SCHEDULING TVA'S RESERVOIRS WITH RIVERWARE

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Abstract

RiverWare is a reservoir management modeling framework for optimization and simulation of multipurpose reservoirs developed at the University of Colorado Center for Advanced Decision Support for Water and Environmental Systems. R&D is sponsored by the Bureau of Reclamation, the Tennessee Valley Authority (TVA) and the U.S. Army Corps of Engineers, and it is used extensively by numerous water management agencies, utilities, research institutions and consultants for planning, analyzing and operating river and reservoir systems. In this paper we illustrate RiverWare's capabilities with TVA's daily operations scheduling models which optimize hydropower value while meeting non-power objectives.

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 covers 40,000 square miles in seven states in the Southeast. In addition to hydropower generation, the reservoir system provides other beneficial services throughout the Tennessee Valley, including minimum depth for navigation, flood risk reduction, flows for water supply and aquatic habitat, and recreation.

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 time step and covers a two week planning horizon. Daily scheduled releases from each reservoir provide input to the second RiverWare model, which uses an hourly time step. This model covers a planning horizon of two days and is used to schedule hourly power generation from each hydropower plant.

In RiverWare's optimization, users express reservoir operating policy as a prioritized list of objective functions and "soft" policy constraints. These can include the economic value of hydropower as well as a wide variety of non-power objectives and constraints such as water supply, navigation, flood regulation, flows for aquatic habitat, recreational flow releases, and special operations. Thus, hydropower can be optimized without violating the other requirements for multipurpose reservoirs. The policies are constructed and modified with an interactive syntax-directed editor. The policy language allows for a wide variety of policies, including total subbasin storage, seasonal elevation constraints, and daily flow averages. Policies can easily be activated, deactivated or reprioritized. In addition, policies can be added, deleted or modified. This flexibility facilitates policy studies and permanent changes in policy.

The policies are automatically translated to a preemptive goal program. The user's priorities are preserved with separate objective functions applied in priority order. Soft constraints within a priority are converted to objective functions by minimizing deviations from the constraints. Users can choose between several options for minimizing deviations. The optimization problem is solved with CPLEX, a robust and efficient third party solver. RiverWare generates a post-optimization rulebased simulation to remove small approximation errors that may have been introduced by optimization. If desired, the user can also selectively override the optimal solution.

The optimization can use either linear programming or integer programming to solve the goal program depending on the user's choice of physical process modeling. Unit level power modeling uses integer programming to reflect the discrete operating zones of individual units. Plant level power modeling uses linear programming and a continuous approximation of the individual unit operations. The continuous approximation is faster and has relatively small error when the computational time step of the model is larger than one hour.

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. The purposes of the Tennessee Valley Authority spelled out in the TVA act are to improve navigation, 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 over time including reservoir operations for water supply, water quality, and recreation.

Prior to the mid-1990s TVA had used models developed in-house and written specifically for the Tennessee Valley reservoir system. In the early 1990s TVA entered 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. Since then, the U.S. Army Corps of Engineers (USACE) has also joined the effort and RiverWare has been adopted by a wide variety of other users including other water management agencies, utilities, research institutions, and consultants.

TVA'S RESERVOIR SYSTEM

TVA is a multipurpose federal corporation which owns and operates 29 conventional hydropower plants in the Tennessee Valley. TVA coordinates the hydropower generation with their generation from other power sources including nuclear power plants, coal fired plants, combustion turbines, and power from the USACE's hydropower on the Cumberland River. 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).

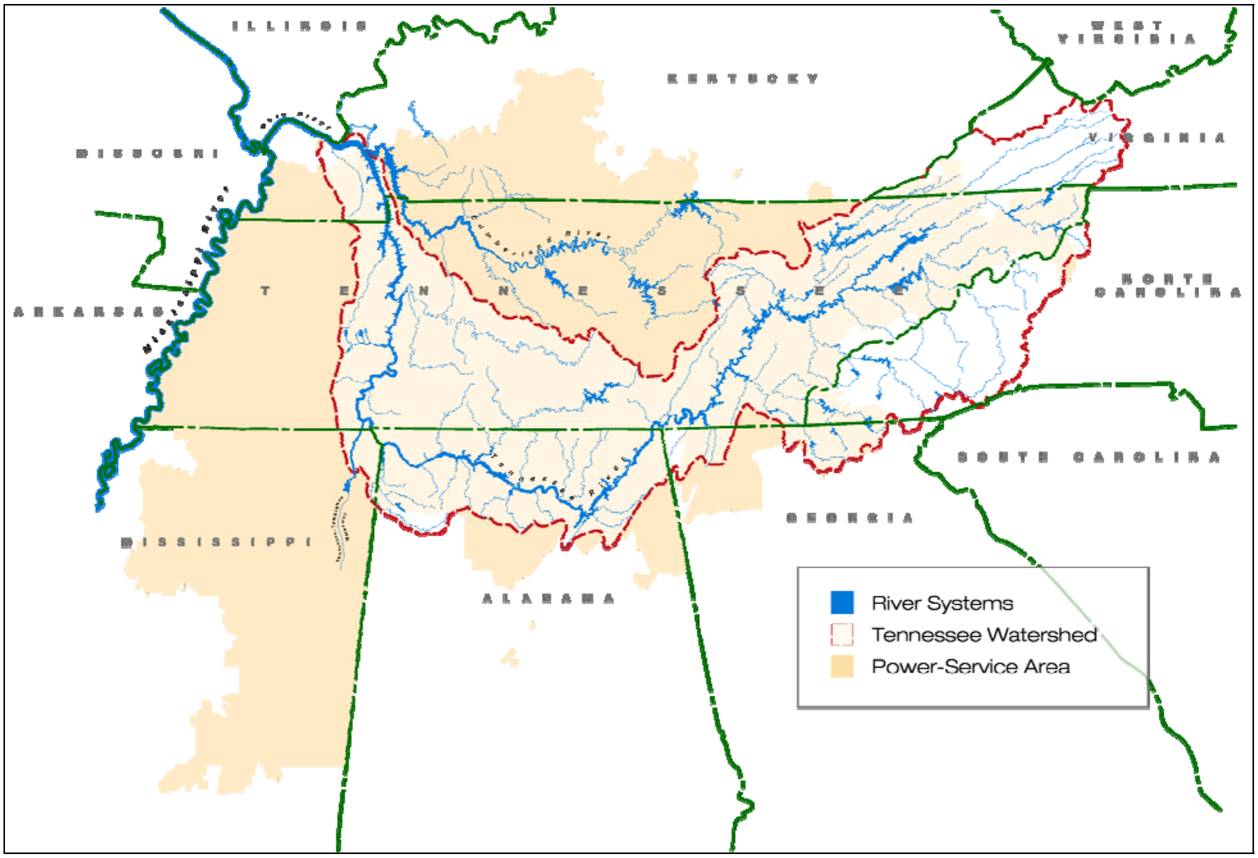


Figure 1 Tennessee Valley Watershed (outlined) and Power Service Area (shaded)

TVA non-power policy includes:

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

After the water policies have been satisfied to the fullest extent possible, the remaining flexibility of the reservoir system is used to optimize the economic value of hydropower. The value depends on the power demand within TVA's power service area and the other power sources TVA has available to meet the load. In addition, TVA can buy or sell power from other power producers. Power demand and value fluctuate with season, day of the week, and time of day. In addition to the power sources already mentioned, TVA has a pumped storage facility at Raccoon Mountain that smoothes weekly power demand variation by pumping during off-peak hours and generating during on-peak hours.

OPTIMIZATION MODELS

TVA's RiverWare optimization models contain a prioritized list of policy constraints that help guide daily and hourly operating decisions. These constraints are used to characterize the operating objectives of the reservoir system. Modelers can activate or deactivate any of the policy constraints contained within the models depending on time of year or scenario being modeled. Once the policy constraints have been satisfied to the extent possible, the economic objective function is maximized. Figure 2 shows the RiverWare workspace with the TVA Reservoir System. The red Avoided Cost object at the center of the workspace contains the information about alternative power sources, power demand, and power value.

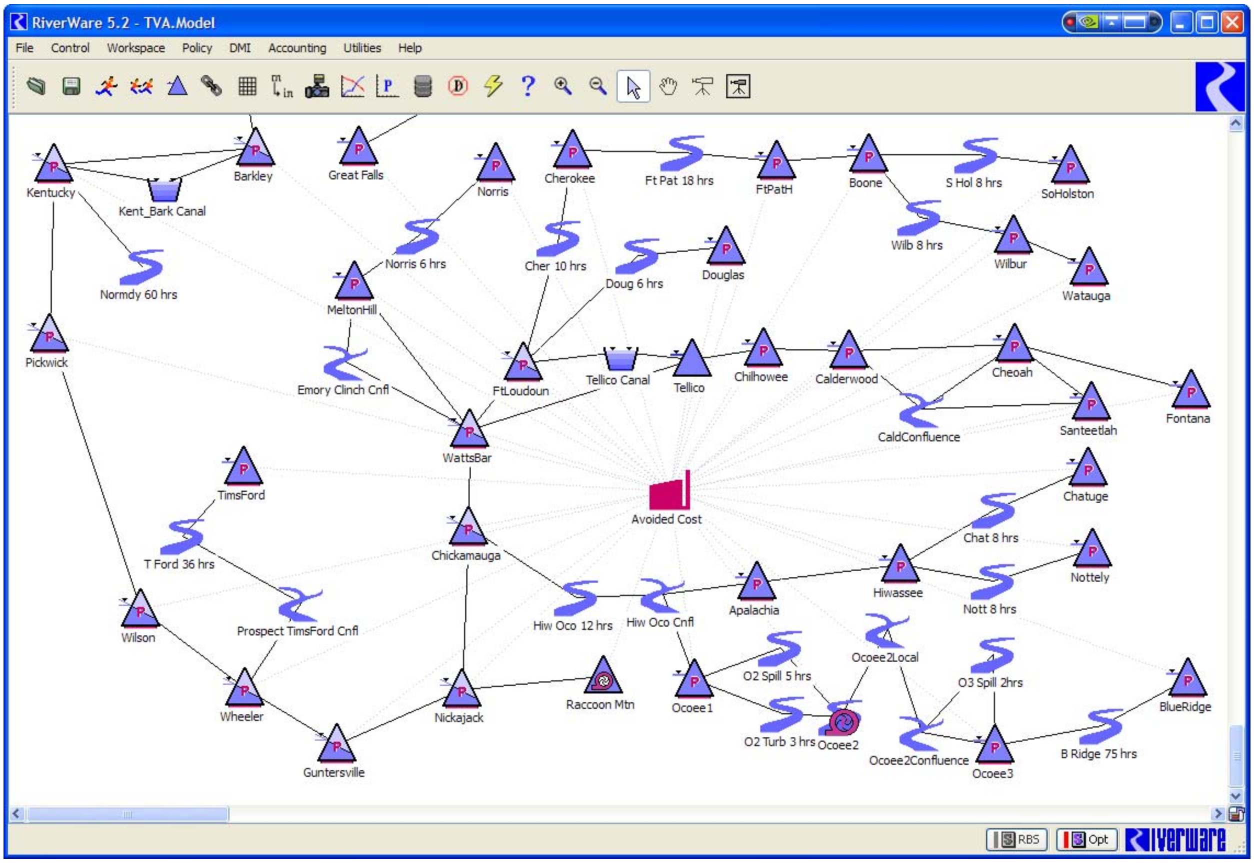


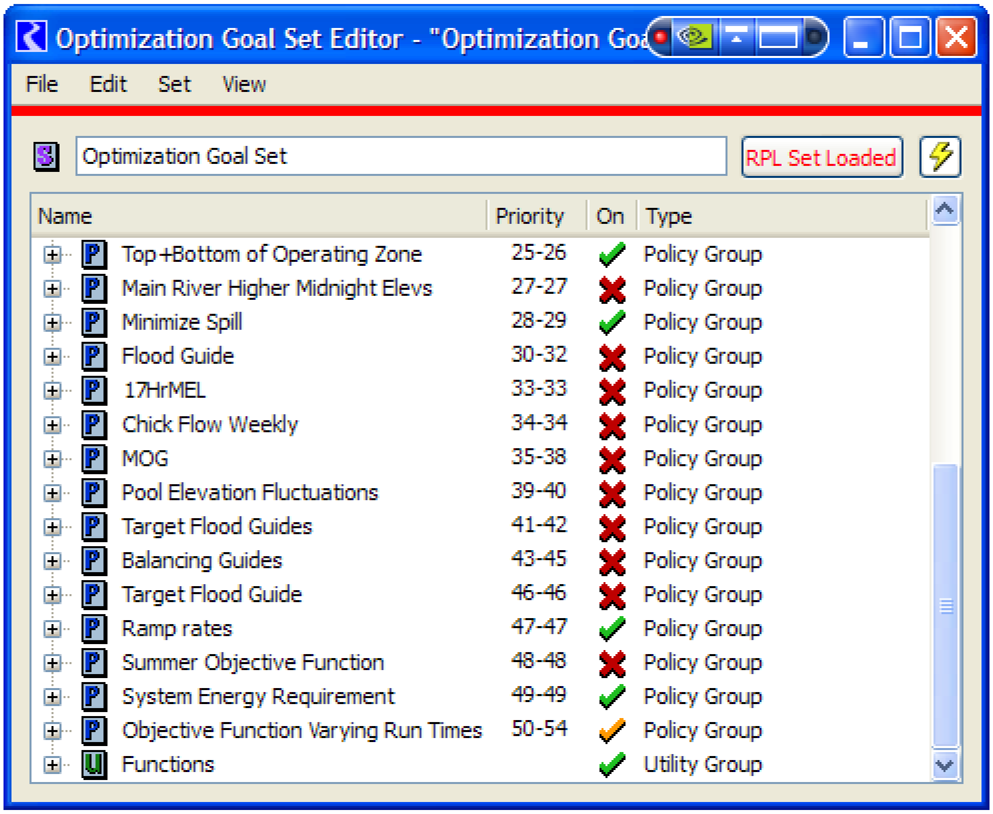
Figure 2 RiverWare Workspace Showing TVA Reservoir System and Thermal Object

TVA uses two different RiverWare models to schedule turbine discharges, spillway releases, power generation, and resulting pool elevations at each of its hydropower reservoirs. The first model uses a six-hour time step and covers up to a two week planning horizon. The second model covers two days and refines the daily schedule into an hourly schedule so that each hydro plant can generate power during the most economic hours while still meeting other multipurpose objectives. Specifically, the hourly model is constrained to have the same daily outflow totals as the six-hour model. Schedulers can and do intervene to modify the schedule. The final schedule 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. Both models are updated and rerun as conditions change during the day.

Inputs to the models include an inflow forecast, a prioritized list of constraints, and a predicted 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.

The policies are constructed and modified with an interactive syntax-directed editor. The policy language allows for a wide variety of policies. Policies can easily be activated, deactivated or reprioritized. In addition, policies can be added, deleted or modified. This flexibility facilitates policy studies and permanent changes in policy.

Some examples illustrate the flexibility of the policy editor. Figure 3 shows part of TVA's policy set with some of the policies activated and others deactivated. Some of the policies have been combined into policy groups for easier visualization. The priority range of eage group is also shown in the set.

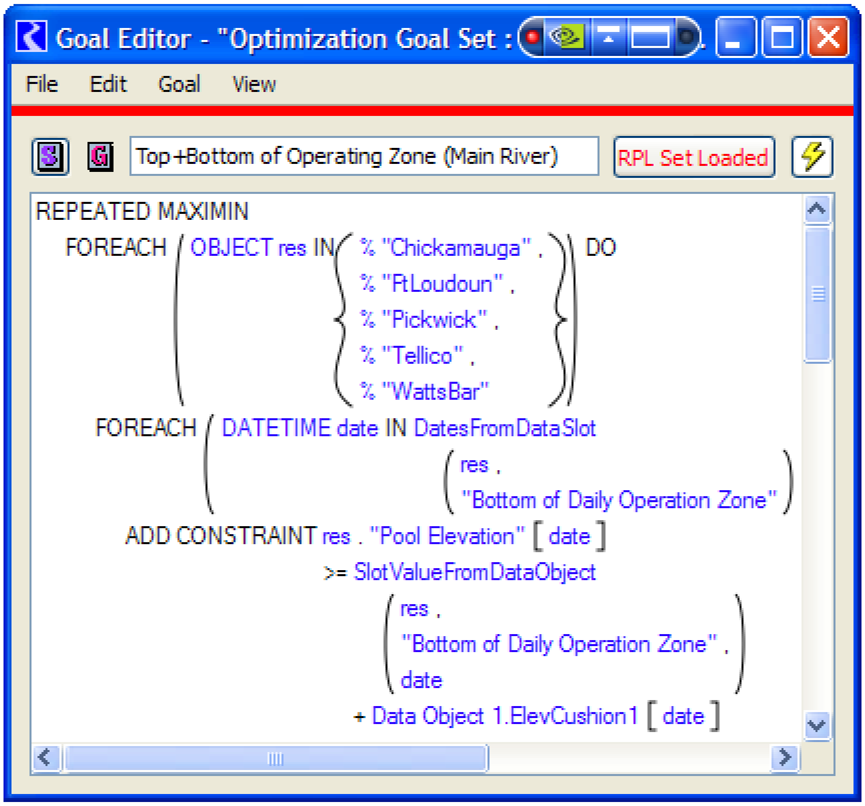


Optimization Goal Set

Name	Priority	On	Type
Top+Bottom of Operating Zone	25-26	✓	Policy Group
Main River Higher Midnight Elevs	27-27	✗	Policy Group
Minimize Spill	28-29	✓	Policy Group
Flood Guide	30-32	✗	Policy Group
17HrMEL	33-33	✗	Policy Group
Chick Flow Weekly	34-34	✗	Policy Group
MOG	35-38	✗	Policy Group
Pool Elevation Fluctuations	39-40	✗	Policy Group
Target Flood Guides	41-42	✗	Policy Group
Balancing Guides	43-45	✗	Policy Group
Target Flood Guide	46-46	✗	Policy Group
Ramp rates	47-47	✓	Policy Group
Summer Objective Function	48-48	✗	Policy Group
System Energy Requirement	49-49	✓	Policy Group
Objective Function Varying Run Times	50-54	✓	Policy Group
Functions		✓	Utility Group

Figure 3 Part of TVA's Optimization Policy Set

Figure 4 shows the detail for one policy, the bottom of the daily operating zone. This policy constrains four reservoirs to be greater than their respective pool elevation curves whenever the curves are defined. The constraints are “soft”, meaning that the optimization will satisfy them if possible, and if not will try to meet them as closely as possible.



Top+Bottom of Operating Zone (Main River)

```
REPEATED MAXIMIN
   FOREACH ( OBJECT res IN ( % "Chickamauga" ,
                             % "FtLoudoun" ,
                             % "Pickwick" ,
                             % "Tellico" ,
                             % "WattsBar" ) ) DO
      FOREACH ( DATETIME date IN DatesFromDataSlot
                                       ( res ,
                                         "Bottom of Daily Operation Zone" )
         ADD CONSTRAINT res . "Pool Elevation" [ date ]
                        >= SlotValueFromDataObject
                                ( res ,
                                  "Bottom of Daily Operation Zone" ,
                                  date )
                         + Data Object 1.ElevCushion1 [ date ]
```

Figure 4 A Soft Policy Constraint: Bottom of Daily Operating Zone

GOAL PROGRAMMING

One way to model the multi-purpose aspect of reservoir management is with preemptive goal programming. Each priority level of a policy set, such as the one shown in Figure 3, is a “goal” with an objective function that is optimized. The “preemptive” aspect of this approach is that low priority goals are constrained by the optimal values of higher priority goals. The objective functions for each goal may be specified directly in the policy set or they may be created indirectly from “soft” policy constraints. The objectives for soft constraints are created by attaching satisfaction variables to each constraint and maximizing a function of the satisfaction variables.

Several alternatives exist for defining a function to balance the satisfaction of competing constraints. If all of the constraints can be satisfied then the choice from the alternatives will not matter. Thus, the primary consideration for choosing a function is how to balance deviations in the constraints when they cannot all be satisfied simultaneously. RiverWare offers three options for balancing these deviations: minimizing the sum of deviations, minimizing the largest deviation, and repeatedly minimizing the largest deviations. The last option first minimizes the largest deviation, and then repeatedly minimizes the next largest deviations to the extent possible without degrading constraints with larger deviations. In practice, TVA has used the last option for a most goals because it balances deviations across reservoirs and across time.

HYDROPOWER OBJECTIVE FUNCTIONS

Water discharged and energy generated at each of the reservoirs 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.

Several different hydropower objective functions are available to modelers and TVA currently uses all but one of these methods. The objective functions differ both in how they model the water remaining in storage and the short term value of generation, and we will discuss the modeling variations for both of these components.

The water remaining in storage can be modeled in two ways. One approach is to constrain the ending storage level. A second approach is to model the economic value of water remaining in storage and allow RiverWare to tradeoff short term generation against the long term value of storage. Because the marginal value of additional storage generally decreases with increasing storage level, RiverWare allows the long term value of storage to be a piecewise value of storage.

During the summer months (June 1 – Labor Day), reservoir system operations are prescribed by the 2004 Reservoir Operations Study. There is a weekly flow requirement at a key control point near Chattanooga, Tennessee, downstream of all of the large tributary storage projects. Above this control point, pool elevations at each of the ten large tributary reservoirs are balanced relative to one another. Therefore, during the summer months, future value of stored water is not an issue. During the rest of the year, the future value of the water is used to trade off against short term generation.

The short term value of generation can be modeled in three different ways in RiverWare. First, a different value of power can be predicted for each time period. This value is sometimes referred to as a “system lambda” value. The second approach extends the first by allowing the marginal value of generation to decrease as generation is increased for each time period. At TVA, the hydropower generation is broken into blocks of 50 MW, with each successive block having a decreasing (or constant) value of generation. When this approach is used the solution tends to allocate power to peak periods resulting in a relatively smooth marginal value of power across time. The third approach is to specify a load to be met and to provide cost information for alternative power sources, typically thermal power units. With this approach, the value of hydropower is the value of the thermal generation it replaces.

When TVA uses the future value of water remaining in storage (non-summer months), the “system lambda” approach is used for short term generation. The reason for this is that the data used to calculate the future value of water lacks the depth used in the “block” approach. Thus, for consistency both the short term and the long term valuations use a system lambda approach. After optimizing for the combined short term and long term value using this approach, the ending pool elevation levels for the reservoirs are fixed at their optimal values, but the rest of the solution is not used.

The "block" valuation of short term generation is used year round once ending pool elevations have been constrained. The ending pool elevations are determined either by optimal pool elevation balancing (Summer) or by trading off the long term value of storage against short term generation (the rest of the year). 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 5.

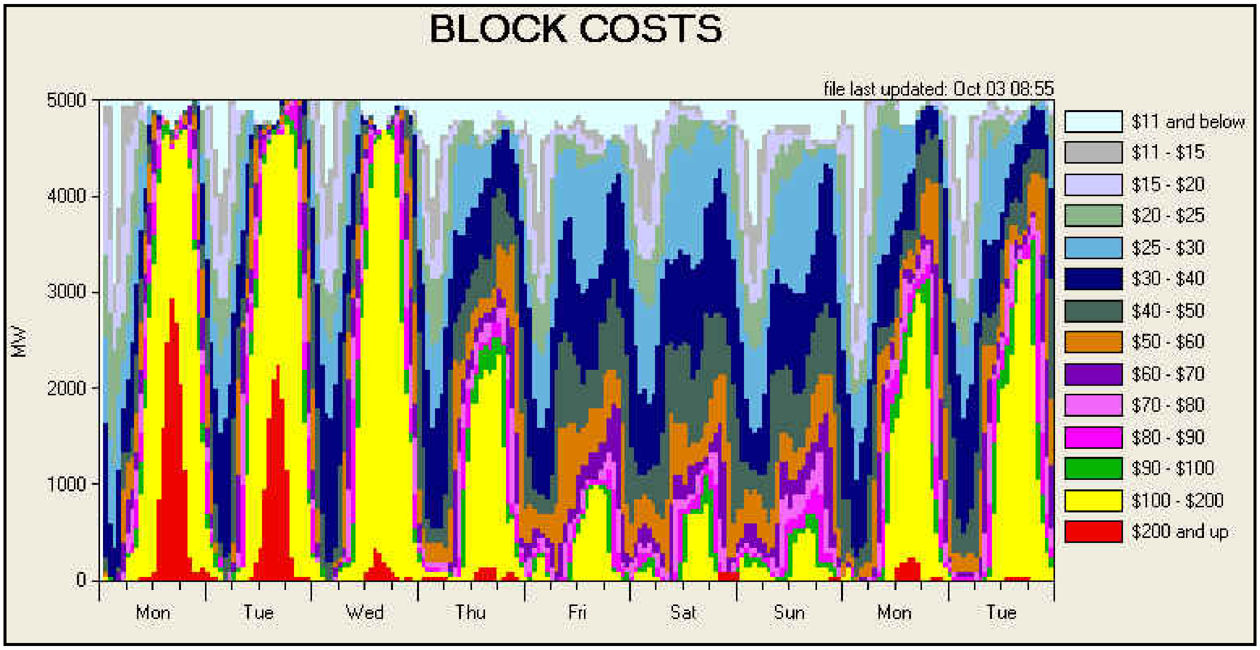


Figure 5 Block Costs Used for RiverWare Hydropower Optimization

SCHEDULING PROCESS

The optimization model is determined by the reservoir method selections and data. Each day, the reservoir elevations and inflow forecast are updated. Some reservoir operations may be specified by input values. Constraints may be activated or deactivated based on seasonality, special operations, etc. An initial simulation is performed to determine the consequences of any input values. Once optimization is started, RiverWare passes a linear programs or integer program to a robust and efficient third party solver, CPLEX. Each goal of the goal program results in a modification of the optimization problem in CPLEX and a new solution.

After optimization, RiverWare generates a post-optimization rulebased simulation. The default rules return the optimal discharge for each reservoir for each time step. If several values have been set as inputs, rulebased simulation may determine that some of the discharges are unneeded and skip them. Modelers can replace the default rule set with their own set of if-then rules and selectively access parts of the optimal solution. Modelers can also 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 time steps 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 time step 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.

POWER MODELING

RiverWare allows hydropower to be modeled in a variety of ways including modeling individual units and modeling at a plant level. Before going into the details, the advantage of plant level modeling is solution speed while the advantage of unit modeling is a more accurate representation.

The plant modeling approach models power as a continuous piecewise linear function of turbine release. Figure 6 illustrates a plant power curve and a piecewise linear approximation to it. The curve has been exaggerated to more clearly show the difference between the actual curve and the approximation, because a more realistic curve would obscure much of the difference. The largest approximation error in practice is in the range between zero generation and best efficiency.

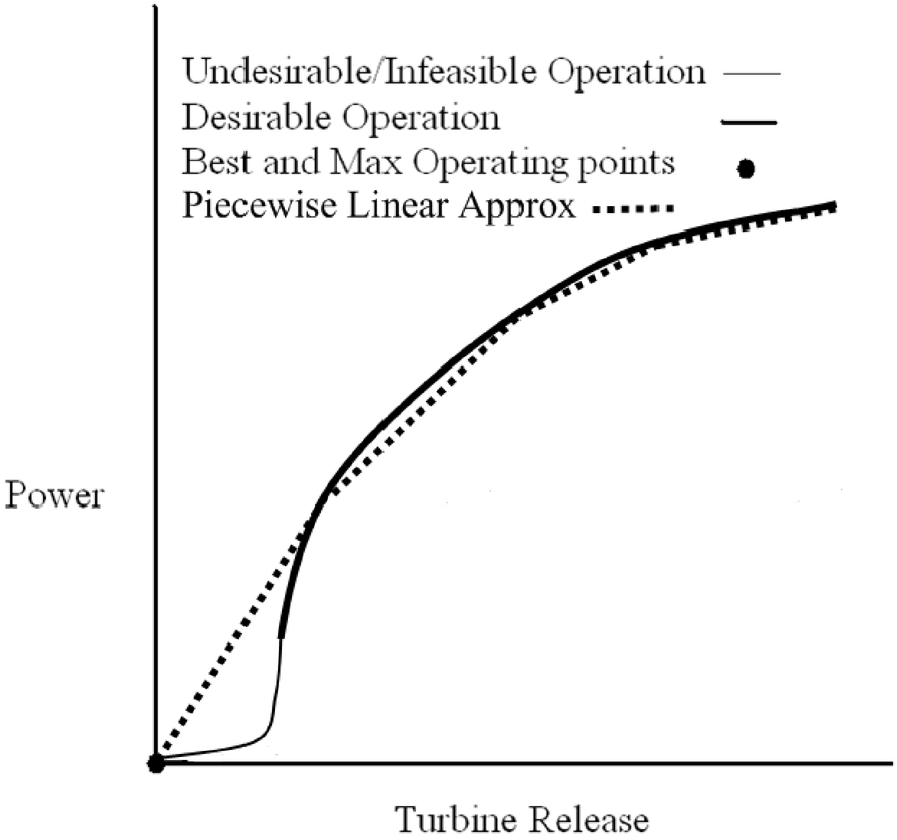


Figure 6 Exaggerated Plant Power Curve and Approximation

This approximation can be solved efficiently with linear programming and is appropriate for any time step larger than an hourly time step. For example, TVA uses this approach in their 6-hour time step model. With a larger time step a solution in a poorly approximated region can be shifted slightly at the hourly level. Operating head can be included in this model in one of two ways. Either the operating head can be estimated prior to optimization or the approximation can include a term to adjust power for operating head.

Modeling at the unit level reduces approximation error, particularly for an hourly time step model. Figure 7 illustrates an operating region for an individual unit with an avoidance zone. The feasible operating region has been divided into triangular regions. RiverWare models the exact power at each point of the diagram and approximates power within each triangular region as a weighted average of its endpoints. Users have full control of the approximation points and can reduce approximation error with smaller triangles but at the cost of increased solution time.

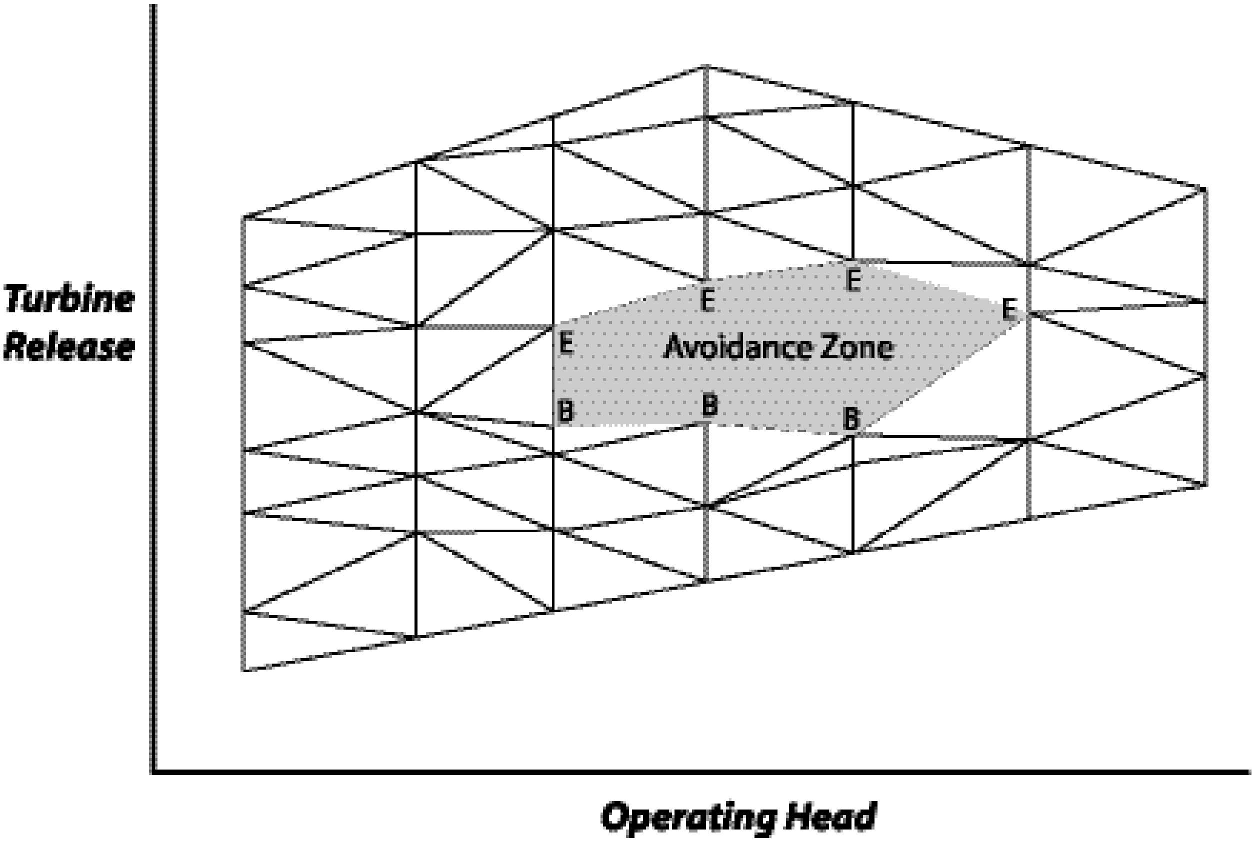


Figure 7 Triangulated Unit Operating Region

This unit modeling provides more accurate modeling in several ways:

- Power is more closely approximated as a function of turbine release and operating head;
- Units are either on or off and minimum generation limits are observed;
- Cavitation and vibration zones are avoided;
- Generation "holes" with a unit off for only one period can be prohibited in policy; and
- Wear and tear" cost of starting a unit can be included in policy.

The discrete aspect of turning units on and off and avoidance zones require integer programming. Integer programming is considerably slower than linear programming. In this particular case, solving the integer program to optimality will usually be unrealistic because of the computation time. For this reason, RiverWare includes a heuristic solution approach when unit modeling is used.

The heuristic gradually imposes integer restrictions. The user can control how the integer restrictions are imposed and thus make a tradeoff between solution time and solution quality. For example, the integer restrictions can be imposed one time period at a time. In this case, the first time period has integer variables while the remaining time periods use a continuous approximation. After solving this problem, the optimal integer values for the first time period are locked in, the second time period variables are required to be integer, and the problem is reoptimized. This process is continued until all time periods have been solved with integer restrictions.

This heuristic should not be confused with solving each time period independently. Instead at each time step of the heuristic the solution is constrained by previously locked integer variables, the continuous relaxation of future integer variables and the constraints for all time periods. Also, the continuous variables for all time periods can change with each solution.

Users can control the heuristic to simultaneously impose integrality restrictions for a block of time periods. If the block is the entire time range, the heuristic is replaced with exact optimization.

This approach has been implemented for a power utility's model. In the future, TVA's hourly model will be converted to use this approach.

CONCLUSION

RiverWare is a reservoir management modeling framework used at TVA and many other organizations. TVA's two daily operations scheduling models which optimize hydropower value while meeting non-power objectives expressed as "soft" constraints. The first model uses a six-hour time step and covers a two week planning horizon. Daily scheduled releases provide input to the second RiverWare model with an hourly time step over two days. Policies can easily be modified, activated, deactivated or reprioritized in a syntax-driven editor. The optimization is a preemptive goal program and can be solved with either linear programming or integer programming depending on whether plant or unit level modeling was selected. Unit modeling is more accurate, particularly for an hourly time step, but results in a computationally more difficult integer program and a heuristic is used to solve it.

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