CALSIM

Water Resources Simulation Model

Manual

Draft Documentation

Introduction

The simulation of large, complex water resource systems for planning studies requires a flexible and efficient modeling tool to assist in the evaluation of rapidly changing alternatives. The California Department of Water Resources has developed a general-purpose water resources simulation model, CALSIM, that enables users to quickly develop system representations and specify operational criteria. CALSIM represents a fundamental change in the modeling approach used to simulate the operation of California’s water resource systems, particularly the coordinated operation of the Federal Central Valley Project (CVP) and the California State Water Project (SWP). Model users now specify the system objectives and constraints as input to the model, rather than embedding the simulation goals and logic in thousands of lines of procedural code as is common in traditional simulation models. While CALSIM is not a prescriptive optimization model, it utilizes optimization techniques to efficiently route water through a network given user-defined priority weights. A linear programming (LP)/mixed integer linear programming (MILP) solver determines an optimal set of decisions for each time period given a set of weights and system constraints.

The physical description of the system is expressed through a user-interface with tables outlining the system characteristics. The priority weights and basic constraints are also entered in the system tables. A new modeling language, Water Resources Engineering Simulation Language (WRESL), has been developed to serve as an interface between the user and the LP/MILP solver, time-series database, and relational database. Specialized operating criteria are expressed in WRESL. The WRESL expressions can be compartmentalized to provide for a highly organized arrangement of logical units and to serve as self-documenting modules. CALSIM is intended to replace the California Department of Water Resources’ existing simulation model, DWRSIM, as well as PROSIM, another simulation model of the SWP/CVP system extensively used by the U.S. Bureau of Reclamation. However, the structure of the CALSIM engine is highly generic, such that the model can be applied to many other water resource systems.

CALSIM Overview

The CALSIM model has been designed to separate the physical and operational criteria from the actual process of determining the allocations of water to competing interests. This separation of ***what*** are the goals of the system from ***how*** the problem is solved represents a fundamental change from traditional systems modeling. In traditional water systems modeling the *what* and *how* are intermingled when stepping through the formalized procedures of water allocation and often result in extremely complex code. Through the use of advanced computer science tools and a component-based structure CALSIM avoids requiring the user to specify procedures and allows for easy specification of system rules and constraints.

A graphical user interface has been developed for the defining the system configuration and basic constraints, as well as viewing the results of a simulation. The model user describes the physical system (reservoirs, channels, pumping plants, etc.), basic operational rules (flood-control diagrams, simple minimum flows, etc.), and priorities for allocating water to different uses entirely in through the user interface. A key component for specification of the specialized operational constraints is the WRESL language. The modeler describes specialized operational rules (delivery cutbacks, salinity-flow requirements, etc) entirely in WRESL statements. The statements are then assembled into WRESL files using a tree-structure for organization of related constraints. At run-time the WRESL statements are converted to generated Fortran90 code by a parser-interpreter program. The parser-interpreter has been developed by the use of the JavaCC parser generator and contains the entire WRESL language syntax. JavaCC, an advanced computer science tool based on the Java language, enables language syntax and functionality to be easily added or modified.

Once the WRESL statements have been converted to Fortran90 code, relational and time-series data are read from separate databases. CALSIM utilizes the HEC-DSS time-series data storage system developed by the U.S. Army Corps of Engineers Hydrologic Engineering Center in Davis, California. Hydrologic data spanning a 73-year period are currently stored in this database. Relational data such as index-dependent flow standards and monthly flood control diagrams are stored in simple, text-based, relational tables. WRESL statements, using SQL-type syntax, allow access to the relational and time-series data. Once the relational and time-series data are read from the databases, the entire problem is assembled into the proper format and passed to the solver. The MILP solver performs the necessary solution algorithms and returns the decision variable results to the time-series database. Diagnostic information from the solver is passed to the controlling user-interface and individual output files. The process involving the generated code, data access, and solver is repeated for each time period until the simulation is complete. The general flow of information is shown graphically in Fig. 1.

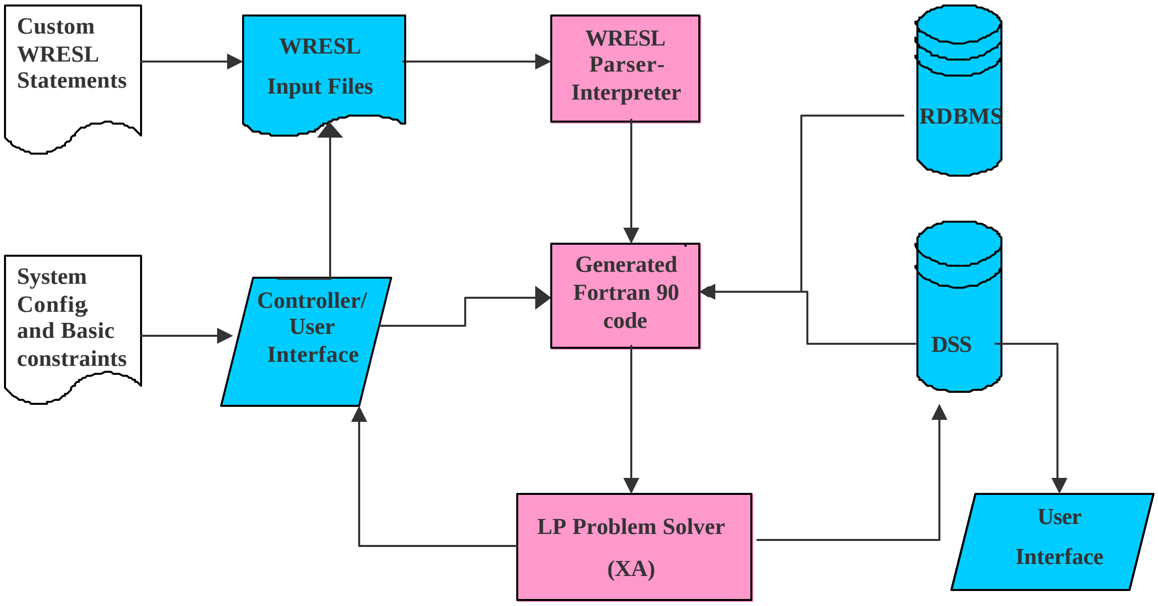

Fig. 1. CALSIM model structure and general flow of information.

The model simulation and output viewing are performed through the CALSIM user-interface. This interface is a Java-based application that allows the user to specify the files and criteria for simulation and provides access to time-series simulation results and input data. The CALSIM Study tab is used for defining the system and controlling the simulation. The CALSIM Output tab generates graphical plots, tables, and specialty reports. Mathematical operations may be performed on data records and saved for use in future studies. Several custom functions provide quick outputs of commonly used operations, such as aggregating all project deliveries and Delta exports. In addition, base and alternative studies may be compared directly from the CALSIM user-interface and statistics performed.

Model Formulation

Model Network

The CALSIM model represents water resource systems, consisting of reservoirs and channels (natural and artificial), as a network of nodes and arcs. Nodes in the network may represent reservoirs, groundwater basins, junction points of two or more flows, or simply a point of interest on a channel. Arcs represent water flows between nodes, or out of the system, and may be inflows, channel flows, return flows, or diversions. An example network is shown in Figure 2.

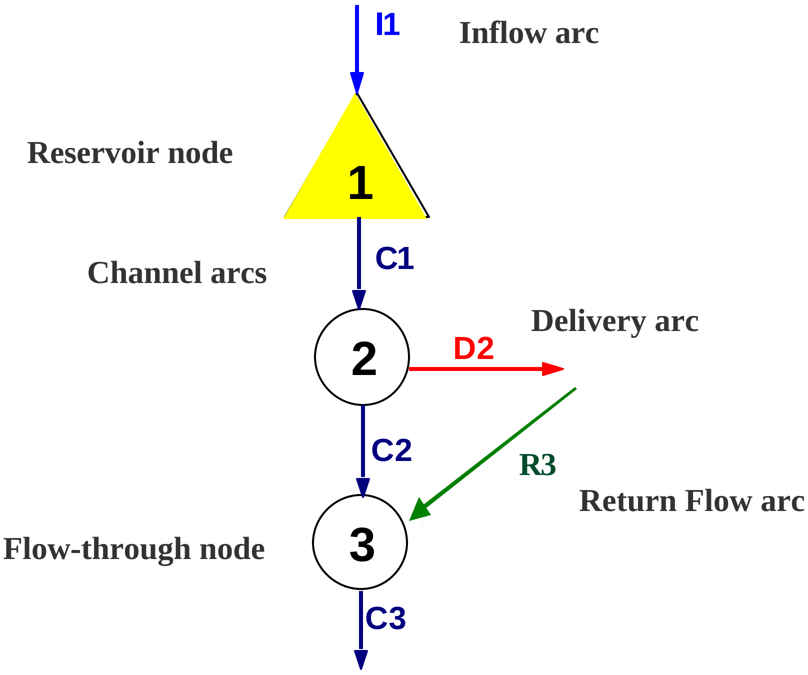

Figure 2. Example CALSIM network.

Mathematical Formulation

The mathematical formulation used in the CALSIM model consists of a linear objective function and a set of linear constraints. The objective function describes the priority in which water should be routed through the network and the constraint set describes the physical and operational limitations toward achieving the objective. CALSIM *maximizes* the objective function in each time period to obtain an optimal solution that satisfies all constraints. Priority weights assigned to variables (flow or storage) in the objective function describe the relative importance of that particular variable in the system operation.

Decision Variables

Decision variables represent the choices available to the LP model for storing water in nodes (reservoirs) or routing water through arcs. Weights on the decision variables encourage or discourage the router to allocate water to the specified variable. The decision variables used in the CALSIM linear programming model are described below.

Decision Variable	*Description*	Example
S_i	end of period storage in node i	S1
S_{ij}	end of period storage in node i, zone j	S1_2
C_i	period average flow in channel arc i	C1
C_{ij}	period average flow in channel arc i, zone j	C1_MIF, C1_EXC
D_i	period average flow in delivery arc i	D6
D_{ij}	period average flow in delivery arc i, zone j	D6_MI, D6_AG
R_i	period average flow in return flow arc i	R7
R_{ij}	period average flow in return flow arc i, zone j	R7_MI, R7_AG
E_i	period average flow in evaporation arc i	E1
F_i	period average flow in non-recoverable spill arc i	F1
A_i	end of period reservoir surface water area in node i	A1

The variables, S_i, R_i, $E_{i,}$ and A_i are not independent decision variables, but rather functions of other decision variables. S_i is the sum of all storage zones, R_i is a fraction of the delivery, and $E_{i,}$ and A_i are ultimately a function of S_i. However, because of their importance and the need to use previous values of the variables, they are included as decision variables.

State Variables

State variables in CALSIM describe the state of the system at the beginning of any time period. The term “state” is used rather loosely in this document to describe data as well as states of the system. These variables have known constant values for the upcoming period and can be thought of as the information available to planner/operator prior to any system operation. Unregulated inflows are assumed to be known for the current period and thus represent a state variable. Several state variables essential to water resources planning/simulation models and are listed below.

State Variable	**Description**	*Example*
I_i	period average unregulated flow in inflow arc i	I1
$S_i level_j$	storage in node i at level j	S1level4
$relcap_i$	maximum release capacity of reservoir i, applied at channel arc i	*relcapC1*
$C_i min$	absolute minimum flow in channel arc i	*C5min*
$C_i max$	maximum flow in channel arc i	C5max
$minflow_i$	minimum instream flow requirement for channel arc i	minflow_C4
$demand_{ij}$	demand for delivery arc i of type j	demand_D2_ag
$rfactor_i$	return flow fraction for return flow arc i resulting from a specified delivery arc	rfactor_R3
ev_i	period cummulative unit evaporation for node i	evap_S1
eff_i	recharge efficiency for a ground water node i resulting from a specified delivery arc	eff_D3
X^{t-1}	value of any decision variable X at any time prior to the current time period t	S1(-1), C5(prevOct)

Constraints

Continuity

To insure that mass balance is maintained at each node, continuity equations serve as constraints at these locations. In general, inflow minus outflow must equal change in storage.

For reservoir node i:

$$\left(\sum I + \sum D + \sum C + \sum R\right)_{in} - \left(\sum D + \sum C + \sum E + \sum F\right)_{out} = S_i^t - S_i^{t-1}$$

For flow-through nodes:

$$\left(\sum I + \sum D + \sum C + \sum R\right)_{in} - \left(\sum D + \sum C\right)_{out} = 0$$

General Water Allocation Constraints

The allocation of water to competing uses in any CALSIM system is performed according to priority weights specified by the user. It is important to recognize that

Storage Zones

Storage zones are specified for each reservoir or ground water basin representing volumes between physical and operational levels. The zones are weighted and dynamically bounded to insure proper filling of the reservoir, meeting target storage levels, and minimizing encroachment in the flood pool. In general the zones are bounded as,

$$0 \le S_{ij} \le S_i level_j - S_i level_{j-1}$$

In addition, the total storage must be the sum of the individual zones,

$$S_i = \sum_{j=1}^{nzones} S_{ij}$$

Channel Capacity Constraints

Channel constraints represent the physical maximum carrying capacity of the channel and the absolute minimum channel flow. The absolute minimum flow is usually zero, but may be negative to describe reverse flows in channel arcs.

$$C_i \min \le C_i \le C_i \max$$

Minimum Instream Flows

A minimum instream flow is formulated in CALSIM by splitting the channel arc into zones and weighting and bounding one zone to the minimum flow target. The other zone(s) are unweighted and unbounded. Arcs with a minimum instream flow are split into two zones, usually named C_i_MIF and C_i_EXC, representing the flow up to the minimum flow requirement and in excess of the requirement, respectively. In general, the minimum instream flow zone is bounded as,

$$0 \leq C_{ij} \leq \min flow_i$$

and the sum of all zones must be equal to the total arc,

$$C_i = \sum_{j=1}^{nzones} C_{ij}$$

Return Flows

Return flows are modeled as a constant or time-varying fraction of the relevant deliveries.

$$R_i = rfactor_i \cdot D_j$$

Deliveries

Deliveries from a node to a demand area, or another node, are specified by assigning a weight and bounding the arc flow. Delivery arcs can also be divided into zones reflecting deliveries to different demand types (Ag, M&I, Refuge, etc) and following the same procedure as the storage zones.

$$0 \leq D_{ij} \leq demand_{ij}$$

$$D_i = \sum_{j=1}^{ntypes} D_{ij}$$

Reservoir Release Constraint

The maximum reservoir release is determined by the hydraulic properties of the outlet works and may be expressed as a nonlinear function of storage. CALSIM obtains the maximum release by interpolating from a storage-outflow curve entering with the beginning of period reservoir storage. This value is applied as a bound to the arc representing the downstream channel.

$$C_i \leq relcap_i$$

Non-Recoverable Spills

Non-recoverable spills (F), are special cases in that they are assumed to be removed from the water supply system. This variable is necessary to avoid potential infeasible solutions during wet periods in which the flood storage is exhausted and the reservoir release exceeds the carrying capacity of the downstream channel. It may also be useful to quantify the amount of flood releases that may occur over the simulation horizon for reservoir enlargement studies. Flood releases are assumed to be lost from the water supply system and are not included in downstream continuity equations. Flow values in these F arcs other than zero should be viewed with suspicion for most systems. This decision variable is unbounded on the upper side.

$$0 \le F_i \le \infty$$

Evaporation

Reservoir surface water evaporation is computed as the period unit evaporation times the period average surface water area. This implies that the beginning and end of period surface water area, a function of reservoir storage, must be known before evaporation can be computed. While the beginning of period surface water area can be found from the reservoir storage at this time, the end of period storage is unknown. Network flow algorithms often iterate until the estimate of evaporation and the actual evaporation converge. CALSIM employs a linearization method to describe the area-storage curve for each reservoir. This method allows for an accurate and fast computation of evaporation without iteration.

$$E_i = ev_i \cdot 0.5\left[A_i(S_i^{t-1}) + A_i(S_i^t)\right]$$

where $A_i(S_i^t)$ is linearized as

$$A_i(S_i^t) \approx A_i(S_i^{t-1}) + coefEV_i(S_i^t - S_i^{t-1})$$

and

$$coefEV_i = \frac{\left[A_i((1+c)S_i^{t-1}) - A_i((1-c)S_i^{t-1})\right]}{2cS_i^{t-1}}$$

The fractional constant, c, indicates the step size for the area-storage slope approximation. It can be estimated as the average percent change in storage over a time period for a particular reservoir. A value of 5-10% works well for most reservoirs in the SWP/CVP system.

“Soft” Constraints

Some operational and institutional constraints may be best modeled as a goal minimizing the deviation between a decision variable and its’ target value (possibly also a decision variable). Balancing storage in two parallel reservoirs is a good example of this goal programming technique. Each reservoir must meet the immediate downstream demands, but there may be demands and minimum flows further downstream that could be satisfied by either reservoir. The constraint can be stated as *“Given the choice between releases from Reservoir A or from Reservoir B to meet the shared Demand C, establish releases such that the resulting storages in A and B are the same”.*

Constraints such as these are termed “soft constraints” because they may be violated when other system constraints do not allow the goal to be achieved. These constraints are internally reformulated by CALSIM by the introduction of auxiliary variables. A “hard” constraint forcing the two decision variables (S_A and S_B) equal may be,

$$S_A - S_B = 0$$

Reformulating the constraint to allow for potential violation (both positive and negative violation) would result in

$$S_A - S_B + x^- - x^+ = 0$$

Two new positive auxiliary variables have been introduced to relax the constraint. x^- is termed a slack variable because it takes up the slack between the original equation’s left-hand-side (LHS) and right-hand-side (RHS) (negative violation) and x^+ is termed a surplus variable because it contains the surplus between the LHS and the RHS (positive violation). The power of this technique lies in the ability to penalize the slack and surplus variables in the objective function, by multiplying the variables by penalty weights (negative values in a maximizing objective function), resulting in the minimization of the deviation between the LHS and RHS. CALSIM allows the user to easily specify goals of this type and the respective penalty weights through the WRESL language.

Integer Constraints

Integer constraints are those in which one or more of the decision variables must take on an integer value (0,1,2,3,…). The mixed integer problem is much more difficult to solve than an ordinary linear programming problem. For each potential integer solution, a separate LP problem is solved using the ‘branch and bound’ technique. The ‘branch’ that satisfies all other system constraints and achieves the greatest objective function value (maximization) is selected as the solution. The LP/MILP solver first finds an optimal solution with all variables considered continuous (non-integer), and then searches for integer solutions. The addition of integer variables may significantly increase solution times and should be incorporated with a degree of caution. For example, if there are n binary integers (0 or 1) the computational expense may increase by a factor as great as 2^n.

In many instances the integer value may be fixed by employing knowledge of the physical system (i.e. in summer months weir flows are zero).

A common usage of integers in the current CALSIM model is to determine which of two requirements must be met, given a condition involving current period decision variables. For example, a legal requirement may be stated as *"If the flow in Reach A is greater than 1000 cfs, then the flow in Reach B must be 25% of the amount above 1000 cfs. If the flow in Reach A is less than 1000 cfs, then the flow in Reach B must be zero."* This constraint can be written as,

$$C_A - 1000 = a - b$$

$$a < Y \cdot Max$$
$$b < (1 - Y) \cdot Max$$

$$C_B = 0.25 \cdot a$$

where a and ß are real positive decision variables and Y is a binary integer variable (0 or 1). If C_A is greater than 1000 cfs, then Y=1,a=(C_A-1000), and ß=0. If C_A is less than 1000 cfs, then Y=0, a=0, and ß=(1000 - C_A). The constant *Max* simply needs to be sufficiently large to serve as an artificial upper bound on a and ß.

Objective Function

The objective function in the CALSIM model is linear combination of decision variables and their associated priority weights. In addition, slack and surplus variables added to the objective function from "soft" constraints are multiplied by their associated negative penalties. The complete objective function is:

$$\max Z = \sum_{i=1}^{nwt} (w_i \cdot X_i) + \sum_{j=1}^{npen} (-p_j \cdot x_j^+ | x_j^-)$$

where X is a decision variable, w is a priority weight, x^- is a slack variable, x^+ is a surplus variable, and p is the penalty weight associated with the slack or surplus variable.
Language Structure

Sequential Linear Programming (SLP)

CALSIM allows the decision maker to specify multiple models to be simulated in a particular order. The modeler decides which parts of a system should be included in which models and the order in which to simulate the models. The decision variable results of each higher order model (ie. simulated prior to the current model) are accessible in the current model. This type of simulation allows the modeler to cycle through components of the system, systematically adding or removing constraints.

Lexicographic Goal Programming (LGP) (Not Currently Active)

Lexicographic goal programming (LGP) is a powerful technique for simulating a multi-objective problem with varying priorities. In the LGP technique multiple objectives are specified for the same system and each objective is assigned an integer priority. The first objective is maximized for the system as in typical LP problems. However, each lower priority objective is then maximized to the extent that it does not reduce the higher priority objective values.

Weighted Goal Programming (WGP) (Not Currently Active)

Weighted goal programming (WGP) is another technique for simulating a multi-objective problem by assigning varying weights to each objective. This technique is useful if a balance of objectives is desired. Different that the LGP procedure, WGP does not guarantee that one objective is satisfied prior to another. All objectives are solved simultaneously with user-specified weights.

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