WATER MANAGEMENT LESSONS FOR CALIFORNIA FROM STATEWIDE HYDRO-ECONOMIC MODELING

A Report for the California Department of Water Resources

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June 2009

Abstract

California's complex water management system often defies comprehensive analysis. This paper presents the results of a decade of quantification and analysis of this system from a hydroeconomic perspective. The paper focuses on the general approach, management and policy insights, and promising directions that consistently emerge from these analyses. Limitations and suggestions for improving hydro-economic modeling for providing insights into contemporary and future water management problems in California also are presented.

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Introduction

This paper provides insights into California's water management and policy arising from a decade of data synthesis, model development, and application of the California Value Integrated model CALVIN (Draper *et al.*, 2003). The general methodological approach is to represent California's complex water supply system as a complex integrated water management system, with a diverse range of water management options available for use at various locations and times in a portfolio-based solution approach. Computerized optimization is used to identify promising portfolios of water management options, having minimal statewide costs, within major physical, environmental, and policy constraints. The range of options includes water conservation, water reuse, desalination, reoperation of reservoirs and aquifers, water markets, capacity expansion, dam removal, and other water management activities. Various model runs examine the performance of California's water management system in adapting to water markets, conjunctive use, reservoir operation, environmental restrictions, watershed restoration, and climate change.

The general approach taken dates back to Roman times, when Frontinus (97 AD) began his oversight of Rome's water system with a systematic inventory and quantification of its water system. This approach has been formalized and expanded in the modern era as economists, planners, and engineers have sought to grapple with complex water management systems and problems. Today, numerous applications of this hydro-economic modeling approach exist worldwide (Harou *et al.*, In press-b; Lund *et al.*, 2006).

This paper is organized as follows. In the next section the development of water resources in California is presented in brief. Then a portfolio approach for water resources in the state is introduced considering a wide array of management options. A section introducing CALVIN, a hydroeconomic model for California, follows. The last few sections summarize insights from CALVIN applications including, integrated water management, groundwater management, climate change in California, restoration of ecosystem services in the Sacramento-San Joaquin Delta and the Colorado River Delta. Conclusions close the paper.

California's Water System and its Challenges

"At night all cats are grey." French proverb

In California water supply and demands do not match in space and time. Most water availability is in the northern part of the state from winter precipitation and spring snow-melt; whereas water demands are more in the south during the dry summer. Consequently, major floods and seasonal and multiyear droughts characterize water resources in California, despite its highly developed and interconnected system of aqueducts, reservoirs, and treatment facilities. The Sacramento-San Joaquin Delta is the major north-south hub for this water network.

With an average of 200 MAF/yr precipitation, about a third of this amount becomes surface streamflow and aquifer outflow, with an additional 4.4 MAF/yr of Colorado River Compact allocation to California (Department of Water Resources (DWR), 2005). Estimated storage in the state includes roughly 40 MAF in surface reservoirs and between 143 and 450 MAF in aquifers (1998). Yearly agricultural urban and water demands in the state average 25 and 7 MAF respectively.

California faces several major water management challenges for the future. The simultaneity of these challenges poses an additional challenge for planning and policy-making in this dynamic system.

Population growth

By year 2050, population in California, could be as high as 65 million according to DWR estimates (1998). Assuming per capita water use decreases from 240 to 221 gallons per day by 2050, statewide urban water demand could be as high as 15.7 MAF/yr. About 700 thousand acres could be converted from agricultural to urban uses by 2050 according to Landis and Reilly (2002) projections.

Climate change

Under warm-dry forms of climate change, runoff reductions of about 26% and water shortages of more than 20 percent could occur statewide by year 2050 (Medellin-Azuara *et al.*, 2009). With agricultural uses bearing most costs from such shortages, important indirect and adverse effects on the regional and local economies are expected in the form of revenue losses, employment and household income. In addition to the cost of decreased water availability, the likely effects of sea level rise and winter flooding events may also bring significant costs to the state. Changing climates make the Delta more important as the main hub of California's water system (Connell, 2009).

The Sacramento-San Joaquin Delta

The main hub of the California water system is threatened by land subsidence of Delta islands, aging and failure-prone levees, sea level rise, declining native ecosystems, and deteriorating water quality (Lund *et al.*, 2008). A major earthquake could flood much of the Delta, curtailing Delta exports to the Bay Area, the southern Central Valley, and Southern California. Improvements in water quality for Delta exports would have significant cost savings in agriculture south of the Delta in the San Joaquin Valley and the Tulare Basin. Loss of Delta exports would have major statewide economic effects and prove disastrous for some local areas (Tanaka *et al.*, 2008).

Ecosystems

California's ecosystems have heightened importance for water management. Hundreds of studies and restoration projects have been undertaken in recent decades and major changes have been made in infrastructure and operations in attempts to improve ecosystem conditions. While in some cases ecosystem services and water economically optimal water management have proven to coexist without great harm to current consumptive uses (Null and Lund, 2006), retaining nature has proven to be a costly and controversial challenge.

Flood management

Flood's are a major risk for economic loss and loss of life in California, and provide important ecosystem benefits. Floods also are a major restriction on development of land uses in floodplains, particularly in the Central Valley. The reservation of reservoir space for managing floods during the wet season and the accompanying design of downstream channel capacities impose limits on water supply storage and operations. Threats from flooding are likely to increase with climate change.

Decentralized governance

The management of California's water system is highly decentralized. About 3000 water districts and agencies govern water management and policy in California. Federal agencies include the US Bureau of Reclamation and the Army Corps of Engineers. State and regional water agencies such as the State Water Project and the Metropolitan Water District of Southern California provide water to retailers and end-users. Water rights and water quality are regulated by the State Water Resources Control Board. However, most water agencies and most funding and expertise for water management reside in the thousands of local water agencies which govern most of California's water-related decisions. Providing a systematic representation of such a complex and decentralized system is a great challenge and a necessity for effective water policy.

Implementing a Portfolio Approach

The complexity of California's water system has allowed extensive (and perhaps excessive) economic development of California's limited and variable water resources, and provides a rich portfolio of actions for adapting water management to evolving problems. California's decentralized governance system has been very effective in water management and introducing local innovations, far more than one would normally expect of a centralized water management system.

A wide range of options for addressing California's water problems are included in Table 1. No single option can solve all California water challenges. Instead, a portfolio of actions is likely to provide a more cost-effective and robust solution. Representing the most important water management options within an integrated analytical framework is necessary to have a technically credibly and effective water management policies and plans for California, and to improve the quality and effectiveness of water policy discussions.

The technical problem with portfolio solutions is that they are much more difficult to analyze, because there are so many possible combinations of options. For n available options and simplifying so each option is either on or off, there are 2^n possible portfolios (combinations of options). For a very simple case with 10 options, there are over 1,000 possible portfolios; for 20 options, over a million possible portfolios; for 100 options, over 10^{30} possible portfolios. Large water management systems have thousands of water management options and an essentially infinite number of possible management portfolios. This type of search can be informed and interpreted by stakeholders, but is poorly done by consensus. Automated optimization approaches, which have their own limitations, can help efficiently and rigorously identify promising portfolios of water management actions for consideration by planners, stakeholders, and policy-makers.

The simultaneity of changes and challenges for California's water system will require much greater analytical capability to inform planning and policy discussions. While developing and employing such capability will be technically and institutionally challenging, failure to do so will greatly detract from our ability to develop and compare promising planning and policy alternatives. We will be planning in a rhetorically-enhanced technical darkness.

Table 1. Water Supply System Management Options

<u>Demand and Allocation Options</u>
General Policy Tools
Pricing*
Subsidies, Taxes
Regulations (water management, water quality, contract authority, rationing, etc.)
Water markets, transfers, and exchanges (within and/or between regions/sectors)*
Insurance (drought insurance)
Demand Sector Options
Urban water use efficiency (water conservation)*
Urban water scarcity (water use below desired quantities)*
Agricultural water use efficiency*
Agricultural water scarcity*
Ecosystem restoration/improvements (dedicated flow and non-flow options)
Ecosystem water use effectiveness (e.g. flows at certain times or with certain temperatures)
Environmental water scarcity
Recreation water use efficiency
Recreation improvements
Recreation scarcity
<u>Supply Management Options</u>
Operations Options (Water Quantity and/or Quality)
Surface water storage facilities (new or expanded)*
Conveyance facilities (new or expanded)*
Conveyance and distribution facility operations*
Cooperative operation of surface facilities*
Conjunctive use of surface and ground waters*
Groundwater storage, recharge, and pumping facilities*
Supply Expansion Options (Water Quantity or Quality)
Supply expansions through Operations Options (reduced losses and spills)
Agricultural drainage management
Urban water reuse (treated)*
Water treatment (surface water, groundwater, seawater, brackish water, contaminated waters)*
Desalination (brackish and sea water)*
Urban runoff/Stormwater collection and reuse (in some areas)

Note: Options represented in the CALVIN model (see text) are denoted by an asterisk (*)

CALVIN hydro-economic model

Hydro-economic optimization models use optimization to integrate a wide range of water management actions at a regional scale and provide hydrologic and economic insights for water management (Harou *et al*. in press). Marginal values for facility expansions indicate systemwide cost reductions from small facility expansions. Results from hydro-economic optimization can be contextualized for a portfolio of water management alternatives. Simulation models of water resources may provide detailed and accurate representation of a system for one alternative. Ideally, simulation modeling can help test and refine promising policies and portfolios identified using optimization (Lund and Ferreira, 1996).

Hydro-economic models integrate regional hydrologic, engineering, environmental and economic aspects of water resources systems within a single coherent framework, to examine water management for diverse types of economic values (Harou *et al*. in press; (Loucks *et al.*, 1981; Maass *et al.*, 1962). Basic components of hydroeconomic models include hydrologic flows, water management infrastructure, economic water demands, operating costs, and operating rules. Boundary conditions in the form of inflows and outflows can occur anywhere in the network (Letcher *et al.*, 2007). In California, optimization modeling has been employed from time to time for parts of the major water supply system (Becker *et al.*, 1976; Lefkoff and Kendal, 1996; Marino and Loaiciga, 1985; Sabet and Creel, 1991; Tejadaguibert *et al.*, 1993; 1995; USACE, 2000; Vaux and Howitt, 1984), land smaller regional systems(SDCWA, 1997; Sun *et al.*, 1995), and is used routinely in the operation of higher elevation hydropower systems (Jacobs *et al.*, 1995).

CALVIN is an economic-engineering optimization model of California developed at the University of California – Davis (Figure 1). CALVIN's major differences are its statewide (rather than project) scale, explicit integration of broad economic objectives, and its consequent applicability to a much wider variety of policy, operations, and planning problems. CALVIN was designed to provide technical and economic insights for large-scale integrated water resources management problems in California.

Originally the area represented California (Draper *et al.*, 2003; Jenkins *et al.*, 2001) and now extends beyond the US Mexico Border in what is called Baja CALVIN[1] (Medellin-Azuara *et al.*, In press). The model includes major surface and groundwater storage, mayor conveyance infrastructure, combined agricultural and urban water demands for nearly 92 percent of the state, environmental water requirements, and select hydropower facilities.

The CALVIN model uses a 72-year monthly time series of hydrology (1921-1993) to represent system variability. Water is managed over this time frame to minimize net water scarcity and operating costs using HEC-PRM, a network flow optimization solver developed by the US Army Corps of Engineers (Draper *et al.*, 2003). CALVIN allocates water to storage and demand locations minimizing scarcity and operating cost within the intertied network of water resources in California.

A portfolio approach has been adopted in CALVIN to suggest insights on water management problems in California. Each CALVIN model run produces a portfolio of economically promising water management options within a set of policy, infrastructure, and water availability constraints. Even this extensive and detailed representation entails large simplifications of the real system. This is inevitable for any model of such a complex system. But these simplifications are far less than the simplifications required for the unaided human mind to ponder such problems.

Applications of this model have been diverse, widely published, and provided a variety of insights for water policy, planning, and management in California. Table 2 summarizes these studies.

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[1] http://cee.engr.ucdavis.edu/bajacalvin

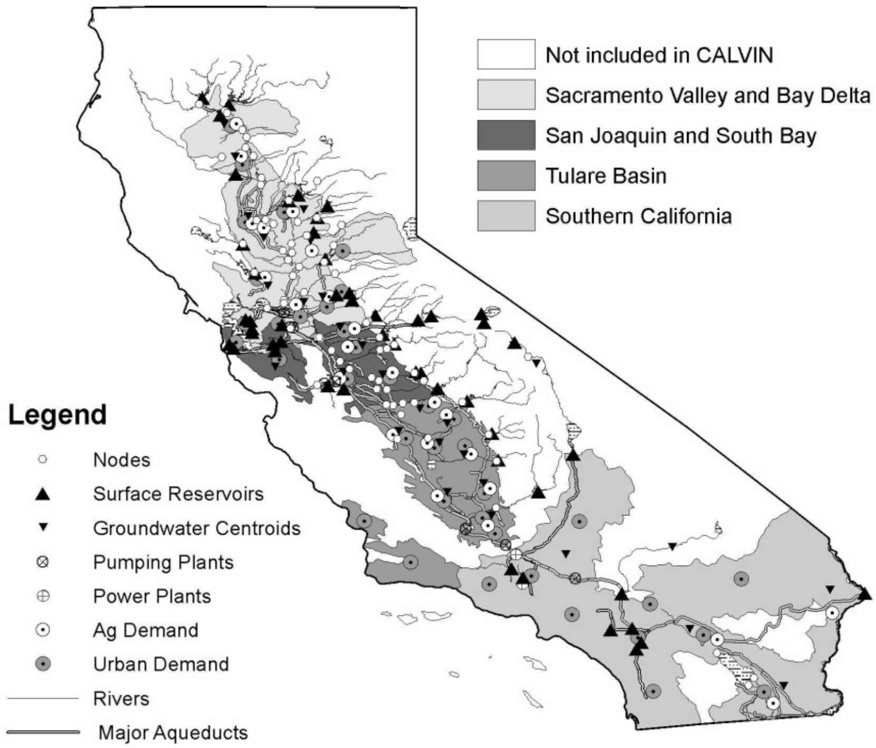


Figure 1. CALVIN, a hydro-economic model for water resources in California (adapted from Draper *et al*. 2003)

Table 2. Applications of the CALVIN model of California

Application	**References**
Integrated water management, water markets, capacity expansion, at regional and statewide scales	Draper et al. (2003); Jenkins et al.(2001; 2004);
Conjunctive use and Southern California	Pulido et al.(2004)
Hetch Hetchy restoration	Null (2004); Null and Lund (2006)
Perfect and Limited Foresight	Draper 2001
Climate warming, wet and dry	Lund et al. (2003); Tanaka et al.(2006; 2008);
Climate warming, dry	Medellin-Azuara et al.(2008a; 2009)
Climate warming, dry and warm-only	Medellin-Azuara et al.(2008a; 2009); Connell (2009)
Severe sustained drought impacts and adaptation (paleodrought)	Harou et al. (In Press-a)
Increasing Sacramento River outflows	Tanaka and Lund (2003)
Reducing Delta exports and increasing Delta outflows	Tanaka et al.(2006; 2008); Lund et al.(2007; 2008)
Colorado River delta and Baja California water management	Medellin-Azuara et al.(2006; 2007; 2008b; In press)
Ending overdraft in the Tulare Basin	Harou and Lund (2008)
Cosumnes River restoration and Sacramento metropolitan area water management	Hersh-Burdick (2008)

Does CALVIN Work?

"All models are wrong, but some are useful?" G.E.P. Box (1978)

Any model of a complex system will have inaccuracies. But perfection is not necessary for a computer model to provide more organization, detail, accuracy, and insights than would be possible otherwise. Indeed, while clearly wrong or incomplete in many regards, CALVIN's suggestions for promising water management activities have coincided well with those actually taken by water agencies.

1) The intertie between Contra Costa Water District (CCWD) and East Bay Municipal Utility District (EBMUD) became operational in 2009. The earliest studies using CALVIN indicated great economic and reliability potential for an intertie between these two agencies, with an average value of $148/af ($1995) of monthly transfer capacity (Jenkins *et al.*, 2001; Jenkins *et al.*, 2004). This benefit arose in dry years from the ability of EBMUD to reduce shortages by accessing water diverted at the Delta using CCWD intakes and in wet years from CCWD using surplus EBMUD Mokelumne River water to reduce its costs of treating Delta water.

2) Water sales from Imperial Irrigation District (IID) to Southern California cities (MWD and Dan Diego). Almost all CALVIN model runs indicate a high value of water transfers from Colorado River agriculture to cities in southern California, with values as high as $800 million annually for 2020 (Jenkins *et al.*, 2001; Jenkins *et al.*, 2004). Such transfers are certainly among the most active and sought-after in California.

3) Water transfers from Northern SWP users to Castaic and Antelope Valley water users. The Monterey agreements changing water contracts for the State Water Project shifted some water use from Kern County to Castaic and Antelope Valley water agencies. The value of these transfers is indicated by CALVIN model results (Jenkins *et al*. 2001, 2004).

4) Flexible and annually varying water market transfers from and within the Sacramento Valley, particularly employing conjunctive use operations with groundwater to reduce overall water scarcity, was indicated from early CALVIN studies (Jenkins *et al*. 2001). Such transfers are commonly sought today.

5) Conjunctive use of ground and surface waters is suggested as being especially promising by CALVIN model results(Jenkins *et al.*, 2004; Pulido-Velazquez *et al.*, 2004). These also are among the most active water management activities in California. As importantly, CALVIN results also show the long-term likely unsuitability and ineffectiveness of conjunctive use projects along the Colorado River Aqueduct, due to conveyance capacity constraints of the aqueduct (Pulido *et al*. 2004).

6) The value of additional surface water storage capacity is small. While political interest exists for constructing additional surface storage in California, there has been little interest from urban and agricultural water users in making investments in such capacity. Almost all CALVIN runs show little economic benefit for major expansion of surface water storage capacity, either in absolute terms or relative to other major infrastructure investments. California is short of water and conveyance more than it is short of storage. CALVIN model results do tend to underestimate the value of water storage capacity, due to its multi-year optimization with perfect hydrologic foresight. Under some circumstances such errors can be fairly large, especially where surface reservoirs are the main source of drought storage. Fortunately, in California, with a large inter-tied system that includes large amounts of groundwater for

drought storage and significant over-year storage capacity in surface reservoirs, this underestimation of the value of surface storage capacity is more modest (Draper, 2001). There might be some economical potential for additional surface storage somewhere in California, but CALVIN results do not find surface storage likely to be of widespread high economic value.

Overall, the CALVIN model seems to have an unexpectedly good ability to track major long-term activities in water management for California. This is remarkable for a somewhat primitive first generation hydro-economic optimization model of a very complex system. This is not to say that the results of any computer model should be taken at face value. But CALVIN does appear to perform sufficiently well to be useful in exploring and developing solutions to the complex integrated water management problems of California. In addition, its representation of California's vast water management system also appears to be sufficient to provide a useful accounting framework for water supplies and demands in the system, even if model results are never used.

Lessons from Integrated Water Resources Using CALVIN

"The purpose of computing is insights, not numbers." R.W. Hamming 1962

Since the first research report about ten years ago (Howitt *et al.*, 1999), CALVIN has provided insights for policy conversations on water issues. These insights can be organized into several areas: integrated water management, groundwater management, capacity expansion, environmental flows, climate change, the Sacramento-San Joaquin Delta, and environmental restoration. The products of modeling with CALVIN have demonstrated that large-scale statewide modeling of California's water system is possible and can produce and substantiate insights useful for policy discussion.

Integrated Regional and Statewide Water Management

Jenkins *et al*. (2004) provide a significant list of lessons from hydroeconomic modeling with CALVIN. This study compared water operations in 2020 based on 1997 water policies with those economically optimized on a regional basis (with 1997 policy levels of inter-regional water transfers) and with those of a statewide optimization (representing an idealized statewide water market). Water markets and exchanges, conjunctive use and system reoperation could add $1.3 billion in annual benefits to the state in year 2020. Most of these benefits came from water transfers within Southern California, many of which have already been made of are in negotiation since this study.

Major policy conclusions included:

"Optimized" operations and allocations can be satisfy most agricultural and urban water demands for the California inter-tied system at 2020 levels. Most unsatisfied demands could be well compensated with revenues from market transactions.

Water conservation is less expensive than satisfying all water demands at all times. Satisfying all water demands is not always economically worthwhile. It is neither economically feasible nor desirable to eliminate all water scarcity and scarcity costs in California. The costs of providing additional water from new sources, efficiency improvements, or reallocations from other water users sometimes exceed scarcity costs associated with conservation or rationing. In such cases, some scarcity is optimal, indicating economically efficient opportunities for increasing local water conservation. (Jenkins *et al.*, 2004)

Regional and statewide water markets, transfers, and exchanges have great potential to improve the flexibility and economic performance of California's water system, considerably reducing both water scarcity and scarcity costs. This was particularly true for water markets within Southern California, from the Colorado River Basin to inland and coastal urban areas. In particular, water markets provide incentives for managers to cooperate and coordinate within a highly decentralized system of governance (Jenkins *et al.*, 2004; Pulido-Velazquez *et al.*, 2004).

Economically efficient improvements in local and regional water management reduce demands for imports. As each region improved the efficiency of its internal water management, it reduced the economic value of imported water.

Ideal water markets never reduced deliveries to any major user more than 15%. For 2020, it appears that no large agricultural region would reduce water deliveries by more than an average of 20% due to participation in water markets. With this level of water transfers, most water scarcity would disappear statewide.

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

Expanded conjunctive use, particularly over inter-annual or drought periods, could result in economic and operational benefits for every region. Most of these benefits occur with regional optimization, but some additional statewide benefits also exist. Greater conjunctive operation of local, regional, and statewide water resources decreases competition with environmental uses, especially in dry years when agricultural and urban reliance on surface flows is significantly reduced from Base Case levels. The availability of conjunctive use operations in CALVIN reduces the value of increasing surface storage at most locations. Conjunctive use has proven to have positive regional economic water impacts. This water management strategy has been widely implemented in the Tulare basin(Harou and Lund, 2008). Conjunctive use also may reduce reliability in large interregional water exports to Southern California (Pulido-Velazquez *et al.*, 2004), reduce diversions in the Sacramento River Basin (Jenkins *et al.*, 2004), and enhance habitat within a basin such as the Cosumnes River Reserve (Hersh-Burdick, 2008).

Some environmental flows impose costs on agricultural and urban users under economically optimized operations, but many flow requirements need not impose significant costs. Flexible operations greatly reduce the costs of environmental flows to other users. This is especially true with statewide optimization. Consumptive wildlife refuge deliveries tend to impose greater costs to agricultural and urban water users than instream flows.

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

The application of large-scale economic-engineering optimization to California's inter-tied water supply system appears to offer benefits to a) Make better sense of complex systems, b) Suggest promising operations and infrastructure, and c) Develop ideas for better management.

Groundwater Management and Conjunctive use

Conjunctive use and groundwater management operations show great promise for California under a wide variety of conditions, with some important caveats and limitations (Harou and Lund, 2008; Hersh-Burdick, 2008; Jenkins *et al.*, 2004; Pulido-Velazquez *et al.*, 2004). CALVIN results regarding conjunctive use reflect the economic value and physical capabilities of the system for conjunctive use operations, but assume a lack of institutional and legal impediments, which often are important. CALVIN results regarding groundwater therefore demonstrate physical and economic promise, but might require additional agreements and institutional changes. CALVIN studies of conjunctive use focused on systemwide value(Jenkins *et al.*, 2001; Jenkins *et al.*, 2004), Southern California (Pulido-Velazquez *et al.*, 2004), the Tulare Basin (Harou and Lund, 2008), and the Sacramento metropolitan area (Hersh-Burdick, 2008).

Substantial economic benefits can be obtained by managing conjunctive use facilities and groundwater storage more flexibly in Southern California (Pulido-Velazquez *et al.*, 2004). In the Colorado River hydrological region of Sothern California, expanded conveyance and storage facilities have significant economic benefits. However, if conveyance capacity of the Colorado River Aqueduct is not expanded, expanding groundwater storage does not provide additional benefits to the region, as the operation of conjunctive use facilities along the Colorado River Aqueduct would reduce the Aqueduct's ability to import water from the Colorado River. Conjunctive use along the Colorado River Aqueduct becomes viable only if there is surplus capacity in the Aqueduct.

In Southern California, storage capacity expansions in the Los Angeles Aqueduct system and in conveyance such as the Mojave pipeline are worthwhile. Increased groundwater storage in the Kern aquifer system is economically preferred to storage in the Diamond Valley reservoir, the main storage facility for the CRA and the SWP due to evaporation losses (Pulido-Velazquez *et al.*, 2004). These two facilities are complementary under a flexible operation and liberalized markets scheme as stored surface water in the wet and normal years and groundwater is used in the dry years.

In the Tulare Basin of the southern Central Valley, ending groundwater overdraft increases water scarcity costs in the region (Harou and Lund, 2008). Aquifer overdraft provides some economic benefit in the Tulare basin at the expense of water quality costs, subsidence and increasing pumping costs. Thus in the long term discontinuing overdraft may be desirable. Additional conjunctive use infrastructure built in the 1990s is critical to support water transfers and groundwater banking which significantly reduce the costs of ending groundwater overdraft in the Tulare basin.

In the Sacramento River Basin, in the greater Sacramento metropolitan area, reduced groundwater storage below the Cosumnes River has reduced its ability to support once high fish populations (Hersh-Burdick, 2008). More active conjunctive use operations can help support reliable supplies to agriculture and urban users in the region (for 2030 demands). To restore base flows in the Cosumnes River with 50 TAF/yr dedicated to restoring groundwater levels, conjunctive use and groundwater management in the system overall allow water deliveries which still provide more than 96% of the agricultural demands.

Capacity Expansion

There is continuing discussion of expanding surface storage, conveyance, and other water management facilities in California. CALVIN model results provide some consistent insights on the benefits of expanding infrastructure as part of California's water supply system (Jenkins *et al.*, 2001; Jenkins *et al.*, 2004). Table 3 shows the marginal economic benefits of expanding various facilities around the state for 2050 water demands, for three different conditions in the Delta, a pre-Wanger decision base case, a 50% reduction in Delta water exports, and an end of all Delta water exports (Tanaka *et al.*, 2008). While these estimates should be taken with some caution, as they are model results, after all, they do make rough sense in comparison with back-of-the-envelope estimates and observed field estimates. Their relative values and changes in value also show important tendencies. These are only the economic benefits of expansion to the system, and do not include the construction and other costs needed to actually make such expansions.

Table 3 - Marginal values of expanding capacities with Delta export restrictions (2050)

North or South of Delta	Name	Average Marginal Value of Expansion ($/af/year) No Exports	50% Reduction	Base Case
Conveyance Facilities ($/af/year)				
North	Freeport Project	7	0	0
North	Mokelumne River Aqueduct	274	0	0
South	New Don Pedro-Hetch Hetchy Intertie	863	428	252
South	Hetch Hetchy Aqueduct	1365	534	480
South	EBMUD-CCWD Intertie	21	0	0
South	Hayward Intertie	766	215	161
South	Jones Pumping Plant	1880	55	0
South	Banks Pumping Plant	1885	61	3
South	Cross Valley Canal	224	1	1
South	Friant-Kern Canal	7	1	0
South	Coastal Aqueduct	0	1313	1371
South	Colorado River Aqueduct	1011	414	362
Surface Reservoirs ($/af/year)				
North	Shasta Lake	8	8	8
North	Black Butte Lake	5	7	8
North	Lake Oroville	12	14	15
North	New Bullards Bar Res	17	17	18
North	Camp Far West Reservoir	3	5	6
North	Folsom Lake	10	12	13
South	New Melones Reservoir	9	9	9
South	San Luis Reservoir	0	0	0
South	New Don Pedro Reservoir	17	17	18
South	Hetch-Hetchy Reservoir	5	5	5
South	Millerton Lake	29	9	6
South	Lake Kaweah	166	95	51

South	Lake Success	148	85	46
South	Lake Skinner	27	470	522
	Artificial Recharge Facilities ($/af/year)			
South	Santa Clara Valley	1873	85	31
South	Mojave	357	394	392
South	Antelope Valley	1715	1109	1051

Note: Marginal values shown are monthly averages.

The generally low value of expanding surface storage capacities is evident, relative to the values of expanding conveyance and recharge facilities. This would be predicted based on reservoir operation theory, given the rapid decline in the marginal water deliveries with larger reservoir size and the already substantial reservoir storage capacity which exists in California (Hazen, 1914). These tendencies are quite robust for a wide range of population and climate conditions (Jenkins *et al.*, 2001; Jenkins *et al.*, 2004; Medellin-Azuara *et al.*, 2008a; Medellin-Azuara *et al.*, 2009; Null and Lund, 2006).

Changes in conditions can greatly change the economic benefits from changing the capacity of facilities. For the case of reductions and ending Delta water exports, the value of facilities which can convey water from upstream of the Delta directly to demand areas (Hetch Hetchy Aqueduct, etc.) increase as direct Delta exports are restricted. The value of conveyance capacity for other non-Delta sources (e.g., Colorado River Aqueduct) also greatly increases. Reducing Delta exports also changes the value of expanded surface storage, reducing the value of storage north of the Delta (since this water source is now less tied to areas with high-valued water demands) and increasing the value of storage in the Tulare basin. Oddly, ending Delta exports does not increase the value of expanding storage on the San Joaquin River, presumably because the greater withdrawals leave less water to be stored in the already large storage capacities on this river. On the San Joaquin River, there is more of a shortage of water than a shortage of storage capacity.

Environmental Flows

Flows for maintaining or improving environmental conditions can be represented as a time-series of required instream flows or water deliveries to wetlands. Such required flow regimes for particular wild life refuges or instream flows can impose costs on other water uses, such as agriculture, urban or hydropower generation. These opportunity costs of environmental flows can vary greatly with location, season, and hydrologic conditions. Regional modeling with CALVIN shows that in drought years, these costs can be as high as $1,400 /acre-foot in the Mono and Owen basins where hydropower is generated (Jenkins *et al.*, 2004). However, designated flow regimes average $35 with regional water management and tend to be lower with statewide water management (Jenkins *et al.*, 2004). Warm-dry forms of climate change pose additional challenges to provide environmental flows. In dry climate scenarios, it can become impossible to meet some current environmental flow requirements and the opportunity costs of environmental flows often greatly increase (Connell, 2009; Medellin-Azuara *et al.*, 2008a; Tanaka *et al.*, 2006).

Climate Change in California

The state of California has led nationwide efforts on climate change research. The California Energy Commission has hosted biannual multidisciplinary assessments for nearly a decade. CALVIN has been a critical component of these assessments with regard to water supply and adaptation to climate change ranging from flood, water supply, reservoir operations and hydropower (Madani and Lund, In Press; Medellin-Azuara *et al.*, 2008a; Medellin-Azuara *et al.*, 2009; Tanaka *et al.*, 2006; Zhu *et al.*, 2007). CALVIN, and other hydro-economic models for high-elevation hydropower, have been used to examine various climate warming scenarios (Connell, 2009; Madani and Lund, In Press; Medellin-Azuara *et al.*, 2008a; Medellin-Azuara *et al.*, 2009; Tanaka *et al.*, 2006; Zhu *et al.*, 2007) as well as a severe, prolonged paleodrought(Harou *et al.*, In Press-a).

Extreme Paleodrought

Prolonged severe droughts may pose a significant challenge to water resources in California. Geologic evidence suggests that multi-decade droughts for California, with reduced streamflows (40-60%) have existed in a geological timescale (Stine, 1990; 1994). If flows were roughly 53 % of the historical record in year 2020, expected water scarcity increases in a tenfold (Harou *et al.*, In Press-a). Total operating costs in this drought scenario are not significantly different to those in under historical hydrologic conditions, suggesting system adaptability to severe drought conditions. Furthermore economic values for expansions in conveyance capacity in southern California in these extreme conditions are significant. Expanded storage capacity has little value for this prolonged drought, as there is insufficient water to fill existing storage capacities. Opportunity costs of environmental flows increase by one or more orders of magnitude. An economically effective response to this extreme drought requires considerable institutional flexibility and use of water markets.

Climate Warming Hydrology

Warm-dry forms of climate change have the most severe effect on surface streamflows, evaporation, groundwater recharge and local accretions, compared to warm only and historical climate conditions. In California by year 2050, under a warm-dry hydrological scenario (GFDL A2) a 27% decrease in precipitation and a 4.5°C increase in temperature are expected (Medellin-Azuara *et al.*, 2009). Groundwater inflows decrease by 10% and reservoir evaporation increases by 37% in average statewide. The Tulare basin faces the more drastic conditions, with a decline in precipitation of up to 44%. With these changes in precipitation a statewide reduction in the order of 28% in total rim inflows is expected. Historical, warm-only, and warm-dry flows for the Sacramento and San Joaquin Rivers are shown in Figure 2.

There are many technical details and aspects of developing climate change hydrology, from the global circulation model's (GCMs) themselves, to their downscaling, and their application to rainfall-runoff and other hydrologic models which provide estimates of inflows important for water supply and flood management. In general, we have found that, for broad management and policy purposes, fairly approximate representations of local and regional hydrologic processes are sufficient, especially given the relatively intertied nature of the statewide system (Connell, 2009; Zhu *et al.*, 2005).

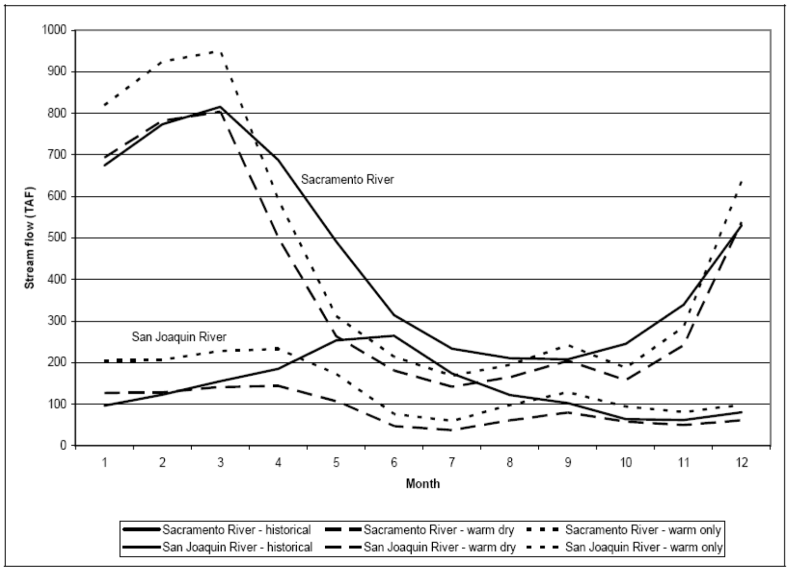


Figure 2. Sacramento River (at Shasta Dam) and San Joaquin River (at Millerton) mean monthly streamflows, 1921-1993, per climate scenario (after Medellin-Azuara *et al.*, 2009)

WATER SUPPLY

As urban uses traditionally have higher scarcity values for water, agriculture is the likely water seller under dry forms of climate change. With a 28% reduced inflows under warm-dry climate change, roughly $900 million dollars in annual scarcity costs are estimated by year 2050 (Medellin-Azuara *et al.*, 2009). Agriculture gets about 79% of target water deliveries and urban uses face less than one percent shortage under optimized warm-dry climate.

Warm-only forms of climate have little increase in water scarcity and cost for agriculture or urban uses in year 2050. While the seasonal short of a warming-only change in climate are inconvenient, they are not catastrophic (Connell, 2009). The existing reservoir storage capacity, if re-operated to move more drought water storage to aquifers, appears able to accommodate most of the seasonal shifts in inflows from reduced snowpack. This CALVIN representation of a warm-only hydrology is likely to be a little optimistic as it assumes no change in annual runoff volume. In reality, a warming-only climate change, with no change in precipitation, would likely be accompanied by an increase in upstream evapotranspiration and a consequent reduction in overall streamflow volumes.

Although agriculture suffers most of the shortages under climate change, revenue reductions for agriculture by year 2050 under warm-dry forms of climate change roughly exceed 11% with respect to historic hydrology conditions (Howitt *et al.*, 2009). This shows the ability of agricultural production to adapt to climate related yield reductions and likely water shortages. As water becomes scarce, the crop mix favors climate resistant, higher value crops. Technological change by year 2050 may boost yields by 27% in average for crops by 2050 with an inherent limit of biomass given by photosynthesis (Howitt *et al.*, 2009).

Reservoir Operations and Flood Control

Hydroeconomic optimization is useful in inferring reservoir operation rules. These are expected to change under climate change (Medellín-Azuara *et al.*, 2008), as storage is likely to peak earlier in the winter but there will be excess storage capacity in the summer (Figure 2). Compared to historical conditions, optimal rates of storage in a warm and dry climate show wider intervals at intermediate levels of storage. This is the case of the Shasta-Trinity-Whiskeytown and the Oroville-New Bullards Bar reservoir systems (Figure 3).

As more severe floods in the winter and early spring could be expected under climate change, flood protection becomes crucial in the floodplains of the Sacramento River basin. Rapid urbanization in the Sacramento area and climate change, make levee setback and raising in the American River a worthwhile strategy for to avoid significant economic losses (Zhu *et al.*, 2007). However, property value changes and expected changes in flooding depending on the form of climate change largely drive the appropriate levee strategy.

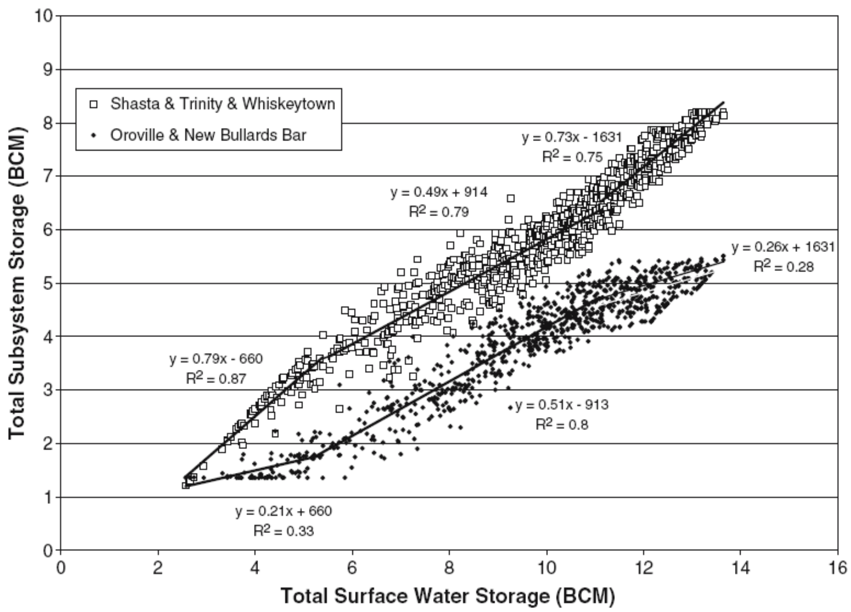


Figure 3. Surface water storage allocation for major reservoir subsystems in the Sacramento Valley (after Medellín-Azuara *et al.*, 2008).

Hydropower

Hydropower in California is a source of clean energy that accounts for roughly 15 percent of total in-state power generation (Aspen Environmental Group and M. Cubed, 2005). Climate change is likely to affect generation, especially under warm-dry forms of climate change. Tanaka *et al*. (2006) estimated a 30 % reduction in low elevation hydropower revenues by year 2100 under a dry PCM 2100 scenario. For year 2050, benefits from low-elevation hydropower generation are reduced only slightly (6.24% per year in dry years) under the warm-dry scenario (Medellin-Azuara *et al.*, 2009).

A separate statewide hydroeconomic model of high elevation hydropower plants in California, the Energy-Based Hydropower Optimization Model (EBHOM) (Madani and Lund, In Press) was developed and predicts an average of 14.4 % statewide revenue reduction (Madani and Lund, In Review) with a dry-warm climate. Under reasonable assumptions, extrapolation of these results to year 2050 may pose a solid lower bound for revenue losses under dry-warm forms of climate change. Benefits from expanding storage are more significant than increasing generation capacity

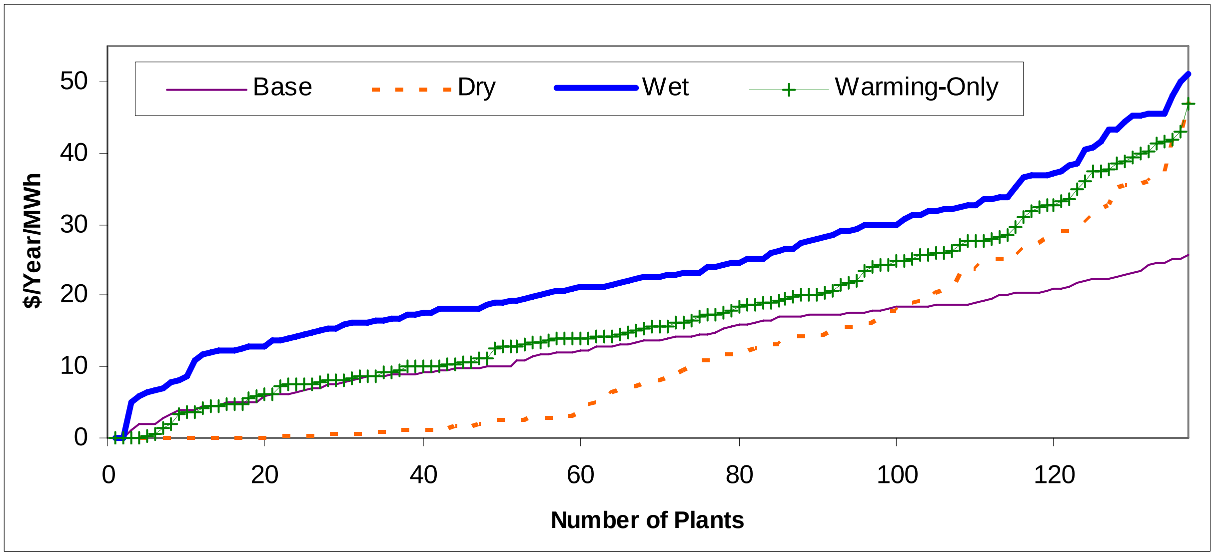
(

Figure 4).

Generally, hydropower production changes directly with the change in average annual streamflow volume (the fuel available for hydropower plants). This proportionality follows especially well for decreases in streamflow. With increases in streamflow, wetter climates, there in an increasingly-felt lack of storage capacity and a consequent increase in reservoir "spills", where water can be neither stored nor run through turbines. The warming climates accentuate this difficulty in storing additional inflows of energy (water), as there is less attenuation of inflows from snowpack storage (Madani and Lund, In Press). In terms of hydropower storage capacity expansions, water storage benefits greatly increase with a wetter warmer climate, increase somewhat with a warmer-only climate, and usually decrease with a drier-warmer climate, but often increase for other hydropower plants (Figure 4).

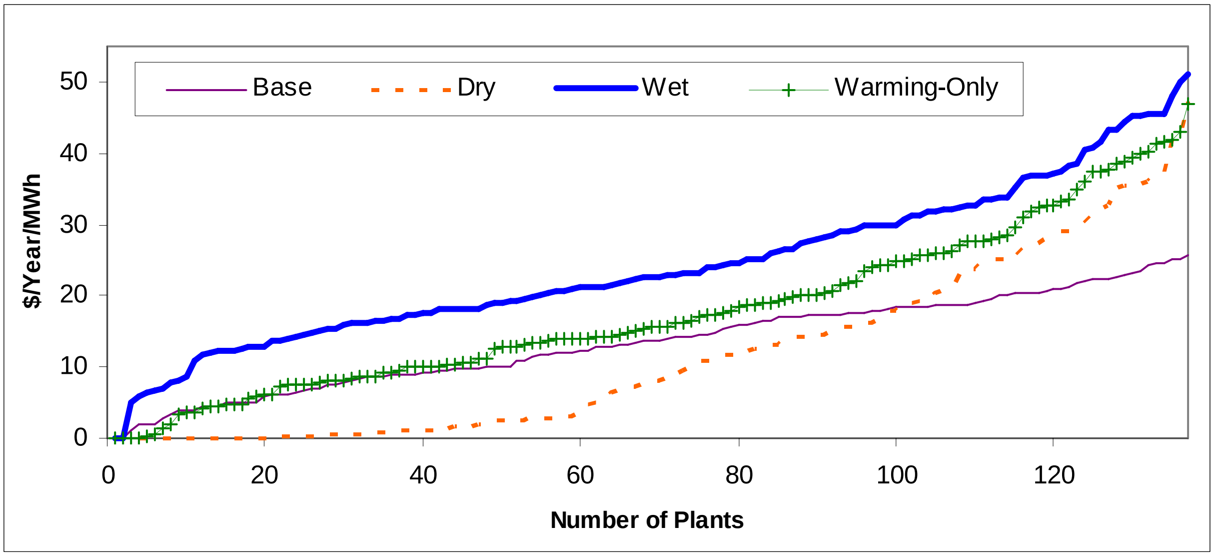


Figure 4. Average marginal values of increased energy storage capacity (found by EBHOM) for 137 hydropower units for California in the 1985-1998 period (after Madani and Lund, In Press).

The Sacramento-San Joaquin Delta

The Delta provides habitat for many endemic plants and fish and at the time serves as the main north-south water hub for California's water supply system. Hydroeconomic modeling in California has highlighted the importance of Delta exports for the Central Valley and Southern California (Tanaka *et al.*, 2008). Pre-Wanger-decision exports of roughly 6 MAF/yr help sustain agricultural and urban uses out of the Delta.

Given the complexities of the system, reduced Delta exports do not necessarily translate directly into increased Delta outflows, due to the abilities of many users to take additional water upstream of the Delta. Similarly, increasing Delta outflows can be supplied both from reductions in Delta exports and reductions in upstream diversions and consumptive uses (Tanaka *et al.*, 2008). If the environmental objective is to reduce exports, it is more economical to reduce export pumping directly than to increase Delta outflow requirements. Conversely, if the environmental objective is to increase Delta outflows, then decreased pumping increases net statewide costs for this objective much more rapidly than allowing all water uses (Delta exports and upstream diversions) to contribute to achieving outflow objectives, say by a combination of direct regulation and water markets (Figure 5).

Additional flows to the Delta also can come from reducing consumptive uses upstream. With flexible water allocation, increasing Sacramento River inflows to the Delta by an additional 3 MAF/yr would not cause significant scarcities for the Sacramento Valley (Tanaka and Lund, 2003); however, increases in the opportunity costs of environmental cost of Delta outflows and environmental flows are expected. Additional storage does not offer economic advantages for this situation.

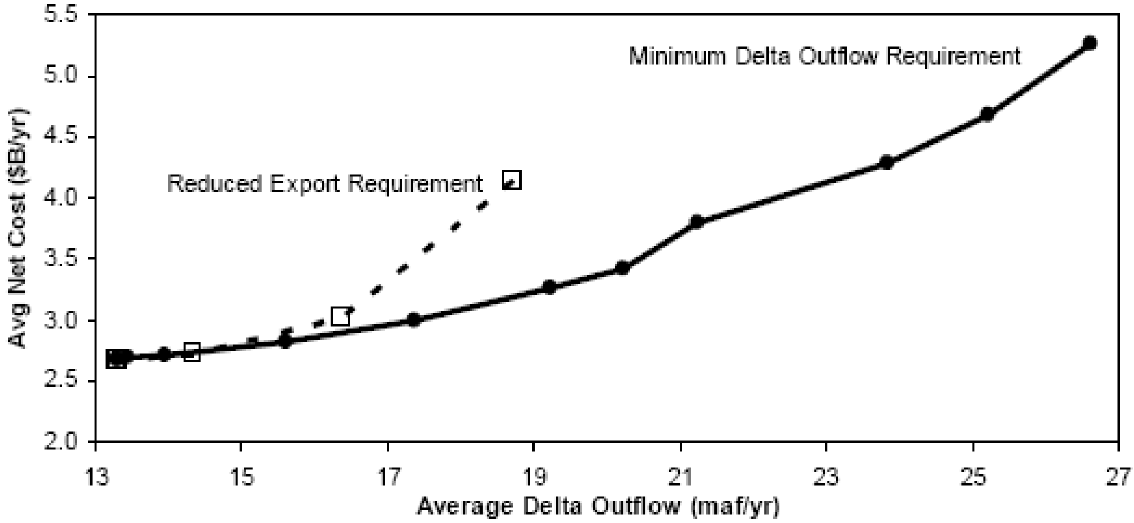


Figure 5. Average Delta outflows and associated statewide net costs (after Tanaka *et al*. 2008).

A peripheral canal pumping better quality north from the Delta and wheeling it south of the Delta, may reduce pumping and fish entrainment (Tanaka *et al.*, 2008) with significant system-wide water quality cost reductions (Medellin-Azuara *et al.*, 2008b). Improving water quality of Delta exports via a peripheral canal provides significant cost reductions for irrigated crops and confined animal operations south of the Delta (Medellin-Azuara *et al.*, 2008b). At current levels of salt exports from the Delta, and rate of net salt accumulation in the aquifers and root zones south of the Delta, more than 200 million dollars per year could be saved from decreasing water export salinity to that of Sacramento River water (Figure 6). Even a small peripheral facility reduces salt loads exported south of the Delta with large economic benefits for income and employment in the southern Central Valley (Medellin-Azuara *et al.*, 2008b).

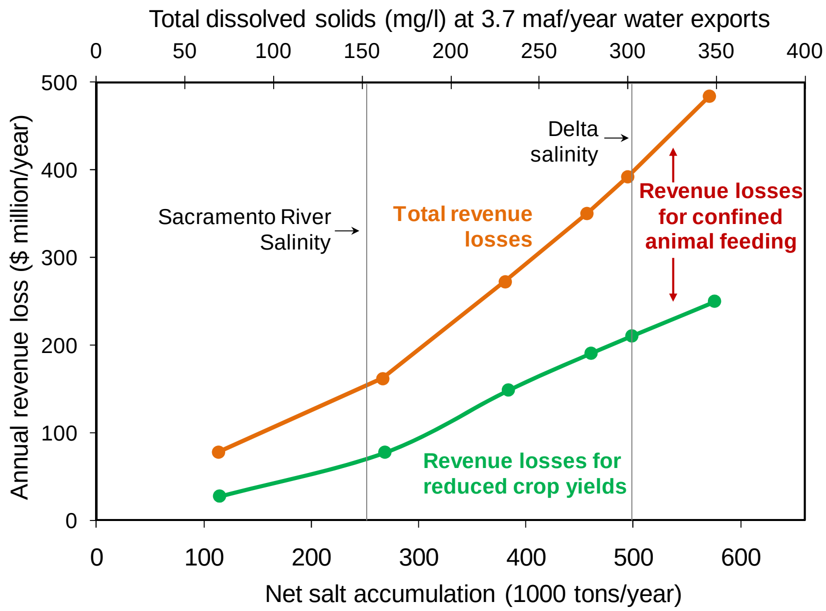


Figure 6. Estimated revenue losses to irrigated agriculture and confined animal feeding operations in the southern Central Valley from net salt imports (after Medellin-Azuara *et al.*, 2008b)

Restoration with Efficiency

Environmental restoration or rehabilitation is a major objective for water management in California. When viewed from a system perspective, dedicating flows to maintain ecosystem functions often need not to result in substantial water scarcity and water scarcity costs for agricultural and urban users. Among the portfolio of water management alternatives, economically optimal water allocations among competing water uses can secure minimum flow policies with often fairly small costs to agricultural and urban water users, as demonstrated by several hydro-economic studies. This has already been shown for some flow ranges for the Delta (Tanaka *et al.*, 2008), but also have been found for other environmental restoration problems using CALVIN modeling studies.

Hetch Hetchy

California's intertied network of water resources sometimes allows flexibility and adaptation to meet habitat restoration and ecosystem functions objectives without significant water curtails to agriculture and cities in some cases. San Francisco area relies almost entirely from water supply the the Hetch Hetchy system on the Tuolumne River. Removing O'Shaughnessy Dam, the main storage element (360 taf) on this system) need not greatly reduce water supply reliability for the San Francisco area, if an additional intertie is bade to take water from the much larger (2 maf) New Don Pedro reservoir downstream into the Hetch Hetchy Aqueduct (Null and Lund, 2006). The infrequent additional shortages which result from reducing system storage capacity under these circumstances can be managed with water purchases from agriculture during droughts and with additional conjunctive use. Nevertheless, hydropower reductions and capital costs for improved drinking water treatment impose large economic costs for restoring Hetch Hetchy Valley.

Cosumnes River

Dedicating flows for the Cosumnes River by means of recharging groundwater underneath needs not to threat supply for cities and agriculture that rely on the system for water (Hersh-Burdick, 2008). Conjunctive use and system reoperation make this possible, with fairly modest costs.

Colorado River Delta

Economically optimal sources of water for restoring the Colorado River Delta in Mexico can be found within the Mexicali Valley in Mexico and in the lower Colorado River Basin in the U. S. (Medellin-Azuara *et al.*, 2007). Prescribed water flow regimes to maintain and improve ecosystem functions in the Colorado River Delta can be obtained from purchasing water from agriculture either in Mexico or in areas in Central Arizona and southeast California that host lower value agriculture. Wastewater reuse is also a promising alternative provided institutional arrangements to sell wastewater restoration at a nominal price are in place. Furthermore, to the extent habitat in the Salton Sea and in the Mexican portion of the Colorado River Delta are substitutes; efforts aimed to restore flows in the Mexican wetlands may provide substantial economic benefits compared existing programs and proposals to maintain the Salon Sea.

Limitations

Although useful policy insights can be obtained from CALVIN hydroeconomic optimization, limitations inherent to the model construction and data quality call for cautious interpretation of results. The systems approach of hydro-economic optimization using CALVIN us useful for both organizing complex water management problems and developing economically promising management alternatives for regional water resources networks. Such systems analysis is a process in which quantitative representation of water management problems are continuously improved. Worthwhile alternatives are evaluated through optimization with respect to predefined performance objectives to minimize operating and scarcity costs. Results are analyzed carefully to improve the model while learning more about problems and potential solutions.

A comprehensive review of hydro-economic modeling limitations using CALVIN is presented in Jenkins *et al*. (2001). Later applications of CALVIN include case specific limitations, in which the range of assumptions, results and conclusion remain reasonable or require more careful interpretations. Limitations can be grouped into three categories namely data quality, construction and limited representation. For data quality, as more information becomes available this can be easily incorporated into the larger analysis framework. Indeed, the CALVIN data management and analysis system support better quality control and integration of data for analytical purposes, and provides a framework for developing and integrating additional data on California's water problems and solutions. Improved groundwater and surface water hydrology from newer simulation model runs have already been used to improve parts of the system (Harou and Lund, 2008). CALVIN's use of the relatively restrictive generalized network flow optimization solver in HEC-PRM imposes some structural limitations on representing many water problems and solutions. We have been able to represent some of these non-linearities by using piece-wise linearization of convex cost functions. Another limitation is the perfect hydrologic foresight in CALVIN operations. This limitation is less important as groundwater storage increases (Draper, 2001; Jenkins *et al.*, 2001). Lastly, system benefits from hydropower, flood control and recreation may be better represented in selected regions of the model.

For more recent studies involving climate change (Medellin-Azuara *et al.*, 2008a; Medellin-Azuara *et al.*, 2009; Tanaka *et al.*, 2006), hydrological representation using the permutation ratios approach (Miller *et al.*, 2003) may impose some bias (Maurer, 2007) as inter-annual variability is assumed to be constant. In the case of a synthetic hydrology for warm-only climate scenarios (Medellin-Azuara *et al.*, 2009), there is a positive bias in the winter streamflows as the perturbed hydrograph concentrates stream flows in the winter.

Although limitations in CALVIN call for model and data updates and improvements, conclusions from the various case studies remain stable for a wide range of assumptions in the California intertied system of water resources. The major insights from CALVIN results have proven to be rather robust to a wide range of climate, population, and land use assumptions, and match well with theory and the many simplified back-of-the-envelope estimates. While CALVIN is a primitive model of a complex system, it has vastly greater capability than unaided intuition and reasoning and provides a framework for continuous improvement and learning, as well as the development of future generations of analytical tools.

Model Development Lessons

Aside from the insights gleaned from the results of over a dozen published studies, the process of developing, maintaining, and improving the CALVIN model offers important lessons for improving the analytical capability supporting water planning and policy discussions in California.

1. Begin with a broad integrated and workable technical plan with ambitious, but limited objectives.

Large-scale modeling for California is indeed possible, if the effort is well organized initially. Attempting to impose organization after model development is underway is much riskier and more difficult. Some data and functionality gaps and uncertainties are inevitable. More powerful computers, more efficient software and data storage formats, may enhance possibilities overtime, but demand for information might advance at a greater pace. So it is important that model planning have a well grounded and tractable technical plan, with a small set of well-defined objectives for each phase of the model development. This will allow enough time to learn from the model and limitations before making subsequent rounds of improvement. A useful model is never completely finished.

2. Organize input data in databases

For many models of large complex systems, data management becomes fundamental. The design of the databases that will contain network configuration, input data, and metadata documenting the origins and quality of input data should be tailored to major model application questions and range of model users, for the desired duration of model use. Platforms with this kind of database capability will allow model and data improvements to be more easily adopted over time, as well as allow for broader use and quality control of model data and easier learning of the model by new modelers.

3. Document data in databases

Useful models are likely to transcend generations of students, practitioners, researchers and managers that get involved other projects or careers. Metadata in model databases becomes the easiest reliable form of retrieving information on input data sources. This allows corroboration of system information and judgment on the reliability of model outcomes in specific areas. It also provides the base for data improvement. Continuous maintenance of the parallel information system in the model should be well represented in the model's time budget, use and maintenance. Documented procedures and protocols should exist to enter, maintain, update or retrieve metadata. Availability of data from the hydro-economic model and its metadata allows informed audiences to provide feedback for improving and understanding the model and its data.

4. What few features should better statewide water planning and policy models have?

To keep models useful, development and improvements should be in line with existing and emerging niches of direct and indirect users and problems. While an informed audience and modelers might not become direct users of a statewide water resource model, results and insights from the modeling exercises should help improve the discussions on water related issues. For a model to be useful, it is helpful if it is designed to answer a modest number of important questions of longstanding value.

5. We need better data

Input data quality is important for model calibration and the general reputation of a model. Higher quality data improves economic representation of water and its infrastructure at all scales as well. Continuously updated and better calibrated simulation models are needed to improve system representation used by hydro-economic optimization models. In California's Central Valley, more integrated groundwater, surface water and agricultural hydrology are needed. These issues are addressed extensively in Jenkins *et al.* .

6. Need policy discussion and decision-making frameworks that can better employ quantitative information

Hydro-economic modeling can help in having more informed discussions on water related issues. However, policy and planning forums must be structured so as to able to take advantage of such information in their discussions. Given the many problems of establishing a dialog among diverse groups of stakeholders and interests, it is likely that quantitative information will be unable to provide a structuring framework without some advance work in the policy discussion process. People do not naturally employ numbers in their deliberations. In business and technical fields, education and institutional expectations are required to ensure that technical information is well developed, integrated, and employed in deliberations.

Summary of Lessons

Some major conclusions arise from experiences in California.

1) It is possible to significantly improve statewide integrated water management and policy studies in California using hydro-economic modeling. Computational challenges of this approach have declined and data availability has improved to the point that such models are practical and offer reasonable insights for water management, planning, and policy.
2) Most water management entities in California benefit from being connected to a wide variety of sources and other water users, facilitating more adaptable water management and water markets.

CALVIN results demonstrate the immense physical and economic flexibility of California's water system and its adaptability to a wide range of potential changes.

3) The Sacramento-San Joaquin Delta is the weakest link in California's water supply system. Change in the Delta is inevitable and major costs can result from different approaches to Delta water management.
4) Water supply has many sources from traditional supplies to conjunctive use of ground and surface waters, water conservation and water reuse. There is rarely a shortage of water, only a shortage of cheap water.
5) Integrated portfolio solutions of traditional and new options tend to be the most cost effective and robust. Most new options, such as conservation, wastewater reuse, water marketing, and conjunctive use, are best managed and financed locally.
6) Of traditional infrastructure, expansions of selected conveyance and aquifer recharge are typically much more beneficial if water operations are well managed.
7) We should have higher expectations for quantitative information for water policy and management. We have fragmented our technical and scientific capabilities and understanding of the system. Better integration and flexibility is needed for our water management system to adapt in coming decades to changed population, land use, climate and ecosystem threats. Effective statewide water management requires, for both technical operations and planning and effective legal and governmental regulation, much greater, more explicit, and more integrated quantitative representation of this vast and complex system. We would not tolerate our current level of data management, water accounting, and modeling capability in any other vital system. Electricity, natural gas, bridges and other physical structures, food supply, and aircraft are all managed with far more quantitative attention to detail than California's water system. Indeed, quantitative water management is much better for local water utilities than it is for statewide operations and regulation.

Acknowledgements

These results were made possible by the research contributions of current and former graduate students and other research associates including: Stacy K. Tanaka, Christina R. Connell, Kaveh Madani, Julien J. Harou, Tingju Zhu, Andrew Draper, Bradlin Newlin, Andrew Draper, Rachael Hersh-Burdick, Siwa Msangi, Kristen Ward, Brian Van Linden, Randall Ritzema, Kenneth Kirby, Arnaud Reynaud, Matthew Elis, Mark Leu, Jennifer Cordua, Pia M. Grimes. We are eternally grateful for financial support for the development, refinement, and application of the CALVIN model from the California Resources Agency, the CALFED Bay-Delta Program, the US Bureau of Reclamation, The Nature Conservancy, the S.D. Bechtel Foundation, The Packard Foundation, the National Science Foundation, the Public Policy Institute of California, and the California Energy Commission. We also are grateful for the immense help received from many state, local, and federal water agencies, non-governmental organizations, and private consultants in developing and improving these representations of California's water system. This paper was supported by the California Department of Water Resources.

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