MULTI-OBJECTIVE MODELING IN RIVERWARE FOR USACE-SWD

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Abstract: The U.S. Army Corps 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 in collaboration with SWD to strengthen their usability and analysis capabilities. The SWD methods include: surcharge release from reservoirs, regulation discharge computations to determine the available space at downstream control points, system-wide flood control algorithm that computes flood control releases at all reservoirs while maintaining balanced storages and releasing flood storage over a forecast period without flooding downstream control points, water supply and stream diversions, minimum flow releases to meet targets while balancing reservoir storage, and hydropower releases to meet system load. The integration of the SWD algorithms brings 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 using a user-define logic to make iterative runs that converge on the demand that empties the conservation pool during a specified hydrologic sequence. RiverWare includes statistical post-processing and a direct data connection to the Corps' Data Storage System (DSS). Numerous studies arise that involve requests for proposed reservoir and system operational changes and associated affects to the existing operating plan. Typical studies include reallocation of authorized purposes, dam safety concerns, navigation enhancement, dependable yield determination, changes in target pool elevations, and downstream channel constraints. Period of record modeling with RiverWare provides tools for evaluating these proposed alternative operating management plans. This paper will also present examples of RiverWare modeling of case studies in SWD Tulsa District. RiverWare was 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

The Corps of Engineers, Tulsa District is responsible for managing 45 multipurpose reservoirs plus five run of river lock and dams. Major river systems in Tulsa District include the Arkansas and Red Rivers with contributing runoff areas extending from central Kansas, southwest

Missouri, all of Oklahoma, northern Texas, Texas panhandle, and western Arkansas, as shown in Figure 1. These reservoirs and river systems have series and tandem configurations with common downstream focus points for operational management, as well as individual reservoir requirements. Management follows existing reservoir and system operating guidance that has been adopted and accepted by the Corps, other Federal and state agencies, and numerous stakeholders. An authorized operating management plan is in place, however public and political interests exist that often conflict with the authorized plan. Examples of authorized purposes for the reservoirs include flood storage, navigation, water supply, water quality, irrigation, recreation, and hydropower. On a regular basis, there are requests for the Corps to investigate proposed changes to the authorized reservoir and system management plan. Some examples include different seasonal guide curves, additional water withdrawals, water quality variations, hydropower loading, and navigation enhancements. Due to the complexity of the reservoir and river system, a modeling approach is needed to investigate impacts of these requested operational changes. The RiverWare program provides a modeling tool for such analyses.

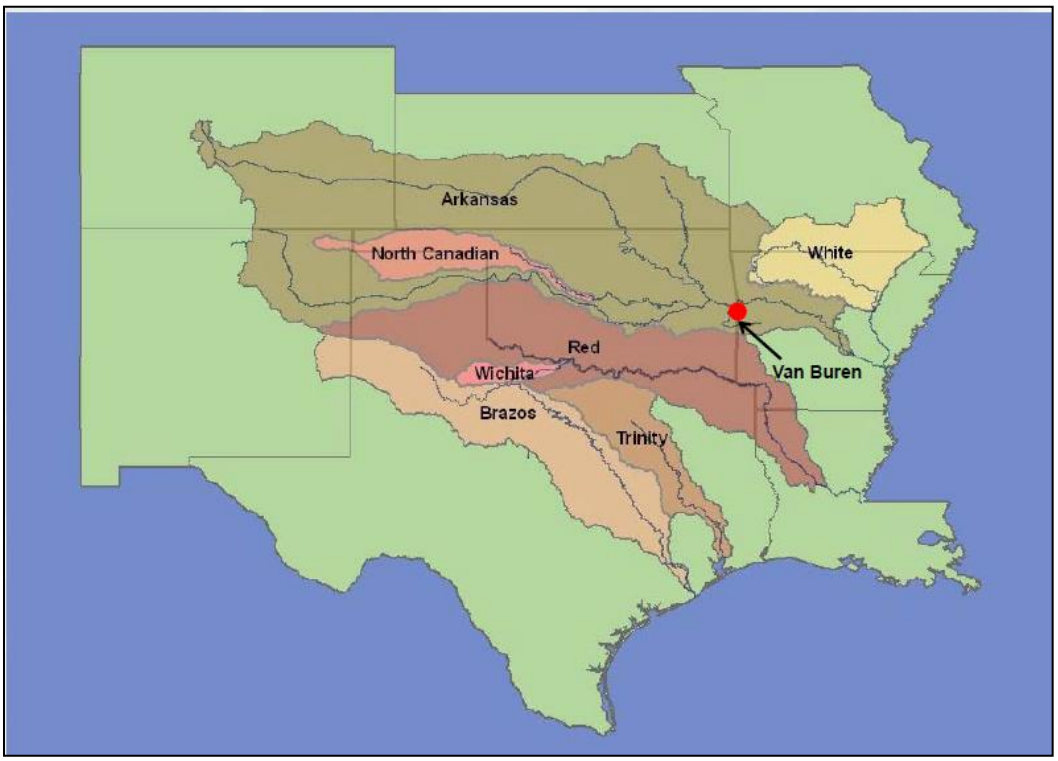


Figure 1 Corps of Engineers SWD-Districts RiverWare modeled basins.

RIVERWARE PROGRAM: TULSA DISTRICT APPLICATION

The reservoirs in Tulsa District were constructed and became operational over a period of time spanning from the late 1930's into mid-1980's. To investigate proposed changes in the reservoir and river system, a period of record planning model with rulebased simulation in RiverWare is used. The RiverWare model configuration for the Arkansas River, as shown in Figure 2 has 21 reservoirs, 48 regulation stream control points, and numerous routing reaches. All reservoirs are

configured in the model as being operational during the entire period of record simulation time frame, thus depicting a present day system condition analysis approach. For the Arkansas River model the period of record spans from January 1, 1940 through December 31, 2008 with daily time step computations. Historic surface water hydrology records are used to obtain local intervening area flow into headwater reservoirs and downstream control points. Historic precipitation and evaporation are applied to reservoir surface areas. During this 69-year timeframe of daily historic hydrology, significant extremes have occurred that provide wide variation of basin hydrologic conditions. Therefore, flood, drought, and average operations can reasonably be investigated.

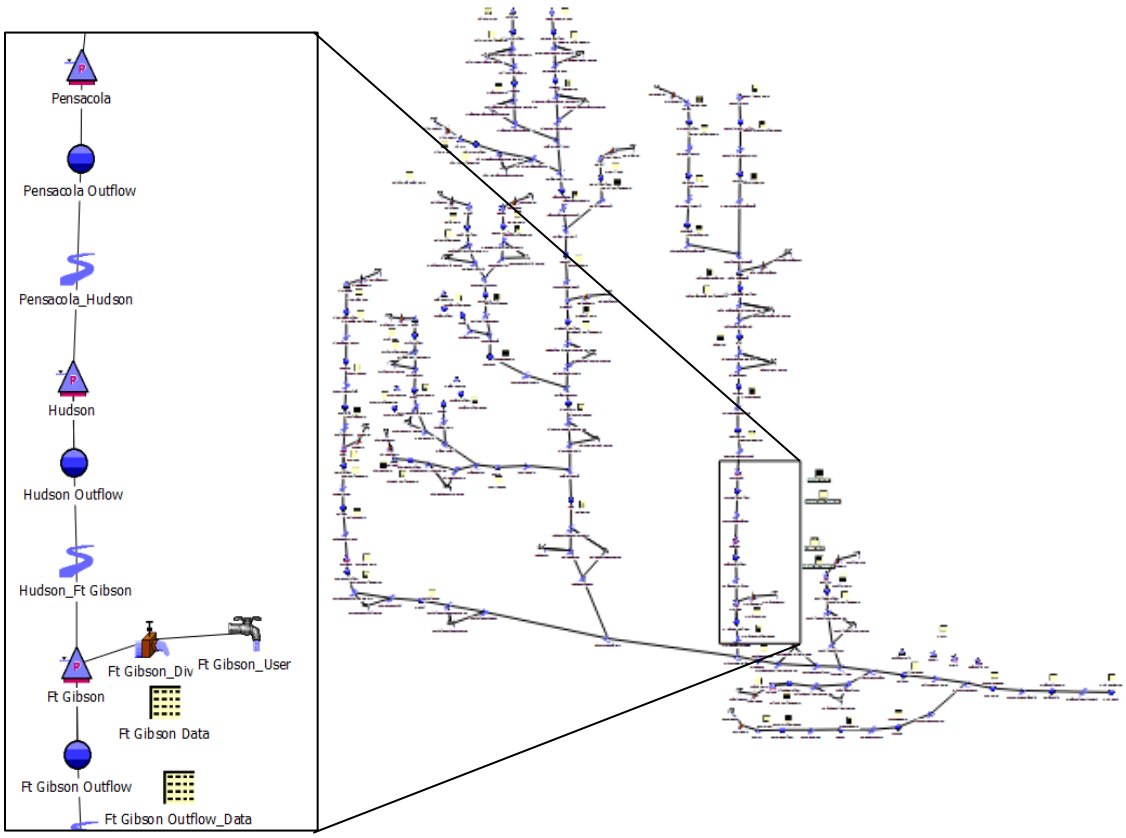


Figure 2 Arkansas River RiverWare model object configuration.

RiverWare's rulebased simulation approach is used by Tulsa District to replicate the reservoir and river system operating criteria. RiverWare is rich with rule development potential, both with pre-configured functions and user developed logic. One of the pre-configured sets of logic involves the Corps of Engineers Southwestern Division (SWD) flood control method which is a system approach to flood storage evacuation. This approach includes predefined functions, user selectable methods on individual objects, and methods that apply across a group of objects called a subbasin. The rules typically execute the methods or do the computation on the objects and subbasin. Data and user configuration options on the objects allow the different calculation approaches for different objects. The results of the computations are values for the decision

variables, usually reservoir releases and/or diversions. A sample ruleset that includes the SWD method for the Arkansas River model is shown in Figure 3.

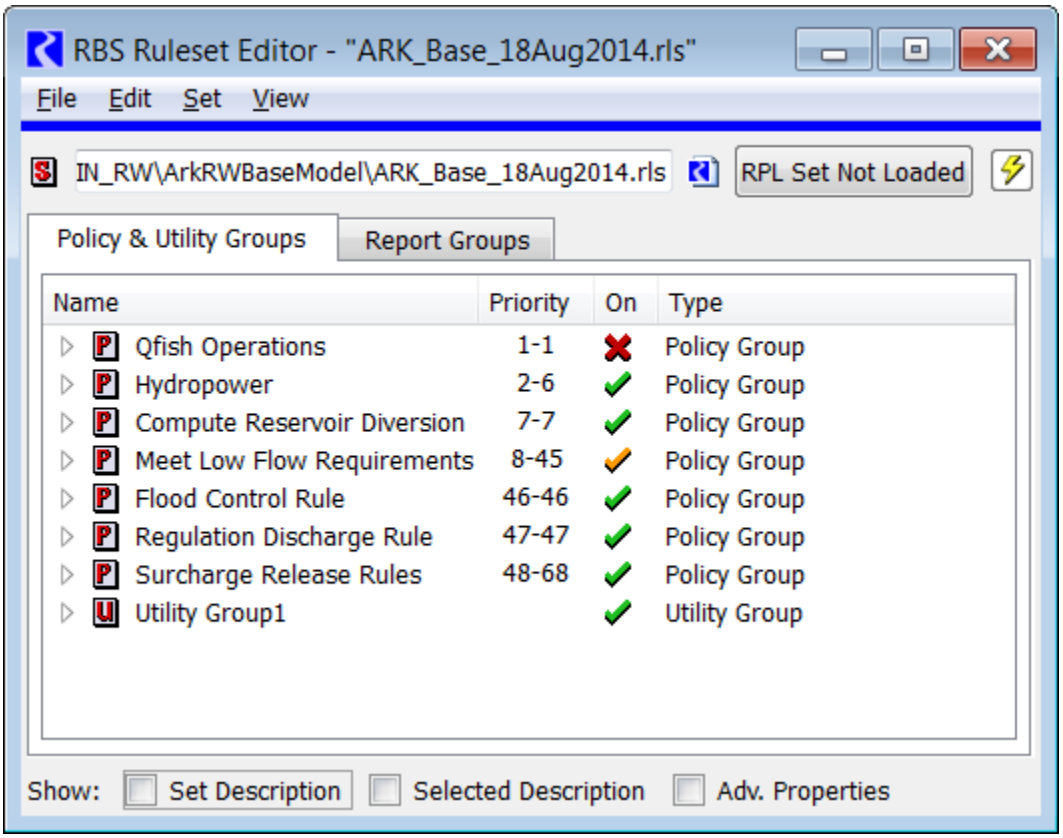


Figure 3 RiverWare ruleset for the Arkansas River basin.

Surcharge Release Rule: The surcharge release rule evaluates if inflow into each reservoir is sufficient to exceed flood storage and enter into surcharge conditions. If so, a release schedule is determined regardless of downstream conditions. The headwater reservoirs are evaluated first, such that any upstream reservoirs' surcharge release becomes part of a downstream reservoir's inflow. All reservoirs are evaluated in this upstream to downstream order to determine these mandatory surcharge releases.

Regulation Discharge Rule: The regulation discharge rule considers available channel space at each downstream regulation control point. The space hydrograph is the difference between the flow limit and actual flow that is a combination of local intervening area runoff flow plus prior time steps routed flow from upstream reservoirs releases. For each control point, a multi-time step space hydrograph is computed for upstream reservoir release potential. There are four general methods for configuring a control point's regulation criteria as used by the SWD:

- channel maximum flow method: The channel method usually involves a single maximum flow limit.
- current level regulation method: The current level regulation method considers an upstream reservoir's fullness at current time.

- future regulation method: The future level regulation method considers an upstream reservoir's fullness over the next several time steps.
- system method: The system percent method considers several upstream reservoirs' collective fullness. A key control point configuration and designation is used in the SWD flood control method to identify those control points that usually govern reservoir releases over other control points.

In the Arkansas River model, the main constraint for reservoir releases on the Arkansas River is Van Buren, Arkansas regulation control point. This location, as shown in Figure 1, has flow limitations based on the fullness of 13 reservoirs that have influence on this location. Flood damage flow is a consideration as well as flow benches for navigation. Flood storage evacuation must also follow a tapering plan for navigation. The Van Buren control point is designated as a key control Point.

Flood Control Rule: The flood control rule evaluates if any reservoir is in the flood storage zone; if so, a multi-day release schedule is developed based on downstream control points' available space as well as its fullness compared to other reservoirs in the system. If several reservoirs are competing for channel space, a priority scheme is used in the SWD flood control method. Each reservoir is configured with a balance level verses percent full of flood storage, Figure 4, which is used to determine priorities for flood storage releases as per the system manual operating criteria. In this way, the flood control logic computes reservoir releases to prevent downstream flooding. When the inflows to the system are reduced, the reservoir releases are computed to recover the flood control space in a balanced manner while not exceeding the downstream flow targets.

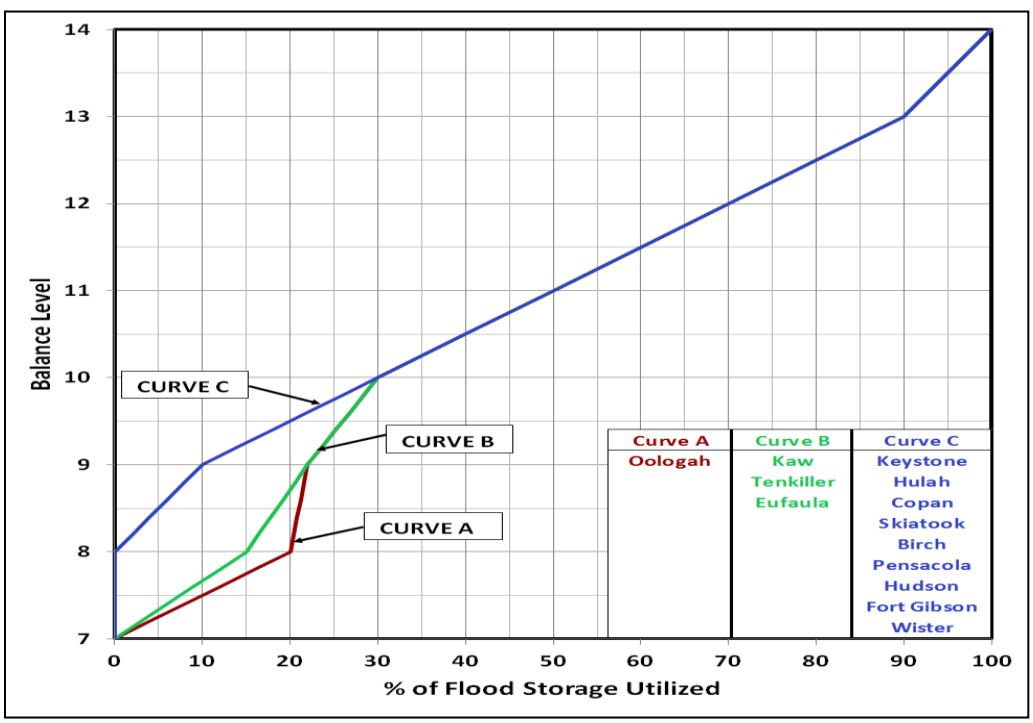


Figure 4 Balance level vs. percent of flood storage for reservoirs.

Low Flow Rule: The meet low flow requirements rule tries to meet low flow targets at several downstream locations from one or more upstream reservoirs. Low flow requirements can be a constant rate or can vary by season, as well as a function of the supplying reservoir's fullness. For example, as the providing reservoir's conservation storage is being depleted, the downstream minimum flow requirement can be reduced. The rules compute the releases to meet the low target based on the fullness of the supplying reservoirs. Releases are made from the fullest reservoir first up to its maximum specified release and then releases are made from the next fullest reservoir, and so on until either the low flow requirement is met or there is no more water to meet low flows.

Reservoir Diversion Rule: The compute reservoir diversions rule evaluates reservoir withdrawals, typically for municipal and industrial (M&I) demands. A monthly request for diversion is input and can be configured with return fraction. Actual withdrawals are based on the reservoir's available storage and the withdrawal can be reduced with depleting storage. The rules compute the available water and compute the flow necessary to meet the demand. Stream withdrawal points can also be configured with dependencies on reservoir conditions in the system.

Hydropower Rule: Any releases made for other purposes are automatically sent through the turbines to the extent possible, but additional power demands may exist that require additional turbine releases. The hydropower rule computes the power load requirements and then makes releases to meet that load. The load can be input several ways in RiverWare. Examples include period of record firm loadings, reservoir guide curve, and system energy in storage. Weekday and weekend loading ratios are available. Downstream channel space availability is considered when making hydropower. A hydropower release is proposed and then the system is solved downstream to ensure that the proposed release does not cause additional downstream flooding. If it does, the hydropower release is cut back. Thermal purchase (power deficiency) and dump energy (power surplus) computations are made in conjunction to input firm power requirements. RiverWare period of record modeling computations for Tulsa District is a daily time step and the computed daily average turbine release for the day may meet a required low flow release for the day on a daily average basis. In reality there are a few hours during the day where this low flow requirement is not being met with turbine release, therefore RiverWare includes functions to consider and account for the partial day of turbine release and resultant low flow release needed for the remaining hours of the day.

Post-Run Analysis: RiverWare has many tools for viewing and analyzing post simulation results. RiverWare's statistical functions on the data object are a common use for Tulsa District, as well as graphical and tabular features. Unique computations of interests can be developed with the expression slot tool. The output manager provides features for configuring and saving outputs. RiverWare's model report tool can be used to develop HTML report files with user selected input for study specific areas of interests. RiverWare's data management interface (DMI) can be used to transfer datasets into and out of the RiverWare interface, such as the Corps of Engineers' DSS file format, commonly used by Tulsa District. An example of the output manager's graphical capabilities is the pie chart shown in Figure 5. This pie chart shows the percentage of flood control storage for a single example time step at 10 reservoirs in the lower

Arkansas River basin. Each wedge represents that reservoir's fraction of the total flood control space. The colored portion of the wedge represents the flood control storage percentage at that time step. Labels and numeric data provide specific information on the flood storage volume and percentage. RiverWare's pie chart function has animation capability that allows viewing over several time steps.

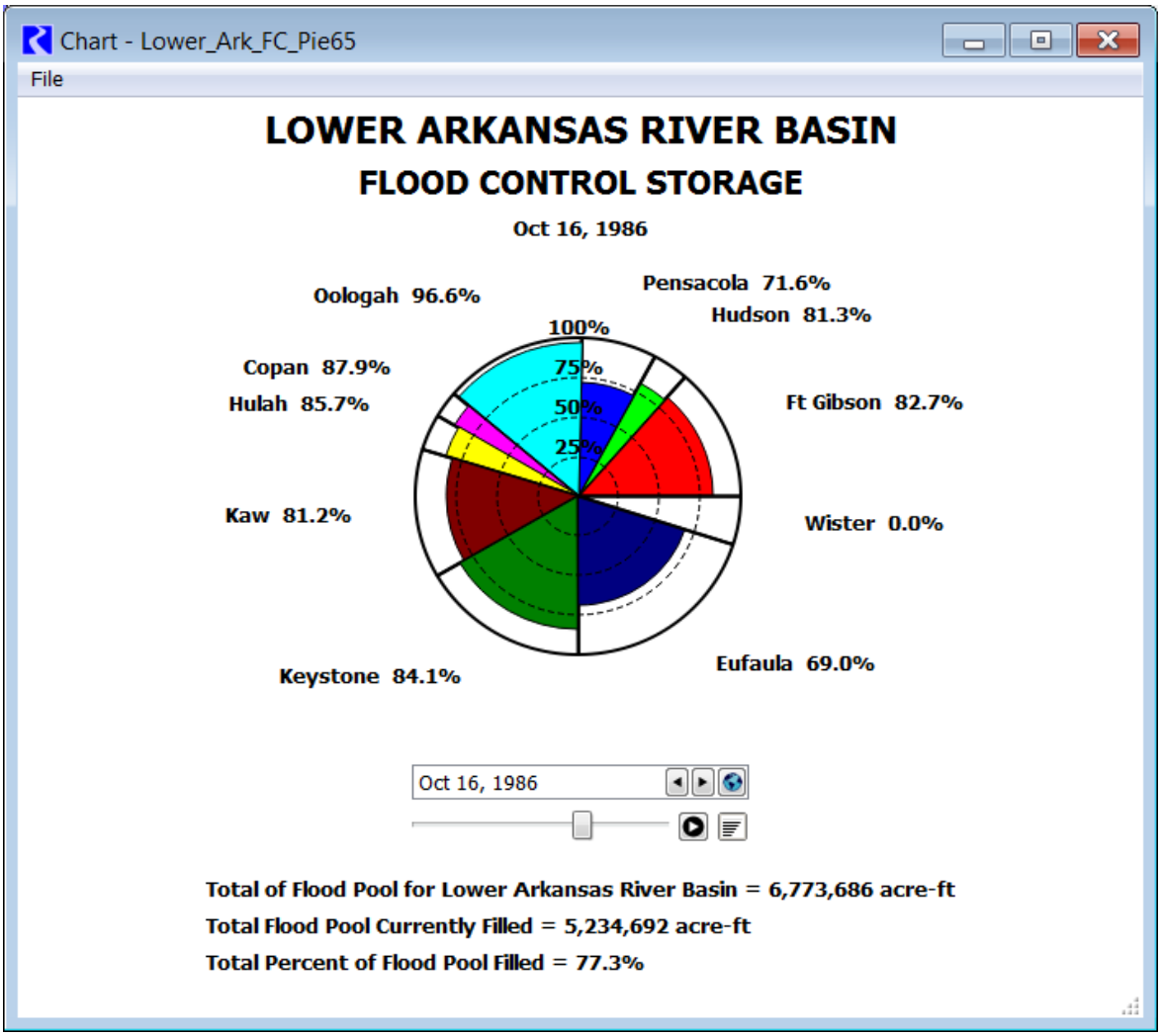
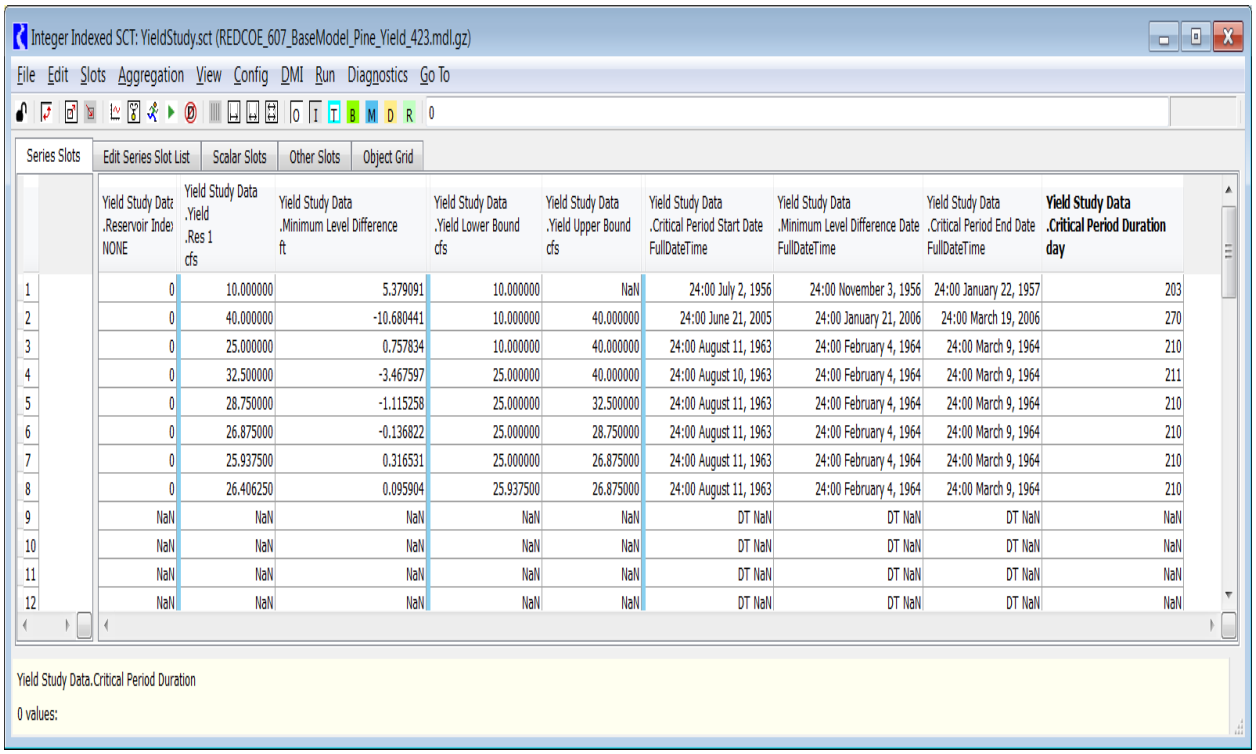


Figure 5 Pie Chart for reservoirs with flood storage.

CASE STUDY: FIRM YIELD ANALYSIS

Tulsa District Corps determines dependable reservoir yield by examining the period of record hydrology and determining the reservoir withdrawal that can be sustained during the most severe drought of record. In other words, what yield (firm yield) can be maintained while exhausting the conservation pool storage without going below the bottom of conservation pool zone. To accomplish this analysis, Tulsa District uses RiverWare's iterative multiple run manager tool to cycle through the period of record to converge on this firm yield value. The iterative MRM makes a run through the period of record and then executes logic to determine if another run is

needed and if so, the variables that should be changed. Using this tool, the period of record can be run many, many times with different inputs to search for the desired solution. For the yield study, an initial estimate for yield is either input or the program uses average annual inflow on the first passes to get bounding conditions. The iterative MRM rules then converge on the yield using a modified bisection algorithm to find the withdrawals that exactly exhausts the storage at some point in the period. The user specifies a tolerance target for convergence limits. RiverWare's system control table (SCT) is used to show the iterative and final values, as shown in Figure 6. This example provides results from a single reservoir yield determination in the Red River multi-reservoir system. This firm yield analysis approach with RiverWare's MRM can also be configured sequentially to compute firm yield for several or all reservoirs in the system.



	Yield Study Data .Reservoir Index NONE	Yield Study Data .Yield .Res 1 cfs	Yield Study Data .Minimum Level Difference ft	Yield Study Data .Yield Lower Bound cfs	Yield Study Data .Yield Upper Bound cfs	Yield Study Data .Critical Period Start Date FullDateTime	Yield Study Data .Minimum Level Difference Date FullDateTime	Yield Study Data .Critical Period End Date FullDateTime	Yield Study Data .Critical Period Duration day
1	0	10.000000	5.379091	10.000000	NaN	24:00 July 2, 1956	24:00 November 3, 1956	24:00 January 22, 1957	203
2	0	40.000000	-10.680441	10.000000	40.000000	24:00 June 21, 2005	24:00 January 21, 2006	24:00 March 19, 2006	270
3	0	25.000000	0.757834	10.000000	40.000000	24:00 August 11, 1963	24:00 February 4, 1964	24:00 March 9, 1964	210
4	0	32.500000	-3.467597	25.000000	40.000000	24:00 August 10, 1963	24:00 February 4, 1964	24:00 March 9, 1964	211
5	0	28.750000	-1.115258	25.000000	32.500000	24:00 August 11, 1963	24:00 February 4, 1964	24:00 March 9, 1964	210
6	0	26.875000	-0.136822	25.000000	28.750000	24:00 August 11, 1963	24:00 February 4, 1964	24:00 March 9, 1964	210
7	0	25.937500	0.316531	25.000000	26.875000	24:00 August 11, 1963	24:00 February 4, 1964	24:00 March 9, 1964	210
8	0	26.406250	0.095904	25.937500	26.875000	24:00 August 11, 1963	24:00 February 4, 1964	24:00 March 9, 1964	210
9	NaN	NaN	NaN	NaN	NaN	DT NaN	DT NaN	DT NaN	NaN
10	NaN	NaN	NaN	NaN	NaN	DT NaN	DT NaN	DT NaN	NaN
11	NaN	NaN	NaN	NaN	NaN	DT NaN	DT NaN	DT NaN	NaN
12	NaN	NaN	NaN	NaN	NaN	DT NaN	DT NaN	DT NaN	NaN

Figure 6 System Control Table with Iterative Multiple Run Manager for firm yield analysis.

CASE STUDY: PINE CREEK LAKE DAM SAFETY

Pine Creek Lake is a headwater reservoir on the Little River in southeastern Oklahoma that is a major tributary to the Red River. Embankment seepage around the gated conduit has been discovered at Pine Creek Dam. The Corps' dam safety team is currently evaluating corrective measures. For precautionary measures the dam safety team has requested a lower operating level for the top of conservation pool elevation. Pine Creek is a multipurpose reservoir with flood control storage, water supply and low flow requirements, and recreation interests. Pine Creek is one of 15 reservoirs in the Red River system that collectively operate for the common downstream regulation point at Shreveport, LA. A RiverWare model was used to investigate various proposed alternative operating levels for Pine Creek in conjunction with the Red River system operating plan. Impacts of reducing the conservation storage needed to be investigated

and mitigated. Figure 7 shows the elevation duration relationship of the normal operating level at elevation 438.0 ft and the reduced operating level at elevation 433.0 ft. The selected interim operating level provides minimal impacts to the system while providing reduced risk of embankment concerns.

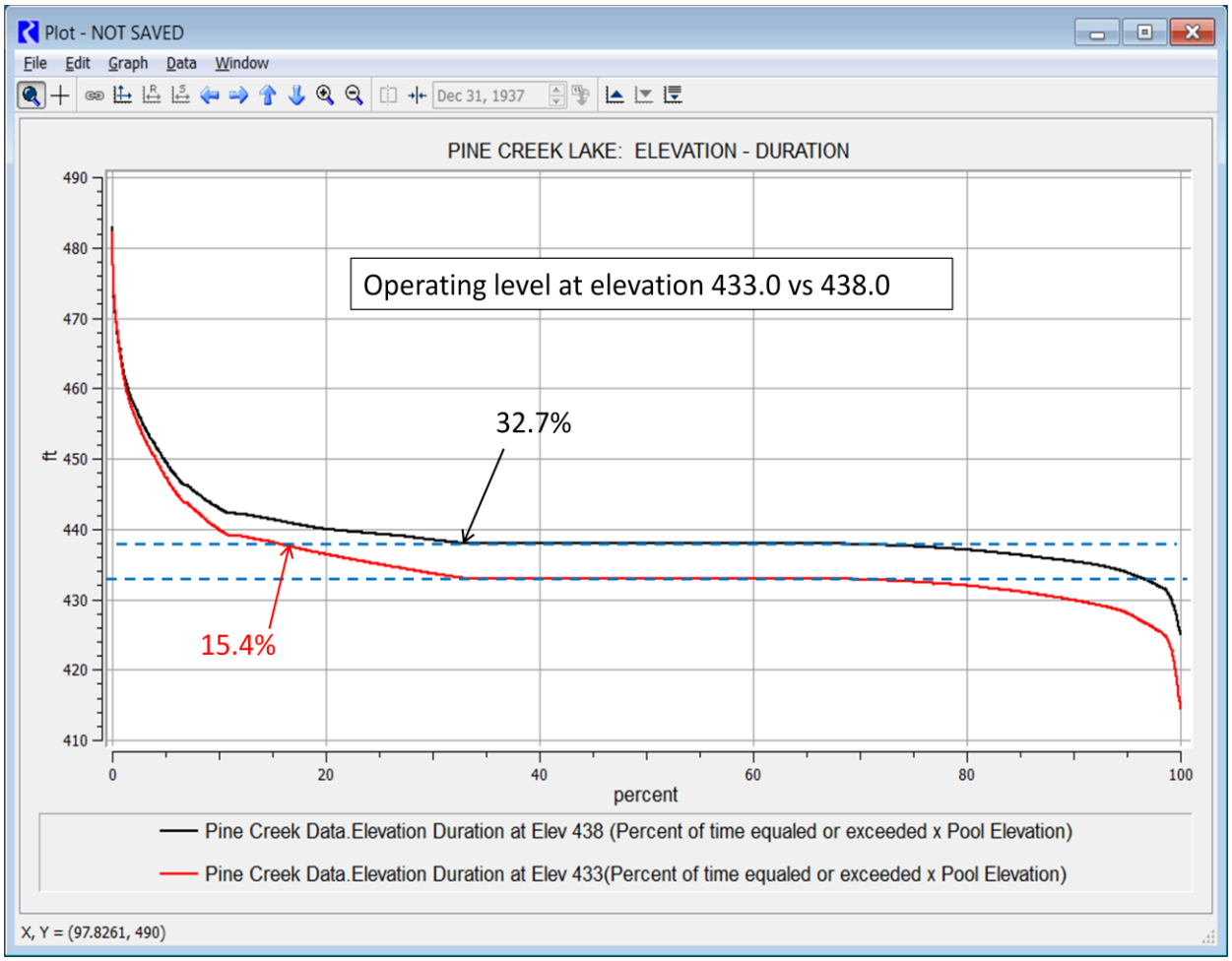


Figure 7 Pine Creek Lake elevation - duration for alternative top of conservation pools.

TYPICAL MISCELLANEOUS APPLICATIONS BY TULSA DISTRICT

On a periodic basis the District's Reservoir Operating Manuals and System Manuals are updated. The period of record hydrology and any operating changes are updated in RiverWare to provide simulated data for these manual updates. The Corps is currently involved with dam safety evaluations, periodic assessments of structures, and levee certifications, hence numerous requests are made of RiverWare's reservoir and system modeling output. RiverWare modeling provides for a rapid and easy tool to investigate potential deviations to operational management. The impoundments in Tulsa District are aging and experiencing depleting storage due to sediment deposition. Figure 8 showing Keystone Lake on the Arkansas River main stem provides an example of reduced storage as measured with periodic resurveys. The effects of depleted capacities can be investigated.

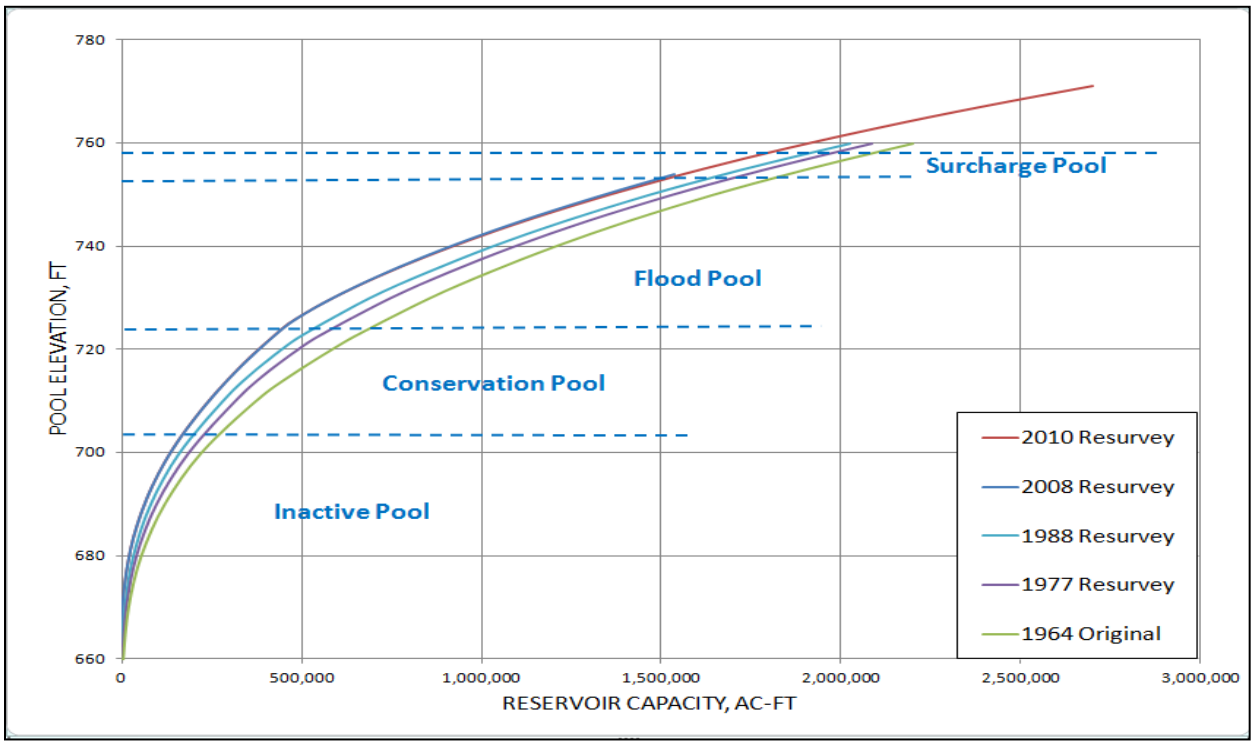


Figure 8 Capacity reduction with sediment deposition for Keystone Lake.

CLIMATE CHANGE ANALYSIS

RiverWare modeling has potential to investigate climate change concerns. In Tulsa District's period of record rulebased modeling, the historic surface water hydrology, precipitation, and evaporation can be adjusted for climate change scenarios. Operational rule logic can be configured to analyze responses to basin conditions and trends. In Tulsa District watershed, most precipitation and resultant runoff typically occurs in the spring months and another inflow season in the fall. Summer and winter seasons typically have less experienced runoff. One example of conditional operation with RiverWare rule simulation that can be applied for climate change effects involves evaluating the inflow into a reservoir during a specified time frame, say the spring months and comparing to a selected threshold. If the threshold is not met an alternative reservoir target operational guide curve is used in an attempt to maintain some additional pool storage in late spring for upcoming dry summer months. In the future, the RiverWare models of the basins will be used to perform this type of studies.

CONCLUSION

Tulsa and other Districts in the Southwestern Division of the Corps have numerous reservoirs that must be operated individually and as a system for existing authorized purposes as well as the many interests competing for finite resources. RiverWare's rulebased simulation modeling provides a study approach for evaluation and decision tools to manage the system as well as compare the effects of proposed alternative operating scenarios.

REFERENCES

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U.S. Army Corps of Engineers Tulsa and Little Rock Districts. (1980). "Arkansas River Basin: Water Control Master Manual."