MULTI-OBJECTIVE MODELING IN RIVERWARE FOR USACE-SWD

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Abstract: The U.S. Army Corp of Engineers Southwestern Division (USACE-SWD) and associated Districts operate numerous multipurpose reservoirs for flood control, water supply, hydropower, navigation, recreation and water quality. They have developed several models in RiverWare for planning studies. This paper describes the methods and functions in RiverWare, how they are applied in the context of the rulebased simulation solver to perform these studies, and some additional utilities in RiverWare developed by the authors in collaboration with SWD to strengthen their usability and analysis capabilities. The SWD methods include: disaggregation of local inflows from cumulative values; surcharge releases at reservoirs; regulation discharge computations to determine the available space at downstream control points; the system-wide flood control algorithm that computes flood control releases at all reservoirs while maintaining balanced storages and releasing flood pool over the forecast period without flooding downstream control points; water supply and minimum flow releases computed to meet targets while balancing reservoir storage; and hydropower releases to meet system load. The integration of the SWD algorithms bring together RiverWare's object-oriented modeling features and the power and flexibility of the priority rulebased simulation. The algorithms are thus implemented in modular, object-specific contexts for ease of maintenance and extension, as well as flexibility of use through user-selectable methods. In addition to these multi-objective planning studies, the capability to perform single or multiple reservoir yield studies was developed by enhancing RiverWare's Multiple Run Manager use a user-define logic to make iterative runs that converge on the demand that exactly empties the conservation pool during a specified hydrologic sequence. Other SWD-sponsored enhancements include a direct data connection to the Corps' Data Storage System (DSS), and the development of statistical post-processing. This paper will also present an example of an application on one of the basins operated by the SWD. RiverWare is developed by the University of Colorado Center for Advanced Decision Support for Water and Environmental Systems (CU-CADSWES) under sponsorship of the Tennessee Valley Authority (TVA), the U.S. Bureau of Reclamation (USBR), and the USACE.

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. 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 (Hula 2000). 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. 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 is a fully-supported and documented general river and reservoir computer modeling application (Zagona et al., 2001 and Zagona et al., 2006). 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 USACE-SWD algorithms solve the network as a system to meet the following objectives:

- Local Inflow Computation: disaggregate and forecast cumulative inflows.
- Flood Control: Make mandatory releases (surcharge) to ensure safety of structure, then determine the available empty space at downstream control points (regulation discharge), and finally, release from the flood pool as quickly as possible while avoiding flooding at downstream channel control points and balancing reservoir storages (flood control releases).
- Conservation Pool Operations: release water for downstream demands and divert water directly out of reservoirs while balancing reservoir storage.
- Hydropower: release for hydropower demand without causing additional downstream flooding.

In Daylor (2006), the authors present the specifics of the flood control algorithm and how it is implemented in RiverWare. Additional RiverWare enhancements and modeling work has been performed to implement the conservation pool and hydropower operations. In this paper, we present each of the above operations and describe how it is implemented in the model. In addition, we present functionality used to perform yield studies.

MODEL COMPONENTS

Objects with Method Selections: 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 main components used to simulate the USACE functionality.

Reservoir Objects: Power and storage reservoirs are used to model water storage and its release. Methods are available to support various types of flood control, low flow releases, and other physical processes. 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 surcharge pool, flood pool, conservation pool, and inactive pool; E.g., balance levels 2, 3, and 4 are in the conservation pool. The operating balance level is used to indicate the "fullness" of each reservoir in the interest of maintaining basin-wide balance.

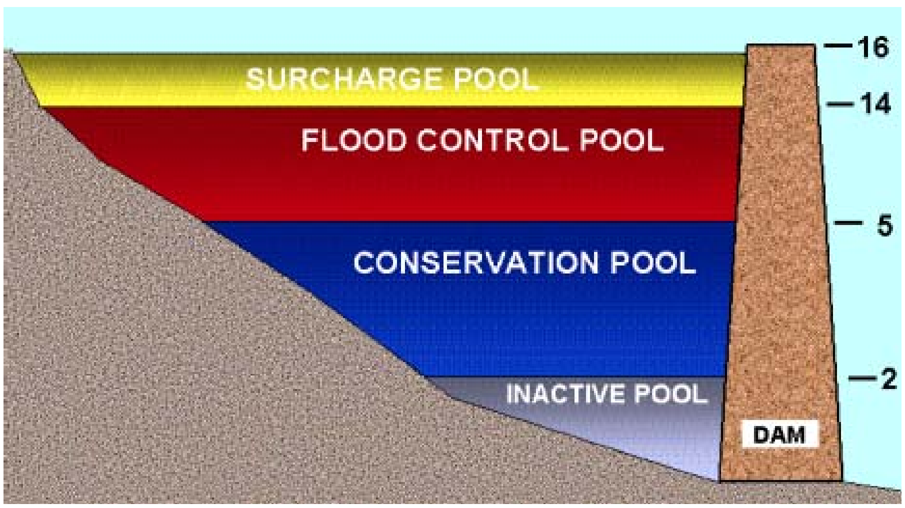

Figure 1 USACE storage divisions and balance levels

Control Point Objects: Control point objects are used in the basin network to represent channel points that influence flood control and low flow releases.

Reaches: River reach objects are used to route the water through the system and allow for diversions. Reaches use linear (Step Response) routing coefficients. During extremely large events with overbank flow, fixed channel routing coefficients are insufficiently accurate to model the routing of water through the reach, i.e., large flows that occupy the overbanks have different travel times. To meet this need, RiverWare was enhanced to provide a variable step response routing method where the coefficients are dependent on flow rate. Each inflow to the reach determines the set of coefficients to use.

Diversions Objects and Water Users: These two objects are used to simulate the removal of water from a reach or reservoir. They solve for the demand, diversion, depletion and/or return flow.

Computational Subbasin: For system-wide solutions such as flood control, RiverWare offers a "Computational Subbasin" which has user selectable method categories, methods, and data slots to support calculations that involve multiple simulation objects simultaneously like flood control, low flow releases, cumulative flow disaggregation, and hydropower releases.

Ruleset: The USACE operations are executed by calling prioritized rules using RiverWare's Rulebased Simulation controller. Rulebased Simulation provides means to execute each operation in a prioritized fashion; higher priority operations can then overwrite the results of lower priority operations. In this framework, the USACE operations are thus implemented in modular, object-specific contexts for ease of maintenance and extension, as well as flexibility of use through user-selectable methods. In essence, each rule represents operations to meet an objective for one or more objects on the workspace. The remainder of this paper describes each operation and how it is modeled.

LOCAL INFLOW CALCULATION

The model is used for long term planning studies using period of record data. If the period of record inflows were input directly, RiverWare would have perfect foresight and simulated operations would be unrealistic. The forecasted inflows over the forecast period are developed at reservoirs and control points where uncontrolled area flows are forecast. 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, usually 5 to 10 days.

Also, in USACE basins, local inflow data represents the spatially cumulative inflow to the river up to that point. These cumulative inflows cannot be routed downstream in RiverWare since the next downstream Control Point also has cumulative inflows. However, routing inflows in RiverWare is necessary so that diversions can be made from Reaches and so that the Reaches will route the correct flows. In order to address this problem, methods on the Computational Subbasin were developed to use the cumulative inflows at Control Points and Reservoirs, and calculate the incremental flows. Because of the forecasting mechanism described above, the methods calculate the forecasted incremental local inflows at each control point and reservoir within a subbasin given the cumulative local inflows at the beginning of each timestep over the forecast period.

FLOOD CONTROL ALGORITHM

The USACE flood control algorithm calculates flood control releases in a basin 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. At each computational timestep, the flood control releases are calculated for each timestep in the forecast period. 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 operation. The algorithm consists of three components, Surcharge Release, Regulation Discharge, and Flood Control Release computations as described in the following sections.

Surcharge Release: 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.

Surcharge Release Rule: There is one Surcharge Release rule for each reservoir object starting at the upstream end of the basin. The rule sets the Surcharge Release Flag on the outflow of the reservoir.

Simulation after Surcharge Release Rules: When the Surcharge Release flag is set, it triggers the reservoir to dispatch (i.e. solve) and compute a surcharge release forecast. During dispatching, the reservoir will compute the surcharge release forecast and set the Outflow slot for the current timestep and all 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: The Regulation discharge operations are used to compute the permitted maximum flow at each control point and the empty channel space based on the current flow. Regulation discharge at each control point is determined based on method selection and the input data at that control point. 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. 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.

Regulation Discharge Rule: After all the surcharge release rules have executed and the flows have been routed downstream, a single rule sets the regulation discharge flag on the "Reg Discharge Calculation" slot for all Control Point objects.

Simulation after Regulation Discharge Rule: The regulation discharge flag triggers each control point to dispatch and execute the selected regulation discharge methods. When this rule executes, each control point contains the flow for each forecast timestep consisting of:

- uncontrolled area inflow forecasts,
- surcharge releases for the current and forecast period, and
- previous timestep releases (for flood control, to meet low flow demands or hydropower releases) which have been routed downstream.

This flow is used to compute the regulation discharge and empty space hydrographs. 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.

Flood Control Release Rule: After the regulation discharge rule has executed, the rule to calculate the flood control releases is executed. This single 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. No physical-process simulation occurs during this algorithm until the flood control function finishes for this timestep. More specifically, the solution works as follows:

First, the reservoirs are sorted by their "fullness", based on operating level. Those reservoirs not in the flood pool are not allowed to make releases that use the downstream empty space but are included for tandem operations. Next, a set of "balance levels" (operating levels) based on computations by key control points is computed. These balance levels are sorted in descending order. A "pass" is run 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.

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.

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.

Simulation after Flood Control Rule: When the Flood Control rule sets the Reservoir's Outflow slots, it 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. 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.

CONSERVATION POOL OPERATIONS

The previous section described operations that deal with releasing water out of the Surcharge and Flood Control Pools as shown in Figure 1. Releases and Diversions are also made from the Conservation Pool to meet demands. Specifically, releases are made to meet downstream low flow or demand targets. Also, diversions are made directly from reservoirs to meet demands. In both cases, if multiple sources can be used to meet the demand, then the algorithm tries to balance the reservoir storages as best as possible. The following sections describe these operations both in terms of the purpose, ruleset, and the resulting simulation of the effects.

Low Flow/Demand Releases: The low flow/ demand policy computes the reservoir outflows to meet a low flow demand at a downstream control point. If a control point's demand can be met by multiple reservoirs, the fullest reservoir is considered first and releases as much as possible, then the next reservoir is considered. To set up this operation, the user selects methods on both the reservoir objects and the downstream control points. These methods specify how the demand will be computed (either as a periodic relationship or based on the level of a reservoir), and which reservoirs can meet the demand. A computational subbasin must be created that contains the appropriate objects (Reservoirs, Control Points, and all intervening objects) and specific method selections.

Low Flow/Demand Rules: A rule must then be defined for each control point that has a low flow requirement, typically starting at the top of the system. The rule then calls a predefined function called MeetLowFlowRequirement. This function computes the required low flow releases for each reservoir as follows:
First, the specified low flow reservoirs are sorted in descending order according to Operating Level. Reservoirs that are below the bottom of the conservation pool are excluded. Next, each reservoir (beginning with the most full reservoir) makes a release until the Control Point's demand is met, the maximum release (on the reservoir) is met, or the reservoir reaches the bottom of the conservation pool (whichever value is lowest). The water is then routed down to the target control point using linear routing coefficients. If there is still demand, the algorithm moves to the next reservoir and makes additional release. The loop is complete when the demand is met or each reservoir has been considered. Again, no slots on the workspace are set in this

algorithm; it is strictly a pseudo simulation. Each reservoir's updated Outflow value is returned to the calling rule.

Simulation after Low Flow Demand Rules:
The low flow/demand rule sets reservoir outflows on the current simulation timestep. The system solves for reservoir storage and routes the water downstream.

This operation deals with making releases to meet a downstream target. It does not deal with the diversion of that water out of the river at or below that location. In the USACE models, direct from reach diversion happen automatically; that is, there is a specified demand for diversion and any water passing that reach can be diverted to meet that demand. Thus, as water is released out of the reservoirs, it flows downstream and can be diverted from the reach as appropriate by downstream water users.

Diversions from Reservoirs: Diversions are made directly out of a reservoir to meet a demand. Demands can be a water user or another reservoir. Each demand can draw from multiple reservoirs and each reservoir can act as a source for multiple water users or demand points.

A diversion consists of a Reservoir, Diversion object, and Water User. In the simplest case, there is one of each. A specific linking structure and method selection must be employed between the reservoir, diversion object, and water user objects. Finally, there must be a computational subbasin that encompasses all the objects under consideration.

Diversions from Reservoir Rules: A rule is used for each subbasin that has reservoirs that divert. The rule calls a predefined function called ComputeReservoirDiversions. This function computes the diversion from each reservoir and the supply to each water user as follows:
For each Water User the following steps are taken: The supplying reservoirs are ranked by fullness (highest level first). Reservoirs below the bottom of the conservation pool are ignored. Loop through each reservoir and set the Diversion to the minimum of the demand, maximum delivery rate, or the amount of water that would draw the reservoir down to the bottom of the conservation pool. Each reservoir is visited until the demand is met or there are no more reservoirs.
The reservoir levels are updated when moving to each water user object because multiple Water Users can divert from the same reservoir. This computation is all done within the predefined function; no "real" values on the workspace have been set or are affected. The ComputeReservoirDiversions function returns a list of slot, value pairs representing the diversion from the reservoir and the supply to the water user.

Simulation after Diversions from Reservoirs:
The rule sets the diversion from each reservoir and the supply to each water user. This allows the reservoirs to re-solve for storage and the water users to determine how much of their request have been met. Note, the reservoir outflows do not changes, so no water is typically routed downstream.

HYDROPOWER RELEASE

A power reservoir may release additional water from its power pool to meet a specified power commitment, i.e., the load specified for that reservoir. Note, that as releases are made using the above rules, power is produced. Thus, this operation only deals with the additional release of water to meet an unmet load. The additional water that is released for hydropower cannot cause *additional* downstream flooding. The user must select methods on each power reservoir involved in the hydropower operation. Also, because the algorithm looks at additional flooding, the same computational subbasin used for the flood control operation must be used here.

Hydropower Rule: A rule is used for each for each flood basin that has hydropower reservoirs that make additional hydropower releases. The same basin used for flood control must be used.

A predefined RPL function, HydropowerRelease computes the additional release from each reservoir as follows: Sort the power reservoirs in the basin according to the relative load shortage (i.e. power demand deficit). The reservoirs with the highest deficit are first, the lowest reservoirs last. In order of priority, hypothetically calculates the additional release to meet the power shortage as the minimum of the following: the Outflow calculated to meet the given required load, the Outflow calculated such that the Pool Elevation would exactly equal the minimum power elevation, the Outflow calculated such that the maximum power pool drawdown is not exceeded, and the Outflow that generate the maximum possible energy. The function then hypothetically makes the release and visits downstream control points until it reaches a tandem reservoir or the end of the subbasin, whichever comes first. If the release causes (additional) flooding at a control point, it reduces the release until flooding is not caused or the release becomes zero.

Once all power reservoirs have been visited (in priority order), the HydropowerRelease() function returns to the calling rule. The result is a list of slots and values including the reservoir Outflow. The rule then sets these slots, if different, and the reservoir and all downstream objects dispatch.

Simulation after Hydropower Rules: When the Hydropower rule sets the Reservoir's Outflow slots, it 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 disaggregated local 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 slots o n 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. The low flow/demand rule executes and invokes the MeetLowFlowRequirement pre-defined function. This function computes the low flow releases for the subbasin and returns the low flow release and outflow values, for the current timestep, for each reservoir. The rule then sets the slots 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
6. The reservoir diversion rule executes and invokes the ComputeReservoirDiversions pre-defined function. This function computes the reservoir diversion for the subbasin and supply to the water users, for the current timestep. The reservoir objects re-dispatch and solve for pool elevation, storage and any other reservoir methods that have been selected.
7. The hydropower rule executes and invokes the HydropowerRelease pre-defined function. This function computes the additional releases for each power reservoir and returns the outflow values, for the current timestep, for each reservoir. The rule then sets the 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.
8. RiverWare moves to the next timestep and the process is repeated

ITERATIVE MODE FOR YIELD STUDIES

The functionality can also be used for a yield study which is used to determine the largest average diversion that can be made from a single reservoir such that the reservoir will not drop below the bottom of conservation pool at any time during the run period. A yield study utilizes RiverWare Iterative MRM mode. Iterative runs are multiple runs where MRM rules at the end of each run examine the state of the system and, if appropriate, set inputs for the subsequent simulation run. In the yield study case, the MRM rules propose a reservoir diversion, make a run, analyze whether the yield conditions were met and then proposes a new diversion. The algorithm starts with a small diversion, makes a run, the tries a large diversion. It then uses either straight bisection or a heuristic approach for subsequent guesses. The runs start at the most upstream reservoir and find the yield for that reservoir, lock in the results, and move to the next downstream reservoir. Note, that the runs are using the standard operating rules described above for each run. The only changes made between runs is the diversion out of the reservoir.

CASE STUDY: EVALUATE PROPOSED CHANGES TO KEYSTONE RESERVOIR AND SYSTEM

Keystone Reservoir in northeastern Oklahoma is one of several reservoirs where its flood storage releases compete for available channel capacity at downstream locations in the Arkansas River basin. Operationally, flood storage in the system is evacuated as quickly as possible, given downstream and system constraints. On the recession side of flood events, there currently exists system regulation criteria for navigation that limit Keystone flood storage releases in favor of other reservoirs' flood evacuation. Keystone dam is being assessed by the Corps of Engineers team for the Dam Safety Action Class process, and during the effort, proposal was made for early screening process to evacuate Keystone flood control storage with the same level of priority as other reservoirs in the system, thus evaluating the risk for Keystone dam. RiverWare modeling program, in conjunction with Southwest Division Corps of Engineers system flood control routine methods in RiverWare, provide tools to obtain results and evaluation of proposal.

The Arkansas River watershed consists of numerous multipurpose reservoirs on its main stem and tributaries. Reservoir management operations consist of flood storage, hydropower, water supply, water quality, recreation, and navigation. During flood events there is a persistent problem with shoaling in navigation channel. In the early 1980's a system plan was developed to use the lower 30% flood storage in Keystone Reservoir to provide sustained flow and water levels in the navigation channel to allow for scour flushing and dredging. In effect, other reservoirs have a higher priority over Keystone for the available downstream channel space when tapering down system flood releases.

A RiverWare model has been developed for the portion Arkansas River watershed that extends from central and southeast Kansas, through Oklahoma, and into Arkansas ending at Little Rock. Major tributaries with reservoirs included in the Arkansas River model are the Neosho River, Verdigris River, Canadian River, Poteau River, Illinois River, and Bird Creek. The watershed includes series and tandem reservoirs that have a dendritic configuration to downstream control points where several reservoir flood releases compete for available channel space. RiverWare model includes 21 multipurpose reservoirs, 50 regulation control points, and nearly 70 routing reaches.

The Arkansas River at Van Buren, Arkansas is a key regulation point for flood and navigation operations. Target flows are based on seasonal guide curve and percent of system flood storage occupied. There are 13 upstream reservoirs that directly compete for channel space at this location. RiverWare's system percent full of flood storage routine method is used for determining available channel space and ranking reservoir release priority. RiverWare model input defines each reservoir with a balance level vs pool elevation table that generally defines balance levels with percent flood control storages. Keystone, along with four of the other larger reservoirs are configured and simulated to provide sustained flow on the recession side of flood events for scour and dredging in the navigation channel. Below 30% flood storage the other eight reservoirs are defined to have a higher priority.

RiverWare modeling was performed for this analysis with a daily time step for the period January 1940 thru December 2000. Historic inflow and gauged stream flow was used to develop full period of record reservoir inflow and intervening area flow. Historic evaporation and precipitation are applied to reservoir pools. All reservoirs were simulated as being operational during this time frame. Existing reservoir and system regulation criteria was configured in the model through the Southwest Division flood regulation methods. Conceptually, on each day of the simulation, a state of the system is determined and releases are made based on the operational criteria. The full range of system features were activated during the simulation that include surcharge operation, control point regulation, flood control release determination, hydropower analysis, low flow releases, and pool yield. Reservoir operation for navigation is implicitly included with these other operations. Initially, an existing conditions run was performed that used existing flood regulation criteria. A second run was made to reflect proposed change of Keystone operation, having same flood storage evacuation priority in the lower 30% of the system storage as other reservoirs in the system.

The effects of the proposed change of operation are evaluated by comparing model results of the existing operational plan to results of the proposed operational plan. Evaluation includes reservoir elevation for Keystone and other reservoirs, flow at downstream control points, hydropower, and navigation. RiverWare's statistical routines are also used to process results and compare the two scenarios. Statistical tools include frequency and duration analyses for reservoir elevation and control point flow, see Figure 2 for elevation vs duration results.

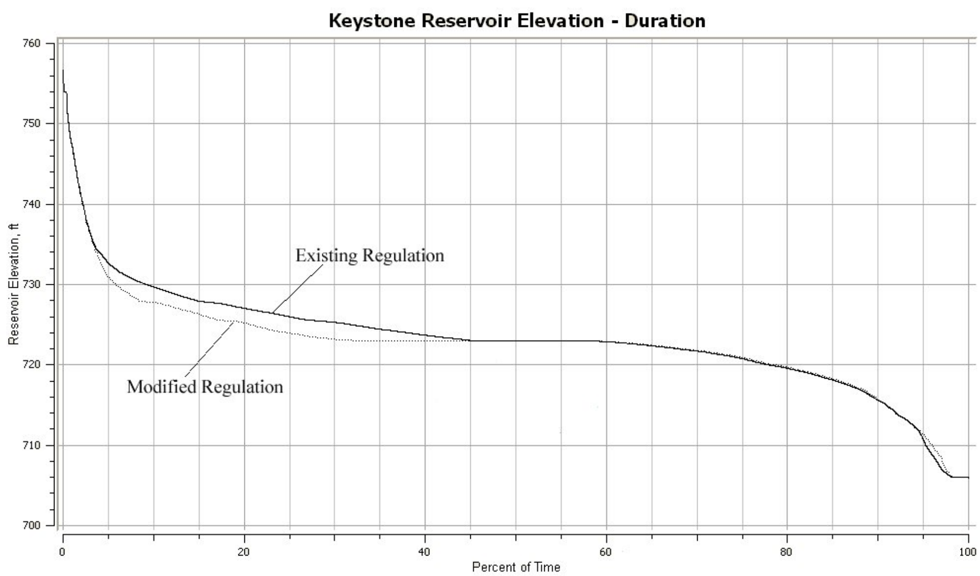

Figure 2 Period of Record Elevation vs Duration

In summary, numerous proposed changes in reservoir and system operation arise that require investigation and evaluation of these proposals. RiverWare modeling with Corps Southwest Division flood routine and methods provide results that can be evaluated for the effects of such proposed operational changes.

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