DEVELOPMENT AND USE OF USACE-SWD FLOOD CONTROL HYDROPOWER ALGORITHMS IN RIVERWARE

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Abstract: The U.S. Army Corp of Engineers (USACE) Southwestern Division and associated Districts operate numerous multipurpose reservoirs for flood control, hydropower, navigation, municipal and industrial, recreation, water quality, and environmental purposes. To manage their water resources effectively, in the mid-1960's they developed a simulation modeling suite of FORTRAN programs called SUPER. SUPER became difficult to maintain with the retirement of key modeling personnel so the Division has decided to replace the model using RiverWare™. Researched and developed by the University of Colorado Center for Advanced Decision Support for Water and Environmental Systems (CU-CADSWES) in collaboration with the Tennessee Valley Authority (TVA), the U.S. Bureau of Reclamation (USBR), and the USACE, RiverWare is a highly-configurable, extensible, data-driven river and reservoir modeling tool that can be run either as a stand-alone application, or in concert with other models and databases. The flood control algorithms used in SUPER solve the network as a system to release the flood pool as quickly as possible, avoid flooding at downstream channel control points, and balance storages in the reservoirs. The integration of USACE flood control release calculations in RiverWare brings together RiverWare's object-oriented modeling features, the power and flexibility of the priority rulebased simulation, and features that allows the execution of multi-object computations from a rule function. This paper presents the USACE flood control algorithm and describes the implementation of the algorithm in RiverWare.

INTRODUCTION AND BACKGROUND

The Corps of Engineers Southwestern Division and associated District offices civil works mission includes operation of numerous multipurpose federal and non-federal reservoirs. Regulation requires management for flood control, hydropower, navigation, municipal and industrial, water quality, recreation, and environmental related issues. The system includes mainstem and tributary reservoirs having multiple series and tandem configurations with common downstream regulation points. Reservoir and system flood storage need to be evacuated as soon as possible given downstream and system constraints. Configuration of these reservoirs is such that a system-management approach is needed to best meet all objectives.

During the late 1960's the USACE identified the need to develop a basin simulation model to analyze operational decisions. In the early 1970's, the initial period of record simulation model "SUPER" was developed by Mr. Ronald L. Hula, Corps of Engineers. The suite of SUPER models are used to perform simulations that are required to evaluate proposed changes to the water control plans, deviations, operation and maintenance schedules, economics, and hydrologic probabilities. Models are also used to answer questions raised by customers, congressional inquiries, and to update reservoir regulation manuals. During his career with the Corps of Engineers of nearly 30 years, Mr. Hula exclusively maintained and enhanced the SUPER modeling program suite, which contains numerous complex subroutines. Mr. Hula is the only one who intimately knows the subroutines and how they work. For any significant logic changes required for special investigations, he is the only one knowledgeable enough to make required software changes.

After Mr. Hula's retirement in 1999, a Southwestern Division (SWD) wide team was created to evaluate existing basin simulation capabilities of the Districts in the short and long term. It was determined that developing a new basin simulation model is mission-essential. The team was given the task of investigating the existing SUPER programs capabilities and alternative programs to meet basin simulation needs. The team's recommendation was to use the RiverWare™ basin simulation program developed at the University of Colorado - Center for Advanced Decision Support for Water and Environmental Systems (CU-CADSWES) in collaboration with Tennessee Valley Authority (TVA), the U.S. Bureau of Reclamation (USBR), and the U.S. Army Corp of Engineers (USACE). RiverWare looked very favorable, however some enhancements were recommended to replicate SUPER's approach. SUPER has been used in the interim, with Mr. Hula's assistance, until RiverWare enhancements are complete. He has also provided consultation to the RiverWare developers and SWD Districts in regard to SUPER algorithms.

RiverWare is a fully-supported and documented general river and reservoir computer modeling application (Zagona et al., 2001 and Zagona et al., 2005). RiverWare simulates the hydrologic response of the river system, given unregulated inflows and management decisions such as reservoir releases and diversions. The management decisions are implemented as rules, defined in an interpreted language by the user. The basic approach to modeling is as follows: objects represent features like reservoirs, reaches, and diversions. For each object, the user selects methods that best represent physical processes such as evaporation, seepage, spill, or stage, depending on the object type. The objects are then linked together to form a network representing the basin. The simulation is then run for the period of record, with rules setting the releases and demands, and the objects propagating the flows downstream.

Unlike many RiverWare applications, the flood control algorithms used in SUPER solve the network as a system to: release the flood pools as quickly as possible, avoid flooding at downstream channel control points, and balance storages in the reservoirs. The algorithm finds a simultaneous solution for releases from all reservoirs, considering all control points (reaches at which flooding is to be limited), calculated over a specified forecast period with forecasted inflows. This paper briefly presents the USACE flood control algorithm and then describes the implementation of the algorithm in RiverWare.

USACE FLOOD CONTROL ALGORITHM

The USACE flood control algorithm calculates flood control releases in a basin (set of reservoirs and control points) with the objectives of balancing the storages in the reservoirs to the extent possible and limiting flows at downstream control points. Reservoirs are considered in balance when they are at the same operational balance level. Each reservoir has its own relationship of elevation to operating level, which includes seasonal variations. Figure 1 shows an example of the USACE storage divisions. On the right side of the figure are typical balance levels in relation to flood pool, conservation pool, etc; e.g. balance levels 2, 3, and 4 are in the conservation pool. The operating balance level is used to a) determine the boundaries of the conservation, flood, and surcharge pools on the reservoirs, and b) to indicate how "full" each reservoir is, in the interest of maintaining basin-wide balance across reservoirs that are in flood.

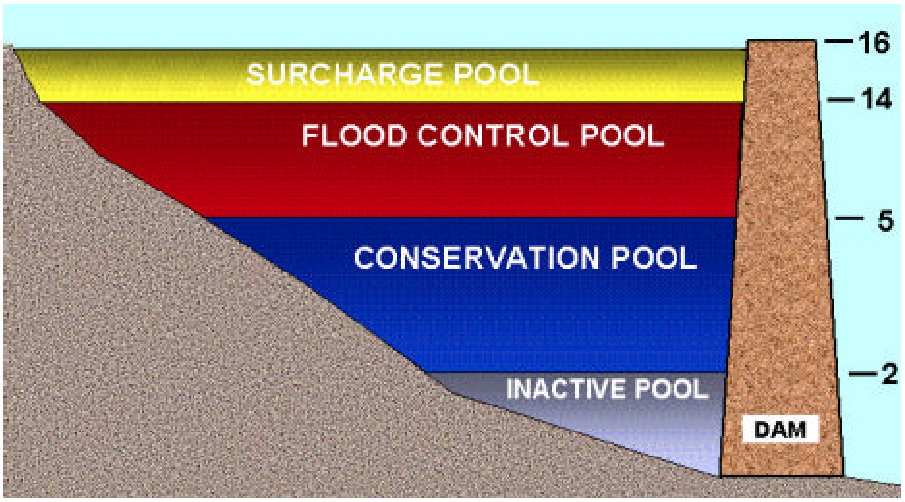

Figure 1 USACE storage divisions and balance levels

At each computational timestep, the flood control releases are calculated for each timestep in the forecast period, a specified number of days. At the end of the calculations, the flood control releases are set in the model for the current computational timestep, the releases are routed, and the simulation moves to the next timestep. The program uses user inputs that describe the reservoir and control point network and other data needed by the flood control routines. There are six major steps that the flood control subroutines perform at each timestep as follows.

Forecasted Inflows The forecasted inflows over the forecast period are developed at each point in the system where uncontrolled area flows are forecast. These points are reservoirs and control points in the basin. The forecasted inflows are calculated at each timestep for the subsequent forecast period by taking the "perfect knowledge" inflows, i.e. historical inflows over the period of record, and applying a recession factor after a specified number of days of perfect knowledge, usually 1 to 3 days. This creates a hydrograph of expected flows for a specified number of timesteps.

Mandatory Releases The mandatory releases are calculated at all reservoirs for all timesteps in the forecast period. These releases protect the dam structure by keeping the reservoirs below the top of gates. The mandatory releases are routed to the downstream control points and added to the forecast to get the total forecasted flows at the control points.

Regulation Discharge Regulation discharge at each control point is determined based on the regulation criterion specified at that control point by the input data. The criteria are, in general, one of the following: 1) a stage limitation in the channel; 2) the current or projected level of a single upstream reservoir; or 3) the percent full of a system of upstream reservoirs. The criteria can change based on date of the year. Based on these criteria, the regulation discharge is calculated, but can be adjusted to allow for a controlled recession once flooding has been experienced up to a certain level, or for lower discharges for a sustained time to allow for field drainage. An empty space hydrograph at each control point is then calculated as the difference between the regulation discharge and the total forecasted flows.

Empty Space Allocation Selected control points are designated “key” and they assist in balancing a set of upstream reservoirs. A key control point allocates percentages of its empty space to each of its associated reservoirs and calculates a balance level that is assigned to the associated reservoirs. The balance level is the level to which all of the reservoirs in the associated set can be drawn down to fill the key control point’s empty space while balancing the ending storage among the associated reservoirs. Every reservoir is assigned a balance level by one or more key control points.

Flood Control Release The flood control releases for the entire forecast period are calculated by successively lowering the balance levels and drawing down reservoirs whose ending storage is forecast to be above that balance level. In this way, flood control releases are increased to the maximum level allowed by the discharge constraints at the control points, while keeping the reservoirs balanced as much as possible. Priority is given to the fullest reservoirs for available empty space at the downstream channel control points. The solution steps through successively lower balance levels, and at each one, flood control releases are calculated for all reservoirs forecasted to be above that balance level at the end of the balance period. For each of these “fullest” reservoirs, flood control releases to get to that balance level are attempted, checking every downstream control point for flow constraints and every downstream reservoir for space to store some of the release. Linear routing coefficients are used to estimate travel times to downstream control points and reservoirs. Constraints on increasing and decreasing releases are also applied. The releases are calculated to balance the reservoirs over the balance period and to empty the flood pools over the forecast period.

Routing The flood control releases for the current computational timestep are added to the mandatory releases and routed downstream to get the total flows at the control points. The linear routing coefficients are used for this routing. The algorithm then moves to the next computational timestep (day) until all days in the simulation have been completed.

IMPLEMENTATION OF FLOOD CONTROL ALGORITHMS IN RIVERWARE

The integration of USACE flood control release calculations in RiverWare brings together RiverWare’s rich set of object-oriented modeling features, the power and flexibility of the priority rulebased simulation, and the “Computational Subbasin,” a feature that allows the execution of multi-object computations from a rule function. The flood control computational code is thus implemented in modular, object-specific contexts for ease of maintenance and extension, as well as flexibility of use through user-selectable methods. This section describes the RiverWare components, rule set components and execution of the rules and methods that simulate the USACE flood control operations.

Model Components The RiverWare model consists of objects (Reservoirs, Reaches, and the like), which contain data attributes ("slots") and method attributes (algorithmic components) that the user selects and configures. The following sections describe the components used to simulate the USACE flood operations.

Reservoir Objects User-selectable methods for surcharge releases, forecasted inflows, and flood control releases support calculations and flood control slots specific to reservoir objects.

Control Point Objects Control Point objects are used in the basin network to represent channel control points that influence flood control releases. User selectable methods on Control Point objects support the calculation of forecasted inflows (uncontrolled area flows), regulation discharge, and empty space hydrographs. Key control points have methods to support their additional computations, such as allocating empty space to upstream reservoirs according to their needs.

Surcharge Release and Regulation Discharge Flags The surcharge release and regulation discharge flags are used to trigger the surcharge release and regulation discharge calculations on reservoirs and control points, respectively. Rules are used to set the surcharge release flag on the outflow slot of each reservoir. When this flag is set, it triggers the reservoir to dispatch and compute a surcharge release forecast. The regulation discharge flag is also set on all control points. This flag triggers each control point to solve for its regulation discharge and empty space hydrographs according to the user methods selected on each control point object.

Computational Subbasin RiverWare includes a feature called a Subbasin, used to group together sets of objects for the convenience of modelers. The concept has been extended to support various specialized computations; for system-wide solutions such as flood control, RiverWare now offers a "Computational Subbasin." The computational subbasin has user selectable method categories, methods, and data slots to support calculations that involve multiple simulation objects simultaneously. The Flood Control category includes two methods that govern the nature of the flood control solution. The Operating Level Balancing method is used to model flood control based on the USACE-SW algorithms. The Phase Balancing method is based on the USACE – Kansas City District flood control operations and is not discussed in this paper.

Rule Set Components Rules for flood control operations can be included in rule sets that implement other operating policies such as meeting water demands, minimum flow releases, hydropower, etc. To execute the full suite of flood control release calculations, the surcharge releases, regulation discharges, and empty space hydrographs must be computed prior to the rule that invokes the FloodControl function. These rules are described below.

Surcharge Release Rules The surcharge release calculations are executed by the reservoir object when the surcharge release flag is set on the outflow slot by a rule. There is one such rule for each reservoir object. The rules start at the upstream end of the basin. When the surcharge release flag is set, the reservoir will dispatch during post-rule simulation if the Inflow to the reservoir is also known. During dispatching, the reservoir will compute the surcharge release forecast and set the Outflow slot for the current timestep and all other timesteps in the forecast period. These outflow values propagate via links to downstream objects and are routed using the selected routing method on any Reach objects that are encountered. When the flow values reach a downstream reservoir, that reservoir will have Inflow slot values for the forecast period. A subsequent rule will set the surcharge release flag on that reservoir resulting in dispatching. In this way, each subsequent downstream reservoir calculates the surcharge releases for the forecast period considering the routed surcharge releases from upstream reservoirs.

Regulation Discharge Rule After all the surcharge release rules have executed and the releases have been routed downstream, a single rule sets the regulation discharge flag on the "Reg Discharge Calculation" slot for all Control Point objects. This triggers each control point to dispatch and execute the selected regulation discharge methods. Because the uncontrolled area inflow forecasts have already been computed and the surcharge releases have been routed downstream, each control point contains the total discharge at its location for each timestep in the forecast period. This information is used to compute the regulation discharge and empty space hydrographs.

Flood Control Release Rule After the regulation discharge rule has executed, the rule to calculate the flood control releases is executed. This rule calls the pre-defined FloodControl function, which executes the selected Flood Control method on the computational subbasin.

At this point, a global solution computes the flood control releases for the current computational timestep using the USACE algorithm described in the previous section. No physical-process simulation occurs during this algorithm until the flood control function finishes for this timestep. More specifically, the solution works as follows:

1) Analyze reservoirs in the basin to determine their "fullness", based on operating level.
2) Select the reservoirs that are in flood, sort them according to fullness (in descending order of operating levels). This prioritizes the reservoirs: fuller reservoirs get priority over less-full reservoirs, meaning that they get first crack a making releases and consuming downstream empty space.
3) Compute a set of "balance levels" (operating levels) based on computations by key control points. Sort these balance levels in descending order. Run a "pass" for each level. A pass consists of two parts: propose flood releases and then apply the flood releases.
    a) **Propose flood releases**: Visit only the reservoirs whose operating level is above the balance level of the pass. Propose releases to bring these reservoirs to the balance level of the pass over the forecast timesteps without violating any constraints. Next, visit all downstream control points, applying successive upper bounds on the releases based on the control points' empty space. When encountering a downstream ("tandem") reservoir, apply a two-reservoir balancing method (if selected) to allow water to be stored in the tandem reservoir up to the point at which both reservoirs are at the same operating level. Any additional water flowing into the tandem becomes part of its flood release. Control points downstream of the tandems are then visited, as described above.

    b) **Apply flood releases**: When the end of the basin is reached, go back and pseudo-simulate as if the flood releases are made from the reservoir. Descend the network again, route these flood releases to the control points, adjust their empty space over the forecast timesteps, route releases to the tandem reservoirs, and adjust their storage.

The last pass is always with the operating level that corresponds to the bottom of the flood pool, so it computes releases that empty the flood pools where possible. Any reserved empty space at key control points on this pass becomes available to all reservoirs on a first-come, first-served basis. At the end of this pass, the global solution is finished for the timestep.

Because the flood control algorithm is computationally intensive, routing of flows from reservoirs to control points within the flood control function execution is approximated by linear routing coefficients. Post-rule physical-process simulation may use non-linear routing methods, which may result in different flows and storages from those predicted by the flood control function; the simulation corrects any such approximation errors before the next computational timestep.

The FloodControl function returns a list of flood control releases that should be made for each reservoir at the current timestep. The flood control rule sets the Outflow slot (flood control plus surcharge release) and Flood Control Release slot on each reservoir, at the current timestep, given the values returned by the FloodControl function. Setting these slots triggers each reservoir to re-dispatch using the new Outflow value. The reservoir objects re-solve, compute new storage and pool elevation values (as well as execute any user selectable methods), and the new Outflow values are routed downstream.

Summary of Rule-Simulation Interaction for each Timestep Following is a summary of the flood control steps that are taken during each timestep.

1. At the beginning of the timestep, a new inflow forecast (uncontrolled area flows) is computed for each reservoir and control point object.
2. The surcharge release rules execute in upstream–to-downstream order and set the surcharge release flag on the Outflow slot of each reservoir. After each rule executes, the affected reservoir dispatches and computes its surcharge release forecast. These releases are routed downstream to the Inflow slot of the next reservoir before the next rule executes.
3. The regulation discharge rule executes and sets the regulation discharge flag on the Reg Discharge Calculation slot on each control point. The control points dispatch and compute regulation discharge and empty space hydrographs for the forecast period.
4. The flood control rule executes and invokes the FloodControl pre-defined function. This function computes the flood control releases for the subbasin and returns the flood control release and outflow values, for the current timestep, for each reservoir. The rule then sets the flood control release and outflow values on each reservoir. The reservoir objects re-dispatch and solve for pool elevation, storage and any other reservoir methods that have been selected. The flows are then routed through the downstream reaches and control points using the physical-process methods selected on the objects.
5. If no other rules exist, the timestep is complete. RiverWare moves to the next timestep and the process is repeated

TEST CASE AND SUMMARY

The Arkansas River system in the Tulsa District is the most complex in the Southwestern Division, thus, the Arkansas River system was selected for the prototype RiverWare enhancement, testing, and evaluation case. This Arkansas River basin contains 21 reservoirs and 47 control points. The period of record simulation approach analyzes the system as if all reservoirs were in operation for the entire period of analysis, regardless of when reservoir construction or impoundment occurred. Simulation logic is such that on a given day in the period of record, reservoir releases are determined based on the current state of all reservoirs, control points, and entire system, and based on regulation criteria with limited forecast knowledge.

The system was modeled in RiverWare using the model and rule set components described above. In addition, functionality was added so that a comparison could be made between results calculated in RiverWare and those made by SUPER. Testing was performed on the Arkansas River system for a 61-year daily timestep simulation. Two general tests were performed using significant precision. The first involved resetting RiverWare storages to that of SUPER for each timestep and comparing computations. The second test involved full period independent simulations. For both cases, surcharge, control point regulation, balance level, and release results were compared directly. Results are very similar; RiverWare and SUPER computations follow the same pattern. There are times when RiverWare releases a little more water than SUPER, however, during later timesteps this is reversed to bring the differences back into balance. Computed storage and release differences are fractions of percents. These differences are so small that from a practical standpoint, results can be considered identical. Generally, RiverWare releases more water from the system than Super, however neither one is a clear winner over the other for better balancing. In addition, Simulation results closely matched actual historical balancing operations conducted by USACE personnel within the system of reservoirs.

Presented in this paper is the flood control algorithm used by the USACE Southwestern Division and its implementation in RiverWare. The algorithm strives to avoid downstream flooding yet must balance reservoir storage and also make mandatory releases to protect the reservoir structures. Implementing this algorithm led to a unique combination of objects, methods, and rule functions that execute a global or network solution. Because of the extensibility of RiverWare, this decision-support tool will help the USACE manage the water resources effectively for years to come.

REFERENCES

Hula, R.L., (2000), “Southwestern Division Modeling System for the Simulation of the Regulation of a Multi-purpose Reservoir System”.

Zagona, E.A., Fulp T.J., Shane R., Magee, T., and Goranflo, H.M. (2001). “RiverWare: A Generalized Tool for Complex Reservoir Systems Modeling,” Journal of the American Water Resources Association, AWRA, 37(4), pp 913-929.

Zagona, E.A., Magee T., Goranflo, H.M., Fulp T., Frevert, D., and Cotter J. (2006). “RiverWare,” Chp 21 of Watershed Models. Ed. Singh, V. and Frevert, D. CRC Press.