Water Management Strategies for the San Joaquin Valley and San Francisco Bay Area: an Engineering-Economic Optimization Study

BY

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B.S. (LeTourneau University) 1994

THESIS

Submitted in partial satisfaction of the requirements for the degree of

MASTER OF SCIENCE

in

CIVIL AND ENVIRONMENTAL ENGINEERING

in the

OFFICE OF GRADUATE STUDIES

of the

UNIVERSITY OF CALIFORNIA

DAVIS

Approved:

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Committee in Charge

March 2002

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ACKNOWLEDGEMENTS

First, I would like to thank members of the CALVIN team. It has truly been a pleasure to work and learn alongside Mimi Jenkins, Guilherme Marques, Stacy Tanaka, Andy Draper, Brian Van Lienden, and Brad Newlin.

Secondly, I would like to thank Richard Howitt and Miguel Marino for serving on my committee, and whose advice was a critical part of completing this work.

Next, I would like to thank Jay Lund, who not only has served as my major professor and committee member, but who introduced me to the "joys" of optimization modeling and has been a continuing source of inspiration.

Finally, and most importantly, I am grateful for the unflinching love and support of my wife, Cristal. It certainly is true that without her encouragement, this thesis would not have been possible. And although they are too young to understand, my children Grace and Nathan show me support in ways only children can.

Randall S. Ritzema

ABSTRACT

Optimization modeling can play a role in identifying alternative water management strategies to meet competing and diversifying water demands in large-scale systems. CALVIN, an engineering-economic optimization model, represents a parallel approach to typical simulation modeling currently used by planning agencies in California by seeking to maximize economic benefit to the state or regions through re-allocation of water supplies. This study utilizes CALVIN to assess the potential economic benefits of re-operating and re-allocating water within the San Joaquin Valley and San Francisco Bay region. In addition to storage operations and water allocations, model results include the marginal economic values of facility expansion. A Base Case replicates current water management and operations, and the Unconstrained Case reflects how the system would be operated in an ideal regional water market subject only to physical, flood control, and environmental constraints. Model results indicate that slight urban scarcities in the Base Case are eliminated in the Unconstrained alternative. Operating costs, rather than water scarcity, drive most of the supply mix changes under an ideal regional market. All scarcity is effectively eliminated in the Unconstrained alternative through supply re-allocation and facility re-operations under the conditions considered, and marginal values on ending groundwater storages indicate potential to alleviate groundwater overdraft in the San Joaquin Valley.

INTRODUCTION

The relationship between California's highly variable water supply and its increasing agricultural, urban, and environmental demands has encouraged the development of tools which control the flow, quality, and timing of water supplies. In the early stages of water development in California, engineering solutions involved the construction of infrastructure (dams, canals, and distribution structures) to move water spatially and temporally to meet the growing agriculture base and urban supplies of the state (Hundley 1992). With the advent of the computer age, limited possibilities for infrastructural expansion, increasing concern with environmental impacts of water development, and ever-increasing urban demands, computer modeling has become the predominant tool for quantifying the effects of large-scale water management decisions on various stakeholders in the state (Jenkins, et al. 2001). Simulation models such as DWRSIM and CALSIM II used by the Department of Water Resources (DWR) and CVGSM by the US Bureau of Reclamation (USBR) provide the framework for testing alternative management strategies for mitigating California's diversifying and increasingly complex water resource issues.

Simulation modeling, though effective at testing outcomes of specific decision sets, is inefficient at evaluating highly complex systems with many possible management alternatives. A prescriptive approach, through the use of optimization modeling, has been shown to be an efficient way of narrowing management alternatives to meet stakeholder objectives. Strategies identified through an optimization model can be verified and further refined through the use of simulation models.

This thesis outlines the efforts to apply such a prescriptive approach to a portion of California's water supply system. The California Value Integrated Network model, or CALVIN, is an optimization model of the entire intertied water supply system of California (Jenkins, et al. 2001). The objective of the model is to maximize economic benefits to the state or region, subject to environmental and physical constraints, by optimally operating and allocating water. This study utilizes CALVIN to assess alternative water management strategies for the San Joaquin Valley and San Francisco Bay region.

The following sections discuss the role optimization has played in large-scale water management studies, CALVIN's modeling framework, and mechanisms currently used to allocate water in California. After an overview of the geography and approach used in modeling the San Joaquin Valley and Bay Area, this thesis presents model results and discusses potential alternative water management strategies in the region. The final section outlines proposed refinements to CALVIN that could potentially reduce its limitations as a planning and management tool for this region.

ENGINEERING-ECONOMIC OPTIMIZATION USING CALVIN

Optimization Modeling in Water Resource Management

Encouraged by the increasing complexity of managing large-scale water resource systems and through rapidly improving computational power, the use of simulation modeling has proved invaluable for evaluating water management strategies. Simulation models are designed to imitate water system behavior under a set of prescribed conditions, and have been described as "what if?" tools (Sterman 1991). Simulation models have several advantages not easily managed by other modeling approaches, including ability to include highly non-linear phenomena, complex decision processes, and feedback loops (Sterman 1991). Though limited in their ability to *suggest* management alternatives, simulations provide a platform for evaluating and fine-tuning previously identified management strategies (Lund and Ferreira 1996, Jenkins, et al. 2001). Many planning agencies at the federal, state, and local levels in California have made extensive use of simulation modeling, some notable examples being DWRSIM and CALSIM II, developed by the California Department of Water Resources (DWR 2000); and PROSIM, SANJASM, and CVGSM, used by the US Bureau of Reclamation (USBR 1997).

In contrast to the descriptive nature of simulation models, optimization models *prescribe* management alternatives, and have been labeled "what's best?" tools (Sterman 1991). Optimization modeling depends upon clearly defined *objectives* to be either maximized or minimized through a set of *decisions*, subject to a set of *constraints*. Many classes of optimization algorithms have been developed in the last fifty years: linear and non-linear, deterministic and stochastic, static and dynamic, lumped parameter and distributed parameter, search methods, etc. (Goodman 1984). This potential to identify promising water management alternatives is the strength of optimization; once objectives are defined, management policies can be quickly narrowed to a smaller set of alternatives, saving time and resources in situations where evaluating thousands of alternatives is particularly daunting (Jenkins, et al. 2001).

Common among these algorithms, however, is a characteristic simplification of element interactions in the system, resulting from the need to fit the system into the structure of the particular algorithm in use. This is perhaps one reason why optimization modeling has experienced less practical application (Rogers and Fiering 1986). Nevertheless, advances in computational power and algorithmic effectiveness have made optimization increasingly attractive, especially when used in conjunction with simulation models, as advanced by Lund and Ferriera (1996).

Recent years have seen increasing use of optimization methods in water resource systems analysis in California. Draper (2001) has catalogued an abbreviated list of studies performed on both the State Water Project (SWP) operated by DWR and on USBR's Central Valley Project. Lefkoff and Kendall (1996) modeled the entire CVP and SWP systems to assess the system benefits for extending the Folsom-South Canal. Other studies, such as Becker and Yeh (1974), Marino and Mohammadi (1983 and 1984), Mohammadi and Marino (1984), Grygier and Stedinger (1985), Marino and Loaciciga (1985a and 1985b), Tejada-Guibert et al. (1990), and Johnson et al. (1991), focus on finding optimal reservoir operations for hydropower and water supply benefits.

Of all optimization methods, linear programming has been the most widely used and arguably the most successful algorithm in many fields, including water resource systems analysis (Goodman 1984). Network flow programming (NFP), an especially efficient (and simplified) subset of linear programming, represents a system by using nodes connected by arcs (Hillier and Lieberman 1995). Nodes may be either storage or non-storage nodes, and arcs represent the flows paths between nodes. Amplitudes on arcs represent gains or losses. The network flow program maximizes or minimizes the objective function by altering flows and storages (objective function terms are linear functions of these flows and storages), governed by conservation of mass and specified upper and lower bounds to storages or flows. NFP affords an efficient, computationally easy approach to solving water resource optimization problems when element relationships are approximated to be linear functions and where flow and storage decisions are not related to non-adjacent elements in the network (Draper 2001).

Several water resource systems optimization codes have been developed with an NFP algorithm, the most notable being the prescriptive reservoir model developed the US Army Corps of Engineer's Hydrologic Engineering Center called HEC-PRM (USACE 1994a). Utilizing inputs of hydrologic time series, reservoir storage characteristics, conveyance capacities, operating costs, sets of storage-dependent linearized hydropower penalty functions, and sequentially linearized economic demand functions, HEC-PRM solves for the storages and flows which maximize economic benefit. Until CALVIN, HEC-PRM has been used on systems with six or less reservoirs (USACE 1992, 1994b, 1995b, 1996). Its ability to solve much larger systems such as the statewide CALVIN model, which includes 51 surface reservoirs and 28 groundwater basins, is a testimony to its flexibility.

CALVIN Model Overview

The CALVIN project was developed at the Department of Civil and Environmental Engineering at the University of California, Davis, and was funded through CALFED, a consortium of federal, state, and local water agencies concerned with meeting California's future water needs. This section of this thesis summarizes pertinent details from the final report of the CALVIN project (Jenkins, et al. 2001), as well as from a previous report (Howitt et al. 1999) by describing the conceptual framework of the

CALVIN model, limitations inherent in its application, and the modeling alternatives considered in this analysis.

As presented earlier, CALVIN is an optimization model of the entire intertied water supply system in the state of California, which includes the entire Central Valley, the San Francisco Bay area, and southern California. This thesis presents the modeling approach and results for one region of the statewide CALVIN model: the San Joaquin Valley from the Stanislaus River watershed south to the San Joaquin River watershed, San Francisco, and the South Bay area. Flows into and out of this region are fixed. In effect, this analysis therefore focuses on potential benefits for more flexible *regional* operations, as well as expected benefit from engaging in transfers with other regions of the state.

Description

CALVIN utilizes an implicit stochastic optimization approach (Draper 2001). A 72-year historic hydrologic sequence functions as the hydrologic input to the model, which runs on a monthly time step. This sequence is considered to be reasonably representative of the spectrum of hydrologic conditions the state faces (Draper 2001). Supplies utilizing this hydrology are then allocated to meet agricultural and urban demands estimated at year 2020 levels. The model is allowed to optimize operations over the entire 72-year period simultaneously, affording it perfect foresight in planning for droughts and floods, with storage nodes representing reservoirs and groundwater basins linked through time in HEC-PRM's network.

The CALVIN model is comprised of two principle components: the HEC-PRM network flow programming solver and a set of databases for defining the model's parameters. An interface allows translation of input data from the databases into the text input format required by HEC-PRM. The DSS database format, developed by HEC for water resource applications, contains hydrologic time series as well as paired data for variable costs and economic demand functions (USACE 1995a). The Microsoft Access© database contains all of the nodes, links, upper and lower bounds, operating costs, and fixed-head hydropower benefits, as well as pathnames to DSS paired data and time series locations where applicable. In addition, the Access database contains metadata concerning model parameters, allowing source documentation to be explicitly included in the model framework. Figure 1 displays the input data required to run CALVIN, as well as the output produced. Generated monthly time series of flows, storages, marginal values, and willingness-to-pay results are post-processed and provide the basis for measuring the system's response to changes in operations.

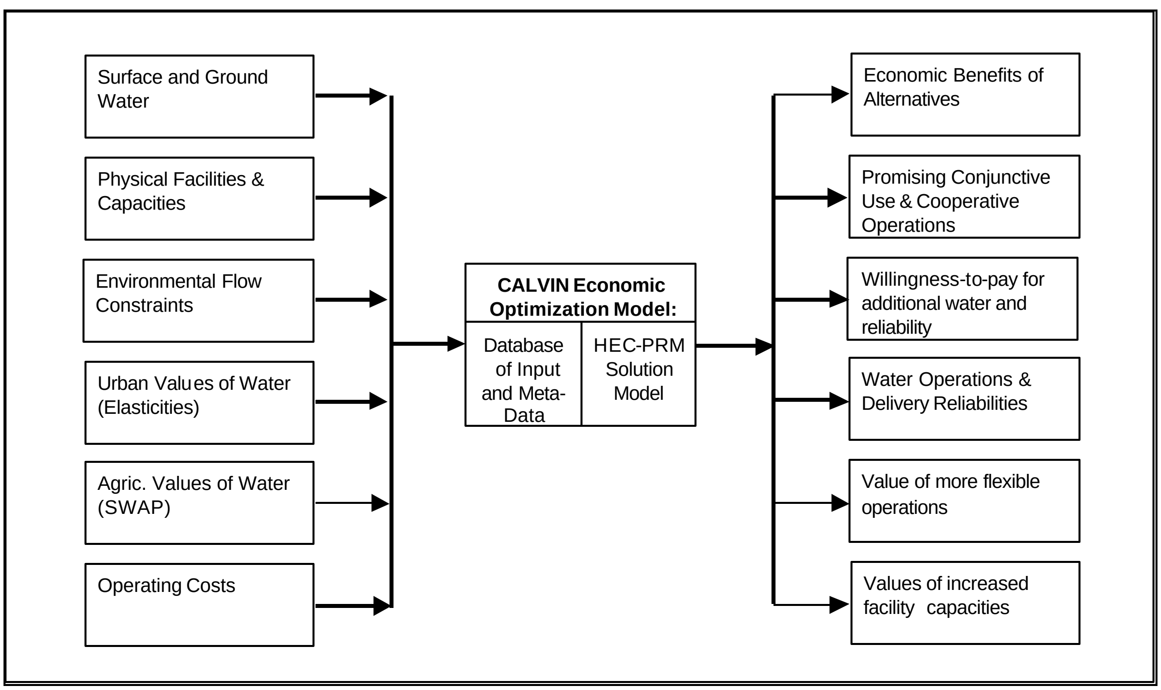

Figure 1. CALVIN modeling framework

Figure 2 shows an example network diagram of CALVIN. Reservoir inflows, groundwater inflows, stream accretions and depletions are represented with fixed time series of monthly flows. Agricultural and urban return flows are modeled using arc amplitudes of less than 1. Examples of links with unit operating costs include pumping plants, treatment facilities, recycling facilities, and groundwater pumping (and a few instances of fixed head hydropower which are assigned a negative unit cost). Lastly, urban and agricultural demands modeled with economic penalty functions utilize paired data in the DSS database. These economic demands, along with operating costs, drive the optimization engine of CALVIN, within the constraints dictated by physical capacities and environmental requirements. Urban, agricultural, and environmental demands representations in the San Joaquin Valley and Bay Area are discussed in the following chapter.

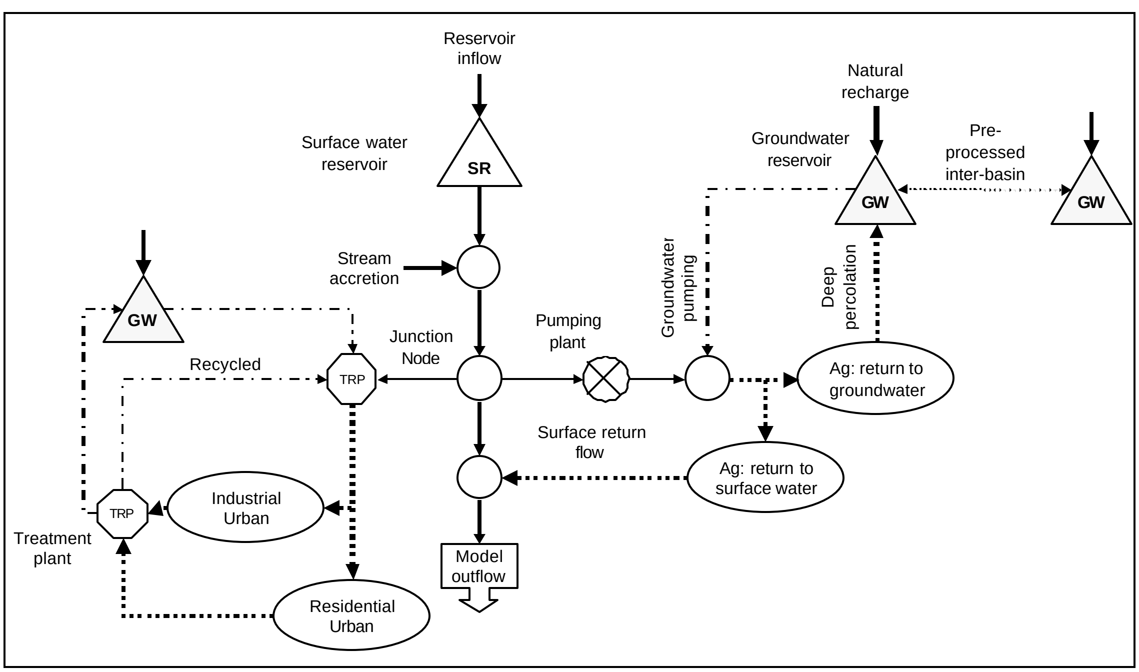

Figure 2. Example network diagram for CALVIN

Limitations

In addition to sometimes inconsistent hydrologic data and assumptions from various sources, several limitations to CALVIN's optimization approach are apparent. These limitations are discussed in detail in Chapter 5 of Jenkins et al. (2001), as well as Draper (2001), but are outlined here for clarity. These limitations mean that results obtained from CALVIN become most meaningful only when overall trends are considered.

Several of these limitations arise from the network flow algorithm used in CALVIN. Obvious limitations arise from CALVIN's simplified representation of actual systems as a series of nodes and links with fixed accretions/depletions. Water quality is a serious consideration for urban water supply, but are only implicitly included in CALVIN through fixed unit costs on treatment links. In actuality, water quality costs are highly non-linear; a common treatment method is blending of high and low quality water, which is difficult to model in an NFP algorithm. Groundwater basins are characterized as lumped-parameter cells with fixed head pumping costs, a representation which may vary considerably from reality under operations prescribed by CALVIN. Furthermore, agricultural and urban demands do not yet vary according to year type in CALVIN, in contrast to actual urban demands which are estimated to vary by as much as 16% relative to precipitation (Jenkins, et al. 2001).

Another important limitation is the perfect foresight with which CALVIN optimizes economic benefit. Because it solves for optimal storages, flows, and diversions over a 72-year period simultaneously, it effectively has no hydrologic uncertainties to consider, allowing the system to prepare for droughts and surpluses in advance. Scarcity, economic benefits, and costs are therefore generally reduced compared to operations with imperfect foresight. The effects of hydrologic foresight seem to diminish considerably in terms of water supply when more groundwater is available for use, representing considerable carryover storage. Draper (2001) has proposed a method for solving this potentially serious limitation, but the method had not yet been implemented at the time of this study.

Finally, variable head hydropower and flood control are not yet included in the economic value functions of CALVIN. Work is currently underway to explicitly include these important economic factors in water supply management.

SAN JOAQUIN AND BAY AREA MODEL DESCRIPTION

Geography

The San Joaquin and Bay Area region of the CALVIN model stretches across the middle of California (refer to Figure 3), bordering the Sierra Nevada range on the east and extending westward to the urban areas of San Francisco Bay. The Upper San Joaquin River defines the southern boundary of the region, while the Stanislaus River to the east and the South Bay Aqueduct toward the west form the northern boundary. The region can be roughly divided into two main areas: the San Joaquin Valley, and the urban demand areas of San Francisco and the South Bay. North Bay communities (in Marin and Sonoma Counties) are not included in CALVIN since their water supply systems operate independently of the statewide network. Several North and East Bay area communities within East Bay Municipal Utilities District, Contra Costa Water District, and Napa and Solano Counties receive water from the Delta and Sacramento Valley directly, and therefore are included in the Lower Sacramento Valley and Bay Delta Region of the CALVIN model.

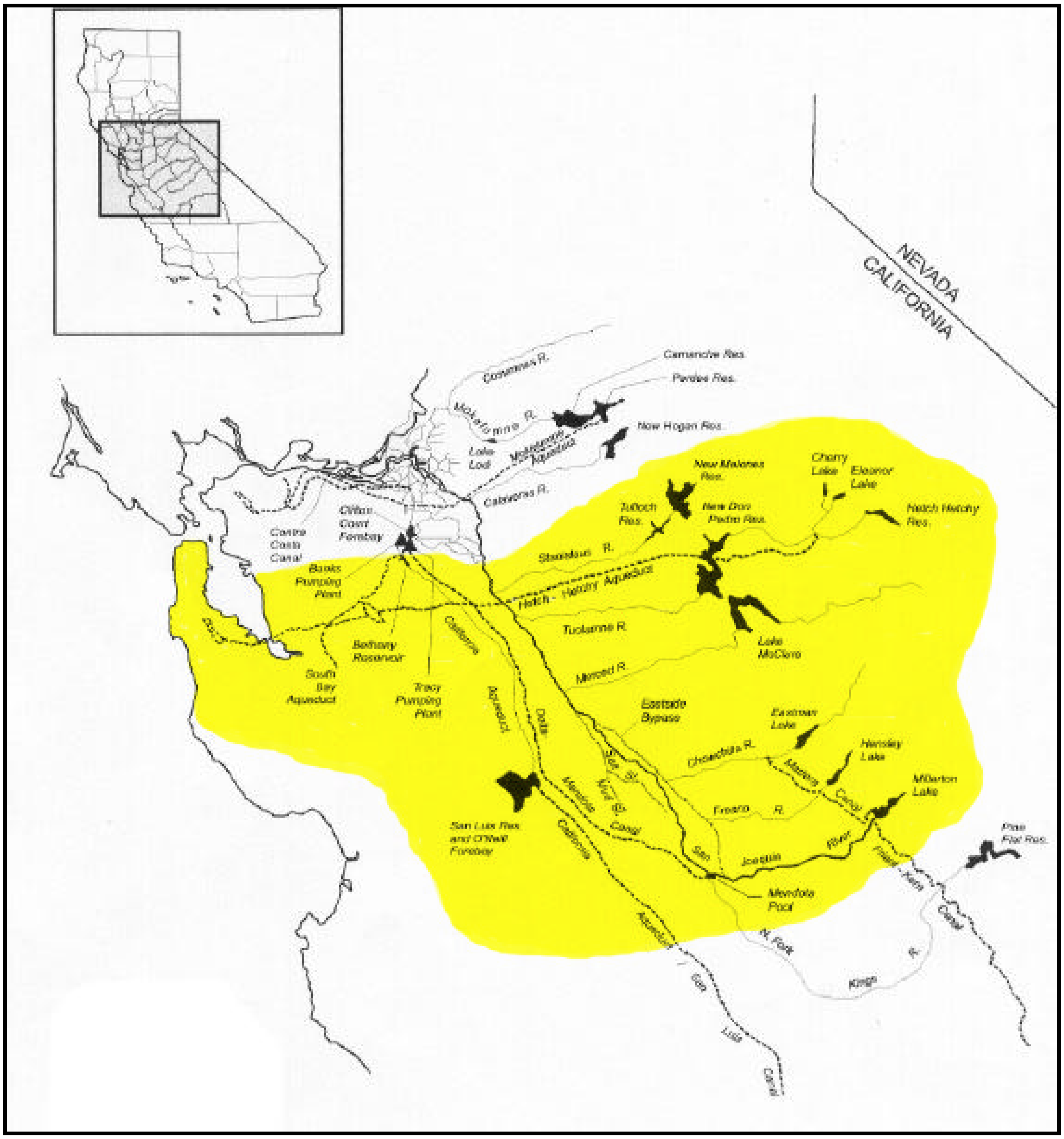

Figure 3. San Joaquin and Bay Area Region

(*Adapted from USBR 1997, Figure III-3)*

Figure 4, the schematic of the San Joaquin Valley and Bay Area of the CALVIN model, shows how water supplies, infrastructure, and demands relate. The top of the schematic is the San Joaquin Valley, while the lower portion of the schematic characterizes the San Francisco and Santa Clara Valley urban areas.

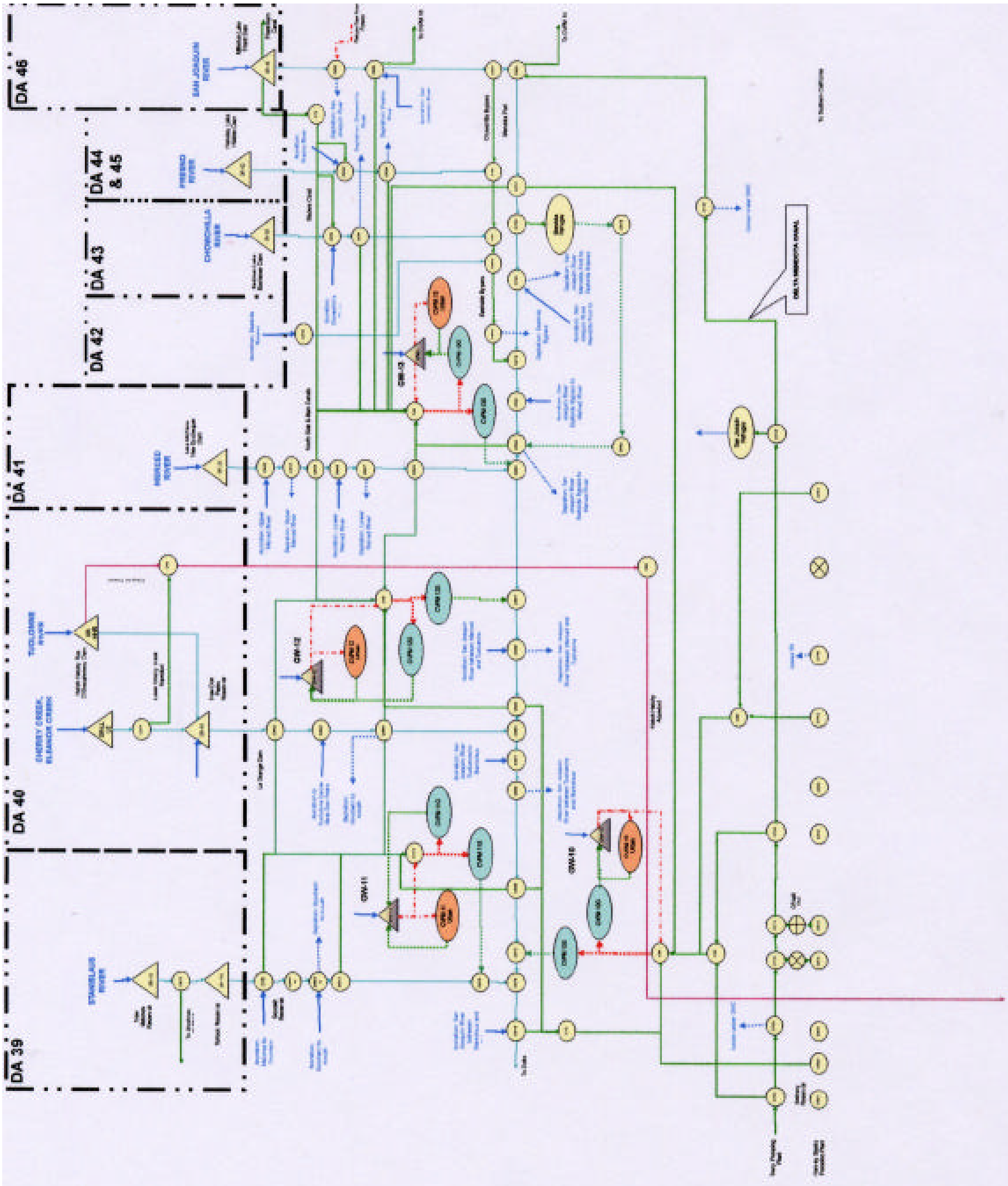

Figure 4. CALVIN schematic of San Joaquin Valley and Bay Area

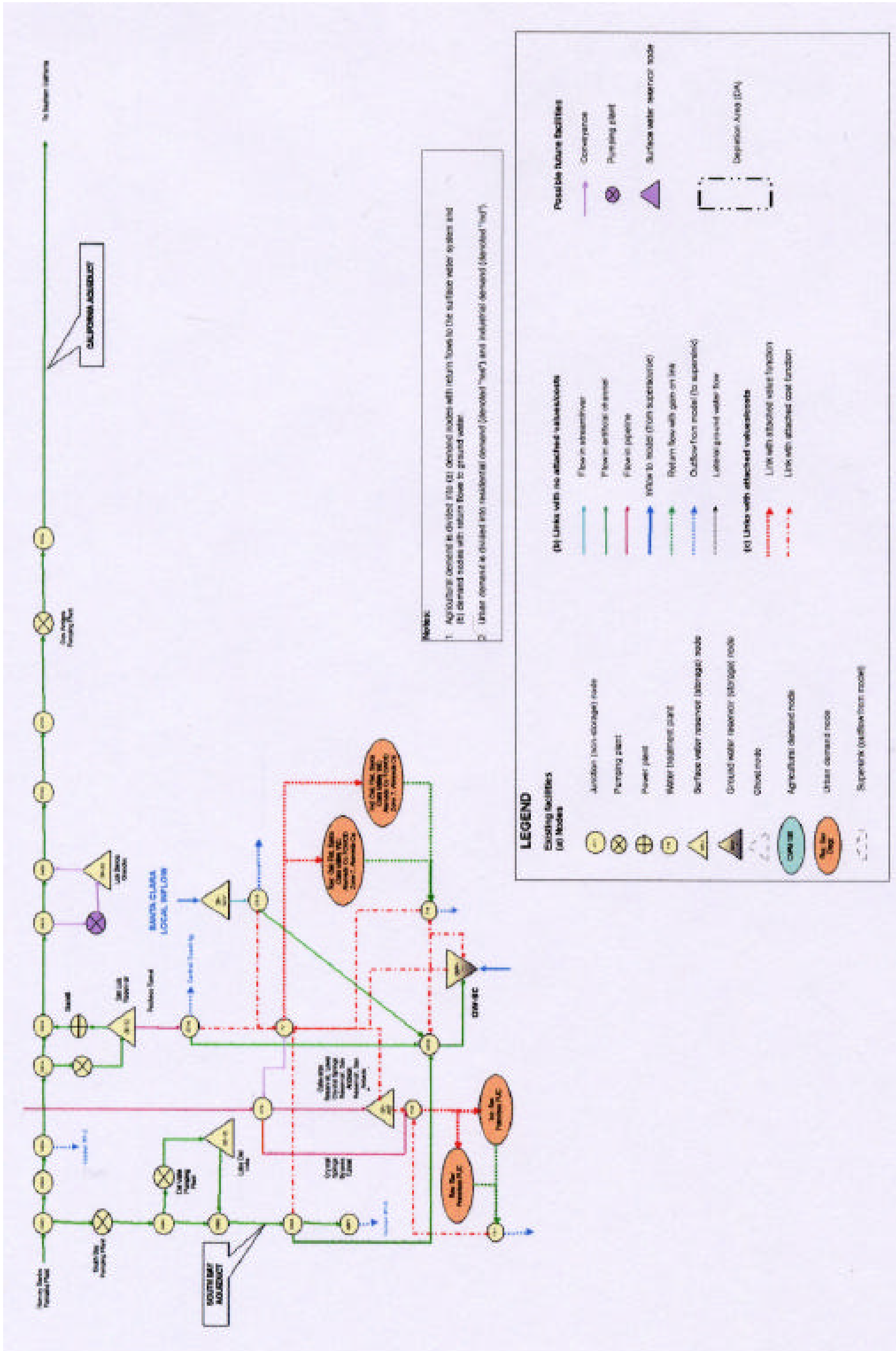

Figure 4. CALVIN schematic of San Joaquin Valley and Bay Area (Continued)

Supply Representation

The dominant hydrologic feature of the region is the San Joaquin River and its tributaries. In addition to several smaller streams like Cherry and Eleanor Creeks, major rivers such as the Fresno, Chowchilla, Merced, Tuolumne, Stanislaus, and San Joaquin are all explicitly modeled. Floods from the King's River to the south, which occasionally spill into the San Joaquin River, are represented by a time series inflow.

California has made extensive use of infrastructure to regulate the flow of water to meet agricultural, urban, and environmental demands. Fourteen reservoirs are represented (see Table 1), nine of which are operated by the Central Valley Project or the State Water Project (indicated by an SR- prefix), and five of which are either locally owned and operated or represent an aggregation of several smaller local reservoirs. The capacities of these reservoirs range from 2.4 maf for the New Melones Reservoir on the Stanislaus River to Lake Del Valle on the South Bay Aqueduct, with a capacity of only 40 taf. Three aggregate reservoirs are modeled to simplify the representation of reservoir groupings that are operated cooperatively, since little data is available regarding actual operations.

Two key facilities instrumental in distributing much of the water needed by agricultural and urban users in Central and Southern California are the Delta Mendota Canal (DMC), owned by the Central Valley Project, and the California Aqueduct, owned by the State Water Project. The DMC is entirely contained within the model except for the Tracy Pumping Plant and eventually flows into the Mendota Pool near the southern boundary. A portion of the California Aqueduct from Bethany Reservoir to Node 744 in DWRSIM includes the diversions serving the San Francisco and South Bay urban areas, as well as CVPM 10.

Table 1. Reservoirs

CALVIN name	Description	Minimum Storage (taf)	Physical Maximum Capacity (taf)
SR-10	New Melones	80	2400
SR-12	San Luis	80	2038
SR-15	Del Valle	10	40
SR-18	Millerton	120	521
SR-20	McClure	115	1024
SR-52	Hensley	4	90
SR-53	Eastman	10	150
SR-81	New Don Pedro	100	2030
SR-ASF	Aggregate SF (Calaveras, Crystal Springs, San Andreas, Pilarcitos, and San Antonio).	31	225
SR-HHR	Hetch Hetchy	36	360
SR-LL-LE	Aggregate Lloyd/Eleanor	30	301
SR-SCV	Aggregate Santa Clara (Anderson, Calero, Chesbro, Coyote, Guadalupe, Lexington, Pacheco, Uyas)	37	170
SR-TR	Tulloch	11	67

The Hetch Hetchy Aqueduct, another key facility, provides water to Bay area cities through diversions from several reservoirs at the headwaters of the Tuolumne River. It is the primary water source for the City and County of San Francisco and supplements supplies for urban areas in the South Bay.

An important feature of CALVIN is its integration of surface and groundwater resources. Five groundwater basins are modeled and are represented as reservoirs with unit pumping costs (see Howitt, et al. 1999, Appendix J). Four representative aquifers underlie the four CVPM regions in the San Joaquin Valley (10 to 13). The fifth represents the aggregated groundwater resources of the Santa Clara Valley Water District, the Alameda County

Water District, and Alameda County Zone 7, which all extensively use groundwater to augment and operate their supplies.

Though variable head hydropower facilities are not included in the model, economic benefits derived from two fixed head hydroelectric facilities, the Gianelli and O'Neill Powerplants, are explicitly modeled. Treatment costs are incorporated in appropriate locations to reflect water quality management costs.

Economic Valuation of Water

Water demands in CALVIN can be represented in one of two ways. In situations where economic data is unavailable, demands are fully supplied using a fixed time series of deliveries. Demands represented in this way therefore are not included in the economic objective function of CALVIN's optimization algorithm. Agricultural and urban *economic* demands were modeled using derived economic values for water, as illustrated in Figure 5. Target deliveries are defined to be the maximum delivery, or the point where additional water has no value. Deliveries less than the target incur a scarcity cost, defined to be the area under the marginal value of delivery curve. The difference between the maximum delivery and actual delivery is called "scarcity" in this study. CALVIN seeks to minimize total costs, comprised of the sum of the scarcity costs for economic demands and operating costs.

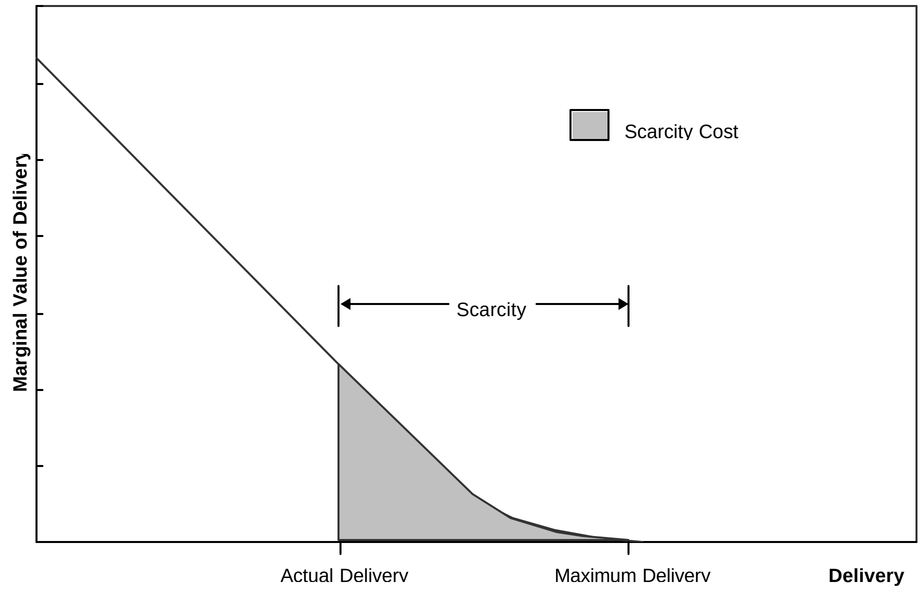

Figure 5. Economic Valuation of Water

Demand Representation

Demands on the region's water can be categorized into three sectors: urban, agricultural, and environmental. Environmental water allocations, such as minimum instream flows and wildlife refuge allocations, have an increasingly important role. Because the economic value of environmental water use is extremely difficult to quantify, environmental demands in CALVIN have been modeled by constraining the system to meet minimum instream flow requirements and mandatory deliveries to the two aggregated refuge areas: the Mendota and San Joaquin Wildlife Refuges.

Data regarding diversions to both refuges come directly from DWRSIM. The San Joaquin Refuge in CALVIN is modeled as a single diversion off of the Delta Mendota Canal, but is actually an aggregation of Volta Wildlife Management Area; and Freitas, Salt Slough, and China Island San Joaquin Basin Action Plans. The Mendota Refuge diversion from the Mendota Pool represents refuge deliveries to Grassland Water District, Los Banos and Mendota Wildlife Management Areas, Merced National Wildlife Refuge, San Luis State Wildlife Refuge, and West Gallo San Joaquin Basin Action Plan.

Implementation of the increased environmental water allocations outlined in the Central Valley Project Improvement Act (CVPIA) will have an important role in water allocation decisions in the future. However, for the purpose of comparison to previous simulation modeling studies, the two alternatives considered here enforce historic refuge allocations (Level 2), not the recently mandated CVPIA (Level 4) demands.

Water demands for agricultural and urban areas throughout the San Joaquin Valley portion of the region are based on two kinds of spatial units employed by the Department of Water Resources and the US Bureau of Reclamation: the Detailed Analysis Unit (DAU), and the agricultural regions of the Central Valley Production Model (CVPM regions). As noted earlier, two simulation models, the Department of Water Resources Planning Simulation Model (DWRSIM) and the Central Valley Groundwater Simulation Model (CVGSM), provide the basis for comparison for CALVIN results. Supplies are derived mostly from CVGSM and DWRSIM, and demands are taken from DAU data. Table 2 outlines how CALVIN represents agricultural water users within the San Joaquin Valley and how they relate to the CVPM and DAU spatial analysis units.

Agricultural demands are modeled using economic value functions for water generated by the Statewide Water and Agricultural Production Model, or SWAP (Howitt et al. 1999, Appendix A). SWAP mimics farmers' decisions in a changing system, and calculates marginal values for agricultural water. From the available land, water, and invested capital, SWAP models crop mixes, land-fallowing, and irrigation efficiencies, and returns marginal values for water which can be mapped into an economic value function.

Table 2. San Joaquin Valley Agricultural Water Users

CALVIN Demand	County	DAU	CVP Contractors	SWP Con-tractors	Others
CVPM 10	Madera, Merced, San Joaquin, Stanislaus	216	Central California ID, Panoche WD, Pacheco WD, Del Puerto, Hospital, Sunflower, West Stanislaus ID, Mustang, Orestimba, Patterson WD, Foothill, San Luis WD, Broadview, Eagle Field, Mercy Springs, Pool Exchange Contractors, Schedule II water rights, Grasslands WD	Oak Flat WD	None
CVPM 11	San Joaquin, Stanislaus	205 206 207	None	None	Stanislaus River water rights: Modesto ID, Oakdale ID, South San Joaquin ID
CVPM 12	Merced, Stanislaus	208 209	None	None	Turlock ID, part Stevinson WD, part Merced ID
CVPM 13	Madera, Merced	210-215	Chowchilla WD, Gravely Ford WD, Madera ID	None	majority of Merced ID

Table 3. San Joaquin Valley Fixed Urban Demands

CALVIN Node Name	DAUs	2020 Population*	2020 Demand TAF/year
CVPM 10 Urban	216	150,580	41.9
CVPM 11 Urban	205, 206, 207	653,470	231.7
CVPM 12 Urban	208, 209	297,770	109.6
CVPM 13 Urban	210-215	422,150	160.8

* DWR DAU 2020 population data (DWR 1998)

Urban demands within the San Joaquin Valley portion of the region (listed in Table 3), include cities like Modesto, Turlock, Merced, Manteca, and Madera and are not economically modeled since water value data was unavailable. Deliveries to these urban regions are fixed at 2020 projected demands in both the Base and Unconstrained Cases (Jenkins, et al. 2001, Appendix B1). These urban areas rely almost exclusively on groundwater.

In contrast to the fixed urban demands in the San Joaquin Valley, urban demands in San Francisco, Santa Clara Valley, and southern Alameda County are represented economically using water value functions. Urban demand models estimate residential and industrial demands for water based on per capita water usage, forecasted population, published residential price elasticities, and other factors (Jenkins, et al., Appendix B1, B2). The "San Francisco Public Utilities Commission" demand area (SFPUC) is an aggregation of the city and county of San Francisco and most of San Mateo County. This area depends on two sources for water: the Hetch Hetchy system, which is owned by San Francisco and delivers water from the Sierras, and five local reservoirs.

The "Santa Clara Valley" urban demand area (SCV) is an aggregation of the Santa Clara Valley Water District, Alameda County Water District, and Alameda County Zone 7 (Howitt, et al. 1999, Appendix B). It includes cities such as San Jose, Santa Clara, Palo Alto, Hayward, Fremont, Dublin, and Livermore. Supplies to the SCV area include SWP water from the California Aqueduct, CVP water from the San Felipe Unit, Hetch Hetchy water purchased from SFPUC, groundwater, and local surface water.

INSTITUTIONAL FRAMEWORK

Federal, state, and local interests have developed a complex framework of institutions to manage California's water supplies, a framework which continues to evolve as needs change. This section outlines how this array of institutions translates to CALVIN's analysis.

Water Rights and Contractual Allocations

Early in California's history, a dual system of riparian and appropriative water rights evolved to meet growing demands for mining, irrigation, and municipal water supply (Hundley 1992). Over time, recognition of the importance of water to the state overall led to a system which governed appropriation of water rights, and eventually emphasized the importance of balancing private rights with water held in public trust (DWR 1998, Appendix 2A). Federal interventions became prominent primarily through the Central Valley Project, but most recently in the enactment of the Endangered Species Act, a piece of legislation which has had far-reaching effects on water allocations (DWR 1998; Hundley 1992). This evolving institutional framework, carried out on many different levels of government, has resulted in an intricate array of water rights founded primarily on geographic or temporal considerations, and at times myopic allocation mechanisms (primarily individual contractual agreements between two parties). These factors prove to be somewhat unresponsive to demands that are rapidly changing in magnitude and complexity (Lund and Israel 1995).

Water Transfers

As possibilities for infrastructural expansion and demand management yield "diminishing returns", water transfers have become a more prominent way to allow limited water supplies to more efficiently meet growing demands (Lund and Israel 1995). Transfer mechanisms include:

- Permanent transfers

- Contingent transfers (for dry years)
- Spot markets
- Water banks
- Transfers of reclaimed, conserved, or surplus water
- Water wheeling and exchanges

These mechanisms are characterized by greater cooperation of a large number of sellers (ultimately water rights holders) and buyers. In theory, transfers are appealing since they more evenly distribute economic benefits between parties, though undesirable effects (such as third party impacts) need to be considered (Howe, et al. 1986).

Modeling Alternatives

Increased use of transfers would necessitate greater flexibility in operations and greater cooperation between water interests than currently characterizes the system. The two alternatives evaluated in this analysis are primarily an attempt to quantify the benefits of greater flexibility, and secondarily to identify which facility capacities would provide the greatest benefit to the system if expanded. This analysis, therefore, must compare possible alternatives to current water management policies; this is performed through the use of a Base Case and an Unconstrained alternative.

Base Case: The Base Case model is designed to mimic water allocations and operations under current operating policies and existing infrastructure. It is constrained to meet projected year 2020 agricultural, urban, and environmental water demands using existing/planned facilities and current operating rules. Base Case operations for reservoir operations, groundwater pumping, and modeled deliveries were derived from two simulation model runs, DWRSIM Run 514 and CVGSM No Action Alternative (USBR

1997; Jenkins, et al. 2001, Appendix 2I), two models currently in use and which use current operating policies.

Of the thirteen reservoirs modeled, eight reservoirs were constrained to match operations in DWRSIM Run 514. Turlock Reservoir on the Stanislaus River below New Melones was included to more accurately depict operations on the Stanislaus. Storage data for New Melones was taken from the No Action Alternative (1997) of SANJASM, a simulation model used extensively in the CVPIA studies. Storage and release data for Hetch Hetchy, aggregate Lloyd/Eleanor, aggregate San Francisco, and aggregate Santa Clara Reservoirs were not available. SR-ASF and SR-SCV were therefore left unconstrained in the Base Case, while SR-HHR and SR-LL-LE storages were implicitly constrained by downstream Tuolumne flows and Hetch Hetchy Aqueduct flows.

The least constrained operations are those within the Bay Area. Imports from SWP, CVP, and the Tuolumne River to SFPUC and SCV urban demands are constrained to Base Case levels. However, operations and allocations between and within the two demand regions are fully optimized, bound only by physical capacities, since little data is currently available to properly represent Base Case local operations within these demand regions.

Unconstrained Case: The Unconstrained Case optimizes water allocation to maximize economic benefit to agricultural and urban water users, given available water and infrastructure. Allocations are constrained only by physical capacities of reservoirs and conveyance facilities, imposed environmental requirements, and seasonal flood control requirements on reservoirs. Surface and groundwater storages are constrained to the same end-of-period storage in the Unconstrained Case as in the Base Case, ensuring that the overall amount of water in the system remains constant between the two model runs. In the Unconstrained Case, CALVIN seeks to allocate and operate water solely to minimize urban and agricultural scarcity costs plus variable operating costs associated with allocations and operations, thus maximizing economic benefit to the entire region. Boundary flows, e.g. Delta imports and exports, are the same as in the Base Case.

In short, this alternative represents ideal water market or other economics-base water operations and allocations, without consideration of contractual or other water rights, and *theoretically represents the best possible performance of the system to meet agricultural, urban, and environmental demands with current infrastructure*. As in the Base Case, perfect foresight can reduce scarcity and costs below levels that actually face decision makers.

COMPARISON OF MODEL RESULTS

In this section, results from the Unconstrained Alternative are compared to the calibrated Base Case results. An initial regional overview of deliveries, surface and groundwater supplies, and scarcity costs given below will provide the context for a subsequent, more detailed analysis of the effect of an 'ideal market' or other economically efficient re-operation and re-allocation of supplies on agricultural and urban demands. In addition, economic values for water at various locations in the region provide insight into water transfer and infrastructure expansion possibilities, discussed in the "Potential for Changes" section below.

Water Delivery Results

A cursory comparison of overall urban and agricultural deliveries suggests that unlike the southern portion of the state, surface inflows from the Sierras and ample groundwater supplies appear to be sufficient to meet demands for the conditions assumed. Table 4 provides a summary of the demands and supplies for the entire San Joaquin Valley and Bay Area Region.

Table 4. Water Budget

		Base Case Average (taf)	Unconstrained Case	
			Average (taf)	Drought** (taf)
Water Demands				
	Urban	1440	1440	1440
	Agricultural	5259	5259	5259
	Environmental (refuges)*	273	273	273
	Total	**6972**	**6972**	**6972**
Deliveries (less conveyance losses)				
	Surface Water***	3699	3697	2716
	Groundwater	2393	2404	3385
	Reuse/Reclamation	864	871	870
	Total	**6956**	**6972**	**6972**
Scarcity		**16**	**0**	**0**

Notes:
** Based on CALVIN results*
*** Drought years throughout this appendix refer to the water years of 1929-1934, 1976-1977, and 1987-1992 (DWR, pg. 3-7)*
**** Does not include surface water used for artificial recharge (this is included in groundwater deliveries).*

The minor scarcities in the Base Case, all of which are from the urban sector, are eliminated in the Unconstrained alternative for both average and dry year conditions. The reliability chart below (Figure 6) portrays total deliveries for the agricultural and urban sectors and provides an introductory glance at how an ideal market policy might compare to allocations under current operating policies and infrastructure.

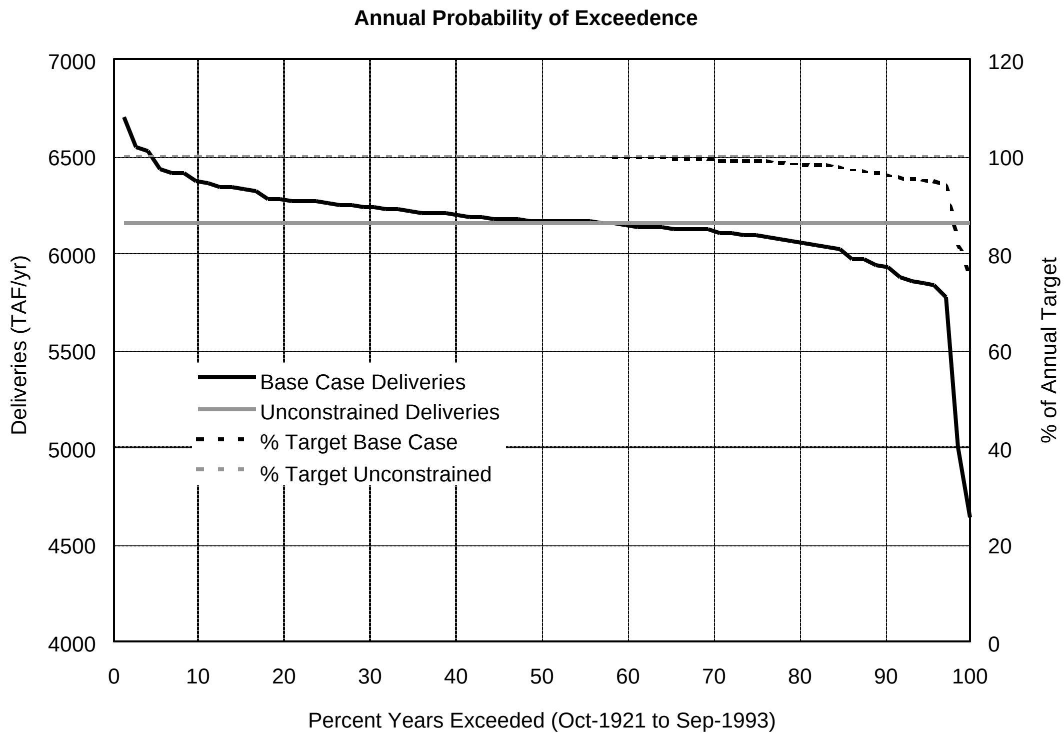

Figure 6. Total Agricultural and Urban Deliveries

The solid lines reflect deliveries in both alternatives (correlating to the left axis of the chart). Deliveries in the Unconstrained alternative meet the target demand in every month of the modeling period. The Base Case "over-deliveries" shown are an unfortunate byproduct of CALVIN's current approach to modeling agricultural demands. The simulation models used to calibrate CALVIN vary agricultural demands according to year type, whereas CALVIN uses fixed demands from year to year. Thus when agricultural deliveries are constrained to match CVGSM deliveries in the Base Case, the model is occasionally forced to deliver more water than CALVIN's demands would call for. Increased reliability of the Unconstrained alternative is reflected in the % Target plots.

Table 5 compares urban and agricultural deliveries under Base Case allocations to those under the Unconstrained alternative. The slight increase in urban deliveries in the Unconstrained run eliminates the 16 taf urban scarcity in the Base Case. Results reported throughout this thesis will indicate that operating costs, rather than scarcity costs, play the most significant role in determining supply mix changes in an ideal market.

Results indicate little difference in overall conjunctive surface and groundwater use as well, though CALVIN was able to satisfy urban scarcities in the Base Case through more efficient use of surface water supplies. Groundwater deliveries are the same between the two runs, since ending groundwater storage in the Unconstrained Run was fixed to match the Base Case.

Table 5. Region-wide Average Annual Deliveries by Source

Water Source	Base Case (taf/yr)			Unconstrained (taf/yr)		
	Agricultural	Urban	Total	Agricultural	Urban	Total
Surface Water	3,408	748	4,156	3,406	764	4,170
Groundwater	1,492	676	2,168	1,492	676	2,168
Total	**4,900***	**1,424**	**6,324**	**4,898***	**1,440**	**6,338**

Note:
**Deliveries may differ from the demands reported in Table 3 because some water supplies are recycled.*

Scarcity and Operating Costs

As stated earlier, CALVIN attempts to maximize economic benefit by minimizing both the cost of water scarcity and operating costs to the system. Table 6 indicates that scarcities were found only in the San Francisco and Santa Clara urban areas in the Base Case. A combined annual average scarcity of 16 taf "cost" roughly $16 million in unrealized economic benefit. These estimates rise to nearly $61 million in Base Case drought years, when urban scarcities rise to nearly 62 taf/yr. Urban scarcity costs are effectively eliminated in the Unconstrained Run in both average and drought year conditions.

Comparison to DWR (1998) shortage estimates in the San Joaquin River Hydrologic Region, which includes the San Joaquin Valley portion of this analysis plus the Consumnes and Mokelumne watersheds reveal potential input data discrepancies in the CALVIN model. DWR estimates that shortages under average year conditions with year 2020 demands for the SJR Hydrologic Region are 63 taf, with drought year shortages rising to over 710 taf. This varies significantly from CALVIN's estimation, which suggests no scarcity in the San Joaquin Valley under both average and drought conditions in the Base Case. Further research is needed to estimate effects of perfect foresight and input data compatibility from the various sources used. Again, overall trends are the important consideration.

Table 6. Average Annual Scarcities and Scarcity Costs

	Model Case	Agriculture			Urban		
		Scarcity (taf)	% Scarcity	Cost ($1000)	Scarcity (taf)	% Scarcity	Cost ($1000)
Annual Average	Base Case	0	0	0	16.0	1.8	15,290
	Unconstrained	0	0	0	0	0	0
Drought Average	Base Case	N/A*	N/A	N/A	61.5	6.9	60,900
	Unconstrained	0	0	0	0	0	0

Notes:
** Distortions to scarcities occur as a result of the calibration procedure, which attempts to match CALVIN agricultural demands (invariant from year to year) to Base Case deliveries (based on varying demands with year type). Drought costs are therefore unavailable. For a further discussion of these issues refer to Appendices 2H and 2I as well as Chapter 5 of Lund, et al. (2000).*

In addition to reducing scarcity costs, the ideal market represented by the Unconstrained Run was successful at reducing operating costs by an additional $21 million dollars on an annual average basis. These operating costs were mainly due to groundwater pumping or recharge, and conveyance pumping. Table 7 depicts how the reduction of both scarcity and variable operating costs result in a $36 million annual benefit to the Bay Area and San Joaquin Valley.

Table 7. Variable Economic Costs (Average Year)

	Base Case ($M/yr)	Unconstrained ($M/yr)	**Cost Difference ($M/yr)**
Scarcity Cost	15.3	0	**-15.3**
Operating Cost	379.1	358.3	**-20.8**
Total Cost	**394.4**	**358.3**	**-36.1**
Note: *Economic benefits from fixed-head hydroelectric power generation are included in this cost total as negative costs.*			

Agricultural Supply Sources

Agriculture within the San Joaquin Valley depends heavily on irrigation from surface water (diverted from a network of rivers and canals), and groundwater. The four agricultural areas represented, all of which are located in the San Joaquin Valley, show differing supply mixes of groundwater and surface diversions, depending on their access to "unrestricted" surface water.

Because the overall amount of groundwater in the system was the same between the two runs and there was no agricultural scarcity in the Base Case, the Unconstrained Run results showed no average overall change in the mix between groundwater and surface water usage throughout the agricultural sector. However, CALVIN attempted to re-allocate surface sources to reduce overall operating costs, resulting in significant supply mix changes in several CVPM regions.

CVPM 10 (see Table 8), located along the western portion of the San Joaquin Valley, showed a slight decrease in reliance on San Joaquin River water, while State Water Project diversions from the California Aqueduct were eliminated (for reasons discussed later). These reductions were compensated by greater Central Valley Project diversions from the Delta Mendota Canal. This shows how CALVIN can suggest optimal modifications to the operation of regional systems.

Table 8. CVPM 10 Supplies (taf/yr)

Supply Source	Base Case Supply	Base Case %	Unconst. Supply	Unconst. %
Lower San Joaquin River	169.2	9.7%	261.0	14.9%
DMC Diversion	477.3	27.2%	621.2	35.5%
Lower Cal. Aqueduct	86.3	4.9%	0.1	0.0%
Upper San Joaquin River	607.2	34.7%	462.1	26.4%
Upper Cal. Aqueduct	4.5	0.3%	0.0	0.0%
GW-10 pumping	*407.6*	*23.3%*	*407.6*	*23.3%*
TOTAL	**1752.0**		**1752.0**	

CVPM 11 in the northeast corner of the San Joaquin Valley, showed almost no change in surface supplies (see Table 9). The assumption of no groundwater pumping was made to force CALVIN to mimic CVGSM's approach to groundwater allocations in both alternatives.

Table 9. CVPM 11 Supplies (taf/yr)

Supply Source	Base Case Supply	Base Case %	Unconst. Supply	Unconst. %
Upper Stanislaus River	582.1	58.0%	562.3	56.0%
Upper Tuolumne River	352.0	35.1%	322.9	32.2%
Lower Tuolumne River	9.6	1.0%	18.5	1.8%
Lower Stanislaus River	48.0	4.8%	75.2	7.5%
San Joaquin River	12.5	1.2%	22.9	2.3%
GW-11 pumping	*0.0*	*0.0%*	*1.6*	*0.2%*
TOTAL	**1004.3**		**1003.5**	

CVPM 12 results, shown in Table 10, also show little difference in supply mixes between alternatives. Diversions from the Merced River decrease slightly, to allow for more diversions to CVPM 13. The difference is met by San Joaquin River water.

CVPM 13, as shown in Table 11, displays perhaps the greatest supply mix changes in the agricultural sector. Diversions from the Merced River increase by over 170 taf/yr on average. Madera Canal water from Millerton Reservoir on the San Joaquin, however, decreases by 171 taf/yr. This, in turn, frees more water for San Joaquin River flows. This may become important when considering San Joaquin River exports to the Delta, as well as transfers to agricultural areas in the Tulare Basin to the south.

Table 10. CVPM 12 Supplies (taf/yr)

Supply Source	Base Case Supply	Base Case %	Unconst. Supply	Unconst. %
Upper Merced River	23.0	2.7%	19.4	2.3%
Lower Merced River	59.9	7.1%	50.2	6.0%
Upper Tuolumne River	561.0	66.5%	553.8	65.6%
Lower Tuolumne River	7.4	0.9%	14.6	1.7%
San Joaquin River	18.8	2.2%	32.0	3.8%
GW-12 pumping	*173.6*	*20.6%*	*173.6*	*20.6%*
TOTAL	**843.8**		**843.8**	

Table 11. CVPM 13 Supplies (taf/yr)

Supply Source	Base Case Supply	Base Case %	Unconst. Supply	Unconst. %
Madera Canal/Millerton	251.3	13.6%	93.0	5.0%
Upper San Joaquin River	5.8	0.3%	7.8	0.4%
Fresno River	51.7	2.8%	52.9	2.9%
Chowchilla River	55.5	3.0%	65.3	3.5%
Upper Merced River	502.2	27.1%	652.2	35.2%
Lower Merced River	20.9	1.1%	28.9	1.6%
Lower San Joaquin River	2.1	0.1%	3.5	0.2%
San Joaquin River, Mendota Pool	50.6	2.7%	36.4	2.0%
GW-13 pumping	*910.5*	*49.2%*	*910.5*	*49.2%*
TOTAL	**1850.6**		**1850.6**	

Urban Supply Sources

In many ways, analysis of the water supply mix to SFPUC and SCV urban demand regions affords the most interesting results in the San Joaquin Valley and Bay Area regional analysis. Though in some ways these urban areas may suffer the effects of aggregation and system simplification in CALVIN, comparison of facility operations under current policies to those under the ideal market may prove helpful in generating new perspectives.

Tables 12 and 13 outline the various urban supplies included in the CALVIN model. San Francisco, though shown to derive its entire water supply from the Hetch Hetchy project, actually depends on local supplies for approximately 15% of its supply (DWR 1998). Details regarding these local inflows were difficult to acquire, however, and were therefore omitted.

CALVIN results show that in an ideal market San Francisco attempts to maximize imports of low-cost, high-quality Hetch Hetchy water, resulting in conveyance capacity flows in every month of the 72 year modeling period. It is important to note that the San Francisco area depends almost completely on surface supplies, and therefore has limited capacity for conjunctive groundwater banking and use.

Table 12. San Francisco Supplies (taf/yr)

Supply Source	Base Case Supply	Base Case %	Unconst. Supply	Unconst. %
Hetch Hetchy	232.3	100.0%	238.0	100.0%
SFPUC Recycling	0.0	0.0%	0.0	0.0%
TOTAL	**232.3**		**238.0**	

Conversely, the Santa Clara Valley urban demand region has one of the most diverse supply systems in California (see Table 13). The region makes extensive use of surface supplies to recharge groundwater; almost 35% of total supplies in the Base Case is surface or reclaimed water that has been routed via groundwater storage and subsequent pumping. SWP and CVP water from the California Aqueduct and Delta Mendota Canal is diverted through the South Bay Aqueduct and the San Luis Reservoir/Pacheco Tunnel system for use in groundwater recharge or is treated for direct use. The SCV region also purchases Hetch Hetchy water from SFPUC.

In the Unconstrained Alternative, supplies through the South Bay Aqueduct are minimized, due to relatively high pumping costs. California Aqueduct water is instead routed through San Luis Reservoir and the Pacheco Tunnel to the SCV groundwater basins. Hetch Hetchy water purchases from San Francisco increase from 58 taf/year to 93 taf/yr.

Table 13. Santa Clara Valley Supplies (taf/yr)

Supply Source	Base Case Supply	Base Case %	Unconst. Supply	Unconst. %
Santa Clara Recharge	2.5	0.4%	0.6	0.1%
Santa Clara Local	116.5	18.0%	118.4	18.0%
Pacheco Tunnel Recharge	103.9	16.1%	200.9	30.6%
Pacheco Tunnel	14.9	2.3%	63.9	9.7%
South Bay Aqueduct Recharge	71.5	11.1%	0.0	0.0%
South Bay Aqueduct	87.5	13.5%	0.2	0.0%
Hetch Hetchy	57.7	8.9%	93.2	14.2%
SCV Reclamation Recharge	48.0	7.4%	34.1	5.2%
SCV Recycling	0.0	0.0%	0.0	0.0%
SCV GW inflow	130.0	20.1%	130.0	19.8%
TOTAL	**646.1**		**656.3**	

As in the SFPUC region, all scarcities in both average and drought years are met in the SCV region (see Table 14).

Table 14. Urban Scarcities

		Annual Average		Drought years	
		Scarcity (taf)	% scarcity	Scarcity (taf)	% scarcity
San Francisco Urban Region	Base Case	5.8	2.4	20.6	8.7
	Unconstrained	0	0	0	0
Santa Clara Urban Region	Base Case	10.2	1.6	40.8	6.2
	Unconstrained	0	0	0	0

Changes in Deliveries and Scarcity Costs

The following plots provide a summary of the changes in deliveries and scarcity costs for the two urban demand regions (see Figures 7 and 8). Plots for the agricultural sector were omitted since there were no scarcities or changes in deliveries between modeling alternatives. Each box reports the change in the Unconstrained maximum (usually occurring in drought years), minimum, and average deliveries and scarcities to Base Case values.

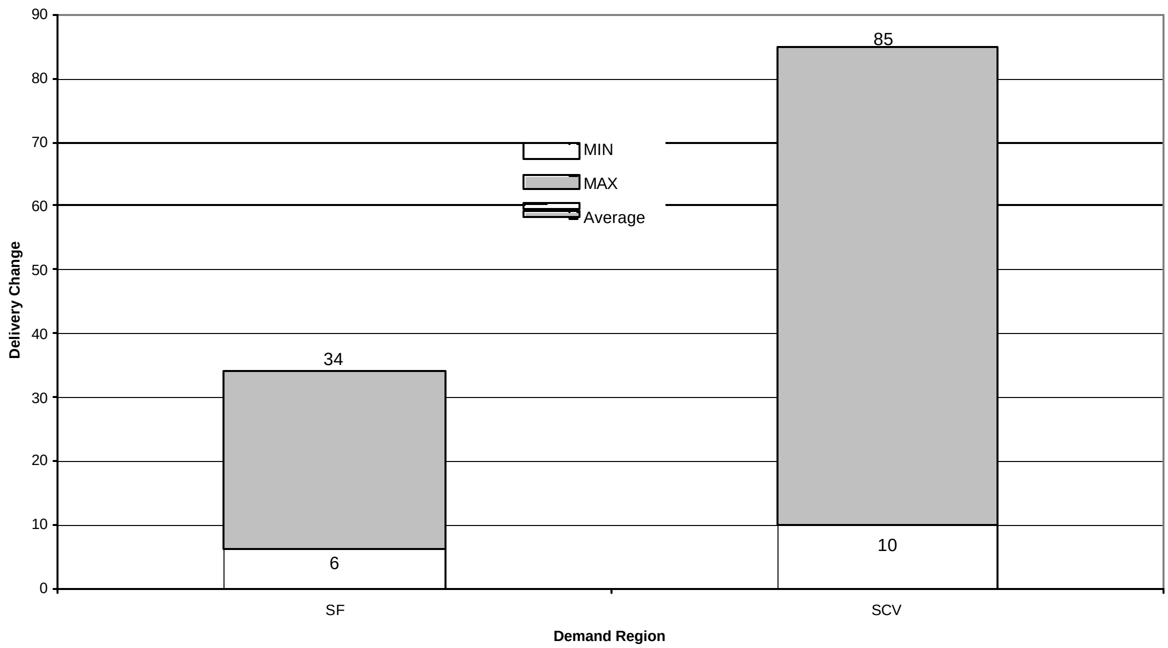

Figure 7. Changes in Annual Urban Deliveries from Base Case to Unconstrained Case (taf/yr)

An average increase in deliveries of 6 taf/yr for San Francisco and 10 taf/yr for Santa Clara effectively alleviates Base Case scarcities in the Unconstrained Run. The worst annual scarcity faced by either urban area was 85 taf in Santa Clara, corresponding to a scarcity cost of over $103 million. CALVIN's re-allocation of surface supplies reduced even this scarcity to zero.

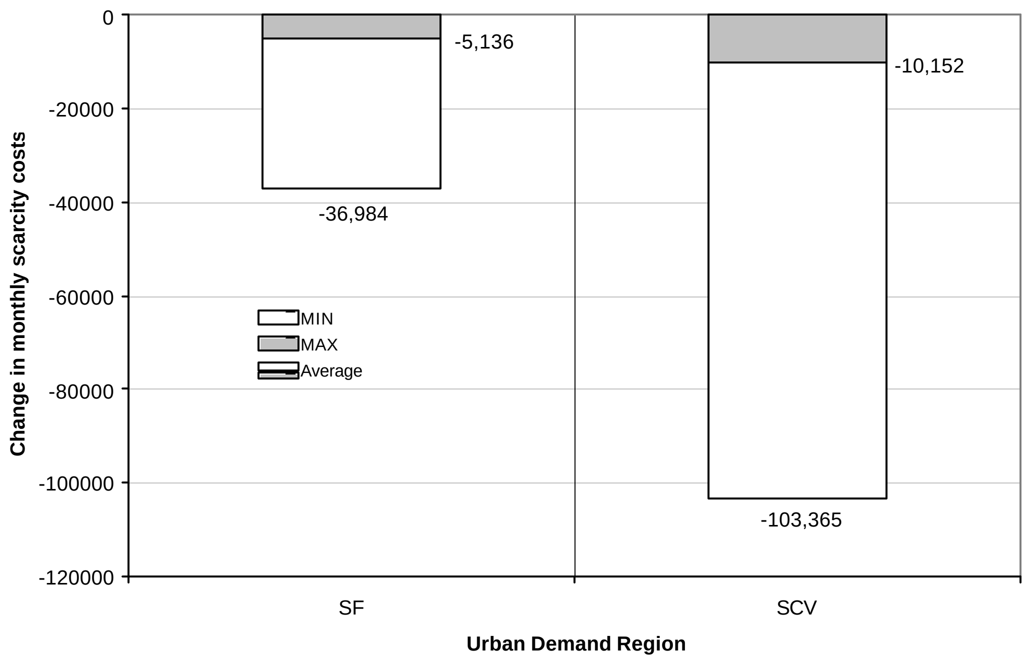

Figure 8. Changes in Annual Urban Scarcity Costs ($1000/year)

Environmental Water Requirements

CALVIN recognizes two specific types of environmental flow requirements. First, refuge demands are fixed diversions from streams and canals for the purpose of maintaining wetland ecosystems. Refuge diversions often make water unavailable for downstream needs by removing it from the system. Second, minimum instream flows are placed on rivers meeting downstream needs, but flow requirements often are maintained by reservoir releases during non-peak economic demand periods.

CALVIN represents environmental flow requirements on rivers as lower bound constraints and wildlife refuge allocations as fixed deliveries (Jenkins, et al. 2001, Appendix F). The minimum monthly instream requirements on the Merced, Stanislaus, and Tuolumne were developed from input data to SANJASM NAA and represent a variety of environmental purposes (USBR 1997). Refuge deliveries are set at the DWRSIM 514 diversion levels, and these environmental requirements remain the same in both model runs. Table 15 compares the Base Case and Unconstrained annual average flows for each location where flow requirements are imposed, while Table 16 lists the drought year flows and requirements. In both modeling alternatives, all environmental requirements are met; however, flow regimes change considerably on some rivers. Diversions to wildlife refuges are equal to the minimum flows required in both alternatives, while instream flows in the Tuolumne, Stanislaus, and Merced Rivers exceed the minimum requirements in both average and drought year conditions.

Table 15: Annual Average Environmental Flows (taf)

	Minimum Flow Requirement	Base Case	Unconstrained	% Difference
Merced River (Upper)	78.9	395.0	265.2	-32.9%
Merced River (Lower)	78.9	374.7	246.6	-34.2%
Stanislaus River	195.6	389.2	417.7	7.3%
Tuolumne River	118.8	543.5	593.9	9.3%
Volta Refuges	35.5	35.5	35.5	0.0%
San Joaquin/Mendota Refuges	237.3	237.3	237.3	0.0%
San Joaquin River (Vernalis)	1030.9	2889.2	3080.7	6.6%

Table 16: Average Drought Year Environmental Flows (taf)

	Minimum Flow Requirement	Base Case	Unconstrained	% Difference
Merced River (Upper)	69.2	154.0	170.9	10.9%
Merced River (Lower)	69.2	112.3	154.9	37.9%
Stanislaus River	157.0	192.8	262.1	35.9%
Tuolumne River	71.7	169.9	140.1	-17.5%
Volta Refuges	34.2	34.2	34.2	0.0%
San Joaquin/Mendota Refuges	229.4	229.4	229.4	0.0%
San Joaquin River (Vernalis)	528.6	1373.8	1506.9	9.7%

The Tuolumne River is a key location for the system due to keenly competing agricultural, urban, and environmental demands. High quality Tuolumne water appeals to urban users, while farmers depend on Tuolumne diversions in CVPM Regions 11 and

12 for irrigation. Hetch Hetchy Reservoir and the upper Tuolumne are located in a region of great natural beauty, making the reduction or perhaps even elimination of facilities environmentally attractive. Despite its importance, data concerning flows, diversions, and reservoir operations for the Tuolumne were difficult to obtain. Appendix 2I (Base Case) and Appendix I (Surface Water Hydrology) of Jenkins, et al. (2001) describe the modeling method used to represent the Tuolumne River and Hetch Hetchy system, and how inflows, diversions, and operations were determined.

As Figure 9 shows, Tuolumne flows far exceed requirements for most of the year on a monthly basis. Peak flows occur in early summer, corresponding to seasonal agricultural demands. Flow requirements are usually binding in September and October from the re-operation of New Don Pedro Reservoir to maximize stored water for peak summer demands. In drier periods, the requirements become binding for longer periods, often between September and March.

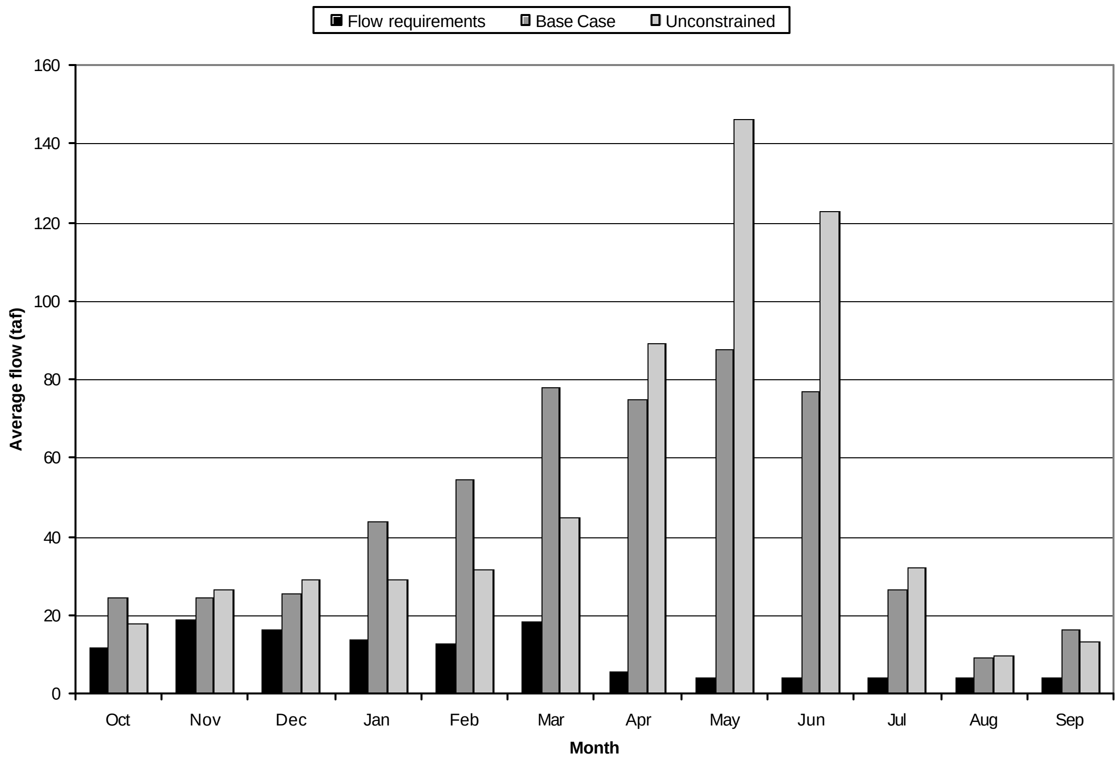

Figure 9. Tuolumne River Average Monthly Flows Below New Don Pedro Reservoir

The San Joaquin River, a major water source for the Delta, also has significant instream flow requirements enforced by the State Water Resources Control Board to ensure adequate water quality and flow levels in the Delta. Historically, these requirements have been placed at Vernalis, just upstream of the Delta. In CALVIN, the San Joaquin River below Vernalis is represented by a boundary outflow. The Vernalis flow requirements are placed on a link just downstream of the Stanislaus confluence and upstream of agricultural diversions into CVPM 10. Figure 10 depicts flow patterns for the two alternatives in relation to SWRCB flow requirements. In both cases, flows are substantially greater than the requirements on an average basis.

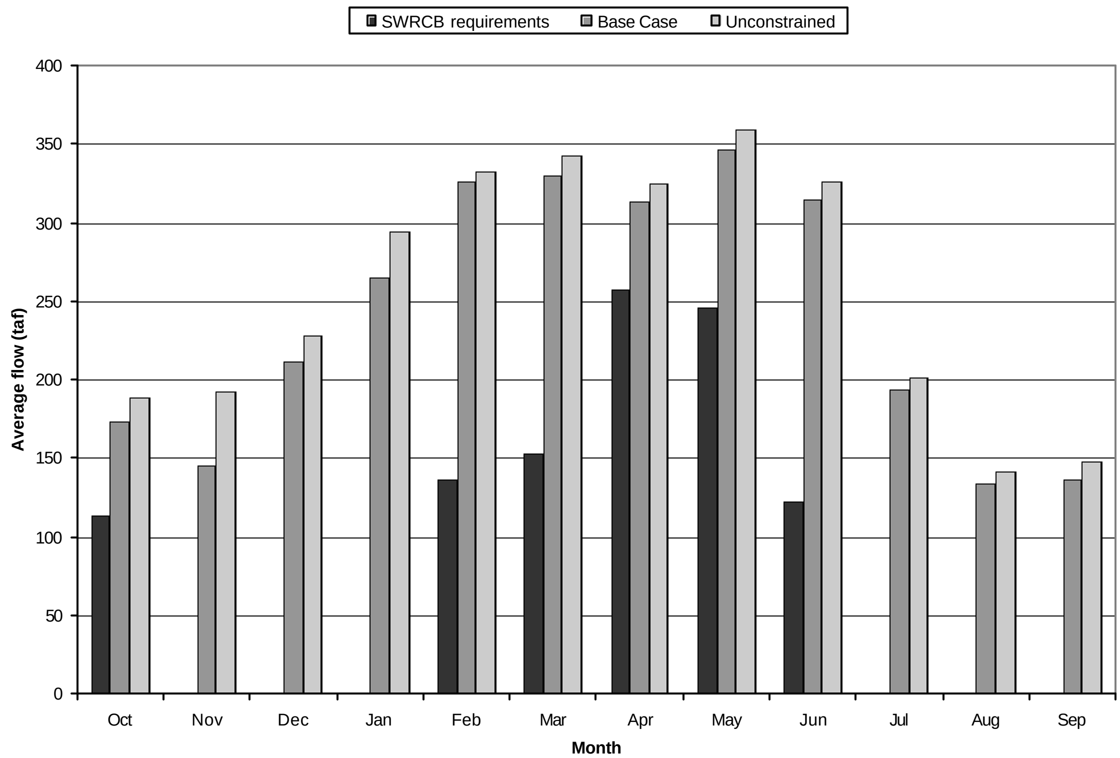

Figure 10. Monthly Average Flow in San Joaquin River at Vernalis

Unfortunately time limitations did not permit detailed post-processing of environmental flows against details of a particularly complex set of flow requirements.

Economic Values of Additional Water

CALVIN reports marginal values of water in two ways. Where constraints placed on river, conveyance, or storage capacity links are binding, CALVIN reports the shadow cost on that element. This shadow cost shows the additional net cost to the region if the constraint is tightened by one unit (or the benefit if the corresponding constraint is slackened by one unit). Negative marginal costs on reservoirs or conveyance facilities indicate a net benefit to the entire region if the limiting capacity is increased. River reaches with binding minimum instream flows, reservoirs drawn down to dead pool, and conveyances without flow generate positive shadow costs, since lower bounds are binding in these cases.

Because negative and positive marginal values refer to different binding constraints on a link, averages of positive marginal values consider positive values and zeros for all other values (negative values are treated as zero values in positive averages). The converse is true for negative marginal value averages. For example, when reservoir storage shadow cost results included both positives (indicating the reservoir was emptied to dead pool) and negatives (indicating the reservoir was filled to capacity), positive values were considered zero values when analyzing the average value of capacity expansion.

In addition to generating shadow costs, CALVIN also reports the marginal value (net benefit to the region) at any *point* in the system of an additional unit of water from an external source. This value, also called the 'willingness to pay' at the point in consideration, is useful in investigating intra- and inter-regional water transfers.

Water Users' Willingness to Pay for Additional Water

Table 17 shows the willingness to pay for an additional unit of water under the Base and Unconstrained Cases at each of the demand areas.

The elimination of Willingness-to-Pay values in the Unconstrained Run reflects the elimination of scarcities; users are unwilling to pay for additional water if they already have all that they need. The advantages of water trading and flexible storage operations, enhanced by CALVIN's perfect foresight, allow the urban sector to weather even drought conditions successfully.

Table 17. Willingness-to-Pay for Additional Water

CALVIN Demand Region	Base Case ($/af)		Unconstrained ($/af)	
	Average	Droughts *	Average	Droughts
CVPM 10	0	N/A	0	0
CVPM 11	0	N/A	0	0
CVPM 12	0	N/A	0	0
CVPM 13	0	N/A	0	0
San Francisco	639	1,204	0	0
Santa Clara Valley	597	1,147	0	0

Notes:
** Drought year WTP values for Base Case agriculture cannot be determined, due to highly constrained system (see Chapter 5 of Lund, et al. (2001)).*

<u>Demand for Inter-regional Transfers</u>

Comparison of marginal boundary values with values in adjacent regions provides a preliminary indication of how water will be re-allocated and traded in the statewide model under the Unconstrained Alternative.

Willingness-To-Pay values shown in Table 18 indicate that exported Delta water is more valuable to the Lower Sacramento Valley and Bay Delta region (as defined in CALVIN, the Lower Sacramento Valley contains the Delta), as evidenced by the Delta Mendota Canal and the California Aqueduct values.

Table 18. Average WTP for Additional Imports/Exports Between the San Joaquin Valley and Bay Area, and the Low Sacramento Valley

Type	Description	San Joaquin Valley/Bay Area ($/af)	Lower Sacramento Valley ($/af)	Difference ($/af)
Out	San Joaquin outflow at Vernalis	7.15	0.01	7.14
Out	Stanislaus export to SEWD, SJID	11.62	12.11	-0.49
In	Banks Pumping Plant: Cal. Aqueduct import	-10.34	0.00	-10.34
In	Tracy Pumping Plant: DMC import	-13.87	0.00	-13.87

Negative values in the "Difference" column indicate that Delta pumping would be reduced in an ideal market. Ironically, San Joaquin River water, important for Delta flow requirements, proves to be more valuable to San Joaquin Valley agriculture than for users downstream in the Delta.

Marginal boundary flow values between the SJV/BA region and the Tulare Basin (see Table 19) suggest that exports to the Tulare Basin would increase in the statewide model. High values on the Friant-Kern Canal, agricultural diversions off the Delta Mendota Canal and the San Joaquin River, and downstream demands for SWP water could shift supplies to meet the higher valued agricultural scarcities and groundwater pumping costs to the south.

Table 19. Average WTP for Additional Imports/Exports Between the San Joaquin Valley and Bay Area region and the Tulare Basin

Type	Description	San Joaquin Valley/Bay Area ($/af)	Tulare Basin ($/af)	Difference ($/af)
Out	DMC export to CVPM 14 and CVPM 15	8.18	40.70	-32.52
Out	Friant-Kern Canal/Millerton export	13.19	49.10	-35.91
Out	SJ River riparian export to CVPM 16	8.52	55.40	-46.48
Out	California Aqueduct export	23.14	43.00	-19.86*
In	N. Kings River inflow from Region 4	8.18	42.30	-34.12
In	Urban return flow to SJ River from Fresno	8.68	0.00	8.68
In	Ag return flow: CVPM 14 to SJ Refuges	7.44	0.00	7.44

*Note: *Results for the California Aqueduct show that trading would increase from SJV/BA to the Tulare Basin if the boundary constraint were removed. This, however, assumes that Delta exports through the Banks and Tracy Pumping plants would remain fixed, and trading would be re-allocation of existing water in the two regions, and not due to changes in Delta pumping.*

Shadow Values of Environmental Flows

In the case of river flows, shadow costs occur whenever diversions are sufficient to lower flows down to minimum instream requirements. Refuge deliveries are always "binding", because in both alternatives they are represented as fixed time series constraints. Table

20 reports both maximum and average positive shadow values, reflecting the region-wide net cost if the minimum instream flows or mandatory refuge deliveries are increased by one acre-foot. The highest values are refuge deliveries, since most of the water delivered to refuges is unavailable for downstream uses.

Table 20. Shadow Values of Environmental Water in Unconstrained Case

	Monthly Maximum ($/af)	Monthly Average ($/af)
Volta Refuges	20.49	8.28
San Joaquin/Mendota Refuges	17.71	6.60
Stanislaus River	13.75	4.42
Merced River (Upper)	13.47	3.11
Tuolumne River	13.61	2.43
Merced River (Lower)	13.62	1.76

Operating costs, as stated earlier, drive substantial supply mix changes to a number of demand regions. Because operating costs are estimated and at times speculative, and CALVIN representations of water supplies and demands are often aggregated, overall water value and supply trends are of greatest importance.

POTENTIAL WATER MANAGEMENT CHANGES

In this section, water values reported in the previous section are used to assess the benefits of potential infrastructure expansion, alteration of environmental flows, conjunctive use, cooperative operations, and reservoir re-operation. Only Unconstrained Case results are used for this analysis. In effect, system operations are optimized to receive the greatest economic benefit for the region through water transfers *before* expensive facility expansion is considered.

Overall trends within the region provide indications for promising solutions to the region's multiplying water supply issues. The following sections outline a number of these trends as they relate to operations, facility expansion, and water marketing or forms of transfers.

Operations and Conjunctive Use Opportunities

The data presented in the previous section regarding surface and groundwater operations suggest significant operational and water transfer potential exists, even without the consideration of facility expansion.

Surface Water Operations- Conveyance

Nowhere do surface water supply operations change as significantly in the Unconstrained Case as in the urban demand areas of San Francisco and the Santa Clara Valley (see Tables 11 and 12). In addition to local supplies, these two urban areas depend on imports from the Hetch Hetchy Aqueduct, DMC, and California Aqueduct. Hetch Hetchy water is of extremely high quality and requires minimal treatment ($5/af operating cost estimate). Conveyance costs for this water are also minimal (perhaps even negative if hydropower benefits were included), since water is transported by gravity from the Sierras to the Bay region. Delta water, conveyed by the California Aqueduct and DMC, is fed to the Santa Clara area through the South Bay Aqueduct and the San Felipe system and requires significant treatment to remove disinfection byproduct precursors (bromide and TOC) and other contaminants from agricultural runoff. Treatment costs in CALVIN for direct urban use of Delta surface water are estimated to be $254/af in 2020 without an Isolated Facility. Additionally, pumping costs on the South Bay Aqueduct and via the DMC/San Felipe Unit are $60.40/af and $30.60/af, respectively. Consequently, CALVIN maximizes the use of Hetch Hetchy water in the Unconstrained Case. Flows in the Hetch

Hetchy Aqueduct increase by over 41 taf/year in the Unconstrained Case, resulting in flows at capacity for every month during the 72-year hydrologic period. Most of this water flows directly into the San Francisco urban area through the Crystal Springs Bypass Tunnel, with excess water being diverted into the aggregate SR-ASF reservoir for transfers into the Santa Clara region.

With an additional 35 taf/yr of increased Hetch Hetchy imports from SFPUC, the Santa Clara Valley urban area is able to reduce its SWP and CVP imports from the Delta by an average of 13 taf/yr. The 265 taf/yr of Delta water it still uses is routed entirely through the San Luis Reservoir and the Pacheco Tunnel, since pumping costs are roughly $30/af lower through the San Felipe system than the South Bay Aqueduct. CALVIN essentially re-operates the California Aqueduct for two purposes: to meet outflow requirements into the Tulare Basin (and ultimately to Southern California) and to provide water to the SCV urban demand region. Virtually all SWP agricultural diversions to CVPM 10 are eliminated and replaced by DMC diversions.

Re-operation of the California Aqueduct effectively lessens urban dependence on Delta Mendota Canal water (CVP) by decreasing pumping through the O'Neill pumping station (which transfers water between the DMC and the California Aqueduct) from 1161 taf/yr to 997 taf/yr, and substituting SWP water via the San Felipe system. The elimination of California Aqueduct agricultural diversions into CVPM 10 is compensated by direct DMC agricultural diversions.

Surface Water Operations- Storage

Reservoirs are used extensively throughout California to provide reliable water supplies, flood control, hydroelectric power, and recreational venues. Reservoir storage is especially crucial for supply purposes in times of drought. Because reservoir operators are unable to forecast drought durations, reservoirs are typically kept full to reduce the risk of water scarcities. However, evaporation losses are greater when reservoirs are filled. Under the Unconstrained Policy, CALVIN has the advantage of maximizing the conjunctive use of all sources in the region, allowing it to keep reservoirs emptier during average and drought years to minimize scarcity and operating costs (see Table 21). Reservoir re-operation effectively maximizes wet year surface water by minimizing spills, replacing groundwater, and minimizing total pumping costs. The storage pattern shown for New Don Pedro Reservoir in Figure 10 is typical of reservoir operations in the region under the Unconstrained Alternative.

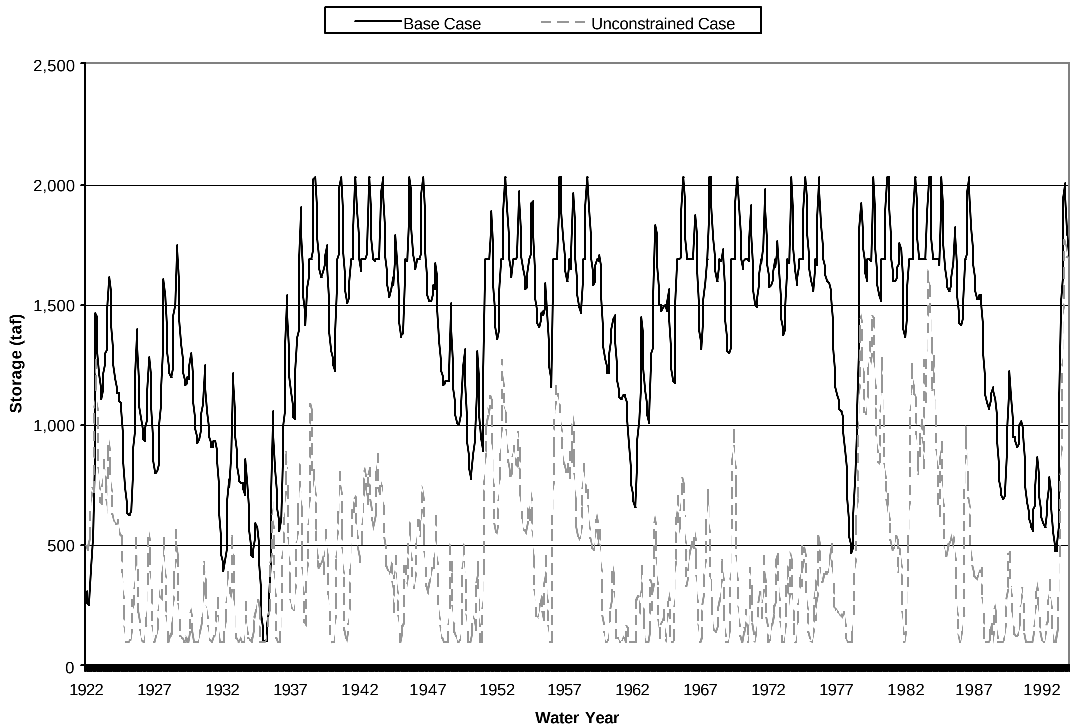

Figure 10. Monthly Storage for New Don Pedro Reservoir (SR-81)

Table 21. Monthly Average Reservoir Storage Comparison

CALVIN name	Description	Base Case (taf)	Unconstrained Case (taf)
SR-10	New Melones	1444	1338
SR-12	San Luis	1245	535
SR-15	Del Valle	32	12
SR-18	Millerton	291	273
SR-20	McClure	697	329
SR-52	Hensley	26	12
SR-53	Eastman	46	26
SR-81	New Don Pedro	1378	427
SR-ASF	Aggregate SF	84	55
SR-HHR	Hetch Hetchy	346	316
SR-LL-LE	Aggregate Lloyd/Eleanor	223	34
SR-SCV	Aggregate Santa Clara	76	75
SR-TR	Turlock	54	12

Figure 11 graphically depicts surface storage trends between the two alternatives.

Decreased storage across the region results in reduced evaporative losses. However, flood control benefits, as well as hydropower costs, could significantly change these storage trends if these economic factors are incorporated into CALVIN.

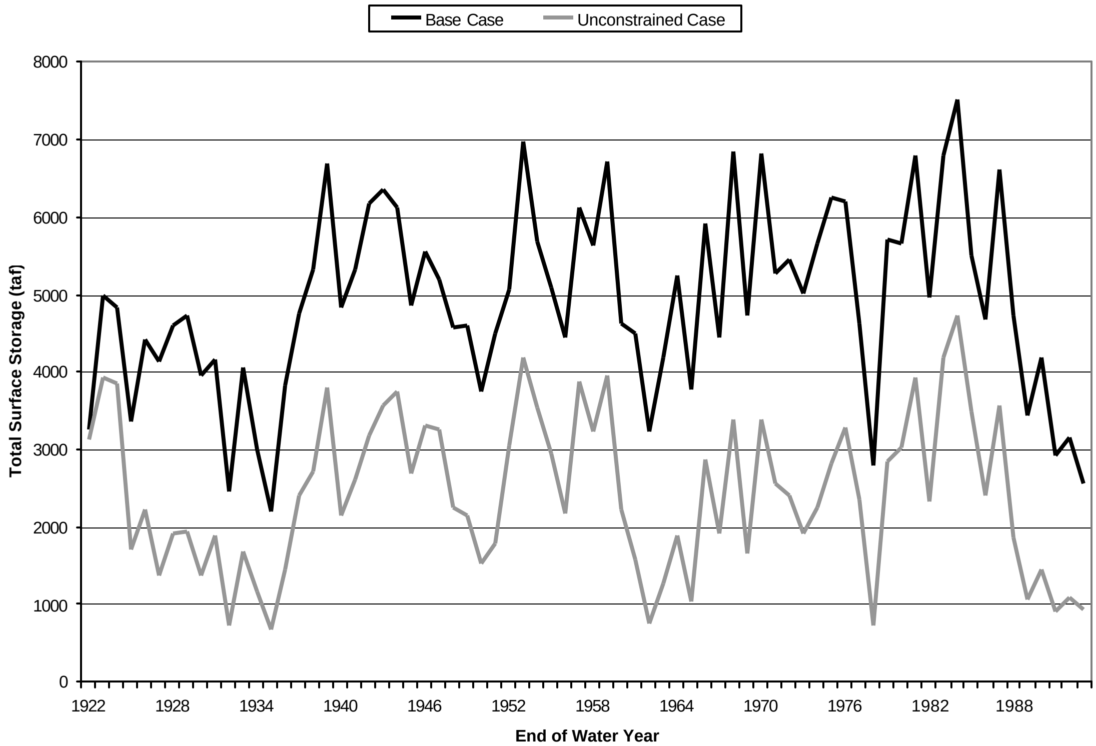

Figure 11. Total Regional Surface Storage (taf)

Conjunctive Use Operations

Historically, agriculture in the San Joaquin Valley has extensively used both surface water and groundwater for irrigation. Some farms do not have access to surface water irrigation diversions, and thus must rely solely on groundwater. Others with access to surface water are able to conjunctively use inexpensive surface water when it is available and supplementary groundwater when surface supplies are insufficient. Comparison of surface and groundwater supply results between the Base and Unconstrained Cases indicate opportunities for conjunctive use, assuming that minimum pumping (representing farmers without access to surface water) is also considered. Similarly, urban areas such as the Santa Clara Valley who already extensively operate their supplies conjunctively, might benefit from considering how operations might change from a regional perspective.

CALVIN has represented groundwater aquifers in the San Joaquin Valley as four separate basins having no dynamic interaction. Because there may be some inter-basin interactions, it is useful to consider overall groundwater storage trends within the region as a more accurate depiction of groundwater results (see Figure 12).

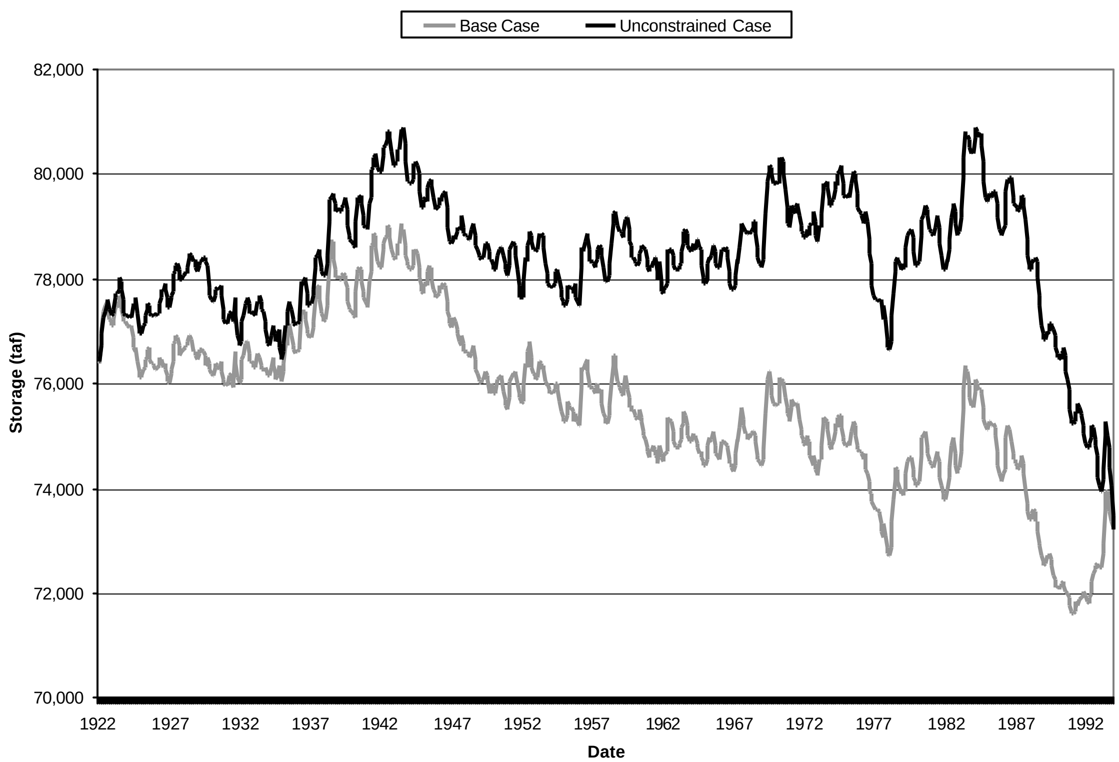

Figure 12. Total Groundwater Storage Pattern

The Unconstrained Case displays more conservative pumping, since CALVIN's re-operation of reservoirs makes more surface water available. Storages are higher in the Unconstrained Case until the drought period of 1987-1992, where groundwater pumping has the greatest value. Results indicate noticeable seasonal variations in groundwater storage, but drought cycle amplitudes appear much larger. For instance, a typical seasonal amplitude seems to be about 0.3-0.5 maf for the unconstrained case. But the 1976-77 drought seems to have about a 2.5 maf amplitude, and the 1988-92 drought has a 5 maf amplitude. Groundwater is therefore the major source of over-year storage for this system. Figure 13 verifies this finding by displaying both seasonal and drought cycle groundwater pumping trends.

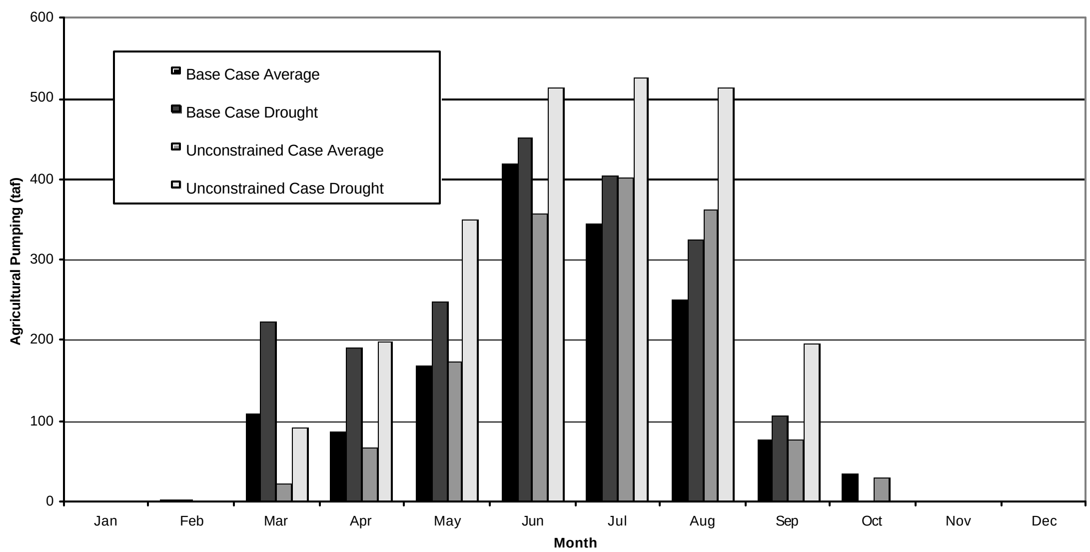

Figure 13. Monthly Agricultural Groundwater Pumping

Agricultural conjunctive use trends evident in the Base Case become even more prevalent under an ideal market. In all four agricultural regions, there was no agricultural pumping in the winter months, but extensive pumping in the high-demand summer months to augment surface water supplies. Essentially, groundwater pumping decreased virtually every winter and increased in almost every summer period.

Santa Clara Valley urban demand region results also indicate that expanded conjunctive use might be beneficial. In the case of Santa Clara, it is less expensive to recharge their groundwater basins with imported Delta water than to treat the water and use it directly.

As noted in Figure 12, the San Joaquin Valley experiences approximately 43 taf/yr overdraft in both alternatives. DWR (1998) reports excessive overdraft in the upper San Joaquin Valley, a trend that is expected to continue. Analysis of Unconstrained Run results show that water marketing may help alleviate groundwater overdraft in this region. Table 22 provides the basis for understanding this overdraft reduction potential. Recall that the groundwater storages for the last year of the 72 year modeling period in the Unconstrained Run was fixed to equal the Base Case ending storages. The marginal ending storage value in the right column of the table indicates the cost to the system if the ending storage constraint was increased by one unit. In other words, it indicates how the system would respond to allowing the ending storage to increase by one unit. For the San Joaquin aquifers, positive marginal values indicate that the system sees a benefit to allowing less groundwater overdraft, with benefits rising as high as $14.94/af in GW-13. Since pumping costs range from $15 to $30/af throughout the Valley, conjunctive surface water use could lessen the agricultural sector's dependence on groundwater. These results suggest that potential exists for alleviating groundwater overdraft throughout the San Joaquin Valley if water could be traded more freely through the system, reducing overall demand on groundwater pumping. Conversely, in the Santa Clara Valley urban area there are advantages to using the groundwater more aggressively. Further analysis is needed, however, to determine the effect of CALVIN's perfect foresight in generating these marginal values.

Table 22. Groundwater Pumping and Marginal Ending Storage Value

	Pumping Costs ($/af)	Marginal Ending Storage Value ($/af)*
GW-10	15.60	0.25
GW-11	20.60	3.94
GW-12	23.60	8.09
GW-13	30.00	14.94
GW-SC	85.00	-61.15
Note: ** Ending storage value valid for Unconstrained results only.*		

Cooperative Operations

The strongest example of cooperative operation changes has already been detailed in the previous section on groundwater operations. The California Aqueduct, operated by the SWP, and the Delta Mendota Canal, operated by the CVP, have historically served both the agricultural and urban sectors. CVP transfers across the O'Neill Pumping Station to the California Aqueduct contribute to diversions to the Santa Clara urban area. Likewise, a portion of SWP water is diverted in the Base Case to meet agricultural needs in the San Joaquin Valley in addition to demands in to the south in the Tulare Basin and southern California. In an ideal market setting, less CVP water is transferred to the California Aqueduct. A larger portion of CVP water is subsequently devoted to agricultural needs, while SWP facilities are more focused on meeting urban needs in the Santa Clara Valley, as well as downstream demands in the Tulare Basin.

Urban cooperation appears stronger in the Unconstrained Case as well. As mentioned earlier, Santa Clara would purchase 40 taf/yr more water on average from SFPUC in an ideal market. Furthermore, marginal values on a theoretical SCV-SF connector in CALVIN indicate that in very dry periods, San Francisco would benefit from the ability to purchase water from Santa Clara sources (values are approximately $250/af in this situation). Earthquake and other unmodeled benefits also might support such a project.

Promising Areas for Facility Expansion

When CALVIN re-allocates water to increase overall regional economic benefit, it is sometimes limited by the capacities of storage and conveyance infrastructure. Scarcities and higher operating costs can be caused either by insufficient water to meet demands or by insufficient infrastructure capacity to move the water to where it is needed. In some cases, there may be both a sufficient amount of water and conveyance capacity, but operating costs on supplies may cause CALVIN to favor one supply link over another. In situations where storage or conveyance capacities are binding, CALVIN's network flow solver generates the value of an additional unit of water if capacity could be increased.

The following analysis considers only the Unconstrained Case, since many of the binding storage and flow constraints in the Base Case are artificially imposed to force CALVIN to imitate CVGSM NAA and DWRSIM 514 results.

Surface Storage

Only two reservoirs in the region show strong promise for capacity expansion. The proposed Los Banos Grandes Reservoir is currently under consideration as one means of increasing storage capacity on the California Aqueduct. CALVIN output suggests (see Table 23) that this off-stream storage reservoir would in fact benefit the region. High marginal values normally occur in January and February, suggesting that filling Los Banos Grandes when Delta water is plentiful would reduce competition for Delta water in drier months. California Aqueduct export requirements to the Tulare Basin and southern

California could be met in the summer months with less scarcity impact on peak summer demands, especially those of Santa Clara Valley that must normally compete with these export requirements.

The aggregate reservoir node representing the Santa Clara Valley local reservoirs shows high marginal values as well, but only in drought conditions, implying that a small amount of additional storage might provide less expensive local water in place of lower quality, more costly Delta imports.

Table 23. Candidate Reservoirs for potential storage expansion

Expected benefit of 1 unit increase in reservoir storage capacity (in $/af)	SR-22: Los Banos Grandes (proposed)	SR-SCV: Santa Clara aggregate
Average annual value	14	13
Maximum monthly value	12	252

Hetch Hetchy Reservoir (SR-HHR), though it is an inexpensive source of high quality water for both the San Francisco and Santa Clara urban regions, shows very little marginal value to storage expansion. This is due to the limiting conveyance capacity of the Hetch Hetchy Aqueduct as shown below; more storage in the reservoir is of little use if it cannot be transported to users.

The small inflow/storage ratio on Millerton Reservoir, in conjunction with highly valued agricultural areas to the south, has lent support to the idea of expanding Millerton's capacity. In addition to regulating flow on the San Joaquin River, Millerton is also used to divert water to the Tulare Basin through the Friant-Kern Canal for agricultural use. Though marginal values on Millerton storage are insignificant in the Unconstrained Case, the $36/af difference in marginal values on the Friant-Kern boundary outflow may cause the value of extra Millerton storage to increase in the statewide model. Millerton

Reservoir operations would also adjust significantly once the reservoir is allowed to meet Friant-Kern downstream needs under a Statewide Unconstrained policy.

New Melones Reservoir on the Stanislaus River, another reservoir with boundary outflows into CVPM 8 in the Lower Sacramento Valley, is an unlikely candidate for expansion or operating changes, since marginal values for Stanislaus water in the Lower Sacramento Valley are lower than the values in the San Joaquin Valley.

Conveyance

Conveyance structures showing promise for expansion were all urban supply links as shown in Table 24. The highest expected values of capacity expansion in the entire region were those on the Hetch Hetchy Aqueduct. Though the Foothill and Coast Range Tunnels on the SFPUC system have a capacity of 620 cfs, the three San Joaquin pipelines carrying water from the SFPUC Sierra reservoirs across the Central Valley have a combined capacity of only 465 cfs. This capacity proves to be binding in every month of the 72-year hydrologic period under the Unconstrained Case.

Table 24. Conveyance Capacity Expansion Values

Conveyance Facility	Expected Benefit of 1 af/mo Expansion	
	Average Annual ($/yr)	Maximum Monthly Value ($/af)
Hetch Hetchy Aqueduct	268	305
SCV groundwater pumping	230	272
SFPUC recycling	55	94
SCV recycling	30	68
SCV groundwater recharge	15	21
SCV/SF hypothetical transfer	5	254

The proposed addition of a fourth San Joaquin Valley pipeline would bring the total capacity of the Hetch Hetchy system to 620 cfs. An Unconstrained model run using this proposed increased Hetch Hetchy capacity shows significant additional changes, beyond those reported here, on both supply mixes and marginal values of water throughout the region.

Wastewater recycling in the Bay Area appears to be another promising expansion alternative, although no capacity was modeled for San Francisco. Though recycling is expensive at $350/af, values average over $660/yr in San Francisco and $365/yr in the Santa Clara Valley for an increase of 1af/month in recycling capacity in the Unconstrained Run. Base Case values, not reflected in the above table, range as high as $3500/yr for San Francisco and $3000/yr for Santa Clara for 1 af/month of additional capacity.

Groundwater pumping shows a markedly high value in the Santa Clara urban region, reflecting the area's desire for cheaper sources over Delta imports (see Table 25). Ending storage for the SCV groundwater basin was fixed to its initial storage, ensuring that for these model runs, the basin under Santa Clara would not be depleted. Positive marginal values on pumping capacity in every month indicate pumping is operated at the estimated maximum capacity of 30.5 taf/mo. This is primarily due to SCV's use of groundwater recharge as a water treatment method; further study is needed to assess whether the SCV groundwater basin could successfully "treat" additional recharge capacity. The 10 taf/yr increase in recharge in the Unconstrained Case occurs through a rise of 30 taf/yr in Delta water recharge and a 14 taf/yr drop in reclamation recharge from Santa Clara (see Table 25).

The value of transfers from Santa Clara to San Francisco is assessed in CALVIN using a connector constrained to zero flow. Small average annual marginal values and a large maximum monthly value suggest that transfers from Santa Clara Valley to San Francisco would be economically beneficial in critically dry periods.

Table 25. Santa Clara Valley Urban Recharge Comparison

Groundwater Recharge Sources	Base Case		Unconstrained Case	
	Average Recharge (taf/yr)	% Contribution	Average Recharge (taf/yr)	% Contribution
Pacheco Tunnel	103.9	16.1%	200.9	30.6%
South Bay Aqueduct	71.5	11.1%	0.0	0.0%
SCV Reclamation	48.0	7.4%	34.1	5.2%
Santa Clara Local	*2.5*	*0.4%*	*0.6*	*0.1%*
TOTAL	225.9		235.6	

Environmental Requirements

Though environmental demands are not modeled economically, marginal values on environmental flows provide useful information regarding the interaction of environmental flows on agricultural and urban demands. This section will focus on discussion of results presented earlier.

Increasing Environmental Flows

This study is largely an analysis of water resource management alternatives for agricultural and urban water supply given environmental supply requirements. Results may be interpreted conversely to analyze what impacts environmental flow changes would have on urban and agricultural demands.

Table 20 reported the shadow costs associated with increasing each environmental flow requirement. Refuge deliveries exhibit the highest values, mainly because water diverted for the refuges (principally from the Delta Mendota Canal/Mendota Pool) becomes unavailable for other uses. Refuge values seem to be driven primarily by competition from the Santa Clara Valley urban area, since agricultural areas downstream of the refuges have both a fixed amount of groundwater to use (meaning pumping costs will not change) and sufficient surface supplies (which have no cost). It is important to recall that the Base Case and Unconstrained Alternative utilize Level 2 refuge demands, which are included in DWRSIM Run 514 and CVGSM NAA 1997. Level 4 refuge demands mandated by the Central Valley Project Improvement Act are significantly higher and will be employed in the near future.

Marginal costs of increasing environmental requirements on the San Joaquin and its tributaries in the unconstrained case reflect minimal impacts to the agricultural sector. Because no further Tuolumne exports to the Bay Area are possible with the Hetch Hetchy Aqueduct at capacity, the impacts of small increased environmental flows are limited to agricultural uses of lower economic value. The two rivers where environmental flow increases would least affect the agricultural sector in the region are the Lower Merced River and the Tuolumne River. Lower Merced River flows are constrained by minimum flow requirements mainly in the months of September and October. Average marginal costs on increased environmental flow on the lower Merced are under $2/af. However, marginal environmental costs on the upper Merced River exceed $3/af.

The Tuolumne River is the next most promising candidate for increased environmental flows with a marginal cost of only $2/af. However, an increase in San Francisco's Hetch Hetchy aqueduct capacity would likely increase the marginal costs of Tuolumne environmental flows, as well as others in the region given the high degree of transferability of agricultural supplies. The Stanislaus River has the highest marginal values at $4.27/af on average, making environmental flow requirement increases the most expensive in the region.

Water Transfers

As Lund and Israel (1995) point out, effective water transfers involve more than financial and legal transactions. An extensive system of conveyance and storage infrastructure must be in place to move water spatially and temporally to provide end users with access at the right place and time. In CALVIN, willingness-to-pay values, and supply mix and scarcity changes between modeling alternatives, indicate the potential effectiveness of water transfers for substantially improving Bay area supply reliability and reducing costs of scarcity and reducing the opportunity costs of environmental water to the agricultural and urban sectors.

Costs and Benefits of Intra-regional Transfers

An analysis of region-wide flows indicates that agricultural-to-urban transfers account for the elimination of urban scarcities in an ideal regional market. An increase of 41 taf/yr in average Hetch Hetchy imports into the San Francisco and Santa Clara urban areas is accompanied by a decrease of 13 taf/yr in lower quality Delta imports. Subsequently, an overall average transfer of 28 taf/yr occurs from the agricultural to urban sectors. 16 taf/yr of this amount covers urban scarcities, and the remaining 12 taf/yr replaces higher cost reclaimed water.

As stated earlier, CVP transfers to the California Aqueduct decrease by 164 taf/yr, but SWP agricultural diversions counter this urban-to-agriculture transfer by decreasing agricultural diversions by 91 taf/yr. The balance of 73 taf/yr of Delta water is then conserved for re-allocation. More efficient surface water operation in the San Joaquin Valley and Sierra reservoirs means that this extra Delta water ultimately flows from the region through the San Joaquin River. In fact, the San Joaquin River boundary outflow increases by 145 taf/yr in the Unconstrained run, showing that 72 taf/yr of extra water in the San Joaquin portion of the Region is conserved in addition to the 73 taf/yr of extra Delta water. The flows pumped from the Delta through both the Delta Mendota Canal and the California Aqueduct are both fixed boundary inflows, resulting in the excess San Joaquin River outflow. If Delta pumping were not constrained, one would expect to see reduced pumping on the Delta Mendota Canal.

An important aspect of water transfer potential is the consideration of downstream demands in a statewide Unconstrained Alternative. Water within the region is very "transferable" inter-regionally in terms of hydraulic interconnections and central location in the state. Significant scarcities to the south would provide a strong market for sales by San Joaquin Valley water right holders. The Friant-Kern Canal and the California Aqueduct prove to be important conveyances for transfers and wheeling in a statewide setting.

The additional capacity of a fourth San Joaquin pipeline on the Hetch Hetchy system, currently under consideration by San Francisco city planners, would increase the potential for agriculture-to-urban water transfers intra-regionally. The Unconstrained Alternative has demonstrated demand for higher levels of urban imports from Hetch Hetchy to reduce Bay Area operating costs and scarcities. These transfers tend to alter supply mixes throughout the region.

Another potential transfer, from a statewide setting, is between the San Francisco Bay urban users and East Bay Municipal Utility District (EBMUD). This is demonstrated by high differences in willingness-to-pay values for these areas, which are geographically in close proximity, but only slightly connected hydraulically.

Regional Economic Impacts of Transfers

Agricultural delivery results show little economic change in the agricultural sector between the Base Case and Unconstrained runs. Agricultural scarcities in both runs are non-existent. Though agricultural supply mixes are altered, land use changes, crop mixes, and income changes are negligible.

Urban benefits derived from the elimination of scarcity, as discussed earlier, top $15 million in an average year and nearly $60 million in dry years. Additionally, as discussed earlier, the entire region accrues an additional $21 million in benefits in reduced operating costs.

As discussed earlier, the net 28 taf/yr transfer from the agricultural sector to the urban sector is not “felt” by agriculture, since agricultural scarcities in both cases are zero. This transfer is merely a result of more efficient surface water operations, which frees up water typically allocated to the agricultural sector to meet urban demands.

CONCLUSIONS

Model results suggest a number of conclusions. These conclusions suggest overall trends and need to be verified through more detailed analyses.

1) *Cooperative operation of the Delta Mendota Canal and the California Aqueduct reduces urban scarcity without adverse effects on agriculture*. In a cooperative setting, a higher percentage of Delta Mendota water is allocated to agriculture, while California Aqueduct water is partially re-directed to meet urban needs.

2) *Conjunctive use benefits evident under current operating policies increase in an ideal water market*. Groundwater is the major source of over-year storage in the system, which according to Draper (2001) has the additional benefit of tempering the effects of perfect foresight.

3) *Water marketing may hold significant potential for alleviating groundwater overdraft in the San Joaquin Valley, especially in the southeastern portion*. Negative shadow values on end-of-period groundwater storage indicate that economic performance would actually improve with less pumping.

4) *The construction of Los Banos Grandes and expanded surface storage in the Santa Clara Valley Urban may provide significant economic benefit*. This is especially true in critically dry periods.

5) *Several conveyance facilities also show significant expansion values, including recycling capacity in San Francisco and Santa Clara Valley, Hetch Hetchy Aqueduct, and groundwater pumping and recharge capacity in the Santa Clara Valley*.

6) *Competition between environmental requirements and urban and agricultural demands decreases under an ideal water market.*

POTENTIAL MODEL REFINEMENTS

CALVIN's representation of water supply and demand in the San Joaquin Valley, though adequate for general investigations of water marketing and facility operation and expansion potential, would provide more accurate output with a number of refinements. The following four improvements would greatly enhance CALVIN's ability to shed light on new ways of managing water in the San Joaquin Valley and Bay Area.

1) *Representation of the San Francisco and Santa Clara Urban Demand Regions:* In an urban region where water supply management is driven by both high water demands and significant operating costs, model representation becomes important. Over-aggregation of facilities and demands tend to distort results. The demands and supply operations aggregated into the Santa Clara Valley urban demand area are especially complex and would benefit from a less aggregated representation. The SR-ASF aggregate reservoir is actually a collection of five reservoirs that tie in to the Hetch Hetchy Aqueduct at different locations; since Hetch Hetchy water is extremely valuable, disaggregation of SR-ASF may give interesting results pertaining to Hetch Hetchy system operation.

In addition, 15% of San Francisco's water supply in reality is composed of local inflows, which have not been represented in CALVIN, due to lack of data. Addition of these local supplies would affect the urban results.

2) *Wildlife refuge representation:* The interaction of the Volta and San Joaquin/Mendota wildlife refuges with both agricultural areas and rivers like the San Joaquin is currently ambiguous. Greater accuracy in modeling these refuge flows would enhance understanding of their effect on urban and agricultural supplies.

3) *Variable head groundwater pumping:* The fixed groundwater pumping costs currently used in CALVIN do not portray the increased pumping costs of lowered groundwater tables in basins where pumping exceeds recharge. Variable head pumping costs would tend to even out groundwater pumping across the region, with consequent adjustments to allocation of agricultural surface water supplies.

4) *Imperfect foresight:* CALVIN's inability to model drought risk aversion causes scarcities and scarcity costs to be biased downward. Re-structuring CALVIN to reflect imperfect hydrologic foresight would make ideal market results and potential facility expansion values more realistic. Reservoir re-operation in the Unconstrained Case would also be more conservative.

5) Reconciliation of input hydrologies and demand estimations: Significant variance between CALVIN's estimation of San Joaquin Valley scarcity and DWR's projected 2020 shortages in the Valley suggest further research is needed in quantifying both water demands and supplies in the San Joaquin Valley. This research may focus on assumptions in the conceptual approach to estimating agricultural demands in CALVIN and SWAP in contrast to CVGSM.

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