiencies;
4) estimates of local accretions in the Central Valley floor; and
5) agricultural water demands.

The hydrologic calibration sequence and procedures, presented below, adjust these aspects of the physically-based model to better accord with DWRSIM and CVGSM representations of the Central Valley.

CALIBRATION SEQUENCE

The calibration of CALVIN involves computing spatially disaggregated adjustments to water quantities and loss coefficients to get groundwater and surface water volumes to match those in CVGSM NAA and DWRSIM 514a. Five sets of calibration adjustments are defined:

1) Groundwater/surface water return flow splits: CVPM region-wide groundwater return flow splits (the fraction of agricultural return flow deep percolating to groundwater in each CVPM region) are computed to match CVGSM NAA deep percolation of applied water. The residual region-wide return flow fraction is routed to surface water.

2) Agricultural reuse rates: Reuse values from CVPM are adjusted downwards where necessary so that the computed groundwater split does not exceed 100% of return flow.

3) Return flow "calibration" link amplitudes: Where the groundwater return flow split would still exceed 100% even after reuse has been reduced to zero, a gain amplitude on the return flow "calibration" link (see Figure 2H-2 of Appendix 2H) is calculated to make up the "excess" deep percolation (above 100% of available return flow) needed to match CVGSM NAA deep percolation volumes. (While these amplitudes are reported here, they are not actually applied in most CALVIN modeling runs, resulting in lower CALVIN groundwater storage levels than occur in CVGSM in the affected basins which all lie in the Tulare Basin Region.)

4) Boosting SWAP demands: Average SWAP demands, based on Bulletin 160-98 planning data, are adjusted upwards, where necessary, to match CVGSM NAA agricultural deliveries and adjusted reuse rates, on an annual average basis.

5) Surface water calibration flows: Fixed amounts of surface water are added to or removed from CALVIN on a monthly basis at key locations throughout the model to match streamflows to those in DWRSIM Run 514a.

The first three adjustments concern calibration of groundwater in CALVIN to the CVGSM NAA scenario. The fourth adjustment involves calibration of agricultural water demands to CVGSM NAA levels of agricultural surface and groundwater deliveries. The last adjustment concerns calibration of surface water to DWRSIM run 514a, correcting for differences in estimates of local accretion volume and timing, differences in agricultural surface water diversions and return flow assumptions (both location and volume), differences in the way the PROSIM and DWRSIM models mathematically represent operating policies (e.g., environmental flow requirements, delivery deficiency rules, reservoir rules, etc.), and a difference between CALVIN's and DWRSIM's method of computing reservoir evaporation (see Appendix H: Surface Water Facilities), among others.

To allow for more detailed scrutiny and a more efficient calibration process, the statewide model is divided into five regional models for the calibration (see Figure 2-2). Each of these regions is described in Appendices 2A through 2E of this report. The steps below constitute the calibration sequence for five regional sub-models.

Step 1: The CALVIN model is sub-divided from north to south into five regions to manage the calibration process. Regions 1 through 4 comprise the Central Valley while Region 5 consists of the area south of the Central Valley (Figure 2-2).   In this step, regional boundary flows are chosen to coincide with Base Case deliveries and/or DWRSIM run 514a control point flows to which CALVIN will be calibrated (see Appendix 2I: Base Case Details for regional boundaries).

Step 2a: Groundwater calibration parameters (the three described above) for each CVPM region are computed analytically based on Base Case deliveries according to the method described in Appendix 2H. The resultant average annual agricultural return flow volume to groundwater in each CVPM region is made to match the average annual volume of agricultural deep percolation in the CVGSM NAA soil budget analysis. The groundwater calibration parameters (see Table 3-1) are input into each of the Base Case regional models.

Step 2b: SWAP demands are adjusted upwards, where necessary, to match average annual Base Case agricultural deliveries at farm level in each CVPM region (see Table 3-3).

Step 3a: The Base Case sub-region models are run with groundwater calibration parameters and adjusted SWAP demands in place, using "debug" links.   Debug links allow for the addition or removal of external water at an extremely high cost and are only used to the extent necessary to close HEC-PRM's mass balance constraint at a node when it is violated by input constraints. Debug flows identify the location and month of any mass balance infeasibilities caused by inconsistent sets of assumptions, methods, and data imbedded in the physical, hydrologic, and operational parameters taken from different models and sources, and by the constraints imposed in the Base Case.

Step 3b: Model results of Step 3a are evaluated. In particular, debug flows required to resolve surface water mass balance infeasibilities are identified and aggregated into one or two locations for each tributary where they occur. Additionally, CALVIN groundwater storages are compared to CVGSM NAA to check groundwater calibration, and agricultural and urban scarcities are evaluated by comparison to CVGSM NAA and DWR Bulletin 160-98.

Step 3c: The consolidated "debug" flows are turned into fixed calibration flows that add and remove water from the system at their required locations and times. The Base Case model is run again to verify that inputs are now feasible with this first set of calibration flows in place.

Step 3d: Results from the Step 3c model are now evaluated to determine any additional flows (negative or positive) required to calibrate the surface water hydrology to match DWRSIM 514a at the 15 "calibration" locations in the CALVIN network (see Table 2H-2 of Appendix 2H for locations). The monthly pattern and amounts of water to add and remove at each calibration location are evaluated and likely causes for their occurrence identified. Time series of these DWRSIM-matching calibration flows are created, added to the Base Case model from step 3c, and the model run for a third time. This step finalizes the set of surface water calibration flows (summarized in Table 3-4) needed to calibrate the surface and groundwater hydrologies in CALVIN.

Step 4: The calibrated Base Case model run results (from step 3d) are processed, evaluated, and reported in the CALVIN results appendices for each of the five regions (Appendices 2A-2F).

CALIBRATION RESULTS

The calibration parameters, volumes of water added to and removed from the model, calibrated surface and groundwater flows, and adjusted agricultural demands under the Base Case assumptions in CALVIN, are presented and discussed in this section. Confirmation of the hydrologically calibrated results is made by comparison to CVGSM NAA groundwater storage levels and DWRSIM run 514 surplus Delta outflow.

Groundwater Calibration Parameters and Results

The groundwater calibration produced reasonable results consistent with the CVGSM NAA scenario except in two cases:

1) Basins where urban pumping demands in CALVIN are estimated to be higher than those in the CVPIA PEIS experience greater groundwater depletion in the CALVIN Base Case compared to CVGSM NAA.

2) In the Tulare Basin Region groundwater calibration was generally problematic, largely because general modeling information and the CVGSM NAA data for this complex conjunctive use area are both very weak.

This section presents the groundwater calibration parameters for each of the 21 CVPM basins in the Central Valley and compares the calibrated Base Case groundwater results to CVGSM NAA groundwater storage levels.

<u>Groundwater Calibration Parameter Values</u>

Table 3-1 presents the groundwater calibration parameters. Values indicate that in CVPM regions 6, 11, 14, 18, 19, 20 (nearly so), and 21 there is no surface water return flow at the region-wide scale. Thus, all non-consumptive on-farm agricultural applied water eventually becomes recharge to the underlying groundwater basin. Reuse rates in these seven regions were adjusted downward in the calibration from the original CVPM values.

In the case of CVPM regions 6, 11, and 20, reuse between districts and among farms within the CVPM region effectively uses up all surface runoff from farms. In CVPM regions 14, 18, 19 and 21, the non-consumptive volume of agricultural applied water (total return flow) after adjusting reuse rates down to zero is still smaller than the volume of deep percolation from agricultural applied water indicated in the CVGSM NAA scenario. These regions require a return flow calibration link amplitude greater than 1.0 to match the agricultural deep percolation volumes and associated groundwater levels in the CVGSM NAA (see last column of Table 3-1). Among other fundamental data problems regarding agricultural water use, there is a clear mismatch between DWR's on-farm efficiencies (assumed in CALVIN) and the CVGSM NAA volumes of agricultural deep percolation. This mismatch is especially pronounced in the Tulare Basin Region. Assuming CVGSM pumping rates are correct, several possible causes, particularly in the Tulare Basin Region, are considered:

1) Agricultural deliveries shown in Table 3-1 may include water used by districts and/or farmers to intentionally recharge groundwater (a different "efficiency" and groundwater return flow split would need to be applied to this fraction of deliveries).

2) Agricultural deliveries shown in Table 3-1 may include unaccounted for recoverable losses to groundwater that occur in the distribution canals within irrigation districts between the point of diversion to the district and the point of diversion at each farm. These losses seem to be implicitly accounted for in CVGSM's soil budget, providing a consistent reason for lower on-farm irrigation efficiencies in CVGSM than those used in DWR Bulletin 160-98 planning data.

3) On-farm tailwater recovery, thought to be widely used in parts of the Tulare Basin Region as a way to avoid discharging surface run-off, may effectively result in lower on-farm efficiencies than estimated (through deep percolation of tailwater) because of the way it is actually managed.

In nearly all CVPM regions, CVGSM effective on-farm irrigation efficiency is lower than the DWR Bulletin 160-98 estimates (see Table 2H-8 in Appendix 2H). The difference translates to 20-40% of the CVGSM NAA estimated volume of on-farm deep percolation for the Central Valley (3,920 taf/yr, see Table 2H-3). Over 50% of this potential deep percolation volume discrepancy occurs in the Tulare Basin Region, but is still significant in other parts of the Central Valley.

It is also possible (though difficult to decipher without more detailed data from the CVPIA PEIS modeling process), that the disaggregated agricultural surface water diversion volumes reported in CVGSM (derived from PROSIM and SANJASM modeling runs and other information), may already include a reuse component. If this is the case, then the discrepancy in on-farm efficiencies between DWR and CVGSM corresponds to the lower error (20%) in agricultural deep percolation reported in Table 2H-8.

CALVIN Calibrated Base Case Groundwater Storage Results

Calibrated Central Valley groundwater storage levels from the CALVIN Base Case model are compared to CVGSM NAA levels in Table 3-2 and Figures 3-1 and 3-2. Calibrated groundwater results for each of the 21 individual CVPM basins can be found in Tables 2H-4 and 2H-5 of Appendix 2H.

Calibrated groundwater in the Sacramento Valley (CALVIN Regions 1 and 2) closely matches CVGSM in Figure 3-1. Small differences in estimates of 2020 urban pumping and rounding on the calibrated groundwater return flow split account for deviations of about minus and plus 5 taf/yr between the CALVIN Base Case and CVGSM NAA average annual overdraft for Regions 1 and 2, respectively. The two regions' deviations cancel when the combined Sacramento Valley long-term overdraft is compared. The situation is markedly different for calibration of groundwater in the San Joaquin Valley including Tulare Basin (CALVIN Regions 3 and 4), covering CVPM basins 10 through 21. Long-term groundwater storage change in the CALVIN Base Case is substantially greater, averaging 500 taf/yr more than in the CVGSM NAA. Furthermore, the calibrated CALVIN Base Case indicates long-term groundwater overdraft at a rate of about 400 taf/yr across the Central Valley while CVGSM NAA results indicate net long-term groundwater recovery of over 100 taf/yr. These estimates contrast with Bulletin 160-98 2020 predictions of about 800 taf/yr of long-term groundwater overdraft in the Central Valley (DWR 1998a).

Table 3-1. CALVIN Groundwater Calibration Parameters

CVPM Region	Base Case Deliveries[a] (taf/year)		GW Split of Return Flow	DWR On-farm Irrigation Efficiency[c]	Adj. Reuse Factor[b]	CVGSM Ag. Deep Percolation (taf/yr)[d]	Return Flow Calibration Link Gain[e]
	GW	Net SW					
1	36.2	117.3	0.44	0.68	1.00	21.4	**-**
2	508.5	131.2	0.77	0.74	1.00	128.5	**-**
3	337.8	1,131.6	0.78	0.67	1.05[f]	338.5	**-**
4	298.8	672.7	0.18	0.67	1.13	41.6	**-**
5	498.3	1,140.2	0.74	0.66	1.06	371.3	**-**
6	447.3	346.5	1.00	0.68	**1.32**	81.9	**-**
7	280.5	242.8	0.55	0.63	1.08	91.2	**-**
8	661.1	151.6	0.21	0.68	1.10	43.9	**-**
9	111.6	958.0	0.70	0.70	1.10	172.0	**-**
10	407.6	1,210.0[g]	0.26	0.62	1.05	146.2	**-**
11	0.0	833.5	1.00	0.69	**1.04**	236.1	**-**
12	173.6	556.2	0.38	0.73	1.10	54.6	**-**
13	910.5	808.5[g]	0.34	0.73	1.10	116.8	**-**
14	725.6	771.3[g]	1.00	0.78	**1**	415.7	1.26
15	1,304.3	583.4[g]	0.40	0.74	1.05	168.6	**-**
16	56.2	395.5	0.31	0.73	1.10	27.9	**-**
17	409.5	349.4	0.61	0.74	1.10	86.6	**-**
18	995.4	942.6	1.00	0.75	**1**	606.4	1.25
19	356.3	606.7[g]	1.00	0.79	**1**	280.4	1.39
20	295.3	337.1	0.99	0.76	**1.07**	117.2	**-**
21	533.3	628.7[g]	1.00	0.75	**1**	373.0	1.28
Total	9,348	12,915				3,919.8	

Notes:

a Taken from CVGSM NAA 1997, GW= groundwater pumping (see file "Policy 4a Pumping 081600.xls" in Software and Data Appendices), SW= surface water deliveries (see file "CVGSM Diversions 2 edMJ 10192000.xls" in Software and Data Appendices)

b Used in CALVIN to multiply deliveries and compute basin level efficiency; initial values taken from CVPM NAA 1997 input. Bold values have been reduced from their initial values in the CALVIN calibration.

c Used in CALVIN to model consumptive use of agricultural applied water at the farm level, taken from DWR Bulletin 160-98 supporting data.

d From CVGSM NAA 1997, derived from Soil Budget (Soil2a_y.NEA output file), see Appendix J (Groundwater Hydrology)

e Calibration factor to adjust agricultural return flows to match those in CVGSM so that GW is calibrated to NAA 1997 run. Note that agricultural demands and on farm efficiencies in CVGSM are different from those in other models such as DWRSIM (depletion analysis) and DWR Bulletin 160-98 supporting data.

f Reduced from the CVPIA PEIS value of 1.09 due to explicit inclusion of Colusa Basin drainage return flow in CVGSM NAA deliveries to CVPM 3.

g Total based on Cal Aqueduct and DMC deliveries taken from DWRSIM Run 514 rather than CVGSM. DWRSIM deliveries are generally lower than CVGSM's (from PROSIM) for the same "no action" or base case operations (see Appendix 2I: Base Case Details).

Table 3-2. CALVIN Groundwater Calibration Results

CALVIN Region	CVPM GW Basins	Long-term Storage Change (taf/yr)		Minimum Storage[a] (taf)		Maximum Storage[a] (taf)	
		CALVIN	CVGSM	CALVIN	CVGSM	CALVIN	CVGSM
1	1 to 4	-4.1	-9.5	34,798	34,425	38,431	38,610
2	5 to 9	-57.4	-52.3	78,981	79,116	84,675	84,689
3	10 to 13	-26.1	+32.2	71,146	74,684	78,388	81,098
4	14 to 21	-301.2[b]	+143.0	269,548	293,324	306,316	316,461
Total	Combined	-388.8	+113.4				

Notes:
a Values are relative to CVGSM NAA layers 1 and 2 (see Appendix J: Groundwater Hydrology)
b Results do not include return flow calibration link gains (in last column of Table 3-1) that increase CVPM basins 14, 18, 19, and 21 irrigation return flows in CALVIN to match the amount of deep percolation indicated in CVGSM.

Issues and Limitations in Calibrated Groundwater Storage Results

Several issues and limitations of the calibrated groundwater results are described below. Some of these limitations could be resolved using a more complex calibration method (see Appendix 2H) or through other proposed improvements to limitations in CALVIN described in Chapter 5.

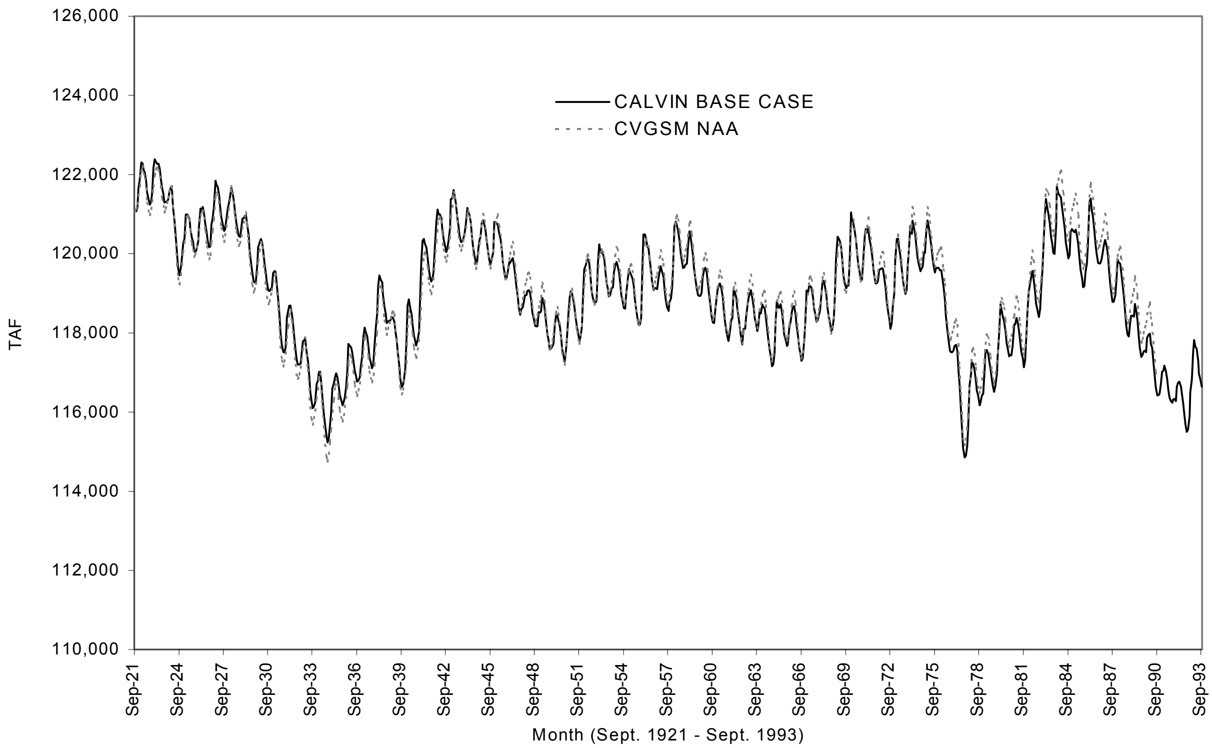


Figure 3-1. Sacramento Valley Calibrated Groundwater Results (CVPM Basins 1-9)

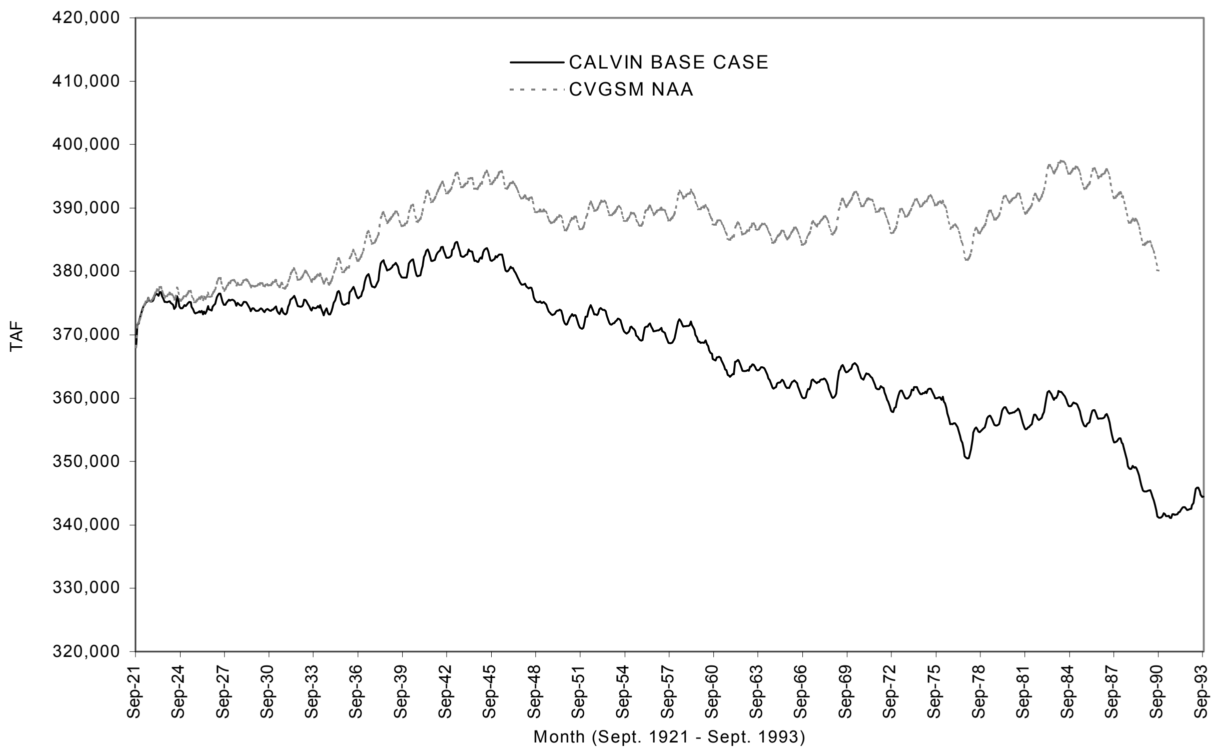


Figure 3-2. San Joaquin Valley Calibrated Groundwater Results (CVPM Basins 10-21)

Seasonal Variation in Return Flow Coefficients

In CALVIN, link amplitudes (gains/losses) must be represented by a single average value. Thus, calibration of groundwater return flow rates is based on average annual behavior over the modeled 72-year hydrologic sequence. Inability to model monthly varying return flow rates for agricultural applied water results in smaller CALVIN seasonal amplitudes in groundwater storage changes compared to those in CVGSM where groundwater return flow (applied water irrigation efficiency) varies by month, being significantly less in summer months (higher efficiencies).

Tulare Basin

Data problems in Region 4 (Tulare Basin) reduce confidence in CVGSM results and make this area particularly difficult to calibrate. Discussion of Region 4 problems appears in Appendix 2I: Base Case Details. Some data problems peculiar to this region include:

- Hydrologic inflows for the four local Tulare Basin rivers in CVGSM appear to be a mixture of unimpaired and impaired historic gage data and analysis may not have been developed to create full unimpaired hydrologies. The impact appears to be particularly problematic on the Tule River.

- Many of the CVGSM NAA diversions seem to be unmodified historic deliveries and gage data, rather than estimates of 2020 level "base case" operating diversions for the Tulare system. Agricultural deliveries from local sources show a marked change starting in the 1950's and 1960's when the four reservoirs in the region were built (Pine Flat, Kaweah, Isabel, and Success). The effects can be seen in the CVGSM NAA groundwater storage pattern which begins to stabilize in the 1950's (see Figure 2H-8 of Appendix 2H), as well as in an upward trend line to the pumping pattern over the 1921-1990 sequence (see Tulare Basin pumping in Appendix 2I: Base Case Details).

- Conflicting estimates of irrigation efficiencies, limited knowledge of pumping rates, few long-term well records, and other poor hydrogeologic data make for rather poor understanding of groundwater, and its use and management in the Tulare Basin.

Urban Water Demands and Return Flows to Groundwater

Urban pumping for 2020 is often greater in CALVIN than in CVGSM NAA. This is due to the use of different data for estimating urban demands in the two models (see Appendix B: Urban Value Function Documentation, for CALVIN urban data). Thus, while CALVIN uses the CVGSM NAA percentages of urban return flow to surface and groundwater (implemented in the Soil Budget, file Soil2a_y.NEA), the annual average volume of net groundwater extraction in the Central Valley attributable to the urban sector in CALVIN (1.36 maf/yr) is higher than in CVGSM (1.16 maf/yr in the NAA). Virtually all of this additional urban extraction occurs in the San Joaquin Valley (CALVIN Regions 3 and 4) from higher estimated urban demands in CALVIN (see details by CVPM basin in Table 2H-6 of Appendix 2H). .

The additional urban net pumping is divided equally between CALVIN Regions 3 and 4, and as seen in Table 3-2, accounts for more than the CVGSM-CALVIN difference in groundwater depletion for Region 3 but less than one quarter of the difference for Region 4.

Agricultural Water Demand Calibration Adjustments

Table 3-3 presents the amounts that SWAP demands are increased to absorb Base Case deliveries. Similar "excess" deliveries were identified in the CVPIA PEIS as "miscellaneous deliveries" beyond theoretical demands based on efficiencies and crop consumptive use (USBR 1997). Total SWAP adjustments of 1,944 taf/yr compare reasonably well with total miscellaneous deliveries identified in the CVPIA PEIS, however, the distribution across CVPM regions is somewhat different for SWAP. CALVIN/SWAP identifies approximately 486 taf/yr of excess deliveries in CVPM regions 1 through 8 where none were identified in the CVPIA PEIS work. There is better agreement between the two modeling sets for CVPM regions 10 to 21.

These adjustments are important to preserve a comparable long-term water balance and level of management flexibility between Base Case and alternative CALVIN runs, as well as between CALVIN and CVGSM representations of Central Valley water demands and management. These increases in demands amount to almost 10% of SWAP and CVPM estimated average agricultural demands. Without them, about 2 maf/year of water would become available for reallocation compared to the Base Case and CVGSM, seriously distorting the economic values estimated for new infrastructure, changes in water management, and other management activities. The annual adjustments for each CVPM region reported in Table 3-3 are applied evenly to each month of SWAP demand as demonstrated by the "raw" and "adjusted" SWAP lines in Figures 3-3 and 3-4.

Table 3-3. Base Case Agricultural Deliveries and SWAP Adjustments (taf/yr)

CVPM Region	Base Case Deliveries[a] to Farms (Applied Water)	Unadjusted SWAP Demand[b]	SWAP Adj.	CVPM Miscellaneous Deliveries[c]
1	153.5	148.0	5.04	0
2	639.7	698.8	0	0
3	1542.6	1,628.8	0	0
4	1097.8	1,035.1	62.7	0
5	1736.8	1,656.5	80.3	0
6	1047.8	788.5	259.0	0
7	565.2	518.8	46.4	0
8	894.1	860.9	33.0	0
9	1176.5	1,184.5	0	0
10	1698.5	1,309.2	389.3	380.7
11	866.8	625.1	241.8	256.2
12	802.8	787.1	15.8	94.2
13	1890.9	1,643.6	247.4	49.2
14	1496.9	1,496.0	0	182.2
15	1982.0	1,991.9	0	73.4
16	496.9	303	193.8	138.0
17	834.8	772.4	62.3	42.0
18	1938.0	2,160.1	0	136.2
19	963.0	849.2	113.8	106.6
20	676.7	653.8	22.8	49.9
21	1162.0	991.7	170.3	99.8
Total	23,663	22,103	1,944	1,608[d]

Notes:

a CVGSM NAA agricultural deliveries times adjusted reuse rate, see Table 3-1 for component values.

b Average year quantity of applied water at the farm associated with the point where the marginal value of water goes to zero in the SWAP value functions. Note that this "maximum" demand is greater than the 2020 Bulletin 160-98 planning average year applied water demand (100% demand point on the SWAP value function) as it represents the additional amount demanded as the willingness to pay or marginal value to production of an additional unit of water goes to zero.

c From Table MISDEL of input to CVPM in the CVPIA PEIS (USBR 1997)

d Total MISDEL for a normal year is shown here. In wet years, total MISDEL increases to 2,121.8 taf/yr for CVPM regions 10 through 21 combined, suggesting that some of these volumes are related to artificial recharge and conjunctive use operations.

Possible Origins of Excess Agricultural Deliveries

Many data, physical, and operational origins could explain the 10% discrepancy between estimated demands and CVGSM deliveries. Additional distribution canal losses and/or deliveries used for intentional groundwater recharge (both components neglected in CALVIN and in CVGSM) are two important and possible explanations for SWAP adjustments and CVGSM NAA miscellaneous deliveries. Calculations indicate additional losses to deep percolation of 842 to 1,692 taf/yr, or 3.8 to 7.6% of Central Valley-wide "base case" agricultural deliveries to CVPM regions. The volume of intentional groundwater recharge reported by Friant-Kern water users (CVPM regions 13, 16, 17, 18, 20, and 21) is about 450 taf/yr (USBR Water Needs Analysis 2000). These and other possible origins for excess deliveries are discussed in more detail in Appendix 2H.

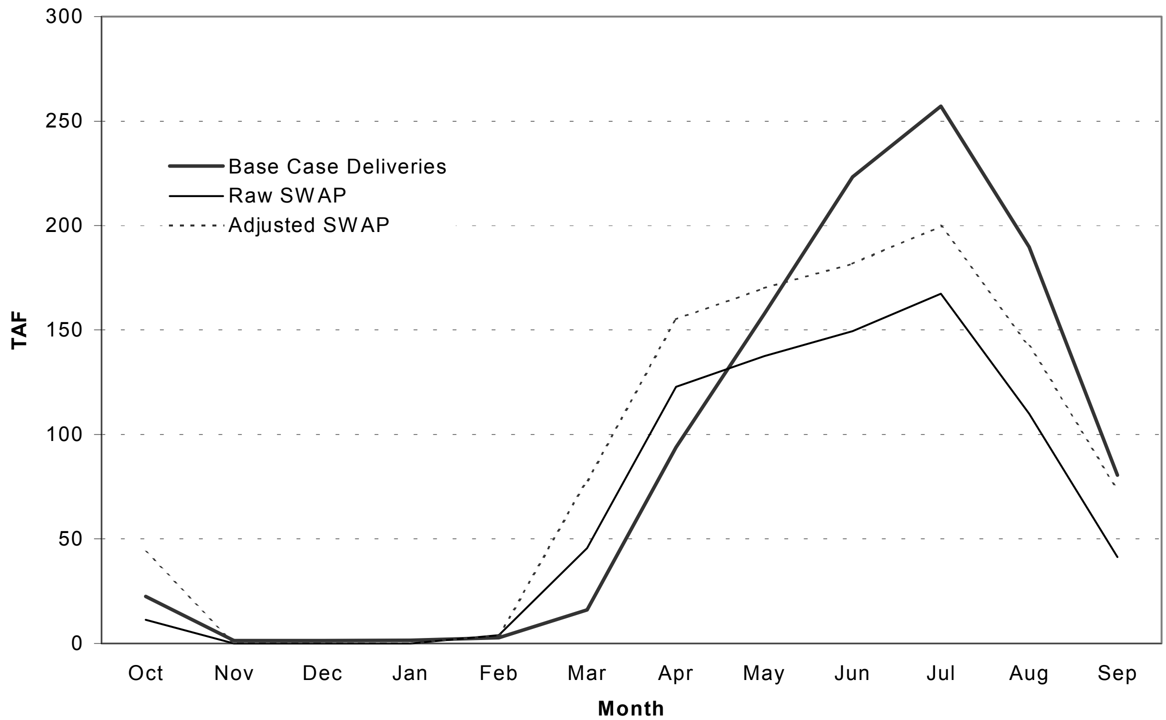


Figure 3-3. Adjusted SWAP Demands (CVPM Region 6 Example)

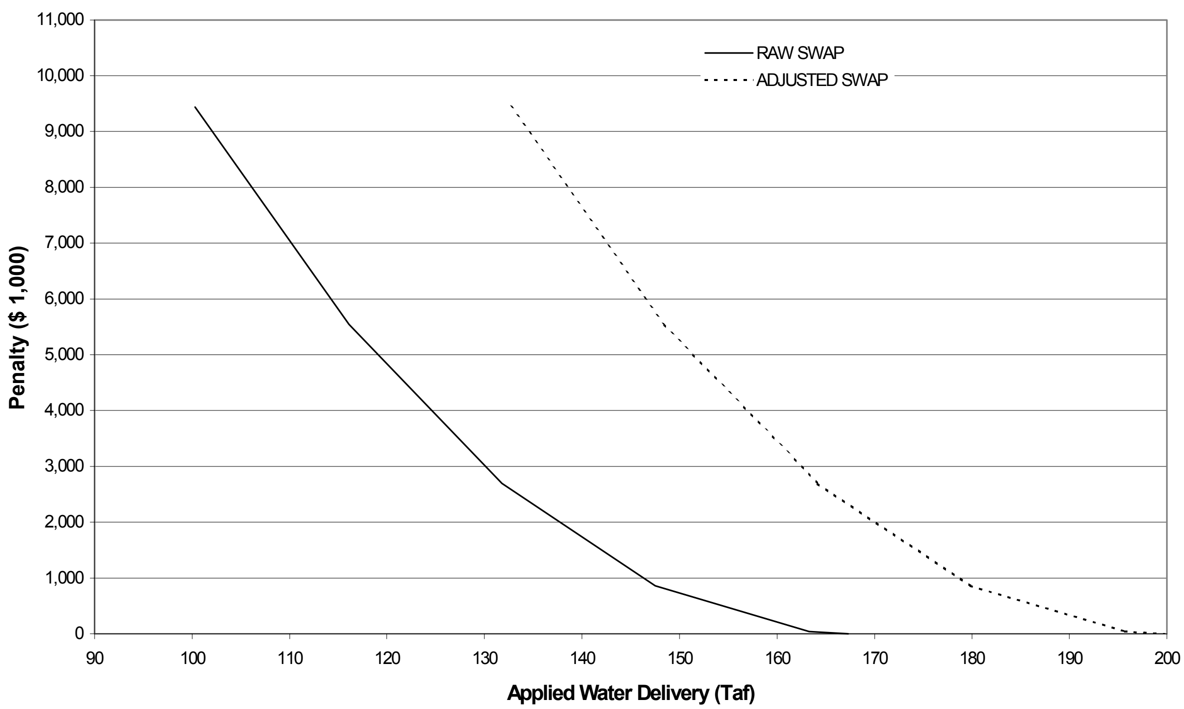


Figure 3-4. Adjusted SWAP Penalty Function (July - CVPM Region 6 Example)

Seasonal Demand Patterns

Apart from the volume difference in agricultural deliveries and demands, there frequently is substantial disagreement between the monthly patterns of deliveries and the monthly pattern of ETAW based on consumptive use models used to develop monthly SWAP demands. Figure 3-3 includes curves comparing average monthly Base Case deliveries to SWAP demands in one CVPM region. Remarkable differences in monthly deliveries and demands were noted in more than half of the 21 CVPM regions, particularly significant for the months of November, December, and January, but also apparent in other months. This short-term discrepancy between agricultural demands and Base Case deliveries is an important limitation with the current CALVIN calibration approach and causes water imbalance in some of the CALVIN sub-regions between Base Case and alternative CALVIN runs (especially apparent in Tulare Basin). These issues are discussed further in the Calibration, Base Case, and regional results Appendices.

Surface Water Calibration Flows and Results

Table 3-4 presents the required surface water calibration volumes added to or removed from the CALVIN network to make Base Case constraints feasible and to match flows to DWRSIM. Data problems and modeling inconsistencies (some small and some large) captured in the reported surface water calibration flow volumes include:

- Differing estimates of local accretions from CVGSM's rainfall-runoff model and DWR's depletion analysis;
- Differing estimates of agricultural and urban return flows from CVGSM and DWRSIM;
- Different representation of "no action" environmental flow requirements by PROSIM (used in CALVIN and the basis for CVGSM surface deliveries) and DWRSIM;
- Different representation of "base case" reservoir operating rules in PROSIM and DWRSIM;
- Different representation of south-of-Delta demands and deficiency rules in PROSIM and DWRSIM;
- Different inflows in DWRSIM and CALVIN at places where small upstream non-DWRSIM reservoirs (i.e., pre-operated in DWRSIM) are optimized in CALVIN;
- Different urban demands in CALVIN and DWRSIM;
- Different method of computing evaporation at reservoirs in CALVIN and DWRSIM (mostly responsible for small infeasibility calibration flows at reservoir locations); and
- Apparent inconsistency between CVGSM and SANJASM NAA local accretions for the San Joaquin Hydrologic Region (CALVIN Region 3).

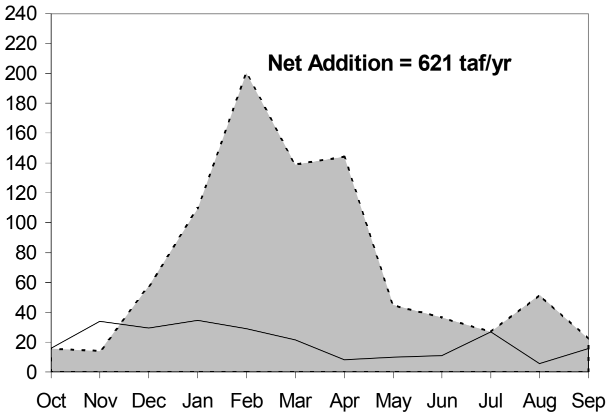
Calibration flows are summarized in Table 3-4 by CALVIN region. Flows added to CALVIN are reported as positive numbers while amounts removed from CALVIN have negative signs. Volumes required to satisfy small infeasibilities in Base Case constraints are reported in the top part of the table. These flows are mostly due to a difference in the CALVIN and DWRSIM methods of estimating evaporation at reservoirs. Larger volumes required to match DWRSIM flows and calibrate the mass of surface water in the system are reported in the lower half of Table 3-4. The 72-year average monthly pattern of CALVIN flow adjustments are plotted in Figure 3-5 for specific locations.

Table 3-4. CALVIN Calibration Flows in the Central Valley

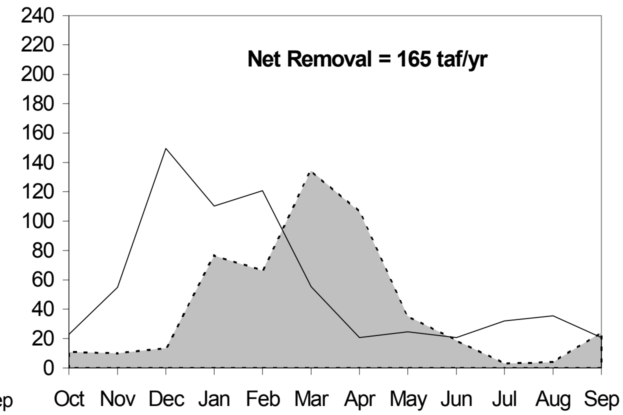
CALVIN Region #	CALVIN Region Name	CVPM Regions	Mean Flow IN (+) (taf/yr)	Mean Flow OUT (-) (taf/yr)	Net Calibration Flow (taf/yr)
Minor Infeasibility Calibration Flows					
1	Upper Sac. Valley	1 to 4	+10	-15	-5
2	Lower Sac. Valley	5 to 9	+63	0	+63
3	San Joaquin	10 to 13	+19	-59	-40
4	Tulare Basin	14 to 21	+7	0	+7
		Sub-total	+99	-74	+25
Major Mass Balance Calibration Flows					
1	Upper Sac. Valley	1 to 4	+922	-242	+680
2	Lower Sac. Valley	5 to 9	+1,165	-1,777	-612
3	San Joaquin	10 to 13	+356	-553	-197
4	Tulare Basin	14 to 21	+142	0	+142
		Sub-total	+2,585	-2,572	+13
Infeasibility and Mass Balance Flows - Grand Total			***+2,684***	***-2,646***	***+38***

Overall, the net amount of water added to CALVIN in the Central Valley is 38 taf/yr. While this is extremely small, at specific locations the mass imbalances are quite large as seen in Figure 3-5 (see also Tables 2H-9 and 2H-10 of Appendix 2H). The largest annual imbalance requires a net addition of 620 taf/yr to the Sacramento River below the Colusa Basin Drain and just above the Feather River junction in CALVIN Region 1 (chart “a” of Figure 3-5). The next largest average imbalances occur on the Lower San Joaquin River at Vernalis in CALVIN Region 3 (-434 taf/yr) and in net consumptive use in the Delta in CALVIN Region 2 (-380 taf/yr) (see charts “i” and “e”). The largest examples of calibration flows are about +/-1,500 taf and occur on the Sacramento River below the Colusa Basin Drain and on the Lower Feather River between Thermolito Afterbay and the mouth.

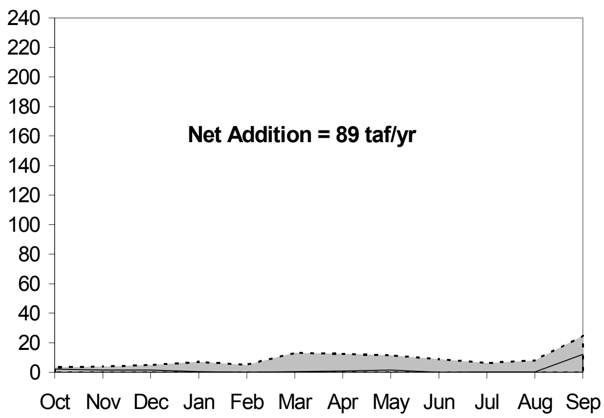
The amount and especially the timing of peak net local runoff in CVGSM and DWRSIM appear to differ in several locations in the Sacramento Valley watershed. Remarkable differences in local accretion/depletion, particularly pronounced in wet years, occur for the Upper Sacramento River (chart “a”), Lower Feather River (chart “b”), the Lower Sacramento Valley west-side contributions to Yolo Bypass (chart “d”), the Eastside streams (chart “f”), and the lower San Joaquin River (chart “i”). These problems are illustrated by the maximum monthly calibration flows reported in Appendix 2H.



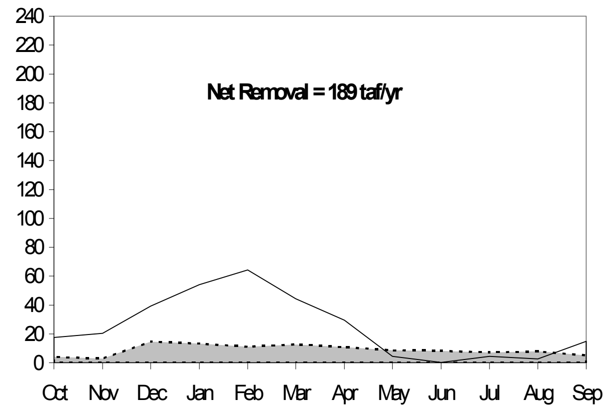
a) Sacramento River below Colusa Drain



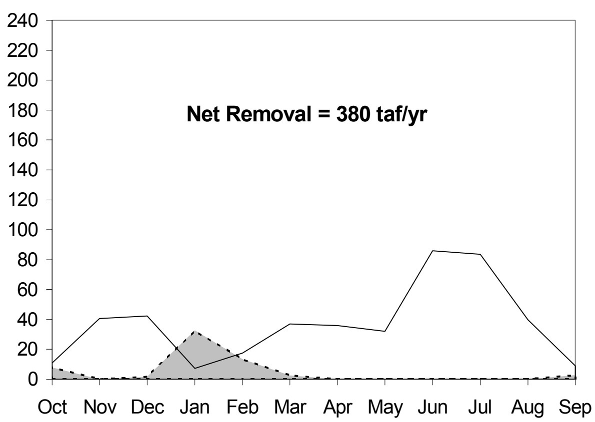
b) Feather River



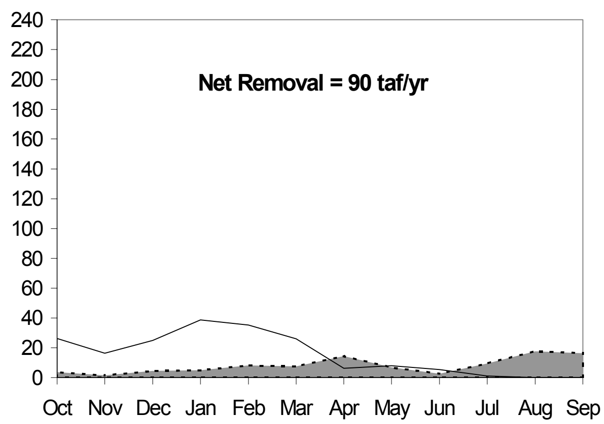
c) American River



d) Yolo Bypass

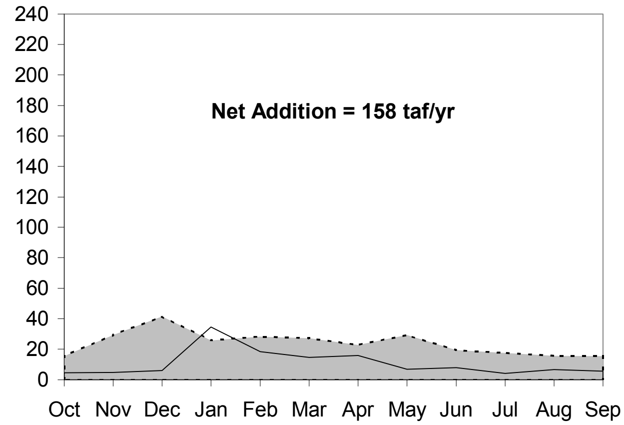


e) In-Delta Consumptive Use

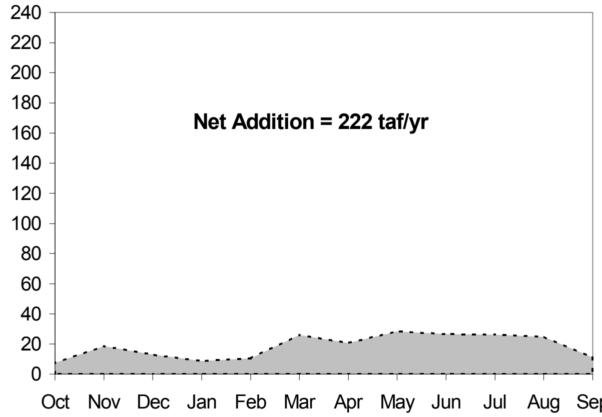


f) Eastside Streams

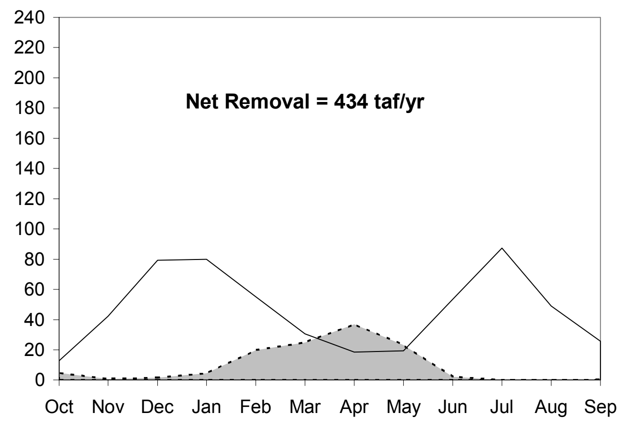
Figure 3- 5. Average Monthly Surface Calibration Water (taf) ▒ Added and ☐ Removed



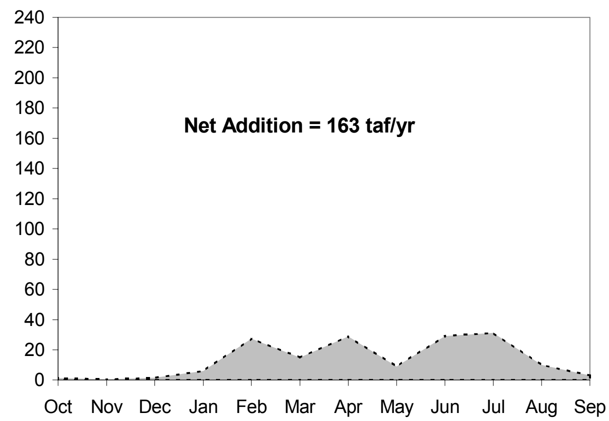
g) Sacramento River at Hood



h) San Joaquin Tributaries



i) San Joaquin at Vernalis



j) Tulare Basin Rivers

Figure 3- 5. Continued. Surface Calibration Water (taf) ▒ Added and ☐ Removed

At other locations (see charts "c", "h", and "j"), rather small consistently regular monthly calibration flows and little or no removed water tend to suggest that imbalances are not a problem with differing estimates of runoff timing and magnitude but a more consistent mass balance accounting problem related to surface diversions and return flows along these rivers, and to environmental flows in some cases like the American River. In some of these cases, calibration inflows are due to CALVIN's aggregation of agricultural surface return flows to a single downstream location relative to diversions, in contrast to spatially disaggregated surface return flows in CVGSM. For example, all calibration flows added to San Joaquin tributary rivers (chart "h") are removed at Vernalis (chart "i"), supporting the theory that calibration problems on the tributaries concern estimates of agricultural return flows and riparian diversions.

The largest net additions of water occur in CALVIN Regions 1 (Upper Sacramento Valley) and 4 (Tulare Basin). CALVIN Regions 2 (Lower Sacramento Valley and Delta) and 3 (San Joaquin River) have net removals of water. In each region, suspected reasons for calibration flows are further discussed in Appendix 2H: Calibration Process Details.

Verification of the surface water calibration, shown in Figure 3-6, is made by comparing CALVIN's calibrated Delta surplus outflow to that in DWRSIM run 514a (8,760 taf/yr average). A small difference in outflow remains after the calibration, averaging 22 taf/yr less in CALVIN.

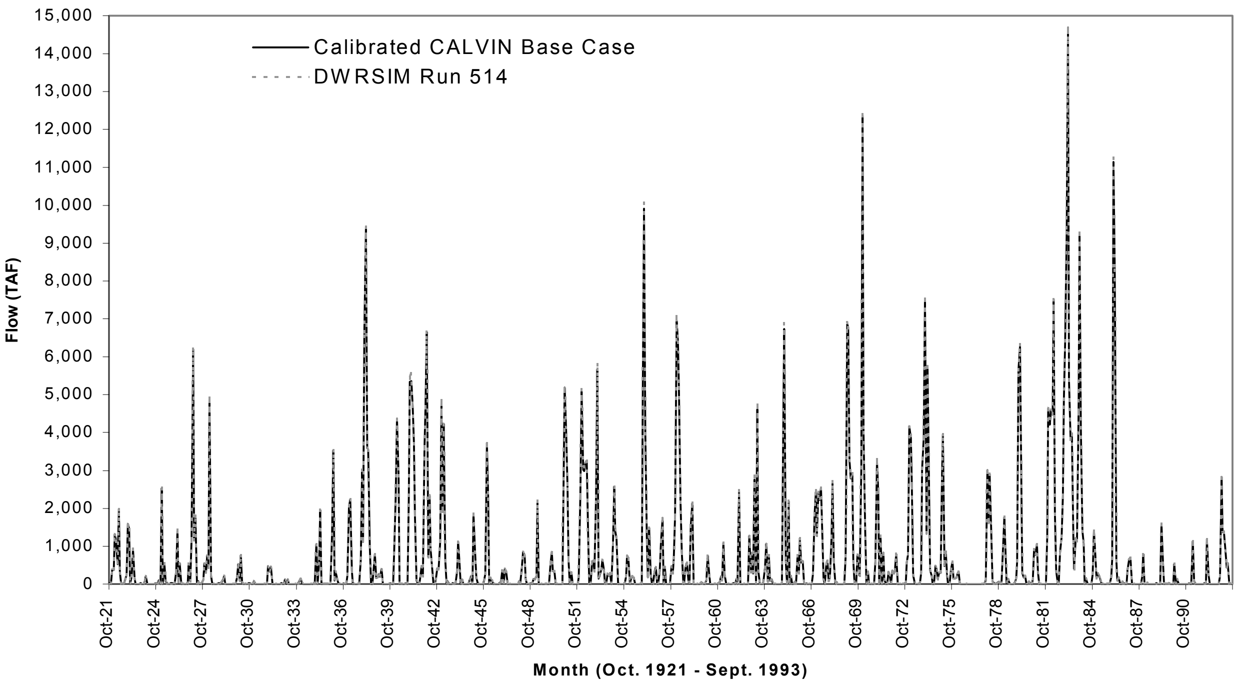


Figure 3-6. Base Case Calibrated Delta Surplus Outflow

The only calibration flows required in CALVIN Region 5 (Southern California) are due to differences in evaporation estimates between CALVIN and DWRSIM. The resultant calibration flows amount to a net removal of 30 taf/yr along the East and West Branches of the California Aqueduct.

IMPLICATIONS OF THE CALIBRATION

Implications concerning the consistency, reliability, and quality of Central Valley and statewide modeling data, emerge from the calibration results. Some of these implications are specific to limited areas of the Valley or state while others are systematic.

Surface and Groundwater Hydrology

Data representing local surface and groundwater resources must be separate and explicit for the Central Valley. This improvement to hydrologic data is especially needed in the Sacramento Valley, but is also relevant to other areas. Recently initiated efforts between the US Bureau of Reclamation and the California Department of Water Resources to develop a joint hydrology are addressing these problems.

Ungaged Streams and Local Accretions

Estimated accretion from local runoff and ungaged streams from mass balance accounting (DWR's depletion analysis) and regression analysis (SANJASM) do not match with the rainfall-runoff model and stream-aquifer interactions used in CVGSM in several places (i.e., Upper Sacramento Valley north-east streams, Feather River, Yolo Bypass, Eastside Streams, and San Joaquin River, see Figure 3-5). Separate and physically-based accounting of major components of surface and ground waters (as opposed to "net" and commingled accounting), improving estimates of the locations and volumes of riparian diversions and surface return flows, and further calibration of the rainfall-runoff model should reduce these discrepancies in estimates of local accretions and depletions.

In-Delta Consumptive Use

A large discrepancy exists between DWR's and CVGSM's estimates of in-Delta consumptive use and net in-Delta depletion. CVGSM's estimates are nearly 400 taf/yr lower than those of DWR.

Agricultural Water Systems

The current level of uncertainty in regional agricultural water use, reuse, distribution losses, and basin efficiency throughout the Central Valley has a significant effect on model operations and scarcity results. These effects are especially important for investigating conjunctive use and conservation opportunities in the Central Valley and gauging the long term sustainability of groundwater use.

Tulare Basin Conjunctive Use Operations

The current developed level of conjunctive use operations in the Tulare Basin Region is not well understood for modeling purposes, leading to significant uncertainties in estimating agricultural applied water use, active recharge, distribution losses, efficiencies, and groundwater depletion in this region. Surface flow representation in this area is particularly poor.

Groundwater-Surface Water Interactions in Tulare Region

The calibrated CALVIN representation of the agricultural system in the Tulare Basin Region suggests that net groundwater extraction in Tulare Basin may be 500 taf/yr greater than indicated by CVGSM under the base case. Assuming higher irrigation distribution losses (or diverting some deliveries to recharge) in CALVIN in the Tulare Basin Region would reduce this discrepancy. However, there is uncertainty about the fundamental reliability of CVGSM NAA estimates of 140 taf/yr long-term groundwater recovery in this region (compared to over 670 taf/yr of long-term groundwater overdraft indicated in DWR Bulletin 160-98 water accounting estimates). An alternative calibration approach is proposed in Appendix 2H that might improve the representation of agricultural water use in this region.

Westlands, Kern, and Other Tulare Basin Deliveries

Recent water market activities by Westlands, Kern, and other Tulare Basin agricultural users appear to indicate that the calibrated CALVIN model has insufficient agricultural water scarcity and scarcity costs for these areas. Comparisons of more recent DWRSIM and CALSIM deliveries to this region with the DWRSIM 514a run indicate no great change in surface water delivery estimates in recent years. However, groundwater representations in this region from

CVGSM are thought to be unreliable. Improved confidence in representing supplies and demands in this region is imperative.

LIMITATIONS OF THE CURRENT CALIBRATION APPROACH

The current CALVIN calibration approach described in this chapter suffers from some remaining limitations and unresolved problems. These are presented below:

1) The method used to adjust SWAP average demands is rather simple and crude and creates distortion in the allocation of supplies in CALVIN in non-average year types. Better representation of inter-annual variability in agricultural water demands is needed. Also, additional effort to adjust the monthly use patterns is desirable in some regions, preferably through explicit improvements in calibration of SWAP. Efforts are underway to improve the HEC-PRM computer code to handle inter-annual variability in economic demands.

2) Policy implications of CALVIN and other modeling results in the Tulare Basin Region, particularly those pertaining to groundwater management, will be difficult to make given the weak source data and difficulty getting the groundwater calibration approach to work in this region.

3) More recent events, such as implementation of CVPIA b(2) environmental water provisions, appear to have reduced agricultural deliveries from that in the CVGSM NAA run. Some revision of CALVIN model environmental constraints is likely to be in order.

An alternative calibration approach, to handle the mismatch in deliveries and SWAP demands is suggested in Appendix 2H: Calibration Process Details. Future efforts to improve CALVIN's calibration might start by evaluating this and other possible solutions to limitations outlined in this report.

CONCLUSIONS

The hydrologic calibration of CALVIN ensures that the model represents water as it has been thought to be available and used in California. However, the calibration exercise has identified fundamental and potentially significant inconsistencies and uncertainties in the available and commonly used hydrologic and water demand data. Such inconsistencies are not surprising given that most of these data were not developed to be consistent with active and integrated surface, groundwater, and water demand management. Additional hydrologic and modeling data development clearly is needed, as identified in Chapter 5 and detailed in Appendix 2H: Calibration Process Details. Such improvements in fundamental hydrologic and water demand data are of great value to any statewide and regional water studies for California, not just those of the CALVIN model. In addition, some improvements in the calibration of CALVIN are desirable, as suggested in Appendix 2H.

CHAPTER 4

SELECTED POLICY RESULTS

"The purpose of models is not to fit the data but to sharpen the questions."
Samuel Karlin, 11th R A Fisher Memorial Lecture, Royal Society 20, April 1983.

INTRODUCTION

California's water problems have grown in complexity and controversy, requiring new forms of analysis and new ways of identifying promising solutions. Advances in computer hardware and the availability of data now make it possible to apply systems analysis to the operation of California's water infrastructure. The CALVIN model is the result of a multi-year effort to develop an integrated, economic-engineering optimization model of California's inter-tied water system.

In the course of this work, CALVIN has been used to examine the economic benefits of more flexible water operation and allocation policies within the state, such as those that might occur with water markets or other forms of economic water management. Three different alternatives are considered for year 2020 levels of agricultural and urban water demands, 1) a Base Case with current water operations and allocation policies, 2) regional water markets within each of five regions of California, but without changes in inter-regional water movements, and 3) a statewide water market where inter-regional transfers are unrestricted.

The Base Case represents the current infrastructure, contractual agreements, and legislative requirements, with 2020 demands. A regionally unconstrained model run represents the existing statewide inter-tied system with 2020 levels of water demand under regional water markets, with the statewide system divided into five regions (the Upper Sacramento Valley, the Lower Sacramento Valley and Bay-Delta, the San Joaquin Valley and South Bay, the Tulare Basin, and Southern California). Water use and transfers within each region are driven by their relative economic values and inhibited only by physical capacity constraints and environmental flow requirements, but inter-regional flows are fixed at Base Case levels. A second unconstrained model run represents the same system, but allows inter-regional flows of water to vary from the Base Case to meet economic demands statewide, essentially representing an economically ideal statewide water market of California's entire inter-tied system. Unconstrained results are compared with results from the Base Case. It should be noted that while the second and third alternatives are referred to as "Regional Water Market" and "Statewide Water Market," these are actually short-hands for economically-driven water operations and allocations at regional and statewide scales. Thus, an advocate of economic performance need not be an advocate of "water markets" to find value in these results.

This chapter begins with a summary of the types of output available from the CALVIN and SWAP models, followed by brief descriptions of the model runs and descriptions of the five CALVIN regions. Presentation of results is divided into three parts. The first results section compares water allocation and economic impacts at the state, regional, and water users' levels for the three alternatives. The next results section examines water values and the potential for changes with regional water markets. The third section examines further changes that occur with the statewide water market. Economic impacts to water users of environmental flows and the locations of promising system capacity expansion are indicated by the Lagrange multipliers (shadow values) on flow and storage constraints produced by CALVIN's economic optimization of the system. These results suggest large economic incentives for modest changes in the allocation and management of the State's water resources. More detailed results can be found in the appendices for each of the five CALVIN regions (Appendices 2A – 2F) and the appendix on statewide CALVIN results (Appendix 2G).

OUTPUTS AVAILABLE FROM CALVIN AND SWAP

Outputs available from CALVIN include physical outputs, which describe monthly water allocations throughout the system over the analysis period, and economic outputs, which describe economic values of these monthly operation and allocation decisions.

Physical Outputs

The following physical information at node and link locations can be obtained from CALVIN output:

Flow

On every link in the system schematic, CALVIN output provides a time series of monthly flow over the analysis period.

Storage and Evaporation

For every storage node, CALVIN output provides a time series of monthly storage levels and evaporation. Where no evaporation rate is defined, such as for groundwater storage nodes, evaporation output is not produced.

Deliveries and Scarcities

For every agricultural and urban demand node, CALVIN produces a monthly time series of deliveries. Deliveries are allocated by CALVIN to maximize system-wide economic benefits, based on the value functions of water that were supplied to the model as inputs. Deliveries are restricted only by physical and environmental constraints in the unconstrained cases. Each demand node has a set of monthly value functions for delivered water. These functions vary for urban and agricultural demand nodes and among individual nodes of each type throughout the system. Because of these differences, there can be significant differences in the level of allocations to urban and agricultural users and to different regions.

Post-processing tools have been developed to translate CALVIN monthly deliveries into equivalent monthly scarcities for each demand node. Scarcity is defined as the difference between the demand node's actual delivery and its maximum demand, when delivery is less than maximum demand in any month. The maximum demand delivery is derived from the economic value function as the point where there is no marginal benefit of additional water or, equivalently, the quantity of water which would be demanded if the price of water were trivial and its availability were unlimited.

Economic Outputs

The following economic outputs at node and link locations can be obtained from CALVIN:

Marginal Willingness-To-Pay for Additional Water

For each agricultural and urban demand node, a monthly time series of the marginal willingness-to-pay (WTP) for additional water is computed. The marginal WTP is the economic value of delivering the next additional unit of water. It is the slope of the economic value function or, equivalently, the price on the urban demand curve or the marginal value of water for agriculture, at the delivered quantity of water. Thus, if the delivery equals or exceeds the maximum demand, marginal WTP is zero.

Cost of Scarcity

Post-processing tools are used to compute the monthly cost of scarcity events for each demand node. Scarcity cost is equal to the economic value of maximum demand water deliveries minus the economic value of water delivered to that location in the model.

Marginal Values of Water

For every node in the system, CALVIN provides a monthly time series of the marginal value of water, defined as the net system-wide benefit in dollars of increasing external inflow into the node by one unit (the DUAL_ORIG value for each node from raw HEC-PRM output). These marginal values can be interpreted as the net value, integrating costs and benefits across the system, of additional water supply at a given location.

Shadow Values on Constraints

Output generated by HEC-PRM includes shadow costs (Lagrange multipliers) for every constrained link in the system at every time step. These shadow costs indicate the net costs of increasing a constraint by one unit, integrated across the whole system network. A negative net cost of increasing a constraint indicates that such action would produce net benefits in the system. When a constraint is not binding, the shadow value is zero. For reservoirs and groundwater basins, shadow values are provided on the storage link that transfers stored water from one time step to the next. Shadow values can be used to evaluate the economic benefits of various changes to the physical or operating limits of the system without having to make additional model runs.

Outputs From the Statewide Agricultural Production Model (SWAP)

Several specialized outputs are available from the Statewide Agricultural Production Model (SWAP). These outputs are post-processed, using CALVIN agricultural deliveries as inputs. This SWAP post-processing provides a check on the economic penalty function representations used in CALVIN as well as additional details useful for assessing local and regional agricultural responses to and economic effects of changes in water deliveries.

Irrigation Efficiencies

SWAP can calculate irrigation efficiencies for twelve crop types in each region. Irrigation efficiency for SWAP is:

$$IE = \frac{ET_{AW}}{AW}$$

Values for irrigation efficiency indirectly reflect the economic value to growers of improving irrigation systems given the water allocations that CALVIN provides. Irrigation Efficiencies in all regions were capped at 0.9, so that SWAP could not predict unrealistically high IE's. Most

Crop Acreage

SWAP can provide acreages for twelve crop types in each region. Comparing the base case to an unconstrained alternative can show shifts away from (or toward) different crop types.

Crop Yield

Crop yields in SWAP are calculated as the product of tons of crop produced per acre and acreage cropped. SWAP predicts both the tons per acre of each crop and the acreage cropped from estimated production functions for each region.

Net and Gross Revenue

In every region, SWAP can also calculate agricultural revenue based for a given agricultural water allocation (see Appendix 2K). Gross agricultural revenue is the tons of crop produced multiplied by the price for the crop. Net agricultural revenue is the gross agricultural revenue less the costs of inputs to the crop.

MODEL RUN AND REGION DESCRIPTIONS

As summarized in Chapter 2 (with details in the appendices), all modeling runs incorporate CALVIN's entire statewide schematic and solve for economically optimal water operation and allocation decisions in every month with hydrologic inputs representing historical hydrology from October 1921 to September 1993. Inputs to CALVIN consist of (1) surface and groundwater hydrology, (2) physical facilities and capacities, (3) urban values of water, (4) agricultural values of water, (5) policy constraints representing environmental and institutional flow requirements, (6) operating costs, and (7) gains/losses on flows. CALVIN uses the Hydrologic Engineering Center's HEC-PRM network flow reservoir optimization solver (HEC 1994) to optimize the operation of system resources over a given hydrologic sequence to maximize statewide net economic returns to agricultural and urban users.

The Base Case constrains CALVIN to operate the system in accordance with current projected operations for year 2020 levels of demand ("no action" alternative). Reservoir operations are based on the Department of Water Resources Planning Simulation Model (DWRSIM, Run 514a). Deliveries and groundwater use are based on Central Valley Groundwater and Surface Water Model (CVGSM, Run NAA) developed for the CVPIA Programmatic EIS (USBR 1997). In the Base Case, deliveries to each CVPM agricultural region and urban imports are constrained, rather than allowing the model to determine flows based on economic benefits (see Appendix 2H: Base Case Details).

Two alternative unconstrained cases are run, which allow for an almost complete economic optimization within the engineering limits of the system. Urban and agricultural economic demands for water are represented at projected 2020 levels of development. Most of the flow and storage policy constraints are removed to allow CALVIN to operate and allocate water to produce the greatest economic benefit. Only a few policy constraints remain in the unconstrained case, representing environmental minimum instream flows, fixed refuge deliveries, and seasonal flood storage capacity requirements. Groundwater basins have maximum storage constraints and all physical capacity limitations remain in place. For the regionally unconstrained alternative, flows between the five hydrologic regions are constrained as in the Base Case, to restrict water transfers to within each region; no inter-regional transfers are allowed. This unconstrained case represents a set of regional water markets (RWM) or other forms of regional economically-driven water management. For the statewide-unconstrained case, policy constraints on inter-regional flows are eliminated, in effect representing an idealized statewide water market (SWM) or other form of economically-driven statewide coordination of water operations and allocations.

In the two unconstrained alternatives the end-of-period surface water reservoir and groundwater storages are constrained to match the ending storages in the Base Case. This assures that all alternatives have comparable water resources for the 72-year hydrologic period of analysis. Detailed regional model results can be found in the regional appendices, Appendices 2A-2F. Detailed statewide model results appear in Appendix 2G.

Descriptions of the five hydrologic regions used for analysis of regional and statewide water markets appear in Chapter 2, with details in Appendices 2A-2G. The regions also appear in Figure 4-1 below. Together, these regions represent 92 percent of California's urban water demands and 88 percent of its irrigation water demands. The smaller agricultural demand regions are mapped in Figure 2-4 and described in Table 2-1.

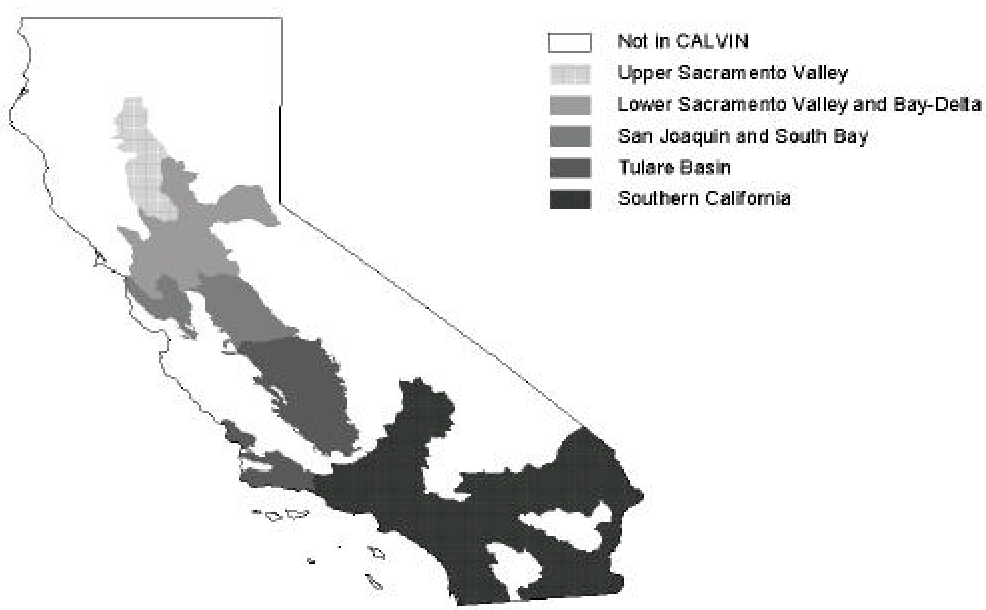


Figure 4-1. Map of California Showing the Five CALVIN Regions

SCARCITY AND COST RESULTS FROM REGIONAL & STATEWIDE MODELS

Scarcity is the difference between maximum economic demand for water, as represented in CALVIN, and water deliveries resulting from the model. Maximum economic demand is the amount of water which users would desire if the price were trivial and supply unlimited. Scarcity costs are the economic losses to water users of being limited by water supply or its cost (price). Neither concept reflects the costs of providing water. The operating costs of providing water (pumping, treatment, etc.) are included in the CALVIN model. Where operating and opportunity costs exceed scarcity costs, some scarcity will be economically optimal. This section provides scarcity and cost results of the regional and statewide unconstrained CALVIN model runs compared with the Base Case.

Scarcity and Scarcity Costs

Table 4-1 contains regional water scarcities and scarcity costs for Base Case, Regional Water Market, and Statewide Water Market conditions. With regional water markets, scarcity is reduced statewide by approximately 11.8% (190 taf/yr). Despite a small reduction in scarcities there are significant reductions in the associated costs. Scarcity costs are reduced by 82.5% ($1.3 billion/year), primarily through intra-regional transfers from agricultural to urban users, but also through improvements in operations and conjunctive use.

Table 4-1. Regional and Statewide Scarcity and Scarcity Costs by Region and for Agricultural and Urban Users

	Average Scarcity (taf/yr)			Average Scarcity Cost ($M/yr)		
Region	**BC***	**RWM***	**SWM***	**BC**	**RWM**	**SWM**
Upper Sacramento Valley	144	157	0	7	5	0
Lower Sacramento & Delta	27	1	1	36	1	1
San Joaquin and Bay Area	16	0	0	15	0	0
Tulare Lake Basin	274	322	33	37	19	2
Southern California	1132	929	857	1501	255	197
TOTAL	1594	1409	890	1596	279	200
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 figure

Under the statewide water market scarcity volumes are reduced from the Base Case by approximately 44.2% (704 taf/yr), through operational improvements such as conjunctive use. Again, the reduction in scarcities resulted in some additional reduction in the associated scarcity costs. Scarcity costs decreased by 87% ($1.4 billion/year) compared to the Base Case, again primarily through transfers from agricultural to urban users, but also through improved operational efficiencies.

The statewide water market decreased scarcities over the regional water markets by a further 519 taf/yr. The associated scarcity costs decreased by an additional $79 million/year from the regional water market. The statewide water market was able to completely eliminate scarcities in the Upper Sacramento Valley and significantly reduce the Tulare Basin and Southern California scarcities compared to the Base Case and regional water markets. Figures 4-2 and 4-3 depict the remaining scarcity costs under a statewide water market.

Changes in Scarcities and Scarcity Costs by Sector and Region

Under the regional water markets, average annual water scarcities increased for agricultural users by 495 taf/yr and resulted in $19.4 million/year in increased agricultural scarcity costs. These decreases in agricultural deliveries occur primarily in Southern California and the Tulare Basin. Urban users see decreases of 678 taf/yr in scarcities and $1.3 billion/year in scarcity costs (Table 4-1). The greatest changes are in Southern California (Region 5, see Figures 4-4 and 4-5).

With a statewide water market, average annual water scarcities increased by much less for agricultural users, 47 taf/yr more than the Base Case (but 449 taf/yr less than with regional water markets). However, this small scarcity increase (5.7%) from the Base Case agricultural scarcity resulted in a $2 million/year decrease in scarcity costs through re-allocation of Base Case scarcity to lower value production. Urban users see a 744 taf/yr decrease in annual average scarcity in a statewide water market from the Base Case level (and a 70 taf/yr reduction from regional water markets). Total scarcity costs decrease by $1.3 billion/year from the Base Case. See Table 4-1 and Figure 4-5 for details.

Under regional water markets, most benefits would go to the urban sector (Figure 4-4), unless mitigated by transfer payments. Urban scarcity and scarcity costs would be drastically reduced, at some expense to agricultural users in Southern California. Urban users typically have higher economic values for water use, which translate to higher willingness to pay for additional supplies. In a regional water market, most urban demands, when not bounded by other constraints, would be filled before those of agricultural users.

In most regional water markets urban users received reductions or eliminations of their scarcities (Figure 4-4). Only in the Southern California and the Lower Sacramento Valley and Bay-Delta Regions were urban scarcities not eliminated completely. The Lower Sacramento Valley and Bay-Delta Region continues to experience urban scarcities, despite complete elimination of agricultural scarcities, due to localized storage capacity and inter-tie constraints. Southern California also continues to see urban scarcities due largely to conveyance capacity constraints. Within the agricultural sector, there is decreased scarcity in some regions and increased scarcity in others, as the model seeks to maximize the net economic value of production and transfers water among agricultural users.

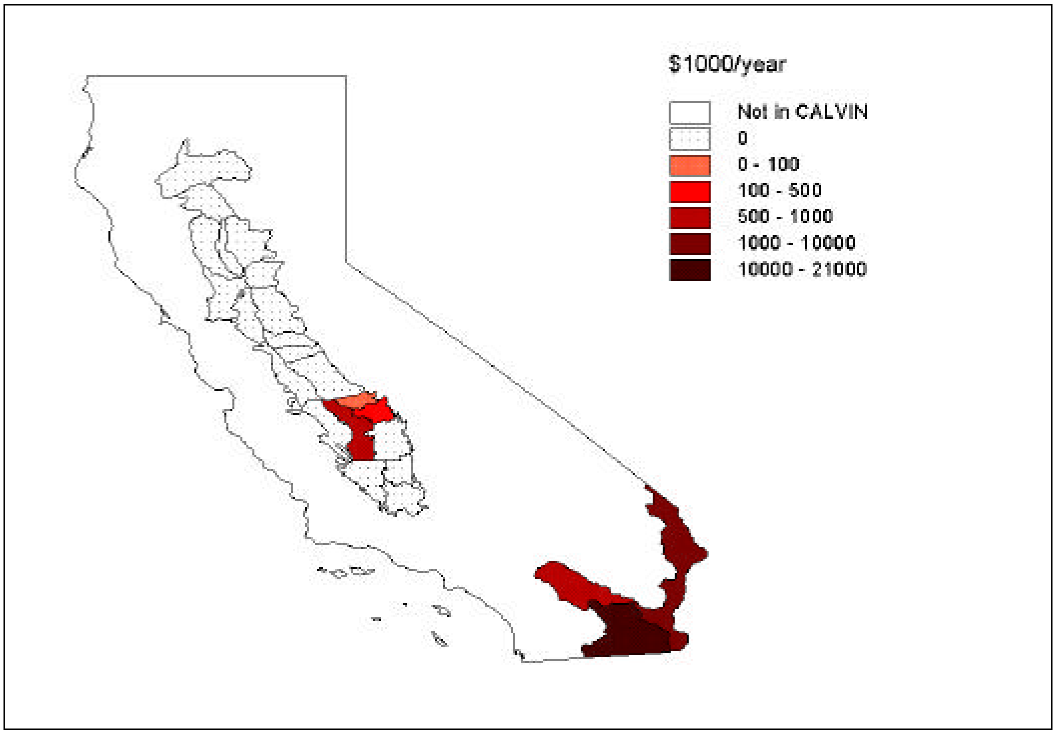


Figure 4-2. Agricultural Scarcity Costs by Demand Area with a Statewide Water Market

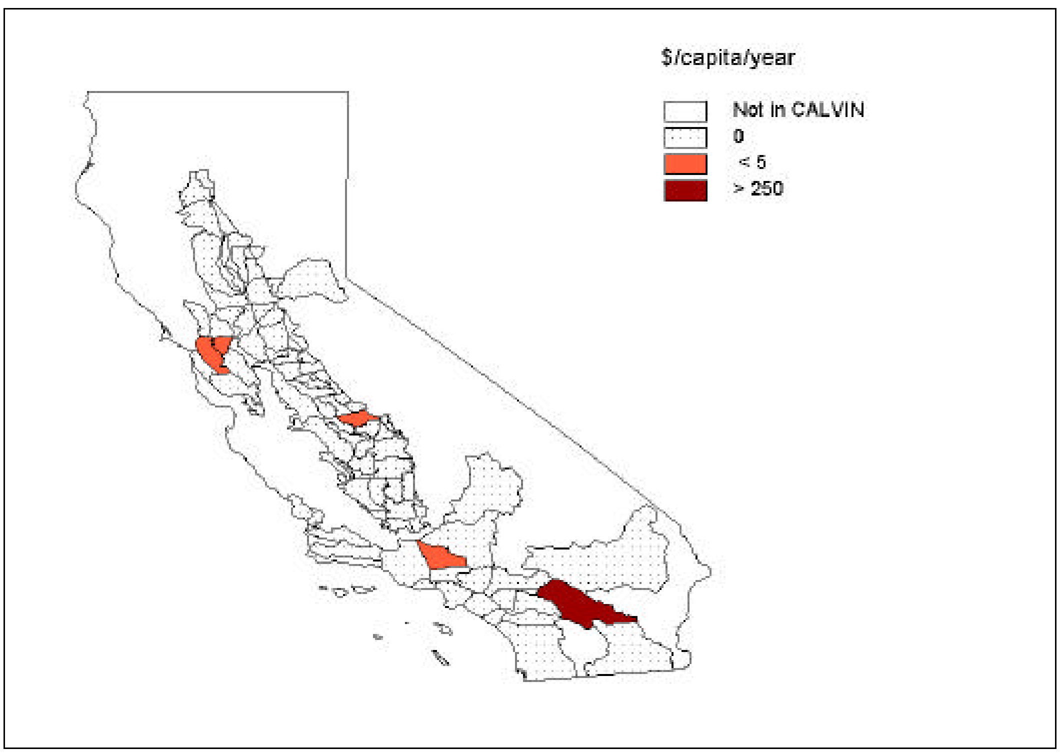


Figure 4-3. Urban Scarcity Costs with a Statewide Water Market

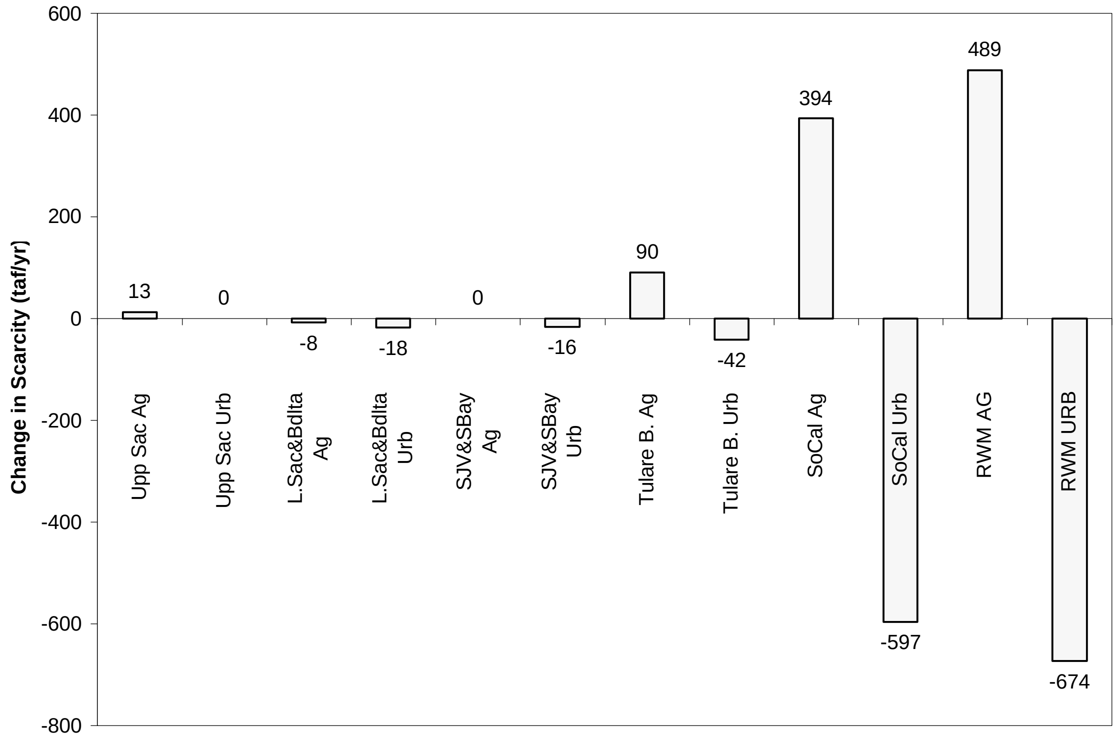


Figure 4-4. Changes in Average Annual Water Scarcity with Regional Water Markets

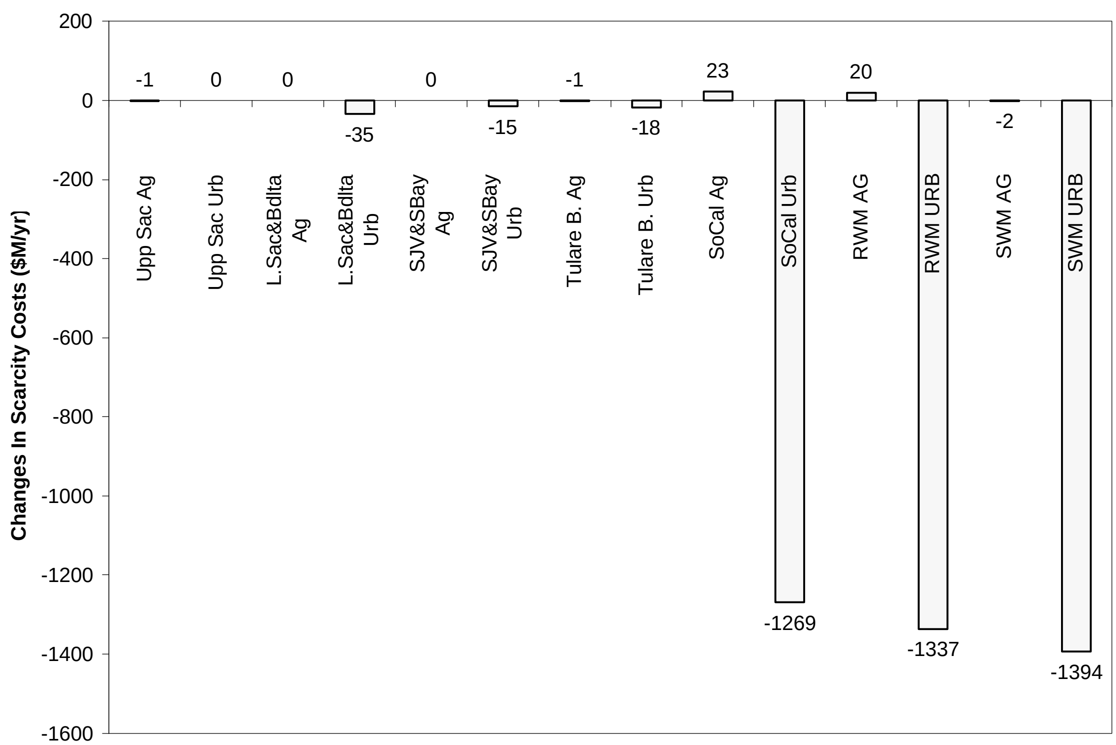


Figure 4-5. Changes in Average Annual Scarcity Costs with Regional Water Markets

Under the statewide water market, most additional reductions in scarcity go to agricultural users, with greater scarcity cost reductions going to urban users (Table 4-1 and Figures 4-3 and 4-7). Agriculture sees a minor statewide decrease in scarcity costs from the Base Case (Table 4-1 and Figure 4-6), while urban users see a much larger reduction, but continued urban scarcities in Tulare Basin, Southern California, and Lower Sacramento Valley and Bay-Delta regions. Reasons for remaining urban scarcities to Southern California and the Lower Sacramento Valley are similar in the statewide water market as those in the regional water market, but also include some cases where scarcity is optimal (water costs exceed urban willingness-to-pay). Fresno (in the Tulare Basin Region) experiences some optimal scarcity in the late summer months (July to September). Castaic Lake Water Authority (CLWA) also experiences some optimal scarcity during almost all months on average (except February).

With a statewide market, agricultural users in Southern California see increases in annual average scarcity volumes from the Base Case (but less than with regional water markets). However, agricultural users of the Upper and Lower Sacramento Valley and Bay-Delta, and San Joaquin and South Bay Regions see complete eliminations of scarcities under the statewide water market in both average and drought years. Agricultural users in the Tulare Basin see significant reductions in scarcity from the Base Case, and considerable reductions in scarcity costs.

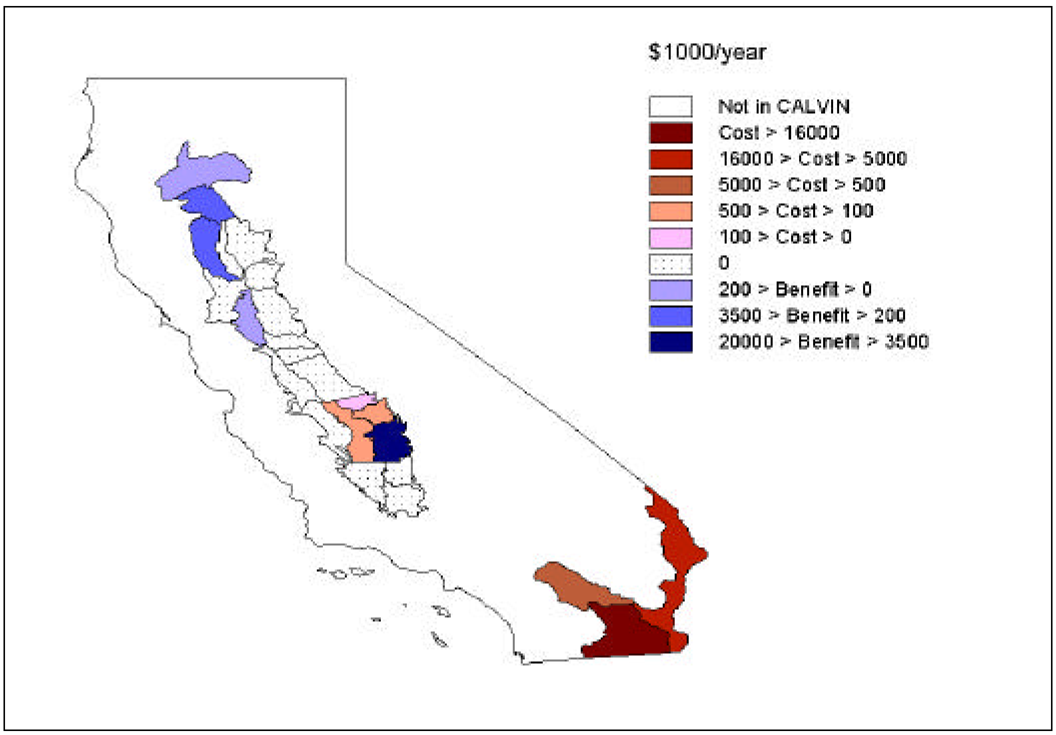


Figure 4-6. Change in Agricultural Scarcity Costs by Demand Area with a Statewide Water Market

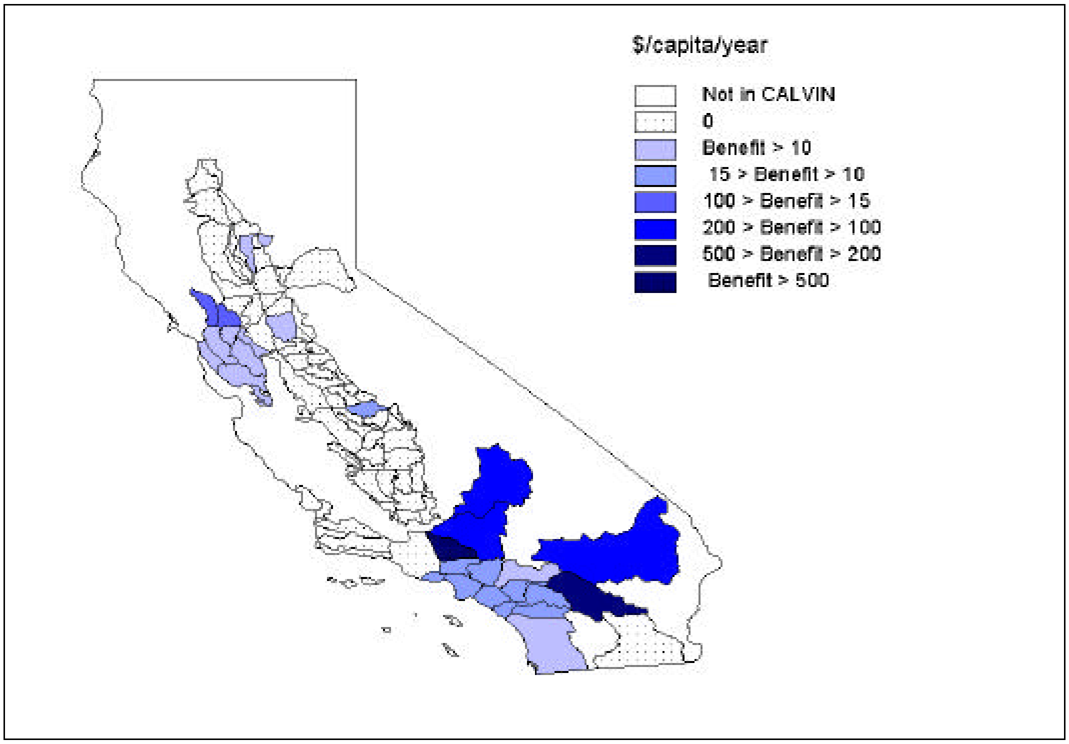


Figure 4-7. Change in Urban Scarcity Costs by DAU with a Statewide Water Market

Total Regional and Statewide Costs

Total regional costs include both costs from water scarcity and variable operating costs of system operations (such as pumping, local distribution, and treatment). Variable operating costs are a significant part of overall system economics (Table 4-2 and Figure 4-8). Overall, regional water markets led to an average annual net benefit (reduction in overall costs) of $1.3 billion/yr statewide. Regional water markets led to reductions in total costs in all regions, but to different degrees. Southern California saw the greatest decrease, while the Upper Sacramento Valley saw the least. The $1.3 billion/yr reduction in total costs is primarily due to reduced scarcity costs in Southern California as operating costs overall only decreased by $12 million/year with ideal regional markets. Table 4-2 presents Base Case, regional and statewide water market costs.

Table 4-2. Average Scarcity, Operating, and Total Costs

	Base Case			Regional Water Market			Statewide Water Market		
Region	Scarcity Cost ($M/yr)	Operating Cost ($M/yr)	Total Cost ($M/yr)	Scarcity Cost ($M/yr)	Operating Cost ($M/yr)	Total Cost ($M/yr)	Scarcity Cost ($M/yr)	Operating Cost ($M/yr)	Total Cost ($M/yr)
1	7	28	35	5	28	34	0	29	29
2	36	176	212	1	165	166	1	165	166
3	15	379	394	0	358	358	0	333	333
4	37	424	461	18	416	434	2	413	415
5	1501	1573	3074	255	1600	1855	197	1640	1838
TOTAL	**1596**	**2581**	**4176**	**279**	**2568**	**2847**	**200**	**2580**	**2780**

All five regional water markets reduce scarcity costs, however, only Regions 2, 3 and 4 have significant decreases in operating costs. For Southern California, operating costs increased by $28 million dollar per year, primarily due to increased water treatment, water quality, and distribution costs as part of reducing urban water scarcity. Increased costs were more than offset by a $1.3 billion/yr decrease in average scarcity costs.

In the statewide water market, operating costs increased by $12 million/year beyond the RWM case, but remained almost the same as in the Base Case. However, scarcity costs decreased from the regional water markets case by $79 million/year, providing a net decrease in total costs under the statewide water market compared to regional water markets of $67 million/year. Total costs in the statewide water market were lower by $1.4 billion/yr than in the Base Case.

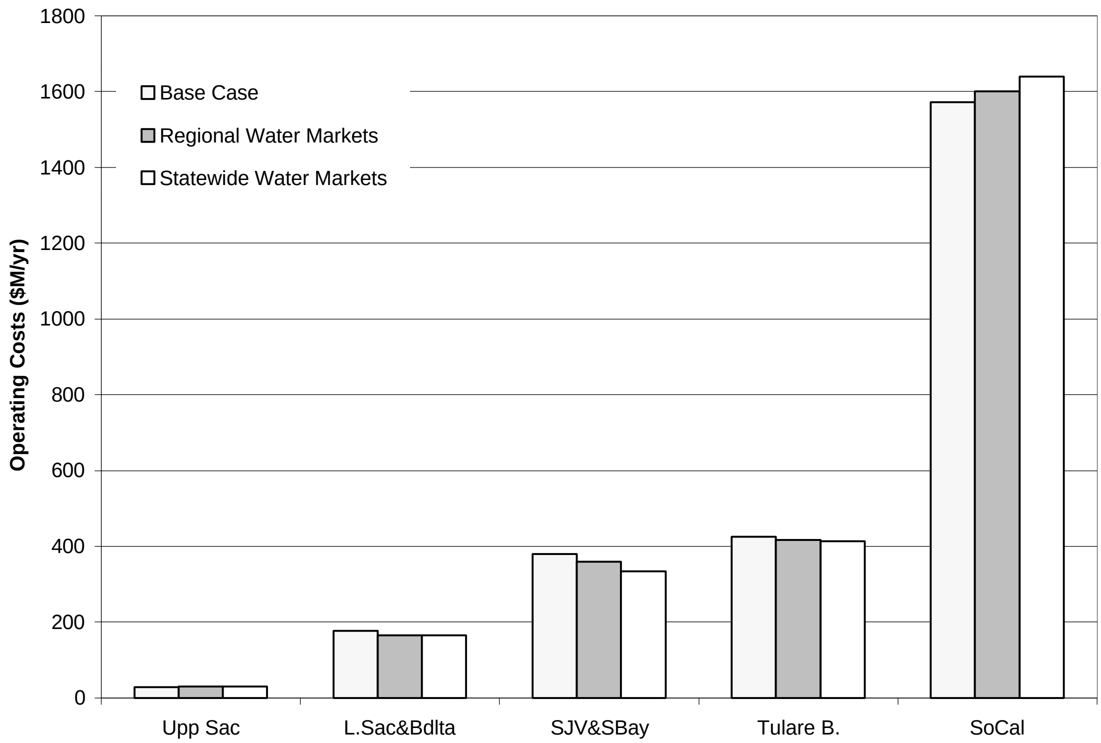


Figure 4-8. Operating Costs by Region ($M/yr)

REGIONAL AND STATEWIDE WATER TRANSFERS

Cooperative operations and transfers between local agricultural and urban users as well as between regions allow for reduction in overall scarcities and scarcity costs. In both the regional and statewide water markets, agriculture saw a decrease in water deliveries (490 taf/yr and 41 taf/yr, respectively). Urban users, on the other hand, saw an increase in deliveries in both water markets (674 taf/yr and 744 taf/yr, respectively). See Table 4-3 for details.

Agricultural regions CVPM 2 and 18 saw the biggest increases from the Base Case to the regional and statewide water markets, while Palo Verde and Imperial saw the largest decreases. Every urban area with scarcity in the Base Case saw an increase in deliveries.

Table 4-3. Average Water Reallocations, Scarcity, and Scarcity Costs by Demand Area

	Deliveries (taf/yr)		ΔDeliveries (taf/yr)		Scarcity Costs ($M/yr)			ΔScarcity Costs ($M/yr)	
Demand Region	Max.	BC	RWM-BC	SWM-BC	BC	RWM	SWM	RWM-BC	SWM-BC
CVPM 1	153	153	-1	0	0.01	0.02	0	0.01	-0.01
CVPM 2	697	640	47	57	3.46	0.22	0	-3.23	-3.46
CVPM 3	1629	1543	7	86	3.15	2.94	0	-0.21	-3.15
CVPM 4	1098	1098	-66	0	0	2.11	0	2.11	0
CVPM 5	1737	1737	0	0	0	0	0	0	0
CVPM 6	1048	1048	0	0	0	0	0	0	0
CVPM 7	565	565	0	0	0	0	0	0	0
CVPM 8	894	894	0	0	0	0	0	0	0
CVPM 9	1184	1176	8	8	0.11	0	0	-0.11	-0.11
CVPM 10	1698	1698	0	0	0	0	0	0	0
CVPM 11	867	867	0	0	0	0	0	0	0
CVPM 12	803	803	0	0	0	0	0	0	0
CVPM 13	1891	1891	0	0	0	0	0	0	0
CVPM 14	1496	1497	0	0	0	0	0	0	0
CVPM 15	1992	1983	-65	-11	0.35	2.90	0.80	2.55	0.45
CVPM 16	496	498	-5	-2	0	0.12	0.05	0.12	0.05
CVPM 17	835	836	-14	-8	0	0.36	0.21	0.36	0.21
CVPM 18	2160	1938	54	222	18.8	10.4	0	-8.41	-18.8
CVPM 19	957	957	-38	0	0	2.51	0	2.51	0
CVPM 20	677	677	0	0	0	3	0	3	0
CVPM 21	1162	1162	-23	0	0	1.43	0	1.43	0
Palo Verde	789	661	-114	-113	1.43	6.91	6.89	5.47	5.46
Coachella	195	195	-14	-14	0	0.87	0.87	0.87	0.87
Imperial	2732	2550	-266	-266	4.35	20.5	20.5	16.2	16.2
Total Agriculture	**27754**	**27067**	**-490**	**-41**	**32**	**51**	**29**	**20**	**-2**
Yuba	53	52	1	1	1	0	0	-1	-1
Napa-Solano	115	105	10	10	22	0	0	-22	-22
Contra Costa	135	135	0	0	0	0	0	0	0
East Bay MUD	297	290	7	7	12	1	1	-12	-12
Sacramento	679	679	0	0	0	0	0	0	0
Stockton	95	95	0	0	0	0	0	0	0
San Francisco	238	232	6	6	5	0	0	-5	-5
Santa Clara Valley	656	646	10	10	10	0	0	-10	-10
SB-SLO	139	139	0	0	0	0	1	0	0
Fresno	380	338	42	40	18	0	0	-18	-17
Bakersfield	261	261	0	0	0	0	0	0	0
Castaic Lake	128	44	75	79	508	5	3	--503	-505
Antelope Valley	277	186	87	91	185	3	0	-182	-185
Coachella	601	348	104	103	367	365	166	-202	-201
Mojave*	352	225	127	127	181	0	0	-181	-181
San Bernardino	283	279	0	4	4	2	0	-2	-4
Central MWD	3731	3534	152	197	183	37	0	-146	-183
E & W MWD	740	706	26	34	33	7	0	-26	-33
San Diego	988	954	26	34	35	7	0	-28	-35
Total Urban	**10147**	**9246**	**674**	**744**	**1564**	**227**	**170**	**-1337**	**-1394**

* - neglects conveyance capacity constraint entering Mojave region

WILLINGNESS-TO-PAY FOR WATER

Additional water is only needed in regions where economic demand is not fulfilled. In these regions there would be some economic value to additional supplies. The user's marginal willingness-to-pay for an additional unit of water indicates where and when there is potential economic value for inter- and intra-regional transfers, new supplies, local water conservation or water reuse, supply capacity, and changes in environmental requirements.

For each demand area, the marginal willingness-to-pay (WTP) for additional water in each time step can be derived based on economic value functions and water deliveries. By comparing these values across nodes and regions, the relative value of additional supply to each region can be estimated. The marginal WTP indicates how much each demand area would be willing to pay to obtain additional water supply. Also available is the economic value (net benefits) of additional inflow at each node in the system, indicating the relative value of water at different locations. This information has several uses, including estimating the value or costs of additional regional imports or exports.

User Willingness to Pay for Water

Under regional water markets, fourteen of the twenty-four agricultural demand regions and eight of the nineteen urban demand regions continued to experience scarcities. As expected, urban users had significantly higher marginal WTP values than agricultural users (Table 4-4). The highest marginal WTP (for both agriculture and urban) occurred in Southern California (Region 5) where the largest and most costly scarcities remained. The only other region with any urban marginal WTP was in the Lower Sacramento Valley and Bay-Delta (EBMUD in Region 2). Agricultural users with remaining marginal WTP occurred in Southern California, Tulare Basin, and the Upper Sacramento Valley.

In the statewide water market, six of the twenty-four agricultural users and five of the nineteen urban users experience scarcities. As expected, urban users had significantly higher maximum marginal WTP values than the agricultural users (Table 4-4), and two (Coachella Urban and Castaic Lake) had average values an order of magnitude higher than agricultural values. The highest marginal WTP occurs in the Coachella urban area (Southern California), which had the largest urban scarcity volume in the statewide water market. Likewise, Imperial agricultural users, which had the largest agricultural volume of scarcity in the statewide water market, had the highest agricultural marginal willingness to pay.

Inter-Regional Boundary Water Values

At each regional boundary, the time series of economic values of additional water (boundary "dual" in mathematical terms) indicates the economic incentives for inter-regional water transfers or other inter-regional shifts in water supplies. The relative economic value of additional water on each side of a boundary indicates the economic desirability of shifting water between regions. Table 4-5 presents the boundary values for the five regional water markets.

Table 4-4. 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

Table 4-5. Inter-Regional Boundary Economic Values of Water for Base Case and Regional Water Markets

		Average Boundary Value ($/af)				
		Upper Sac.	Lower Sac. & B.Delta	SJV & S.Bay	Tulare	So.Cal
Sacramento River	BC	119	629	-	-	-
	RWM	45	0.1	-	-	-
	SWM	0.3	0.2	-	-	-
San Joaquin River	BC	-	619	143	392	-
	RWM	-	0.1	9	45	-
	SWM	-	0.2	20	25	.
Delta Exports	BC	-	619	106	313	2,849*
	RWM	-	0.1	-10	21	133
	SWM	-	0.2	24	35	297
Delta Mendota Pool	BC	-	-	143	346	-
	RWM	-	-	8	43	-
	SWM	-	-	19	31	-
Friant-Kern	BC	-	-	143	392	-
	RWM	-	-	13	44	-
	SWM	-	-	30	29	-
Mono-Owens	BC	-	-	-	-	917
	RWM	-	-	-	-	628
	SWM	-	-	-	-	486
Colorado River	BC	-	-	-	-	739
	RWM	-	-	-	-	105
	SWM	-	-	-	-	105

* - ignoring Castaic Lake

Changes in boundary values from the Base Case to the regional unconstrained case reflect the re-allocation of water within each region. For example, in a statewide or inter-regional water market, the Upper Sacramento Valley might retain more of the Sacramento River, because of its higher value compared to those adjacent agricultural areas. On the other hand, Southern California would place the greatest emphasis on increased Delta exports, while the Tulare Basin would seek more San Joaquin River water. In general, values for all water supply sources decrease with regional water markets, but are especially reduced for Delta exports. In all cases, economically efficient use of water within each region tends to significantly dampen economic demand for additional water imports.

ENVIRONMENTAL FLOW SHADOW VALUES

Over the last few decades California water resource management has placed more importance on maintaining water levels in streams and rivers for environmental purposes. Many rivers within California have minimum instream flow requirements and environmental refuges are located through out the state.

In CALVIN environmental demands are modeled as constraints (lower bounds on stream flows for minimum instream requirements and fixed deliveries for refuges). Environmental requirements are not modeled as economic demands, but do impose restrictions that may affect deliveries to urban and agricultural demands. A total of 15.9 maf/yr on average is allocated to environmental purposes in CALVIN (see Appendix F for details). The extent to which environmental demands impose economic scarcities can be seen in the Lagrange multipliers (shadow values) generated for each environmental demand, indicating the marginal cost of environmental requirements on agricultural and urban water users. These are shown in Table 4-6 for the environmental water demands in CALVIN.

Table 4-6. Shadow Values of Environmental Flows to Agricultural and Urban Users

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

* Includes lost hydropower values

Environmental Shadow Values with Regional Water Markets

The shadow values on the Kern National Wildlife Refuge (NWR) and Pixley NWR display a fairly repetitive pattern, with non-zero values occurring from February through October. In November, December, and January there is no value to the Tulare Basin from reducing these two refuge demands. These months coincide with the periods of no Tulare Basin agricultural demands in CALVIN and SWAP. There are a few months when the shadow values on the Kern NWR requirements peak. These times primarily coincide with periods of drought.

The Trinity River minimum and Sacramento West Refuge shadow values are consistently high. There are only five periods when there is no value to reducing the wildlife refuge demands. The economic values to agricultural and urban users from reducing environmental demands reflect the region's scarcities and operating costs under the regional water market. Water diverted to fulfill the Trinity River minimum flows or delivered to the refuges is unavailable for use within the Upper Sacramento Valley where agricultural areas experience scarcity in the regional water market.

The environmental requirements to Mono Lake and Owens Lake divert water that is then unavailable for economic demands in Southern California. Shadow values on the requirements are almost always non-zero in the regional water market, reflecting mostly high economic values for hydropower and urban water quality (these are the only locations where hydropower values are included). As expected, the shadow values are the highest during the periods of drought and lowest in extremely wet years.

Numerous other environmental requirements exist throughout the state, but the shadow values are generally reduced to near zero with regional water markets. This includes the required Delta outflow in Northern California (at least as it represented in CALVIN). Shadow values presented in Table 4-6 only reflect the remaining economic scarcities in their respective regions and are fairly similar to the boundary values (Table 4-5) in the regional unconstrained run, as expected.

Environmental Shadow Values with Statewide Water Markets

Just as with the regional water markets, environmental flow requirements continue to produce some significant shadow values. However, in the statewide water market North-of-Delta requirements (such as Trinity River minimums, Sacramento Wildlife refuges, etc.) do not produce significant shadow values. These now come only from south-of-Delta environmental requirements (Table 4-6).

As expected, the Southern California environmental requirements (Mono Lake and Owens Lake) produce the largest shadow values in the state, in part because they include substantial hydropower benefits (the only hydropower locations included in CALVIN currently), as well as water quality benefits over alternative water sources. Kern National Wildlife Refuge's shadow value dropped by $12.2/af with a statewide water market. Pixley National Wildlife Refuge's shadow value also dropped in the statewide water market (by $17.2/af).

POTENTIAL FOR PHYSICAL INFRASTRUCTURE CHANGES

Shadow values on storage and conveyance capacity indicate the value (net economic benefits) of increasing facility capacity. Shadow values can be used in conjunction with users' marginal willingness-to-pay to indicate which facilities are economically promising for expansion, which demand areas will benefit most from expansion, and how much demand areas would be willing to pay for construction and additional water. Because they only denote the value of small increases in capacity, shadow values on each facility are most valuable when deciding which facility expansion alternatives to study in future model runs. Values of both existing and proposed facilities can be tested in this manner. For example, if proposed facilities are included in the system with zero capacity (as with the Folsom South Canal extension for EBMUD), the shadow value on that capacity will help indicate whether it is worth further analysis to investigate developing this facility.

Reservoir Expansion

With regional water markets, some regions have insufficient reservoir capacity to prevent scarcities (especially during drought periods). Of the five regions, only the Upper Sacramento Valley (Region 1) does not have significant value to increase reservoir capacity. The greatest values would come from expanding reservoirs in the Tulare Basin Region. See Table 4-7 for details.

Table 4-7. Marginal Economic Values of Selected Facility* Expansion Options

Region	Facility*	Physical Capacity	Marginal Value ($K/yr/unit capacity) RWM	SWM	Present Value[a] ($K/yr/unit capacity) RWM	SWM
	Surface Reservoirs	(taf)				
2	Pardee	210	14.5	14.5	483	483
2	East Bay Local	153	13.7	13.7	457	457
2	South Bay Local	170	12.5	12.4	417	413
4	Kaweah	143	55.6	31.7	1853	1057
4	Success	82	48.2	26.4	1607	880
5	Grant	47	42.5	38.3	1417	1277
5	S. Cal. SWP Storage	694	12.1	2.8	403	93
	Conveyance	(taf/yr)				
2	EBMUD/CCWD Cross Canal	0	146	145	4867	4833
2	East Bay/South Bay Connector	0	237	253	7900	8433
2	Folsom South Canal Extension	0	26.0	26.0	867	867
3	Hetch Hetchy Aqueduct	336	268[b]	280	8933	9333
5	Colorado River Aqueduct	1303	351	209	11,700	6967
5	Los Angeles Aqueduct	565	15.2	13.0	507	433
	Other Facilities	(taf/yr)				
2	EBMUD Recycled Water Facility	25	20.2	20.2	673	673
2	SCV Groundwater Pumping	366	230[b]	178	7667	5933
2	SFPUC Recycling	0	55.0[b]	71.5	1833	2383
2	SCV Recycling Facility	16	30.4[b]	46.5	1013	1550
5	Coachella Artificial Recharge	120	2,654	2,796	88,467	93,200

* - Facilities reported with greater than $10/yr/af annual average value to expansion
a - Assuming a 3% real interest rate and very long life span
b - Region 3 shadow values for RWM do not reflect the cost of pumping water from the Bay Delta via Tracy or Harvey Banks pumping plant and thus are underestimated by approximately $22/af.

Increased storage in Pardee and East Bay Local reservoirs would reduce the scarcities to East Bay Municipal Utilities District (EBMUD) during the 1976-1977 drought. It should be noted that EBMUD was the only area to experience any regional water market scarcities in the Lower Sacramento Valley and Bay Delta regional water market. During the remaining months, there is little value to expanding Pardee or East Bay Local Storage.

The South Bay Local reservoir represents the aggregate storage reservoirs in the Santa Clara Valley demand area (the aggregation of three Bay Area urban agencies). High shadow values occur only in drought conditions, implying that a small amount of additional storage could provide less expensive local water in place of lower quality, more costly Delta imports.

Expansion of Lake Kaweah and Lake Success in the Tulare Basin Region could potentially reduce agricultural scarcities, which increased in the regional water market. Marginal values for increased storage reflect agricultural users' willingness-to-pay values (Table 4-6). In general, capacity constraints affect Lake Success more frequently, but with smaller shadow values.

Expanded capacity of Grant Lake, the Los Angles Aqueduct (LAA) storage facility, would provide significant benefits to Southern California. Presently, the facility can store the lowest cost water in Southern California and is the source of the most spills. Increased Lake Grant capacity would reduce spills and provide significant hydropower benefits and additional supplies during critical periods. Also in Southern California, expanding the State Water Project (SWP) East and West Branch storage reservoirs would allow more mostly seasonal storage of California Aqueduct water. The majority of these storage expansion benefits would come during droughts, but there are significant benefits in non-drought years as well, especially at Lake Grant.

In a statewide water market, the three reservoirs with the greatest water supply benefits from capacity expansion are still Lake Kaweah and Lake Success in the Tulare Basin Region and Los Angeles Aqueduct Storage (Grant Lake) in Southern California. Reservoirs with the highest expansion values are almost the same in both the regional and statewide water markets. In the statewide water market, the shadow value on increased storage capacity in the SWP East/West Branch Storages fell to $2.8/af. In general the average value of expansion has either decreased (Grant, Success, Kaweah, South Bay) or remained the same (Pardee and EBMUD) from the regional water market to the statewide case.

Conveyance and Other Facility Expansions

Increased conveyance capacities could potentially enable economically driven demand areas to receive additional water. In some regions, the greatest benefits come from expanding conveyance facilities; see Table 4-7.

For the regional water market within the Lower Sacramento Valley and Bay-Delta Region (Region 2), a canal linking the Mokelumne Aqueduct and Contra Costa Canal could yield the greatest benefits. There would be consistent value, with a peak occurring during the 1976-1977 drought, indicating that EBMUD would want to obtain more water from sources other than the Mokelumne Aqueduct during critically dry periods. During the remaining time, Contra Costa Water District (CCWD) receives water quality benefits from importing surplus Mokelumne water from EBMUD. The Folsom South Canal Extension has the potential to divert water from the American River via the Mokelumne Aqueduct to EBMUD during critically dry periods. Alternatively, EBMUD would benefit from having expanded water-recycling capacity during critically dry periods.

The value to expanding the Hetch Hetchy Aqueduct is always non-zero. The proposed addition of a fourth San Joaquin Valley pipeline would bring the total capacity of the Hetch Hetchy system to 620 cfs. In the regional water market, this proposed increase in Hetch Hetchy conveyance capacity shows significant additional changes, beyond those reported in this chapter, on both supply mixes and marginal values of water throughout the San Joaquin and South Bay Region. Shadow values in the South Bay on conveyance links and groundwater pumping reflect economic value of using cheaper sources to replace Delta imports (with a variable cost minimum of $375/af to delivery and treat overall). Additionally, increased recycling capabilities ($350/af variable cost) for both the South Bay and San Francisco represent additional sources of water to reduce more costly Delta imports.

Increases in Coachella's ability to store groundwater using artificial recharge would reduce scarcities and lower remaining scarcity costs in Southern California (Table 4-7). Under the regional water market both the urban and agricultural users of Coachella Valley experience large scarcities (7.3% agricultural scarcity and 24.7% urban scarcity). Increased recharge capacity would allow more Colorado River water to be recharged and pumped to Coachella Valley urban users.

The other major piece of infrastructure with significant expansion shadow values is the Colorado River Aqueduct that provides water to urban users in Coachella Valley and MWD areas. Both areas experience scarcities under the Southern California regional water market. Increased capacity would allow additional supplies to be transferred from Colorado River agricultural users to decrease remaining urban scarcities and associated costs in Southern California.

With a statewide water market, conveyance capacity expansions have significant, but somewhat less economic value. The greatest benefits would come from expanding Coachella's artificial recharge facility in Southern California and the Hetch Hetchy Aqueduct in the San Joaquin and South Bay Region.

Reasons for the high economic expansion values of key facilities in the statewide water market are the same as those under regional water markets (in general). The shadow values for Region 3 facilities (Hetch Hetchy Aqueduct, San Francisco Recycling, South Bay Groundwater Pumping, and South Bay Recycling) now reflect the Delta export pumping costs ($22/af). Had the pumping costs been correctly reflected in the regional water market, statewide water market shadow values would be lower than the corrected regional water market values for these four facilities. To reiterate, all conveyance and other facilities with significant shadow values, currently are proposed to provide water to demand areas that experience scarcities in the statewide water market. The highest expansion values are on Coachella artificial recharge, which supplies water to Coachella urban users. The average shadow value for Coachella artificial recharge increases in the statewide water market because the statewide water market unconstrained model had to be run using three sequential time periods to cover the 72-year hydrologic period. Since end-of-period storages were set to their Base Case values for each sequence, Coachella scarcity costs were sometimes greater in the statewide market. The value of expanding the Folsom South Canal and/or building the proposed connector canal between the Mokelumne Aqueduct and Contra Costa Canal do not change from the regional water market to the statewide because scarcities and associated costs to Contra Costa Water District and East Bay MUD do not change between the two market scenarios. The value of the proposed East Bay to/from South Bay reversible connector increases slightly in the statewide water market.

The expansion value for the Colorado River Aqueduct decreases from the regional water market to the statewide water market because scarcities in Central MWD, East and West MWD, and San Diego decrease with increased Delta imports. Decreased shadow values for the Region 3 facilities reflect the decreased reliance on California Aqueduct water.

CONJUNCTIVE USE OF GROUND AND SURFACE WATERS

Conjunctive use refers to the coordinated use of both groundwater and surface water to meet a region's demands. The regional and statewide water markets use groundwater in conjunction with surface water for over-year storage to a greater extent than the Base Case (Figure 4-9). In wetter years, more surface water is used than for the Base Case, and in dry years more groundwater is used. On a monthly or seasonal basis (Figure 4-10), the regional water market decreased average groundwater pumping during the wet months (January and February) and increased average pumping during the drier months (July and August). This seasonal trend is somewhat greater with a statewide water market. Some specific instances of conjunctive use operations are explored in sections below and in the regional and statewide Appendices 2A-2G.

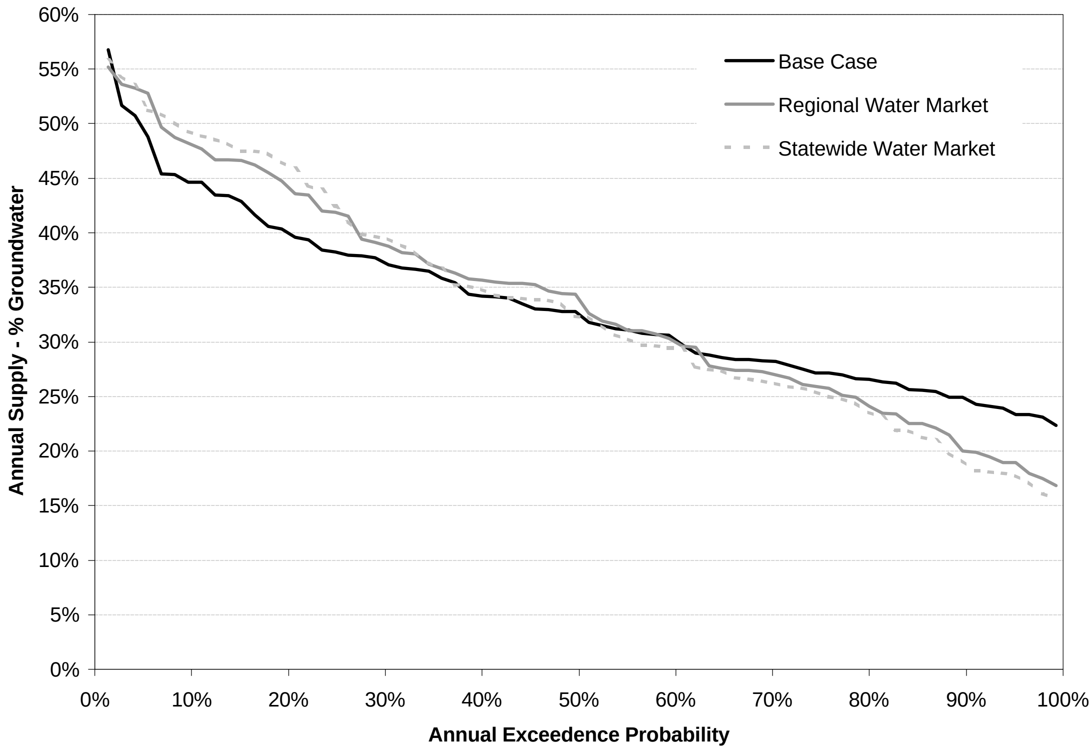


Figure 4-9. Reliance on Groundwater and Conjunctive Use

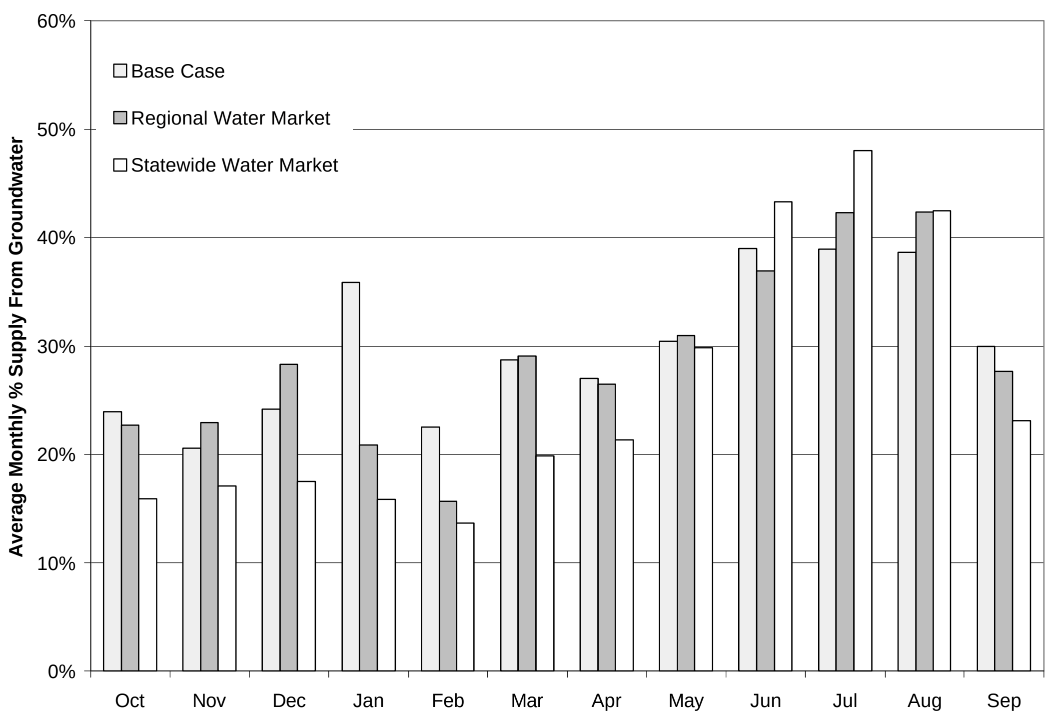


Figure 4-10. Monthly Percent Supply from Groundwater

CHANGING OPERATIONS WITH REGIONAL WATER MARKETS

In each regional water market, water is distributed, stored, and moved differently within the existing infrastructure. These CALVIN model results are idealized in the sense of perfect foresight and do not reflect all considerations, such as hydropower, water temperature, and real time flood control operations. These results are interesting and useful, but not necessarily conclusive from the broader operating context. More examples of operational changes are examined in the Appendices 2A-2F, which examine each region separately.

Conjunctive Use Operations

In several cases, changes in surface and groundwater use improved supply reliability to users and/or decreased operating costs (related to delivery and urban water quality). There are examples of improved conjunctive use operations that involve urban and agricultural transfers as well as agricultural to agricultural transfers.

Greater Sacramento Region

In the Lower Sacramento Valley and Bay-Delta regional model, Greater Sacramento eliminated all diversion from the Sacramento River, significantly reduced American River diversions, and replaced these supplies with more pumping from CVPM 7 and 8 groundwater basins. This enabled CVPM 7 to withdraw more water from the Sacramento River and decrease its groundwater pumping from CVPM basin 7. Likewise, CVPM 8 was able to withdraw more from the American River via the Folsom South Canal and also decrease its CVPM 8 groundwater basin pumping. The two agricultural regions saw decreased operating costs as a result of decreased pumping ($5.8 million/yr and $0.7 million/yr, respectively) while Sacramento saw decreased operating costs for surface water treatment. For Sacramento pumping groundwater from the two available basins at $57/af and $55/af is cheaper than treating Sacramento and American River water ($70/af and $60/af, respectively). Overall, Sacramento saw a $3.0 million/year reduction in operating costs for a combined agricultural-urban operating benefit of $9.5 million/year. These changes in the inter-annual patterns of Sacramento and American River diversions may have other impacts for instream flow conditions (see "Other

Stockton Urban Area

The urban users in Stockton decreased groundwater pumping (by 10 taf/yr) and increased Stanislaus and Calaveras River deliveries. Both the Stanislaus and Calaveras Rivers have lower treatment costs ($25/af and $40/af, respectively) than groundwater pumping ($70/af). The result is that Stockton saw a $0.7 million/yr decrease in operating costs.

Tulare Basin

However not all changes in conjunctive use resulted in benefits to all users. Agriculture users in the Tulare Basin experience some increased scarcities as urban users increased their ground and surface water use.

The city of Fresno depends on groundwater. In the regional water market, CVPM 16 decreased groundwater pumping by 42.5 taf/yr. Offsetting reductions in pumping with more surface water diversions, CVPM 16 then experienced a relatively small increase in scarcity, resulting in $0.1

million/year in scarcity costs. However, the reduced groundwater pumping decreased operating costs by $1.3 million/year, so that CVPM 16 experiences a net decrease of $1.2 million/year in total costs.

Fresno was then able to pump 42.5 taf/yr more groundwater (given up by CVPM 16) to reduce its scarcity to zero. As a result, Fresno saw an increase in operating costs ($3.4 million/year), but it was offset by a $17.7 million/year decrease in scarcity costs.

Bakersfield increased surface water deliveries and decreased groundwater pumping in the regional water market to reduce its operating costs by $6.1 million/year. The deliveries to Bakersfield reduced the amount of surface water available to CVPM 21, which meant they pumped additional groundwater but were unable to achieve full deliveries. Thus CVPM 21 saw increased scarcity costs as well as operating costs ($1.4 million/year and $4.4 million/year, respectively).

Upper Sacramento Valley

The Upper Sacramento Valley's agricultural users changed their surface and groundwater deliveries in the regional water market. Groundwater consumption and operating costs increased for CVPM 1 and 2 ($6 thousand/year and $262 thousand/year, respectively) and decreased for CVPM 3 and 4 ($74 thousand/year and $50 thousand/year, respectively). CVPM 2 and 3 increased deliveries from the Sacramento River, which reduced their scarcity and associated scarcity costs (by $3.2 million/year and $0.2 million/year, respectively). On the other hand significantly less water was delivered from the Sacramento River to CVPM 1 and 4, which experienced increased average scarcity and scarcity costs ($9 thousand/year and $2.1 million/year, respectively). However, despite the increased operating and scarcity costs to two of the CVPM regions, overall the Upper Sacramento Valley saw a $1.2 million/year decrease in total costs.

Cooperative Operations

Cooperative operations, water exchanges, and water transfers under regional water markets could occur between urban and urban, agricultural and agricultural, and urban and agricultural users. On average, agricultural users would see increased annual scarcities, while urban users would see reductions. Only the Lower Sacramento Valley and Bay-Delta along with the San Joaquin and South Bay Regions' agricultural sectors would see elimination of scarcities. Urban users in San Joaquin and South Bay and Tulare Basin Regions would see complete eliminations of scarcity, as well as all but one urban user in the Lower Sacramento Valley and Bay-Delta. (The Upper Sacramento Valley has no economically driven urban demands represented in the model.) The agricultural sector in Southern California would see an annual average increase of 406 taf/year of scarcity under a regional water market. However, the urban sector of Southern California would see an annual average reduction of 597 taf/year in scarcity.

Although agricultural water scarcity increases, total costs (scarcity and operating) decrease for both agricultural and urban users in the regional water markets. An aggregate improvement may not be enough to convince individual agricultural users to face the risk of increased scarcity and scarcity costs. Individual urban users should be willing to participate in regional water markets without facing significant risks of increased scarcity or scarcity costs.

Exchanges to Enhance Water Quality and Reliability

Each surface supply for an urban area has a treatment cost which reflects the quality of the available water. Lower quality sources are more expensive to treat and many urban areas changed supply mixes in the unconstrained alternatives to increase deliveries from higher quality (cheaper) sources. Trades of water to better match source quality to users' needs typically occurred between urban and agricultural users. Agricultural users are less concerned with water quality than urban areas (i.e., agricultural users generally do not pay treatment costs for water).

For example, Napa-Solano in the Lower Sacramento Valley relied entirely on water deliveries from the Putah South Canal (Lake Berryessa) in the regional water market. In the Base Case, the urban area relied equally on deliveries from the Putah South Canal and the North Bay Aqueduct (Sacramento River). Treatment and distribution costs of Putah South Canal water are $65/af, while treatment and distribution costs from the North Bay Aqueduct are $75/af. By eliminating Sacramento River water, Napa-Solano reduced surface water operating costs. In turn CVPM 6, which used water from Putah Creek in the Base Case, increased Sacramento River deliveries. For CVPM 6, Sacramento River and Putah Creek waters are economically equivalent.

Another example of water quality-based trades and other exchanges for reduced operating costs occurred between Bay Area and San Joaquin agricultural users. Santa Clara Valley eliminated deliveries via the South Bay Aqueduct and increased deliveries from SFPUC (Tuolumne River) and via the Pacheco Tunnel. Both the South Bay Aqueduct and Pacheco Tunnel deliver Delta exports, however the Pacheco diversion is located further south and has lower pumping and treatment cost ($375/af) than those of the South Bay Aqueduct ($404/af). CVPM 10, which diverts water from the California Aqueduct south of the South Bay Aqueduct and north of Pacheco Tunnel, eliminated California Aqueduct deliveries and substituted Delta Mendota Canal water. For CVPM 10 in CALVIN, California Aqueduct and Delta-Mendota Canal water are economically equivalent.

Trades between various users (primarily agricultural and urban) have the potential to reduce operating costs for both agricultural and urban users. If an urban user can substitute higher quality water for lower quality water, then treatment costs will decrease. Agricultural users rarely see major differences between surface water supplies and therefore should not incur increased economic costs when trading with urban users in many of these cases.

Potential Environmental Benefits

Environmental demands could benefit from regional water markets. As presented earlier, shadow values on environmental requirements decreased with regional water markets. Flows increased through some reaches with minimum flows, and decreased in others. Most minimum flow requirements are on Northern California Rivers, principally the Sacramento, American, and Feather Rivers as well as Delta outflows.

<u>Sacramento Valley Flows</u>

Flows in the two critical reaches of the Sacramento River changed little in the regional water market. Sacramento River below Keswick saw a 78.3 taf/year (1.2%) average decrease in flows, while the Sacramento River at the Navigation Control point saw a 32.6 taf/year (0.4%) increase. Clear Creek saw large increases in flows in the regional water markets.

The American River saw a small decrease (89.1 taf/year or 3.6%) in average flows through the minimum instream flow reach with the regional water market. Flows were higher in April through July and lower in other months (see Figure 4-11). The Feather River saw a 322.9 taf/year (11.2%) average increase in flows through the critical reach in the regional water market, higher in all months except June and July (see Figure 4-12).

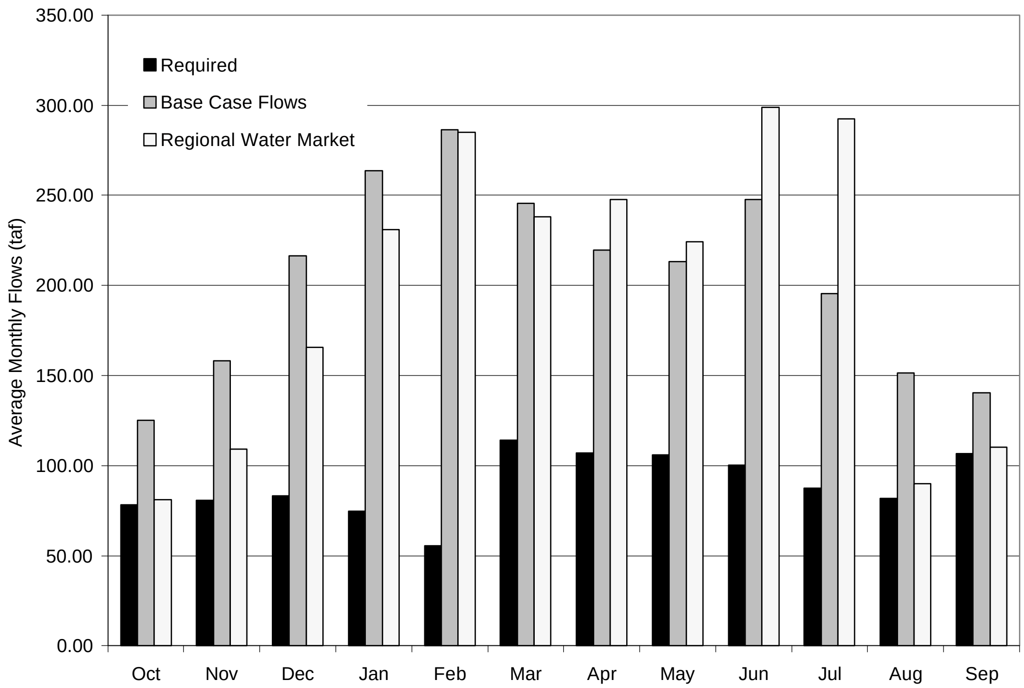


Figure 4-11. Monthly Average Flows for the American River (taf)

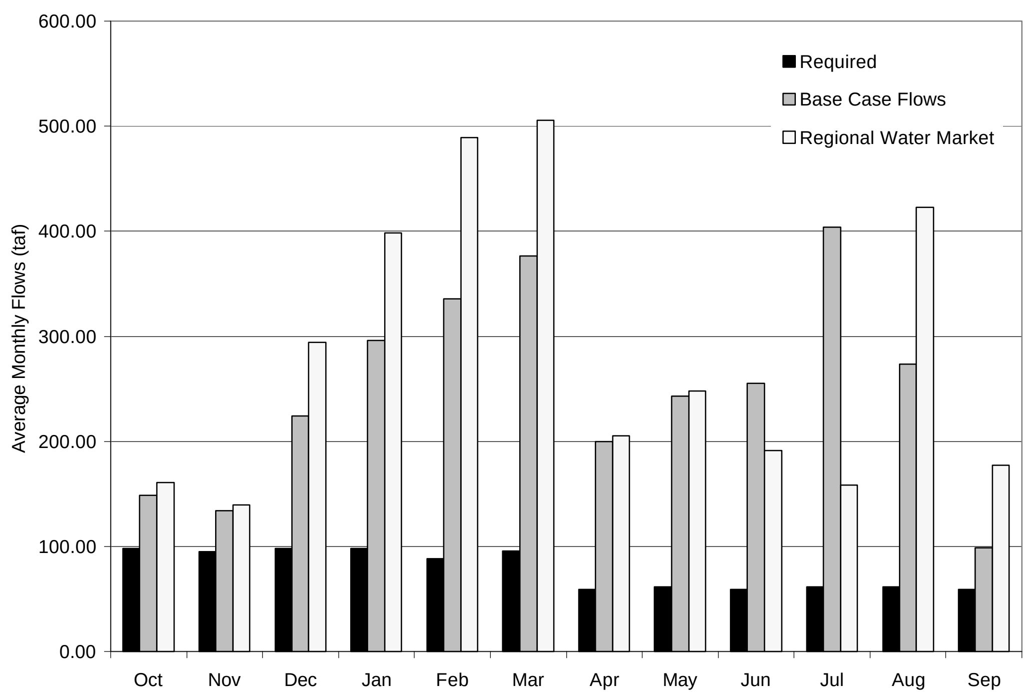


Figure 4-12. Monthly Average Flows for the Feather River (taf)

Changes in monthly average flows through the critical reaches (both increases and decreases) tend to occur over consecutive months. Depending on the reason for the minimum instream flow requirement (fish, wildlife habitat, recreation, etc.) these changes may or may not be beneficial. Minimum flows on both the American and the Feather Rivers are, in part, to help protect and promote fish populations. The late fall through early spring months (October through May) are the most important periods for critical fish species found in the area. Since the increased flows in the Feather River occur from August through May, it would appear that the regional water market would benefit the environment. However, the American River flows decrease from August through March, which probably would not be beneficial.

Another important issue regarding the environment is how much water is available during critically dry periods (14 drought years of the 72-year hydrologic period). Figures 4-13 and 4-14 show a general decrease in drought year flows in the American River during critical months and an increase in such flows in the Feather River. Flows on the American increased in April through July, but decreased in other months, with a net decease of 58.6 taf/year in drought years from the Base Case. Feather River flows increased in October, January, February, March, June, and August, with a net increase over the Base Case of 220 taf/year during drought years.

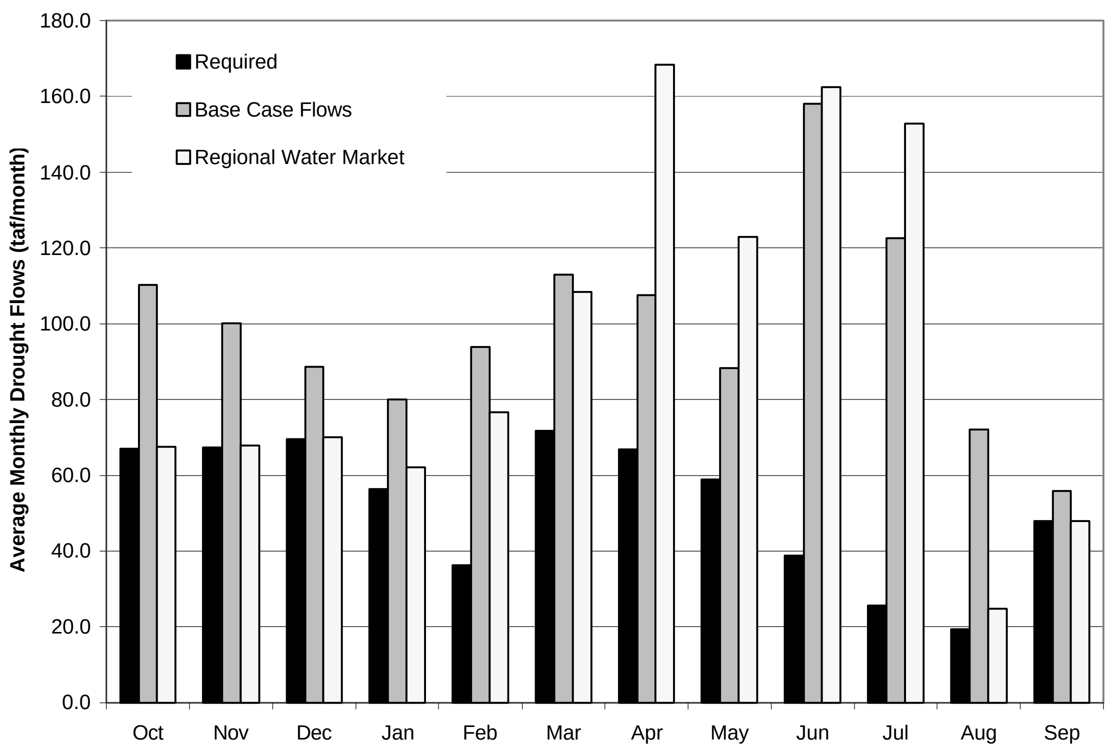


Figure 4-13. Monthly Drought Flows for the American River (taf)

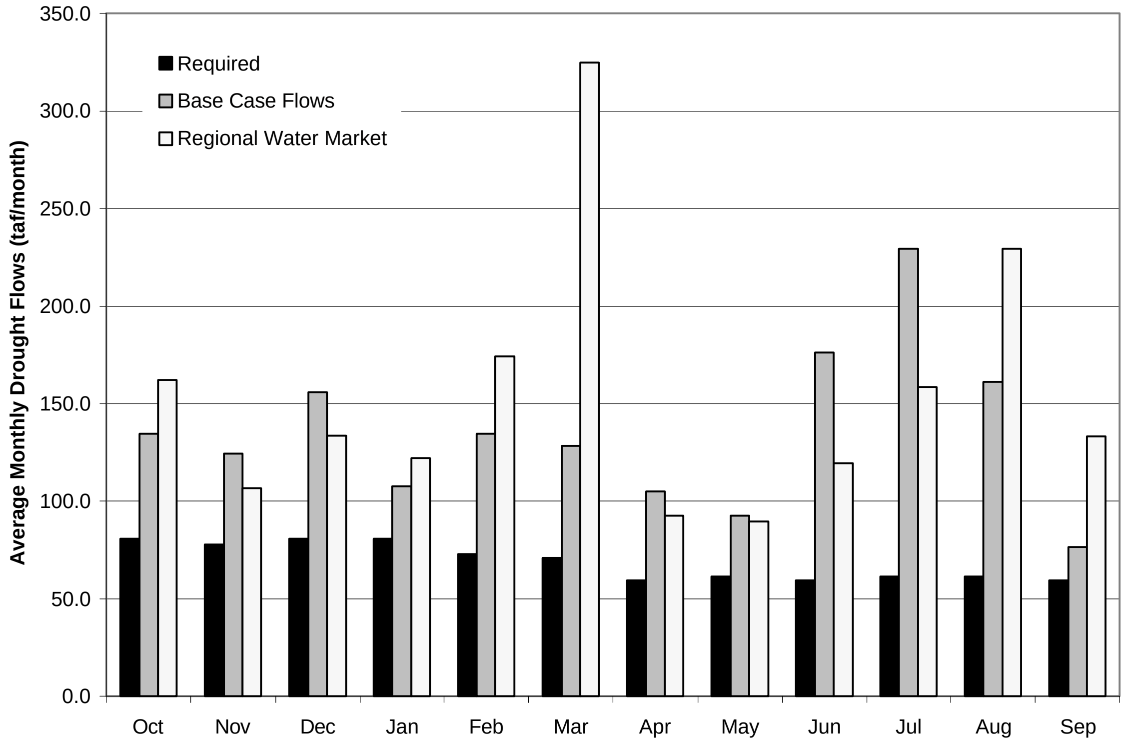


Figure 4-14. Monthly Drought Flows for the Feather River (taf)

<u>Delta Outflows</u>

The other major environmental flow requirement is for the Bay-Delta. Over 5,500 taf/year of Delta minimum outflow is required on average, to protect and restore the wildlife habitat in the area and prevent salinity intrusion, among other things. In addition to the required Delta outflow, surplus Delta outflows are sometimes available. Surplus Delta outflows are flows in excess of required outflows. With regional water markets, there is approximately 78 taf/year less surplus Delta outflow (0.9% less than the Base Case) (Figure 4-15). During drought periods there is little to no surplus flow available from May through September (Figure 4-16). On average during critically dry months there is approximately 203 taf/year less surplus Delta outflow.

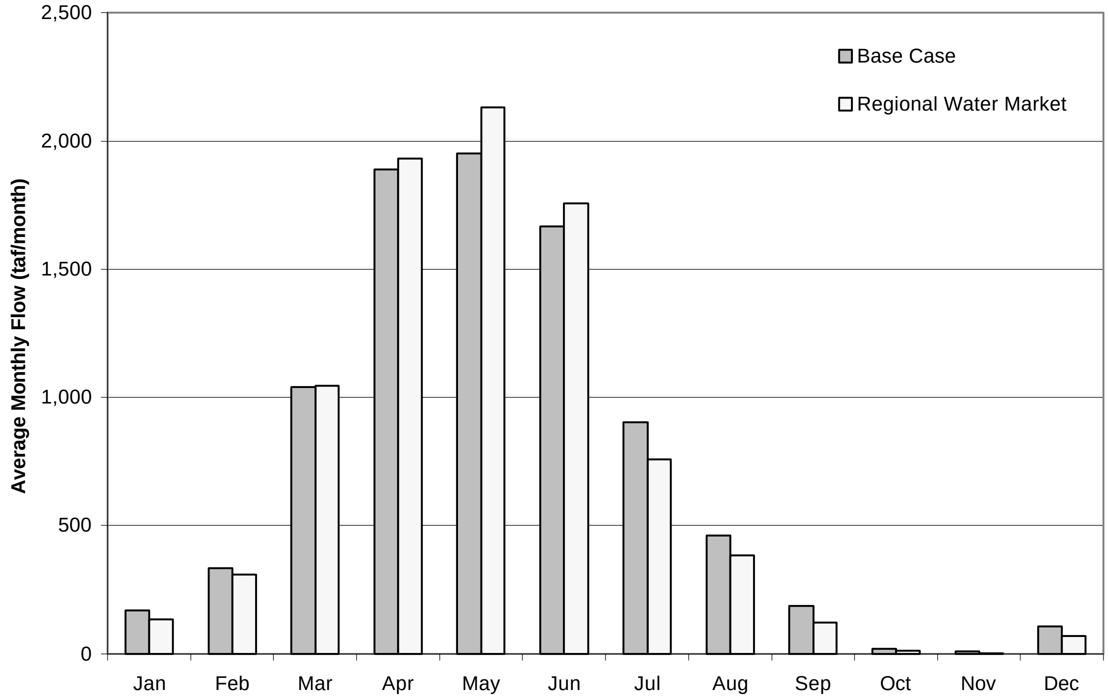


Figure 4-15. Monthly Average Surplus Delta Outflows (taf)

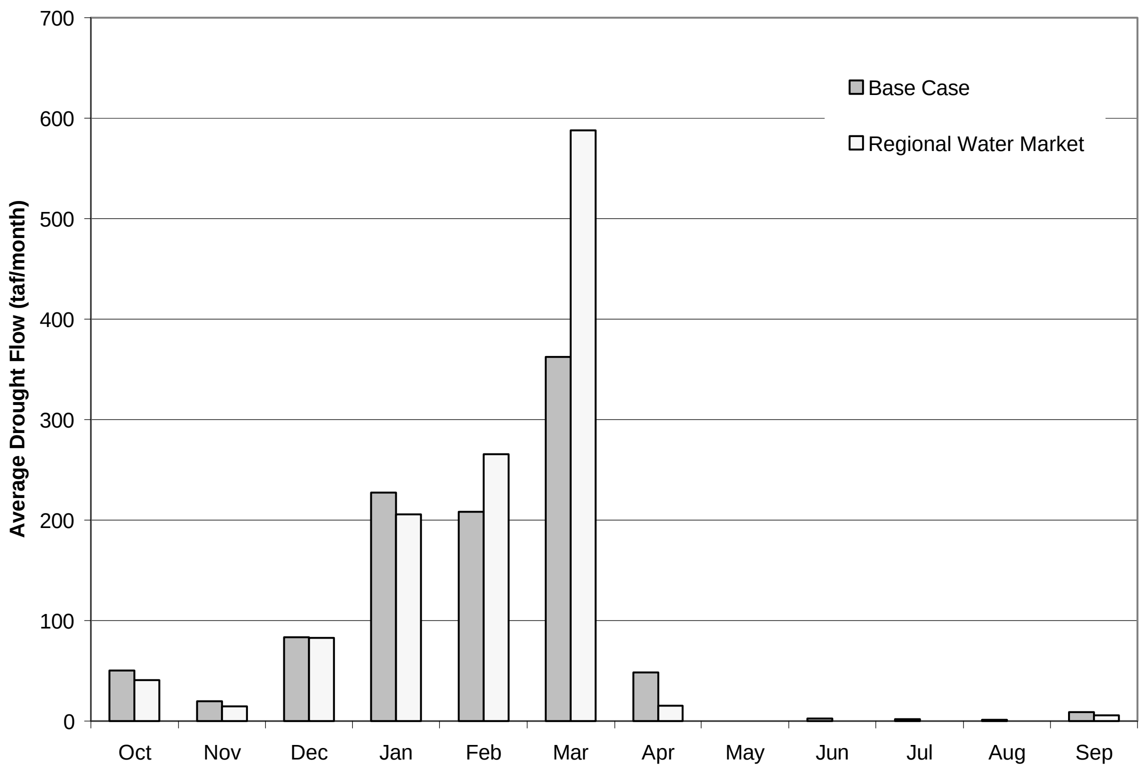


Figure 4-16. Monthly Drought Surplus Delta Outflows (taf)

CHANGING OPERATIONS WITH STATEWIDE WATER MARKETS

This section presents some operational changes suggested by CALVIN model results with an ideal statewide water market. Significant changes in operation occur in the Sacramento Basin, in south-of-Delta operations, and in the Bay-Delta. The results are interesting and useful, but are not necessarily conclusive for the broader operating context. More details on these and other operational changes appear in Appendix 2G.

Conjunctive Use Operations

Re-operation of the surface water sources and increased conjunctive use opportunities alter the way water is distributed and stored given the existing infrastructure, water resources, operating costs, and economic demands in the statewide water market. See Figure 4-9 and 4-10 for overall changes in groundwater pumping with a statewide water market.

Sacramento Basin Conjunctive Use

The Sacramento Basin includes demands north of and in the Bay-Delta (CVPM agricultural regions 1 through 9, Yuba, Sacramento, Stockton, CCWD, EBMUD, and Napa-Solano). In addition to these economic demands is the Delta itself, one of California's most important and sensitive environmental areas. Many of upstream rivers (such as the Sacramento, Feather, and American) are subject to minimum instream flows to provide sufficient water for environmental purposes.

The Sacramento and American Rivers not only have large minimum instream flow requirements, but also are major water sources shared by many local water users. Figure 4-17 illustrates increased conjunctive operation of Sacramento basin surface and groundwater resources under the statewide water market. The figure also compares Base Case and statewide water market use of the three sources in drought and non-drought years. In both the Base Case and statewide water market during non-drought years (normal and wet), the largest supply source is the Sacramento River, with groundwater pumping a close second and the American River a distant third. However, under optimized statewide operations, Sacramento River in-basin use in non-drought years is higher than in the Base Case, contributing over half of the supply (Table 4-8). Non-drought year diversions from the American River and groundwater pumping are lower than for Base Case operations.

During drought years (14 out of the 72-year hydrologic period) the situation is markedly different. While the Base Case obtained a little more than half (53%) of its supply from groundwater during drought years (Figure 4-17), the statewide water market used significantly more groundwater, providing 64% of drought year supply. Simultaneously, withdrawals from the Sacramento and American Rivers drop respectively 430 taf and 228 taf, in the statewide water market compared to Base Case drought year operations (Table 4-8).

An important limitation is that minimum groundwater pumping requirements are not imposed in CALVIN. In practice not all agricultural water users in a CVPM region have access to surface water, and some must pump groundwater. Every CVPM region has some minimum amount of groundwater pumping which may not be respected in the CALVIN results.

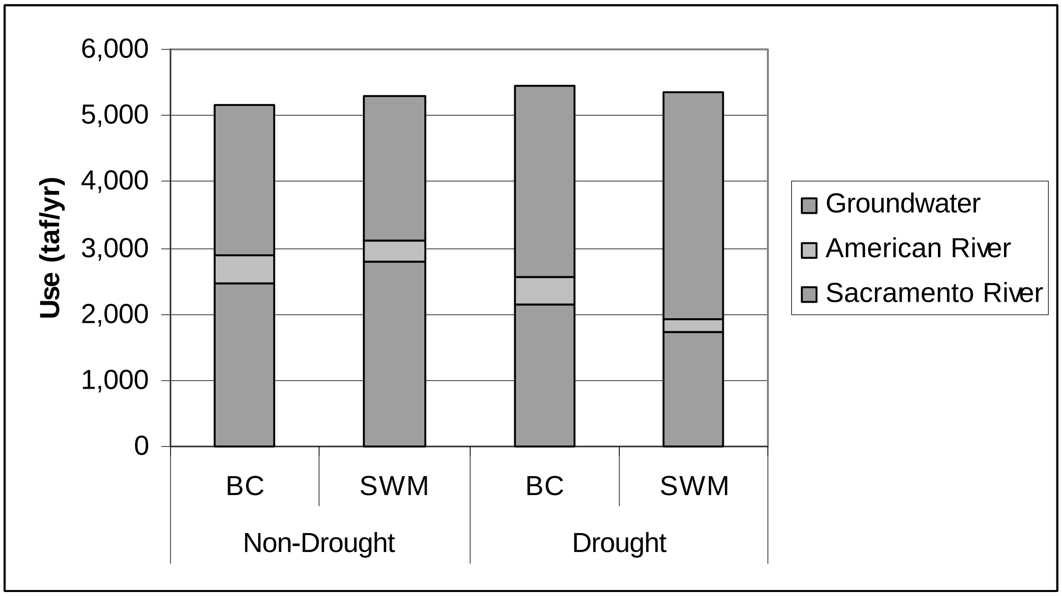


Figure 4-17. Sacramento Basin Supplies for Base Case and Statewide Water Markets

Table 4-8. Sacramento Basin Conjunctive Operational Changes

		Non-Drought		Drought	
		Average Diversions/Pumping (taf/yr)	% of Supply	Average Diversions/Pumping (taf/yr)	% of Supply
Sacramento River	BC	2468	48%	2164	40%
	SWM	2794	53%	1734	32%
American River	BC	432	8%	406	7%
	SWM	324	6%	178	3%
Groundwater	BC	2262	44%	2894	53%
	SWM	2167	41%	3449	64%
Total	**BC**	**5161**		**5463**	
	SWM	**5285**		**5361**	

BC = Base Case, SWM = Statewide Water Market

Changes in diversions from the Sacramento and American Rivers under the statewide water market re-operations can have significant consequences for the environmental concerns in the region. In the Base Case, diversions from both the Sacramento and American Rivers are fairly consistent across all years, even during critically dry periods (Figures 4-18 and 4-20). In contrast, under the greater basin-wide conjunctive operations of the statewide water market, diversions are much more variable, depending on hydrologic conditions. They frequently drop much lower than in the Base Case, especially during critically dry periods (Figures 4-19 and 4-21) and rise to higher levels during wet years.

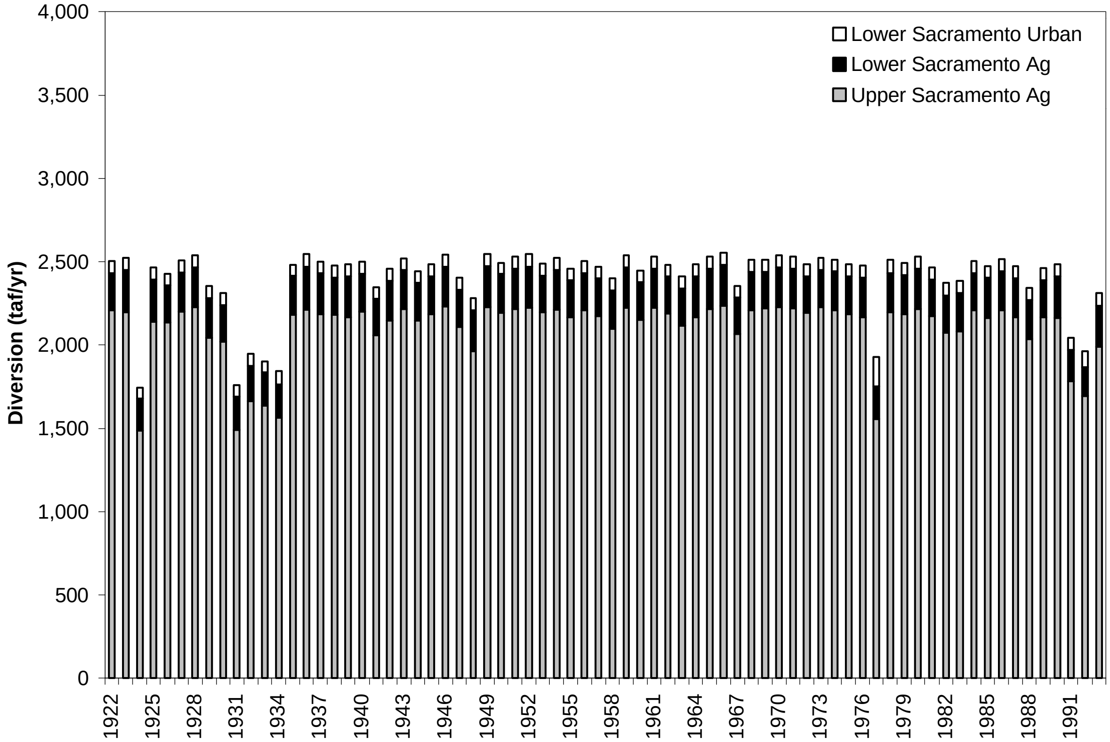


Figure 4-18. Base Case Sacramento River Annual Diversions (taf)

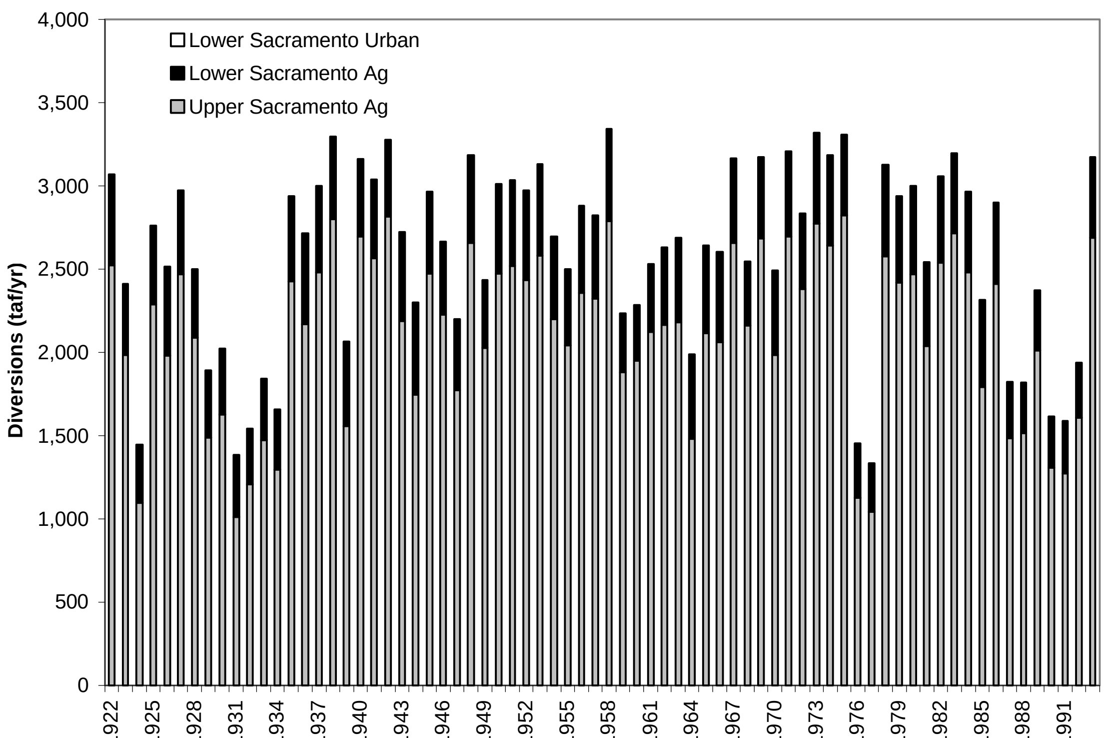


Figure 4-19. Statewide Water Market Annual Sacramento River Diversions (taf)

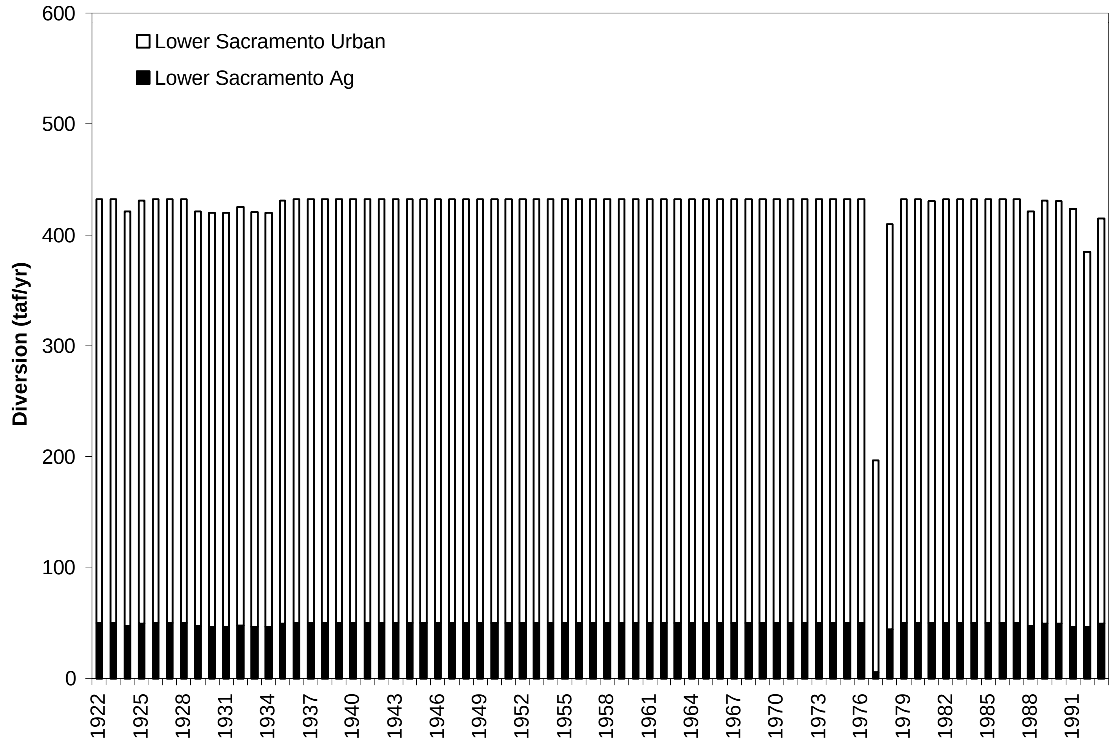


Figure 4-20. Base Case Annual American River Diversions (taf)

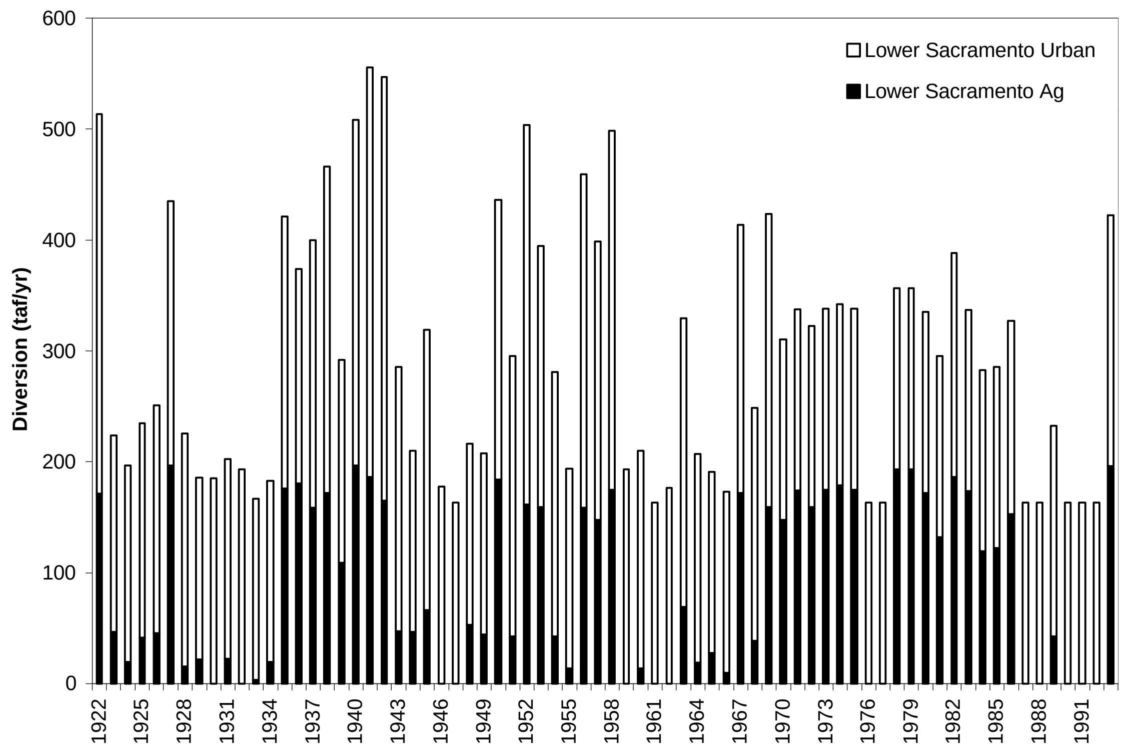


Figure 4-21. Statewide Water Market Annual American River Diversions (taf)

In the statewide water market, the Lower Sacramento urban area (Greater Sacramento) completely eliminated diversions from the Sacramento River. Water from the Sacramento River has the highest treatment costs ($70/af) of the sources available to the area (not counting recycled water treatment costs). Pumping groundwater from the two available basins (CVPM 7 and 8) at $57/af and $55/af or using American River water ($60/af) is cheaper than treating Sacramento River water. Thus ideally urban users would want to minimize diversions from the Sacramento River, which is what occurs with the statewide water market.

In non-drought years, statewide water market allocations from the Sacramento River increase by 326 taf/yr, on average, over the Base Case while allocations from the American River and groundwater pumping decrease. During drought years, allocations from the Sacramento River now are 430 taf/yr less than in the Base Case. The difference is made up in the statewide water market by greater groundwater pumping. Diversions from the American River drop even lower in drought years under the statewide water market (Table 4-9). Overall under the statewide water market, diversions are reduced during drought periods by 1206 taf/yr from non-drought year averages, compared to only 330 taf/yr reduction in Base Case diversions from non-drought to drought years.

Table 4-9. Comparison of Sacramento and American River Diversions

	Sacramento River		American River	
	BC	SWM	BC	SWM
Drought Average Diversions (taf/yr)	2164	1734	406	178
Non-Drought Average Diversions (taf/yr)	2468	2794	432	324
Change in Diversions (taf/yr)	-304	-1060	-26	-146

BC = Base Case, SWM = Statewide Water Market

It should be noted that the maximum channel capacity for American River diversions to CVPM 8 was mistakenly set in these CALVIN runs at 19.7 taf/month greater than what is physically possible. As a result, CVPM 8 may withdraw too much water from the American River in these results. Thus the conjunctive and cooperative operations results may have small inaccuracies in the details, but the overall trends are not affected.

South-of-Delta Re-Operations

Under the statewide unconstrained alternative, the area of the state south of the Delta experiences significant changes in conveyance and reservoir operations. These changes are driven by both agricultural-to-urban transfers and through re-operation of the SWP and CVP facilities, which export water from the Delta to the Bay Area, agricultural users in the San Joaquin and Tulare Basin portion of the Central Valley, and urban areas of Southern California. Table 4-10 indicates trends in conveyance re-operations.

Table 4-10. South-of-Delta Major Conveyance Operational Changes

	Average Annual Flows (taf/yr)		
	BC	RWM	SWM
California Aqueduct			
Banks Pumping Plant	3544[a]	3544[b]	4142
Region 3 to 4	4174	4174[b]	3736
Region 4 to 5	2079	2079[b]	2169
Delta Mendota Canal			
Tracy Pumping Plant	2646[a]	2646[b]	1691
Entering Mendota Pool	857	877	996
TOTAL SOUTH OF DELTA PUMPING	6190	6190[b]	5833
Hetch Hetchy Aqueduct			
Into Bay Area	297	336	336
Friant Kern Canal			
Diverted from Millerton Reservoir	1125	1125[b]	1470
After CVPM 16 and 17	1052	1037	1373
After CVPM 18 and 19	366	316	492
Los Angeles Aqueduct			
Owens Valley Power Plant	n/a	387	390
After Agricultural Diversions	343	387	390
Colorado River Aqueduct			
Pumped from Colorado River Aqueduct	850	1303	1303
Emptying into Lake Matthews	402	509	505

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

[a] Though it appears Delta pumping shifts dramatically away from the DMC to the California Aqueduct in the SWM, CALVIN routes DMC deliveries through the Aqueduct via the O'Neill power station.

[b] Constrained to value in the base case, as a regional boundary

Table 4-10 indicates how Delta pumping responds to a statewide water market. CALVIN routes Delta water to DMC contractors through the O'Neill power station to gain additional benefit, ultimately resulting in a 300 taf/yr increase in DMC deliveries, despite a decrease of almost 1 maf per year in pumping from Tracy (as indicated in Figure 4-23). However, a net decrease in California Aqueduct flows of 660 taf/yr reduces total exports from the Delta by an average of 360 taf/yr. Specifically, California Aqueduct diversions to demands in the Tulare Basin decrease by almost 440 taf/yr, while exports to Southern California increase by only 90 taf/yr. In summary, decreased Delta exports prioritize agriculture in the San Joaquin Valley and Southern California urban use, and reduce Delta exports to the Tulare Basin (Figure 4-22).

In concert with the changes in California Aqueduct operations, deliveries through the Mendota Pool and the Friant Kern Canal play a greater role in meeting Tulare Basin demands. Friant Kern Canal diversions from Millerton Lake increase by almost 350 taf/yr and Tulare Basin agricultural supplies from the Mendota Pool increase by 81 taf/yr. Since these increased flows reduce water to the San Joaquin River system, the Delta Mendota Canal increases supplies to San Joaquin River users through the Mendota Pool. Ultimately, about 440 taf/yr of California Aqueduct diversions to the Tulare Basin Region are replaced with water from the San Joaquin system. This supply change facilitates more efficient use of surface supplies, reduces operating and scarcity costs, and helps eliminate the large Base Case agricultural scarcities in CVPM 18 (see Appendix 2G for Tulare Basin details). This strategy, which emerges from the optimization model, of using San Joaquin River water for the Tulare Basin and Delta water for the San Joaquin Valley, accentuates a statewide water management strategy in place since the 1930 California Water Plan.

Despite significant scarcities in Southern California in both the Base Case and regional market, California Aqueduct flows over the Tehachapis increase by only 90 taf/yr. Instead, approximately 400 taf/yr of agricultural transfers of Colorado River water are used to alleviate urban scarcities in the Southern California at less cost than SWP imports. Additional urban supplies from the Colorado River for Coachella, San Diego, Central and Eastern and Western Metropolitan Water District demands allow some SWP imports to be reallocated to urban areas such as Mojave, Castaic Lake, and Antelope Valley in the statewide water market. As reported earlier in this chapter, the high shadow value on the Colorado River Aqueduct provides strong incentive for expanding the capacity of this facility. Figures 4-22 and 4-23 graphically display these conveyance re-operations.

At reported earlier, significant expansion values remain in a statewide market for several south-of-Delta reservoirs, including Lake Kaweah ($32/af/yr) and Lake Success ($26/af/yr) in the Tulare Basin Region, and Grant Lake ($38/af/yr) on the Los Angeles Aqueduct. Expansion of these reservoirs would allow greater flexibility in operations, particularly in dry periods.

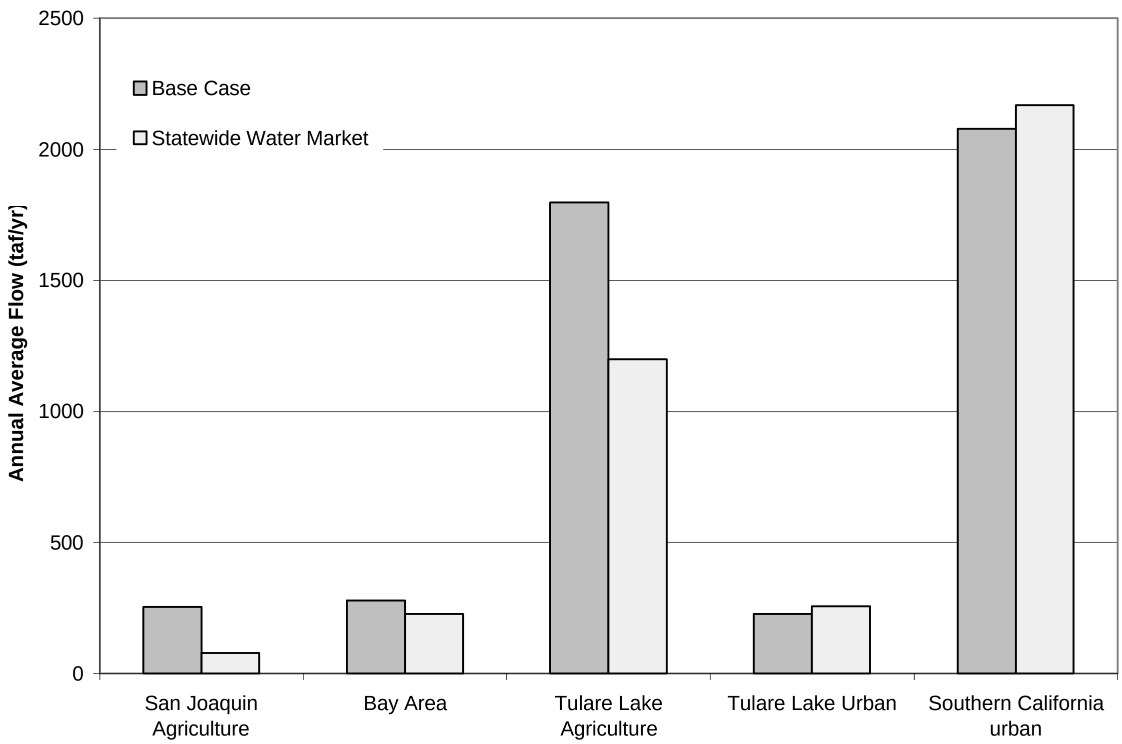


Figure 4-22. California Aqueduct Diversions with a Statewide Water Market

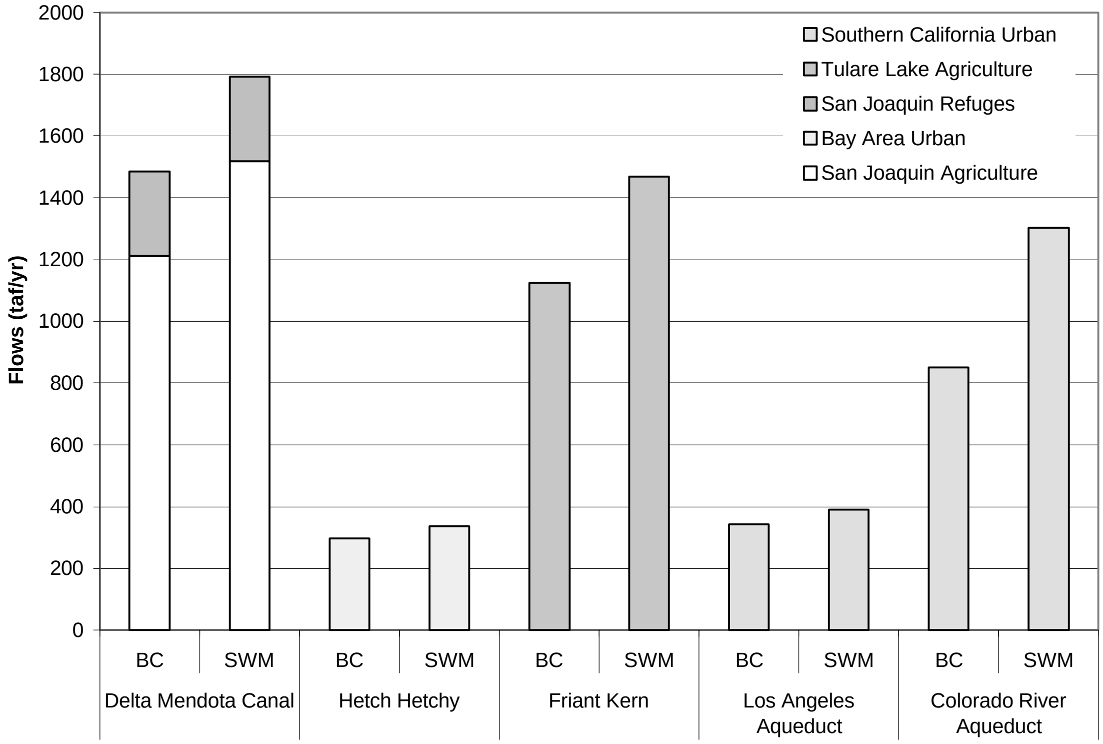


Figure 4-23. Major Conveyance Re-operation with a Statewide Water Market

Impacts on the Delta

Re-operation of the state's water supply, both north and south of the Delta, leads to changes in the amounts of water available in the Bay-Delta. The Bay-Delta is supplied from rivers in the northern portion of the state and is a major supply source for south-of-Delta demands. Both the California Aqueduct and the Delta Mendota Canal deliver water from the Bay-Delta (via Tracy and Harvey Banks Pumping Plants) to agricultural and urban demand areas in the San Joaquin and South Bay Region, Tulare Basin, and Southern California (CALVIN Regions 3, 4, and 5).

During drought years, Delta exports increase from 4.1 maf/yr in the Base Case to 4.8 maf/yr in the statewide water market. However, average non-drought year Delta exports decreased by 609 taf/yr in the statewide water market (Table 4-11).

Table 4-11. Delta Exports Comparison

	Average Exports, Non-Drought (taf/yr)	Average Exports, Drought (taf/yr)
Base Case	6,695	4,097
Statewide Water Market	6,086	4,822
Change (BC – SWM)	-609	725

The statewide water market increased Delta Exports in summer months and decreased exports in the winter months (Figure 4-24). (Some of these seasonal changes result from different seasonal patterns of SWAP demands compared to Base Case agricultural deliveries.) A similar pattern can be seen in average Delta exports during drought periods (Figure 4-25). Despite the increased drought exports, overall average Delta exports were smaller in the statewide alternative (Figure 4-26). For example, Delta exports exceeded 7021 taf/yr in 27% the years under the Base Case, but only 3% of years with the statewide water market.

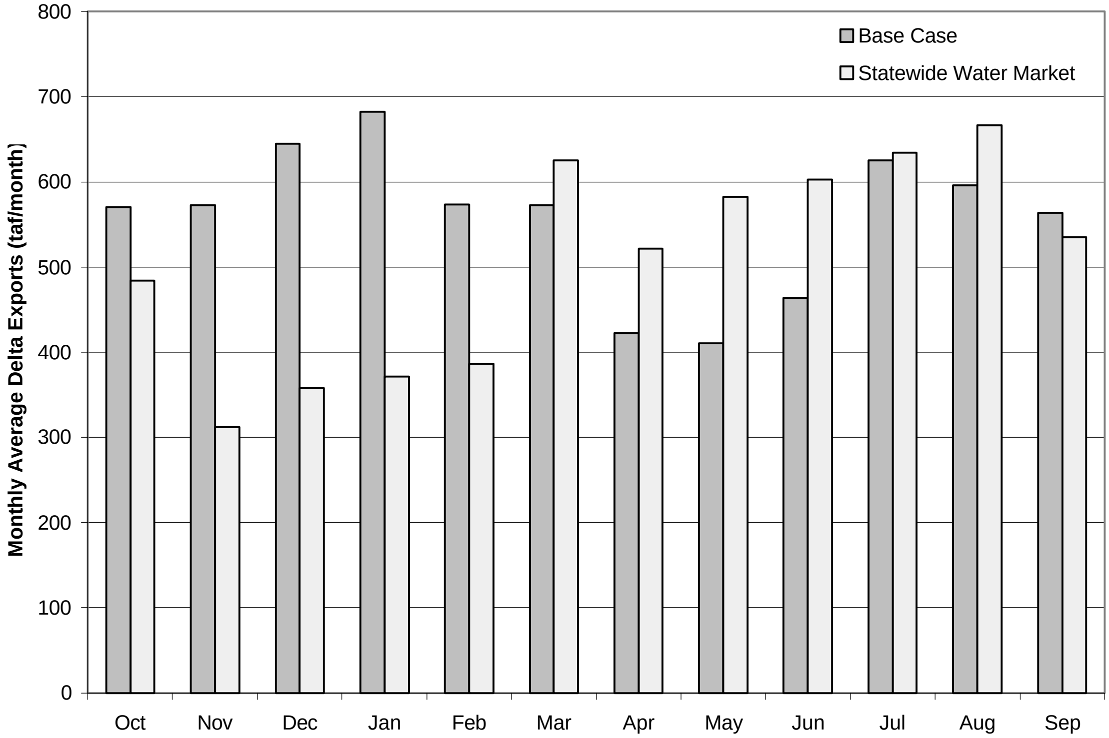


Figure 4-24. Non-Drought Year Average Monthly Delta Exports (taf)

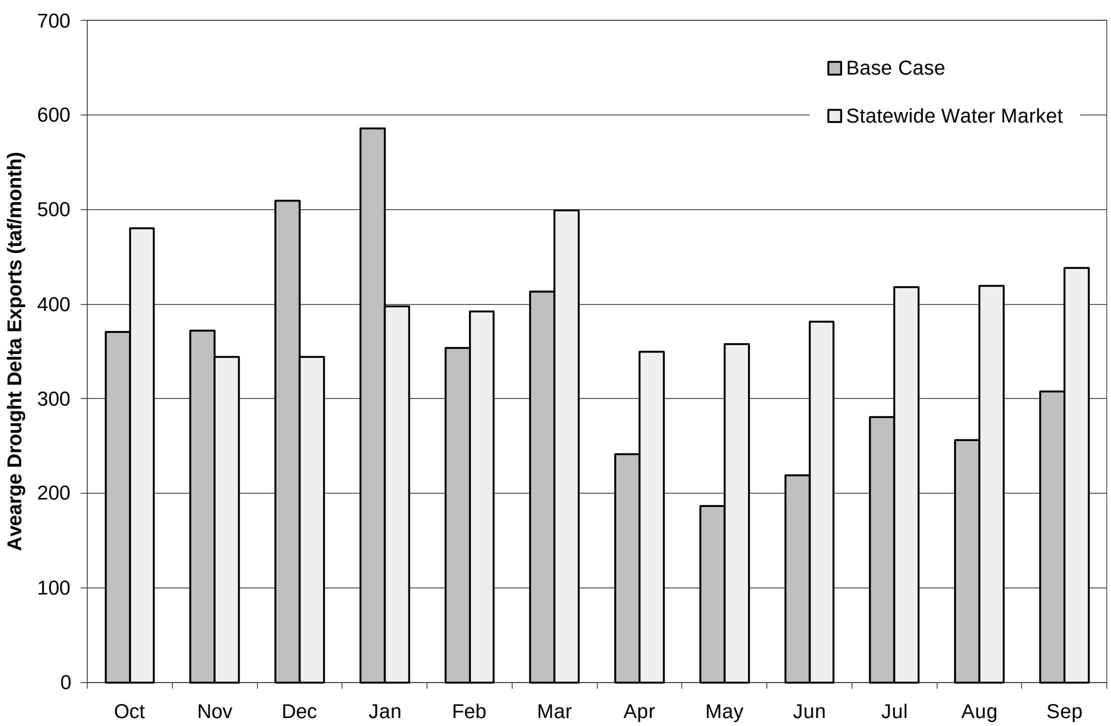


Figure 4-25. Drought Year Average Monthly Delta Exports (taf)

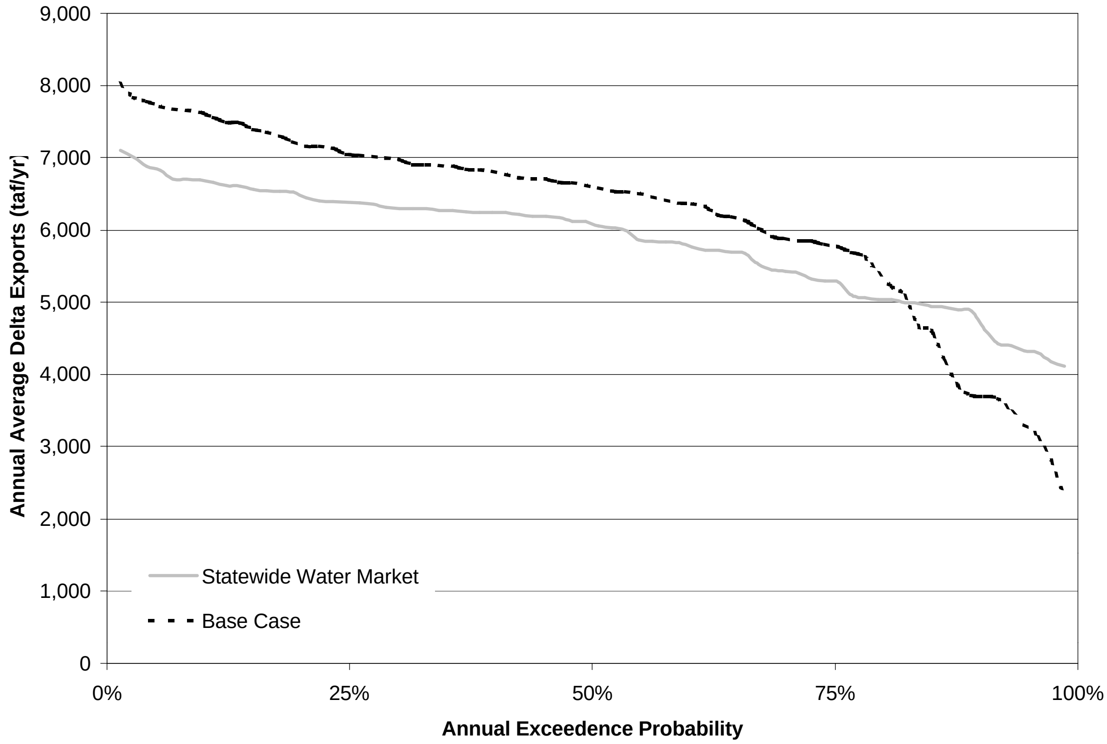


Figure 4-26. Annual Exceedence Probability of Delta Exports (taf/yr)

Changes in Delta inflows and exports affect the amount of water available for Delta outflows to San Francisco Bay. Surplus Delta outflow decreases by approximately 52 taf/yr in non-drought years and increase by 214 taf/yr in drought years (Table 4-12). On average surplus Delta outflows decrease by only 1 taf/yr in the statewide water market, which is in contrast with regional water markets where surplus Delta outflow decreased by 78 taf/yr from the Base Case. Surplus Delta outflow actually increases during drought years with a statewide water market, largely due to the greater conjunctive use of surface and groundwater that occurs with statewide water market re-allocations and re-operations.

Table 4-12. Surplus Delta Outflows (taf/yr)

	Surplus Delta Outflow, Non-Drought Years	Surplus Delta Outflow, Drought Years	Surplus Delta Outflow, All Years
Base Case	10602	1016	8738
Statewide Water Market	10550	1230	8737
Change (SWM – BC)	-52	214	-1

Despite having similar annual average values, the monthly distribution of the surplus Delta outflow varies between the Base Case and the statewide water market. Slightly more outflow occurs with the statewide water market in the winter and early spring months, with less flow in the summer and fall months. The same seasonal trend appears during drought years, except there is little to no surplus Delta outflow in summer and significantly higher outflow in winter. Thus the increased surplus Delta outflow presented in Table 4-12 in both non-drought and drought years is due to higher winter flows (Nov. to Mar.), rather than increased flow in all months (Figures 4-27 and 4-28).

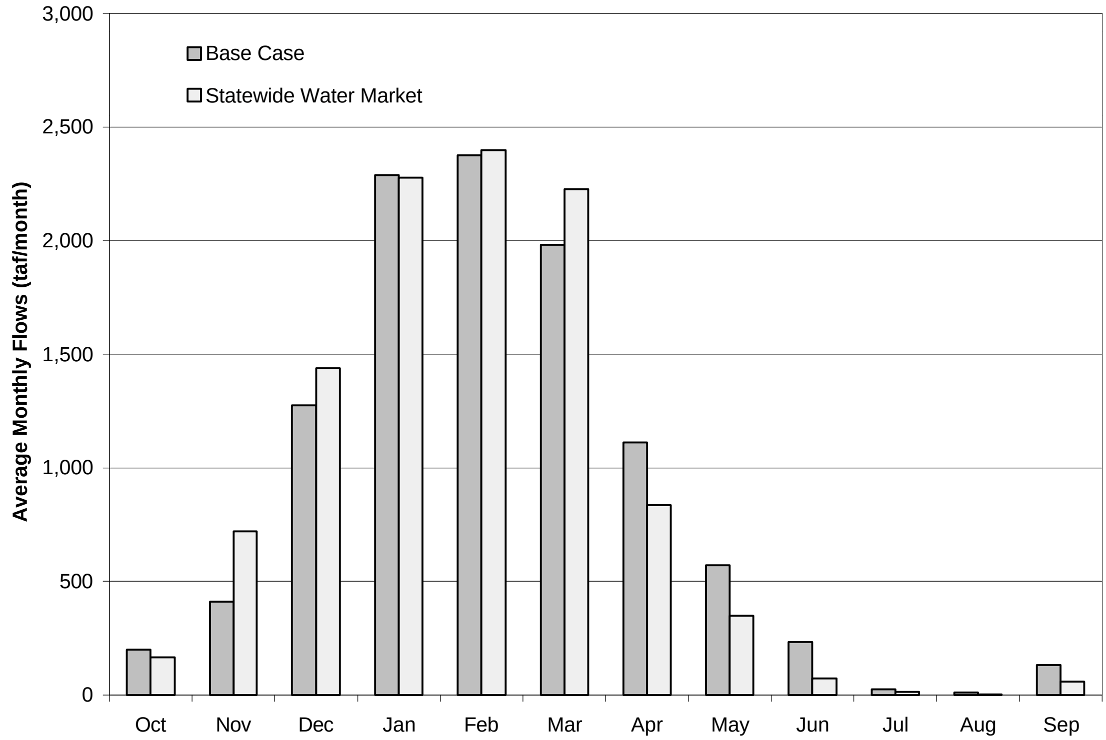


Figure 4-27. Non-Drought Year Average Surplus Delta Outflow (taf)

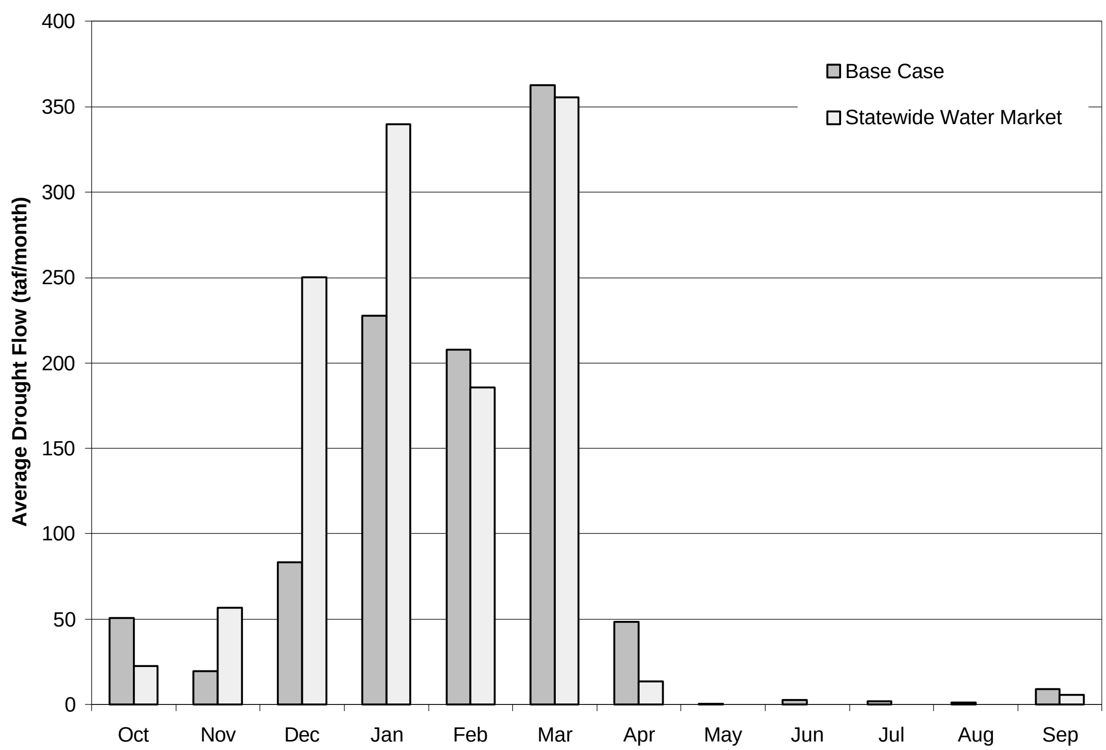


Figure 4-28. Drought Year Average Surplus Delta Outflow (taf)

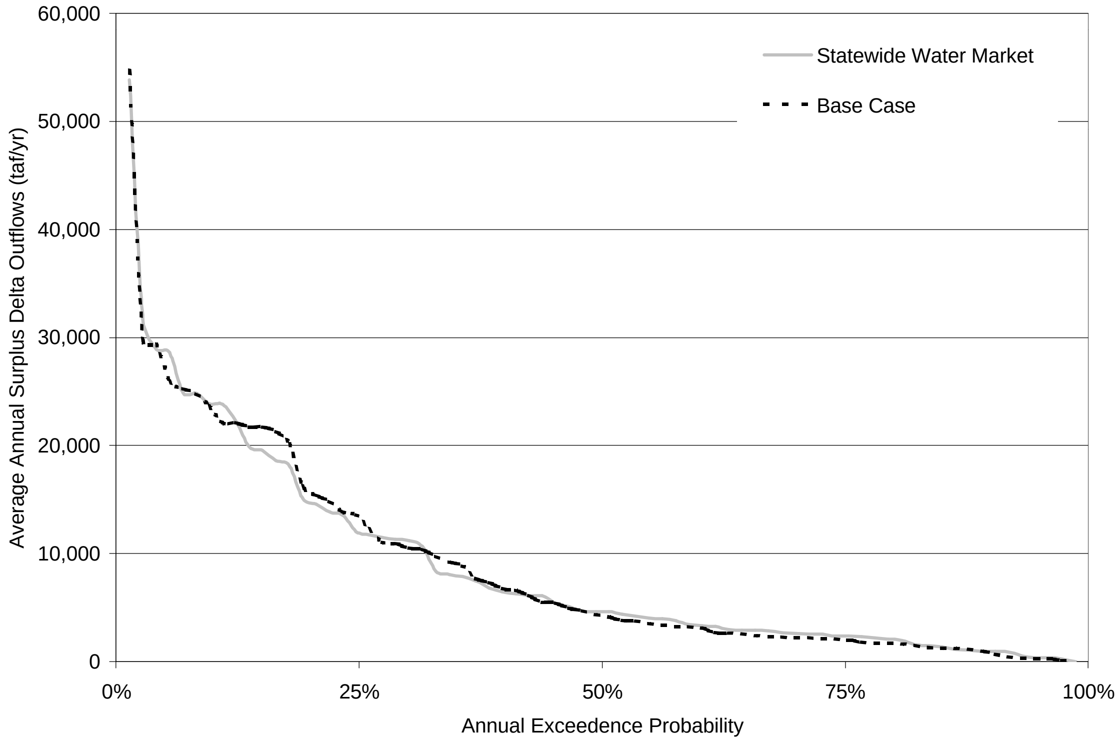


Figure 4-29. Annual Exceedence Probability for Surplus Delta Outflow (taf)

The annual exceedence curves are almost the same between the Base Case and the statewide water markets (Figure 4-29). This reflects the similarity in flows between the two alternatives. The minimum and maximum annual surplus outflow differ slightly, but in general the flows have the same annual distribution. There are differences as the flows increase, but only by 200 taf/yr at most and by 1 taf/yr on average.

SWAP RESULTS FOR REGIONAL & STATEWIDE MODELS

The water delivery results from the regional and statewide water market runs were post-processed using the State Wide Agricultural Production Model (SWAP, Appendix A). In general the irrigation efficiencies did not change significantly for any region. The most significant change in crop acreage occurred in Southern California and the least in the San Joaquin and South Bay region. In terms of average yield, again Southern California experienced the greatest increase and the Upper Sacramento Valley had the least. Economically, Tulare Lake Basin experienced the greatest change in gross and net revenues, while the San Joaquin and South Bay experienced the least change. See Tables 4-13 through 4-16 for details.

Overall irrigation efficiencies increased from the Base Case to the Regional Water Markets and the Statewide Water Market. In the Regional Water Markets, the Upper Sacramento Valley, Tulare Lake Basin and Southern California all saw improvements in irrigation efficiencies. However, with a statewide water market, only Southern California saw increased efficiency with decreases in efficiencies for the Upper Sacramento Valley and Tulare Lake Basin, owing to reductions in agricultural scarcities in these regions.

Table 4-13. Change in Irrigation Efficiencies (%)

	RWM	SWM
Upper Sacramento Valley	1.0	-3.5
Lower Sacramento Valley and Bay Delta	0.0	0.0
San Joaquin and South Bay	0.0	0.0
Tulare Lake Basin	1.0	-1.6
Southern California	12.3	12.3
Total	14.3	7.2

[a] Negative value indicates a decrease from the Base Case. Numbers may not add up due to rounding.

Table 4-14. Crop Acreage (thousand-acre)

				Change[a]	
	BC	RWM	SWM	(RWM-BC)	(SWM-BC)
Upper Sacramento Valley	941	944	944	3	3
Lower Sacramento Valley and Bay Delta	1502	1502	1502	0	0
San Joaquin and South Bay	1379	1379	1379	0	0
Tulare Lake Basin	2958	2955	2966	-3	8
Southern California	702	692	692	-10	-10
Total	7483	7472	7483	-11	0

[a] Negative values indicate an decrease from the Base Case to the Unconstrained Case. Numbers may not add up due to rounding.

Table 4-15. Gross Agricultural Revenues ($M)

				Change[a]	
	BC	RWM	SWM	(RWM-BC)	(SWM-BC)
Upper Sacramento Valley	904	905	910	1	6
Lower Sacramento Valley and Bay Delta	1462	1462	1462	0	0
San Joaquin and South Bay	1829	1829	1829	0	0
Tulare Lake Basin	4484	4477	4500	-7	16
Southern California	1268	1249	1249	-19	-19
Total	9947	9922	9949	-25	2

[a] Negative values indicate an decrease from the Base Case to the Unconstrained Case. Numbers may not add up due to rounding.

Table 4-16. Net Agricultural Revenues ($M)

				Change[a]	
	BC	RWM	SWM	(RWM-BC)	(SWM-BC)
Upper Sacramento Valley	311	311	312	0	1
Lower Sacramento Valley and Bay Delta	570	570	570	0	0
San Joaquin and South Bay	842	842	842	0	0
Tulare Lake Basin	2008	2005	2014	-3	6
Southern California	593	588	588	-5	-5
Total	4325	4317	4327	-8	2

[a] Negative values indicate an decrease from the Base Case to the Unconstrained Case. Numbers may not add up due to rounding.

Overall, gross and net agricultural revenues decreased from the Base Case to the Regional Water Markets, and increased slightly from the Base Case to the Statewide Water Market. Regionally, the Upper Sacramento Valley, Tulare Lake Basin and Southern California agriculture saw decreases in net revenue in the RWM. In the SWM, all regions, except Southern California, either saw increases in net revenue or remained unchanged. However, all these changes were very minor (less than 1.0%).

The general magnitudes of agricultural economic impacts from SWAP post-processed results agree with estimates of scarcity costs from the SWAP-generated penalty functions used in CALVIN (which exclude water operating costs applied elsewhere in CALVIN). The average magnitudes of agricultural gains and losses (comparing Tables 4-1 and 4-16) are small for the more rigorous SWAP post-processed results, but the overall statewide impacts are similar, and very similar for the statewide water market.

LIMITATIONS

In all three modeling alternatives CALVIN does not impose a minimum groundwater pumping requirement. Thus CALVIN has more latitude to change the conjunctive use operations than may be possible with existing infrastructure, especially in the statewide water market. Another issue is the seasonal pattern of SWAP demands, which have an effect on seasonal changes in streamflow availability, Delta outflow and Delta exports to south-of-Delta users. An additional limitation of the results from the unconstrained cases is the perfect hydrologic foresight that CALVIN employs, allowing it to anticipate droughts and floods. This can result in unrealistic over-year storage operations. Prior to wet years carryover storage is too low and prior to dry years carryover storage is too high. Perfect foresight of future reservoir inflows allows the model to reduce spills. Deliveries are therefore slightly higher and storage needs under the ideal water market allocations are less than they would actually be. Perfect foresight can lead to some under-valuation of system expansion opportunities. See Appendix 2K for more details on the magnitude of effects of perfect foresight. A full set of limitations is presented in Chapter 5.

CONCLUSIONS AND DIRECTIONS

Regional water markets in California would reduce scarcities and their associated costs. Operating costs in some cases increased, but the overall trend is to decrease total costs. In most regions, both agricultural and urban users would benefit from regional water markets. For three of the five regional water markets, urban scarcities were eliminated. Agricultural scarcities were eliminated in two regions and increased in the remaining three. However, except in Southern California, agricultural scarcity costs decreased. Urban scarcity costs decreased in all regions, especially in Southern California, which had the highest scarcity costs in the Base Case.

A statewide water market would further reduce scarcities and their associated costs. Agricultural scarcities were eliminated in three of the regions and significantly reduced in the Tulare Basin, while leaving Southern California agricultural scarcity at the same level as with the regional water market. Urban scarcities were reduced in Southern California, but increased slightly in Tulare Basin compared to the regional water markets. Total costs decreased (or remained the same) for all regions in the statewide water market compared to the regional water markets.

Agriculture, in general, experienced increased marginal willingness-to-pay values in the regional water market. This can be attributed to their increased scarcities resulting from water transfers (which decreased scarcities elsewhere). All urban users saw decreases in marginal willingness-to-pay (reflecting decreased urban scarcities). With a statewide water market, agricultural willingness-to-pay was reduced (or remained near zero) for many users (19 out of the 24 agricultural regions) from the Base Case. All urban areas saw decreases in the marginal willingness-to-pay values from both the Base Case and all but one from the regional water markets.

In general the same reservoirs, conveyance, recharge and recycling facilities had the greatest economic values for increased capacity in both the regional and statewide water markets. The statewide values were slightly lower, reflecting the decreased scarcities and scarcity costs. The highest expansion benefits are from facilities in the southern portion of the state (Tulare and Southern California) for both regional and statewide economic operation of water supplies.

There is less competition for environmental water requirements in both the regional and statewide water markets, compared with the Base Case. Changes in operations and conjunctive use allow for decreased competition for water on rivers with critical environmental flows (such as the Sacramento and American Rivers and the Bay-Delta). Thus environmental allocations have lower opportunity costs if the regions were allowed to optimize the operation and allocation of their water supplies. This trend continues with a statewide water market. An especially important potential consequence of the water markets is that there often is increased availability of streamflow for environmental purposes during critically dry periods.

Reductions in scarcities and scarcity costs are seen in both types of markets, with the statewide seeing significant additional reductions in urban scarcity. Agricultural users would face increased scarcities in some regions (but often decreased costs) with a water market, *neglecting revenues from water sales*. On a whole, the state would see significant reductions in scarcity and total costs with both types of markets when compared to the base case. However, the state would not see a huge additional reduction in scarcity costs from the regional water markets to the statewide water markets (the reduction is $79 million/yr in scarcity costs and $55 million/year in total costs). In general the state would benefit from both regional and statewide water markets, or other forms of re-operation and reallocation based on economic performance. These results show the likely magnitudes of economic benefits of various capacity expansion, re-operation, and re-allocation policies.

CHAPTER 5

LIMITATIONS

Le mieux est l'ennemi du bien."
"The best is the enemy of the good."
French saying

INTRODUCTION

All models require simplification of the true conditions, processes, and operations occurring in a given system and are heavily reliant 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 appropriateness of some model applications. This is no less true for CALVIN, representing the diverse and complex nature of the State's inter-tied surface and groundwater systems and water uses in an optimization modeling approach. This chapter discusses current limitations in the CALVIN model arising from a number of sources. It also sets out some priorities and directions for improving the CALVIN model to reduce limitations on interpretation and use.

Limitations of the CALVIN model arise from three main sources:

1) The input data used to characterize surface and groundwater supplies, water demands, and base case operations in the CALVIN model are limited by the quality of existing data sets, by weak or unavailable information for some parts of the state, as well as by our own project time constraints. The CALVIN calibration, 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.

2) Choice of a network flow with 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.

3) Exclusion of hydropower, flood control, and recreation benefits from reservoir operations in this initial model development may distort operations of some parts of the model and limit the identification of opportunities for storage re-operation. It does, however, make interpretation of CALVIN results somewhat easier. This limitation reflects mainly a time constraint for this initial phase of model development.

SURFACE WATER HYDROLOGY

CALVIN is a deterministic optimization model, whose results can be used as part of an implicitly stochastic optimization (Lund and Ferreira 1996). It prescribes monthly system operation based on a time series of monthly inflows. CALVIN represents demands and infrastructure for a year 2020 planning horizon. Demand is estimated from a static agricultural production model and a static urban demand model. Results, in particular deliveries, should therefore be interpreted in terms of supply reliability, rather than indicating any particular sequence of flows. The input hydrology is based on the historic hydrologic record. The selected 72-year period, October 1921-September 1993, was chosen due to the ready availability of data prepared for State and Federal simulation models. This period also represents the extremes of California's weather. Included in the time period are the three most severe droughts on record: 1929-1934, 1976-1977, and 1987-1992.

CALVIN represents surface water supplies as a time series of monthly inflows (or outflows). In HEC-PRM terminology, these inputs are referred to as "external flows", and represent an inflow from a "super source" to a model node (USACE 1999). The external flows can be divided into two categories:

- Rim flows; and
- Local water supplies.

Rim flows represent flows that originate outside, and cross the boundary of the physical system being modeled. Typically they are either inflows to surface water reservoirs explicitly represented in CALVIN (typically in the mountain foothills) or unregulated stream inflows. Local water supplies represent surface water that originates within the boundary of the modeled region, either from direct runoff or through surface water-groundwater interaction. In some studies, these local water supplies are called gains or accretions and depletions.

The majority of ground-surface water interactions have been preprocessed and are not represented dynamically in CALVIN. The exceptions are active recharge programs and incidental recharge from irrigation and urban applied water. Stream losses to and gains from groundwater are based on the CVGSM model (No-Action Alternative run 2A) (USBR 1997).

Very little surface water hydrology has been developed for Southern California. Except for coastal streams, the region depends on surface water imports or local groundwater supplies. The availability of local supplies for the South Coast Hydrologic Region is represented as a fixed inflow time series or in some cases accounted for by adjusting demands to the net of these local supplies (see Appendix B-1: Urban Representation). Local supplies are based on data received from MWDSC and other local reports. Imports from the Colorado River are constrained to an annual maximum of 4.4 maf. No over-year storage of this water is permitted in Colorado River reservoirs, though there is no constraint on in-year storage. The existence of surplus flows in the Colorado River has not been considered. Imports from Owens Valley via the Los Angeles Aqueduct are modeled in the Base Case using a fixed time series of flows obtained from MWDSC. Mono-Owens Valley surface hydrology for the unconstrained case was developed from information obtained from LADWP and the system calibrated to match the Base Case exports to Los Angeles (see Appendix I: Surface Water Hydrology).

The principal source of surface water is the Central Valley. Because of its fundamental importance to the State's water supply, several large-scale water resources simulation models exist, developed by State and Federal agencies (e.g., DWRSIM, PROSIM, SANJASM, CVGSM). There is good consensus for rim inflows to the major reservoirs. These account for 26.5 maf/yr under average conditions. For undeveloped watersheds inflow is the unimpaired historic flow. For watersheds with agricultural, urban, and hydropower development or other storage/regulation facilities, projected inflows for the 2020 level of development are derived from separate reservoir operation studies. Rim flows from ungaged streams account for an additional 2.4 maf. The majority of this flow is derived from tributaries to the Sacramento River. Greater uncertainty surrounds these figures, particularly for flows from the group of streams in Northeastern Sacramento Valley.

The major source of concern for the accuracy of the surface water hydrology relates to the estimates of local water supplies. There is a divergence of approaches used by existing models. For the Sacramento Valley, DWRSIM and PROSIM local supplies are based on a depletion analysis. From this analysis, it has been impossible to disaggregate inflow due to direct runoff and groundwater accretion from that due to historic groundwater pumping. In the San Joaquin Valley, DWRSIM and SANJASM rely on estimates based on limited flow measurements and regression analysis. CVGSM uses empirical equations to estimate direct runoff (SCS Curve Number Method) and stream percolation to groundwater (Darcy's Law). Without detailed calibration of input parameters these equations can be considered to give order of magnitude estimates only. Nevertheless, CVGSM estimates for local water supplies have been adopted for CALVIN to: (a) provide a consistent approach for the Central Valley; and (b) to assure internal consistency in CALVIN between surface water and groundwater hydrology in the Central Valley. Since CVGSM data is available for water year 1922-1990, local water supplies for water years 1991-1993 are developed based on similar precipitation years. Average annual local water supplies total 4.1 maf, of which nearly 80% occurs in the North and Central Sacramento Valley.

The final area of concern is the estimate of local water supplies within the Sacramento-San Joaquin Delta. Ground level for many of the Delta islands is below sea level. Extensive levees are required to protect against flooding. Precipitation is effectively trapped within the levees and crop water requirements are met through a mixture of surface irrigation and subsurface irrigation from a high water table. DWRSIM's water balance for the Delta is based on precipitation and seepage inflow and evapotranspiration outflow from crops, native, and riparian vegetation. It is assumed there is no net groundwater use. This approach is not possible in CALVIN as agricultural penalty functions are based on applied water demand. Analysis is further hindered as the Delta Region consists of both uplands and lowlands. The net effect of Delta agriculture in DWRSIM is an average annual net depletion of 914 taf/yr. This compares with an average annual depletion (assuming full crop demand is met) of 372 taf/yr in CVGSM. Clearly the CVGSM model for the Delta is inadequate.

GROUNDWATER RESOURCES

Representation of groundwater hydrology in the CALVIN model is highly simplified largely because of the restrictions imposed by the choice of a network flow with gains optimization solver. Particularly weak data for the Tulare Basin Region and in areas of Southern California limit the ability to model groundwater resources and interpret overdraft conditions in some of these areas. Simplified assumptions about pumping capacity and costs impose some limitations on interpretation of individual basin changes in groundwater behavior in CALVIN under the unconstrained scenario. Finally, CALVIN inherits all the limitations of CVGSM as the source of all of the model's Central Valley groundwater input data.

Hydrology

Only agricultural and urban pumping and return flows are dynamically operated in CALVIN. Recoverable conveyance losses, inter-basin subsurface groundwater flows, subsurface boundary and streamflow exchanges, and deep percolation from rainfall have been pre-processed from CVGSM NAA results into a fixed time series of monthly groundwater inflows (both negative and positive volumes) for each of the 21 CVPM basins in the Central Valley. Limited ability to model complex flow constraints in a network flow with gains program precludes dynamically modeling more of the groundwater flow components. This limitation could be overcome by using a more complex optimization solver for the HEC-PRM engine, however this option has other concerns (such as solution time, availability, and expedient practicality).

<u>Simplified Stream-Aquifer and Inter-basin Interaction</u>

The head dependent relationship between the stream network and an adjacent aquifer and between two adjacent basins is not dynamically represented in CALVIN. Instead the gains and losses across these boundaries are pre-operated in CALVIN, as indicated above, based on conditions in the CVGSM NAA. If streamflow or groundwater storage levels in a particular CALVIN model run deviate substantially from those that occur in the CVGSM NAA model, then the assumed stream-aquifer gains/losses and the inter-basin net flows would likely be incorrect. This may only be an important error in those parts of the system where these components of groundwater hydrology are significant. Deviations in groundwater storage levels occur in some areas under the unconstrained scenario. However, some caution is warranted in interpreting changes to groundwater storage in individual CVPM basins because of the simplified representation of pumping costs (see below).

The only way to assess impacts to groundwater hydrology when streamflow or storage levels deviate substantially from 'base case' conditions (CVGSM NAA) is to run the CVGSM model under the new set of CALVIN water allocations in question, and examine changes to the groundwater hydrology components. If the changes are significant, a re-run of CALVIN would be required using a corrected set of groundwater inflows and stream depletions. Iterating through these steps would ideally achieve a convergence of groundwater storage levels between CALVIN and CVGSM. This is far easier said than done.

<u>Extension of Hydrology to 1993</u>

CVGSM NAA, the source data set for groundwater inflows in CALVIN, runs from October 1921 to September 1990. Consequently, a simple method based on similar precipitation years (see Appendix J: Groundwater Hydrology) has been used to extend the flows to September 1993 to cover the historic period simulated in CALVIN. Doubt about the representativeness of precipitation data used in extending the groundwater inflow time series, combined with the extension of Base Case groundwater pumping, limits our confidence in the CALVIN Base Case groundwater storage results during the last 3 years of the 72 year hydrology.

Limitations in CVGSM Groundwater Data

The various weaknesses in the CVGSM NAA groundwater modeling data are carried over into CALVIN. This section addresses some important concerns with the groundwater data from CVGSM.

Artificial Recharge

Artificial recharge by agriculture, a significant source of recharge to groundwater in some parts of the San Joaquin and most of the Tulare Basin Regions, is not modeled explicitly in the CVGSM NAA and consequently not in CALVIN. Artificial recharge volumes in CVGSM seem to be included in deliveries and routed thru the soil water budget accounting model.

Lateral Distribution Losses

Recoverable lateral distribution losses or those that occur *within irrigation districts* via the distribution network of laterals that move district level surface water deliveries to the farm gate of each farm are not explicitly accounted for anywhere in CVGSM that we can determine. Rather, CVGSM seems to ignore this flow path in the agricultural system and routes 100% of surface water deliveries (including both non-recoverable and recoverable losses in the local distribution systems and any artificial recharge deliveries) as applied water on the farm through the soil budget. In contrast, conveyance losses on surface water deliveries *to the CVPM region* via major canals are accounted for in the "Recharge" component of the groundwater budget in CVGSM (see NAA output file Gw2a_y.nea).

As with artificial recharge by agricultural users, lateral distribution losses are masked as on-farm losses to deep percolation and get accounted for in an overall reduced on-farm efficiency in the soil budget of CVGSM. For developing CALVIN we had no way to correct this misrepresentation of agricultural water flows as they affect groundwater recharge because we did not have a consistent set of data for separating these losses and artificial recharge volumes from applied farm water across CVPM regions in the Central Valley. (Some information is available from SWAM for such lateral distribution losses in San Joaquin River areas as explained in Appendix K: Irrigation Water Requirements.)

Modeling of Groundwater in Tulare Basin Region

Large volumes of agricultural surface return flows are routed to Tulare Lake and Buena Vista Lake in the CVGSM model. In turn, very large monthly volumes of inter-basin subsurface flow occur in erratic unsteady patterns among groundwater basins in this part of CVGSM. Artificial recharge by farmers is especially important, and may average over 450 taf/yr according to data in USBR Water Needs Assessment for Friant Kern Contractors in Tulare Basin and San Joaquin (USBR 2000). Other non-Friant-Kern contractors, such as KCWA and KWB are likely to increase the total amount of agricultural deliveries in this region that are actually used for direct artificial recharge.

Numerical Scheme Stability and Accuracy

Elsewhere concerns have been expressed about the numerical solutions of the groundwater and particularly the groundwater-surface-water interaction equations in IGSM, the solution code for CVGSM. Such issues are currently being considered by the Bay Delta Modeling Forum.

Limited Information for Bay Area and Southern California Basins

Because of lack of data, synthetic groundwater inflows based on precipitation patterns were developed from very rough groundwater balance accounting data for Santa Clara Valley, Antelope, Mojave, Coachella, and Imperial basins (see Appendix J: Groundwater Hydrology).

Groundwater Pumping

Some simplifications in representing groundwater pumping were necessary in this initial development because of solver limitations, time constraints, and limited data availability.

Fixed Head Pumping Costs

It was not possible to put in variable head pumping costs at this time mostly because of lack of reliable and consistent data. We also have concerns about the additional solution time needed for HEC-PRM to solve the optimization problem with the iterative hydropower solver, which can also model variable-head pumping cases.

Minimum Pumping

CVPM agricultural regions are not homogenous. Some areas and farms do not have access to surface water, but use groundwater exclusively (and vice versa). Currently CALVIN treats all farms in a CVPM region as having access to all water sources. Minimum groundwater pumping levels could be imposed to account for agricultural lands without an ability to exploit surface water. However, CVGSM NAA monthly pumping data did not match the SWAP monthly agricultural demand pattern very well. Taking the monthly minimum pumping from CVGSM risked causing other distortions. The minimum calendar year amount of agricultural pumping from the 1922-1990 CVGSM NAA pumping data is not always respected in the unconstrained CALVIN results (see results in Appendices 2A-2D and 2G). This limitation could be corrected with more time and effort to develop a minimum monthly pattern of pumping appropriate for SWAP demands that more closely matches the CVGSM annual minimums in each CVPM region.

Pumping Capacity

Very simple estimates of pumping capacity were developed from the maximum monthly levels of CVGSM NAA agricultural pumping (see Appendix H) and are imposed in CALVIN.

WATER DEMANDS AND DELIVERIES

Modeling of demands and water deliveries requires many assumptions. These are described in great detail in the technical appendices of this and the previous CALVIN report (Howitt et al. 1999). Some limiting assumptions used to represent demands and deliveries in CALVIN are discussed below.

Urban Demands

The representation of urban demands has several important limitations that could, in some cases be corrected with more time and data.

Simple Economic Model

Characterization of urban water demands is simplified into residential and industrial sectors only. Information and empirical data are lacking on economic values of water use in the commercial and public sector. There is very little empirical study of price elasticity of commercial sector water use in California or elsewhere. Yet, commercial demands account for about 25% of urban water use in California. We know that commercial water demand is more valuable than residential water use, at the margin, and that commercial uses are less valuable at the margin than industrial uses, but there is little basis for assuming an elastic response.

No Year Type Demand Variation for Most Areas

No variation in urban demand by year type is made except for MWDSC demand areas, for which data were supplied by MWDSC. This can be significant in large urban demand areas, as seen in the MWDSC service area where the variation by year type in 2020 demands is up to 7% more (360 taf/yr) in the driest years and 10% (500 taf/yr) less in the wettest years. The standard deviation in year-type demand for MWDSC areas is 4% of the mean demand.

Limited Consideration of Water Quality

Water quality for urban areas is considered economically in terms of variable costs for treatment, and post-treatment salinity damage costs of urban water deliveries, i.e., to consumers and subsequent ‘downstream’ uses (see Appendix G: CALVIN Operating Costs). Fixed costs for additional levels of treatment cannot be explicitly represented in CALVIN. CALVIN can represent monthly average variation in water quality as it affects these costs, but this has not been incorporated due to time limitations. Annual variation in monthly effects of water quality could be done with small modification to the HEC-PRM solution software to handle annually varying penalty functions.

Agricultural Demands

Representation of agricultural demands in CALVIN also suffers from some important limitations that could, in some cases, be corrected with more time and data. In other cases, the lack of systematically consistent and reliable data to represent the complex flows of water in agricultural systems underlies the limitations.

No Variation of Demand with Precipitation

Precipitation, particularly in the Sacramento Valley, meets a significant portion of agricultural demand. Estimates of the percentage of precipitation that is ‘effective’ in meeting crop consumptive use vary across data sources. Annual values of ETAW predicted by DWR’s consumptive use model, for example, differ significantly from Bulletin 160-98 values (see Appendix K: Irrigation Water Requirements). Precipitation also varies significantly from year to year, resulting in annual variations in the crop agricultural demand for irrigation water (ETAW).

SWAP currently estimates agricultural demands based on average precipitation values only, using constant average annual ETAW estimates from Bulletin 160-98 data (DWR 1998a, 1998b). Consequently, water deliveries are somewhat under-estimated in dry years (agricultural demands too low) and potentially over-estimated in wet years. Variation between average and critical dry years, and average and wettest years in base case agricultural deliveries across the Central Valley can be as large as 2 maf (CVGSM NAA delivery data).

No Variation in Monthly On-farm Efficiency

In reality on-farm efficiency varies by month. This is not represented in CALVIN where efficiency corresponds to its an annual average value. This could be represented with a minor change in the HEC-PRM code and a set of monthly varying efficiencies.

Limited Understanding of Agricultural Water Flows

There are considerable uncertainties about reuse, distribution efficiencies and non-recoverable losses for agricultural water use. These uncertainties are most apparent for the Tulare Basin but exist in other parts of the Central Valley as well.

The use of deliveries for artificial recharge by farmers is highly uncertain, but is important for some regions (see discussion of groundwater hydrology limitations above). There is some thought that this might be derivable from miscellaneous deliveries compared to annually varying ETAW demand in CVGSM input files. Even so, this issue merits more scrutiny, particularly for the Tulare Basin.

Deliveries

The representation of parameters in CALVIN affecting water deliveries also suffers from some limitations, as reviewed here.

Simplified Conveyance Loss Factors on Surface Water Deliveries

Conveyance losses on links are based on averaging loss rates on all surface water links for a given CVPM region. Such uniform rates were used to minimize distortions to the supply decisions in CALVIN from small differences in gain factors.

CALVIN Assumptions about Pumping

CALVIN assumes fixed head pumping for all groundwater basins, as mentioned above. This may be problematic for some basins. For the reasons cited above, a fixed minimum groundwater pumping rate and possibly minimum deliveries of some surface water (or disaggregation of demands to separate out areas that depend solely on groundwater) also seems desirable to avoid unrealistic changes in water supplies relative to existing agricultural and urban water delivery infrastructure, under less constrained scenarios.

Operation and Availability of Local Urban Supplies

Limited time and restricted access to information has meant that representation of available local supplies and operations of local infrastructure in CALVIN for urban areas are sometimes omitted, simplified using a simulated or estimated pre-operated inflow time series, or allowed to be optimized within the statewide operations represented in CALVIN. Improvements in the representation of local supplies and operations for CALVIN urban demands such as SFPUC, Napa-Solano, SCV, and the three large MWDSC demand areas would lead to small improvements in the accuracy of estimates of urban scarcity. In particular, Base Case CALVIN yield-reliability of urban supplies from local sources and infrastructure is better than would occur under actual current operations in these areas. Improvements in this area would be possible with more time and better data from local agencies.

Operating Cost Data on Deliveries

Data for estimating operating costs has been very scarce for many specific locations. Only the variable part of operating costs is appropriate for CALVIN. Urban water treatment costs and how they are affected by water quality are approximate, as are artificial recharge operating costs.

Base Case Deliveries

There is some incompatibility of DWRSIM with CVPIA PEIS assumptions (PROSIM NAA) used for Base Case deliveries.

"Miscellaneous" deliveries to agriculture in CVPIA PEIS are problematic to understand and represent. SWAP demands are adjusted in the calibration process, but this is often very approximate and misses important considerations such as artificial recharge and lateral distribution losses. Better representations are possible, but require separation of the different components of excess deliveries.

Base Case deliveries to the Tulare Basin agricultural demands from CVGSM NAA are highly approximate in many cases and do not appear to represent a 2020 scenario of current operations. Westlands Water District (CVPM 14) receives 100% of demands in almost all years (surface water shortfalls made up fully by groundwater pumping), while other regions (CVPM 16, 17, 18, others) contain historic trends that occurred with the construction of local reservoirs on the Tule, Kaweah, Kings, and Kern Rivers.

CVGSM NAA stops in September 1990, thus various correlation methods were used to extend the Base Case delivery data to September 1993. There may be some weaknesses, especially for groundwater pumping, in the method and data used to extend these deliveries (see Appendix 2I: Base Case Details).

DWRSIM 514 is the basis for all SWP base case deliveries in CALVIN. The Title A entitlements for this model run are outdated and do not reflect more recently negotiated SWP transfers under the Monterey amendments. Consequently, CALVIN Base Case shortages to Castaic, Napa-Solano, and several other SWP urban contracts maybe higher than would occur if these new entitlements were considered in 'current' operations.

ENVIRONMENTAL REGULATIONS

Restricted ability to represent constraints in network flow programming is the main cause for limited ability to represent environmental regulations, operations, and demands. This is particularly significant for modeling the Delta. In addition, minimum instream flow requirements that are contingent on concurrent flow or storage conditions cannot be dynamically determined in CALVIN, but must be pre-operated based on some assumed conditions. This is the case for several instream flow requirements on the American, Sacramento, Stanislaus, and San Joaquin Rivers, where environmental flows are a complex formula of several storage, inflow, and water quality conditions (see Appendix F: Environmental Constraints).

CALVIN also cannot explicitly represent water quality, such as temperature, dissolved solids, salinity, or other constituents.

PERFECT FORESIGHT

Optimization models provide a means of rapidly screening alternate water resource developments, and suggesting promising new integrated solutions. However, optimization algorithms usually require considerable simplification of the system being modeled to be computationally tractable. Promising alternatives, therefore, usually require more comprehensive testing using simulation models. Simulation models require predefined rules for reservoir operation and water allocations. An important aspect of optimization has therefore been the development of rules to be subsequently refined during simulation (Lund and Ferreira 1996).

Reservoir operation has been described as a multistage dynamic stochastic control problem, yet solutions to an explicitly stochastic formulated multi-reservoir operation problem remain problematic. First, a stochastic hydrology must be developed. Probability distribution functions must be assumed and moments estimated from stream data. Spatial and temporal correlation of monthly stream flows must be correctly modeled. Simple hydrologic models are unable to represent the observed persistence of dry years. Since 1921, California has been subject to one two-year drought and two six-year droughts. Second, inflows must be discretized and their conditional probabilities of occurrence calculated. Lastly the model must be solved. Stochastic dynamic programming has proved popular in the academic literature. Recent advances in computing processing speeds and sophisticated iterative approximation techniques have allowed systems of 10-15 reservoirs to be modeled. However hydrologic models must be simple to keep the dimensionality of the problem sufficiently small.

Implicitly stochastic optimization (ISO) techniques, though less intellectually satisfying, are computationally simpler and thus can allow better representation of other aspects of the system, such as additional spatial detail. Time series of inflows are pre-calculated based on either the historic flow record or synthetic streamflow generation. Reservoir operation is solved for the deterministic set of flows based on perfect information or perfect foresight. This type of analysis can be regarded as answering the question: " with hindsight, what is the 'best' we could have achieved?"

Despite development of new techniques, ISO models solved using LP (or one of its derivatives, such as the network flow programming used here) remain one of the most applicable to the analysis of complex systems. However, the perfect foresight of these models can limit the immediate usefulness of such models and hinders the derivation of operating rules for simulation models. Perfect foresight can result in unrealistic reservoir operation: insufficient carryover storage prior to wet years and excessive carryover storage prior to drought. Perfect foresight can undervalue existing facilities and reduce the economic benefits of additional storage facilities. It is the upper bound on what is possible and a lower bound on the value of new facilities.

To analyze the impact of perfect foresight, research has been directed at the development of a modified "limited foresight" CALVIN model. Limited foresight is achieved by reducing the period-of-analysis to a single 12-month segment. A set of model runs using sequential annual segments provides a prescribed operation over the full length of the deterministic flow record. Individual model runs are linked through starting and ending storage conditions. Ending storage represents reservoir carryover storage for the following water year. The value of this water held in storage is represented using a piecewise linear approximation of a quadratic penalty function. In each 12-month run, the model balances the cost of current year shortage against the cost of reducing carryover storage below some target value. An 'optimal' penalty function on carryover storage is one that results in the minimum aggregate cost for the individual 12-month runs and so reflects the expected value of water in future use. This optimal penalty function is determined using an iterative non-linear search algorithm in conjunction with reservoir balancing rules. Although the limited foresight model has been successively tested on small parts of the system, it has yet to be applied to the full inter-tied system.

Experiments have been undertaken to examine the importance of perfect foresight for realistic California cases (Appendix 2K). These experiments have compared CALVIN results (with perfect foresight) for limited regions with the limited foresight model outlined above and stochastic dynamic programs (forms of explicit stochastic optimization). The experiments have examined the importance of limited foresight for cases with different amounts of overyear surface storage, groundwater storage, and dependence on groundwater pumping. In general, the importance of perfect foresight decreases dramatically as greater amounts of groundwater storage (representing substantial carryover storage) become available for use.

Another estimate of the importance of perfect foresight has been undertaken for the Southern California model results (Appendix 2F). For this region, changes in water operations and allocations from the Base Case were substantial, but very regular – not varying greatly from year to year. With such regularity in the changed operations and water allocations, the accuracy of hydrologic forecasts was found to have relatively little importance, accounting for less than 10% of re-operation benefits.

FLOOD CONTROL AND HYDROPOWER

Flood control and hydropower are important operating purposes for many parts of California's inter-tied water supply system. They are not included in the current CALVIN model, mostly due to lack of time. Considerable hydropower modeling already is undertaken for large parts of the system, so data for representing hydropower should be fairly available. Only time is needed to develop and test economic representations of hydropower for CALVIN, except for the additional computational difficulties that variable-head hydropower is likely to impose on the model. Hydropower has been represented successfully in HEC-PRM models of the Columbia River System (USACE 1993, 1995, 1996). With the computational demands of variable head hydropower, there is significant room to improve the model using fixed-head assumptions – often these are wholly appropriate.

Flood control benefits for reservoir operations are not represented in the current CALVIN model. However, maximum storage capacities of reservoirs are reduced during the flood control season to reflect the need to preserve reservoir storage capacities during this period to dampen floods occurring on shorter than a monthly time scale. Flood damage functions are currently being developed for the USACE for their comprehensive studies. These should be available to be adapted for explicit representation of flood control benefits in future CALVIN versions.

Recreation also is a valuable use for many parts of the water system. Yet, there is very little systematic data collection that would enable economic values for recreational uses to be easily produced. This must await additional background technical studies. Nevertheless, once such background studies have been completed, there is little to prevent recreational benefits from being included in CALVIN's objective function. Such benefits have been included, sometimes prominently, in other HEC-PRM applications, notably on the Missouri River and Columbia River systems (USACE 1991c, 1993).

PRIORITIES AND DIRECTIONS FOR CALVIN IMPROVEMENTS

For a large-scale model of an important system, there is always much to be done. But only a limited amount can be accomplished at one time, lest an excess of ambition threaten the integrity of the entire enterprise. The table below lists solution actions available or possible to correct some of these limitations and priority and ease of doing these future improvements/enhancements.

Table 5-1. Directions and Priorities to Reduce CALVIN Limitations

Limitation	Solution Options	Priority	Difficulty
Agricultural demands – no year type variation	1) Develop time series shifts to agricultural demands to reflect ETAW changes due to precipitation; or 2) Modify HEC-PRM code to accept different year type penalties and develop new SWAP penalties by year type.	H H	L M to H
Urban demands – no year type variation	1) Develop time series shifts to urban demands to reflect changes due to temperature and precipitation (similar to MWDSC demand variations now in CALVIN) 2) Develop urban monthly penalty functions that vary by year type	H* H	L to M H
No hydropower	Apply economic and physical data to represent economic values of hydropower at key locations using fixed-head assumptions or the existing HEC-PRM hydropower algorithm, as appropriate.	H	M
Perfect foresight	Develop annual carry-over storage value functions for all major reservoirs and groundwater storage in CALVIN.	H	H
No minimum CVPM pumping	Use CVGSM NAA minimum annual level of pumping during 1921-1990 period and the SWAP monthly pattern of demands to develop a month varying minimum pumping requirement for each CVPM region that is consistent with monthly SWAP demands.	M to H	L
Artificial recharge mixed in agricultural deliveries	Use CVGSM input data on ETAW variations by year and month to estimate the portion of deliveries in appropriate CVPM regions that can be attributable to artificial recharge. Develop cost and capacities for current levels of agricultural artificial recharge.	M to H	M to H
Fixed head groundwater pumping	1) Develop economic and physical data to estimate the average variable head costs of groundwater pumping for each CVPM region and each urban area, model in CALVIN using existing HEC-PRM hydropower algorithm. 2) Use data from 1 to estimate a simpler non-linear cost function for groundwater pumping, based on volume pumped.	M M	H M to H
No values for flood control	Develop damage functions for critical flood reaches in CALVIN, test and fine tune flood storage operations.	M to L	M to H

Notes:
** Already employed for the three South Coast urban demand areas of Central, Eastern & Western, and San Diego.*
H = high, M = medium, L = low ratings of priority or difficulty.

Table 5-1 Continued. Directions and Priorities to Reduce CALVIN Limitations

Limitation	Solution Options	Priority	Difficulty
No accounting for agricultural system lateral distribution losses	Gather more data to estimate appropriate gain factors on applied water deliveries in each CVPM region, from SWAM and other sources.	L to M	L to M
No variation in on-farm efficiencies	Modify HEC-PRM code to handle monthly varying gains and estimate appropriate monthly varying values by agricultural demand region.	L to M	L
No variation in urban water quality costs	Develop monthly average estimates of water quality and associated changes for urban water quality treatment and salinity costs.	L to M	L to M
Urban local supplies & infrastructure operations	Gather more data and refine network to better represent local infrastructure, supplies and their base case operations.	L to M	H
Extensions to 1993 of CVGSM NAA pumping data	Replace current set of extensions to AG pumping data in CALVIN Base Case with CVGSM NAA 1922-1990 average by year type for each CVPM region.	L	L
Outdated DWRSIM Base Case SWP-CVP deliveries	Develop a new CALVIN Base Case, based on updated CVGSM and DWRSIM modeling runs to reflect changes in current Table A Entitlements, in environmental regulations, and other operations since CVPIA PEIS and DWRSIM run 514 modeling was done.	L	H

Notes:
H = high, M = medium, L = low ratings of priority or difficulty.

PRIORITIES AND DIRECTIONS FOR STATEWIDE MODELING DATA

In addition to improvements to overcome limitations in the CALVIN model listed in Table 5-1, the CALVIN calibration has identified some significant hydrologic and water demand data problems and data management concerns that should be addressed to improve future modeling efforts (see Chapter 3). These issues are relevant for any statewide and regional water resources modeling or planning studies, not just for the CALVIN model. Table 5-2 summarizes some of the most significant directions for statewide data improvement that have emerged out of the CALVIN modeling effort. Underlying these efforts is a need for a concerted data management strategy for California water management.

Table 5-2. Directions for Improving Statewide Data and Data Management

Problem Area	Data Needs	Suggestions
Tulare Basin Hydrologic Data	Improved understanding of and data for surface and groundwater system and their use; improved representation of groundwater recharge and agricultural pathways in CVGSM; planning models of joint operation of local and regional reservoirs	Substantial effort is needed to develop data for the complex conjunctive use operations that occur in this important region.
Estimating Agricultural Demands and Deliveries	Deliveries and demands are inconsistent given current data and representation of agricultural water use; accurate and consistent statewide data is needed for agricultural demands at farm, district, & basin scales; separate accounting of applied water from other agricultural system water uses is needed.	Develop data and data management for a more physically-based “flow path” accounting model of statewide surface and groundwater supplies and demands starting at smallest scale of analysis.

Table 5-2. Continued.

Problem Area	Data Needs	Suggestions
Inter-annual and Seasonal Variability in Demands	Statewide representation and centralized data management of these variations in agricultural and urban demands that is consistent with local planning.	DAU-based system of data management provides an organized basis for developing this information.
Central Valley Surface and Groundwater Hydrology	Reconcile DWRSIM and PROSIM hydrologies; consistent estimates of local accretions with separate surface and groundwater contributions.	These issues should be addressed in the joint DWR-USBR hydrology. May need better independent estimates of groundwater pumping by agricultural users.
Agricultural Return Flows	Statewide consistent set of return flow estimates to surface and groundwater is needed; important discrepancies exist between estimated agricultural efficiencies, reuse, and subsequent volumes of return flow to surface and groundwater.	A physically-based “flow path” accounting model, as mentioned above, would provide a framework for organizing and managing the data for different scales of analysis/aggregation.

CONCLUSIONS

This chapter has presented the major limitations of the CALVIN model, some of which could be reduced with time and effort as suggested in Table 5-1. In other cases, underlying limitations in the available statewide data impose restrictions on the accuracy of CALVIN results. These statewide data limitations pose serious problems for any regional or statewide analysis for policy, planning, or operating purposes, not just for the CALVIN model. CALVIN modeling and data limitations are described in more detail in the relevant modeling, calibration, and results chapters and appendices of this report. Despite these limitations, important insights about the system and implications for improved water management can still be learned from the current CALVIN modeling results.

CHAPTER 6

IMPLICATIONS FOR WATER POLICY AND PLANNING

"Optimization models frequently beg the question of greatest … interest; how the optimal strategy is implemented." G.F. Oster and E.O. Wilson (1978), *Caste and Ecology in the Social Insects*, p. 300.

"La nuit tous chats sont gris."
French saying

"At night all cats are gray." Without analysis to shed light on the subject, all alternatives for managing water in California appear equally tenable and progress will be at the murky confluence of contending ideologies and beliefs. This is not to say that more formal analysis of alternatives will make progress easy or that everyone will agree on the definition of progress. Analysis is necessary, but not sufficient. Improvements in data, computer modeling, and communications have vastly improved the potential of modeling to explicitly improve California's complex water supply system. The CALVIN project is an example of how new technology can help us better understand California's water problems and explore new and old approaches for improving solutions to these problems. But a mere model cannot solve problems. What is needed to realize the policy and planning potential of new data and technology? And, how might water managers and policy-makers best take advantage of this technology?

The CALVIN economic-engineering optimization model for California's statewide water supply system rests on the development, over several decades, of theory, data, and software in many areas. As such, CALVIN is merely a step in a direction that is reasonable for our time, making use of contemporary expertise and data, and extending it incrementally to integrate this information and provide useful results for California water management. While the technical steps of CALVIN are very incremental, the conceptual steps and policy implications of this type of economic and engineering capability are more dramatic. Following a brief overview of how water is managed in California, this chapter identifies some implications of large-scale economic-engineering optimization capability for California water management.

BACKGROUND: LOCAL MANAGEMENT AND STATEWIDE WATER SUPPLIES

All agricultural and urban water use is local, and the preponderance of water management and planning is local. Any tally of the revenues, expenditures, staff, and capital involved in California water management will show the dominance of local levels of government, such as city water departments, irrigation districts, and other forms of local water institutions. The local level is where urban and agricultural water users operate, in homes, offices, factories, and farms. Costs of local water distribution and treatment are the greater part of most water supply costs. Water conservation and wastewater recycling are largely local matters.

Of necessity in semi-arid California, regional and statewide water supply systems (e.g., Metropolitan Water District of Southern California, the CVP and SWP) have evolved to supplement and add flexibility to local systems. Statewide water supplies underpin the economic development of some sizable agricultural and urban regions. However, in many more cases, it is the flexibility of statewide supplies, more than their average volume, which has enhanced the reliability of local water supplies. Today, 24% of all water used for agricultural and urban purposes in California is imported from another hydrologic region. Four regions, Tulare Lake, South Coast, San Joaquin, and San Francisco depend most on imported water, although San Joaquin is a net export region for water. These data are shown in Table 6-1 below.

Table 6-1. Applied and Imported Water by Hydrologic Region

Hydrologic Region	Agricultural & Urban Use (Av., 1995, taf/yr)	Average Imports (1995, taf/yr)	Net Average Imports (1995, taf/yr)	Imports as % of Applied Water	Net Imports as % of Applied Water
North Coast	1,063	2	-912	0	0
Sacramento River	8,831	903	-5,037	10%	0
North Lahontan	569	0	-8	0	0
San Francisco	1,353	966	966	71%	71%
San Joaquin	7,601	1,464	-379	19%	0
Central Coast	1,478	28	28	2%	2%
Tulare Lake	11,426	3,633	3,633	32%	32%
South Lahontan	570	80	-280	14%	0
South Coast	5,124	3,124	3,124	61%	61%
Colorado River	4,536	58	-1,135	1%	0
Statewide	42,551	10,258	0	24%	NA

From Bulletin 160-98 data (DWR 1998)

As water demands grow, the reliability and quality of regional and statewide supplies become increasingly important. While local water users typically prefer local supplies, expanding local supplies is no longer possible, politically palatable, or economically justifiable in many cases. In addition to water conservation and recycling, which have their own economic and social limits, local water users and agencies have come to rely more on regional and statewide water sources. Thus, local water operations, plans, and use have regional and statewide implications. Since many regions rely on imported water (or fear its over-export), greater regional and statewide coordination becomes essential and unavoidable. Statewide supplies are no longer supplemental for much of the state, but have become essential for the well-being of the majority of local water users.

Increased reliance on non-local supplies has increased competition for water. Since imported water must be delivered in times, qualities, and quantities to match local supplies and demands, local demands often conflict with regional and statewide water management. Environmental demands have intensified this competition by reducing availability of water for export, reducing availability of local water, and reducing flexibility in water management.

Politically, increased statewide and regional competition for water has shifted some responsibility for water problems to regional, state, and federal officials and away from local water managers who are closer to actual water demands. But regional, state, and federal officials have seen a steady erosion of their authority, budgets, and staffs since the 1980s. Occasionally, demands for imported water have increased due to inadequacies in local water management, or local inability to implement projects. While water users ideally prefer local alternatives, these are limited and it is sometimes institutionally easier to ask for more water from outside a region than to improve local or regional efficiency.

As we return to the implications of the CALVIN effort for statewide and regional water management, planning, and policymaking, we should remember that water use and economic impacts are predominantly local and despite greater reliance on statewide supplies, water management authority and capability remains strongest at local levels. One of the greatest contributions of the CALVIN effort is an improved ability to consistently and explicitly integrate state and regional water management efforts with local water management activities. A flexible mix of statewide, regional, and local activities is needed. California will need advanced technical tools to achieve this flexibility, as well as changes in institutional relationships to implement actions across the wide range of parties involved.

THE END OF WATER "REQUIREMENTS"

The historical objective of California water planning was to supply all local water "requirements," typically water quantities that would not limit local agricultural and urban development. Storage and conveyance infrastructure was built to eliminate any "shortage" between local supplies and these local "requirements." This traditional engineering approach was adequate and expedient when developing new sources was relatively inexpensive and environmental impacts were not of great concern. In those times, limitations on data, conceptual understanding, and computational ability also precluded more in-depth analyses.

"Requirements"-based planning no longer provides clear or even promising directions for managing water in California. Planning to always supply all water "requirements" everywhere is prohibitively expensive without massive subsidies and would impose politically intolerable environmental impacts. Local areas of California cannot expect to receive all the water they would like at minimal cost. The cost of providing water (including its "opportunity cost" to other users) now exceeds the economic value of some water uses traditionally considered "requirements."

Water is scarce in California, just as energy, land, housing, and transportation are scarce. We will not pay any price for these things, and so most of us use less of these resources than we would like if they were abundant and free. California must manage water carefully, because there is a shortage of inexpensive water. This is a different approach to thinking about water management in California, and one that requires different forms of analysis to inform decision-making.

WHAT DOES ECONOMIC-ENGINEERING OPTIMIZATION PROVIDE?

The CALVIN economic-engineering optimization model does not solve California's water problems, but it does provide economic and engineering information that should be useful for policy making and planning. This information includes:

- Suggestions for economically promising combinations of actions for water management

- Preliminary economic valuation of the benefits of water management alternatives to agricultural and urban users
- Identification of specific promising opportunities for expanding facilities, water transfers, and cooperative and conjunctive operations of surface and underground water storage
- Economic valuation of changes in water supplies and reliability to local and regional water users
- Quantification of the economic costs to agricultural and urban users of environmental and other regulations
- Estimation of water user willingness to pay for additional water supplies and reliability
- Evaluation of the economic balance between supply and demand management activities
- A framework for organizing, accounting, and reconciling water availability and use accounting data consistently and transparently across the state.

Such information should be useful in making policy decisions regarding evaluation and selection of new projects and management strategies, project finance, project operations, and water allocation. This kind of information also can aid in operations planning. Some potential applications of CALVIN model results are described elsewhere in this report. More specific implications of making these types of information available are described in the following sections.

WHAT DOES THIS MEAN FOR ME?

More sophisticated forms of modeling and data have implications for most people concerned with water management in California. These implications are potentially far-reaching. The CALVIN economic-engineering optimization model is only one manifestation of these newer technologies. Some practical implications of economic-engineering optimization modeling are described below.

Implications by Profession

Different professions have different concerns for water management in California. Table 6-2 summarizes implications of economic-engineering optimization technology for each of several professional or activity areas. In most cases, these implications involve the ability to explore additional options and to have ready preliminary estimates of economic and financial performance of alternatives.

Table 6-2. Implications of Economic-Engineering Optimization by Professional Interest

Area of Interest	Summary of Implications
Political-level policy-making	Easier comparison of economic impacts to local areas Suggestions of opportunities for cooperation and mutual benefit
Lawmakers	Local and regional costs and benefits of legal barriers to cooperative operations
Finance	Ability to identify beneficiaries of changes in infrastructure and management Ability to economically value changes
Institutional Coordination	Suggestions for potential cooperative projects and management: - Conjunctive use of ground and surface waters - Coordinated operation of reservoirs and conveyance - Various water transfer arrangements
Planning	Economic values of alternative additions to supply or changes in demand
Operations	Suggestions for cooperative operations and the economic potential of such opportunities
Demand management	Relative economic value of changing demand relative to changing supply Economic value of changes in demand, locally and statewide
Environmental regulation	Urban and agricultural costs or benefits of changes in environmental water requirements
Data collection	Increased documentation and quality control of data will be needed. Data management and availability is important.
Modeling	Local, regional, and statewide data and modeling effort would be better coordinated.

Implications for Local and Regional Water Managers

Since most water management is local, what does all this mean for local and regional water managers? For local water managers concerned with imported water supplies, larger-scale economic-engineering optimization can help identify opportunities for cooperation with other areas, the benefits (and costs) of cooperating with other local water users, estimate the economic value of additional supplies and reliability, and quantify the economic costs of losses of water supplies or reliability. Model results can aid discussions of the proper balance of local water conservation and wastewater recycling efforts with water supply enhancements. To improve the statewide and regional operations that affect their imports or potential imports, local water managers have an interest in improving and verifying the representation of local systems in larger-scale models and maintaining local water demand and supply data which is consistent with those of other regions. Such data also improve the ability of local areas to make water management decisions when considering the availability and costs of imported supplies.

Regional water managers can use such modeling capability to examine the economic and financial basis for planning and managing regional projects, identify opportunities for new projects within a region, identify opportunities for improved water management within a region, and identify opportunities for cooperation with other regions. Such opportunities might include changes in infrastructure, infrastructure operations, or water transfers. However, such information is more reliable and useful if consistency is maintained across the local data used for regional water management.

The kinds of systematic and integrated information gathering required for the kinds of analysis we advocate also provides the kinds of information which greatly improves the ability of local and regional water managers to negotiate and enforce their own agreements for improving management of regional water resources. The systematic provision of information is often seen as necessary for managing common resources (Blomquist 1992; Ostrom et al. 1994).

Table 6-3. Implications of Economic-Engineering Optimization Modeling by Area

Area	Implications
Local	Opportunities for cooperation with other areas Benefits and costs of cooperation for local urban and agricultural users Economic value of additional water supplies and reliability to the area Economic costs of losses of water supplies or reliability to the area Economic potential of water demand management and recycling activities Need to improve and verify local representations of local water supplies and demands and maintain such data consistent with those of other locales
Regional	Economic and financial basis for planning regional projects and management Opportunities for new projects within a region Opportunities for improved management within a region Opportunities for cooperation with other regions Need for consistency of data among local and regional water users

Implications by Type of User

Different types of water users tend to have different concerns for water management. Some implications of economic-engineering optimization capability are summarized below for agricultural, urban, and environmental water users, as well as those concerned with multiple use.

Table 6-4. Implications of Economic-Engineering Optimization Modeling by User Type

Use Type	Implications
Agricultural	Economic value of additional supplies Economic losses from lost water supply reliability Financial opportunities from water sales Opportunities to improve economic performance through water transfers, conjunctive use, or additional facilities Economic costs of water regulations
Urban	Economic value of additional supplies, recycling capacity, and conservation Economic losses related to supply interruptions Opportunities to improve economic performance through water transfers, conjunctive use, or additional supplies Economic costs of water regulations
Environmental	Economic costs to agricultural and urban users of water regulations
Multiple	Economic mechanisms for balancing different water interests Opportunities to improve agricultural and urban economic performance within environmental regulations

POLICY IMPLICATIONS

The technical ability to develop, plan, construct, and operate more complex and integrated water systems does not mean that there is a political ability to support, finance, and operate such water systems, or even to plan for them. A great deal of political and legal work is needed to take advantage of potential technical solutions for improving California's water system.

To some degree, new technical tools, data, and computer models can aid in negotiating such legal and political infrastructure. With these tools, more complex alternatives, which might be agreeable to more parties, can be more rapidly considered. Reasonable estimates of economic values and costs of changes in system infrastructure and management should provide insights for discussions of finance, cost allocation, and compensation.

Some specific institutional infrastructure needed to support integrated technical studies includes:

- Agreement on data standards-setting bodies
- Forums for planning across agencies and local, regional, and state levels
- Procedures for cost allocation among benefiting agencies
- Procedures to compensate regions which forego water deliveries
- Means to insure local regions against potential losses

Some of the technical objectives needed to realize the full advantages of this new technology are described below.

Perhaps the most important implication of these new technologies is that they should be able to help us think more creatively and cooperatively about how to plan, operate, and manage California's enormous inter-tied water systems and its regional sub-systems. This applies to all types of water users, all management activities, and all levels of water management. It should be much easier to explore diverse mixtures of actions with more consistent hydrologic and demand data and improved modeling tools. For such a complex and controversial system, this is a much-needed capability.

NEW TECHNICAL TOOLS AND CONSISTENT DATA ARE NEEDED

Coordinating the planning and operation of water supplies statewide to satisfy several thousand local water demands and a complex variety of environmental and operating constraints is a difficult task. The task becomes more difficult as water demands increase. Simultaneously balancing water "check-books" for water users throughout the state with only a limited income without becoming overdrawn demands more accurate and reconciled information/data, as well as the modeling capability to keep track of water movements under varying conditions. Both improved data and modeling capability are needed.

Data and Data Management

The quality and quantity of data must increase as one demands more of a water system. When demands are small relative to supplies, management is relatively easy and little data are needed. But as demands grow and sometimes exceed supplies, supplies must be allocated among many users under many conditions and large quantities of high quality data become essential for reasonable planning and reliable operations. The CALVIN effort has highlighted several important data needs for the state and for local water users depending on statewide supplies, as detailed in Chapter 5 and in Appendix 2H of this report. Others have found similar data problems (USBR 1997). These data needs are summarized below.

Hydrology

Hydrology data consists of surface water inflows, groundwater inflows, groundwater storages, and return flow representations for applied water. Ideally, representations of groundwater-surface water interactions also are included.

Large amounts of water data have been collected and developed over time for different purposes. Most data was developed for managing surface water facilities to supply fairly fixed delivery contracts with relatively fixed groundwater operations. We now see value in varying groundwater operations, surface water operations, and demands flexibly and simultaneously. Thus, existing raw hydrologic data need to be re-examined fundamentally and probably re-developed extensively for this more demanding purpose. Groundwater and surface water data must be dynamically reconciled, and further reconciled with water demand estimates.

Water Demands

Water demand data traditionally consists of either contract amounts or other amounts representing delivery quantities desired locally. As state, regional, and local officials look increasingly to flexibly and dynamically move water about the system and between water users, in a system often with insufficient water to supply all local desires, some precise value or priority of each water demand is needed to make legal or economic allocations. If substantial use is made of water transfers and water marketing or if the "user pays" principle is to be seriously applied, economic values are desirable for representing local users' willingness to pay for water.

Water demand data and demand valuations must be developed considering that demands and supplies will be varied dynamically and flexibly. These demand data must be reconciled with the hydrology discussed above.

Data Management and Quality Control

For the water controversies of California, data used in analysis must be well-documented, transparent, and readily available. If an analysis of water management is technically controversial, it will be less useful in resolving political controversy. To the degree possible, hydrologic and water demand data must be well understood by the technical experts of the major interest groups. (This also implies that the major parties need capable experts who can work with others.)

Making data collection and development well documented and reconcilable with other data efforts can be difficult when many parties conduct such work independently. Standards and data protocols are needed. Such standards typically are developed by agencies or professional groups. State agencies, such as the Department of Water Resources, in consultation with local agencies and professional groups, might sponsor such standards. DWR or SWRCB might also be able to enforce such standards, given the reporting relationships of local agencies to the State. Professional groups, such as the Bay-Delta Modeling Forum, also might develop or sponsor such standards, although standards enforcement is more difficult by this route.

The reconciliation of surface and groundwater data statewide is likely to require oversight by the State Department of Water Resources, particularly for the Central Valley, but is also likely to require other parties with hydrologic expertise. Development of water demand data is likely to require more local involvement under State protocols and standards. Development and support of consistent databases is also likely to be a State activity.

Modeling Capability

Current modeling capability is not yet sufficient for developing and examining the range of alternatives needed for California's water problems. Many of the options being considered cannot be represented and there is extraordinary difficulty representing novel mixes of options. Current models generally operate surface water facilities, or groundwater, or water demands, but not two or three aspects of the problem together. New modeling software also needs to be well documented and represent California's water system in ways that are transparent to technical representatives of major water interests.

Simulation Capability

Fortunately, the need for more advanced simulation model capability has been evident for some time and the Department of Water Resources is replacing its core simulation model (DWRSIM) to partially overcome this problem. This new CALSIM software should provide much more flexibility and speed in model analysis. With such new modeling software, representations of California water management can be improved and extended to areas of the state that are scantily-modeled.

In particular, surface water and groundwater must be jointly operated with water deliveries. To do this will require more explicit and adaptive representations of groundwater and water demands, well beyond the DWRSIM simulation. These models (e.g., CALSIM) should also be extended to become statewide in scope.

Optimization Capability

CALSIM and the existing models of California are simulation models, meaning that they attempt to derive the implications of specific alternative scenarios. Given the complexity of California's water problems and the almost infinite number of options available, many thousands of simulation model runs would need to be set up, run, and interpreted to assure that the best options have been considered. To address this problem, a different type of computer model is needed, called an optimization model. An optimization model, such as CALVIN, is given a description of the system, an objective to be maximized, and the model proceeds to suggest which operations, allocations, or facilities, best achieve that objective. Unfortunately, the fancier algorithms of an optimization model usually require simplifications of the system. (CALVIN's limitations are described in Chapter 5.) Thus, while optimization models can help suggest promising management alternatives, these management alternatives usually require refinement and testing using more detailed simulation models before they are considered in detail.

CALVIN is a first attempt at a statewide economic-engineering optimization model. This effort has shown considerable promise and insight into water management problems for California. Additional application and development within State, Federal, or regional agencies would be useful to the state and to local water users.

CHANGED TECHNICAL ACTIVITIES NEEDED TO SUPPORT COOPERATION

CALVIN is only one example of the types of technologies now available for use in managing California's water problems. Better spatial information systems, large-scale and spatially and temporally detailed simulation models of water quantity, quality, and economics, improved water trading information systems, and improved environmental monitoring and information systems are some other examples of technologies which show considerable promise. CALVIN and these other technologies are only one side of the equation, however. To make the best use of these technologies, there needs to be an evolution in the institutions that manage water at local, regional, and statewide levels.

While the state, federal, and local governments invest much for the collection of data, relatively little effort is expended to ensure that these data are compatible and useful for broad policy, planning, and operational purposes. A concerted effort to improve the technical and data basis for policy, planning, and operations, primarily through systematic improvement in surface and ground water hydrologic and water demand data, would greatly improve the ability to examine novel and promising solutions to California's water supply problems.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

> "Now there were, in the aggregate, 12,755 quinariae set down in the records, but 14,018 quinariae actually delivered; that is, 1,263 more quinariae were reported as delivered than were reckoned as received. Since I considered it the most important function of my office to determine the facts concerning the water-supply, my astonishment at this state of affairs stirred me profoundly and led me to investigate how it happened that more was being delivered than belonged to the property, so to speak." Sextus Julius Frontinus (97 AD), *The Aqueducts of Rome*

Several conclusions and recommendations are well supported by the results and model development process to date, including consideration of the limitations of the data and methods employed.

CONCLUSIONS

Several policy and methodological 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 models 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 important 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.

b) Economically efficient local and regional water management improvements reduce demands for imports. Economically efficient operation and allocation of water within each region can 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 the 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 for groundwater storage, recharge facilities, and the Colorado River Aqueduct in Southern California.

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 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 critically 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. However, the results of the current CALVIN model strongly support several policy conclusions despite limitations on the conclusiveness of some results for specific locations. 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. Recommendations are made to pursue some of the major model and data limitations.

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 data for 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 representations of the Westlands and Kern County areas in this and 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.

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