Hydroelectric System Operations Optimization

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Abstract

The purpose of hydroelectric system optimization is to maximize the value of water resources by providing rapid and informative recommendations based on current data and dynamic forecasts of hydrology, energy prices and loads at individual hydro plants and within the overall system. A version of the same software running from a more static database can be used for planning studies and to schedule maintenance.

This type of comprehensive optimization software is called a "decision support system" because it recommends quickly how to maximize hydroelectric benefits while meeting non-energy aspects of water management, such as effects on the river downstream and on the forebay upstream. Decision support systems currently in operation include single generating stations, cascades of dams, and complex river networks. The paper presents some of the author's experiences with development of decision support systems. It will interest utilities that are planning to develop a decision support system or to update software currently being used..

Key Words: Hydroelectric, operations, optimization, decision-support-systems.

Decision Support Systems

The components of decision support systems depend on how rapidly specific decisions must be made. Figure 1 illustrates the components of a comprehensive decision support system developed by Charles Howard & Associates Ltd. (now Powel Mini-Max) for operations and for planning.

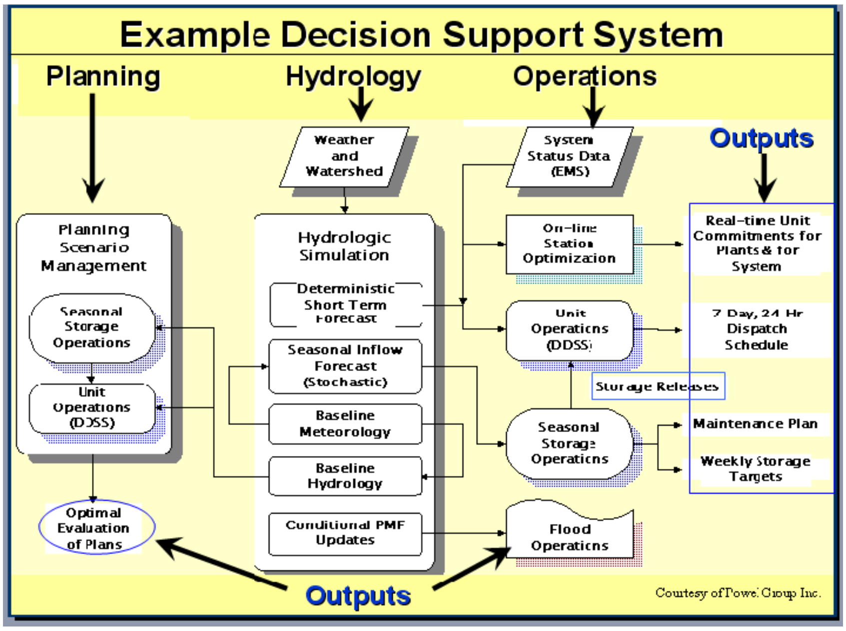
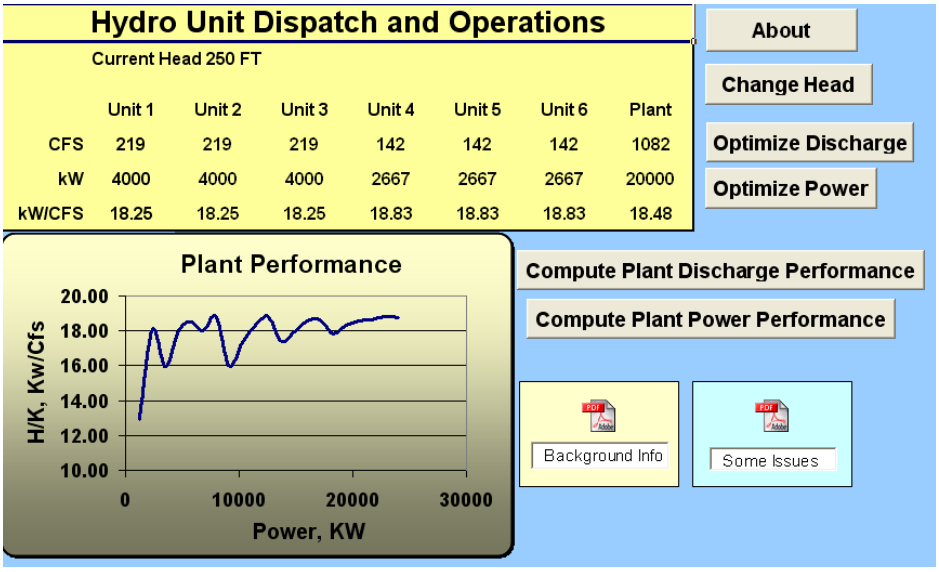


Figure 1 Components of a Comprehensive Hydroelectric Decision Support System

The purpose of decision support systems is to ensure that the best available data are used in an uncompromisingly comprehensive analysis that captures the maximum benefit from the investment in the system of reservoirs and generation facilities. With a properly designed decision support system this goal often can be achieved with little routine effort during day-to-day operations. A decision support system provides an objective method for measuring how well a hydroelectric system has been operated – a valuable component in due diligence investigations when assts are sold or purchased. The software can provide training for new operators, and retraining when operating conditions or facilities change.

Short-term hourly schedules provide advice for water management and determine optimal system-wide unit scheduling for generation planning and bidding into the energy market over a weekly cycle. Optimum reservoir storage and release advice depends on mid-term forecasts and targets based on probabilistic optimization over several weeks or more. Maintenance scheduling considers seasonal hydrology, energy prices and loads, and the work crews that are available for tasks of various durations.

Near-real time (5 minutes) advice within each hydro plant considers unit commitment (which units to run at a given time) and how the units meet the current plant load, or discharge the currently required amount of water, or to determine set points for AGC. Figure 2 is a screen from such a decision support system[1]. The plant performance curve illustrates how load on the hydro system must be allocated carefully to individual dams so their generating units can operate at points that maximize the overall efficiency of each power station.



Hydro Unit Dispatch and Operations

Current Head 250 FT

	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6	Plant
CFS	219	219	219	142	142	142	1082
kW	4000	4000	4000	2667	2667	2667	20000
kW/CFS	18.25	18.25	18.25	18.83	18.83	18.83	18.48

Figure 2 Hydroelectric Plant Operations Decision Support Software

Decision support systems are highly interactive and graphically informative. For reservoir operations they consist of a database and water management modules. The database includes historical basin data; real-time (or near real-time) data; and the methods for acquiring, editing, storing, and retrieving the data. The water management modules optimize the use of storage based on continuously updated deterministic short-term inflow forecasts, and probabilistic long-term inflow forecasts adjusted for current conditions.

The optimization is constrained by the physical limitations of the facilities and the license conditions for their operation. A set of prioritized objective functions quickly guides the analysis to the appropriate recommendations for using the storage. Predetermined rule curves are not used in this process. In effect, a decision support system develops an optimized rule curve continuously as data and circumstances change.

The objective function should make efficient use of the generating units to maximize the sum of relative values for energy over a prescribed time horizon, say 168 hours. The efficiency curves for all of the generating units are incorporated into the optimization matrix. The goal is to achieve a desirable sequence of operations within operating constraints while using all of the available water as efficiently as possible to generate energy benefits.

Additional terms in the objective function guide solutions towards desirable ramp rates and target levels while maintaining consistent unit operations within water management goals. The optimization model for scheduling the generating units maintains reserve requirements and recommends energy purchases depending on the availability of water and the effect of constraints on scheduling decisions. Typical water management constraints include absolute limits on the amount and timing of changes to flows and levels, maximum outflows and generation, and transfer functions that describe river routing to downstream projects in a cascade.

Experience with Decision Support Systems

Since the 1980’s the author has directed development of decision support systems at a number of hydroelectric projects in North America. The decision support system for the two hydroelectric projects of Powell River Energy in the coastal mountains of British Columbia includes a calibrated probabilistic forecast model of the hydrologic cycle that provides input to a probabilistic optimization model of reservoir operations[2]. The optimization is updated weekly.

The computer system developed for Yadkin, Inc. in North Carolina consists of a deterministic hydrologic forecast model and an economic optimization model that incorporates the reservoir operations and the operating characteristics of the thirteen generating units in the four plants[3]. Over a 168-hour time horizon the hourly energy costs are used to optimize globally the generation schedules of the units and the allocation of storage. An important part of this system was installation of several new weather stations and river gages, interpretation of real-time satellite data, and an interactive map based overview of current water conditions throughout the basin.

The John Hart project is upstream from the City of Campbell River in British Columbia. The river here can reach flood stage if high powerhouse releases coincide with high tides. An important goal is to minimize flooding of the town downstream and the lakeside residents upstream. The three-reservoir decision support system developed in 1992 for the John Hart Project is a set of integrated models including deterministic hourly hydrologic forecasting, site specific tide forecasting, reservoir and spillway operation optimization, and scheduling of the generation units.

Flood forecasting and reservoir routing for John Hart is conditional on observed rates of actual snow melt in the surrounding mountains. The reservoir inflow forecast is based on the actual current hourly melt rate reported automatically at high elevation snow pillows and the probable maximum precipitation determined by previous studies. The hydrologic model uses these data dynamically to determine the current value of the “conditional” probable maximum flood. This conditional probable maximum flood is always less than the probable maximum flood (PMF) developed for spillway design because once the snow is depleted there is no possibility of a PMF. The reservoir can therefore be allowed to rise higher to provide more storage for regulating these less severe floods. The result is reduced flooding at the City downstream and increased generation after the flood recedes.

FPL Energy-Maine’s decision support system was developed in 1995 and includes fourteen dams on three river systems in southern Maine[4]. The purpose is to maximize the value of generation while meeting environmental requirements and operational commitments to other dam owners on the river system. Since its inception, the scope has expanded to include all aspects of river management, including bidding into the wholesale electricity market, and for relicensing studies.

The decision support system at FPL Energy-Maine has nine main software modules:

1. Satellite down-link, hydrometric data viewer, and editing module;
2. Deterministic short-term inflow forecast module;
3. Stochastic mid-term inflow forecast module;
4. Dispatch decision support system for 168-hour unit operation schedules;
5. Stochastic storage optimization including energy price forecasts;
6. Maintenance scheduling optimization;
7. Station optimization module for near real time unit loading;
8. Engineering module for facilities data management; and
9. Relicensing module that uses the dispatch decision support module.

Like many utilities FPL Energy-Maine has a central database that supports various workstations over the corporate wide area network. The database includes a comprehensive system of usage tracking and data set version control to facilitate ease of use, system security, and data ownership. Some of the modules, especially the near real-time unit commitment and loading module, are part of the core business processes and are used on a daily basis. There are data problems with hydrologic forecasting and difficulties in convincing managers of other entities on the river systems that the results will benefit them as well as FPL-Maine.

Bonneville Power Administration (BPA) is implementing a decision support system with some components similar to the FPL-Maine system and other components that are unique to the ten major Federal projects in the Columbia River basin. The BPA decision support system consists of:

- A near real time model for generating unit commitment and loading.
- A basin-wide mid-term (52 weeks) stochastic optimization model.
- A basin-wide short-term (2x168 hours) deterministic operations model.

The software includes all of the features that are essential to realistically schedule operations, including access to transmission facilities and compliance with environmental constraints. BPA’s near-real time module has been in use for approximately one year and has demonstrated direct efficiency improvements and led to overall heightened awareness of other opportunities for improvement[5]. The basin-wide modules are still being used in parallel with traditional methods. It is too soon to tell how effective the entire suite of BPA software will be or how it will be accepted by the dam operating entities within the Federal system.

Development Methods: Difficulties and Solutions

Conventional approaches used for determining optimum solutions for reservoir planning and operations are summarized by Labadie[6]. Some of these methods apply to hydroelectric systems although site-specific approaches are usually necessary to deal with the operational details of hydro systems. Dynamic programming sometimes is an efficient method. It has the advantage of correctly representing non-linear and discontinuous functions. It is basically an efficient trial and error method with the disadvantage of excessive execution time for many practical applications. Non-linear mathematical programming can be based on reasonable approximations to nonlinear functions but execution time may be impractical for routine operations planning of large hydroelectric systems, especially if integer variables are included.

Large scale hydroelectric decision support systems that are highly non-linear use clever formulations to accommodate quadratic programming or linear programming methods of solution[7]. The basic reason for this is to achieve speed of execution that makes optimization decision support systems practical for operations. For example, non linear stage storage curves may be approximately linear over the upper range of operation. A different formulation or a more complex approximation may be necessary to represent ramp rates at lower elevations where stage storage curves are more curvilinear. Generating unit efficiency curves may be reduced to discrete operating points to be selected by the model. River routing may be approximated by linear convolution with a unit impulse response function having variable coefficients determined by iteration. Computer codes that preserve the basis are used to facilitate iterations that adjust coefficients for non linear behavior.

Each hydroelectric system presents its unique challenges and decision support system development requires innovations along the way to success. Time and cost budgets are often exceeded because of unanticipated difficulties with data, integration into the utility computer systems, and ongoing increases in scope (scope creep). The development team should cover all the necessary disciplines related to a hydroelectric operations and software development. A significant investment in data acquisition, assembly, and quality control often is required because data that assembled for archival purposes may not be suitable for model development, calibration, and verification.

The components of decision support system are often different from one hydroelectric system to another, reflecting different priorities and anticipated benefits and costs. Decision support systems are usually site specific and not readily transferable from one hydroelectric system to another. They can be time consuming to develop and are often expensive. Some systems currently in use have taken years to develop, verify, modify, and verify again before being put into practice. Reliable data are often not available for development - for operations it may be difficult to obtain timely data, especially for hydrologic forecasting. Other systems with carefully defined limited scope have been developed comparatively quickly and economically[8]. System design should recognize the pace of technology development and anticipate the capabilities that will be available when the system becomes operational.

An overly ambitious scope can lead to overzealous and impractical objectives that are difficult to pin down into quantitative acceptance criteria. Acceptance criteria for a decision support system are quite different from criteria normally employed in purchasing hardware such as turbines. Criteria based on a specified level of improvement in operation may be impossible to achieve in practice because of uncertainties in the basic data.

Functional acceptance criteria are practical. Acceptance might consider if the decision support system consistently operates without failing because of data or operator errors and provides consistency in operation at a level as good as or better than the best operator. Offline demonstrations might provide a basis for partial acceptance before the software becomes fully operational. A useful decision support system requires serious support from senior management, a dedicated champion as a project manager, and an experienced development team deeply committed to success. Delays in reaping the benefits from the implemented software are costly - modules can be prioritized according to when they can begin to produce net benefits.

Benefits from Decision Support Systems

A common bottom line question among water resource system managers is, “What is the net value of a decision support system?” The answer is not simple. The goal is to achieve benefits that are measurable in terms of operating efficiency gains and increased revenues or reduced energy purchases. Once the software becomes operational a method must be found to determine what would have been done without the software. This can pose difficulties because hydrologic data, energy prices, and some operational constraints and targets are not constant from one year to another.

In the author’s experience at least three methods have been used in practice. First, the potential value of a specific decision support system can be estimated by comparing actual operating history with a reconstruction based on optimizing each step as each operating decision was made. As an example, during a three year period at the project studied by Van Do and Howard, the stochastic optimization model provided a 2-percent improvement over Rule Curve decisions[2].

At Powell River in the coastal mountains of British Columbia there are two hydroelectric plants that provide most of the energy for a pulp and paper complex. For the five years between 1989 and 1993 the energy actually produced was 100, 93, 98, 94 and 96 percent of the theoretical maximum determined by deterministic optimization with perfect foresight. There were equipment failures and operator errors and benefits might have been higher if the recommended use of the reservoir could have been followed more closely.

Another method for estimating benefits is to compare the actual generation with the theoretical generation calculated on an hourly basis from station discharge and net head. As the decision support is implemented the comparison from one year to the next should show an improvement as efficiency moves closer to the theoretical maximum for the generating stations. The third method is to use recent operational history to look for obvious upward shifts in generation or revenue[9]. Whichever method is used the process should be automated so that the decision support system can support the evaluations that are a routine part of doing business.

Decision support systems also are used for planning - they open a broad avenue for investigating how a proposed project or license condition will actually affect overall system benefits. In planning studies the software operates from historical data that is brought into the analysis in the same manner that data would be brought in during actual operations. The goal in planning is to closely replicate the actual day to day decision process, including uncertainties. As the planning analysis moves ahead, the day-to-day outcomes of decisions are determined as the historical inflows come sequentially into the analysis. Continuously updated day-to-day operating decisions during a planning study are based on continuously updated reservoir levels, inflow probabilities and current performance criteria. This dynamic updating is different from the traditional simulation approach, in which target levels or flows determine operational decisions in rule curves established before the simulation begins.

Conclusions

Many utilities have overcome technical and practical difficulties and have found decision support systems economically efficient and operationally beneficial. Decision support systems should fit within the overall enterprise functioning of the utility. This may include support for performance evaluations, meeting new operational requirements and license conditions, planning for upgrades and new facilities, support for power rate hearings and energy price determinations, due diligence for sales or purchases of generating assets, and to smoothly adjust to changing circumstances in the operating environment.

The benefits and costs are not uniform for all systems because of the scope of the decision support system, relative importance of uncertainties, and the multitude of institutional and physical constraints on operation. A decision support system can contribute to staff training and lead towards consistent decisions across all schedulers and plant operators; it provides comprehensive data acquisition and management, the ability to assess proposed expansions or changes in operation, and a tool to respond to unexpected contingencies. Decision support systems provide an objective tool for evaluating environmental compliance and supply the data and monitoring system for improving environmental protection through adaptive management.

There are many examples of decision support systems currently in operation, a few of which were mentioned in this paper. The author directed similar decision support system developments in the 1990's for The USA Department of Energy's Southeastern Power system, Housatonic Hydro in Connecticut, ALCAN's Kemano project in northern British Columbia, and Northeast Utility System's pumped storage at Northfield Mountain in Massachusetts, and others. While some utilities still cling to rule curves, many utility operators use decision support systems incorporating optimization routines as essential components of their hydroelectric system. The decision support systems described here were implemented for hydro systems ranging from a few tens of megawatts to over ten thousand megawatts. The direct economic benefits from just one year of operation of a decision support system can be far less than the costs[5].

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