

MANAGING TVA'S HYDROPOWER SYSTEM USING RIVERWARE

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Abstract

The Tennessee Valley Authority (TVA) is a multipurpose federal corporation which owns and operates 29 conventional hydropower plants and one pumped storage hydropower plant in the Tennessee Valley. The Tennessee Valley watershed, covering parts of seven states in the Southeast, is about 40,000 square miles in area. In addition to hydropower generation, the reservoir system provides other beneficial services throughout the Tennessee Valley, including minimum depth for navigation, flood risk reduction, minimum flows for water supply and aquatic habitat, and recreation.

Day-to-day management and long-term planning for the TVA reservoir system requires sophisticated forecasting and modeling of reservoir inflows, storages and releases, and power generation. To meet this need, TVA and the U.S. Bureau of Reclamation cosponsored the development of RiverWare by the Center for Advanced Decision Support for Water and Environmental Systems (CADSWES) at the University of Colorado. Two of RiverWare's solution methodologies, optimization (preemptive goal programming) and simulation, are used for daily operation of the hydropower reservoirs in the Tennessee Valley.

TVA uses two different RiverWare models to schedule turbine discharges, spillway releases, power generation, and resulting pool elevations at each of its 29 conventional hydropower reservoirs. The first model uses a six-hour timestep and covers a two week planning horizon. This model is run up to four times per day, depending on variations in inflows and system demands. Daily scheduled releases from each reservoir provide input to the second RiverWare model, which uses an hourly timestep. This model covers a planning horizon of up to two days and is used to schedule hourly power generation from each hydropower plant.

TVA's optimization model contains a comprehensive list of policy constraints that guide decisions about water releases and pool elevations at each reservoir. Policy constraints are prioritized and must be satisfied to the extent possible before an economic objective function can be maximized. Policy constraints include water supply, navigation, flood regulation, flows for aquatic habitat, recreational flow releases, and special operations.

The second RiverWare solution methodology, simulation, is used following each optimization model run. Simulation allows modelers to make manual changes to optimization results. Hourly hydropower schedules for the following day and daily average discharges and pool elevations for the upcoming two week period are then distributed to plant operators, recreationists, barge operators, and others throughout the Tennessee Valley.

In this paper, the modeling of the TVA reservoir system is discussed in more detail and enhancements that are in various stages of development such as: ancillary services, integer programming, and stochastic programming are presented.

INTRODUCTION

The Tennessee Valley Authority (TVA) was established in the 1930's by the TVA Act as part of President Franklin D. Roosevelt's New Deal. As stated in the TVA Act, the purposes of the Tennessee Valley Authority are to improve navigation along the Tennessee River, control flooding, and generate electricity to the extent possible. In addition to these reservoir system operating objectives, many other demands have been placed on the reservoir system as the population and economy of the Valley have grown. Some of these demands include reservoir operations for water supply, water quality, and recreation.

TVA began using RiverWare to model its hydro system in the mid-1990s. Prior to this, TVA had used models developed in-house and written specifically for the Tennessee Valley reservoir system. In the early 1990s TVA reservoir operations personnel decided that a collaborative effort with another federal agency, the U.S. Bureau of Reclamation (USBR), and the Center for Advanced Decision Support for Water and Environmental Systems (CADSWES), would benefit not only TVA, but many other water system planners and managers. TVA, USBR, and CADSWES spent several years developing the simulation capabilities of RiverWare prior to TVA using the software for daily scheduling of the 29 hydro plants in the Tennessee Valley. Zagona, et al. (2001) describe the evolution and development of RiverWare.

In 1998, TVA began using the optimization features of RiverWare to help meet the multipurpose operating objectives of the reservoir system while also maximizing the economic value of this resource. Eschenbach, et al. (2001) describe the Preemptive Goal Program in RiverWare. Magee, et al. (2002) describe the use of RiverWare at TVA up until that time.

TVA and USBR continue to sponsor further development of RiverWare. Additionally, many other federal, state, and local agencies and private companies have purchased licenses to the software. Along with the features developed jointly by TVA and CADSWES, many licensees have worked with CADSWES to develop additional functionality. All of RiverWare's functionality is available as part of the license.

TVA'S RESERVOIR SYSTEM

TVA is a multipurpose federal corporation which owns and operates 29 conventional hydropower plants in the Tennessee Valley. The Tennessee Valley watershed, covering parts of seven states in the Southeast, is about 40,000 square miles in area. In addition to hydropower generation, the reservoir system provides other beneficial services throughout the Tennessee Valley. Figure 1 illustrates both the watershed of the Tennessee River (outlined) and TVA's power service area (shaded).

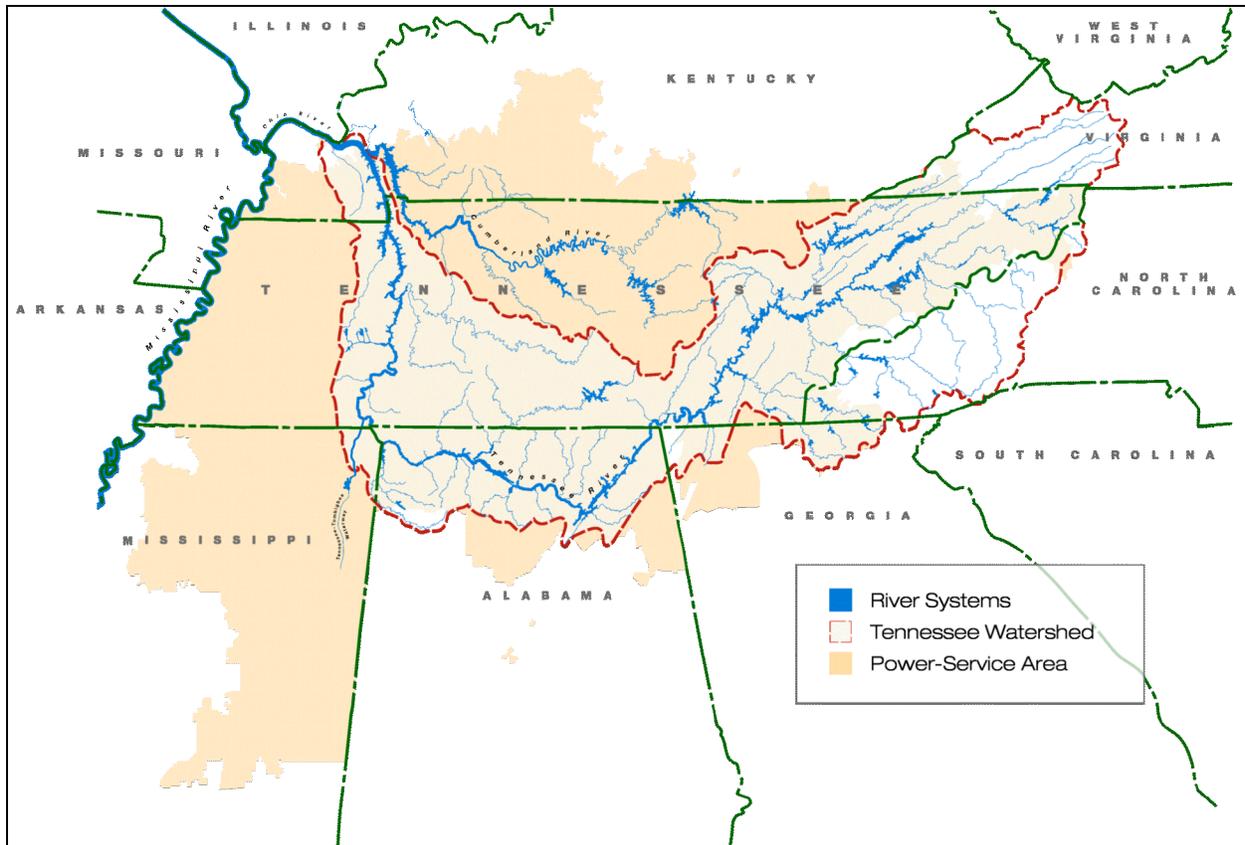


Figure 1 Tennessee Valley Watershed (outlined) and Power Service Area (shaded)

TVA policies governing the management of the Tennessee River system include:

- Navigation;
- Flood risk reduction;
- Recreation on reservoirs and streams;
- Water quality;
- Water supply, including municipalities, industries, and cooling water for TVA's own thermal power plants.

After the water policies have been satisfied to the extent possible, the remaining flexibility of the reservoir system is used to optimize the economic value of hydropower. This value depends on several factors and involves the coordination of alternative power sources. First, TVA must meet the fluctuating demand for power within its power service area, either with its own generation or by purchasing power. This demand varies with season, day of the week, and time of day. Second, hydropower is just one of many power sources that TVA has available to meet this demand. Others include nuclear and coal powered plants and combustion turbines.

Additionally, ALCOA owns and operates four hydro plants in the Tennessee Valley. Because three of these plants are located on the Little Tennessee River between two TVA reservoirs, TVA schedules these plants as well. Finally, TVA has a pumped storage facility that pumps during off-peak hours and generates during on-peak hours.

located in the Tennessee Valley. A daily schedule is created for the next 14 days and can be updated multiple times per day depending on conditions. An hourly hydrogenation schedule is created for each hydro plant for the next two days and is also updated multiple times per day. Both the daily and hourly schedules are created using RiverWare's optimization and simulation solution methodologies. A RiverWare model is first run for a forecast period of up to 14 days using six-hour timesteps. The results of this model scenario are provided as inputs to an hourly timestep RiverWare model. Specifically, the hourly model is constrained to have the same daily outflow totals as the six-hour model. Results of the second RiverWare model are used to create an hourly schedule which is further reduced to a 15-minute schedule using a post-processing tool. This final product is then transmitted electronically to TVA's Hydro Dispatch Control Cell (HDCC) which monitors all 109 units at the 29 hydro plants. Most units are operated automatically using the 15-minute schedule.

Inputs to both the six-hour and hourly timestep RiverWare models include an inflow forecast, a prioritized list of constraints, and a prediction of the value of hydropower generation for each time period. The inflow forecast is comprised of runoff resulting from observed precipitation plus one of several available rainfall forecasts. The prioritized list of constraints reflects the operating policies governing the TVA reservoir system. Depending on time of year and current system conditions, any of the over 900 policy constraints can be activated or deactivated as needed. In general, fewer constraints are needed in the hourly model because the total daily release has been specified for each reservoir. One reason for two different models is that the hourly model can take advantage of relatively detailed and accurate power forecasts for the next two days that are unavailable two weeks into the future.

HYDROPOWER OBJECTIVE FUNCTIONS

Two different hydropower objective functions are available to modelers. One objective function is used for summer operations and another is used for all other times of the year.

TVA's recent Final Programmatic Environmental Impact Statement – Tennessee Valley Authority Reservoir Operations Study (ROS), adopted by TVA's Board of Directors in June 2004, changed the policies that guide operation of the reservoir system. During the summer months (June 1 – Labor Day), reservoir system operations are prescribed by the 2004 Reservoir Operations Study. First, there is a weekly flow requirement at a key control point on the Tennessee River (near Chattanooga, Tennessee), which is downstream of all of the large tributary storage projects. This weekly flow, combined with a commitment to balance pool elevations at each of the ten large tributary reservoirs relative to one another, determines how much water is released from each project during each week. Because the weekly flow through the control point allocates the total volume of water that can be released from the upstream reservoirs, future value of stored water is not an issue. Therefore, modelers utilize an objective function that does not contain a future value of water component.

Water discharged and energy generated at each of the 29 TVA and four ALCOA hydro plants is allocated to six-hour intervals throughout the model period, which covers between eight and 14 days depending on the day of the week the model is being run. This allocation is made by first satisfying all physical and policy constraints. Then energy generation is scheduled during the

most economic time periods. These economics are calculated using a set of 100 block cost values per six-hour timestep. Each block represents the replacement power cost for 50 megawatts (MW) of generation per hour. The block costs are updated multiple times per day and reflect power system status, load forecast, market price forecasts, and other factors. A graphic representation of the block costs is shown in Figure 3.

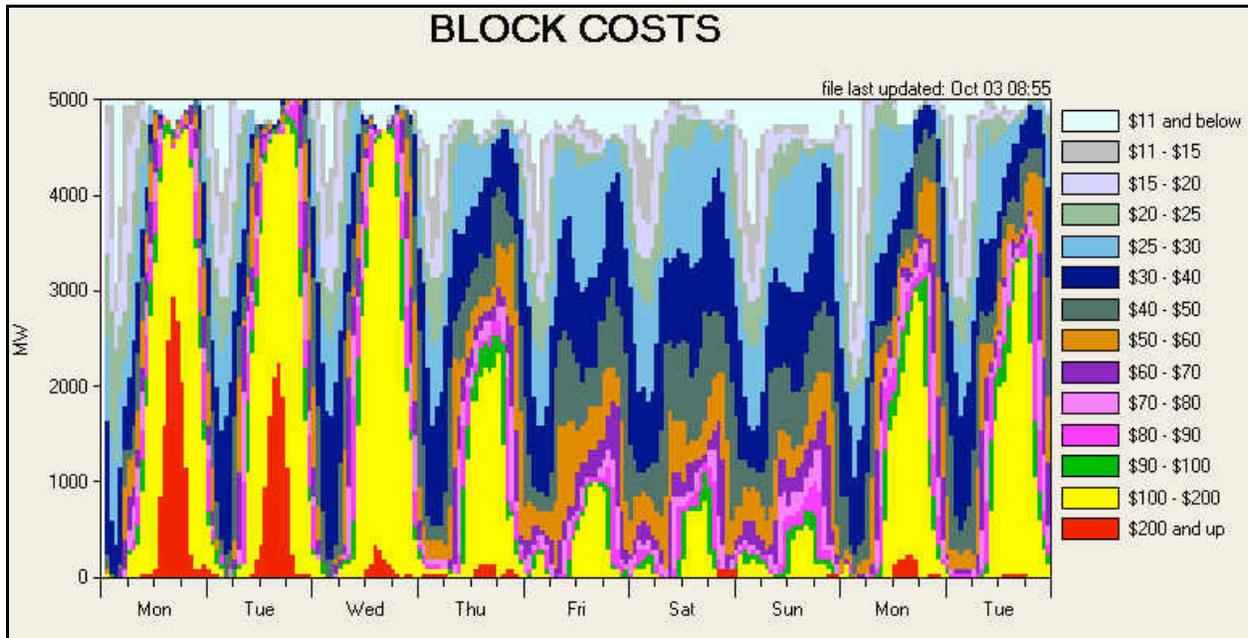


Figure 3 Block Costs Used for RiverWare Hydropower Optimization

During winter, spring, and autumn many of the relevant constraints for summer operation are deactivated and a different objective function is utilized. Tributary reservoir balancing and weekly system flows are not the driving factors for water allocation. Economically balancing near term hydro generation with maintaining water in storage for future power demands drives RiverWare toward an optimal solution while first satisfying all nonpower operating objectives. These nonpower objectives are similar to those used during the summer months and include meeting minimum flow requirements, maintaining adequate flood storage space, and many others.

In order to balance near term and future hydro generation, two optimization models are run sequentially using two different sets of cost forecasts. An additional input to non-summer optimization models includes an estimation of the future value of water in storage. To calculate this future value, a six-month hourly marginal cost forecast is used. The same marginal cost forecast is provided as input to the first optimization model run. This, combined with all policy constraints, allows RiverWare to economically allocate water to maximize the value of current generation and storage for future generation. The resulting ending pool elevations are then specified as input to a second optimization model. Additionally, a second and more detailed cost forecast is input. This cost forecast is the same one as is used during the summer months. It contains 100 blocks per timestep of \$/MWh with each block representing 50 MW.

Outputs of the RiverWare optimization are in terms of total discharge for each reservoir for each timestep. Total discharge, along with the selected inflow forecast, are simulated to compute storage, pool elevation, and energy generation for each reservoir. Modelers can then make manual changes to optimization output through a graphical user interface (GUI) called a Simulation Control Table (SCT) and re-simulate to obtain new results. The SCT is a user defined spreadsheet-like interface. It shows values of multiple variables for multiple model timesteps in one window.

After any necessary manual changes are made through the SCT and a suitable daily schedule is finalized, the scheduled daily volume of water for the second and third days of the forecast period are provided as part of the input to an hourly timestep model. In addition, the same inflow forecast, block cost values, and constraints are input to the hourly model. Modelers then run the hourly RiverWare model using the optimization solution methodology followed by simulation. Any necessary manual changes are again made through the SCT followed by a post processor, which sets the hourly generation at each plant to the nearest unit setpoint. The final hourly schedule of hydropower generation is the most optimal plan for meeting all reservoir operating requirements while utilizing the flexibility of the reservoir system to be the most economic option.

FUTURE ENHANCEMENTS

Three enhancements to RiverWare are in various states of development and deployment: ancillary services, integer programming, and stochastic programming.

Relatively recent trading of ancillary services between utilities suggests that this may become a valuable aspect of power generation in general and hydropower in particular. Hydropower plants equipped with Automatic Generation Control (AGC) are well suited to providing ancillary services because they can adjust to changes in power demand relatively quickly and with little additional cost compared to coal or nuclear powered plants. In particular, hydropower plants are well suited to power regulation to meet fluctuating power demand. The ability to schedule regulation has recently been added to RiverWare. This capability is being tested, but hasn't been put into production use at TVA at this time.

Regulation is modeled both physically and economically. Power regulation is modeled at the hydropower plant level in coordination with the power schedule. The amount of regulation that can be scheduled is limited by the fact that (1) combined power and scheduled regulation must be less than the plant capacity, and (2) power minus scheduled regulation must be greater than the minimum plant generation. Regulation is added to the objective function using a block cost method that is similar to the valuation of power generation.

Thus far, RiverWare's Preemptive Goal Program has used a linear programming engine to solve each goal. Occasionally, RiverWare will generate power solutions that are between physical operating points for power plants or will generate solutions that are problematic from an operations viewpoint. For example, when possible, it is not desirable to turn a plant off for a single hour and then resume generation. Cleaning up these aspects of the solution are one of the current post-processing activities. In the next year CADSWES plans to incorporate integer

variables into RiverWare that will model these power considerations more accurately and should dramatically reduce post processing of the solution.

In the past year, CADSWES developed a new type of stochastic programming, Network Stochastic Programming (NSP), and added a prototype to RiverWare (Emmert, 2005). Unlike Stochastic Dynamic Programming or traditional Stochastic Programming with Recourse, the time to solve NSP grows only polynomially, rather than exponentially with respect to both the number of reservoirs and the number of time periods modeled. Initial testing has demonstrated that NSP has reasonable computation times and can improve upon deterministic solutions. Additional testing and improvement of the user interface are the next steps in development. If these steps are successful, we anticipate that NSP will eventually replace the current computation of the future value of water, one of the inputs to the six-hour model.

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