INTEGRATED ECONOMIC-ENGINEERING ANALYSIS OF CALIFORNIA'S FUTURE WATER SUPPLY

EXECUTIVE SUMMARY

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

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

California's water supply problems involve great financial and economic issues. What economic benefits arise from new water storage and conveyance facilities? Would significant economic benefits result from changing legal, contractual, and environmental limits on operating California's water system? What is the value of regulated water markets? What are the most beneficial new facilities and management changes? Who would be willing to pay for such facilities or institutional changes, and how much would they pay? What is the reliability of both water supply and revenues for new facilities? These are the kinds of questions this project has begun to answer.

This project takes an economic approach to managing and financing California's future water supplies. This new approach uses a computer model that combines water management and economic performance. The computer model (CALVIN) represents California's statewide water system, including its surface water and groundwater resources, storage and conveyance facilities, and agricultural, environmental, and urban water uses.

The model suggests how to operate the system to maximize statewide economic returns from agricultural and urban water uses, given specific practical and policy limits. These limits include the physical availability of water, storage and flow capacities of physical infrastructure, and environmental flow and other policy constraints. This is an economics-driven optimization model. There are no operating rules in the conventional sense of DWRSIM, PROSIM, or other common simulation models.

This economically-based modeling approach provides a variety of benefits for long-term planning. Specifically, model results can be used to:

1) Estimate regional and statewide economic benefits from new or enlarged storage and conveyance facilities or changes in water management policies;

2) Quantify changes in economic and supply reliability from changes in system facilities and management;
3) Assess the willingness to pay of different water users for specific new storage and conveyance facilities or changes in water management policies;
4) Explore how system operations and economic performance might change with different forms of water transfer activity; and
5) Suggest economically promising forms of coordination among regional water systems and promising forms of water transfers.

This report details this new approach and places it in the context of California's water supply problems and its structural, nonstructural, and institutional options. Examples of how the approach can be used are presented. The report also outlines additional work desirable to take this project beyond proof-of-concept and preliminary results. This executive summary briefly reviews the origins of this project, the modeling approach, sample results, innovations and limitations, accomplishments, technical lessons, future directions, and policy conclusions.

ORIGINS OF THIS PROJECT

The State of California Resources Agency funded an 18-month study starting in January 1998 to analyze finance options for California's future water supply. The study is entitled "Quantitative Analysis of Finance Options for California's Future Water Supply," or, the "Capitalization Project" for short. A team of University of California Davis economists and engineers performed this study.

This project began with an interest in the ability and willingness of the private sector to participate in water facilities of statewide significance for California. Rudimentary calculations showed that with CALFED costs ranging between $4 billion and $16 billion and likely state and federal funding in the range of perhaps $3 billion to $8 billion, that there remained a substantial potential finance gap. How much would users be willing to pay for water supply alternatives and could the private sector help?

It was realized quickly that this was an immense task. So much can change and be changed over such a long-term planning horizon. An economic-engineering analysis would be needed of unprecedented scope and flexibility. An optimization modeling approach was selected.

The project further evolved, with the support of its Advisory Committee, to have a broader interest in economic values of facility and management options for California's statewide water system.

MODELING APPROACH

The modeling approach taken for this problem differs from that commonly used for operations planning in the Central Valley. Currently, all operations models for the Central Valley are *simulation* models which use operating rules to allocate water and operate reservoirs. This study uses an *economic optimization* modeling approach, with no operating rules or explicit water rights or contracts, except where added as constraints to the model. Water is moved and stored only to maximize the total statewide economic performance, limited only by physical, environmental, and policy constraints on flow and storage.

Over the planning horizon for new facilities, many changes can be made in water contracts and operating agreements. In particular, water transfers, markets, and wheeling are likely to become more common. Such operational changes may have significant economic benefits and may reduce the need for costly structural solutions. Among the questions for this study is, “What is the economic value of more flexible and coordinated operation of California’s water system?”

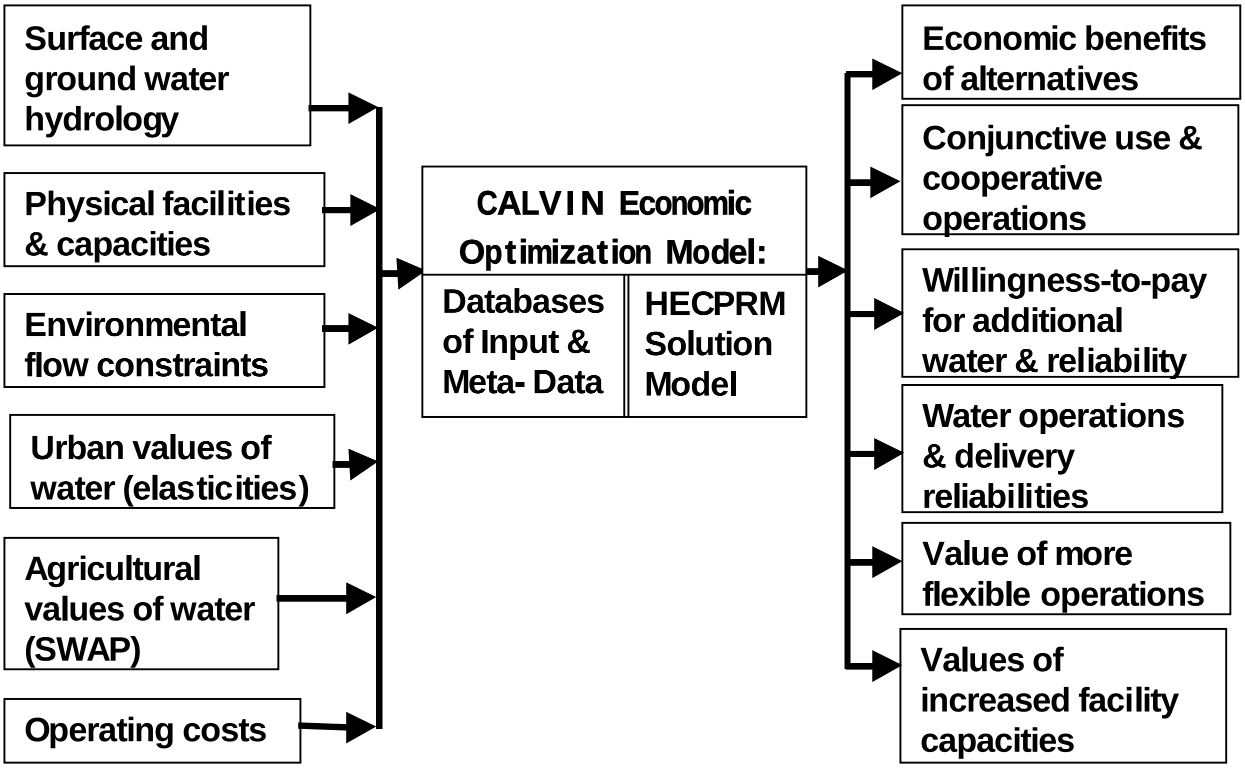
This optimization modeling approach is intended to answer specific economic and management questions and point towards promising potential solutions that are unlikely to emerge from simulation modeling. However, economic optimization does not replace simulation models. Optimization models usually require significant simplifications relative to simulation models. Simulation models are needed to conduct more detailed studies that test and refine planning and operating suggestions provided by optimization results. Together, these two types of models give an ability to look rigorously both at the big picture (optimization) and details (simulation).

The economic optimization model is called CALVIN (California Value Integrated Network). Required model input includes valuation of water uses by month. Values for agricultural water uses are estimated using a new model, SWAP (Statewide Water & Agricultural Production), that extends the approach of earlier CVPM models. Urban values for water use are estimated based on price elasticities of demand.

As illustrated in Figure ES-1, CALVIN consists of a database of model inputs and assumptions and a reservoir system optimization model. The database defines the state’s network of water infrastructure and includes capacities, losses, variable operating costs, and minimum instream flows for each element of the network. In addition, it includes surface and groundwater inflows and the economic values of water use at each major agricultural and urban water use location. The database also includes information on the origins of all input data, called metadata. The CALVIN model schematic represents California’s water supply system with roughly 1,250 spatial elements, including 56 surface water reservoirs, 38 groundwater reservoirs, 47 agricultural demand regions, 20 urban demand regions represented by 38 demand nodes, 163 stream reaches, 150 groundwater flow, pumping, and recharge reaches, 257 canal and conveyance reaches, and 78 diversion links.

The optimization solver for the water resource system is HEC-PRM (Hydrologic Engineering Center-Prescriptive Reservoir Model), a network flow optimization computer code developed by the US Army Corps of Engineers’ Hydrologic Engineering Center in Davis, CA. It was developed specifically to examine the economic operation of large water resource systems. HEC-PRM has been applied to the Columbia River, South Florida, Missouri River, Panama Canal, and Carson-Truckee systems by the US Army Corps of Engineers and the University of California, Davis.

Figure ES-1. Data Flow for the CALVIN Model



SAMPLE RESULTS

Preliminary results from CALVIN for the Central Valley and Southern California indicate that the model is working satisfactorily for initial runs. Current results are partial and preliminary and so are unsuitable for policy purposes. Nonetheless, current results can be used to illustrate uses for CALVIN model results. From model results for Southern California, an example urban water demand is supplied with less than full deliveries in 53 percent of all years, with a maximum shortage of 7 percent. Figure ES-2 illustrates the time-series of monthly shortages for the demand area during the hydrologic period from February 1958 to February 1963. The time-series of that area's marginal willingness-to-pay for additional water also is shown, with a peak willingness to pay of about $1,200/af. This particular demand area is supplied largely by imported water through an external canal to a medium-sized local storage reservoir. Figure ES-3 shows the unit value of increasing the capacity (shadow value) of the supply canal and storage reservoir during this period. Just before each shortage, there is considerable value to increasing storage capacity (while there is water and source capacity to fill any new storage). Towards the end of each shortage event, when normal reservoir storage is exhausted, there is value to accessing the "dead storage" at the bottom of the reservoir (appearing as negative values for local storage). This would be the value of pumping additional water from the bottom of the reservoir during these shortages. During the shortage event, additional source canal capacity has considerable value, as high as $1,000/af-month. These types of results are useful for identifying desirable locations in the network for capacity expansion (raising storage capacities, accessing dead storage, or increasing conveyance capacities) and estimating local willingness to pay for additional water. Chapters 7 and 8 discuss additional sample model results and additional uses of CALVIN model results.

Figure ES-2. Example Local Shortages and Willingness to Pay for Additional Water

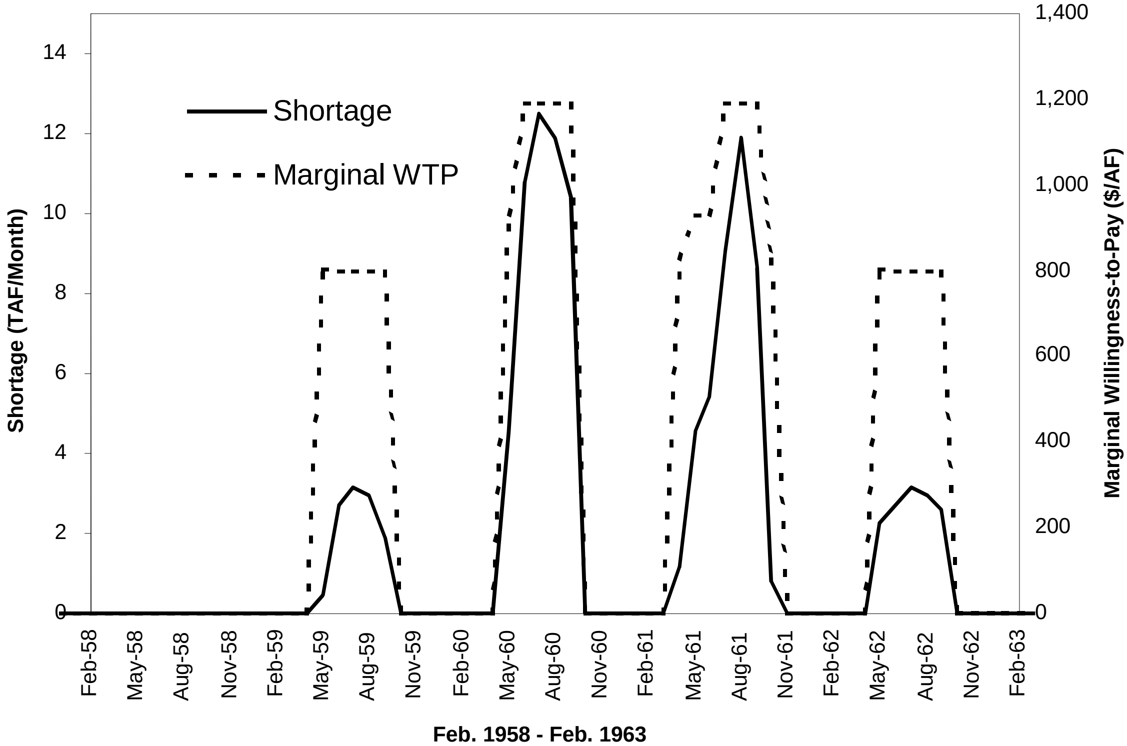
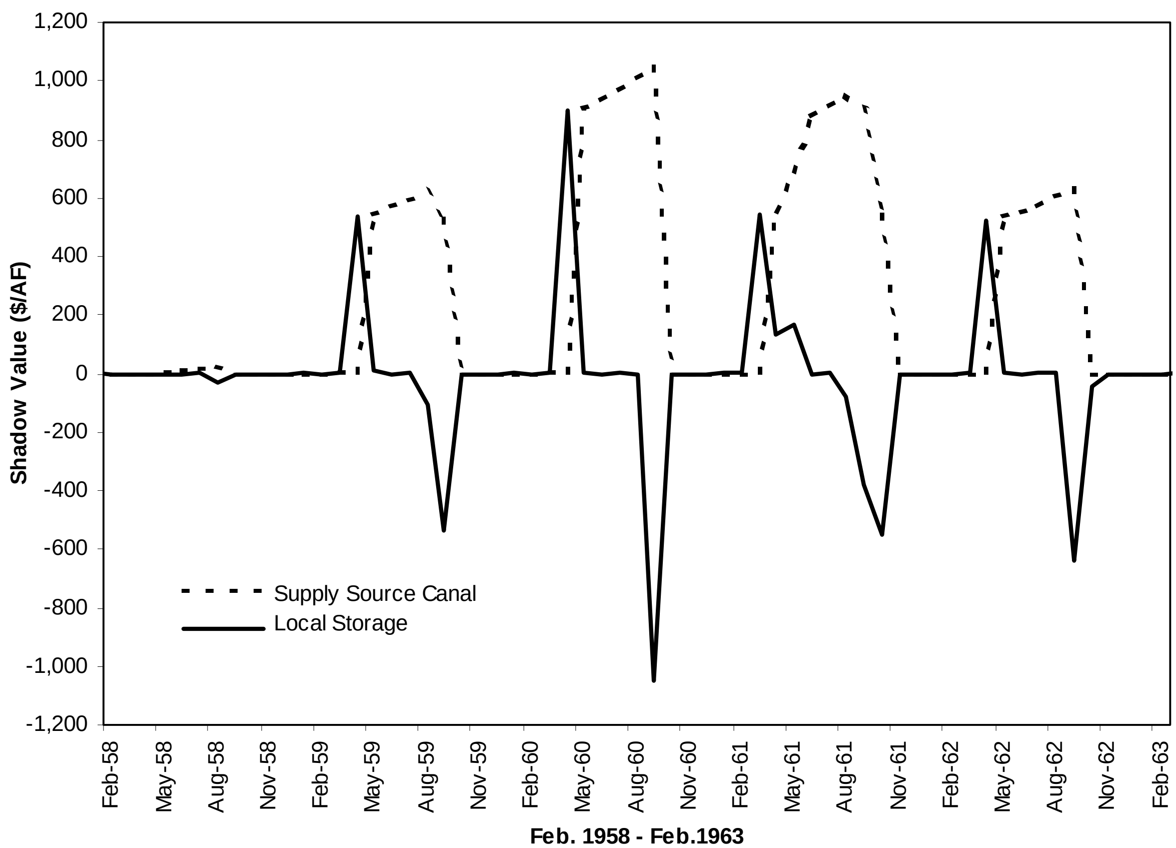


Figure ES-3
Supply Canal and Local Storage Capacity (Shadow) Values



INNOVATIONS AND LIMITATIONS

Some of the major project innovations are listed in Tables ES-1. These innovations were required for the purposes of this project and represent, in most cases, some attempts to broaden the analytical capabilities available for long-term water planning in California. Some of the limitations of the approach are included in Table ES-2. These and other limitations are further elaborated later in the report. Many of these limitations are the subject of additional work to be completed over the next 18 months.

Table ES-1: Selected Project Innovations

1. Optimization model
- More flexible operations and allocations can be examined
- System operations explicitly pursue economic performance objectives
- Provides rapid identification and preliminary evaluation of promising alternatives

2. Statewide model
- Model goes from Shasta to Mexico
- Tulare Basin, SF Bay area, South Coast, and Colorado R. areas are added
- Explicit examination of potential statewide impacts, operations, and performance

3. Groundwater
- Groundwater use is explicitly, though imperfectly, included
- Groundwater use is fully integrated with surface supplies and water demands

4. Economic Perspective
- Statewide economic performance is the explicit objective of the model
- Economic values for new storage and conveyance capacity are provided by the model
- Greatly enhanced capability to model water marketing/water transfers

5. Data and Model Management
- Explicit data management tools and documentation of model assumptions
- Relative ease of understanding and modifying assumptions
- Model, data, documentation, and software are public domain

6. Economic Values of Water Use
- Statewide understanding of economic values of water for agricultural & urban uses
- Reformulation and extension of CVPM models of agricultural water values (SWAP)
- Economic models developed and applied to Southern California agriculture
- Consistent, though simplified, statewide representation of urban water values

7. New Management Options
- Various statewide water marketing options
- Integrated operation of existing and new facilities
- Potential for private facility investments
- Flexible facility operations and flexible water allocations

8. Systematic Analytical Overview of Statewide Water Quantity
- Hydrology (surface and ground waters)
- Facility capacities
- Environmental limits, institutional limits, economic values

Table ES-2: Selected Project Limitations

1. Limited Ability to Represent Water Quality
- Water quality must be represented indirectly with costs and constraints
- Urban water quality impacts are represented by surrogate treatment and consumer costs

2. Environmental Flows
- Environmental flows are represented in very simplified ways, only as minimum flows

3. Limitations of Input Data
- Many sources of data; need to further reconcile data from different sources

4. Effective Precipitation for Agriculture
- Variation in effective precipitation by year is currently neglected

5. Optimization Limitations
- Requires significant simplifications over simulation modeling; groundwater is especially simplified
- The first models assume perfect hydrologic foresight
- Some system aspects are imperfectly represented as network flow optimization
- Additional detailed modeling is usually needed to refine and test the details

6. Simplified Representation of Groundwater
- Groundwater is modeled as simple storage reservoirs

7. Simplified representation of urban water shortage costs
- Elasticity approach is very simple, 2020 demand levels are controversial
- No annual variation in demands with weather

8. Monthly time step necessitates simplification of more complex phenomena

9. Hydropower currently not included in the initial analysis

10. Operating Cost Data
- Cost values from different sources are estimated inconsistently

ACCOMPLISHMENTS OF THE PROJECT

This project required completion of a number of activities, products, and tasks, summarized in Table ES-3. These are elaborated on and presented in the report and its appendices.

Table ES-3: Completed Activities, Products, and Tasks

1. Draft California Water System Schematic
2. Statewide Model Schematic
3. GIS Maps for Documentation and Post-Processing
4. New Economic Production Models for Agricultural Areas (SWAP)
5. Monthly Agricultural Water Valuations for the 21 Central Valley CVPM Regions
6. SWAP Model Extension to Southern California
7. Assembly of Operating Costs Systemwide
8. Monthly Urban Water Valuations for 20 Major Urban Areas
9. Preliminary Synthesis of Surface and Ground Water Hydrologies Statewide
10. Assembly of System Capacities
11. Assembly of Environmental Flow Requirements
12. Database for Input Model Data and Metadata
13. Software for Entering Data into HEC-PRM Model
14. Improvements to HEC-PRM Model
15. Design for Modern Data-Model Interface and Data Management System
16. CALVIN Model Runs for the Central Valley and Southern California
17. Conceptual Design for Post-Processing Tool
18. Interim Post-Processing Software
19. Model and Data Documentation

TECHNICAL LESSONS

Most of our technical lessons learned involve data, its availability, and data management.

Statewide Water Management Modeling is Possible

Model development, data gathering, and preliminary model runs completed so far are sufficient to indicate that it is possible to model the economic management of water statewide. Five years ago, the available data, software, and computing power were insufficient for an optimization model as integrated and disaggregated as the current CALVIN model. While important gaps, uncertainties, and limitations remain, the state's water management community should begin to consider how to use such integrated modeling to help resolve pressing policy evaluation, economic impact, coordinated operation, and project finance problems.

Most Data are Available

A great deal of useful water resources data and information has been collected and developed over the last century in California. Particularly in the last decade, much information and modeling has been developed which is useful for large-scale operations and planning modeling purposes. However, the development and use of data and information must continue to adapt to the newer problems faced by the state in recent decades.

High Level of Technical Cooperation

To develop the data for the economic optimization model, we have contacted dozens of agencies statewide. Almost all parties have been very helpful in providing data and useful information for this project. Without this high level of cooperation, our model would be far more approximate.

Data Gaps, Limitations, and Uncertainties

Some types of data need additional work to improve the value of statewide analysis. As detailed in the report, these areas include surface water and groundwater hydrology, local water management, and economic valuation of water demands.

Data Management is Important

For large-scale models intended for use in public resolution of controversial problems, the clarity and reasonableness of the model and its input data will be severely tested. In these situations, the modeling approach and supporting data should be transparent. This implies that information on the origins and quality of model data (metadata) should be readily available. The CALVIN model's input data is stored in a searchable Access database, including metadata on the origins and limitations of these data. Ultimately, these data and metadata will be accessible from the model schematic.

FUTURE DIRECTION

The project has demonstrated the feasibility of using a statewide economic optimization model to help plan for California's future water supplies, including estimating the value of particular proposed new facilities and changes in water management policies, such as water marketing. Such results can be used for evaluating various user financing mechanisms for particular system components, the economic desirability of various alternatives statewide or regionally, and suggesting various economically promising planning and operations alternatives. The interaction of groundwater, surface water, and water policy alternatives can all be preliminarily examined using this approach. Various data management ideas for making large-scale operations models more accessible for California water planning also will be demonstrated and developed.

For the results of this project to have more practical, widespread, and direct use for California, additional development and investment will be required. Some specific products for a one- to three-year time-frame are identified and discussed below. CALFED has agreed to fund much of the basic work needed along these lines over the next 18 months.

Some specific future development objectives include:

Better Data Management and Model Enhancements

Data-Model Input Interface Completion
Data Checking and Revision
Post-Processing Software
Variation of Urban and Agricultural Water Demands by Year-Type
Add Hydropower and Head-Dependent Pumping
Add Quadratic Economic Value Functions for Agricultural and Urban Water Demands

Applications

Groundwater Management and Economic Impacts
Develop Promising Conjunctive Use and Cooperative Operation Alternatives
Support for Economic and Financial Analysis of CALFED Alternatives
Implied Valuation of Environmental Water Use
Economic Evaluation of New Facilities and Alternative Water Transfer Policies
Finance of New Facilities or Management
Disaster Economic Impacts and Flexible Response

Longer Term Developments

New Optimization Algorithms
Web-based interface

POLICY CONCLUSIONS

1. *The complexity, controversy, interdependence, and importance of California's water supply system have grown to require new approaches to their analysis.*

California's water issues are interconnected statewide; water management and use in one area commonly affects water use in other areas. Surface water and groundwater systems are highly connected. Almost the entire system is complex and controversial. Most current analysis models used in California were developed at an earlier time to examine limited surface water options for a specific water project. Over time, these models have been expanded, but have become increasingly difficult to apply. More modern analysis methods can help.

2. *Economics should have a greater role in analysis of California's water system.*

The greater controversy, variability, and diversity of water uses and supplies in California's water system have made economic indicators of system performance increasingly desirable. Economics-based analysis and economic measures of performance provide a fairly direct basis for:

- Evaluation and comparison of alternatives;
- Developing new economically promising structural and non-structural alternatives;
- Financial and willingness-to-pay studies;
- Cost or benefit effectiveness studies;
- Development and evaluation of integrated effects of multiple water management options;
- Quantifying trade-offs among system objectives; and
- Quantifying benefits to society and users of changes in facilities, environmental flow requirements, and institutional policy constraints.

Water supply "yield" has become an increasingly obsolete and contentious indicator of performance. The economic value of water deliveries has become a more reliable and direct indicator of system performance that can better incorporate reliability and water quality concerns for agricultural, urban, and perhaps ultimately environmental water uses. While improvements in these estimates are desirable, there is sufficient data and professional consensus to use these economic methods in long-term water planning.

3. *Advances in computing and software provide substantial opportunities to modernize and improve the analysis of California's water resources*.

The California water community is at an unusual point in time where the limitations of old methods and the promise of new technologies are both abundantly apparent. This is a pivotal time for the California water community to develop new approaches, methods, tools, and data for planning, managing, and operating water statewide over the long term. Without such modernization, proposed solutions are less likely to perform effectively, and are therefore more likely to become controversial, discredited, and short-lived. DWR and USBR have moved energetically in this direction with the development of the CALSIM simulation model, which provides a platform for additional modernization efforts.

This project has demonstrated the feasibility and desirability of several more modern approaches to large-scale water system analysis. These include:

- More transparent data-driven modeling;
- Database documentation of model assumptions and parameters;
- Large-scale economic optimization; and
- Structures for automated computer management of modeling data.

The primary advantages of these techniques are to speed development and analysis of alternatives and to increase the transparency of modeling assumptions and results.

4. *California can choose from a wide variety of structural and non-structural options for addressing its pressing water resource problems.*

Chapters 3, 4, and 5 present a diversity of structural and non-structural options available to local, state, and federal agencies, firms, and water users. Nonstructural options are especially important and are necessary complements to structural options. In highly interconnected systems, such as California, the benefits of new water facilities are often reduced unless accompanied by complementary changes to the operations and management of other water facilities. However, it is typically difficult to study, develop, and integrate nonstructural options using conventional simulation models, prompting the need to use newer and more flexible analytical techniques. The need to integrate all manner of water management options further motivates the use of more modern system analysis methods.

5. *Groundwater must be integrated into the analysis of California's water supplies, even though we know relatively little about it.*

Groundwater provides about thirty percent of California's agricultural and urban water supplies in an average year. In drought years, use of groundwater increases greatly, and provides California's greatest source of drought water storage. While there is relatively less knowledge and regulation of California's groundwater, realistic analysis of California's water supplies must include explicit integration of groundwater. Such integration will support development of promising conjunctive use projects and accelerate development of improved understanding of the state's groundwater systems.

6. *Economic-engineering optimization models are feasible and insightful for California's water problems.*

This study has demonstrated the capability of a new analysis approach for California water using the CALVIN model. CALVIN is an economically-based engineering optimization model of California's water supply system. Given economic values developed for agricultural and urban water supplies, environmental flow constraints, inflow hydrologies, operating costs, and facility capacities, CALVIN suggests economic-benefit-maximizing operations of the statewide system, integrating all resources and options. This phase of work has proven the data availability and software performance required for CALVIN and the feasibility of implementing such a modeling approach.

7. *New optimization modeling analysis will almost always require more focussed and detailed simulation modeling to refine and test solutions*.

As good as optimization models have become, they do suffer some limitations and require sometimes important simplifications relative to simulation models. (CALVIN, for instance, has fairly crude methods of representing water quality.) Optimization model solutions provide promising solutions for refinement and testing by simulation studies, allowing simulation efforts to focus on the detailed analyses they are better suited for. For large, complex, and controversial systems, simulation and optimization methods complement each other.

8. *Better data is needed in some areas to allow better solutions to be realized.*

In assembling and developing input data for the CALVIN model, we identified some areas which merit greater long-term data development. These areas include:

- Surface water and groundwater hydrology;
- Operations and costs for local water facilities;
- Urban water demands and economics; and
- Water quality economics.

CALFED, DWR, and USBR are devoting effort to improving data in some of these areas, particularly regarding surface water and groundwater hydrology in the Central Valley.

9. *CALVIN needs more work.*

While this first phase of work has proven the concept of applying economic-engineering optimization to California's water system, much data checking and development is needed before useful policy-relevant results can be produced. Additional work in this regard is being undertaken with support from CALFED.