CalSim: A Generalized Model for Reservoir System Analysis

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Abstract: The California State Department of Water Resources and the United States Bureau of Reclamation Mid-Pacific Region have developed a general-purpose reservoir-river basin simulation model for the planning and management of the State Water Project and the federal Central Valley Project. The California Water Resources Simulation Model (CalSim) brings a fundamental change to modeling of these systems. Model users specify system objectives as input to the model. System description and operational constraints are specified using a new water resources engineering simulation language. A mixed integer linear programming solver efficiently routes water through the system network given the user-defined priorities or weights. Simulation cycles at different temporal scales allow for successive layering of constraints. The power and flexibility of the model is demonstrated by its ability to simulate the operation of complex new environmental water accounts.

Introduction

Management models have been widely used to support water resources planning since the 1960's. Many models are descriptive in nature, simulating reservoir operations using simple mass-balance accounting. Explicit operating rules define what action is to be taken at each time-step given the state of the system. For complex systems this rule-based approach has many disadvantages. It leads to the adoption of an over-simplified and inflexible rule set. Operating rules may be inefficient at achieving their objectives, and can only be refined through repeated simulation. It is time-consuming to reformulate rules for different modeling alternatives (e.g. additional storage and conveyance facilities). Generalized models such as HEC-5 (USACE 1998) or WEAP (SEI 2001) severely restrict the form of the operating rule, while site-specific models often embed intricate operating rules in procedural code. Coding complex rules becomes a specialized task, often with loss of transparency to the end user.

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By the late 1970s network flow algorithms were widely recognized as a powerful tool for making model reservoir release and water allocation decisions. The use of single-step optimization to partially replace complex operating rules eliminates many lines of code and increases the readability of the model. Network flow solvers are fast and computationally efficient but their application to complex systems is severely restricted by the need to represent all constraints as simple lower and upper bounds. This can be partially overcome by employing iterative solution techniques such as embedded in the later versions of MODSIM (Labadie 1995). With the increase in computer processing time single-step linear programming (LP) and mixed integer linear programming (MIP) solvers are now more common (e.g. Randall et al. 1997). Prescriptive, multi-period optimization has been successfully applied to model real systems (e.g. Martin 1983). True optimization eliminates the need for strategic rules to guide long-term operations, but requires a greater simplification of the physical system (Wurbs 1993). There is a general consensus that true optimization models are better suited to screening studies or the development of the much-needed operating rules for simulation.

Natural language interfaces have been advocated as a way to make planning models more accessible. Several models use a high-level modeling language to specify complex operating objectives and constraints to overcome the limitations of the fixed operating rule form imposed by many older generalized models. RiverWare (Zagona et al. 2001) uses a “simulation and rule language”, OASIS (Sheer et al. 1999) uses Operations Control Language (OCL) and MODSIM allows the user to specify constraints using the Perl language.

This paper describes the California Water Resources Simulation Model (CalSim), a general-purpose reservoir-river basin simulation model jointly developed by the California Department of Water Resources (DWR) and the U.S. Bureau of Reclamation (Reclamation). CalSim builds on recent modeling developments. Its features include single-step optimization combined with a simulation language for specification of objectives and constraints. The model has the flexibility to implement various multi-objective programming techniques. Simulation cycles permit a successive layering of constraints. Position analysis capabilities allow the user to identify the range of possible short-term consequences of particular management decisions. The application of CalSim to model the California State Water Project (SWP) and the federal Central Valley Project (CVP) is described.

CalSim Model Description

CalSim is a data-driven simulation model that uses single time-step optimization techniques. Rather than specifying how a particular operating policy is to be implemented, the user specifies a series of objectives in the form of relative priorities for water allocation and storage. Physical capacities and specific regulatory and contractual requirements are input as linear constraints on system operation using a new water resources simulation language (WRESL). The process of routing water through the channels and storing water in reservoirs is efficiently performed by a MIP solver. For each time period the solver maximizes the objective function to determine a solution that delivers or stores water according to the specified priorities and satisfies system constraints. The sequence of solved MIP problems represents the simulation of the system over the period of analysis.

Operational objectives

Multi-purpose reservoir systems must be operated to meet competing demands. A diverse set of objectives, such as fish protection and recreational needs, can not usually be quantified in simple commensurate units as required for linear programming. Multi-objective programming methods are discussed by Cohon and Marks (1975), Can and Houck (1984) and Loganathan and Bhattacharya (1990). The traditional approach is to include only one objective in the objective function and incorporate all other objectives as constraints set at user-specified levels. In CalSim different objectives are added as weighted components of the objective function. The weights are subjective factors that indicate the users preferences. The relative magnitude of the weights may be designed to allow trade-offs between objectives or structured so that prioritized goals are met sequentially with no degradation of previously satisfied goals. CalSim also allows the user to specify objectives using a weighted goal-programming technique pioneered by Charnes and Cooper (1961).

Multiple simulations or cycles may be embedded within each time-step. The current cycle has access to the value of decision variables determined in previous cycles. This allows new priorities (or constraints) to be introduced once some of the decision variables have been fixed in a previous cycle, as in pre-emptive goal programming (Can and Houck 1984). This layering provides the ability to operate one part of the system independent of the rest of the network. For example local project operations may be determined independently to state and federal project operations.

System Constraints

The dynamic evaluation of constraint coefficients at run-time is an important feature of CalSim. Constraints may be conditional on the state of the system (e.g. minimum instream flow requirements that are dependent on water year type or on the volume of water in storage). The state of the system at the beginning of a time period is defined by state variables that are input directly to the model (e.g. reservoir inflows, target demands) and by the value of decision variables in previous time-steps or cycles. Constraint coefficients are evaluated at the start of each time-step or cycle before being transferred to the solver.

Constraints may be expressed as hard constraints that may not be violated or formulated as soft constraints with associated penalties for deviating from user-specified target values. These constraints are internally reformulated by CalSim by the introduction of auxiliary slack and surplus variables in the constraint equation and associated penalties on these variables in the objective function. Soft constraints guard against infeasibilities when other system constraints do not allow the goal to be achieved.

The MIP solver enables CalSim to represent non-linear “if-then” type constraints using binary integers such as required for modeling weir operations. Binary integers are also required for the linearization of convex functions (assuming maximization) or non-linear constraints. While binary integers have successfully been used in CalSim, their number should be limited. The MIP problem is much more difficult to solve than its LP counterpart. Experience in the application of CalSim to the CVP-SWP system has shown that they can significantly impact model run time.

Model Structure

WRESL text files that describe the system being modeled and the priorities for allocating water are generated automatically by CalSim from a set of standardized tables that are created through the model user interface. WRESL statements that express operational constraints may be written using any text editor and are grouped into files and directories using a tree-structure for organization of related constraints. Time-series data are stored using the Hydrologic Engineering Center's Data Storage System (HEC-DSS) (USACE 1995). Initial conditions and state variables such as system inflows are stored in separate DSS files. All relational data such as reservoir area-elevation-capacity data, wetness-index dependent flow standards and monthly flood control requirements are stored in simple space delimited text files called look-up tables.

At run-time the WRESL statements are converted to generated Fortran90 code by a parser-interpreter program. Execution of the compiled Fortran code starts a repetitive cycle of solving one or more optimization problems for each time-step in the period of simulation. For each cycle or time-step, data is read from the database, conditional statements evaluated and the objective function and constraints passed to the solver in the form of a row-column-coefficient matrix via a dynamic link library. CalSim uses the XA solver (Byer 2001), which returns the value of the decision variables along with any requested diagnostic information.

WRESL Language

The WRESL language is powerful enough to represent most physical systems, and operational requirements yet sufficiently simple to be readily accessible to the model user. The syntax of WRESL is based on the Java language and Structured Query Language (SQL) statements for accessing relational data. The entire language description is contained in just 13 short pages. The main elements of the language are contained in five statement types that are described below.

"Sequence" statements define the order and any conditions in which to undertake a study consisting of multiple cycles. The "model" and "include" statements define which WRESL statements are used to define the MIP problem for a particular cycle. All physical and operational constraints are specified using the "define" and "goal" statements. The define statement identifies variables as either state or decision variables. Decision variables are declared as real numbers or as binary integers. The value of state variables is established as part of the define statement. Values may be constant or retrieved from HEC-DSS or the relational lookup tables. Alternatively they may be assigned using a call to an external function. Goal statements specify study requirements in the form of linear constraints involving both decision and state variables. The value of state variables and the formulation of particular goals may be a function of a set of conditions (the state of the system) that evaluate to true or false.

Model User Interface

Input

The CalSim software incorporates a spreadsheet input tool for defining the system. A set of seven standardized text files or tables describe system connectivity, the separate system components (reservoirs, channels, deliveries, return flows and inflows) and the assigned weights. CalSim automatically generates corresponding WRESL files that can be interpreted by the WRESL parser. The generated files contain all the required variable declarations, mass balance constraints and standardized algorithms such as reservoir evaporation routines. This automation frees the user from the more tedious, routine tasks while maintaining complete transparency: the generated WRESL files may be viewed (and edited) as any other text-based WRESL file.

Output

CalSim includes a set of tools to display model results and compare results from alternate model runs. Time-series data may be viewed as charts or tables according to various user-defined formats. Mathematical functions of single or sets of time-series can be stored by CalSim and used to generate standard user-defined outputs (e.g. total system storage or total system deliveries).

Position Analysis

Delivery reliability may be determined through simulation of the system over a long hydrologic sequence. However system operators are typically concerned with a shorter time-span and the consequences of particular reservoir release and delivery decisions under a range of possible future hydrologic conditions. This type of conditional reliability can be addressed in CalSim using a position analysis (Palmer 1988), a form of Monte Carlo simulation. Under a position analysis the initial (typically current) state of the system is defined. Multiple simulations of system operation are made for a relatively short duration (typically less than two years) all starting from the same state. The input hydrology for each simulation may be based on the historical record or a synthetic sequence, but the start year for the simulation is advanced one year for each model run. Results indicate the range of impacts a set of decisions would have under all the different conditions contained in the input hydrology, and can aid project operations in the short or medium-term.

The CVP-SWP System

Model Application

The application of CalSim to the CVP-SWP system is called CalSim II to distinguish it from the underlying software. CalSim II is currently being applied to examine a diverse range of options to improve the CVP-SWP supply reliability. Its use has also been advocated to support more general state-wide planning. DWR and Reclamation have released a set of project benchmark studies to provide a common baseline for all planning investigations. The studies and accompanying documentation are available from DWR's web-site: http://modeling.water.ca.gov. A key factor in the rapid adoption of CalSim II over other existing models has been CalSim's unique ability to dynamically model operation of environmental water accounts resulting from the 1992 Central Valley Project Improvement Act (CVPIA) and the 2000 CALFED Record of Decision (ROD).

The CVP built by Reclamation and the SWP built by DWR serve the multiple objectives of flood control, water conservation, power generation, recreation, and streamflow and water quality protection. The locations of the principal project facilities are shown in Fig. 1. Both projects have major storage facilities in Northern California that store winter and spring surplus runoff to meet predominantly agricultural demand in the Sacramento Valley and to provide water for export to the San Joaquin Valley and the urban central and south coast regions of the State. Water released from project reservoirs flows to the Sacramento-San Joaquin Delta (Delta) where it is exported south by the Tracy Pumping Plant to the CVP's Delta Mendota Canal and the Banks Pumping Plant to the SWP's California Aqueduct.

Although the CVP and SWP are operated by the two separate agencies, they are physically interdependent: releases from upstream reservoirs co-mingle in the Sacramento River and Delta. The projects share some storage and conveyance facilities south of the Delta and have joint responsibility to comply with Delta standards for water quality and fish and environmental protection. The projects must also consider local water use by non-state and non-federal agencies within the Sacramento-San Joaquin drainage system as it affects the available project water supply.

Central Valley Project

The CVP is the largest surface water storage and delivery system in California, with a geographic scope covering 35 of the state's 58 counties. The project supplies water to more than 250 long-term water contractors in the Central Valley, the Santa Clara Valley and the San Francisco Bay area. Historically, approximately 90 % of the CVP water has been delivered to agricultural users, including prior water right holders. Total annual contracts exceed 11 Gm^3 (9 maf) per year. The CVP includes 20 reservoirs, with a combined storage capacity of approximately 13 Gm^3 (11 maf).

State Water Project

The SWP distributes water to 29 urban and agricultural water suppliers in Northern California, the San Francisco Bay Area, the San Joaquin Valley, the Central Coast, and Southern California. These agencies have long-term water supply contracts totaling approximately 5.1 Gm^3 (4.2 maf) annually from the SWP, of which about 5.0 Gm^3 (4.1 maf) are for contracting agencies with service areas south of the Delta. About 70 % of this contract amount is for urban users and the remaining 30 % for agricultural users. The principal storage facility for the SWP is Lake Oroville, located on the Feather River within the Sacramento Valley, with a gross storage capacity of 4.3 Gm^3 (3.5 maf). The principle conveyance component of the SWP is the California Aqueduct that extends 715 kilometers from the Delta to terminal reservoirs in Southern California.

Joint Facilities

The San Luis Reservoir is a 2.5 Gm^3 (2.0 maf) off-stream storage facility constructed south of the Delta for re-regulation of exports. The reservoir is jointly owned and operated by DWR and Reclamation. An intertie between the Delta Mendota Canal and the California Aqueduct allows the projects to make joint use of the reservoir. The 170-kilometer reach of the California Aqueduct south of San Luis Reservoir, known as the San Luis Canal, is also a joint-use facility. With its present Delta export facilities, the CVP lacks the pumping and conveyance capacity to supply all of its existing and potential contractors south of the Delta. Wheeling arrangements govern the use of any excess SWP pumping and conveyance capacity for the CVP.

Sacramento-San Joaquin Delta

The Sacramento and San Joaquin rivers meet in the Delta region and flow through Suisun Bay, San Pablo Bay and San Francisco Bay before reaching the Pacific Ocean. The Delta provides a unique environment supporting diverse plant and animal life and is an important fishery habitat. Reclaimed marshland protected by an extensive network of levees support over 500,000 acres of agriculture. The Delta has been called the hub of the State's water supply, and maintaining the health of the Delta ecosystem is essential if CVP and SWP exports are to be sustained. Native fish populations, listed under the state and federal Endangered Species Act, are affected by the projects through reduced Delta outflows and entrainment at the export pumps. Delta operations are controlled by both state and federal water quality and flow standards. Current project responsibilities for meeting standards are defined by the State Water Resources Control Board in Water Right Decision 1641 (D-1641) (SWRCB 2000).

California's Water Supply Needs

The 1987-1992 six-year drought showed that the State's existing water infrastructure and management systems are no longer sufficient to provide a reliable water supply to project contractors. The l998 California Water Plan Update (DWR 1998) estimated a statewide difference between supply and demand by the year 2020 of between 2.9 and 7.6 Gm^3 (2.4 and 6.2 million acre-feet) depending on hydrologic conditions and what actions are implemented over the next decades. Recent actions to improve California's water supply are described by Chung et al. (2002).

System Representation

CalSim II models all areas that contribute flow to the Delta. The geographical coverage includes: the Sacramento River Valley; the San Joaquin River Valley; the Sacramento-San Joaquin Delta; the Upper Trinity River; the CVP and SWP deliveries to the Tulare Basin; and the SWP deliveries to central and south coast regions. The network includes over 300 nodes and over 900 arcs, representing 24 surface reservoirs and the interconnected flow system. Fig. 2 shows a simplified system network for illustration purposes. The actual CalSim II schematic is too detailed and complex to include in this paper.

Hydrologic Input Data

Water Supplies

CalSim II simulates operation of the CVP-SWP system for a 73-year period using a monthly time-step. The model assumes that facilities, land-use, water supply contracts and regulatory requirements are constant over this period, representing a fixed level of development. The historical flow record October 1922 – September 1994, adjusted for the influence of land-use change and upstream flow regulation, is used to represent the possible range of water supply conditions. Groundwater has only limited representation in CalSim II. This resource is modeled as a series of inter-connected lumped-parameter basins. Groundwater pumping, recharge from irrigation, stream-aquifer interaction and inter-basin flow are calculated dynamically by the model.

Water Demands

Demands are pre-processed independent of CalSim II and may vary according to the specified level of development (e.g. 2001, 2020) and according to hydrologic conditions. Agricultural land-use based demands are calculated from an assumed cropping pattern and a soil moisture budget. Projected crop acreage is calculated by an economic production model using positive mathematical programming (Howitt 1995). Urban demands are typically set to contract amount but with reductions in wet years based on recent historical data. Both land-use based demands and contract entitlements serve as upper bound on deliveries. Environmental demands such as minimum reservoir storage requirements, minimum instream flows and deliveries to national wildlife refuges and wildlife management areas are as stipulated in current regulatory requirements and discretionary inter-agency agreements.

System Objectives

Month to month system objectives are specified using a mix of weights on decision variables and penalties on deviations from specified target values. The smallest (most negative) weights are associated with artificial arcs that are added to prevent solver infeasibilities. The flow in these arcs should always be zero. Large negative weights are also associated with flood storage. The largest positive weights are attached to reservoir dead storage. Balancing between reservoirs is achieved through a range of weights associated with three or more reservoir conservation zones. Weights also trigger releases from north of Delta storage for transfer to San Luis Reservoir. Environmental demands have a higher priority than water deliveries. Penalties on "surplus" Delta outflow ensure that as much water as possible is designated for use by the projects. Weights also ensure that north of Delta deliveries are met prior to those for south of Delta, and that senior water right holders have priority over project service contractors. Small "persuasion" penalties are used to influence water routing or to obtain a unique solution in cases where the model would otherwise be indifferent.

Cycles

The regulatory environment under which the projects must operate includes SWRCB water right decisions, state and federal biological opinions, U.S. Army Corps of Engineers permits and inter-agency agreements. Seven sequential cycles are required to simulate system-wide operations for each time-step for a given regulatory environment. The first five cycles simulate the San Joaquin River basin as an isolated system. The sixth cycle simulates system-wide operation. The last cycle revises operation of the California Aqueduct for wheeling of deliveries to Reclamation's Cross-Valley Canal contractors. Additional longer cycles of 12-month duration are required to model different regulatory environments. This is described in a later section. The Vernalis Adaptive Management Program (VAMP) illustrates the need for cycles. VAMP is an experimental science program to study the effect of various flow regimes in the San Joaquin River and pumping curtailment on fish populations. It specifies 31-day pulse period (April 15th – May 16th) flow targets and total Delta export reductions concurrent with the flow targets. It also provides for the collection of experimental data during that time to further the understanding of the effects of flows, exports, and Delta barriers on salmon survival. Under the San Joaquin River Agreement irrigation districts that are member to the San Joaquin River Group Authority (SJRGA) agreed to provide water to meet the VAMP target flow or 135 Mm^3 (110 taf), whichever is less. VAMP flow targets are predicated on forecasted operations under "existing" or pre-VAMP flows. In CalSim II the VAMP requirements are implemented in cycle 5 by introducing an additional layer of constraints. The VAMP requirement is computed from a lookup table based on the water year type and the pre-VAMP flows calculated in cycle 4. VAMP flows in cycle 5 are met through additional reservoir releases or imposed deficiencies on the SJRGA members.

System Constraints

The operational requirements for the CVP-SWP system are too numerous to describe in a short paper. Instead this paper focuses on the current operations in the Delta to illustrate the ability of CalSim to model complex water right permit requirements and project sharing agreements.

Delta Outflow Objectives

The Net Delta Outflow Index (NDOI) is a performance measure used to ensure protection of aquatic habitat, Delta fish populations and provision of transport flows for anadromous fish. Defined in the 1995 Water Quality Control Plan (WQCP)(SWRCB 1995), NDOI is calculated from a hydrologic mass balance of stream inflows, in-Delta net crop and vegetation consumptive use and project exports. The WQCP specifies NDOI requirements in terms of minimum average monthly flows. For the five-month period February to June the WQCP specifies additional criteria in terms of the position of the 2,000 ppm (2.64 mmhos/cm) isohaline (known as X2). X2 is an index of estuarine conditions and is used as a standard to regulate freshwater inflow to San Francisco Bay. The WQCP specifies the number of days in each month when the maximum daily average electrical conductivity (EC) at various water quality control stations must be less than or equal to 2.64 mmhos/cm. CalSim II uses the Kimmerer-Monismith equation (Kimmerer and Monismith 1992) to calculate the required outflow to maintain the EC standard as a function of the compliance location and the previous month's X2 position.

Delta Water Quality Objectives

The WQCP specifies water quality standards for M&I, agricultural and fish and wildlife objectives. These standards must be translated into flow equivalents to be modeled in CalSim II. However flow-salinity relationships in the Delta are highly non-linear and are dependent on both current and previous month flows through the various Delta channels. CalSim II uses an external module to estimate the salinity at four water quality stations within the Delta. The module consists of an Artificial Neural Network (ANN), trained using a one-dimensional hydrodynamic finite difference model of the Delta's channel system. CalSim II passes antecedent flow conditions and known (from a previous cycle in the same time-step) or estimated current month flows to an ANN dynamic link library (DLL). The DLL returns coefficients for a linear constraint that binds Sacramento River Delta inflows to Delta exports based on a piecewise linear approximation of the flow-salinity relationship.

Minimum Required Delta Outflow

The Minimum Required Delta Outflow (MRDO) as measured by the NDOI is the minimum controlling outflow considering flow, salinity and X2 standards. The MRDO is calculated in CalSim II as the monthly outflow determined from daily controlling requirements. Given the required outflow for the flow, salinity and daily X2 standards an external function determines the weighted average MRDO for the month. Salinity requirements are translated into a MRDO based on the linear constraint between Sacramento River flow and Delta exports, the assumption that exports are equal to south of Delta delivery targets plus the filling of San Luis Reservoir to target storage, and an overall mass balance for the Delta.

Delta Export Limits

The WQCP sets limits to Delta exports (E) expressed as a fraction of total Delta inflow (I). Fixed monthly values of the maximum E/I ratio vary from 0.35 to 0.65. Low E/I ratios from February through June result in high carriage water costs for transfer of project water across the Delta. Between April 15th and May 15th additional constraints are imposed on exports based on the San Joaquin River flows at Vernalis.

Coordinated Operations Agreement

The 1986 Coordinated Operations Agreement (COA) is an agreement between Reclamation and DWR to coordinate the operations of the CVP and SWP. Its purpose is to ensure each project obtains its share of water from the Delta while meeting obligations to protect other "in-basin use" within the Sacramento Basin. In-basin use covers all legal use of water in the Sacramento Basin including project storage withdrawals to meet contract demands, in-Delta consumptive use and required Delta outflow for maintaining Delta water quality and flow standards.

COA defines sharing formulas for meeting in-basin use and for the partition of excess flow. The responsibility for meeting in-basin use with storage withdrawals is shared 75% for the CVP, 25% for the SWP. The capture and/or export of excess flows are shared 55% for the CVP, 45% for the SWP. A project's share of surplus flows includes project storage increase and Delta exports.

Modeling of COA requires the use of a binary integer to indicate the existence of unstored water for export. The COA sharing formulas are used as model constraints. If total CVP and SWP exports exceed storage withdrawals, then there exists unstored water for export. Conversely if total CVP and SWP storage withdrawals are greater than the total exports, then there is in-basin-use. Often after meeting its COA obligation one of the projects (usually the CVP) can't export all its entitled water due to limited capacity. The logic in CalSim II allows the other project to take any unused portion. Negative weights are placed on each projects unused share to dissuade one project from releasing water specifically for the other project's benefit.

Explicit Model Operating Rules

Single-step optimization is too myopic for long-term decisions. Explicit model operating rules must be formulated for decisions with consequences beyond the current time-step. In CalSim II operating rules are required to determine annual water allocations, to establish reservoir carryover storage targets, and to trigger transfers from north of Delta to south of Delta storage.

CVP-SWP Delivery Logic

The CalSim II delivery logic for the CVP-SWP system attempts to mimic the actual delivery decision process used by the two agencies. It is an extension of the procedure described by Leaf and Arora (1995). Annual delivery allocations and carryover storage targets are established at the start of the contract year based on project system storage and runoff forecasts. These delivery decisions are updated monthly as water supply parameters become more certain until 1st May after which the delivery level is fixed for the remainder of the contract year. The monthly decisions represent a minimum firm delivery commitment to contractors. Carryover storage is adjusted downwards to redress any subsequent supply shortage.

The determination of annual delivery allocations is a two-step process based on water supply indices (WSIs) for the two projects and rule curves for carryover storage. The WSIs are revised each month until the final delivery commitment is made. The Demand Index (DI) represents the pool of water that is available for delivery or carryover storage and is determined from WSI vs. DI curves that are established for each project. Subsequently a “delivery versus carryover risk curve” is used to disaggregate deliveries and carryover storage from the DI pool. Generation of the WSI:DI curves has been automated in CalSim using an iterative process of successive model runs that progressively minimize the sum of the squared error between the DI and the sum of actual deliveries and carryover storage. The WSI:DI relationship captures the essence of all constraints in delivering project water, whether due to competing beneficial uses, limits of physical infrastructure, water right permit conditions or imperfect forecasts. The delivery versus carryover risk curve is input by the user and if necessary is subsequently manually adjusted to maintain minimum deliveries.

Reservoir Rule Curves

Operation of San Luis Reservoir plays an important role in the system-wide performance of both the CVP and the SWP. The ability to store water south of the Delta increases project yield through improved flexibility of project operations. The timing of water transfers through the Delta can be matched to salinity conditions in the Delta and periods of low carriage water cost, rather than dictated by south of Delta demands. Rule-curves in CalSim II, one for the SWP portion and one for the CVP portion of San Luis Reservoir, are used to trigger water transfers from north of Delta storage based on the relative weights assigned to different storage zones (decision variables) in the objective function. The rule-curves are a function of north of Delta carryover storage, permitted maximum Delta pumping and south of Delta forecasted deliveries. The filling cycle is from October to April. As a general guideline filling of San Luis Reservoir from storage withdrawals is delayed as far as possible to take advantage of surplus Delta outflow. The reservoir is drawn-down from May to September in proportion to the remaining delivery allocation to maintain operational flexibility.

Modeling of CVPIA (b)(2) and EWA

The Central Valley Project Improvement Act (CVPIA) of 1992 amended the previous authorizations of the CVP to include fish and wildlife protection, restoration, and mitigation as project purposes having equal priority with irrigation and domestic uses. The Act specifically dedicates 978 Mm^3 (800 taf) or 734 Mm^3 (600 taf) in drier years of project annual yield to fish and wildlife. This action was contained in Section 3406 (b)(2) of the law and is commonly called (b)(2). The baseline regulatory condition from which the impacts of all (b)(2) actions are to be measured is the 1978 Water Right Decision 1485 (D-1485) (SWRCB 1978). Water costs to the CVP associated with D-1641, which superseded D-1485, are attributed to (b)(2).

The Environmental Water Account (EWA) is a cooperative management program to protect the fish of the Bay-Delta estuary through environmentally beneficial changes in the operations of the CVP and SWP. The EWA was established as part of CALFED’s Programmatic Record of Decision (ROD)(CALFED 2000), which also outlined the program’s general operating principles. Under the “No Harm” principle specified in the ROD, operation of the EWA shall not change the timing, location, or amount of water delivered by the projects under the regulatory baseline. This requires the acquisition of alternative sources of project water supply, called

“EWA assets,” which will be used to augment stream and Delta flows, and to replace the regular project water supply interrupted by EWA changes to project operations. The baseline level of protection from which project deliveries are guaranteed consists of the 1995 WQCP codified in D-1641, the 1993 and 1995 Biological Opinions for winter-run Chinook salmon and Delta smelt, and implementation of (b)(2).

Modeling of the CVPIA (b)(2) and the EWA represents a significant departure from the traditional long-term planning analyses. Layering of criteria, and accounting based upon water supply with and without particular actions, necessitates an analysis of project operations under different regulatory environments. CVPIA (b)(2) accounting procedures require that the state of the system be known under D-1485 and D-1641 operations. Similarly, the project water supplies (storage and delivery) that must be maintained by the EWA are determined in part from the CVPIA (b)(2) analysis. CalSim II incorporates new procedures for dynamic modeling of CVPIA (b)(2) water and EWA. This requires running a series of CalSim II studies that individually represent different regulatory environments. The studies are linked through the use of the same starting conditions at the beginning of each water year and through the transfer of data from one study to the next. The values of decision variables determined in one study are available as state variables in the following studies. A complete EWA model run consists of five separate component studies: D1485, D1641, B2, JPOD and EWA. The Joint Point of Diversion (JPOD) refers to the ability of SWP to wheel water for the CVP through Banks Pumping Plant when unused capacity exists. Each component study is run for the same 12 month period. After all five component studies have been run, the cycle is repeated for the next water year *but* with initial conditions as determined under the EWA run. Matrices of program environmental actions are defined for both the CVPIA (b)(2) and EWA. These actions are implemented dynamically in CalSim II according to monthly accounting of program reserves or assets.

Example Study and Results

This section describes a comparative study of the water supply benefits of increasing the allowable pumping limit at the SWP’s Banks Pumping Plant in the South Delta. The results from a “with project” simulation are compared to the results of a baseline simulation to determine the incremental effects of the project. The baseline was developed jointly by DWR and Reclamation and corresponds to a 2001 level of development. Project operations conform to CVPIA (b)(2) and CALFED’s EWA operations superimposed on a D-1485 and a D-1641 regulatory environment. However assumptions related to CVPIA 3406(b)(2) and EWA are under review and are subject to refinement as these adaptive management programs continue to mature.

Banks Pumping Plant has an installed capacity of 292 m^3/s (10,300 cfs), however current (baseline) regulations limit pumping between March 15th and December 15th to 189 m^3/s (6,680 cfs) except under certain hydrologic conditions. As part of the goal to improve conveyance through the Delta, it is proposed to raise this limit to 241 m^3/s (8,500 cfs). This action would improve water supply reliability through restoring SWP’s operational flexibility that has been eroded by recent protective fishery measures and allow greater diversion during periods of high water quality. Approval for increased pumping is conditional upon avoiding adverse impacts to water supply and navigation in the South Delta. In both the baseline and 8,500 cfs alternative 14 m^3/s (500 cfs) of Banks pumping is dedicated to the EWA for the months of July through September.

The benefits of increased pumping capacity are tied to contractual conditions. SWP allocation decisions in April result in guaranteed firm (Table A) deliveries. Additional "Article 21" water may be delivered when there is surplus water in the Delta that is not otherwise required to meet Delta standards, project contractual commitments or south of Delta storage.

System Deliveries

System performance is measured in terms of the project long-term average annual yield and the project deliveries during the critically dry period May 1928 - October 1934. The Delta is a critical constraint on the export of water from the Sacramento Valley. Project deliveries are therefore classified in terms of north of Delta and south of Delta.

Model results are given in Table 1. For the base study, the average annual SWP south of Delta firm delivery is 3,703 Mm^3 long-term. The average annual SWP Article 21 water is 193 Mm^3 long-term. The average annual CVP south of Delta delivery is 3,120 Mm^3 long-term. The average annual increase in total SWP/CVP delivery under the 8,500 cfs alternative is 128 Mm^3 long-term but only 35 Mm^3 in the historical dry period. The majority of the long-term gains are due to increases in Article 21 deliveries in many of the above normal and wet years. An analysis of binding constraints from the MIP solution provides additional information. During the 1928-1934 dry period, baseline Banks pumping is constrained by the permit limit in only six of the 77 months. In contrast during the six-year wet period 1969-74, the permit limit constrains deliveries in 28 months. Figure 3 shows the nature of the controlling Delta constraints for this wet period.

Summary and Conclusions

Projected water shortages make it essential that California adopts an integrated long-term approach to water resources planning. The complexity and inter-dependence of the system requires the use of sophisticated computer modeling tools to support analysis. Over the last five years DWR and Reclamation have worked collaboratively to develop a joint model of the CVP-SWP system using the new generic water resources software CalSim.

CalSim is entirely data driven and replaces less flexible, site-specific models. Representation of the physical system and all operational constraints are input by the user using WRESL, a high-level language created specifically for CalSim. Rather than specify complex operating rules, the user attaches weights to storages, flows and other system variables to define relative priorities. Each time-step a MIP solver is used to efficiently route water through the system according to these priorities.

CalSim has successfully been applied by both DWR and Reclamation to examine both structural and non-structural changes to the CVP-SWP system. Use of a shared model with common assumptions and input data has facilitated cooperation between the planning staff of the two agencies. The flexibility of CalSim has allowed the two agencies to model complex environmental regulations and many facility alternatives without the need to change and adapt the underlying software. The use of readily readable text-based WRESL input files has allowed greater participation by engineers and stakeholders in the modeling process. Although developed for use in California, CalSim can be readily applied to other water resources systems.

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Fig. 1. General location of SWP and CVP facilities

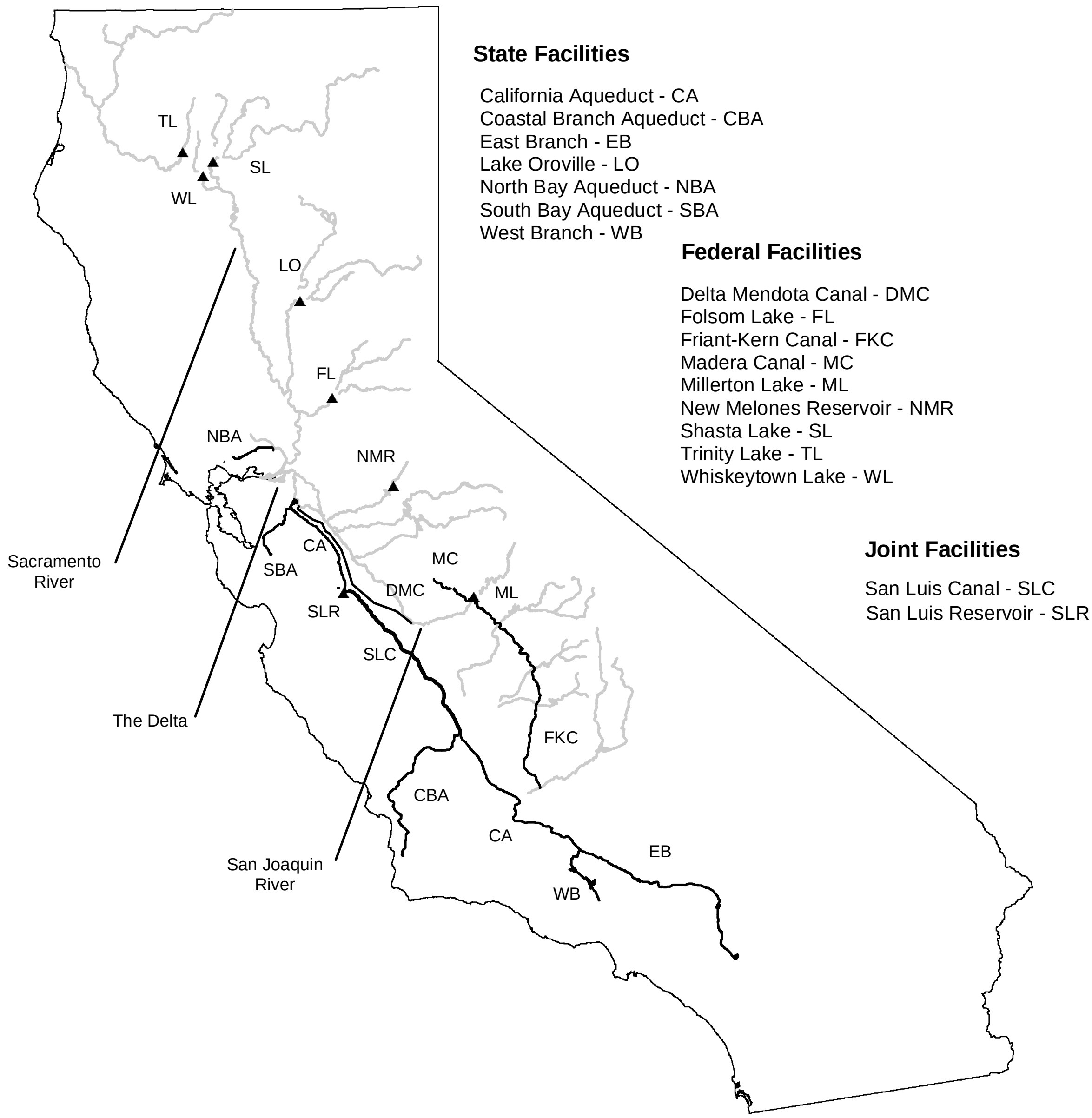

Fig. 2. Simplified schematic of CVP-SWP System
(CalSim II schematic has considerable greater detail)

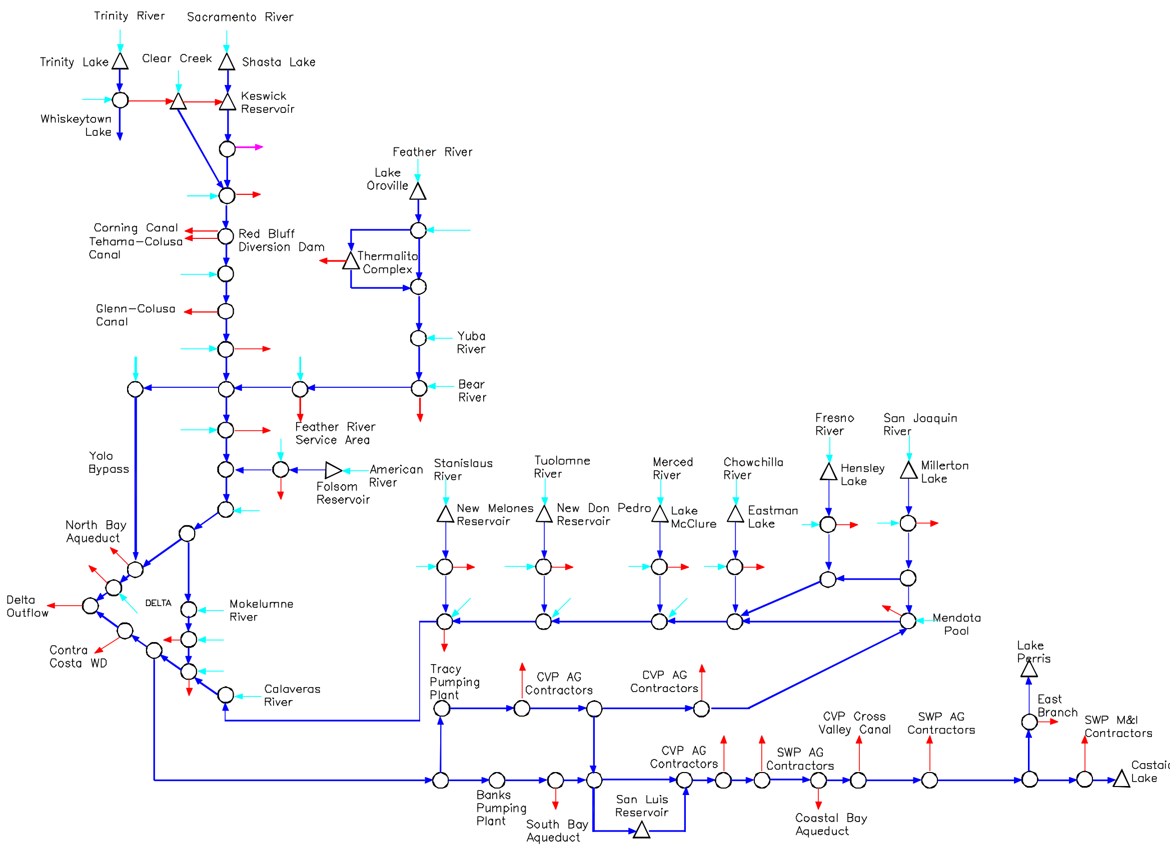

Fig. 3. Example wet period controlling constraints for SWP exports

WY	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
1969			B	B	B	SL	PP	PP	SL		B	B
1970	B	B	B	SL	SL	SL	PP	PP				B/EI
1971		B	B	B		B	PP	PP	EI	B	B	B
1972	B			B	EI	B	PP	PP				EI
1973		B	B	B	SL	SL	PP	PP				B/EI
1974	B/EI	B	B	B	SL	SL	PP	PP	EI	B	B	B

Based on D-1641 operations prior to simulation of (b)2 and EWA

EI E/I Ratio; B Banks Capacity; PP Banks Pulse Period Limit; SL SWP San Luis Full

COA In-Basin Use

Surplus Delta Outflow

Table 1. Comparison of total water supply benefits, 2001 level of development (Mm^3/yr)

	Baseline		8,500 cfs Banks		Difference	
	1928-1934 Dry Period Av.	1922-1994 73-Year Period Av.	1928-1934 Dry Period Av.	1922-1994 73-Year Period Av.	1928-1934 Dry Period Av.	1922-1994 73-Year Period Av.
North of Delta Delivery:						
SWP	1,142	1,196	1,144	1,196	2	0
CVP	2,527	2,694	2,532	2,694	5	0
Total North of Delta:	3,669	3,890	3,676	3,890	7	0
South of Delta Delivery*:						
SWP Firm**	2,244	3,703	2,280	3,726	35	23
SWP Article 21	198	193	198	262	0	68
CVP including CVC	2,055	3,120	2,055	3,157	0	37
Total South of Delta:	4,497	7,016	4,532	7,145	35	128
South of Delta Exports:						
Banks SWP	2,129	3,758	2,189	3,861	60	103
Banks CVP	61	163	68	226	7	64
Tracy CVP	1,882	2,762	1,872	2,740	-10	-22
Total CVP	1,943	2,924	1,941	2,966	-2	42
Total SWP & CVP:	4,073	6,682	4,130	6,827	57	144
Banks EWA	213	115	208	136	-5	21
Total SOD Export	4,285	6,797	4,338	6,963	53	165
Delta Outflow to S.F. Bay:						
Required	5,633	7,610	5,661	7,733	28	124
Surplus	993	9,854	938	9,575	-55	-279
Total Outflow	6,626	17,463	6,599	17,308	-27	-155

1 Mm^3 = 0.818 taf
* includes North Bay Aqueduct, ** includes SOD purchases