Economic-Engineering Optimization for California Water Management

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Abstract: An economic-engineering optimization model of California's major water supply system is presented. The model's development, calibration, limitations, and results are reviewed. The major methodological conclusions are that large-scale water resources optimization models driven by economic objective functions are both possible and practical; deterministic models are useful despite their limitations; and data management, reconciliation, and documentation are important benefits of large-scale system modeling. Specific results for California indicate a great potential for water markets and conjunctive use to improve economic performance and significant economic value for expanding some conveyance facilities. Overall, economic-engineering optimization (even if deterministic) can suggest a variety of promising approaches for managing large systems. These approaches can then be refined and tested using more detailed simulation models. The process of developing large-scale models also motivates the systematic and integrated treatment of surface water, groundwater, facility, and water demand data, and identification of particularly important data problems, something of long-term value for all types of water resources analysis.

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Introduction

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

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

In recent times, the economic, social, and environmental effects of water management and development have come under intense economic, social, and political scrutiny and urban and environmental water demands continue to grow. A wide variety of water management and development alternatives are being considered, ranging from new off-stream surface reservoir sites, expanded on-stream reservoirs, greater conjunctive use of groundwater storage, additional water conveyance capacity, more expensive and effective forms of water treatment and wastewater recycling, water transfers among water users, water use efficiency and demand management, as well as experimental forms of environmental restoration. The integration of such a variety of options into an already complex water management system is a difficult task. This task can be made somewhat easier by the judicious use of optimization modeling.

This paper presents the development, calibration, limitations, and preliminary results of an economic-engineering optimization model of California's main intertied water system, including the Central Valley, most the San Francisco Bay metropolitan area, and Southern California. The details of this work can be found in Jenkins et al. (2001) and its associated appendices and web site. The model CALVIN (California value integrated network) operates surface and groundwater resources and allocates water over the historical hydrologic record to maximize the economic values of agricultural and urban water use statewide, within physical, environmental, and selected policy constraints. CALVIN is based on data from existing large-scale simulation models, with the addition of economic values for agricultural and urban water use at various locations throughout the system and a network flow optimization solver provided by the U.S. Army Corps of Engineers (USACE) (*HEC-PRM*). This relatively simple, if large-scale, optimization model supports several technical and policy conclusions with long-term significance for management of California's water. While there have been other optimization models of water in California (Becker et al. 1976) and economic optimization models of large systems in California (Vaux and Howitt 1984; Jacobs et al. 1995), this model is of much greater spatial scope and detail.

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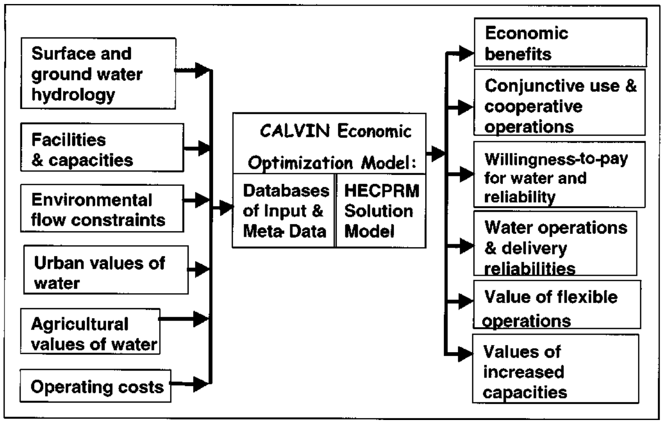

Fig. 1. Data flow schematic for CALVIN

Modeling Objectives and Approach

No model solves all problems. And most models, like most oracles and many experts, provide only imperfect answers. The CALVIN model is intended to help with the following activities in the context of California's water supplies:

- Identification of economically promising facility capacity changes,
- Assessment of user willingness-to-pay for water,
- Identification of promising water transfers,
- Integration of facility operations (including conjunctive use),
- Data assessment and reconciliation,
- Demonstration of advances in modeling technique and documentation, and
- Identification of promising solutions for refinement and testing by simulation studies.

In doing so CALVIN demonstrates the feasibility of using economic-engineering optimization for the planning of California's water resources.

The general approach of the CALVIN model is to use optimization to suggest water facility operations and allocations that maximize the economic value of agricultural and urban water use in California's main intertied water supply system. Agricultural and urban water demands are represented by economic value functions for year 2020 levels of development (population and land use). Monthly operation and allocation decisions are made for a 72-year period based on the 1922–1993 hydrologic period, representing the range of likely hydrologic conditions. These operations are limited by environmental flow requirements as well as facility capacities and flood control operations. All sources of water and storage are considered, including surface water, groundwater, and incidental and intentional reuse. Data flows to and from the model are depicted in Fig. 1.

Network Flow Optimization with Gains/Losses

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

Minimize

$$Z=\sum_i \sum_j \sum_k c_{ijk} X_{ijk} \tag{1}$$

subject to

$$\sum_i \sum_k X_{jik}=\sum_i \sum_k a_{ijk} X_{ijk}+b_j \quad \text{for all nodes } j \tag{2}$$

$$X_{ikj} \leq u_{ijk} \quad \text{for all arcs} \tag{3}$$

$$X_{ijk} \geq l_{ijk} \quad \text{for all arcs} \tag{4}$$

where Z = total cost of flows throughout the network; X_{ijk} = flow on the kth arc leaving node i toward node j; c_{ijk} = economic costs or loss of benefits (agricultural, urban, and operating); b_j = external inflows to node j; a_{ijk} = gains/losses on flows in arc ijk; u_{ijk} = upper bound on arc ijk; and l_{ijk} = lower bound on arc ijk.

The objective function, Eq. (1), represents the minimum of all flows in the network each weighted by a unit cost that can vary between arcs. Costs include convex economic losses to agricultural and urban regions, urban water quality costs for salinity and treatment, and pumping and other operating costs. Eq. (2) represents conservation of mass at each node in the network; the sum of all flows from a node must equal the sum of all flows to that node. Each flow leaving other nodes for node j is weighted by a loss factor ($a_{ijk}=1$ represents no loss). The numerical solution of network flow formulations is faster than the less restrictive linear programming and such algorithms are in the public domain (USACE 1994).

This simple formulation can be adapted and extended to solve a wide variety of problems. Using arcs to represent flows in time as well as space permits dynamic formulations including surface and groundwater storage. Convex piecewise linear cost functions can be represented by using several subarcs to represent one physical arc, with each subarc k having an appropriate upper bound and unit cost. The losses a_{ijk} in Eq. (2) can be used to represent reservoir evaporation.

This optimization problem is solved using the U.S. Army Corps of Engineers Hydrologic Engineering Center's *HEC-PRM* software, which uses a network solver developed by Paul Jensen of the University of Texas. This code has been applied to many water systems in the United States (Israel 1996; Lund and Ferreira 1996; USACE 1996, 1998a,b) and Panama (USACE 1999) in the last decade and is the numerical core of the CALVIN model.

Pure network flow optimization (without gains and losses) has long been used to model water problems (Water Resources Engineer 1969; Orlob et al. 1971) and remains quite common (Labadie 1997). The additional ability to use gains and losses allows for a more explicit representation of return flows, system losses, and differences between applied and consumptive water use, along with their economic effects. While this simple but fast formulation permits spatially detailed modeling, it poses other limitations as discussed later.

Statewide Intertied System

The demand areas covered by the model appear in Fig. 2. A network schematic is available from the project's web site ⟨http://cee.engr.ucdavis.edu/faculty/lund/CALVIN/⟩. The schematic includes the entire Central Valley, the Trinity River system reservoirs which supplement the Central Valley Project, the parts of the San Francisco Bay area that use water which originates in the Central Valley (San Francisco, East Bay, Contra Costs, Santa Clara Valley, etc.), Metropolitan Water District of Southern California, and other major contractors receiving water from the State Water Project (SWP), and agricultural and urban users of California's portion of the Colorado River. The Owens Valley and Mono

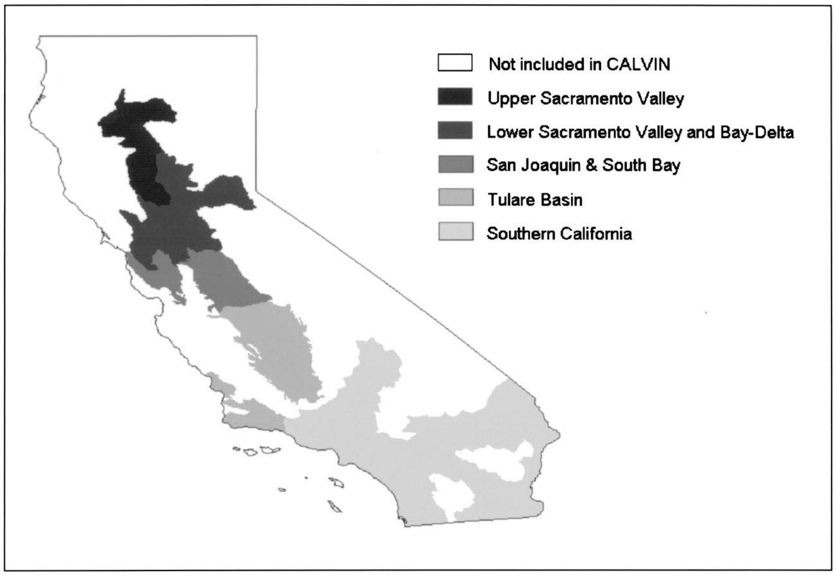

Fig. 2. Agricultural and urban demand regions represented in CALVIN

Basin sources of water and water facilities also are included. Groundwater and surface waters are represented for all these regions.

The network has been cut in several places to avoid modeling the details of relatively minor portions of the overall system. At these locations, demands have been estimated and valued. For example, demands of the Santa Barbara and San Luis Obispo regions via the Coastal Aqueduct of the SWP are represented as a time series of demands for water, valued for urban water use. Since maximum demand through the Coastal Aqueduct is approximately 60×10^6 m^3/year, the details of local water operations were not seen as having great implications for statewide operations.

CALVIN is the first model to represent explicitly the waters of the entire Central Valley, imports from the Trinity system, and Colorado and Eastern Sierra supplies to major water uses of California, with simultaneous optimization of surface and groundwater supplies and major water demands. This intertied water system stretches from the Shasta-Trinity system to the All-American Canal adjacent to the Mexican border. The CALVIN model covers 92% of California's population and 88% of its irrigated acreage (Fig. 2), with roughly 1,400 spatial elements (links) and 704 nodes, including 51 surface reservoirs, 28 groundwater basins, 19 urban economic demand areas, 24 agricultural economic demand areas, 39 environmental flow locations, 113 surface and groundwater inflows, and numerous conveyance and other links. Solution of the network for the entire 72-year historical record involves solving over 1.2 million flow and storage decisions.

Economic Performance Objective

The objective is to maximize the year 2020 net economic benefits of water operations and allocations to agricultural and urban water users throughout the statewide intertied system over the range of hydrologic conditions represented by the 1922–1993 historical period. Water is valued according to the economic principle of willingness-to-pay, i.e., water is worth what users are willing to pay for it. Variable costs of water supply operations are also included in this economic objective. (The formulation for the solver is standardized equivalently as a minimize net economic losses to California, with economic losses or penalties to users calculated as reductions from maximum useful water deliveries to users.)

Agricultural Economic Values for Water Use

Agricultural economic values for water use are estimated for the 21 regions of the Central Valley and three regions of Southern California. For each region, an economic loss function is derived which decreases with water delivery to the agricultural region. This convex economic loss represents the reduction in net farm profits that results from limited water deliveries.

The economic benefit and loss functions for farm water use were derived using the Statewide Agricultural Production model (SWAP), which is a separate optimization model that maximizes farm profit for each agricultural demand area, given a quadratic crop production function with water, land, technology, and capital inputs, and constraints on water and land availability. Year 2020 acreages for agricultural lands availability are assumed. The model is similar to other agricultural production models commonly used in California water studies, but provides monthly (as opposed to annual) results and estimates its production function differently. The production function is calibrated against actual cropping decisions in each region (Howitt et al. 1999, Appendix A). An example economic benefit function appears in Fig. 3. Benefit functions are converted to equivalent loss functions for optimization by calculating the departures from maximum economic benefits for different delivery volumes. Marginal values of water range from zero, where water availability no longer limits farm profits, to over \$250/thousand m^3 for high valued crops.

Urban Economic Values for Water Use

Economic losses from urban residential water scarcity are estimated based on economic demand curves for urban water use (Jenkins et al. 2001, Appendix B). Demand curves are assumed to have constant elasticity, which varies between summer, winter, and intermediate months. Demand curves are based on 1995 estimates of elasticity (Renwick et al. 1998) and are scaled for each of 19 urban regions by their 2020 populations. Industrial water scarcity costs are taken from a statewide study and scaled for each

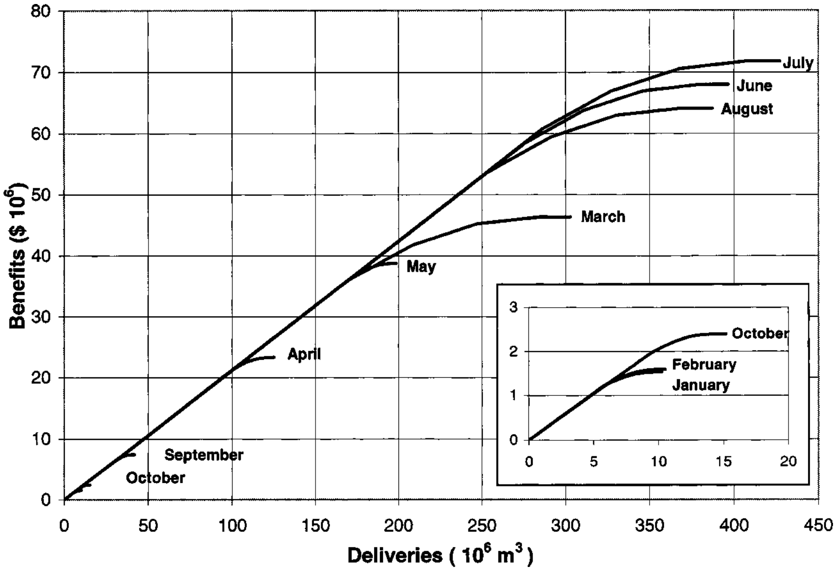

Fig. 3. Example set of agricultural water value functions

urban region (CUWA 1991). Commercial and institutional water demands are taken from 2020 estimates and are assumed fixed, because these demands are thought to be much less elastic than residential demands and no information on the costs of commercial shortages could be found in the literature. An example set of urban loss functions appears in Fig. 4. These cost functions vary by month, but not between years, except for the Southern California region, where estimates were available for the interannual variability of urban demands.

Operating Costs

Variable operating costs and benefits are also included in CALVIN's objective function. Pumping costs include both energy costs and additional "wear and tear" variable maintenance costs, but currently assume fixed pumping heads. Hydropower benefits are largely excluded at this time, but are being added. Recharge facility costs are also estimated as variable costs, since they typically divert land from agricultural production. Variable costs for urban water treatment (which vary with quality), recharge, and wastewater recycling are included, as have water quality costs for salinity reflecting mainly consumer costs.

Environmental Constraints

Environmental objectives are represented by a series of minimum flow constraints on selected river locations and minimum flows to major wetlands. These constraints represent current projected 2020 environmental regulations. Environmental flows are generally taken from existing operations models and represented as time-series constraints within the model for each environmental flow location. Some updating is desirable for some of these constraints, particularly for the Sacramento–San Joaquin Delta.

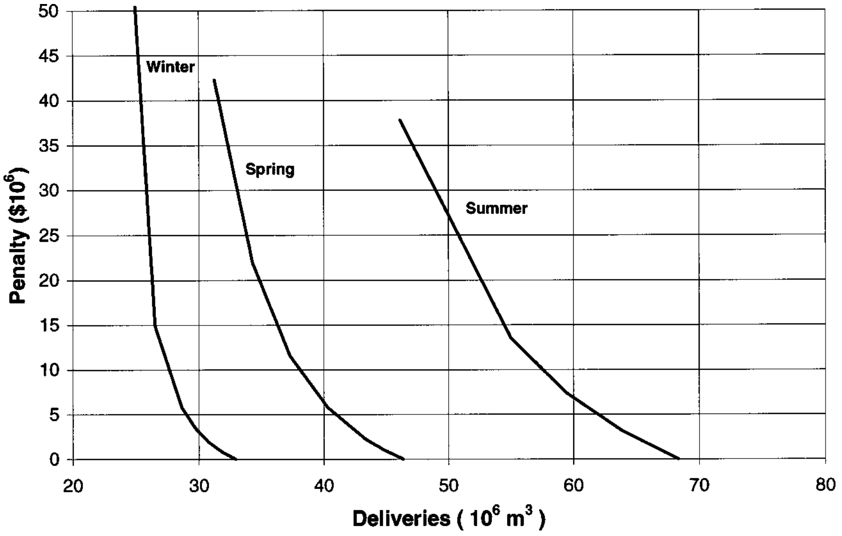

Fig. 4. Example monthly urban residential loss functions

Monthly Model over Historical Hydrology

The hydrologic representation in the model consists of surface water inflows, groundwater inflows, and return flows to surface and groundwater resulting from urban and agricultural water uses. These are taken to represent years 1922–1993 monthly hydrology under year 2020 development conditions. Major surface flows into the rim of the Central Valley are taken from existing surface water operations models. Groundwater hydrology in the Central Valley has been taken from an integrated surface water groundwater finite element model (CVGSM). The Colorado River water is assumed to provide 5.4×10^9 m^3 (4.4 million acre-ft)/year. Local inflows and return flows have been compiled from a variety of sources. Since this hydrologic information had not been reconciled before for a statewide model where all water sources and demands could be simultaneously operated, a major calibration exercise was required, as discussed in a later section.

Facility Capacities

CALVIN includes representations of most of California's major water management facilities with limits on their storage and flow capacities. Major reservoirs often have seasonally-varying limits to conservation storage capacities to reflect flood control operations. Facilities are also subject to losses of water through evaporation and seepage. Reservoir evaporation is represented as a simple linear function of storage. Canal losses are represented as a simple proportion of flows. Most capacities and losses are taken from existing operations models or from local project-specific documents.

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

Model and Data Transparency

For any model of the scope, complexity, and controversy of California's water system, model and data documentation is essential. Transparency is needed for those working with the model to understand what they are doing and for those inspecting model results to try to understand their limitations and see if they are reasonable. This modeling effort is based on a database of flows and facilities that includes documentation of the data (''metadata'') and extensive and critical documentation of the methods, data, and sources used in the model and model data. The statewide model also has been calibrated and documented on a more comprehensible regional basis both for more effective calibration, but also to make the model and model results more understandable. To be practical, and indeed to survive several years of model development, the model required the development and use of database and documentation software as described in the next section. Full documentation of the model, along with its database and metadata are available on the web (Jenkins et al. 2001).

Solution Software

A typical *HEC-PRM* application runs using a *HEC-DSS* file for hydrologic inflow time-series and penalty functions and a text input file of network configuration and capacities, fixed costs, and other model parameters. For earlier *HEC-PRM* applications, this text file could be several to a dozen pages long. For the California system, this text file would have had to be hundreds of pages long, with a myriad of typographical errors and confusion for data entry and debugging.

For CALVIN, special software in *Visual BASIC* was written to write the appropriate text input file for *HEC-PRM* from a relational database. Keeping network parameters in a database allowed for more systematic entry, modification, and documentation of parameters within a single database. This reduced confusion and improved quality control in development and testing of the model and provides an efficient means of detailed model documentation. Without this type of software, such an extensive network would be difficult to implement and modify for practical model runs.

Databases and Metadata

Model data and metadata are stored in two types of databases. A MS-ACCESS database, accessed using *Visual BASIC* software, stores basic information on all network elements (links and nodes). These data include the connectivity of elements, capacities, costs, and gains/losses. For each piece of data for each spatial element, there are metadata fields for the source, source contact information, citation of data-related documents, commentary on the data, an indicator of the perceived reliability of the data, and the project staff who entered the data. Thus, most fields in the database deal with documentation of the model's data (metadata). All time series data and final penalty data are stored in *HEC-DSS*, as required by *HEC-PRM*. These are referenced and documented in the MS-ACCESS database, but are much more efficiently stored and accessed in *HEC-DSS* form. Appendices and brief reports referenced in the database describe details of data development and how the data are used in the model.

Model Runs

For such a large-scale model, each model run has the potential to overwhelm users with information. Indeed the time required to comprehend results from a model run greatly exceeds model run times. Run times for CALVIN can vary between hours and days, while analysis can require several days or weeks. Postprocessors using *EXCEL* have been developed to standardize much data analysis and presentation. The data processing plan for CALVIN includes further development of postprocessors. The automated organization, maintenance, and detailed documentation of model runs for various alternatives are anticipated in future work.

Comparison with Other Available Models

A variety of simulation models have been used for examining water supply issues at large scales in California. These include models developed by the California Department of Water Resources (DWRSIM) and the U.S. Bureau of Reclamation (USBR) (PROSIM, SANJASM, and CVGSM). Recently, the joint State-Federal model CALSIM has replaced surface operations models DWRSIM, PROSIM, and SANJASM.

CALSIM is a simulation model based on sequential monthly integer-linear-programming of operational decisions to minimize a priority-based penalty function of delivery and storage targets. The end-of-period storages from each optimization are used as the initial conditions for the next month's optimization. Between months, nonlinear simulation-style adjustments can be made to reflect more complex environmental regulations, groundwater dynamics, etc. These models focus mostly on the Sacramento and San Joaquin Valley systems with some representation of surface deliveries to the Tulare Basin and Southern California urban areas. The CALSIM model is currently being expanded to more explicitly represent groundwater.

CVGSM (Central Valley groundwater simulation model) is a simulation model of Central Valley groundwater (USBR 1997). The model was used extensively for recent studies of the Central Valley Project Improvement Act and provides the basis for CALVIN's representation of groundwater and local urban and agricultural water deliveries for the Central Valley.

For system operations modeling in California, the major innovations of CALVIN are:

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

Calibration

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

Outcomes of CALVIN's calibration include: (1) a workable model consistent with established representations of California's hydrology and water demands; and (2) identification of problems and regions where additional data reconciliation may be needed. This is essentially a spatially disaggregated physical calibration of the mass of water in the Central Valley's interconnected surface and groundwater system. In performing the calibration, we have tried to isolate calibration parameters from more physically based parameters in the CALVIN model to better identify parameters and regions which appear to need further attention.

Overview of Calibration Steps

Two CALVIN modeling sets are used in the calibration process: the Unconstrained and Base Case alternatives. The Base Case represents current operation and allocation policies for year 2020 conditions, while the Unconstrained Case excluded delivery and operation policy constraints (retaining the same economic objective function and physical capacity, flood control, and environmental flow constraints). These data sets are revised systematically from an initial physically based, but uncalibrated model (Howitt et al. 1999) to the calibrated model needed to represent water quantities as they are commonly understood and modeled in California. The following steps outline the calibration approach.

Step 1. Uncalibrated Physical CALVIN Model

Flows, demands, and return flows represent available physical understanding of the system in this uncalibrated physical model (Howitt et al. 1999). When this model is run, its results are not in accord with conventional understanding of how the system operates nor with the distribution of water scarcity across the state. Notable are a nearly complete absence of water scarcity throughout the 1922–1993 hydrologic record, conservation of mass infeasibilities in some locations, and distorted reservoir and Delta operations. Fundamental problems appear to be difficulties reconciling surface hydrology, groundwater hydrology, and water demands which each come from different sources.

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

Statewide agricultural production model agricultural water demands used in CALVIN are adjusted (usually increased) to reflect the greater amounts of water deliveries seen in earlier studies (USBR 1997). Return flow coefficients to split surface and groundwater portions of agricultural return flow are established and water reuse factors for agricultural demand regions are adjusted (usually decreased) so groundwater storages match results from earlier detailed simulation modeling efforts.

Changes in the return flow splits between surface and groundwaters significantly improved representation of groundwater volumes relative to the commonly accepted CVGSM model (USBR 1997). Adjustments were also made in agricultural water reuse rates, return flow amplitudes, and overall agricultural demand volumes and their seasonal distribution to reconcile the model water balances with those most commonly accepted regarding agricultural water use and groundwater levels. Central Valley agricultural water demands required increases averaging roughly 10% (2.3×10^9 m^3/year) to calibrate the model.

Step 3. Adjustment of Surface Water Flows

Time series of surface inflows (positive and negative) are added to CALVIN to correct infeasibilities (typically at reservoirs) and to match streamflows in the CALVIN Base Case to those in earlier surface water simulation results at 15 matching control point locations. This calibrated surface flow volumes in CALVIN to those common for surface water models and eliminated infeasibilities in the base case resulting from discrepancies in underlying data. Adjustments to surface water flows averaged a modest 47×10^6 m^3/year on average. These calibration quantities were often small to account for differences in the representation of reservoir evaporation. However, these quantities could be as large as 1.3×10^9 m^3/month to account for differences in data sources regarding the entry of floods into particular locations in the system.

Step 4. Hydrologically Calibrated CALVIN Model
The resulting physically based CALVIN, with adjustments to demands, reuse, return flows, and streamflows, matches demands and hydrologies to those accepted for the Central Valley, as represented by both California Department of Water Resources (DWR) and U.S. Bureau of Reclamation models of surface and groundwater flows and demands.

Implications of Calibration

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

Surface and Groundwater Hydrology
Local surface and groundwater flows must be independently identified and explicitly modeled in the Central Valley. This improvement to hydrologic data is especially needed in the Sacramento Valley, but is also relevant to other areas.

Ungaged Streams and Local Accretions
Estimated accretion from local runoff and ungaged streams from mass balance accounting (DWR's depletion analysis) and regression analysis (SANJASM) do not match with the rainfall-runoff model and stream-aquifer interactions used in CVGSM in several places (i.e., Upper Sacramento Valley north–east streams, Feather River, Yolo Bypass, Eastside Streams, and San Joaquin River). More detailed accounting of surface and groundwaters, improving estimates of the locations and volumes of riparian diversions and surface return flows, and further calibration of the rainfall-runoff model should reduce these discrepancies in estimates of local accretions and depletions.

In-Delta Consumptive Use
A large discrepancy exists between State and Federal estimates of in-Delta consumptive use and net in-Delta depletion. Federal estimates are nearly 500×10^6 m^3/year lower.

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

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

Groundwater–Surface Water Interactions in Tulare Region
The calibrated CALVIN representation of the agricultural system in the Tulare Basin Region suggests that net groundwater extraction in Tulare Basin may be more that 600×10^6 m^3/year greater than indicated by CVGSM under the base case. Assuming higher irrigation distribution losses (or diverting some deliveries to recharge) in CALVIN in the Tulare Basin Region would reduce this discrepancy. However, there is uncertainty about the fundamental reliability of CVGSM NAA estimates of 170×10^6 m^3/year long-term groundwater recovery in this region (compared to over 820×10^6 m^3/year of long-term groundwater overdraft indicated in State (DWR 1998) water accounting estimates. Alternative calibration approaches are being considered for this region.

Westlands, Kern, and Other Tulare Basin Deliveries
Recent water market activities by Westland, Kern, and other Tulare Basin agricultural users appear to indicate that the calibrated CALVIN model has insufficient agricultural water scarcity and scarcity costs for these areas. Comparisons of more recent DWRSIM and CALSIM deliveries to this region with the calibration data set indicate no great change in surface water delivery estimates in recent years. However, groundwater representations in this region from CVGSM are thought to be unreliable. Improved confidence in representing supplies and demands in this region is imperative.

Limitations of Current Calibration Approach

The current CALVIN calibration approach suffers from some remaining limitations and unresolved problems. (1) The method used to adjust SWAP average demands is rather simple and crude and distorts the allocation of supplies in CALVIN in nonaverage year types. Better representation of interannual variability in agricultural water demands is needed. Also, additional effort to adjust the monthly use patterns is desirable in some regions, preferably through explicit improvements in SWAP calibration. (2) For the Tulare Basin, detailed policy implications and other modeling results, particularly those pertaining to groundwater management, will be difficult to make given the weak source data and difficultly getting the groundwater calibration approach to work in this region. (3) More recent events, such as implementation of the Central Valley Improvement Act, appear to have reduced agricultural deliveries from those in the calibration data. Revision of environmental constraints also is likely to be desirable.

Limitations

The major limitations of the CALVIN model arise from three sources: (1) The input data used to characterize surface and groundwater supplies, water demands, and base case operations in the CALVIN model are limited by the quality of existing data sets, by weak or unavailable information for some parts of the state, as well as by our own project time constraints. The CALVIN calibration, with its own limitations, attempts to rectify and resolve inconsistencies in data sets to achieve an integrated surface and groundwater hydrologic balance for the Central Valley. (2) Choice of a network flow with gains optimization solver (*HEC-PRM*) imposes several restrictions on the model's ability to represent the system accurately. In particular, flow relationship constraints such as those involved in environmental regulation,

Table 1. Average Water Scarcity and Total Costs

Region	Average Scarcity (10^6 m^3/year)			Average Total Cost ($M/year)		
	BC	RWM	SWM	BC	RWM	SWM
Upper Sacramento Valley	178	194	0	35	34	29
Lower Sacramento and Delta	33	1	1	212	166	166
San Joaquin and Bay Area	20	0	0	394	358	333
Tulare Lake Basin	338	397	41	461	434	415
Southern California	1,396	1,145	1,057	3,074	1,855	1,838
Total	1,965	1,737	1,097	4,176	2,847	2,780

water quality, and stream-aquifer and other groundwater behavior, must be simplified. In addition, water allocation and storage decisions are biased somewhat by perfect foresight in the deterministic optimization solution. (3) Exclusion of hydropower, flood control, and recreation benefits from reservoir operations in this initial model development may distort operations of some parts of the model and limit the identification of opportunities for storage re-operation. It does, however, make interpretation of CALVIN results somewhat easier. This last limitation reflects mainly a time constraint for this initial phase of model development.

The approach taken to modeling the California water system is a technologically simple one. This simplicity allows a much more detailed spatial representation of the system than would be possible with other available solution methods, such as stochastic dynamic programming or even linear programming. This better representation of spatial complexity comes at a cost of a lesser ability to represent temporal uncertainty in hydrology and water demands. The problem of perfect hydrologic foresight has been considered in several ways. First, the hydrologic record used for this model is moderately long, at 72 years, and there is some basis in the literature to indicate that the operating rules that would be derived from such models would closely approximate those of more formal, but here computationally impossible, methods (Jettmar and Young 1975; Lund and Ferreira 1996). Second, it appears that the regularity of many operational and allocation changes with optimization are insensitive to foresight (Newlin et al. 2002). Third, the large amounts of groundwater carryover storage give considerable flexibility and greatly reduce the effects of foresight on operating behavior. Nevertheless, we are looking at additional approaches to better incorporate hydrologic uncertainty into the model (Draper 2001).

Data problems will always exist for such a large system. A major feature of the project has been the identification and documentation of major data problems. These data problems are limitations for any form of statewide water analysis, whether conducted by optimization or simulation methods. The optimization model results, particularly shadow values, can be employed as indicators of where data problems are particularly likely to affect model results. For example, small errors in inflows are unlikely to be important at times and locations where shadow values of additional water are zero.

Selected Model Results

A variety of informative results are available from the CALVIN model. Direct outputs include: time series of monthly flows and storages for each location in the network, marginal economic values of water for each node in the network, and the shadow value of upper and lower bound constraints on any network arc. These time series directly lead to conclusions about deliveries and operational decisions, as well as the economic value of changes in facility capacities and user willingness-to-pay for water. Flow values can be postprocessed with the penalty functions to produce statistics of economic costs or losses to individual water users or facilities, regions, or the entire network.

The model was run for three conditions: (1) a base case (BC) representing current projected operating and water allocation policies; (2) a regional water market (RWM) case, where flows in and out of each of five hydrologic regions were held at BC levels, but operations and water allocations within each region were allowed to change to reach economically optimal levels; and (3) a statewide water market (SWM), where the entire state was operated in a completely flexible and integrated system for economic objectives. Actual model results are discussed more extensively in Jenkins et al. (2001). Below are a few illustrative results. These are not intended to comprise anything more than an illustration of the kinds of results the model can produce. Presentation and discussion of results from a management and policy perspective are provided elsewhere (Jenkins et al. 2001; Newlin et al. 2002).

Water Scarcity and Total Costs

Water scarcity is the difference between modeled water deliveries and the amount of water that users would take if it were freely available at zero marginal cost. This provides an economic basis for a volumetric definition of shortage. Total costs include the economic ''losses'' to consumers of this water scarcity as well as system operating costs (pumping, treatment, etc.). In the CALVIN model, only variable operating costs are considered. Fixed costs are considered sunk.

Table 1 below presents regional and statewide water scarcity volumes and total costs for the three conditions described above. As expected, the systematic removal of constraints between the BC, RWM, and SWM alternatives allows the optimization engine to seek increasingly flexible and economically attractive solutions in each region and ultimately statewide. In some cases water scarcity actually increases with more flexible economic operations, although total costs (including scarcity and operating costs) decrease. Several interesting conclusions are that: (1) the greatest potential for economic improvement lies in Southern California; (2) there is little additional economic benefit from statewide optimization compared with regional optimization; and (3) no region is necessarily worse off economically if water operations and allocations are optimized statewide. The Southern California case is described in more detail in Newlin et al. (2002).

Shadow Values

The economic basis for the model allows shadow values to have an economic interpretation. This allows estimation of economic willingness to pay for additional water at any node and time step in the model (including demand areas, as well as water source and operating locations), the marginal economic value of expanded (or reduced) facility capacities, and the marginal economic costs of environmental flow requirements to agricultural and urban users. In all these cases, the optimization and foresight assumed in the CALVIN model tends to lead to underestimation of these values. But in many cases this underestimation will not be substantial (Draper 2001).

The highest average willingness-to-pay for water occurred under 2020 Base Case conditions for Castaic Lake urban users in Southern California ($8/m^3). This was reduced to $0.5/m^3 with a Southern California water market and $0.4/m^3 with statewide-optimized operations, still a substantial value. Most urban water scarcity and willingness to pay was eliminated with regional and statewide markets, except where capacity constraints restricted water availability. Santa Clara Valley had an average marginal willingness to pay of $200/thousand m^3 (tcm) under the base case, which was entirely eliminated with regional and statewide water markets. Most agricultural regions also saw increased average deliveries and reduced willingness to pay for additional water with regional and statewide-optimized operations. One agricultural region in the Sacramento Valley reduced its willingness to pay for additional water from $34/tcm to $12/tcm with regional optimization, and to zero with statewide optimization. In the Tulare Basin, one agricultural region reduced marginal willingness to pay from $131/tcm to $32/tcm with regional optimization and zero with statewide optimization. Only in Southern California did agricultural willingness to pay for water increase with economic optimization, reflecting water transfers from these users to nearby cities. Imperial Irrigation District's willingness to pay increased from $19/tcm with current operations to $55/tcm with regional and statewide water markets.

As examples of environmental flow requirements, the average marginal economic costs of Trinity River flows (releases from Lewiston Lake) in the northernmost part of the state, reduces from $37/tcm with a regional water market to less than $1/tcm with a statewide water market. Flows to suppress dust in Owens Lake, part of the Los Angeles water supply system, cost $608/tcm with regional water markets and $500/tcm with statewide markets, reflecting fixed-head hydropower losses and higher water quality for these flows as well as small increases in imported water to Southern California with statewide operations. Flows to the Kern wildlife refuge have an average marginal cost of $35/tcm (and a high of $70/tcm) with regional water markets, reducing to an average of $28/tcm (maximum $31/tcm) with statewide operations.

Shadow values of water management facilities were also instructive. Reservoirs tended to have relatively low values for expansion. Part of this is due to the lack of hydropower representation in most of the model and the physical, but perhaps unrealistic, availability of groundwater storage. Kaweah reservoir in the Tulare Basin showed the greatest expansion value of $45/tcm year with a regional water market, reducing to $26/tcm year with a statewide market. Conveyance facilities tended to have greater economic expansion potential. Expanding the Colorado River Aqueduct had a value of $280/tcm year with a regional water market ($170/tcm year with a statewide market). Several nonexistent conveyance facilities also showed promise, such as an intertie between two Bay Area utilities (Contra Costa Water District and East Bay MUD) with a value of $118/tcm under a regional water market, decreasing by $1 with a statewide market. Recharge, pumping, and water reuse facilities also showed economic benefits for expansion via their modeled shadow values.

Conclusions

CALVIN is an economic-engineering optimization model of California's intertied water supply system. The model is intended to provide planning information that is currently unavailable or difficult to obtain. Previously this type of planning was conducted using a loosely knitted mix of separate surface water, groundwater, and agricultural and urban economic models, or was considered impossible. CALVIN's network representation of the system is an assemblage of data from other more geographically and thematically restricted studies of water demands, hydrology, and operations conducted over several decades by many different agencies. While attempts have been made in developing CALVIN to do quality control and reconciliation of these data, gaps and disagreements among sources do exist; these have been documented. The major conclusions of this work are:

1. It is possible to conduct optimization using economic objective functions for systems as large and complex as California's. The computational challenges of this remain substantial, but are not overwhelming and promise to decrease with time. The development and calibration of economic objective functions for many water management purposes is not especially difficult, though it is unfamiliar to most engineers.
2. The management and documentation of data is one of the most important aspects of large-scale system modeling (unglamorous though it is). The systematic assembly, reconciliation, and documentation of data and data problems for a large system, found through an explicit model calibration and reconciliation process, can be a major product of an optimization model development process, with implications relevant for any form of regional or statewide analysis.
3. Deterministic optimization allows far greater detail to be represented in the modeling of actual systems compared with most forms of explicit stochastic optimization. It is inconceivable that an explicit stochastic optimization for a system this large could be calibrated or solved within a reasonable time period, at least for the foreseeable future.
4. The results of such a model, despite their practical and theoretical limitations, point to interesting and practical conclusions for water operations, allocations, plans, and policies over the long term.

Further development of the model includes the addition of hydropower and flood control penalties with application of the model to examine adaptation and adaptability under various climate and water demand growth scenarios.

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