Application of a New Tool to Optimize Hydropower Day-Ahead Scheduling and Real-Time Operations

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ABSTRACT

A team of national laboratories is developing and demonstrating a suite of advanced, integrated analytical tools to assist managers and planners in increasing hydropower resource efficiencies while enhancing environmental performance. As part of this effort, Argonne National Laboratory (Argonne) is developing the Conventional Hydropower Energy and Environmental Systems (CHEERS) model to optimize day-ahead scheduling and real-time operations. This work is funded and supported by the U.S. Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy (EERE), Water Power Program.[1]

CHEERS will aid operators in making decisions about unit commitments and turbine-level operating points using a system-wide approach to increase hydropower efficiency and the value of power generation and ancillary services. The model determines schedules and operations that are constrained by physical limitations, characteristics of plant components, operational preferences, reliability, and environmental considerations. The optimization considers head and tailwater implications, cascade interactions, turbine efficiency curves and rough zones, switch and transformer limitations, and operator preferences.

This paper addresses optimization techniques, model applications, and operational issues. During its development, CHEERS is being applied at demonstration sites such as the Glen Canyon Powerplant, the Aspinall Cascade, and the Oroville-Thermalito Complex. The optimization for each site simultaneously considers, over time, the interactions among all water and power resources, hydropower economics, ancillary services, customer loads, and complex environmental constraints. Power marketers, day-ahead schedulers, and plant operators provide system configuration and detailed input data, along with feedback on model design and performance. Model results suggest alternative operational regimes that improve the value of demonstration site resources to the grid while enhancing environmental performance and complying with water delivery obligations for non-power uses.

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1 INTRODUCTION

CHEERS is part of the larger Water Use Optimization Project, for which a team of DOE National Laboratories is developing and demonstrating a suite of advanced, integrated analytical tools that facilitate more efficient water use, improved power and ancillary services generation, and enhanced environmental performance in conventional hydropower systems. The Water Use Optimization Project is described in more detail in Gasper et al. [1]. The tool suite will be tested and demonstrated using data from hydropower sites that are representative of different operational and environmental conditions across the United States. Performance will be assessed and evaluated against baseline operational performance characteristics. Modifications and refinements will be made as required to help ensure that the tool set is practical and useful to hydropower planners and operators. The long-term goal is that the tool set will be deployed to assist hydropower planners and operators in market, schedule, dispatch, and operational decisions.

In Section 2, we describe the CHEERS model design and the methods by which the user interacts with the software to create a power system network focused on hydropower. Section 3 addresses the structure of the underlying mathematical formulation and the optimization techniques that are used to solve it. In Section 4, we describe one of the demonstration sites to which the model will be applied, the Oroville-Thermalito Complex, which is owned and operated by the California Department of Water Resources (CDWR). In Section 5, we explain the particular CHEERS network we have developed to represent the Oroville-Thermalito Complex. Sections 6 and 7 present conclusions and references, respectively.

2 CHEERS DESCRIPTION

The objective of CHEERS is to enhance the performance of both hydroelectric and environmental resources by improving day-ahead scheduling and real-time operations. These two goals are distinctly different and often conflicting. CHEERS simultaneously represents both within a framework that facilitates the simulation and optimization of an integrated network of water, hydropower, and environmental systems. Here we provide a brief description of the model. A more detailed description is given in Veselka et al. [2].

The design of CHEERS is being guided by a technical review committee consisting of hydropower operators from several sites, including the demonstration sites where the model will first be applied. However, the model will not be limited to addressing the needs and characteristics of those sites. A CHEERS user can create a network of any design by placing nodes and links on a “blank canvas.” Nodes represent individual network components (e.g., hydro reservoirs, powerplants, energy demand centers, river gauges). Links represent the connections among those components (e.g., rivers, bypass channels, transmission lines). A user also defines system granularity, including the simulation time step and time horizon. The model also contains user-defined objectives, system relationships and constraints, and several options for managing time and spatial boundary conditions. The modeling framework enables any level of granularity consistent with the application, project resources, data availability, and required simulation accuracy. The scope of CHEERS is open ended, because it is dependent on the application and user inputs rather than on the tool structure and design.

A physical resource conveyed through the network to and from nodes and along links is referred to as a commodity in CHEERS. Commodities that are currently simulated at demonstration sites include water, electricity, and money. All commodities in a CHEERS network are user-defined, and for each commodity, the user also defines one or more associated attributes. For example, the water commodity might have attributes of temperature, turbidity, and dissolved oxygen content. These user-defined commodities with associated attributes flow into, through, and out of network nodes and links. Along the various network pathways a commodity may be created, converted to a different commodity, or combined with another commodity to form a new one. In addition, attributes associated with both nodes and commodities may change over simulated time as commodities flow through the network.

Node and link types are generic, enabling a component to represent a wide range of physical objects and processes. The key advantage of this approach is its flexibility: because the approach uses generic, rather than specific, components, the user can model any physical object without depending on the developers of the model to have anticipated the need for that object. For example, CHEERS does not provide one node type that has been specifically designed to represent a hydro reservoir and another node type that has been specifically designed to represent a battery. Instead, CHEERS provides a generic "storage node," and the user supplies the details about what is being stored (e.g., water, electricity, or something else) and storage characteristics (e.g., maximum storage capacity). In addition to the storage node, CHEERS provides the following components:

1. A functional boundary node represents the entrance or exit of a commodity into or out of the modeled network, such as water flows into a hydro reservoir;

2. A conversion node represents the transformation of one commodity into another, such as a hydropower plant that converts water into electricity;

3. A junction node represents the joining together of several homogeneous commodities, such as the confluence of two rivers; and

4. A link carries the modeled commodities between nodes.

Commodity attribute properties are computed by CHEERS at various points in the system. These computations can be used simply for informational purposes, or the user can place limitations on attributes in order to constrain system operation. In general, there are two types of object constraints: (1) "generic" or rule-based limitations and (2) those that are associated with a specific point in time or "timestamp." Rule-based constraints apply to a generic definition of time, such as the day type (e.g., weekday, weekend, holiday). Timestamp limitations are for a specific point in time, such as August 16, 2012, at 06:00 a.m. Constraints can also be imposed on groups of objects.

The CHEERS timeframe is flexible and defined by the user. The model includes standard units of time, such as week, day, hour, minute, etc., as well as user-defined time periods, such as off-peak and on-peak period designations. This flexibility allows CHEERS to simulate a host of operational aspects, such as generator ramp-rate limitations; unit commitment schedules; and multi-time-period constraints, including maximum and minimum water releases from a reservoir over simulated and optimized periods. Simulated time is also critical for solving network interdependency problems because CHEERS recognizes object connectivity and the time it takes for a commodity to be conveyed between objects via a connected link. For example, CHEERS can model water travel between cascaded reservoirs. The user may also set bounds on system-level rules to guide operations based on overall system requirements. For example, the user-defined objective may be to find the operational solution that maximizes the amount of energy the system produces, creates the highest revenue stream, or results in the best possible environmental conditions for native fish in a river channel. The user can include several objectives in the model—some of which are conflicting—and weight the relative importance of each.

After the network is built and populated with data, the user specifies a simulation period and begins a simulation of the system. The simulation period may consist of several different sub-periods that are each treated differently. For example, within the *historic* sub-period, the system is constrained to match operations that have actually occurred. The historic sub-period is needed to provide the initial conditions for the model, as well as to provide information about past conditions. These conditions must be known when deciding on future operations to account for certain operating rules. The *forecast* sub-period covers the future and is the period in which the model has the most flexibility to determine system operation. In the *preschedule* sub-period, which lies between the historic and forecast periods, the model has control over system operation but not with as much flexibility as in the forecast sub-period.

When the simulation is started, the network and associated data are fed into a routine that translates the information into a mathematical formulation consisting of an objective function, a set of constraint equations, and bounds. This mathematical model is solved using software that maximizes the objective function within user-defined constraints and bounds. The solution is transferred to the model database and interface, where one or more postprocessor routines perform additional calculations and summarize output data in the form of tables and graphs.

CHEERS can be operated independently or as part of the integrated suite. All of the following tools in the suite share a common user interface, database, and network structure.

- The Hydrologic Forecasting tool provides inflow forecasts, which populate functional boundary nodes that represent water inflow points.

- The Seasonal Hydrosystems Analysis tool performs tradeoff and scenario analysis of medium- to long-term operations and guides the constraints placed on storage node reservoir water releases in CHEERS.

- The Environmental Performance tool facilitates the incorporation of ecological parameters and performance objectives into the day-ahead and real-time operation decisions made by CHEERS.

- The Unit and Plant Efficiency tool determines unit performance characteristics for the scheduling and dispatch of hydropower units.

3 CHEERS MATHEMATICAL MODEL AND SOLUTION TECHNIQUES

CHEERS is a network model that we use to describe and optimize the operation of one or more interdependent systems. In this section, we describe the approach that the model uses to mathematically formulate a problem and solve it.

Generally, an optimization problem involves finding the values of certain “decision variables” to minimize a given function, called the “objective-function,” while satisfying given inequalities on other functions called “constraint-functions.” When some of variables are allowed to assume only integer values in a solution, we call the problem “integer optimization.” It is conveniently written as

$$
\begin{aligned}
&\min_{x} f(x) \\
&\text{subject to: } g_i(x) \leq 0, i = 1, \dots, m \\
&x_i \in \mathbb{Z}, i \in I,
\end{aligned}
$$

where m, I, f, g are given. In general, the sense of the inequality of any constraint may be reversed. A constraint may also be equality. When f and $g_i, i = 1, \dots, m$ are linear functions, we call the problem a mixed-integer linear program (MILP).

MILPs belong to a class of NP-hard (non-deterministic polynomial-time hard) problems [3]; the time required to solve MILPs by any known algorithm grows, in the worst case, exponentially with the number of integer variables. However, the behavior is usually much better in practice, particularly when the branch-and-cut algorithm is used to solve MILPs. Several software products, both open-source [4, 5, 6] and proprietary [7, 8, 9], are available that implement this algorithm. These solvers have been shown to solve real-life problems with up to tens of thousands of variables and constraints.

On the other hand, if either f or any $g_i, i = 1, \dots, m$, is not linear, the problem is called a mixed-integer nonlinear program (MINLP). MINLPs, in general, are much more difficult to solve than MILPs, and the solvers available are much slower and less robust. Many difficulties arise if the nonlinear functions are not convex or have discontinuities or poor numerical stability. While there are a growing number of solvers available to solve MINLPs [10–14], they often have difficulties solving even problems with up to 100 variables and constraints.

Although the CHEERS model has, by design, wide-ranging applicability, in this paper we describe its application only to constrained water and hydropower optimization problems. Therefore, the description below is not intended to be a comprehensive mathematical treatment of all aspects of CHEERS. Instead, we focus on key model features that are applicable to the simulation and optimization of operations at the Oroville-Thermalito Complex demonstration site.

Water, hydropower, and environmental systems are inherently nonlinear and discontinuous, seriously challenging the limitations of leading optimization software packages and the computational capabilities of our most advanced computer systems. For example, the elevation of water in a reservoir changes nonlinearly as a function of water storage volume. Such changes, in turn, affect the amount of electricity that is produced by a hydropower turbine, which is a nonlinear function of both the flow rate and the hydraulic head. In addition, hydropower turbines have minimum technical production levels and rough operating zones that must be avoided to prevent equipment degradation.

While an MINLP can most accurately represent the problems modeled by CHEERS, the current state of MINLP technology limits its use to tiny models only. Therefore, we approximate the nonlinear functions by using piecewise linear functions that are combined with integer variables to provide solutions. We then use the solution obtained from the MILP to solve a nonlinear model to correct for differences between the piecewise linear approximations and the original non-linear model.

Although the CHEERS optimization model resembles a network flow optimization problem [15], there are some fundamental differences. Unlike in traditional network flow models, the commodities in the CHEERS network are transformed in the conversion nodes. Also, the network has several temporal constraints, which are more common in sequencing and scheduling problems. Considering the complex structure of the model, we use a general-purpose MILP solver to find the solution. The next sections describe the objective function and constraints in the optimization problem and the methods used to transform non-linear equations into step functions with one or more variables.

3.1 Objective Function

Our objective in applying CHEERS to the Oroville-Thermalito Complex is to optimize the economics of hydropower operations while complying with existing environmental regulations and, at the same time, honoring current water delivery obligations. Section 4 provides a more detailed explanation of Oroville-Thermalito topology and object (i.e., node and link) attributes.

Equation 3.1 shows the demonstration site objective function we used to maximize the economic value of the hydropower resource. This value includes power grid benefits associated with electricity generation from water releases through a water turbine T at plant p over all time steps t during a modeled time period. A vector of electricity market prices P is used as a surrogate for its economic value. In addition to the economic benefits of energy, we also account for revenue streams from the sale of ancillary services. For the Oroville-Thermalito Complex demonstration, this includes both up- and down-regulation services, along with spinning and non-spinning reserves. On the cost-side, we account for direct and indirect expenses associate with unit start-up and shut-down.

Eq 3.1

$$\text{maximize}\, Z = \sum_{p}\sum_{t}\sum_{T}\left(P^{t}G_{T}^{t} + S_{uT}^{t}V_{u}^{t} + S_{lT}^{t}V_{lT}^{t} + A_{sT}^{t}D_{sT}^{t} + A_{nT}^{t}D_{nT}^{t} - W_{uT}^{t}C_{uT}^{t} - W_{lT}^{t}C_{lT}^{t}\right),$$

where

Z = net economic value of Complex operations over the optimization period,
G_T^t = power generated at turbine T at time t,
P^t = market price per unit of energy at time t,
S_{uT}^t and S_{lT}^t = market value of regulation up and down services, respectively,
V_u^t and V_{lT}^t = level of regulation services (decision variables),
A_{sT}^t and A_{nT}^t = market value of spinning and non-spinning reserves, respectively,
D_{sT}^t and D_{nT}^t = level of reserves provided (decision variables),
W_{uT}^t and W_{lT}^t = turbine startup and shutdown cost, respectively, and
C_{lT}^t and C_{uT}^t = whether a unit is turned on or off, respectively (integer variables).

The maximization objective is subject to a set of constraints that restrict the operation of power production and reservoirs in a cascade by the following means:

1. A “balance” is maintained at every node in the network;

2. Total water release volume from each storage node over the optimized time period must be within minimum and maximum levels;

3. Reservoir elevation (and thus, operational volumes) must be limited to a specified range; and

4. Base unit time changes in water flows (hourly for this application) through hydropower turbines and from reservoirs must be limited to a specified range.

Two functions, formulated as constraints, are used to model the physical characteristics of reservoirs and hydropower production:

1. Reservoir water elevation as a function of volume; and

2. Unit-level power generation as a function of head and turbine flow rate.

These constraints are described in detail in the following sections.

3.2 Upper and Lower Bounds

Many of the variables in the model are not allowed to attain values above upper bounds or below lower bounds. These restrictions may arise out of physical constraints, engineering limits, or regulations. An example of a physical constraint is the flow rate in a link, which cannot be less than zero. In the CHEERS model, a user may specify lower and upper bounds for any variable. Mathematically, the constraints take the following form:

$$L \le x \le U,$$

where L and U are the bounds on variable x. If a variable must be forced to a fixed number, the values of both bounds are made equal.

3.3 Balance Constraints

We ensure that the quantity of a commodity, in this case water or electricity, entering each junction node equals the quantity leaving it in each time period. It is mathematically modeled as the following constraint:

Eq 3.2

$$\sum_{i:(i,n)\in L} Q_{in}^{t} - \sum_{j:(n,j)\in L} Q_{nj}^{t} = 0, \qquad \text{for all time periods } t, \text{for all junction nodes } n,$$

where Q_{in}^{t} refers to the flow variable in link (i, n), at time t. The constraint for a boundary node is only slightly different:

Eq 3.3

$$\sum_{i:(n,j)\in L} Q_{nj}^{t} - \sum_{j:(i,n)\in L} Q_{in}^{t} = B_{n}^{t}, \qquad \text{for all time periods } t, \qquad \text{for all boundary nodes } n,$$

where B_{n}^{t} is an input parameter denoting quantity entering the network from the boundary node n at time t. At storage node, we also need to take into account the quantity in storage that is carried over from the previous time period:

Eq 3.4

$$\sum_{i:(i,n)\in L} Q_{in}^{t} - \sum_{j:(n,j)\in L} Q_{nj}^{t} + S_{n}^{t-1} - S_{n}^{t} = 0, \; \text{for all time periods } t, \; \text{for all storage nodes } n,$$

where S_{n}^{t} is the variable denoting the quantity stored in storage node n at the end of time t.

3.4 Ramping Constraints

The release of water through turbines is not allowed to change beyond a specified limit. This constraint is modeled using the following equation:

Eq 3.5

$$-R_{TL} \leq Q_{T}^{t} - Q_{T}^{t-1} \leq R_{TU}, \qquad \text{for all time periods } t, \qquad \text{for all turbines T},$$

where R_{TL}, R_{TU} are parameters denoting maximum ramp-up and ramp-down limits for turbine T, and Q_{T}^{t} is a variable denoting the quantity of water released through turbine T at time t. Similar ramping constraints are added for restrictions on the total water released from a reservoir and for changes in water flows in river channels.

3.5 Piecewise Linearization of Water Elevation in Reservoirs

The elevation of water in a given reservoir at a given time is a nonlinear function of the volume of water the reservoir holds. This elevation varies according to the topology of the reservoir. Typically, it will increase relatively quickly as a function of water-storage volume when the reservoir is empty (e.g. forebay elevation is at a low point) but slowly increase in elevation when storage is nearly full (forebay elevation near the top of the crest elevation). Figure 3.1 shows an example of this relationship. In order to obtain a piecewise linear approximation of the function, we need to identify the breakpoints where the pieces will meet and the slope for each piece. We also need to solve for function's y-axis intercept. The number of pieces to be used is either specified by the user or a default preset value. We determine the slopes and intercept that give the minimum sum-of-square error. In general, the sum-of-square error for piece-j is given by the following equation:

Eq 3.6

$$e_j = \sum_{i=1}^{k} \left(a_j x_{ij} - b_j - \hat{y}_{ij}\right)^2,$$

where x_{ij} is the volume associated with the point i lying in piece j, and $y_{ij}$is the observed height. If the breakpoints are fixed, then a_j, b_j are obtained by solving a convex unconstrained problem. The best breakpoints may be obtained by iterating this procedure over several different possible locations.

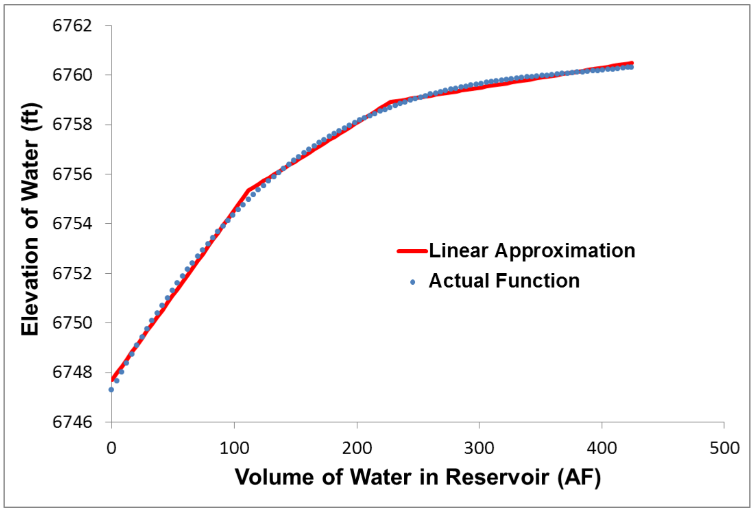


Figure 3.1 Relationship between Reservoir Volume and Elevation

For the CHEERS Oroville-Thermalito Complex application, we find that only a small portion of a reservoir's volume-elevation curve is needed for day-ahead and real-time optimization. Therefore, we describe only that portion of the curve that is applicable for a simulation period in terms of a piecewise linear curve. This approach allows us to significantly reduce the error between the piecewise relationship and the non-linear function. We can also accurately describe this relatively small "top layer" of reservoir storage with few line segments, thereby increasing computational efficiency. For Lake Oroville, which has a very large storage volume with little elevation change over the course of a day, we find that it is sufficient to describe elevation changes using a single line. The slope of this line is the first derivative of the volume-elevation function, which is in the form of a polynomial equation. The derivative is computed for the point on the curve that represents the average anticipated next-day reservoir elevation.

Once an appropriate piecewise linear function has been obtained, we use Specially-Ordered-Set of type 2 (SOS-2) constraints to represent it in the model. SOS-2 constraints are a compact and computationally more efficient representation of piecewise linear functions. Such representation ensures that the MILP solver recognizes the piecewise-linear structure, which may be lost otherwise. This representation also enables the solver to use techniques specially designed for these structures [16].

3.6 Piecewise Linearization of Power Generated from Turbines

The power generated from a turbine is a nonlinear function of two variables: head and flow rate. We cannot use the SOS-2 representation directly here because the power function is bivariate. An SOS representation in higher dimensions [17] has been proposed to solve for functions of this type, but it is not recognized by most solvers and modeling languages. Model users would need to implement customized routines specific to the optimization solver in order to use SOS extensions, an approach that is impractical for a general framework like CHEERS. We instead use a two-step method to create a linear approximation of the function. This approach keeps the framework independent of the optimization solver used, while preserving the accuracy of the formulation. Figure 3.2 provides a plot of the power conversion factor as a function of the head and the flow rate through a turbine. The plot in Figure 3.3 shows the variation in this factor as flow rate changes at a fixed head of 300 ft. Figure 3.4 shows the variation with the head when flow rate is fixed at 100 cubic-feet per second (cfs). Figures 3.3 and 3.4 are slices of the three-dimensional plot of Figure 3.2.

In the first step, we fix the head to a certain base reference. This value is typically based on the anticipated average value of the head during the simulated time period. Using the approach described above, we obtain a piecewise-linear representation of the power function for the fixed head. In the second step, keeping the slopes of the pieces (i.e., water-to-power conversion factors) constant, we determine the best flow-rate break-points for a slightly different head value. The difference in the interval lengths associated with the base value and the new value gives us the factor by which we should increase or decrease the intervals with change in head.

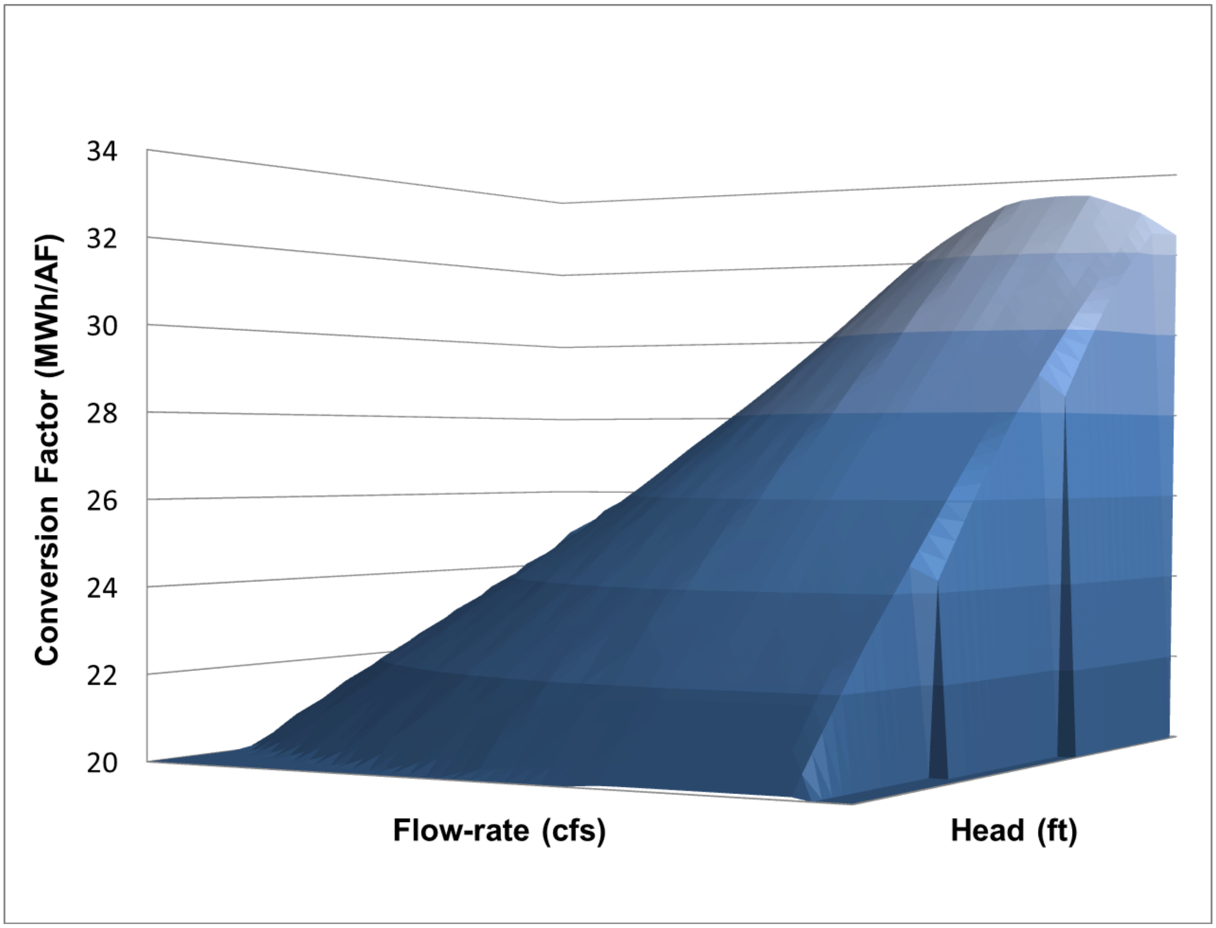
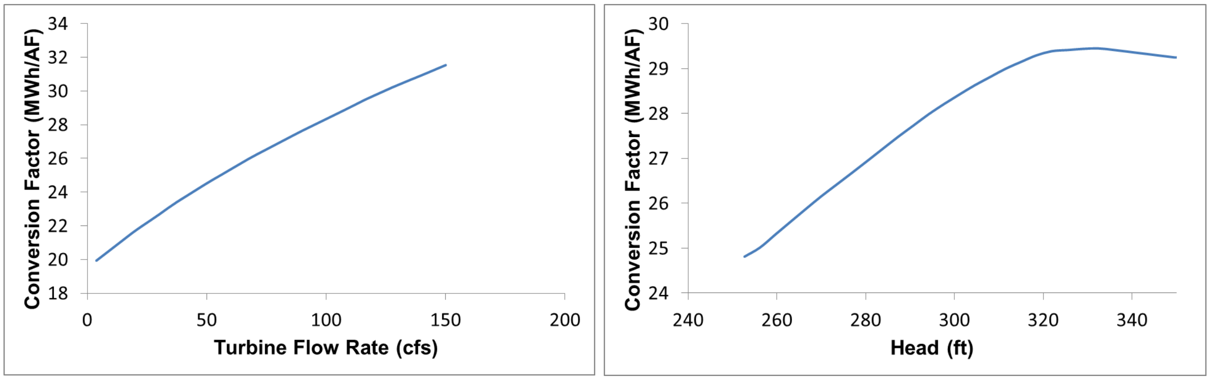


Figure 3.2 Power Conversion Factor as a Function of the Head and the Flow Rate through a Turbine



Figures 3.3 and 3.4 Variation of Power Conversion Factor with a Fixed Head (3.3) and Fixed Flow Rate (3.4)

Although we discuss the use of step functions to represent reservoir elevations and power production, it should be noted that CHEERS allows the user to use piecewise linear relationships to represent a commodity attribute for any network object. For example, at model demonstration sites, we represent the draft tubes for the maximum water flow rate as a step function that relates maximum flow to head.

3.7 On/Off Constraints

Certain constraints require discrete choices. For instance, there is a cost associated with starting a turbine, but the cost is incurred only if the turbine was off in the previous time period and on in this period. This cost and other such discrete phenomena are modeled using binary variables. A binary variable is one that is required to be either 1 or 0 in a feasible solution. To model the turbine startup cost, we use the binary variable S_T^t, which is assigned 1 if the turbine T is starting up in time period t. The startup cost is represented by the following:

Eq 3.7

$$C = \sum_t \sum_T C_T S_T^t,$$

where $C_T$is the cost of starting up turbine T. We use binary variable O_T^t to denote if the turbine T is on at time t. Then variables S_T^t and O_T^t are related by the following constraints:

$$O_T^t \geq S_T^t, \text{ and} \qquad \text{Eq 3.8}$$

$$S_T^t \geq O_T^t - O_T^{t-1}. \qquad \text{Eq. 3.9}$$

The first constraint ensures that O_T^t is 1 whenever S_T^t is 1. The second constraint ensures that S_T^t is 1 whenever O_T^t is 1 and O_T^{t-1} is 0. More binary variables are similarly used to model other constraints, like those related to rough zones of the turbine frequency that must be avoided when it is generating electricity. We also use binary variables to model piecewise linear functions like those described in Sections 3.5 and 3.6.

3.8 Travel Time Distribution Functions

When some quantity of water is released from a node, the entire quantity does not flow at the same speed. If the geographic distances among nodes in a network are significant, as they are in river channels below the Oroville-Thermalito Complex, a fraction of water entering a river reach will arrive at a downstream point more quickly or more slowly than the rest of the water. In general, the quantity of water reaching the downstream point follows a continuous distribution. The shape of this distribution usually resembles the shape of a normal distribution, but it may vary according to the characteristics of the river channel, travel distance, and the volume of flow. These functions are not limited to water flowing through a channel; they may also be applied to other commodities.

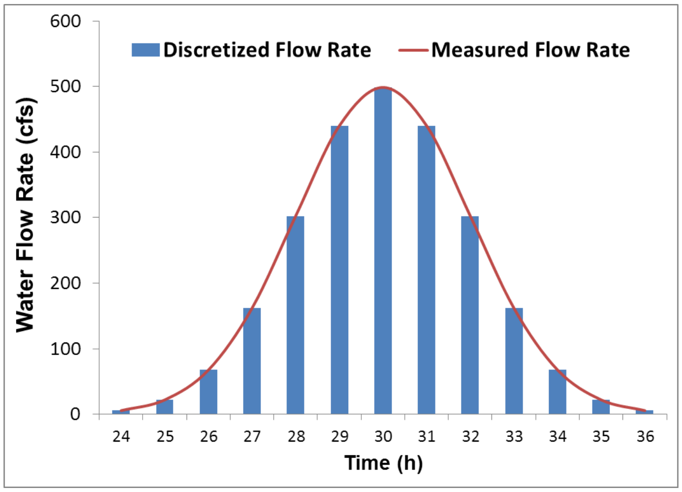


Figure 3.5 Water Travel Time Distribution Function

If quantity Q_i^t of water is released from node i at time t, the time to reach downstream node j may follow a continuous distribution, as shown by the hypothetical smooth curve in Figure 3.5. We discretize this curve per base time-unit (hourly, in this case) so that the quantity of water is conserved, and the discrete function closely resembles the measured flow rate. Mathematically, the quantity of commodity flowing from node i measured at node j at time t is given by the following equation:

Eq. 3.10

$$Q_{ij}^t = \sum_{\tau=1}^{K_{ij}} Q_i^{t-\tau} f_{ij}^{\tau},$$

where f_{ij}^{τ} is a parameter obtained from discretizing the time-travel distribution function, and K_{ij} is the number of time periods within which the discharge from node i affects distribution at node j.

Where applicable, we also use a loss factor to account for commodity loss that may occur between the entry and exit points on a link. For example, some water in a river channel may evaporate as it travels downstream.

3.9 Solving the Mathematical Model

The CHEERS framework generates the MILP model in the AMPL (a mathematical programming language) format [18]. The AMPL modeling language allows model developers to write optimization problems in a format similar to the mathematical notation needed to express them. Several solvers — including CBC, SCIP, CPLEX, and GUROBI — are capable of solving

AMPL models. This approach thus provides flexibility in selecting a solver and avoiding solver "lock-in."

Branch-and-cut is the most popular algorithm for solving MILPs, and it is implemented by all of the solvers mentioned above. The method is a combination of two algorithms: the branch-and-bound and cutting-plane algorithms. In both, a linear programming (LP) relaxation obtained by ignoring the integrality restrictions on variables is first solved. If the relaxation is infeasible, then so is the MILP. If the solution of LP relaxation satisfies the integrality restrictions, then it is the optimal solution of the MILP. Otherwise, the two algorithms use different approaches to proceed, as follows. In branch-and-bound, we divide the feasible region into two or more smaller regions and solve their LP relaxations. If the solution value is worse than the incumbent, the problem is discarded. Otherwise, the solvers check for integrality or proceed with more branching. Thus, a solver needs to solve many progressively smaller LP relaxations. In a cutting-plane algorithm, instead of branching, a solver adds a new inequality that cuts off the current LP solution. The new LP, with additional constraints, is solved again, and the process is continued until a solution is found or the LP relaxation becomes infeasible.

Different solvers combine the branch-and-bound and cutting-plane algorithms to achieve the maximum efficiency in solving real-life problems. In addition, they use several primal heuristics to find good, feasible solutions quickly. Other advanced techniques like preprocessing, exploiting symmetry, and search-restarts are used to enhance the solution speed. These solvers can also accept a starting solution, which may help them find the optimal solution more quickly.

3.10 Application of Non-linear Functions and Relationships

As described above, MILP results are largely based on a linearization of the problem. Therefore, CHEERS employs a post-processor routine that uses key MILP results and recomputes values based on either a set of non-linear equations or look-tables containing raw data. These data tables describe non-linear aspects of system operations. Currently, this routine recalculates reservoir elevation (both forebay and afterbay water levels where applicable), tailwater/tailrace elevation, head, power generation, and the economic value of energy production. As the model evolves, other values may be added to this list of recomputed variables as CHEERS demonstrations progress, and additional model requirements are identified. We store results from both the MILP formulation and the post-processor. When significant differences arise, it is an indication that the MILP representation and formulation of the problem need to be revised. Future plans include further developing the post-processor routine to search for better solutions that are in the "vicinity" of the one solved for by the MILP model.

4 OROVILLE-THERMALITO COMPLEX DEMONSTRATION SITE

The CHEERS model is currently being demonstrated at the Oroville-Thermalito Complex. This complex is an efficient water storage and delivery system and electricity producer. As shown in Figure 4.1, the complex is located in northern California. It is part of the California State Water Project (SWP), the largest state-built water system and electric power project in the United States. This project includes pumping-generating powerplants; reservoirs, lakes, and storage tanks; and canals, tunnels, and pipelines that capture, store, and convey water to 29 water agencies. The Oroville-Thermalito Complex is owned and operated by the CDWR [19, 20].

As depicted in Figure 4.2, the Oroville-Thermalito Complex comprises Lake Oroville and the Oroville Dam, Hyatt Pumping-Generating Powerplant (PGP), Thermalito Diversion Dam (TDD) and Powerplant, Feather River Fish Hatchery, Thermalito Power Canal, Thermalito Forebay, Thermalito PGP, Thermalito Afterbay, and the Lake Oroville Visitors Center. Lake Oroville is the SWP's largest reservoir. The Oroville-Thermalito Complex stores about 3.5 million AF of water and generates power from water releases through three generating powerplants [21].

Figure 4.1 Location of the Oroville-Thermalito Complex in California

Lake Oroville is located in the foothills on the western slope of the Sierra Nevada, 1 mile downstream of the junction of the Feather River's major tributaries. Rain and snow melt drains from the surrounding mountainsides into waterways that lead into Lake Oroville. Work on the dam site began in 1961, and the reservoir was filled to capacity in 1967. The reservoir has a maximum operating storage of 3,537,580 AF of water at an elevation of 900 ft above sea level. At this elevation, the surface area of the lake is 15,810 acres, and the shoreline extends 167 miles. The lake stores water and releases it into the Feather River to meet SWP needs. The lake also provides pumped-storage capacity, 750,000 AF of flood control storage, recreation, and freshwater releases to control salinity intrusion in the Sacramento-San Joaquin Delta and for fish and wildlife protection [22].

Oroville Dam is a zoned, earth-filled structure comprising 80 million cubic-yards of material that contains Lake Oroville. At a height of 770 feet, it is the tallest dam in the United States. The dam's crest elevation is 922 ft above sea level. It has a crest length of 6,920 ft and a crest width of 50.6 ft. In 1967, the California Society of Professional Engineers named the Oroville Dam one of the seven engineering wonders in California.

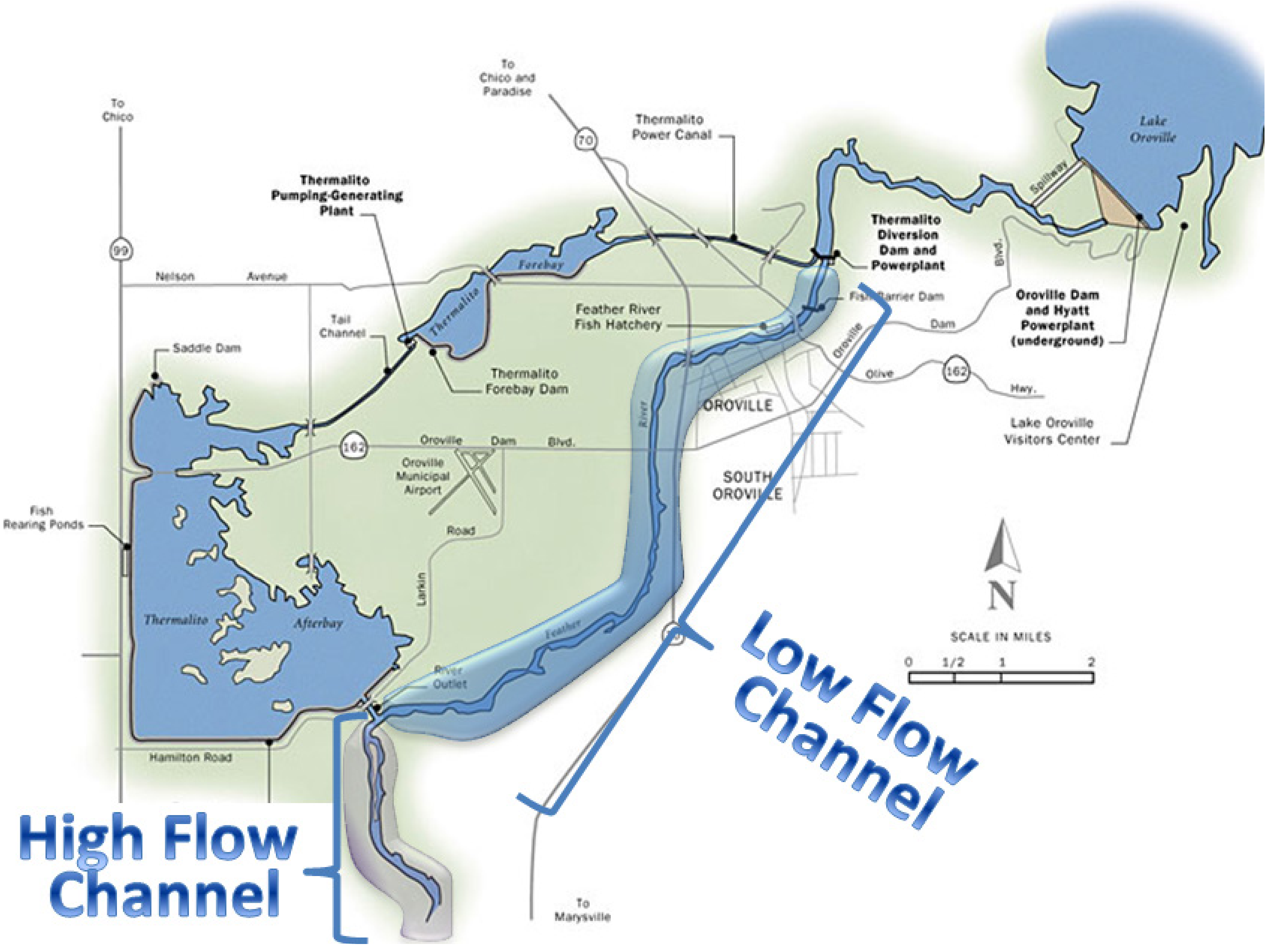


Figure 4.2 Map of the Oroville-Thermalito Complex [23]

Water is released from Lake Oroville through the Hyatt PGP, river outlets, the Palermo Canal Outlet Works, spillway, and the emergency spillway. Turbine water flows for power generation are controlled by wicket gates and can also be stopped by spherical turbine shutoff valves. Water releases through the dam's two river outlet tubes, which bypass the turbines, are controlled by fixed-dispersion cone valves. Water is also released through the Palermo Canal Outlet Works to serve local water needs. Lastly, emergency spillway water releases are controlled by eight radial gates. A sophisticated water intake structure for turbine water releases allows reservoir water to be withdrawn at different reservoir depths to regulate downstream water temperatures in the Feather River.

4.1 Hyatt PGP

The Edward Hyatt PGP is an underground, hydroelectric, pumping-generating facility. Construction of the plant began in 1964 and was completed in 1967. The Hyatt PGP is the largest powerplant in the Oroville-Thermalito Complex, with a total installed generating capacity of 819 mVA [23] and a pumping capacity of 387 MW. The PGP is operated to maximize the value of the hydropower resources. Pumped-storage operation is one example: water, released for power in excess of local and downstream requirements, is returned to storage in Lake Oroville during off-peak periods and is used for generation during peak power demands.

Located in the bedrock cavern under Lake Oroville, the powerplant facilities include an intake structure, two penstock tunnels, six penstock branch lines, three turbine units, three reversible pump-turbine units, two tailrace tunnels and outlet works, and a switchyard. Water from the lake is conveyed to the units through two penstocks, each with a diameter of 22 ft.

Three of the six generating units are motor-generators coupled to Francis-type, reversible pump turbines that permit the off-peak pumped-storage operations at the Oroville-Thermalito Complex. In generation mode, each vertical Francis turbine can accommodate a water flow rate up to 2,800 cfs, producing 115 MW. After passing through the turbines, water is discharged into the Feather River via draft tubes to two tailrace tunnels: one free-surface and the other full-flow. Using a maximum of 173,000 horsepower (hp), each of the three units can pump water at a rate up to 1,870 cfs at a rated head of 592 ft.

The three other units at Hyatt PGP are conventional generators driven by vertical-shaft, Francis-type turbines. Each generating unit has a maximum output of 173,000 hp. Water releases for power at each unit are up to 2,850 cfs, discharged into the Feather River via the draft tubes and tailrace tunnels described above. Each unit has a generating capability of about 123 MW [24].

4.2 TDD and Powerplant

The TDD is located on the Feather River, about 4.5 miles downstream from the Oroville Dam. Construction of the 143-ft-high, concrete, gravity diversion dam began in 1963 and was completed in 1968. The dam comprises 154,000 cubic yards of material and has a crest length of 1,300 ft. The crest elevation is 233 ft above sea level. Releases from both the Hyatt PGP and the Kelly Ridge Powerplant drain into a pool contained by the TDD. This tailwater pool serves as a lower reservoir for Hyatt PGP pumping needs. At an elevation of 225 ft above sea level, the pool reaches its maximum water operating storage of 13,350 AF with a water surface area of 320 acres and a shoreline that extends for 10 miles.

The Kelly Ridge Powerplant is a run-of-river hydropower resource that is owned and operated by the Oroville-Wyandotte Irrigation District. It sends water from the Miners Ranch Reservoir into the Kelly Ridge Tunnel, which leads to the powerplant penstock. The powerplant has a generating capacity of 10 MW and produces an average of 3.8 gigawatt hours (GWh) of electricity monthly [25]. For day-ahead and real-time operations, water discharges into the pool can be projected with a high level of certainty.

The TDD serves three purposes: (1) to divert water into the Thermalito Power Canal for power generation at the Thermalito PGP; (2) to create a tailwater pool called the Thermalito Diversion Pool for the Hyatt PGP; and (3) to provide headwater for the TDD Powerplant.

The Thermalito Power Canal, a bidirectional flow canal, links the Thermalito Diversion Pool to the Thermalito Forebay. The canal is designed to convey a maximum of 16,900 cfs of generating flow and 9,000 cfs of pumping flow.

The Diversion Pool serves as a forebay when the Hyatt PGP is in pumping mode. With a maximum elevation of 225 ft, the pool stores a maximum of 13,350 AF with a water surface area of 320 acres and a shoreline that extends 10 miles. The pool elevation impacts the height that water is pumped up from the lower reservoir to the upper reservoir (i.e., Lake Oroville). All other factors held constant, the higher the Thermalito Diversion Pool, the lower the amount of electrical energy that is required to pump water into the lake. On the other hand, the diversion pool elevation typically has no impact on power generation.

Water releases from the diversion dam into the Feather River maintain fish habitat between the diversion dam and Thermalito Afterbay Outlet The majority of the river water typically flows through the one-unit TDD Powerplant, which came on-line in 1987. Two slide gates provide isolation of the two penstocks that channel water through the powerplant turbine. This water empties directly into the Feather River via discharge lines.

The unit at the plant has a maximum output capacity of about 3 MW and a maximum turbine flow rate of 615 cfs. Turbine water flows downstream over the Fish Barrier Dam that is located about a half of a mile downstream of the TDD. Water can also be released from the diversion dam directly into the Feather River via a spillway that is controlled by 14 radial gates.

A slide gate at the diversion dam controls the amount of water that flows to the nearby Feather River Fish Hatchery (less than 1 mile downstream) for use within the hatchery itself and for the hatchery fish ladder. This water bypasses the powerplant; therefore, it produces no power. Hatchery water releases join the Feather River less than a half of a mile below the fish barrier.

4.3 Fish Barrier Dam and the Feather River Fish Hatchery

The Feather River Fish Barrier Dam is downstream of the TDD and immediately upstream of the Feather River Fish Hatchery. The Fish Barrier Dam diverts fish from moving upstream to the diversion dam, directing them into the Feather River Fish Hatchery via a fish ladder. Fish that are diverted include salmon and steelhead, returning to spawn. When these fish species reach spawning age, and conditions are right, they instinctively swim upstream. Because the barrier dam stretches across the river, the only upstream route is up the fish ladder. This ladder connecting the Feather River near the fish barrier dam to the hatchery is a 2,150-ft-long, 6-ft-wide concrete structure. When used, the water flow rate in the ladder is 10 cfs with a minimum 2-ft pool depth in each stair. The maximum drop between adjacent stairs is 1 ft. Hatchery facilities also include a spawning building and rearing raceway [26]. As described previously, the water source for fish ladder flows is the Thermalito Diversion Pool; flow is controlled by a slide gate.

4.4 Thermalito Power Canal

The Thermalito Power Canal is a concrete-lined structure extending 10,000 ft from the head-works structure at the TDD to Thermalito Forebay. The canal was constructed between 1965 and 1967. The Thermalito Diversion Pool and the Thermalito Forebay can be isolated by three radial gates at the TDD. Typically these gates are open, allowing the canal to convey water in either direction between Thermalito Diversion Dam and Thermalito Forebay. When operating in a generation mode, water released through the Hyatt PGP increases the water volume stored in the Thermalito Diversion Pool, thereby raising the pool's water surface elevation. To reach equilibrium between this pool and the surface water elevation in the Thermalito Forebay, some of the water is conveyed to the forebay through the diversion dam and the canal. In the generation mode, the canal's maximum flow rate is 16,900 cfs from the Thermalito Diversion Pool to the Thermalito Forebay. In pump mode, canal water flows in the opposite direction from the Thermalito Forebay to the Thermalito Diversion Pool. In pump mode, the maximum water flow rate is 9,000 cfs.

As described in more detail in Section 4.5, both water releases and pumping at the Thermalito PGP affect Thermalito Forebay water levels and therefore the elevation balance between the forebay and the diversion pool. Although water elevation differences between the afterbay and pool occur, the difference is typically minimal.

4.5 Thermalito Forebay Dam, Forebay, and PGP

Located about 4 miles west of the city of Oroville, the Thermalito Forebay was constructed between 1965 and 1968. It stores water released from the Thermalito Diversion Pool through the Thermalito Power Canal. Reservoir waters are contained by the Thermalito Forebay Dam on the south and east and by Campbell Hills on the north and west. As described in Section 4.4, the forebay conveys generating and pumping flows between the Thermalito Power Canal and the Thermalito PGP and provides regulatory storage and surge damping for the Oroville-Thermalito Complex. The reservoir has a maximum operating storage capacity of 11,770 AF. At this storage level, the water surface elevation is 225 ft and the forebay water covers 630 acres with a 10-mile shoreline.

The Thermalito Forebay Dam is a homogeneous, zoned, earth-filled structure with an embankment volume of 1,840 thousand cubic yards. The structure is 91 ft high with a crest length of 15,900 ft. The crest is 231 ft above sea level.

Thermalito PGP construction began in 1964 and was completed in 1969. The first unit came on-line on February 9, 1968. It currently has four units, three of which have pumping capabilities. Each of the three pumping units can generate up to 28 MW of power. The generation-only unit has a capacity of 36 MW.

Thermalito Forebay Dam releases water through the powerplant flow into the Thermalito Afterbay. The penstock that channels forebay water through the generation-only turbine is 24 ft in diameter at the water intake, narrowing to 21 ft near the penstock outlet. Three penstocks convey water through the pumping-generating units: one penstock per unit. The diameter of each penstock ranges from 21 ft at intake to 18 ft near the turbine. In generation mode, the maximum turbine flow rate for the pumping-generating units is 4,200 cfs, while the generating-only unit has a maximum flow rate of 4,800 cfs.

Operations of the Thermalito PGP are coordinated with those of the Hyatt PGP. While in pumping mode, the three units with an installed pumping capacity of 120,000 hp are used to lift water from the afterbay to the forebay at a rate of 9,120 cfs. Water released for power in excess of local and downstream requirements is conserved by pump-back operation during off-peak hours through both powerplants into Lake Oroville. This excess water is subsequently released for power generation during periods of peak power demand.

4.6 Thermalito Afterbay Dam and Afterbay

Constructed from 1965 to 1968, the Thermalito Afterbay Dam and the Thermalito Afterbay control water flows into the Feather River downstream of the Thermalito PGP. Water released into the Feather River is regulated by five radial gates at the dam outlet structure, situated in the southwest corner of the afterbay. The confluence of this Thermalito Afterbay outlet structure and the Feather River is about 10 river miles below the TDD.

The afterbay also provides water storage when the powerplant is operating in pump mode; that is, it serves as the lower reservoir for pumping purposes. The afterbay is shallow, and the sun warms basin water for agricultural deliveries to farms located to the east.

The Thermalito Afterbay has a water storage operating capacity of 57,040 AF. When the afterbay is full, it has a water surface elevation of 136.5 ft above sea level, covering a surface area of 4,300 acres with 26 miles of shoreline.

Water in the afterbay is contained by a homogeneous, earth-filled dam comprising more than 5 million cubic yards of material. At a height of only 39 ft, it is a relatively low structure compared with other Oroville-Thermalito Complex dams. On the other hand, it is the longest dam in the complex, with a crest length of 42,000 ft. The crest elevation is 142 ft above sea level [27].

4.7 Feather River Flow and Reservoir Operating Criteria

Water releases from Oroville-Thermalito Complex operations must comply with a set of Feather River instream flow and temperature requirements that vary according to season and hydrology. For regulatory purposes, the Feather River in the Oroville-Thermalito Complex footprint is separated into a low-flow channel (LFC) and a high-flow channel (HFC). As illustrated in Figure 4.2, the LFC reach begins just below the TDD and extends downstream to the point where the Thermalito Afterbay releases water into the river. The HFC begins at that confluence and extends downstream.

Under current operating conditions, the flow rate in the LFC must be at a minimum of 600 cfs. This LFC minimum may change upon the issuance of the new Federal Energy Regulatory Commission license for Lake Oroville. To ensure compliance, the CDWR operates the system so that a slightly higher flow rate is typically attained. Note that this flow rate is roughly the maximum turbine release rate of the 3-MW unit at the TDD Powerplant. Because the flow requirement applies year round, the powerplant is essentially base loaded whenever it operates.

Under flooding conditions, LFC flows are determined on a case-by-case basis. Incremental water releases into the Feather River above the generator's production capacity or beyond the maximum turbine flow rate do not produce additional power. Therefore, there is an economic incentive to divert water down the Thermalito Power Canal into the Thermalito Forebay for power production at the Thermalito PGP. Also, the Thermalito PGP has a higher dynamic head and therefore typically produces more energy per unit of water released through its turbines than the TDD Powerplant.

In addition to the minimum flow requirement, environmental regulations also limit the water flow rate change in the LFC between two consecutive days. When flows are between 600 and 2,500 cfs, the maximum decrease allowed in daily average flows is 300 cfs per day. This maximum daily decrease requirement is 500 cfs per day when flows are between 2,501 and 3,500 cfs. The requirement is further relaxed to 1,000 cfs per day when flows are between 3,501 and 5,000 cfs.

Minimum water flow requirements for the HFC are more complicated. The year is divided into three periods. Period 1 is from October through February; Period 2 is March; and Period 3 is from April through September. The HFC flow is dependent on forecasted elevation and the previous year's April through July unimpaired runoff into Lake Oroville. For this paper, we classify the hydrological states as dry, moderate, and wet, as defined below.

- ***Dry*** — Lake Oroville surface water elevation is projected to be less than 733 ft (about 1.5 million AF), and the previous year's April through July unimpaired runoff into Lake Oroville was less than 55% of the historical mean (1,942 thousand acre feet [TAF]), or 1,068 TAF.

- ***Moderate*** — Lake Oroville surface water elevation is projected to be greater than 733 feet, and the previous year's April through July unimpaired runoff into Lake Oroville was less than 55% of the historical mean (1,942 TAF), or 1,068 TAF.

- ***Wet*** — Lake Oroville surface water elevation is projected to be greater than 733 feet, and the previous year's April through July unimpaired runoff into Lake Oroville was greater than 55% of the historical mean (1,942 TAF), or 1,068 TAF.

Table 4.1 lists minimum HFC flow requirements as a function of hydrological classification and time period. When water flows in the HFC are less than 2,500 cfs, channel flows are not permitted to decrease by more than 200 cfs in any 24-hour rolling period.

Further downstream of the Oroville-Thermalito Complex, maximum allowable flows have been established for flood control purposes. The Feather River flows above the Yuba River confluence must not exceed 180,000 cfs; downstream of the Yuba River confluence, the maximum allowable flow rate is 300,000 cfs; and at the confluence with the Bear River, the maximum allowable flow rate is 320,000 cfs.

Operational limitations have also been established for the Oroville-Thermalito Complex reservoirs. As listed in Table 4.2, Lake Oroville has a wide range of reservoir operations. Because Lake Oroville has a large surface area and storage capacity (i.e., maximum operating storage of 3,537.6 TAF), changes in reservoir water surface elevations during day-ahead and real-time operations are small.

Table 4.1 Feather River HFC Minimum Flow Requirements

Hydrologic Classification	Time Period	Minimum Flow Requirements (cfs)
Wet	October through February	1,700
	March	1,700
	April through September	1,000
Moderate	October through February	1,200
	March	1,000
	April through September	1,000
Dry*	October through February	900–1,200
	March	750–1,000
	April through September	750–1,000

* These flow requirements reflect a 25% reduction under certain conditions.

Table 4.2 Oroville-Thermalito Complex Reservoir Operating Criteria

Reservoir	Normal Minimum Elevation (ft)	Normal Maximum Elevation (ft)	Absolute Maximum Elevation (ft)
Lake Oroville	640.0	900.0	901.0
Thermalito Diversion Pool	221.0	225.0	225.0
Thermalito Forebay	221.0	225.0	225.0
Thermalito Afterbay	124.0	136.0	136.5

On the other hand, the water elevation in the Thermalito Diversion Pool and Thermalito Forebay change comparatively quickly during a day. Under typical operating conditions, these waters — along with those in the power canal — are essentially the same body; therefore, water elevations move up and down in tandem. The combined maximum operating storage of Thermalito Diversion Pool and Thermalito Forebay is 25.2 TAF — roughly 0.74% of Lake Oroville's maximum operating storage.

Additional storage requirements for the Thermalito Afterbay have been established to maintain brood ponds and enhance habitats for nesting waterfowl, including grebes (freshwater diving birds) and giant garter snakes. Reservoir operational requirements change from year to year based on hydrologic conditions; however, typical operational requirement are provided below.

- For waterfowl nesting, a water elevation of 133.5 ft must be reached every 9 days from March 15 through May 31, without exceeding 134 ft.

- For grebe nesting, water elevations must be within a range of 132 to 135 ft from the beginning of July through mid-August. This restriction is relaxed to a range of 131 to 136 ft from mid-August through mid-September.

- For the giant garter snake, a water elevation of 133.5 ft must be maintained for a continuous 12-hour period at least once a month from May 1 through October 1.

As shown in Figure 4.3, Lake Oroville goes through an annual fill-and-drain cycle. On average, the lake is at an annual low point in October. This void allows the reservoir to capture and store winter run-off and spring snowmelt. Electricity demand during this period is typically less than in the summertime, so outflows for power production tend to be lower.

Typically, the reservoir is at its peak storage level in May. After May and through September, precipitation and snow melt levels are significantly reduced. Yet, at the same time, the demand for electricity increases. The result is reservoir draw-down during this period, as water releases for power production significantly exceed reservoir inflows. On average, the annual change in storage throughout the course of a year is about 880 TAF. Data plotted in Figures 4.3 and 4.4 were obtained from the CDWR Data Exchange Center. Average values are based on data for 1969 through 2005 for Lake Oroville [28] and on data from 1968 through 2005 for the Thermalito Afterbay [29].

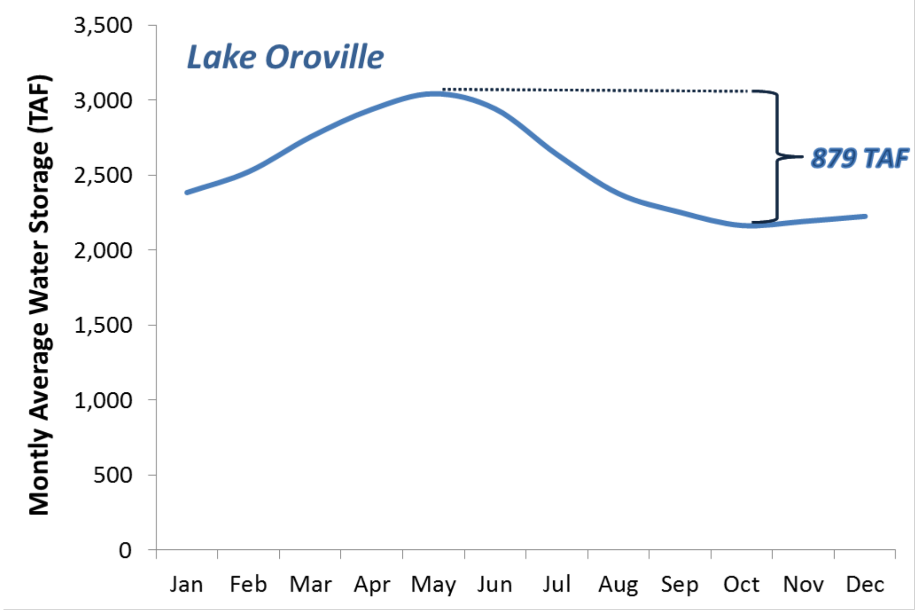


Figure 4.3 Historical Monthly Average Water Storage Levels for Lake Oroville

As shown in Figure 4.4, monthly average storage at the Thermalito facilities is much smaller and displays significantly less fluctuation throughout the year. As discussed above, some of the storage fluctuations in the Thermalito Afterbay result from environmental operating criteria imposed on reservoir operations.

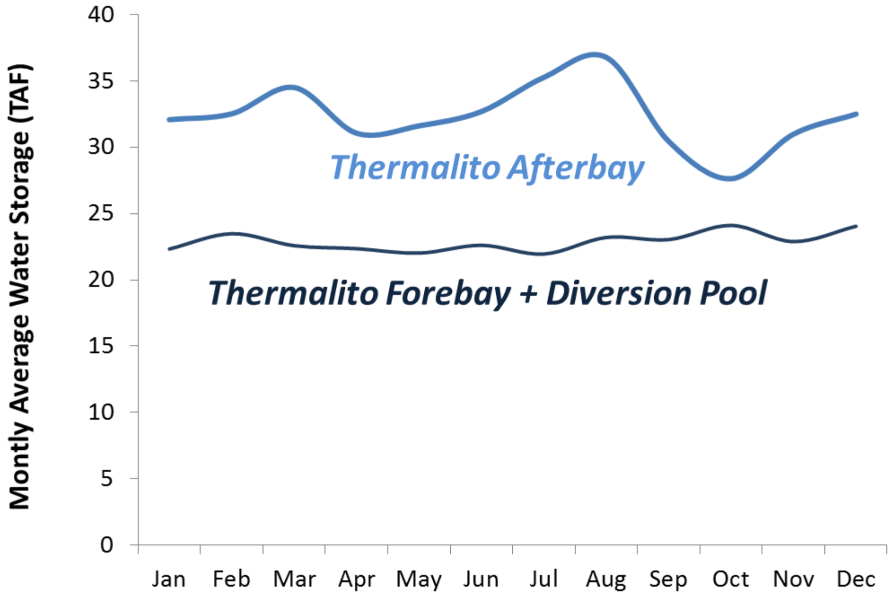
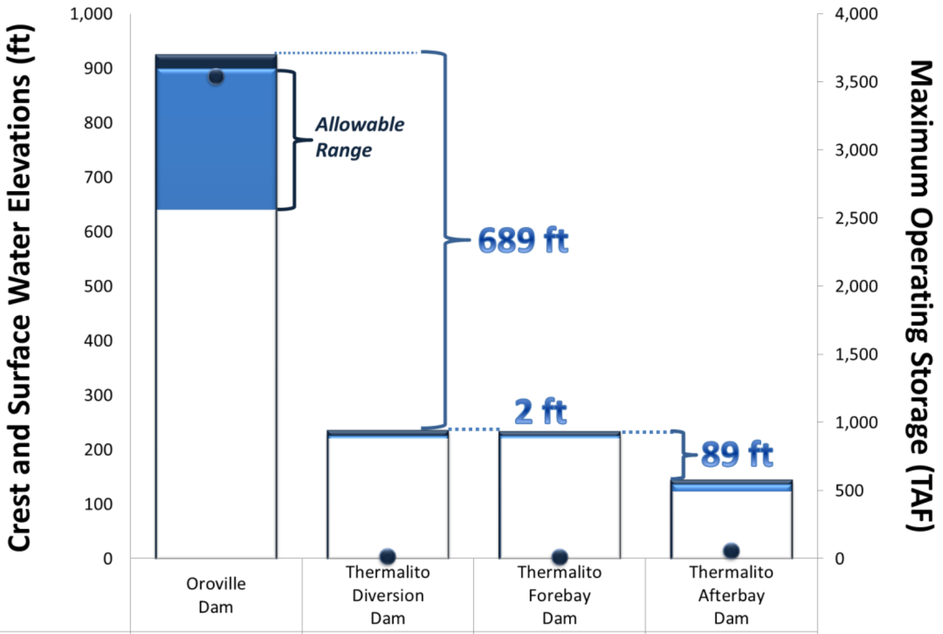


Figure 4.4 Historical Monthly Average Water Storage Levels for Thermalito Reservoirs

4.8 Oroville-Thermalito Complex Resource Overview

This section provides an overview of the Oroville-Thermalito Complex and its components. As illustrated by the blue dots in Figure 4.5, Lake Oroville's maximum operating storage dwarfs those of the other water storage facilities. There is also a very large vertical drop in elevation between the Oroville Dam and the TDD. The TDD and the Thermalito Forebay Dam are essentially at the same elevation and have identical maximum operating storage elevations. These two reservoirs also have roughly the same water storage volumes. At the bottom of the cascade is the Thermalito Afterbay. The drop in elevation from the Thermalito Forebay to the Afterbay is on the same order of magnitude as the drop from the TDD to the Fish Barrier Dam, which has an elevation of 148 ft [30].

Although Lake Oroville dominates the system in terms of its size, operations at the Lake Oroville Dam must be sensitive to operational restrictions at the lower reservoirs and comply with Feather River flow requirements. This situation highlights the fact that system operations are tightly coupled; the actions taken at one facility impact one or more of the other parts of the system. For example, the amount of water released from Lake Oroville impacts water flows throughout the rest of the complex. Therefore, operations at the Hyatt and Thermalito PGPs have historically been conducted in tandem.



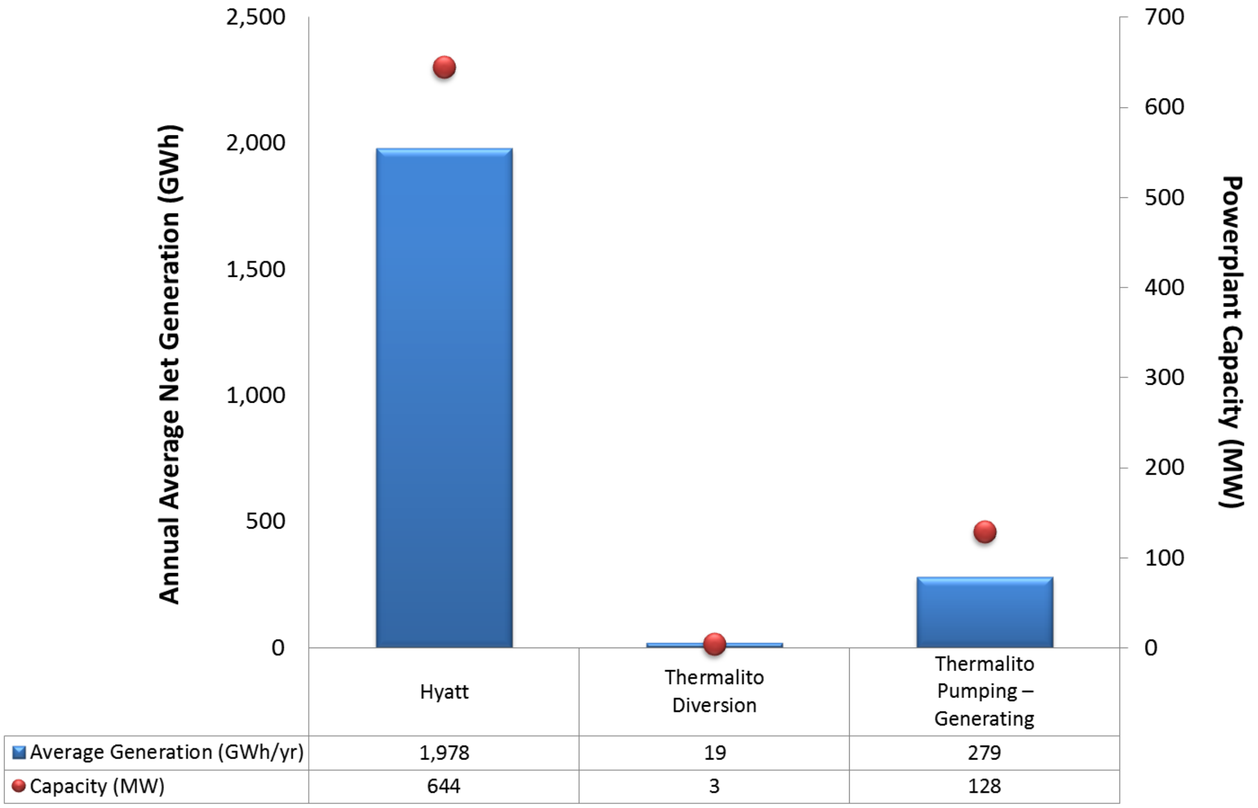
	Oroville Dam	Thermalito Diversion Dam	Thermalito Forebay Dam	Thermalito Afterbay Dam
■ Crest Elevation (ft)	922	233	231	142
■ Pool Elevation @ mos (ft)	900	225	225	136.5
☐ Normal Minimum Elevation (ft)	640	221	221	124
● Max Operating Storage (mos) (TAF)	3,537.6	13.4	11.8	57.0

Figure 4.5 Elevation Characteristics of the Oroville-Thermalito Complex Reservoirs

These system interdependencies do not only occur over space, but also over time. For example, when water is released from a reservoir, the water is not available for release at some other point in time. A water release also lowers the reservoir elevation, thereby reducing the conversion of water releases into electricity by the powerplant at the dam. Depending on the situation, this loss may persist over a long period.

Lake Oroville not only dominates the system in terms of water, but the Hyatt PGP produced the majority of the system's power production and accounts for most of its capacity. The average annual generation shown in Figure 4.6 is based on data collected and maintained by the U.S. Energy Information Administration (EIA) (Forms EIA-423 and EIA-906) for the 1985 through 2005 time period.

As described in Section 3, electricity produced by hydropower plants, including those in the Oroville-Thermalito Complex, is primarily a function of head (which is dictated primarily by reservoir elevation) and turbine flow rate. Therefore, water operations in the Oroville-Thermalito Complex drive hydropower production.



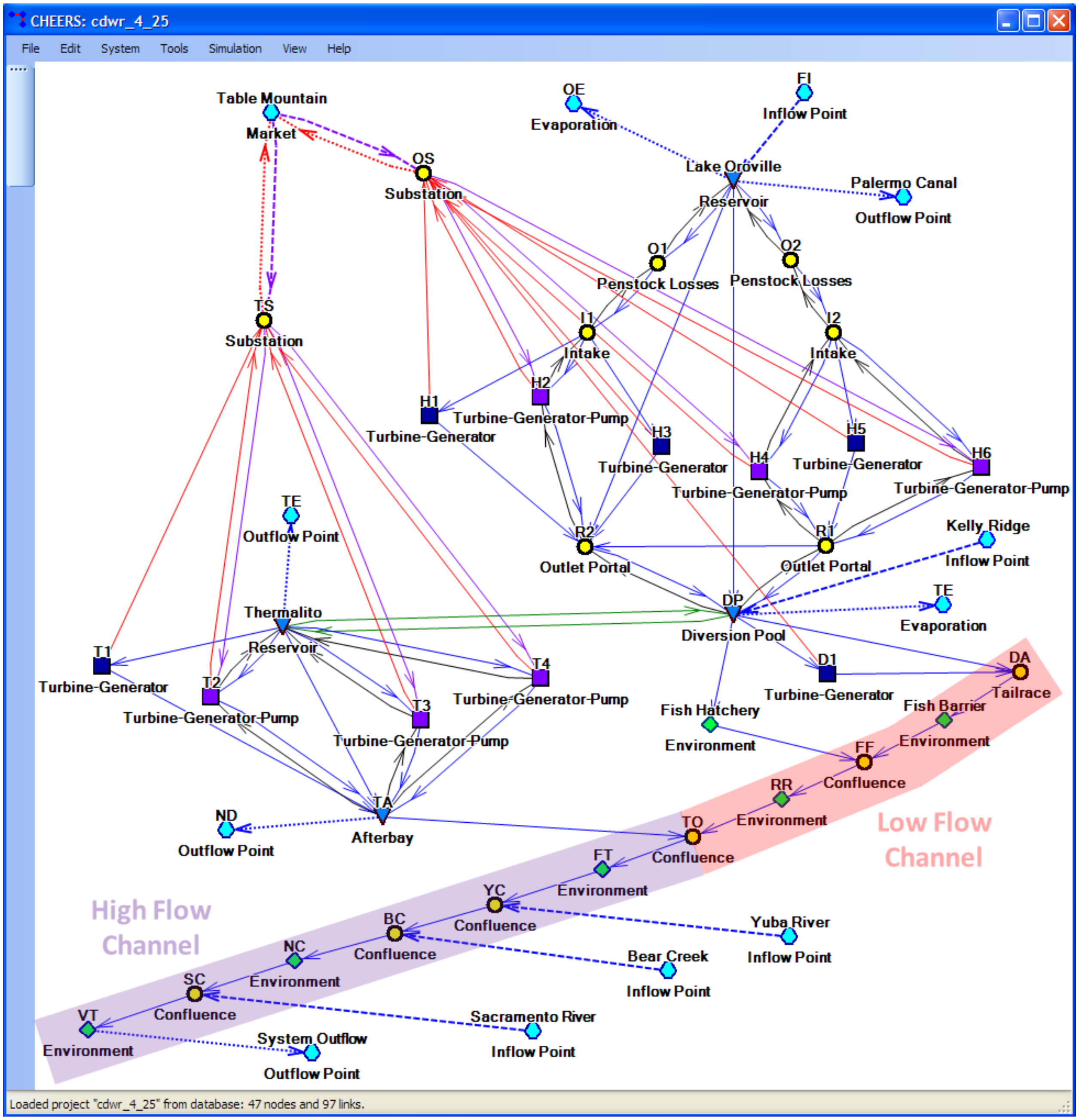
	Hyatt	Thermalito Diversion	Thermalito Pumping – Generating
🟦 Average Generation (GWh/yr)	1,978	19	279
● Capacity (MW)	644	3	128

Figure 4.6 Oroville-Thermalito Complex Powerplant Capacities and Historical Generation Levels

It should be noted, however, that water is not the only operational driver for electricity production. The demand for electricity, coupled with market forces (i.e., prices) for energy and ancillary services, significantly influence temporal electricity production patterns. Among many factors, the physical limitations and performance characteristics of power equipment, along with power dispatch goals and guidelines, further complicate system dynamics. We are therefore applying the CHEERS model with a systemic formulation to optimize the value of Oroville-Thermalito Complex operations over time and space within water and power limitations. The details of this formulation are provided in Section 5.

5 OROVILLE-THERMALITO COMPLEX NETWORK AND CHEERS APPLICATION

We used the CHEERS graphical user interface to create a network that represents the Oroville-Thermalito Complex. Shown in Figure 5.1, the network comprises a set of node objects that are connected by links. Water and electricity are both modeled as flow among nodes via links on an hourly time step. All four CHEERS node types (i.e., functional boundary, storage, conversion, and junction) are used.



Loaded project "cdwr_4_25" from database: 47 nodes and 97 links.

Figure 5.1 CHEERS Network of the Oroville-Thermalito Complex

It should be noted that the Oroville-Thermalito Complex network and supporting database are not only used for CHEERS, but also by all other tools in the Water Optimization Toolkit. This design feature facilitates toolkit data consistency and sharing of both inputs and results among the tools. Each node and link in the network is assigned a key site name and key function name; these are used by the tools to determine what types of calculations should be performed at each object. For example, the hydrologic forecasting tool provides inflow forecasts only at nodes that have the key function name “Inflow Point” and is not concerned with the other types of nodes. In

Figure 5.1, key function names are displayed below each node and a user-given label is displayed above.

5.1 Lake Oroville and the Hyatt PGP

The water commodity enters the network at the Inflow Point node labeled FI, located at the top of the network. This functional boundary node uses a vector of projected and/or historical water inflows. When optimizing future operations, these data may be based on either results from the toolkit's Inflow Forecasting routine or projections made by another means. When performing backcasting analyses, we may use historical inflow data. For initial model testing, we use historical cases.

For this application, water inflows are treated as given values that are outside the control of Oroville-Thermalito Complex operators. Inflows are conveyed directly into Lake Oroville on a link (dashed blue line) that has been defined by the user to transport water. Note that all boundary nodes that function as either a network commodity source and/or sink are displayed in the network as light blue nodes such as node FI.

Lake Oroville is represented by a storage node. All storage nodes/reservoirs are displayed in the network as blue triangles. The amount of water that a reservoir holds is based on the mass balance equation described in Section 3; that is, it is simply a function of how much water the reservoir initially holds plus the amount of water that enters it minus the amount of water that is released. The initial reservoir elevation is the last time-step entry in the CHEERS model historical period. As discussed in Section 3, the historical period represent events and the state of commodity attributes that have occurred in the past. Historical events cannot be altered in the modeling framework and are therefore represented as set values in the model formulation. Historical events may affect optimization results for the future. In this case, Lake Oroville storage operations are sensitive to initial reservoir conditions when the lake is near either the top or bottom of the permitted operating range.

Reservoir water volume is computed for each hourly time step and used to estimate lake water elevation. As described earlier, we use a single straight line to compute Lake Oroville elevation. Bounds are also placed on lake operations so that the minimum and maximum allowable levels described in the operating criteria are not violated.

Because the Hyatt PGP has a high dynamic head, water-to-power conversion is fairly insensitive to small errors in elevation computations. Therefore, power generation remains fairly accurate despite these elevation errors.

Water exits Lake Oroville through evaporation, discharges to the Palermo Canal Outlet Works, Hyatt PGP releases, and non-power releases. Both Palermo Canal releases and evaporated water exit the Oroville-Thermalito Complex network on links connected to functional boundary nodes. For this application, these two functional boundary nodes utilize set schedules entered by the user. On the other hand, all other water releases from the lake are optimized by CHEERS. Powerplant water enters two penstock tubes via the Hyatt PGP intake structure. Each penstock branches out into three pathways leading to six powerplant units (labeled H1 through H6). Each one generating unit is represented by a CHEERS conversion node. In the Oroville-Thermalito Complex network, a single conversion node represents both a turbine and generator, which we referred to in this paper as a “unit.” Water enters and exits the conversion node, producing electricity.

Penstock branching in the network utilizes a junction node (yellow circle). In this case, a single link enters the node, and three links exit it. As described in Section 3, a simple mass balance equation is applied at these nodes. We also use maximum flow rate functions for the two Hyatt penstock links. These functions relate maximum penstock flow rate to head. Depending on the required accuracy of the model application, maximums can be represented by a single straight line or as a step function.

As shown in Figure 5.1, there are three units that only generate electricity (dark blue squares) at the Hyatt PGP. Note that each generation-only unit (nodes H1, H3, and H5) has a single water link that enters it. A continuous blue line in the network represents water that flows from a higher elevation to a lower one. Each generation-only node also has two links that exit it: the blue exit link represents draft-tube water that flows downward to an outlet portal and the red exit link carries electricity. In this case, electricity flows from the six Hyatt units to the Hyatt PGP Switchyard and then on to the Table Mountain Substation.

The three Hyatt PGP units that are pumping-generating units (purple squares) are represented by the conversion nodes labeled H2, H4, and H6. Note that, in addition to the blue water links that enter this type of conversion node, there is a black line that connects it to the river outlet portal. Black lines in this network represent water that is pumped up from a lower elevation to a higher one. In the Hyatt topology, water flows from the Thermalito Diversion Pool up to Lake Oroville, passing through several nodes on the way. Also note that links that transport electricity not only exit these nodes, but also enter them. These entering links represent grid energy consumption when the reversible Francis turbines are operating a pumping mode.

As described in Section 3, electricity production is based on step functions that relate power production to both head and turbine water flow rate. Step functions at the Hyatt PGP units serve several purposes: (1) estimating the amount of water that is released to produce electricity (i.e., the average and incremental water-to-power conversion); (2) placing a limit on unit power output based on generator/turbine capacities; and (3) indirectly limiting penstock flow rates in high-head situations (i.e., turbine flow, as described by the step function, becomes the binding flow constraint in the system). We also represent the minimum unit generation level as the first step in the function. By applying an on/off variable at this first step, we ensure that the production level does not fall below a unit’s technical operating minimum.

Non-power releases from Lake Oroville via spillways and river outlet tubes are represented as a single blue link in the network that connects the lake to the Thermalito Diversion Pool. We use a very simple representation in the model for these dam features. We assumed that these non-power releases are under the control of an operator and limited by a single maximum flow rate. This maximum is based on the combined flow capacity of these water routes, which is based on the initial reservoir conditions. If the need arises, a more sophisticated approach to these non-power releases will be implemented.

When applicable, guidance on total daily and weekly water release volumes from Lake Oroville will be based on results from the Seasonal Hydrosystems Analysis tool. This toolkit component has coarser time and spatial resolutions than CHEERS, but it projects operations much further into the future, allowing water scheduling over a seasonal timeframe and accounting for factors that are well beyond the CHEERS projection horizon. The same approach is used for limiting CHEERS total water release volumes from other reservoirs in the complex.

5.2 Thermalito Reservoirs and Powerplants

Releases from Lake Oroville into the Thermalito Diversion Pool, along with flows out of the Kelly Ridge Hydropower Plant, move downstream though the Thermalito system. The diversion pool is modeled as a storage node. Because it is relatively small and the pool elevation is fairly sensitive to changes in storage volume, we compute water elevations by using a step function. Construction of the step function employs the methodology described in Section 3 based on the range of pool water storage anticipated during the optimization period; that is, construction of the step function is based on only that portion of the water volume-elevation curve that is applicable.

Kelly Ridge water contributions to the Thermalito system are modeled by using a functional boundary node and a link that connects powerplant water releases to the diversion pool. We assume that these flows are outside the control of Oroville system operators. However, inflows are known in advance and modeled using set values.

Diversion pool water is released through the TDD Powerplant and flows down the Thermalito Power Canal to the Thermalito Dam Forebay. The single 3-MW unit in the powerplant is modeled using the conversion node labeled D1 in a manner similar to that used for the conversion nodes representing a Hyatt generation-only unit. The D1 node has one blue link that enters it and one blue link that exits, representing the flow of water through the unit’s turbine. A red link connecting the unit to the Hyatt PGP Switchyards transports unit power to the grid. To represent non-power water releases into the Feather River, a blue link connects the diversion pool to the tailrace junction node. This representation in the model functions very similar to the Oroville Dam non-power link.

Under normal operating conditions, water flows through the diversion dam into the Feather River at a constant rate. We therefore place zero ramping restrictions in both up and down directions on the two links that feed into the tailrace node labeled DA. As dictated by Feather River LCF requirements, turbine water releases can be considered constant for day-ahead and real-time modeling. Therefore, we use a simpler and more mathematically efficient function to represent diversion dam power generation than the ones used for Hyatt PGP units. The function applied at the diversion dam unit relates power generation solely to head instead of both head and flow rate.

The Thermalito Power Canal is represented in the model as two separate links: one for each direction. These two links (green lines) transfer water between the diversion dam pool and the Thermalito Forebay. Furthermore, we assume that when diversion dam gates leading to the canal are open, the water surface elevations of the pool and forebay are identical. To keep the two bodies of water in a state of equilibrium, CHEERS transfers water between the two via the canal link within the bidirectional flow limits of the canal. In general, in generation mode, canal flows typically convey water from the diversion pool to the forebay. The opposite occurs in pumping mode.

In order for the model to simulate canal flows with sufficient accuracy, the forebay elevation calculation error must be small. Therefore, as for the diversion pool, we use a storage node with a step function to compute the Thermalito Forebay elevation. For modeling purposes, water contained in the Thermalito Power Canal is accounted for in the afterbay reservoir volume-elevation function.

The Thermalito PGP is modeled by using four conversion nodes, one per unit using the same methods applied at the Hyatt PGP. One unit, labeled T1, only generates electricity, while the other three, labeled T2, T3, and T4, also have pumping capabilities. Lastly, a blue link connecting the Thermalito Forebay to the Thermalito Afterbay is used to model non-power flow.

Water withdrawals for agricultural uses from both the forebay and afterbay are modeled by functional boundary nodes TE and ND, respectively. Withdrawals occur on a given user-specified schedule.

Because afterbay reservoir elevations provide an important habitat for several animal and plant species, we compute afterbay water elevations using a step function. Within the physical maximum flow limit of the Thermalito Afterbay Outlet, CHEERS releases afterbay water to ensure that flows in the Feather River HFC comply with regulatory limits.

5.3 Feather River HFC

Controlled water releases from the Thermalito Afterbay merge with Feather River water (node labeled TO) a short distance below the Thermalito Afterbay Outlet. Downstream of this confluence, the CHEERS topology contains several water balance nodes as water from the Feather River combines with water flows from creeks and rivers.

The flow rates at each CHEERS node in the HFC are based on the time it takes water to travel from a link's entry point to its exit point. We use the travel time distribution factors described in Section 3 to simulate the way water travels at different speeds depending on the route it takes in the channel.

5.4 Environmental Checkpoints and Regulations

The Oroville-Thermalito Complex network contains several nodes that we refer to as environmental checkpoints (green diamonds). The model "monitors" key attributes at these points and applies constraints to comply with environmental regulations. For the Oroville-Thermalito demonstration, environmental checkpoints are used to compute flow rates and schedule reservoir releases so that flows are compliant with the criteria described in Section 4.7. Constraints are also applied to all reservoirs/pools so that water levels are also compliant.

Although operations at the Oroville-Thermalito Complex are subject to temperature constraints at some of the environmental checkpoints, these constraints are not modeled by CHEERS. However, temperature operating criteria are included in the Hydrologic Forecasting tool and information pertinent for day-head and real-time operations, such as Oroville intake depths, will be conveyed to CHEERS via the toolkit's database.

5.5 Ancillary Services

The CHEERS optimization function discussed in Section 3 includes components that account for the economic value of ancillary services provided by Oroville-Thermalito Complex powerplants. In some model applications/studies, a distinction is made between conventional and flexibility reserves. Conventional reserves compensate for instantaneous changes in load and very quickly fill supply voids when there are sudden forced/unscheduled outages in one or more grid resource components. For power systems with significant supply contributions from variable resources, additional reserves, typically referred to as "flexibility reserves," are needed to ensure grid stability and reliability, primarily because power production forecasts for wind and solar resources are not always accurate [31]. Although California has significant wind and solar resources, the grid code currently makes no distinction between conventional and flexibility reserves. Therefore, this distinction is also not included in the CHEERS demonstration.

For the Oroville-Thermalito Complex demonstration, we include both up and down regulation services, as well as contingency reserves. Regulation services compensate for (or react to) very short-term (in the range of seconds to minutes) changes in the grid through the use of automatic generation controls in the power generation units. In this context, grid changes include both fluctuations in load and variable resource production. Because these changes occur very quickly, the time needed to balance the grid via system re-dispatch is insufficient. Regulation service timeframes are also shorter than the CHEERS time step (i.e., 1 hour) used for this demonstration; we cannot model second-by-second load changes and the deployment of hydropower plants to provide these services. Instead, we reserve Oroville-Thermalito Complex capabilities to provide these services. Figure 5.2 shows powerplant resources that are reserved for regulation services. It shows that providing these services reduces the range of operations or flexibility at a powerplant to follow load and/or market prices. Regulation up lowers a plant's maximum schedule, whereas conventional regulation down increases the minimum. This

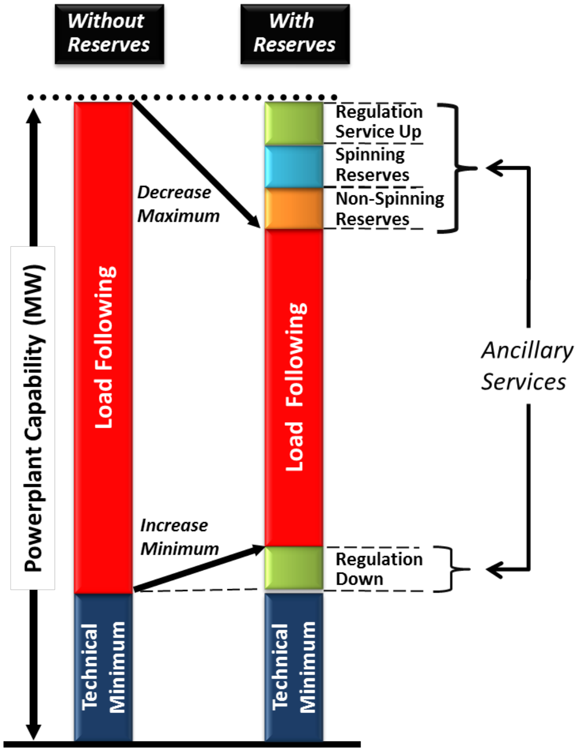


Figure 5.2 Diagram of Typical Powerplant Capability with and without Ancillary Services

adjustment allows for adequate generator capabilities to respond to instantaneous decreases and increases in load, respectively.

Spinning reserves accommodate grid resource supply changes or outages. Powerplants that provide this service must be synchronized to the grid and respond to grid events within a 10-minute timeframe. Therefore a unit must be either producing power or releasing some turbine water to maintain a spin-state to provide this service. As shown in Figure 5.2, spinning reserves lower the maximum generation schedules at a powerplant. Finally, non-spinning reserves have a minimum response time requirement of 30 minutes and do not have to be synchronized to the grid. We assume that an Oroville-Thermalito unit does not need to be on-line to provide this grid service, because it can transition from an "off" state to an "on" state within a few minutes.

In addition to reserving power capabilities for ancillary services, water and storage resources are reserved by CHEERS to accommodate ancillary services. For example, the reservoir storage maximums are reduced to accommodate water that would be used in the event that spinning and/or spinning reserves must be deployed.

6 CONCLUDING REMARKS

With support from the DOE EERE Water Power Program, we are creating and applying the CHEERS model to optimize day-ahead scheduling and real-time operations. Our goal is to aid Oroville-Thermalito Complex operators in making decisions about unit commitments and turbine-level operating points using a system-wide approach. Optimization is performed while complying with existing environmental operating criteria that often conflict with goals to increase hydropower efficiency and the value of power generation and ancillary services while accounting for unit startup and shut-down costs.

The optimization is a formidable task because water, hydropower, and environmental systems are inherently nonlinear and discontinuous. We therefore make some simplifications when formulating the optimization problem, including linearizing some properties of the system. For initial model testing, we use historical cases to assess potential improvements in system operations. The next step is to optimize future operations in a test/offline environment.

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Acronyms

AF	acre-feet
AMPL	a mathematical programming language
Argonne	Argonne National Laboratory
CDWR	California Department of Water Resources
cfs	cubic feet per second
CHEERS	Conventional Hydropower Energy and Environmental Systems
DOE	U.S. Department of Energy
EERE	Office of Energy Efficiency and Renewable Energy
EIA	U.S. Energy Information Administration
ft	feet
GWh	gigawatt hour(s)
h	hour(s)
HFC	high-flow channel
hp	horsepower
Hyatt	Edward Hyatt Powerplant
LFC	low-flow channel
LP	linear programming
MILP	mixed-integer linear program
MINLP	mixed-integer nonlinear program
MW	megawatt(s)
MWh	megawatt hour(s)
NP-hard	non-deterministic polynomial-time hard
PGP	pumping-generating powerplant
rpm	revolutions per minute
SOS-2	specially-ordered-set of type 2
SWP	State Water Project (California)
TAF	thousand acre-feet
TDD	Thermalito Diversion Dam

Biographies

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