CHAPTER 6

ECONOMIC ANALYSIS OF STATEWIDE WATER OPTIONS

"The man that would be truly rich must not increase his fortune, but retrench his appetites."
Lucius Annaeus Seneca (circa 70 AD), *Of a Happy Life*.

"The stoical scheme of supplying our wants, by lopping off our desires, is like cutting off our feet when we want for shoes." Johnathan Swift (1706), *Thoughts on Various Subjects.*

California's water scarcity problems reviewed in Chapter 2 are forecast to increase. If no new actions are undertaken, by 2020 average year shortages of 2.9 maf are forecast, increasing to 7.0 maf in a drought year (DWR 1998a). However, as reviewed in Chapters 3, 4 and 5, numerous institutional and infrastructure options are available to accommodate, mitigate, and reduce these shortages. This chapter presents the development of a set of economic analysis tools for evaluating structural and non-structural water supply options statewide. These tools are organized into a new optimization model, named CALVIN (California Value Integrated Network).

WHY ECONOMIC ANALYSIS?

Current water policy is often driven by historical water allocation mechanisms intended to stimulate the development of the Western US. A new phase of possible system expansion and re-operation requires a different paradigm for policy making. In an increasingly populous and thirsty state, we need to revisit historical allocations and management of very limited supplies. If system expansion is to be undertaken, we should know how the state's economy would benefit, who would be the beneficiaries and how the great costs of expansion should be allocated or recovered. Federal financing of new water projects is no longer assured. Could new infrastructure investment attract private investment? Users' willingness-to-pay for additional water supply reliability should be the cornerstone for assessing the need for additional facilities, both storage and conveyance. The original operational objectives of the State Water Project (SWP) and Central Valley Project (CVP) have changed and will continue to evolve. Economic performance provides a suitable measure for comparing the great variety of alternatives. Water markets and water transfers are possible reallocation mechanisms for closing the gap between supply and demand. An economic model would reveal the benefits achieved through trade by exploiting spatial and temporal differences in the marginal valuation of water. Economic models might also help point to promising roles for private and inter-governmental involvement in financing and managing water facilities.

SELECTION OF AN ANALYTICAL TOOL

Requirements

This study's objectives are outlined in Chapter 1. The purpose of an analytical tool is to investigate ways of improving water supply reliability and to quantify the associated benefits. As such the chosen tool should:

- Identify promising sites or ‘hot spots’ for economical new infrastructure development;
- Show how the operation of new facilities could be integrated into California’s existing water system;
- Identify the potential economic gains from changes in the current operating procedures, policies and regulations; and
- Quantify willingness-to-pay by group or agencies for system changes.

Computer models are necessary for working with complex systems, such as California’s water supply. A plethora of water management models are already used by California’s water agencies, ranging from simple spreadsheets to very large FORTRAN models. The complexity of these simulation models has increased over time in response to changing water management issues and the increasing interdependency within the system. Solutions to new problems require the examination of many alternatives. It is often difficult and time-consuming to use existing detailed simulation models to analyze large numbers of alternatives. In such cases, it is desirable to develop a separate “screening model” for identifying promising solutions and assessing preliminary performance of a wide range of alternatives. A smaller number of promising alternatives can then be refined and tested with more detailed simulation modeling tools.

Existing Models

Why yet another model and what is different about CALVIN? Before answering these questions, existing large-scale models for California’s water system are briefly described. It should be noted that all of the models described are procedural in design, driven by operating rules derived from current water allocation practices. None includes explicit measures of economic performance.

<u>DWRSIM</u>

The DWR Planning Simulation Model (DWRSIM) was developed by DWR for water resources planning studies related to the operation of the CVP and SWP (Barnes and Chung). The model was originally based on HEC-3 Reservoir System Analysis for Conservation model developed by the USACE’s Hydrologic Engineering Center (HEC) at Davis, CA. However, since its conception DWRSIM has undergone many additions and enhancements. This includes the addition of a network flow algorithm to model the operation of the California Aqueduct (Chung et al. 1989). DWRSIM utilizes reservoir rule curves based on pre-determined target storage levels to balance storage between reservoirs and between months. The model operates the system for a mixture of water supply, flood control, instream flow augmentation and hydropower generation (DWR 1985).

<u>PROSIM</u>

PROSIM is USBR’s Projects Simulation Model. It is a monthly planning model designed to simulate the operation of the CVP and SWP (USBR 1997). It is used by USBR to analyze long-term water supply impacts on the CVP-SWP system primarily due to regulatory changes affecting system operation. The area represented by the model includes the entire SWP system and the CVP system north of the Stanislaus River.

SANJASM

Similar to PROSIM, the San Joaquin Area Simulation Model (SANJASM) is a monthly planning model developed by USBR. The modeled system covers the east-side streams that are tributary to the Delta and the San Joaquin River Basin (USBR 1997). Much of the SANJASM has been incorporated into DWRSIM.

CVGSM

The current Central Valley Groundwater and Surface Water model (CVGSM) was developed as part of the Programmatic Environmental Impact Statement for the CVPIA (USBR 1997). It is Valley-wide groundwater model that simulates changes in groundwater storage in response to groundwater pumping, and both artificial and natural recharge. The model is based on the Integrated Groundwater and Surface Water Model (IGSM) code that was developed under funding by DWR, USBR, SWRCB and the CCWD. The model includes: a soil moisture budget to simulate direct runoff, infiltration, deep percolation and evapotranspiration; a 1-D stream flow network; unsaturated flow simulation; and groundwater flow simulation using a multi-layered 2-D finite element grid.

Need for a New Model

None of the existing models that simulate operations over a hydrologic period-of record are statewide. None use economic performance as a criterion for operating the system and none of the larger models are sufficiently flexible to screen large numbers of alternative operation and system capacities. It was therefore decided to use a model that is driven by economic indicators of system performance and is designed to examine and choose between large numbers of alternatives. This latter requirement resulted in the abandonment of simulation modeling in favor of optimization. It should be emphasized that while CALVIN represents a new approach in modeling California's water system, it uses existing and previously used and well tested computer programs as its core. The particular technique chosen for CALVIN is known as network flow programming, a subset of linear programming (Jensen and Barnes 1980). Optimization models have previously been used to model the operation of the SWP (Lefkoff and Kendall 1996), but not with an economic objective function. The use of economic optimization models for large-scale water resources planning has been used by the World Bank as part of its investment studies (World Bank 1993).

Optimization

Optimization, a form of mathematical programming is well documented in academic and research literature but its application to real water resources problems is relatively new. An optimization model will set the value of all decision variables so as to maximize (or minimize) the value of the objective function subject to meeting all constraints. To apply an optimization model to a particular problem several questions need to be answered:

- What variables are to be optimized?
- What is the performance objective to be maximized or minimized?
- What constraints should be considered?
- What models/mathematical solution techniques should be used?

As applied to this particular study, the performance objective is to maximize statewide economic benefits for agricultural and urban water use minus operating costs. The decision variables to be optimized are a time-series of reservoir storages and water allocations. Constraints include the need to conserve mass (inflows - outflows = change of storage), capacity limits of the system (storage, conveyance, and treatment) and regulatory or policy requirements (minimum instream flows, restrictions on allocations and transfers etc.).

Optimization models differ from the simulation models described above section in that they are not driven by a predetermined set of operating rules. Optimization models determine the "best" water allocations and operations given a set of economic values. In contrast, simulation models could be used to derive the economic benefits from a *given* a set of water allocations. These two types of model should be used together. An optimization model can be used to quickly assess many alternatives but requires many simplifications. Detailed simulation modeling of promising alternatives is subsequently required to confirm the potential and refine or adjust promising solutions (Lund and Ferreira 1996).

Network Flow Programming

This study uses network flow programming to represent California's water system and solve for economically desirable operation. Network flow programming involves representing the system as a network of nodes and links. For a reservoir/stream system, nodes represent reservoirs, points of diversion, return flow locations or other fixed-point features. The nodes are connected by links that represent possible paths for flow between the nodes. To represent time, identical networks are 'placed parallel to each other- each network representing a particular time step. Links connect reservoirs on adjacent networks so that storage can be conveyed through time. Cost factors or penalties are attached to the links. Where the cost factors are non-zero, each unit of flow through the link will incur a penalty. These penalties may have constant unit values or vary as a function of flow through the link (see Appendix C of USACE 1991a).

The network flow algorithm computes the value of flows in each link at each time-step that optimizes the objective function subject to the constraints of maintaining a mass balance at nodes and not violating user-specified upper and lower bound on flow through the links. Network flow programming has long been used to help solve complex logistics problems in commercial and military areas. In water management, network flow programming has long been used as part of some simulation models (Israel and Lund 1999); some parts of DWRSIM use this technique to achieve storage and delivery targets (Chung et al. 1989).

Economic Objective Function

The objective function consists of a single equation that expresses the objective in terms of decision variables. An economic objective function may be either to maximize benefits or minimize costs. Benefits for CALVIN are based on water user's willingness-to-pay. This is defined as the amount a rational informed buyer should be willing to pay for an additional unit (of water). Under a competitive, unregulated market the willingness-to-pay will equal the market price.

Optimization models with economic objective functions provide, in addition to the value of the objective function, additional economic information in the form of shadow prices or dual costs.

The shadow price represents the increase in the objective function performance for a unit relaxation of a constraint. Given that flow and storage are constrained by system capacities, the shadow price identifies directly the economic benefits of increasing those capacities. The shadow price for a particular facility will vary with time. For example, the value of additional conservation storage will only be non-zero only when the reservoir is full and forced to spill.

CALVIN MODEL OVERVIEW

CALVIN is a collection of computational tools and data that permit the economic analysis of California's inter-connected water infrastructure using optimization. The optimization engine uses a generalized network flow to allocate water to maximize economic benefits (or minimize economic penalties). Economic demands for water use are represented at a fixed 2020 level of development. Supplies are represented by a time-series of monthly inflows based on the historic Oct. 1921- Sep. 1993 hydrology. Table 6-1 summarizes the components that differentiate CALVIN from other existing models.

Table 6-1. Comparison of Selected California System Models

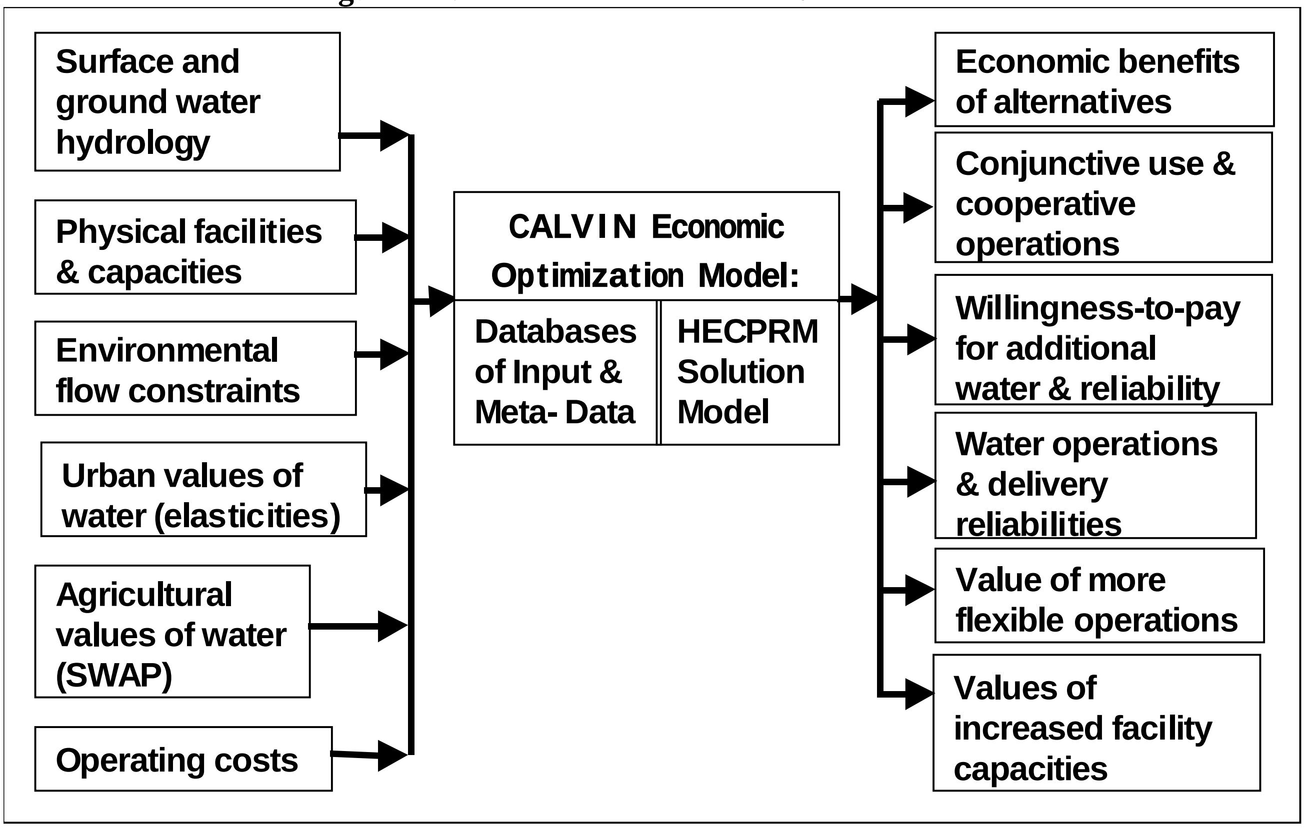
	DWRSIM	PROSIM/ SANJASM	CVGSM	CALVIN
Operation				
rule-based	✓	✓	✓	
economically based				✓
legal/contractual	✓	✓	✓	
Projects/regions represented				
CVP	✓	✓	✓	✓
SWP	✓	✓	✓	✓
Tulare Basin				✓
S. California				✓
Outputs				
time-series of deliveries	✓	✓	✓	✓
quantified benefits				✓
"best" operation				✓
Data-driven				✓

Figure 6-1 represents the flow of data through CALVIN. Model inputs are composed of six components: (1) network representation of California's rivers, reservoirs, aquifers, canals, aqueducts and demands; (2) surface and groundwater inflows; (3) urban economic value functions; (4) agricultural economic value functions; (5) environmental flow requirements; (6) other policy and physical constraints. The derivation of these six inputs to CALVIN is described in later. For urban and agricultural value functions, separate economic models have been developed.

CALVIN can be decomposed into two major components: a set of databases and a reservoir system optimization model. The optimization model is a generic network flow optimization solver that is entirely data driven. All the inputs that define its application to the California system are stored in the databases.

Output from the model consists of a monthly time-series of storages, flows and water allocations over the 72-year modeled period. This output is postprocessed to obtain information on the benefits of different alternatives to system management and operation.

Figure 6-1. Data Flow for the CALVIN Model



Model Components

Databases

Input data for the optimization model consists of the network configuration for California, time-series (hydrologic inflows and time varying constraints), scalar values (fixed constraints, fixed costs and fractional gains and losses) and relational or paired data (functional relationships e.g. between elevation-area-capacity for reservoirs, between quantity of water delivered and the cost of shortage for urban and agricultural users). Time-series and paired data is stored using the HEC'S Data Storage System (HECDSS). This system was developed specifically for water resource applications (USACE 1994). It provides storage of continuous data. An Excel 'add-in' or utility has been developed to store (or retrieve) data from Excel to DSS. All other input data is stored in a Microsoft Access database. Within the database, tables define the properties associated with nodes and links within the network and pathnames to access data from DSS.

Too often large computer models are poorly documented and inscrutable to the user. For modeling intended for use in public policy discussions, model assumptions and data should be readily available and understandable. This study has taken a new approach in storing metadata within the Access database. Metadata is descriptive information about model data. For

CALVIN the metadata contains information on the origins, content, quality and reliability of all inputs to the model.

Reservoir System Optimization Solver

The optimization solver for CALVIN is the HEC-PRM (Hydrologic Engineering Center-Prescriptive Reservoir Model), a network flow optimization computer code developed by the USACE's Hydrologic Engineering Center in Davis, CA. Base on user-specified value functions of system performance, the model produces a time-series of flows and reservoir storage scenarios that optimize system operation. Developed specifically to examine the economic operation of large water resource systems, HEC-PRM has been applied to many systems by USACE and the University of California, Davis. These studies are summarized in Table 6-2.

Table 6-2. Previous Optimization Studies Using HEC-PRM

Year(s)	Basin (No of Reservoirs)	Study Purpose(s)	Citation(s)
1990-1994	Missouri River (6)	Economic-based Reservoir System Operating Rules	USACE 1990, 1991a, 1992a, 1992b, 1994b; Lund and Ferreira 1996
1991-1996	Columbia River System (14)	Economic-based Reservoir Operating Rules Capacity, Expansion, & Multi-Purpose Operations Seasonal Operations	USACE, 1991b, 1993, 1995, 1996
1997	Carson-Truckee System (5)	Prioritization of Uses & Performance Assessment	Israel 1996; Israel and Lund 1999
1997	Alamo Reservoir (1)	Multi-objective reservoir operation	Kirby 1994; USACE 1998b
1998	South Florida System (5)	Capacity Expansion & Multi-objective performance	USACE 1998a
1999	Panama Canal System (5)	Drought Performance & Economic Reservoir Operations	USACE 1999
1999-present	California Intertied System (86)	Economic Capacity Expansion & Financing	Present report

As reflected in the number of reservoirs, the present study represents a very large increase in the size of the system modeled. This has been made possible due to recent and continuing increases in computer processing speed. In addition some specific alterations and enhancements have been made to the HEC-PRM code as part of the study. This includes output of shadow prices and reduced costs, which can be interpreted as the value of relaxing the constraints.

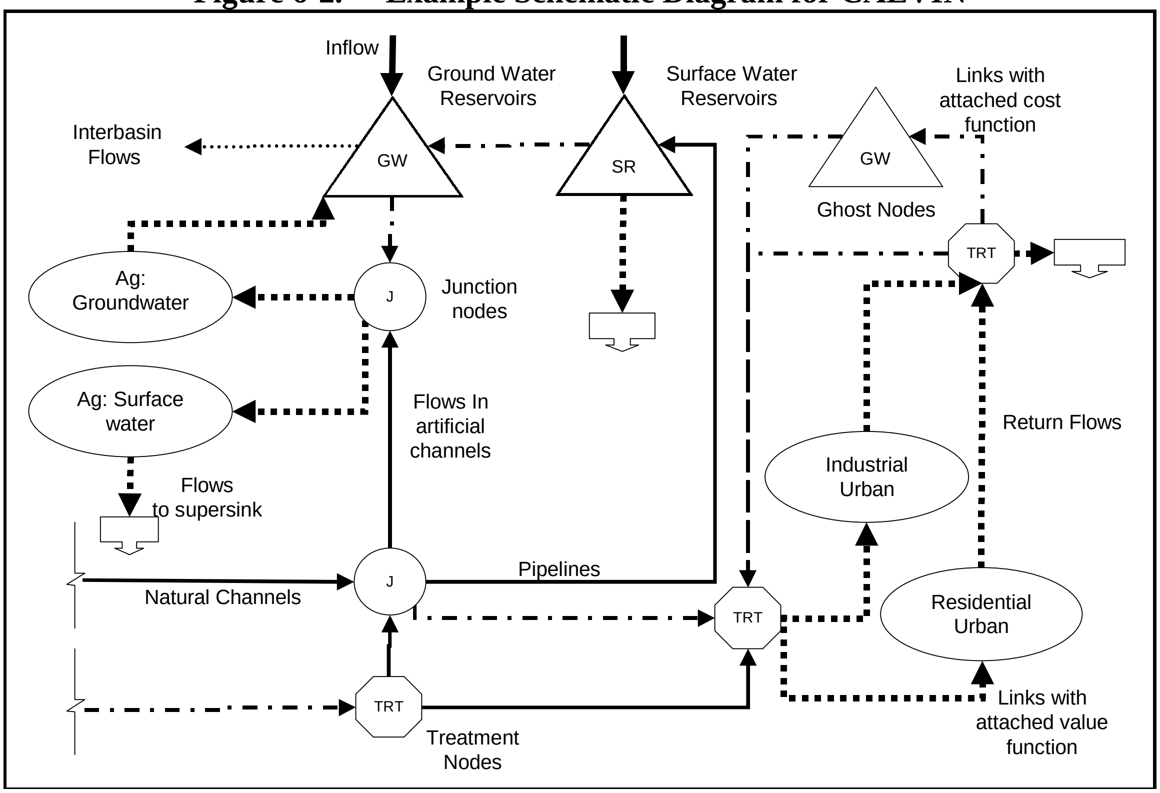
The following sections describe how the various CALVIN model inputs have been established.

NETWORK REPRESENTATION OF CALIFORNIA'S WATER

California's inter-connected hydrologic system has been represented by a network flow diagram as a series of links and nodes as illustrated in Figure 6-2. Where possible, this representation is based on DWRSIM but is extended to include the Tulare Basin, Owens Valley, Imperial & Coachella Valleys, the Colorado River and the South Coast. The CALVIN network is also entirely physically based. Each element of the network has a physical counterpart. The representation of the intricate MWD delivery system is based on an aggregation of MWD's Integrated Resources Planning Distribution System Model (IRPDSM). Conversations with MWD staff and data availability led to the disaggregation of MWD into three components: MWD's central pool (including 24 of MWD's water contractors), Eastern and Western MWD (2 MWD water contractors), and the San Diego County Water Authority (1 MWD water contractor).

The actual schematic is contained in Figures 6-3 and 6-4. Although it is difficult to interpret when printed at this scale, these figures illustrate the complexity of both the system and how it is being modeled.

Figure 6-2. Example Schematic Diagram for CALVIN



Network Flow Diagram Elements

<u>Storage Nodes</u>

Storage nodes represent both surface reservoirs and groundwater basins. Each storage node may have any number of inflows and outflows but mass balance requirements must be met. Included in CALVIN are 56 surface water storage nodes and a further 30 groundwater storage nodes.

Surface Reservoirs

In general only surface reservoirs with a usable capacity exceeding 50 taf were included in CALVIN. In two cases a single storage node represents two adjacent reservoirs with a combined capacity. For each surface storage node constraints are set on the minimum/maximum monthly storage volumes and beginning/end-of–period storage. Monthly evaporation is calculated from

NETWORK SCHEMATIC

NETWORK SCHEMATIC

the product of monthly evaporation rates and reservoir surface area. The surface area is estimated by multiplying the storage by a constant factor.

Groundwater Reservoirs

The division of groundwater basins into discrete reservoirs is somewhat subjective. Within the Central Valley, groundwater is represented by 21 reservoirs. The boundaries of these reservoirs follows those established for the CVGSM model and coincides with the definition of agricultural model regions (see Appendix A). Outside of the Central Valley, a further nine groundwater basins are represented for Southern California. Associated with each reservoir are links representing natural and artificial recharge, pumping, and regional groundwater movement. Similar to surface water storage nodes, the groundwater nodes have specified usable storage capacities and both initial and end-of-period storage volumes. In addition, constraints are set on minimum and maximum monthly pumping and recharge.

<u>Junction Nodes</u>

Junction nodes provide for the interconnection of links. They may represent pumping and power plants, diversion points, or forks in pipelines, channels, and rivers. They also represent points on the model boundary and, as such, receive inflows or ‘external’ flows. The only imposed limitation on junction nodes is the requirement that the sum of inflows equals the sum of outflows. Although some of the 303 junction nodes on the schematic represent hydropower operations, hydropower analysis is excluded from this initial phase of the study.

<u>Demand Nodes</u>

Demand nodes represent some aggregation of agricultural, urban or environmental demand for water. They are essentially identical to junction nodes – representing a specific location within the network - but are distinguished from junction nodes by having a single inflow and a single outflow. The inflow represents deliveries and has a value function associated with it. Consumptive use at the node is represented by a gain factor on the downstream link. The “gain” factor is the ratio of link outflow to link inflow. For example, consumptive use equal to 80% of deliveries is represented by a gain factor of 0.20 on the downstream link. The limitation of a single outflow necessitates the splitting of each agricultural demand: one demand node has return flows to the surface water system; the other returns to groundwater (see Figure 6.2).

<u>Links</u>

Links represent either a stream, artificial channel, or pipeline and can be constrained by minimum and maximum flows. Over 770 links exist within CALVIN. In some cases a single link represents the aggregation of many minor canals. For example, the CALVIN representation of the Kings River designates only two diversions from the Kings River to the Fresno area. These links represent upwards of 100 diversion canals and ditches used by several different local water districts (Woodman et al., 1997). Determining the canal capacity on such an aggregated system would be very time-consuming so that in such a case it has been assumed that canal capacity is not a constraint on deliveries. Operating costs are imposed on some links to represent pumping and treatment costs.

External Flows

External flows represent the addition of surface water and groundwater to the system and are specified for each month of the modeled period. They are described below.

HYDROLOGY

Time Horizon

Although CALVIN's operation is based on a monthly time-series of inputs, CALVIN is in some sense a static model. Demand is estimated from a static agricultural production model and a static urban demand model. The time-varying hydrology can be viewed as representing the possible future range of flows. In this sense the model is static with an implicitly stochastic representation of input hydrology. The chosen level of development is the year 2020.

The hydrologic period represented in CALVIN is Oct. 1921-Sep 1993. This 72-year period was chosen primarily due to the ready availability of data prepared for other large-scale simulation models. This period also represents the extremes of California's weather. Included in the 1921-1993 time period are the three most severe droughts on record: 1928-1934, 1976-1977, and 1987-1992 (DWR, 1998a). Table 6-3 illustrates the severity of these droughts in the Sacramento and San Joaquin Valleys.

Table 6-3. Severity of Extreme Droughts in the Sacramento and San Joaquin Valleys

Drought Period	Sacramento Valley Runoff		San Joaquin Valley Runoff	
	(maf/yr)	(% Av. 1906-96)	(maf/yr)	(% Av. 1906-96)
1929-34	9.8	55	3.3	57
1976-77	6.6	37	1.5	26
1987-92	10.0	56	2.8	47

Source: DWR (1998a)

Surface Water

Adjustment of Historic Flows

California's hydraulic infrastructure has progressively developed over the last 60 years. Matching this development has been the conversion of native vegetation to agriculture and spreading urbanization. These two developments have changed the hydrologic regime that existed historically. Land use changes have altered the amount and timing of runoff. On-stream storage and diversion of stream flows have modified the seasonal variation in stream flow. To determine the input hydrology, CALVIN uses the same approach as existing Central Valley simulation models, such as DWRSIM and PROSIM.

Rim Flows

For inflows from areas upstream of the modeled region, the historic flow is modified to reflect the stream flow that would have occurred with the current infrastructure in place, but with a projected operation and under a 2020 projected land use. This can be interpreted as the flow that would occur if the historic pattern of precipitation were repeated.

Accretion/Depletions

Inflows that originate within the modeled area, resulting from direct runoff or groundwater gains and losses along a stream, are represented slightly differently. Assuming that all major facilities, stream diversions and return flows are represented explicitly in CALVIN, the historic accretions/depletions are modified for land use changes only.

The derivation of surface water inflows is discussed in detail in Appendix I.

Groundwater

Flows in and out of groundwater reservoirs or basins have been divided into several components:

- Natural recharge from precipitation
- Lateral groundwater movement between reservoirs representing large-scale regional flows
- Accretion/depletion to/from stream flow
- Subsurface inflow from outside the model area
- Groundwater pumping
- Recharge from irrigated agriculture and wastewater
- Artificial recharge (conjunctive use/groundwater banking)

Only the last three components are determined dynamically by CALVIN. All other components of groundwater flow and recharge are pre-processed and are represented as fixed inputs. Details of how these flows have been estimated are described in Appendix J.

Data Sources

Surface water inflows for the Central Valley are primarily based on DWR's depletion analysis (see Appendix I). This is supplemented by USGS and USACE data for the Tulare basin. For Southern California data was obtained from the Los Angeles Department of Water and Power and the City of San Diego.

Groundwater flows for the Central Valley are based on the CVGSM groundwater model constructed as part of the CVPIA Programmatic Environmental Impact Statement (USBR 1998). Elsewhere groundwater flows are estimated from published model studies and water master reports.

ECONOMIC VALUE FUNCTIONS

Operations and allocations made by CALVIN are driven by economic values for agricultural and urban water use in different parts of the state. These water demands are estimated using separate economic models for each water use sector. The economic value functions implicitly include the economics of water conservation measures by water users.

Statewide Agricultural Production Model (SWAP)

<u>Origins</u>

The Statewide Water and Agricultural production Model (SWAP) has been developed in parallel with CALVIN to value the economic use of water and how this varies in time and space. SWAP is an economic optimization model that maximizes farmer's returns from agricultural production subject to production and resource constraints on land and water. SWAP extends the work presented in the Central Valley Production Model that was developed as part of the CVPIA Programmatic Environmental Impact Statement. SWAP uses much of the original data contained within CVPM. The model represents the original 21 CVPM regions that cover agricultural within the floor of the Central Valley as well as agricultural production regions in Southern California within Imperial, Riverside and San Diego counties. Details of the SWAP model are presented in Appendix A.

Model Enhancements

SWAP represents various enhancements and changes to the original CVPM model. These are summarized in Table 6-4. The most important change for CALVIN is the use of a monthly rather than an annual time step. Agricultural production is still modeled on the basis of an annual or seasonal planting decisions. However additional constraints are introduced into the model so that monthly water use can be estimated. The revenue from producing a particular crop is distributed across the growing season in accordance with crop water requirements so that the marginal value of water is equal across months.

Table 6-4. Agricultural Model Comparison

Aspect	CVPM	SWAP
Regions	21 regions of Central valley	26 regions for Central Valley and Southern California
Production cost function	Single crop quadratic PMP costs	Quadratic multi-crop costs estimated from maximum entropy
Production technology	Fixed yield CES trade-off between cost and water use	Variable yield with CES production function in land, water and cost
Output price	Prices change with total production	Fixed price with regional differences
Water use	Annual	Monthly

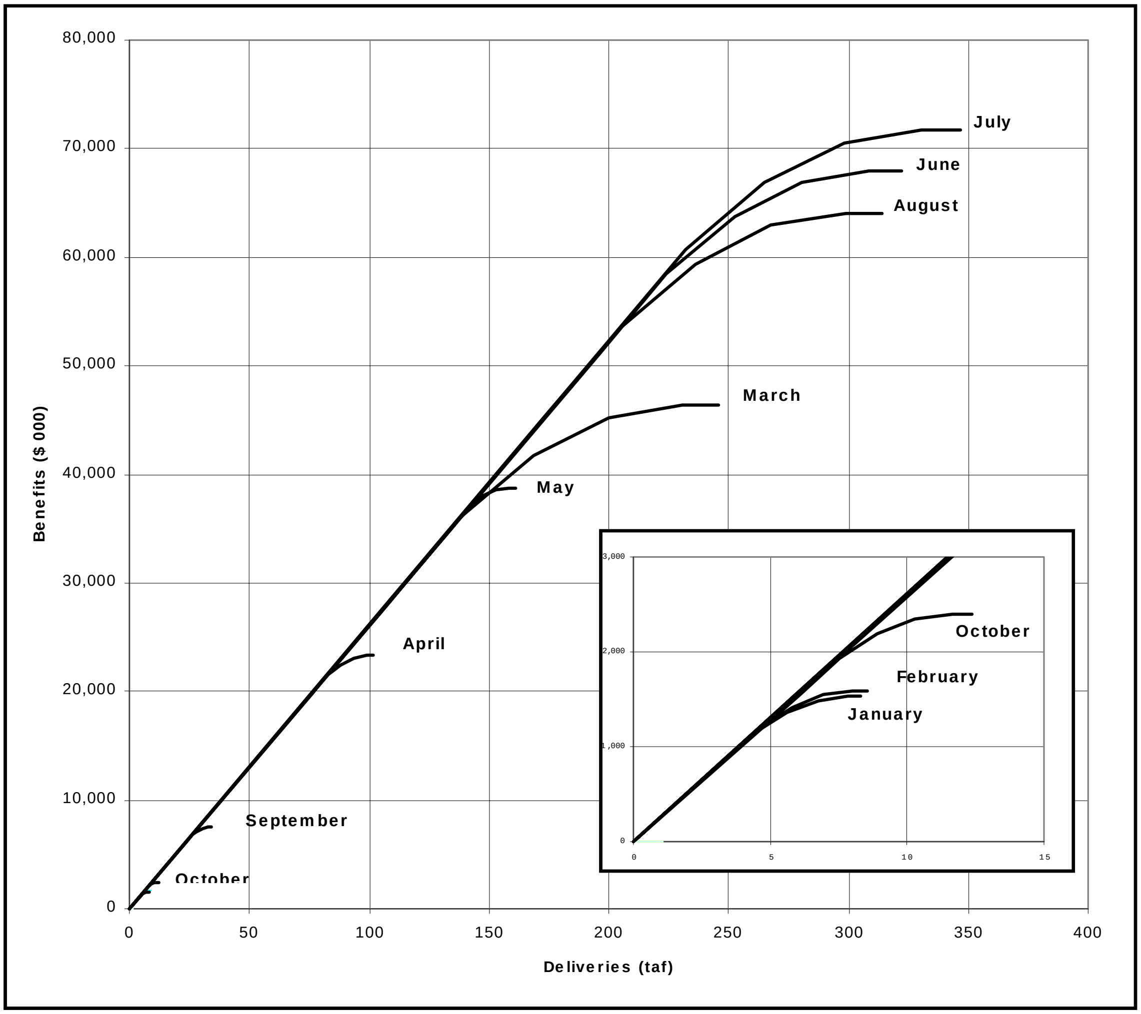
Crop Production

Crop production is modeled using a production function that varies for each region and for each crop. The wide range of agricultural inputs have been aggregated and simplified to just three: land, water and capital. The model captures the manner in which farmers adjust crop production when faced with changes in the price or availability of water. This reaction was observed during California's recent drought. Farmers can make three adjustments. The largest impact on water use is brought about by a reduction in cropped area, i.e. land fallowing. A second means of reducing water use is the adjustment of the cropping mix. Finally farmers can practice, to a limited extent, deficit irrigation.

Water Value Functions

The SWAP model is run several times for different levels of water availability. The marginal value of water is imputed from the shadow prices associated with the different water constraint levels. Typically, shadow prices for eight water availability levels are obtained for each region and for each month. Plotted against water availability they represent points on a continuous function. The integrated area under this function is the value of agricultural production as a function of water. For input to CALVIN this relationship is approximated by a piecewise linear function. These value functions vary from region to region, reflecting the diversity of California agriculture and also vary from month to month indicating the temporal variation in the value of water. A typical set of functions for input to CALVIN is shown in Figure 6-5. Since the value functions represent the net values of irrigation water, maximizing the function yields the "maximum demand" for irrigation water, in the absence of system operating costs or constraints.

Figure 6-5. Agricultural Value Functions



Urban Demand Model

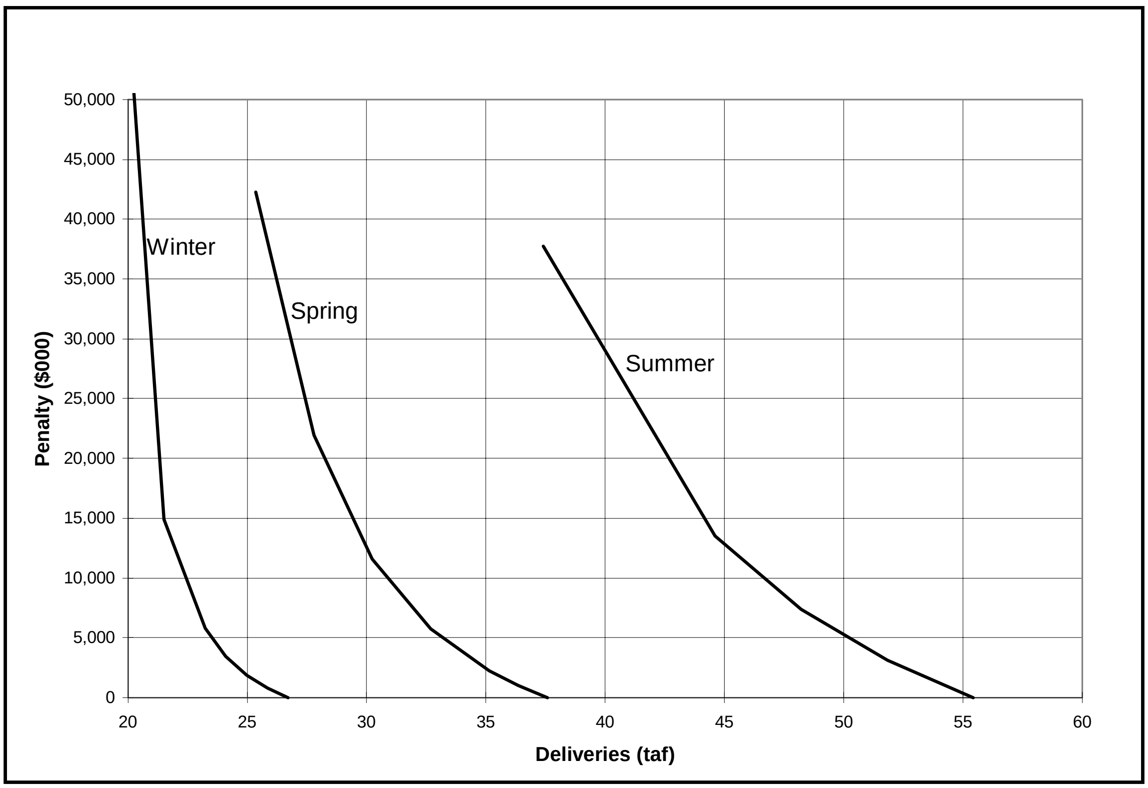
Like the agricultural regions, urban value functions will be preprocessed as input to CALVIN. As reflected in the Figure 6-2, urban regions are separated into industrial and residential demand nodes for most areas of California. Residential nodes include residential, commercial, and public (government) water use sectors. The maximum demands are based on the 2020 projected population levels and per capita use factors.

Residential water use values are based on monthly residential water demand functions derived from published price elasticities of demand, observed retail prices (in 1995 dollars), and observed residential water usage (see Appendix B). Commercial and public water usage, for which neither price elasticity estimates of demand nor other economic value data exist are treated as having zero elasticity and are added to the residential demand function. In effect, the residential demand function is shifted to the right by the target demand for commercial and public water use. This composite residential demand function is then integrated to determine the costs (lost consumer surplus) associated with delivery levels to the residential, commercial, and public sectors that are less than the maximum demand in 2020.

Industrial water use values are derived from survey data on the value of production lost in different industries in California under hypothetical shortages (CUWA 1991). Industrial value functions are derived from these production values for each month and county in the Bay and Southern Coastal areas of California for 2020 projected levels of industrial water usage.

Typical urban value functions for the residential sector are shown in Figure 6-6. Due to lack of data related to the value of water deliveries at low volumes, the figure expresses ‘value’ in terms of the cost of shortage measured relative to a target delivery.

Figure 6-6. Urban Residential Monthly Cost of Shortage



Operating Costs

Unit operating costs are attached to links to represent operation costs. Costs include only those variable costs associated with a specific operation related to water delivery: surface and ground water pumping, groundwater recharge, waste water discharge, and water quality treatment. Capital and administrative costs are excluded. These unit costs are assumed to have a constant value and are expressed in terms of a cost per unit of flow through the link. Total operational cost along a link during a time period (one-month) is equal to the unit cost times the volume of water passing the link during the month. Details are given in Appendix G.

Surface Water Pumping

Pumping costs associated with surface water conveyance are included only for the major aqueducts and canals. Pumping within local delivery systems is excluded. In all cases a fixed pumping head is assumed. Costs are calculated using a unit cost of $0.05/af per foot.

Groundwater Pumping for Agriculture

Unit costs are assigned to links that represent withdrawal from groundwater. These costs include energy costs based on typical local pumping lifts and an allowance for maintenance costs such as pump impeller wear. They do not include for capital depreciation or pump replacement. Pumping lifts represent average values for an assumed groundwater operation and do not vary dynamically in the model. Results will be post-processed to check that groundwater levels do not depart significantly from these values. The pumping lift includes an allowance for pipe friction, seasonal drawdown and local drawdown around the well. Pumping lifts are typically100 feet greater than the depth to groundwater. The assumed pumping cost is $0.20af per foot (~0.20KWh/af per foot) of pumping head. In the Central Valley the average depth to groundwater was computed from ground surface and initial groundwater elevation data contained in the CVGSM No Action Alternative (USBR, 1997). Outside of the Central Valley, depth to groundwater was assessed by review of representative wells and water resources / master reports.

Groundwater Pumping for Municipalities

Urban pumping costs are largely based upon published groundwater extraction costs for urban areas and information contained in local watermaster and planning reports. In addition to energy and O&M, operational costs include groundwater treatment (limited to chlorination).

Water Treatment

Unit water treatment costs have only been applied to differentiate the water quality of alternate water supplies.

Waste Water Discharge

By law, direct recharge of reclaimed wastewater requires additional treatment to remove nutrients and further minimize health risks. Where treated wastewater is directly recharged to an aquifer, an incremental wastewater treatment cost was assessed of $33af. The incremental cost reflects the difference between treatment of effluent for discharge to a water body (which is required at wastewater treatment plants and not included in the model) and treatment for direct recharge (Richard et al, 1992).

Artificial Recharge

Artificial recharge costs represent O&M of the spreading basins and the opportunity cost of the land affected by the works. Two values are used in CALVIN: $5/af in rural areas and $10/af within urban areas.

CONSTRAINTS

Physical, institutional, and environmental constraints all limit the way in which the system can be operated. In CALVIN all constraints must be represented as either an upper bound, lower bound or equality constraint on flow through a particular link during a particular time step. Flow constraints in cfs must be converted to average monthly values in taf. If a constraint is dependent on other parameters, such as year type, the values must be preprocessed.

Environmental Flow Requirements

CALVIN has no explicit environmental value functions. All environmental flow or storage requirements are represented as constraints. These may represent minimum instream flow requirements or fixed monthly deliveries to wildlife refuges. Where restrictions are based on water quality, such as specified salinity limits in the San Joaquin River at Vernalis, they must be interpreted in terms of monthly discharges. DWRSIM provides the basis for establishing the majority of environmental constraints within the Central Valley together with State Water Resource Control Board (SWRCB) mandates.

Physical Capacity

Physical constraints within CALVIN represent capacity constraints (flow and storage) usually modeled as an upper bound or a lower bound on reservoirs representing dead storage or a usable limit on groundwater.

Operational Constraints

Operational constraints usually dictate minimum and maximum monthly storage levels. For surface water reservoirs these reflect the upper limit on the conservation pool that varies according to the need to maintain flood storage. Recreation needs also may dictate storage levels.

Unless deliberately trying to mimic output from simulation models, CALVIN does not use target storage levels, such as minimum carry-over storage.

Institutional Constraints

Different policy constraints may be included in CALVIN depending on the scenario being analyzed. Priority in CALVIN is determined according to economic value. The value of deliveries is weighed against associated costs, e.g. pumping. However minimum or maximum deliveries may be specified to mimic contractual agreements. CALVIN's initial analysis does not include any such institutional constraints.

MODEL EXECUTION

HEC-PRM is a data driven model that requires an ASCII main input file to specify the network structure and file locations for hydrologic inflows, economic value functions, and constraints. Time-series and relational data inputs must be stored in HECDSS format. To make the model more accessible to users without specialized knowledge of HEC-PRM, several utilities have been developed using Visual Basic to create the required input file directly from the Access database.

INITIAL MODEL RUNS

To aid debugging during model development and testing, the State was divided into five regions. Initial runs were made for Region 1 only, but with appropriate boundary conditions to represent flows to Regions 2 through 5. Once the results had been inspected and appeared reasonable further regions were added working from the north to the south of the State. This staged approach eased the identification of input data errors, conceptual errors in the network representation causing infeasibilities and shorter initial run times. Table 6.5 describes the delineation of the five regions.

Currently two models are working. The first consists of Regions 1 to 4 and represents California north of the Tehachapi Mountains. The second model represents Region 5 or Southern California. A single boundary flow links these two models: the California Aqueduct.

Table 6-5. Regions used for CALVIN Development

Region	Description	Northern Boundary	Important Surface Water Sources
1	Northern Sacramento Valley	Lake Shasta, Englebright Reservoir	Sacramento R., Trinity R., Feather R., Yuba R., Bear R.
2	Southern Sacramento and the Delta	Feather-Sacramento confluence, Knights Landing Ridgecut	Sacramento R, American R, Cache Ck, Putah Ck, Cosumnes R, Mokelumne R
3	San Joaquin Valley	Banks PP, Tracy PP, Mokelumne River Aqueduct	SWP/CVP import, Stanislaus R., Tuolumne R., Merced R, Chowchilla R., Fresno R., San Joaquin R.
4	Tulare Basin	San Joaquin River, Mendota Pool	SWP/CVP import, Kings R., Kaweah R., Tule R., Kern R.
5	Southern California	Edmonston Pumping Plant	SWP import, Owens R., Colorado R.

MODEL OUTPUT AND POSTPROCESSING

Model output consists of a time-series of flows (e.g. diversions, deliveries, releases and groundwater pumping), volumes (e.g. storage and reservoir evaporation) and economic values (dual costs or shadow prices) of water at links and nodes throughout the network. This output is written to a HECDSS file. In addition, CALVIN produces a total minimized cost (‘penalty’) for each model run reflecting the integrated value of all water allocation decisions represented in the model. Interpretation of the considerable volume of results output from CALVIN is a challenging task. Postprocessing software is being developed to distill information from the considerable volume of output from each model run (see Appendix E). The design is object-oriented and can be applied to time-series and paired data from water resources system models. Its development in subsequent phases of this study could be of general value to water resources agencies and institutions in California.

The function of the post-processor is to analyze, combine, compare and display in tables and charts the different model runs. This often requires manipulating both input data (e.g. value functions for agriculture and urban water) with output data (e.g. time-series of deliveries). Results are usually displayed in the form of summary statistics and exceedance plots. These summarize the cost of water shortage and indicate the reliability of water supply to different users.

INNOVATIONS OF THE STUDY

Some of the major project innovations are listed in Table 6-6. CALVIN represents a new approach in large-scale water resources planning. The model determines water operations and allocations based on economic performance. CALVIN is the first statewide model and includes both surface and groundwater explicitly. Model results therefore provide: (a) a systematic overview of statewide water availability; (b) quantitative analysis of statewide economic impacts due to changes to the system's infrastructure and/or operation. The use of an optimization engine allows the rapid identification and preliminary evaluation of promising alternatives to the current system. This combined with the economic measures of performance gives the model several new and innovative capabilities. It is able to:

- Provide an understanding of the statewide economic value of water for agriculture and urban use
- Quantify the economic value of new storage and conveyance capacity
- Represent water marketing and water transfers
- Identify the potential for private facility investment
- Calculate the economic cost of increasing environment flow requirements

CALVIN also represents a new approach in data and model management. All input data is stored in a set of databases. Metadata is provided that describes the content, source and reliability of this data. Software tools have been developed to allow the user to quickly inspect, compare and edit all input data without accessing the databases directly. This approach ensures that data is entered in the correct format and is internally consistent. Software is also being developed to handle and store the multiple file and data sets required for multiple runs of the model.

Table 6-6. 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 primitive, 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

LIMITATIONS TO CALVIN MODEL

Along with its advantages and disadvantages, CALVIN, like all models, has limitations. Such limitations must be borne in mind when considering model results and in refining a model approach. Some limitations of CALVIN are described briefly below.

Limited Ability to Represent Water Quality

Water quality is a crucial element in urban water supply and one of the key reasons to construct an isolated facility around the Delta. Water quality is represented in CALVIN by assigning different water treatment costs to different water sources. CALVIN will allocate water to urban users by selecting the least cost water source – this may include other delivery costs in addition to water treatment (e.g. pumping costs, opportunity costs). In practice this decision process is complicated by the process of blending, where a water user may blend lower quality supplies with higher quality supplies to meet the necessary standards. Blending capability may depend on the amount of local supply, the desired use of water, and the specific constituent concentration, parameters largely simplified or ignored in CALVIN's formulation. Given the inherent relationship between water quality and quantity, CALVIN's representation of water quality remains a serious limitation.

Environmental Values Modeled as Constraints

No explicit economic value functions for environmental needs are included since few, if any, credible statewide estimations of environmental cost functions exist. While dollar values have been assigned to specific environmental benefits through contingent valuation techniques, these numbers have yet to be developed to levels of consensus comparable to agriculture and urban water demands (Colby 1990; Water Resource Update 1997).

Implicit valuation of environmental constraints can be derived from the sensitivity analysis when such constraints "bind' system operation. However these values reflect only the urban and agricultural water users' willingness-to-pay and not society's existence values.

Limitations of Input Data

One of the most common problems in modeling efforts is the availability of reliable data. While CALVIN was fortunate enough to benefit from data collection efforts of several other modeling efforts (DWRSIM, SANJASM, PROSIM, CVGSM, and several local sources), it also inherits all of the limitations of these data. The reliability of the hydrology is particularly in question. There are many difficulties in estimating surface water supplies from incomplete records and ungaged streams. The problem is compounded by changes in land use affecting runoff. There have been difficulties in disaggregating surface and groundwater supplies from water supply availability calculated using DWR's depletion analysis (see Appendix I).

Effective Precipitation for Agriculture

Precipitation, particularly in the Sacramento Valley, meets a significant proportion of agricultural demand. Rainfall during the winter and spring decreases pre-irrigation requirements or contributes directly to meeting crop evapotranspiration. Estimates of the percentage of precipitation that is 'effective' in meeting demand vary substantially. DWR's Consumptive Use model appears to be over optimistic.

Precipitation varies significantly from year to year. However, SWAP currently estimates agricultural demand for irrigation based on average precipitation values. This will result in an overestimate of the water supply in drought years. In the next phase of the project it is hoped to develop agricultural water demands that vary by year type.

Optimization and Foresight

The algorithm used to find an optimal solution to water allocations involves a systematic and efficient examination of all possible solutions. A set or matrix of equations is created that describe all possible flows in links and all possible storages at nodes for all time steps. As such the optimization model has perfect foresight and is able to adjust reservoir operation in anticipation of flood or drought.

Although an initial reaction might be to reject this approach as unrealistic, it has several advantages and implications. It should be noted that for the California system foresight beyond 5-6 years has little value as the recurrence of wet years fills reservoirs to capacity and precludes any hedging. The implications of this perfect foresight are as follows:

- Results will represent an upper bound to the potential or economic benefits of a particular system configuration and set of constraints;

- Although the model can be run consecutively for shorter time periods this poses difficulties in specifying economic values for the end-of-period storage to prevent reservoirs being drawn-down dry;

- Operating rules for new facilities based on CALVIN's prescribed operation, will include some measure of hedging for shortage events.

Previous applications of this approach have been successful despite perfect foresight, and techniques are available to handle this limitation (USACE 1994b, 1995, 1996, Israel 1996).

Network Flow Algorithm

Network flow solution algorithms offer advantages of efficiency and speed. However, the use of a network flow formulation for CALVIN limits the ability of the model to represent complex environmental operating constraints. All constraints must be represented as bounds on flow through a link. This requires approximating environmental restrictions that depend on other state variables within the system such as reservoir storage. Examples of this type of constraint are:

- 'If … the reservoir level [Oroville] will be drawn to elevation 733ft, releases for fish life … may suffer monthly deficiencies…(DWR 1986)

- Carriage water is additional water required to prevent saline intrusion into the Delta. It becomes effective as a function of the Delta pumping to Delta outflow ratio.

These types of constraints are represented by assuming a certain system operation and calculating the required environmental flows that become fixed model inputs. Model output has to be subsequently postprocessed to check that the constraints have not been violated under the prescribed model operation.

Additional simplifications are necessary to model non-linear physical constraints, such as reservoir release capacities that are a function of head.

Simplified Representation of Groundwater

Modeling groundwater aquifers as simple reservoirs ignores the effect of piezometric head on regional groundwater flow and stream flow interaction. Much of the data used in CALVIN's groundwater system is derived from a particular model run (‘no action alternative’) of CVGSM and is not determined dynamically within the model. Implicit is the assumption that groundwater will be exploited in a similar manner to the specific run. Postprocessing is required to check the validity of this assumption. When operations do vary considerably new groundwater inflows will need to be developed.

Primitive representation of urban water shortage costs

Given the heterogeneous characteristics of California urban areas, splitting water demands into residential or industrial sectors offers a crude approximation of the many different sectors that actually exist. Difficulty was found in extrapolating demand functions beyond observed price and use levels. Elasticity approaches, while conventional and feasible for application across California are very simple representations of fairly complex demand processes.

Monthly time step necessitates simplification of more complex phenomena

Several system constraints and operations criteria are based on finer time scales. For example water pumped from the Sacramento-San Joaquin Delta is constrained by real time salinity levels. Additionally, some reservoirs base their flood control rules on antecedent rainfall conditions, soil moisture conditions, and snow pack levels - all parameters absent from CALVIN.

Hydropower is not included in the initial analysis

Although a crucial part of the California water economy, time constraints prevented reservoir hydropower benefits from being included in CALVIN. Future efforts will be directed towards including hydropower.

CONCLUSIONS

Recent developments in computing, data, and data management allow water managers to practically employ more extensive, detailed, and explicitly performance-based approaches to water supply planning. These new tools allow us to explore and analyze new approaches to water management. It is fortunate that these technological and data developments have appeared at a time when the historical management of California’s, and many other large region’s, water resource systems have become ill suited or acutely controversial with present and growing societal demands for water uses.

This chapter reviews the methods and approaches used to apply large-scale databases and economic-engineering optimization to California’s water supply system. The details of the approach appear in appendices to this report. This economic-engineering optimization approach is an extension of similar exercises undertaken in recent years for river basins throughout the US.

Each of the components of this approach has achieved a reasonable degree of professional and technical consensus. While there are difficulties and limitations in implementing and integrating these components, these can be addressed and improved with time and attention. Perhaps the greatest challenges are in expanding our understanding of water management to allow development of improved water management infrastructure, policies, and operations.