River and Reservoir Operations using RiverWare within the Corps Water Management System (CWMS)

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Abstract

RiverWare, a planning and operations modeling tool, is used by a number of USACE Districts for detailed multi-objective management of river and reservoir systems. For near-real time operations applications, RiverWare models are integrated into the suite of models, analysis and database tools provided by the Corps Water Management System (CWMS) such as HEC-MFP that simulates precipitation, HEC-HMS for modeling rainfall-runoff, HEC-RAS for detailed hydraulic analysis, and HEC-FIA for flood impact analysis. CWMS features a sophisticated control and visualization interface (CAVI) with a GIS integrated with model schematics, allows evaluation of operational alternatives, and manages data inputs, outputs and inter-model data transfers via a database. The CWMS architecture allows additional non-USACE models and customized computational tools to be tightly integrated via plugins; USACE Southwest Division has sponsored the integration of RiverWare into CWMS via this plugin mechanism. The RiverWare plugin allows RiverWare model objects, plots and data to be displayed in the CAVI, RiverWare models to be run in full integration with the other CWMS applications and database, and access to the native RiverWare software if needed.

This paper details the implementation of RiverWare models in the CWMS framework including data connections, data aggregation and disaggregation and the operator interaction with the tools. We will illustrate the features and functionality in a case study of a USACE model, the White River in Arkansas and Missouri, developed by Little Rock District. These models are used in the CWMS framework to assist water managers in making critical decisions on a day-to-day and hour-by-hour basis.

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), U.S. Bureau of Reclamation (USBR), and U.S. Army Corps of Engineers (USACE) and distributed by the University of Colorado Office of Technology Transfer.

Introduction

RiverWare, a planning and operations modeling tool, is used by a number of U.S. Army Corps of Engineers (USACE) districts for detailed multi-objective management of river and reservoir systems. 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), U.S. Bureau of Reclamation (USBR), and USACE, and distributed by the University of Colorado Office of Technology Transfer.

A number of USACE districts have used RiverWare for many years for planning purposes, running period-of record models with proposed facility or operation changes to investigate the impact. Recently, some of these districts have developed near real-time operations models to simulate short term operations, primarily to determine how to schedule releases and movement of water during flood control operations. For near-real time operations applications, RiverWare models are integrated into the suite of models, analysis and database tools provided by the Corps Water Management System (CWMS). This suite consists of multiple models such as the Hydrologic Engineering Center's (HEC) Meteorological Forecast Processor (HEC-MFP) that simulates precipitation, Hydrologic Modeling System (HEC-HMS) for modeling rainfall-runoff, River Analysis System (HEC-RAS) for detailed hydraulic analysis, and Flood Impact Analysis (HEC-FIA) for detailed impacts analysis. CWMS features a sophisticated Control And Visualization Interface (CAVI) with a GIS integration of model schematics, allows evaluation of operational alternatives, and manages data inputs, outputs and inter-model data transfers via a database.

The CWMS architecture allows additional non-USACE models and customized computational tools to be tightly integrated via plugins. USACE Southwest Division has sponsored the integration of RiverWare into CWMS via this plugin mechanism. The RiverWare plugin allows RiverWare model objects, plots and data to be displayed in the CAVI, RiverWare models to be run in full integration with the other CWMS applications and database, and access to the native RiverWare software if needed.

This paper details the implementation of RiverWare models in the CWMS framework including data connections, data aggregation and disaggregation and the operator interaction with the tools.

We will illustrate the features and functionality in the context of the USACE's model of the White River in Arkansas and Missouri, developed by the Little Rock District. This model is used in the CWMS framework to assist water managers in making critical decisions on a day-to-day or hour-by-hour basis.

RiverWare Modeling

Some USACE districts have developed multi-objective RiverWare models of their systems geared toward planning applications. The purpose of these models is to compare a base run against a proposed change in facilities or operating policies with one or more sets of hydrological inputs. Avance (2010) and Daylor (2015) provide a good overview of the approach and the functionality modeled by the Southwestern Division (SWD). In general, the planning models attempt to minimize flooding throughout the network, especially at the key regulation control locations. The system flood evacuation plan calls for releases that evacuate the flood storage as quickly as possible without causing flooding at downstream control points, while still balancing the system storage and tapering down the flows.

SWD has sponsored development of RiverWare functionality and methods including: disaggregation of local inflows from cumulative values; surcharge releases at reservoirs; regulation discharge computations to determine the available space at downstream control points; a system-wide flood control algorithm that computes flood control releases at all reservoirs while maintaining balanced storages and releasing flood pool water 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. These simulation methods are each general and can be applied in various applications; but together they constitute a specific USACE modeling approach that can be implemented, in a template-like fashion, on other USACE basins.

The RiverWare modeling described above is geared toward planning studies, especially as implemented in the SWD. The model is typically run over the "Period of Record" consisting of 60-100 years of daily inflows, demands, and other hydrologic data. The rulebased simulation rule logic decides how much water to release on each timestep in the run based on the state of the system and assumed forecasts. There is no operator or user interaction within a run. In addition, many assumptions are made and data is aggregated to simplify the system. These simplifications are reasonable for planning when the purpose of the model is comparing one run to an alternative run. For example, in these planning models, reservoir release gate changes may be made each timestep when in reality, changes may be only made less frequently. These simplifying assumptions are valid over a Period of Record as the outflows will average over time.

Recently, the USACE has determined that the RiverWare models and interfaces could also be useful in short-term operations. In addition, many legacy tools have reached the end of their useful life and replacements are needed. Thus, some districts have converted, re-implemented, or developed sub-daily timestep models (1hr or 6hr) of their systems. Steffen (2015) describes a 6-hr model of the Arkansas River developed by the USACE Tulsa district for operation of the drawdown of reservoirs after a flood. This model implements the USACE approach and methods (like flood control and regulation discharge) but still allows overrides and operator judgement when necessary. Below, we describe another application on the White River in Arkansas and Missouri.

These RiverWare operations models are powerful by themselves, but become even more powerful when integrated with other USACE models that compute the inputs and process the outputs from the RiverWare models. The following section describes the Corps Water Management System, a framework that integrates many USACE models, including RiverWare to provide end-to-end modeling support.

CWMS Integration

The Hydrologic Engineering Center website states, "The Corps Water Management System (CWMS) is the automated information system used by the U.S. Army Corps of Engineers (USACE) to support its water control management mission." The system is "... used to derive the hydrologic response throughout a watershed area, including short-term future reservoir inflows and local uncontrolled downstream flows. The reservoir operation model flows are then processed to provide proposed releases to meet reservoir and downstream operation goals. Then, based on the total expected flows in the river system, river profiles are computed, inundated areas mapped, and flood impacts analyzed." (HEC Website 2018)

Thus, CWMS is a framework that integrates models together, moves data from one model to another, executes runs in order, manages data alternatives, and displays results in an easy to use interface. CWMS uses HEC-DSS as the intermediate data repository but can also extract data from the USACE Oracle database.

CWMS Architecture and Supported Models

The CWMS architecture allows additional non-USACE models and customized computational tools to be tightly integrated via a plugin architecture. Each model is essentially an independent plugin that can be inserted into the framework as needed.

Some of the supported models include:

- HEC-MFP – Precipitation analysis
- HEC-MetVue – Precipitation analysis
- HEC-HMS – Rainfall runoff
- HEC-ResSim – Reservoir Modeling
- RiverWare – River and reservoir modeling
- HEC-RAS – Flood inundation and hydraulic analysis
- HEC-FIA – Flood Impacts Analysis

RiverWare Functionality in CWMS

RiverWare was implemented as a plugin to CWMS through funding from the USACE-SWD. It consists of the “CWMS RiverWare Plugin” that is freely available on the RiverWare.org website. The user copies this set of files into the CWMS installation directory and modifies a few text files indicating that they wish to use this plugin.

Note, CWMS is only available to USACE offices, but the Hydrologic Engineering Center's (HEC) Real Time Simulation (HEC-RTS) software is based on the CWMS software for use by non USACE offices. Below we will reference the HEC-RTS documentation as that is publicly available, whereas the CWMS documentation is not.

CWMS features a sophisticated Control And Visualization Interface (CAVI) with a GIS integration of model schematics, allows evaluation of operational alternatives, and manages data inputs, outputs and inter-model data transfers via a database. All of the CWMS functionality will not be discussed here, as that is provided in the user manual (Real-Time Simulation User’s Manual, 2017).

Each model/application implemented in CWMS requires the modeler to do the following:

- Specify the name of the model file to use
- Specify which pieces of data are to be extracted from a database and which will be provided by models earlier in the run sequence
- Specify which pieces of data are to be written to the DSS database for use by models later in the run sequence
- Configure the order of model runs
- Choose a naming convention for the HEC-DSS database

The majority of the RiverWare plugin’s functionality is accessed via general mechanisms that apply to all models, as described in the user manual. However, when the modeler imports a

RiverWare model, the plugin presents a dialog to configure how RiverWare will work in the system. The following is the list of configurations:

- Specify the model alternative name
- Select the model file. For rulebased simulation models, the policy (global function sets and ruleset) must be saved within the model file
- Specify the input and output Data Management Interface (DMI) names
- Specify which RiverWare System Control Tables to show
- Specify which RiverWare Plots, Output Canvasses, and Scripts to show
- Choose which RiverWare Policy Language Sets (often the rules) are available from the CAVI

Operator Interactions

Once configured, the RiverWare object icons display in the CAVI map. Based on the configuration, the following RiverWare dialogs are directly accessible from CAVI buttons and right-click context menus:

- RiverWare Policy Language (RPL) editors
- System Control Tables (SCT)
- Plot Page dialogs
- Chart dialogs
- Output Canvas dialogs
- Script Dashboard dialogs
- Open Object dialogs. **Figure 1** shows one sample way to access this dialog from the right-click context menu on the CAVI maps
- Diagnostic Output dialog
- The RiverWare workspace (from which all RiverWare dialogs are available)

As noted in the last bullet, the RiverWare workspace, or standalone model, once opened can then open any other RiverWare dialog. This allows the modeler to easily access the common dialogs, but also access any other dialog as needed.

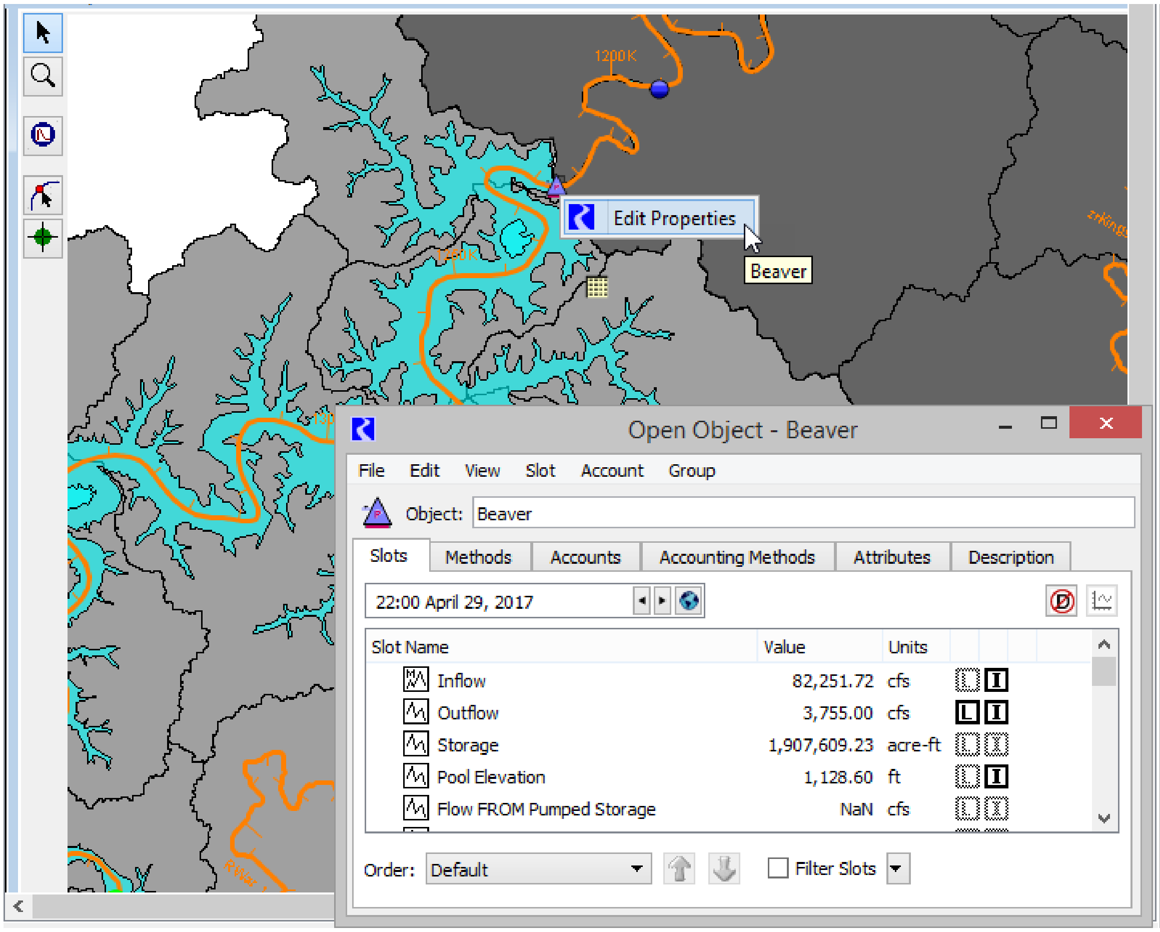


Figure 1. CAVI Setup map showing access to the RiverWare objects

Model Timesteps

Frequently, meteorological and rainfall-runoff modeling is performed at a very small timestep size, often 5 minute, 15 minute or 1 hour, while Reservoir operations are managed and modeled at larger timesteps, often 6 hour or 1 day. Flood hydraulic analysis is often performed at smaller timesteps as well. As a result, the framework must support running RiverWare models at timesteps that are different, often larger, than the other models.

The CAVI instructs RiverWare to start a run by calling the RiverWare plugin. The CAVI provides the run time window which includes the CAVI run timestep, start date and end date. The plugin passes the timestep to RiverWare, which enables RiverWare to check that the timestep is compatible with the RiverWare timestep. The assumption is that CWMS has a smaller timestep which falls on the larger RiverWare model timestep. If the timesteps are compatible, the plugin can then start the run.

Because of the potential timestep mismatch between the CAVI and the RiverWare run, there must be tools to aggregate and disaggregate data between models. In the currently proposed approach, this is performed within the RiverWare model using RiverWare aggregation and disaggregation functions and slot utilities. Time aggregation RPL functions aggregate data from small timestep custom slots to a larger timestep slot on the simulation objects. The run is then made. At the end of the run, recently developed Time Disaggregation Series Slot transform the specified results into the required small timesteps using the desired disaggregation functions, including a step function or interpolation. These disaggregated values are stored on custom slots which can be exported to the DSS file for use in subsequent models within CWMS.

Case Study

This section describes a case study of CWMS on the White River basin in Arkansas and Missouri that incorporates a RiverWare model.

White River in Arkansas and Missouri

The following section describes the use of CWMS and RiverWare in the White River basin.

Basin Background: The White River consist of five multipurpose reservoirs: Beaver, Table Rock, Bull Shoals, Norfork and Greers Ferry. The operational authorizations are flood control, hydropower, water supply, recreation and environmental stewardship. The CWMS model was primarily developed for the flood control operations. The flood operation of the upper four-lake system, Beaver, Table Rock, Bull Shoals and Norfork, is constrained by regulation points at Batesville and Newport. In addition, Greers Ferry releases flow into the Little Red River and has a regulation point of Judsonia and Georgetown. There is a large uncontrolled drainage area from both the Black and White Rivers to Newport and Georgetown. This means that all of the reservoirs in the system have to hold water for long periods of time and often enter into an induced surcharge operation to maximize flood storage available. The system is operated to prevent flooding at the regulation points and then to evacuate the flood control pool as quickly as possible in a balanced and controlled fashion.

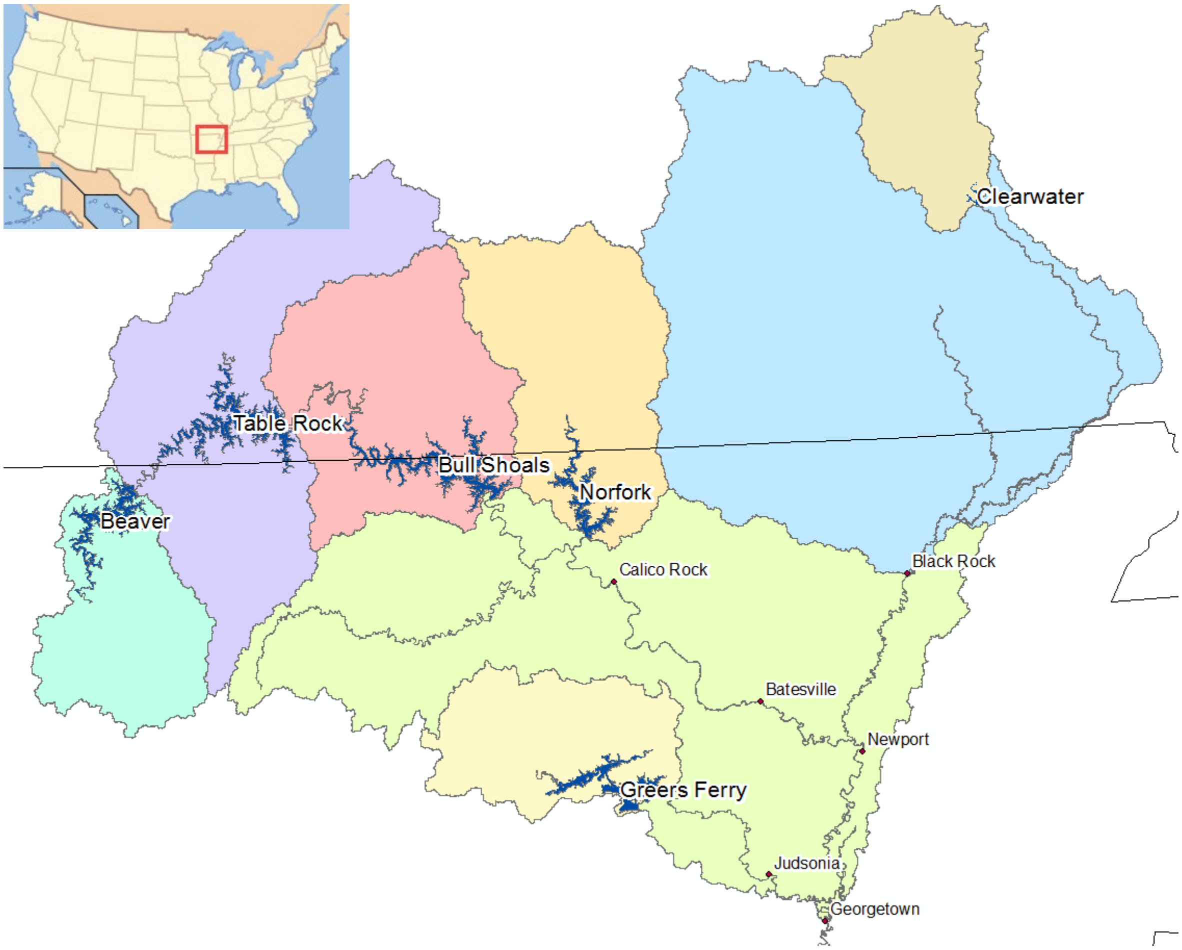


Figure 2. Map of White River Basin

CWMS Implementation: Within the Little Rock District, HEC-MFP or HEC-MetVue is used to view and analyze the rainfall and send it to a rainfall-runoff model HEC-HMS. The HEC-HMS model is then run to forecast the inflows into all of the reservoirs and local areas. The flows are sent into a RiverWare reservoir operation model to determine the release plan. Then the final release plan is sent to HEC-RAS, as needed, to develop water depth and inundation graphs. The results of HEC-RAS can be sent to HEC-FIA for impacts analysis.

The White River basin RiverWare model was developed concurrently with the HEC-HMS and other models implemented in CWMS. As a result, the district had the luxury of developing the RiverWare model to exactly match the layout and naming convention of the other models, particularly the HMS model, in the system. Although there are mapping tools within RiverWare data management interfaces, it is easiest for debugging and comparison between models if the names and locations map directly between models.

Example Operation: This section describes a sample operation to show how the CWMS and RiverWare model was used to operate the system during a sample precipitation event.

During April 28^{th} to May 10^{th} 2017, the White River system had repeated precipitation events ranging from 3 inches to 15 inches throughout the basin, with the majority of the rainfall in the basin averaging 9-10 inches of rain.

To operate the system, the first step in the process is to open CWMS and define a new “forecast” to set up the run ranges for all of the models.

Next, CWMS is run to "Compute all Models". In order, each model:

1. Runs an "Extract" to import any required timeseries data from the USACE Oracle database.
2. Imports all required data from the CWMS DSS file that was computed by upstream models
3. Simulates
4. Exports specified results to the CWMS DSS file.

Once RiverWare is run, the district operators look at the results in CWMS. This section will focus on the RiverWare results. The operators access the preconfigured plot dialogs, object dialogs, rules, System Control Tables, and other output devices directly from CWMS. **Figure 2** shows a sample view of the White River CAVI with the Modeling tab displayed. Highlighted are the RiverWare actions to open dialogs. The arrows show the dialogs that are opened.

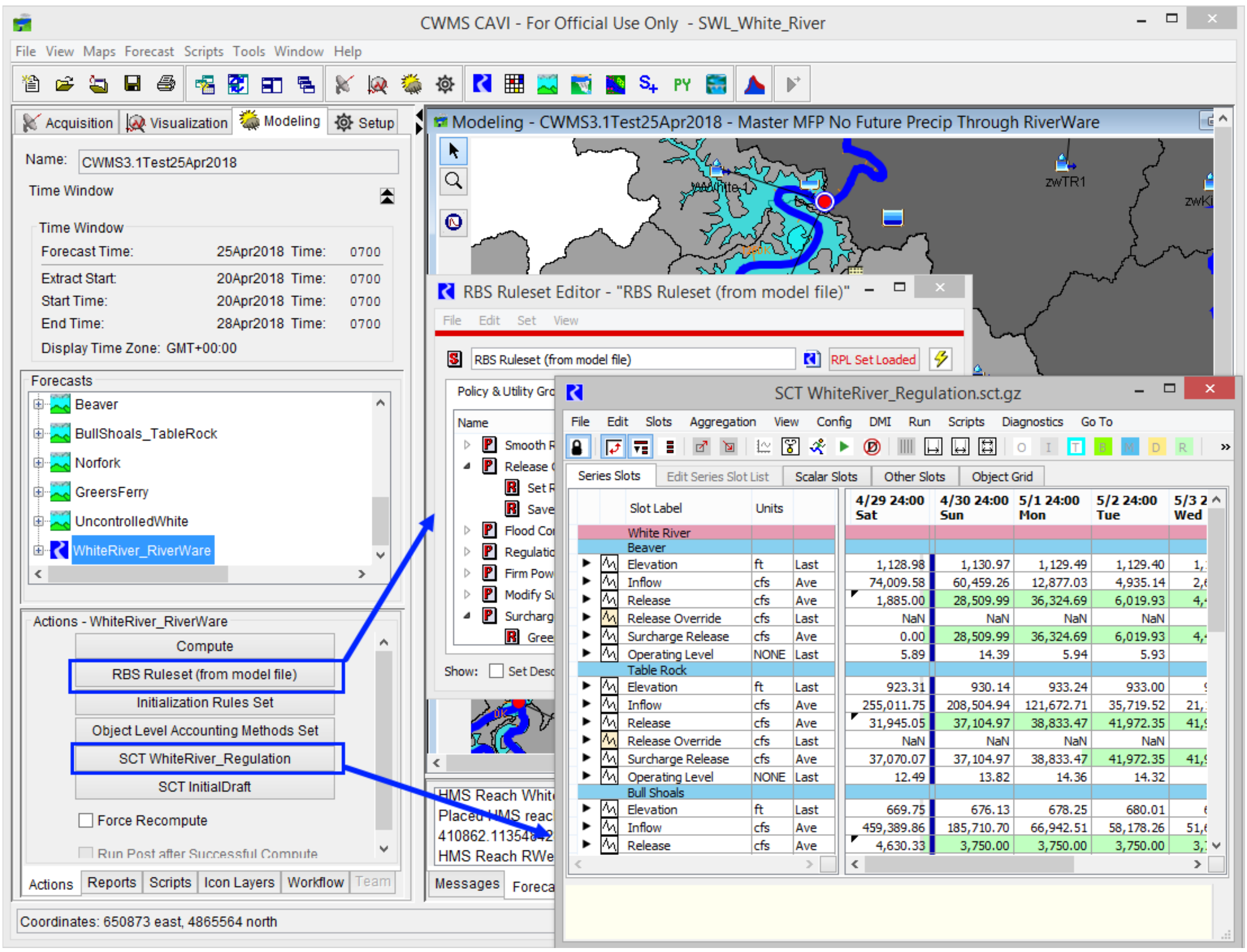


Figure 3. Screenshot of the CAVI modeling tab with RiverWare actions highlighted with their associated dialogs

At this stage, RiverWare has computed an answer, but the model has perfect foresight; it knows the inflows coming into the lake for the next several days, exactly. The real world is imperfect, with inaccuracies and limitations, which is where engineering judgement comes in; operation still requires engineers to regulate the lakes.

The following are tools that have been created to help aid in the process of making changes to the release schedules, and to aid the regulators in making their release decisions.

The regulators can adjust many items including:

- Precipitation forecasts and running the entire suite again
- Changing inflows and re-running just RiverWare
- Changing targets and re-running RiverWare
- Turning on or off rules depending on the situations and rerunning RiverWare
- Changing reservoir releases due to unexpected conditions or requirements and rerunning RiverWare.

For the storm in question shown in **Figure 2**, the black line shows the release that RiverWare developed. The blue line represents the pool elevation. The solid red line shows the top of the flood pool. So this rainfall event raised the pool above the top of the flood pool and into the surcharge pool.

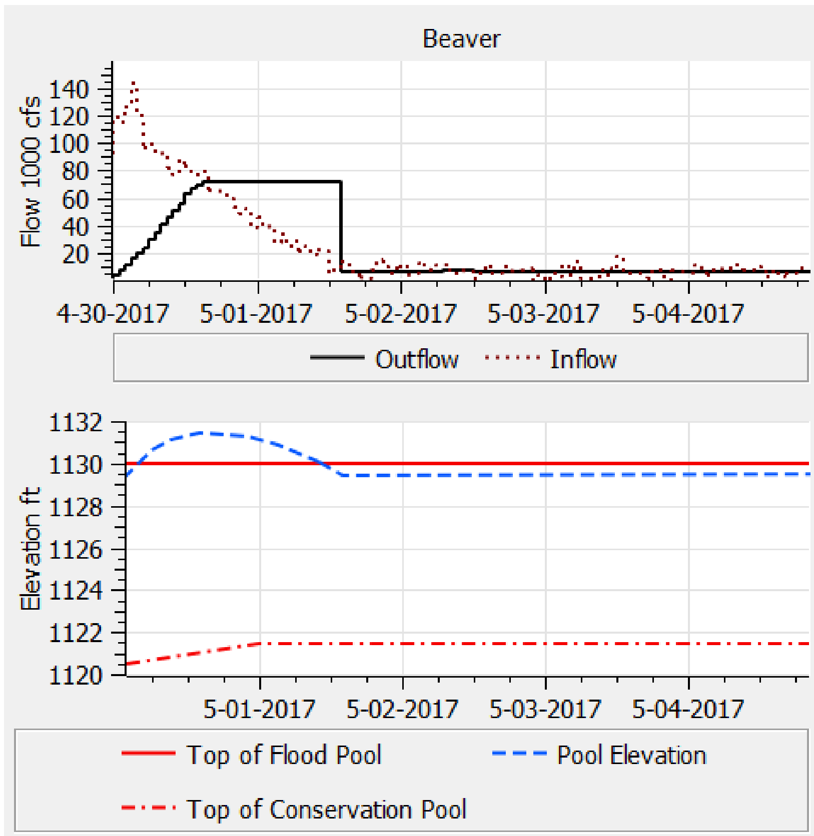
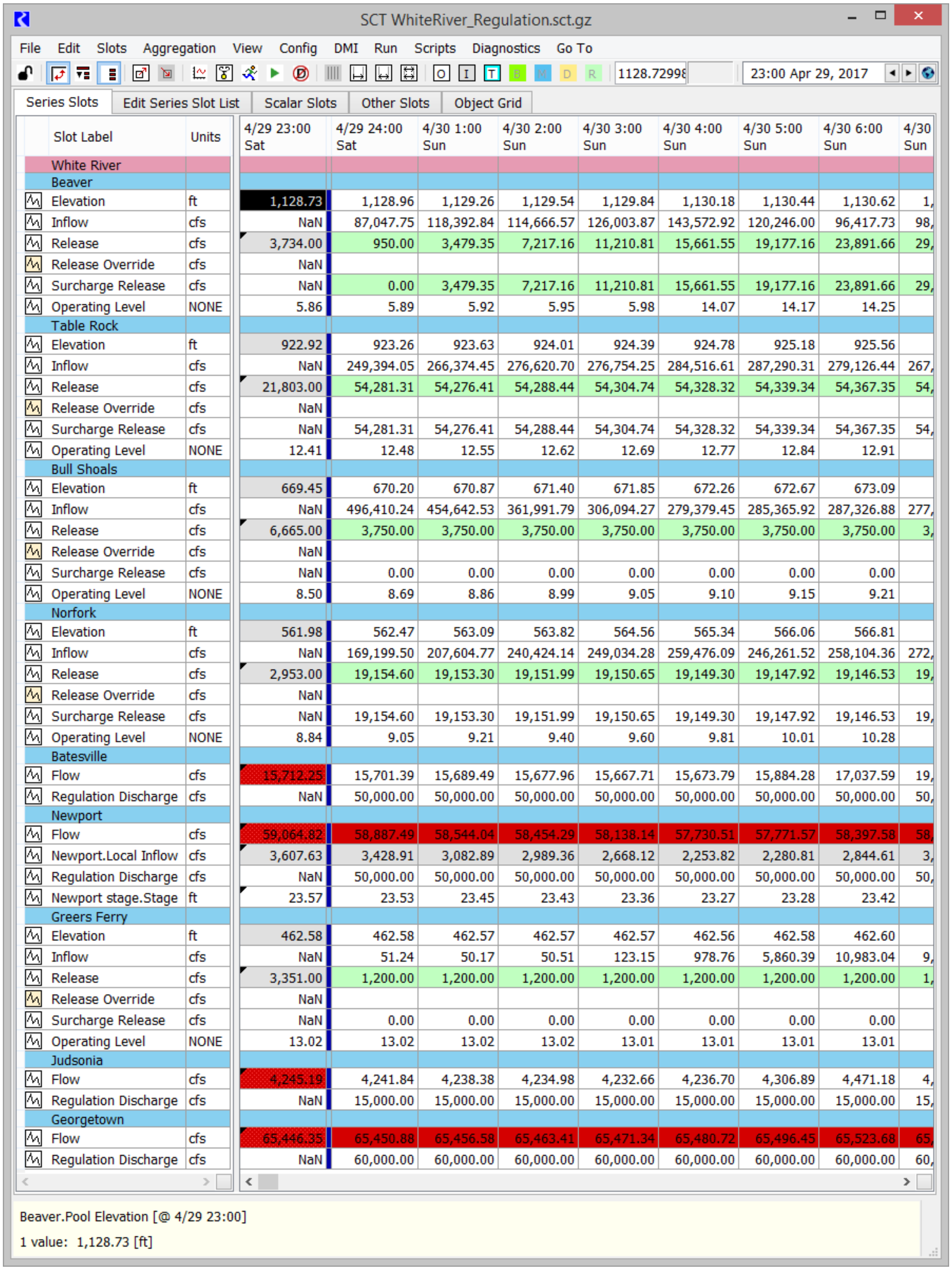


Figure 4. Plot of raw results from RiverWare

Notice, on April 30th, the Outflow changes each timestep as it is ramped up to 70,000 cfs. The project personnel will not appreciate if asked to make a gate change every single hour, unless absolutely necessary. To adjust this, the operator opens a saved System Control Table (SCT) to view and modify data.

The SCT is a customizable view of the data in the RiverWare model. The operator can organize the data as they like and have one or more SCTs open at a time. Operators report that the SCT helps guide them in their engineering decisions; they can quickly see the data they need to see in one place and can color code cells based on the values. **Figure 3** shows a sample SCT displaying an hourly timestep. It can also be configured to show aggregated daily values. Color alerts are shown in red, indicating that regulations limits downstream at Newport and Georgetown have been exceeded.



Slot Label	Units	4/29 23:00 Sat	4/29 24:00 Sat	4/30 1:00 Sun	4/30 2:00 Sun	4/30 3:00 Sun	4/30 4:00 Sun	4/30 5:00 Sun	4/30 6:00 Sun	4/30 Sun
White River										
Beaver										
Elevation	ft	1,128.73	1,128.96	1,129.26	1,129.54	1,129.84	1,130.18	1,130.44	1,130.62	1,
Inflow	cfs	NaN	87,047.75	118,392.84	114,666.57	126,003.87	143,572.92	120,246.00	96,417.73	98,
Release	cfs	3,734.00	950.00	3,479.35	7,217.16	11,210.81	15,661.55	19,177.16	23,891.66	29,
Release Override	cfs	NaN								
Surcharge Release	cfs	NaN	0.00	3,479.35	7,217.16	11,210.81	15,661.55	19,177.16	23,891.66	29,
Operating Level	NONE	5.86	5.89	5.92	5.95	5.98	14.07	14.17	14.25	
Table Rock										
Elevation	ft	922.92	923.26	923.63	924.01	924.39	924.78	925.18	925.56	
Inflow	cfs	NaN	249,394.05	266,374.45	276,620.70	276,754.25	284,516.61	287,290.31	279,126.44	267,
Release	cfs	21,803.00	54,281.31	54,276.41	54,288.44	54,304.74	54,328.32	54,339.34	54,367.35	54,
Release Override	cfs	NaN								
Surcharge Release	cfs	NaN	54,281.31	54,276.41	54,288.44	54,304.74	54,328.32	54,339.34	54,367.35	54,
Operating Level	NONE	12.41	12.48	12.55	12.62	12.69	12.77	12.84	12.91	
Bull Shoals										
Elevation	ft	669.45	670.20	670.87	671.40	671.85	672.26	672.67	673.09	
Inflow	cfs	NaN	496,410.24	454,642.53	361,991.79	306,094.27	279,379.45	285,365.92	287,326.88	277,
Release	cfs	6,665.00	3,750.00	3,750.00	3,750.00	3,750.00	3,750.00	3,750.00	3,750.00	3,
Release Override	cfs	NaN								
Surcharge Release	cfs	NaN	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Operating Level	NONE	8.50	8.69	8.86	8.99	9.05	9.10	9.15	9.21	
Norfork										
Elevation	ft	561.98	562.47	563.09	563.82	564.56	565.34	566.06	566.81	
Inflow	cfs	NaN	169,199.50	207,604.77	240,424.14	249,034.28	259,476.09	246,261.52	258,104.36	272,
Release	cfs	2,953.00	19,154.60	19,153.30	19,151.99	19,150.65	19,149.30	19,147.92	19,146.53	19,
Release Override	cfs	NaN								
Surcharge Release	cfs	NaN	19,154.60	19,153.30	19,151.99	19,150.65	19,149.30	19,147.92	19,146.53	19,
Operating Level	NONE	8.84	9.05	9.21	9.40	9.60	9.81	10.01	10.28	
Batesville										
Flow	cfs	15,712.25	15,701.39	15,689.49	15,677.96	15,667.71	15,673.79	15,884.28	17,037.59	19,
Regulation Discharge	cfs	NaN	50,000.00	50,000.00	50,000.00	50,000.00	50,000.00	50,000.00	50,000.00	50,
Newport										
Flow	cfs	59,064.82	58,887.49	58,544.04	58,454.29	58,138.14	57,730.51	57,771.57	58,397.58	58,
Newport.Local Inflow	cfs	3,607.63	3,428.91	3,082.89	2,989.36	2,668.12	2,253.82	2,280.81	2,844.61	3,
Regulation Discharge	cfs	NaN	50,000.00	50,000.00	50,000.00	50,000.00	50,000.00	50,000.00	50,000.00	50,
Newport stage.Stage	ft	23.57	23.53	23.45	23.43	23.36	23.27	23.28	23.42	
Greers Ferry										
Elevation	ft	462.58	462.58	462.57	462.57	462.57	462.56	462.58	462.60	
Inflow	cfs	NaN	51.24	50.17	50.51	123.15	978.76	5,860.39	10,983.04	9,
Release	cfs	3,351.00	1,200.00	1,200.00	1,200.00	1,200.00	1,200.00	1,200.00	1,200.00	1,
Release Override	cfs	NaN								
Surcharge Release	cfs	NaN	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Operating Level	NONE	13.02	13.02	13.02	13.02	13.01	13.01	13.01	13.01	
Judsonia										
Flow	cfs	4,245.19	4,241.84	4,238.38	4,234.98	4,232.66	4,236.70	4,306.89	4,471.18	4,
Regulation Discharge	cfs	NaN	15,000.00	15,000.00	15,000.00	15,000.00	15,000.00	15,000.00	15,000.00	15,
Georgetown										
Flow	cfs	65,446.35	65,450.88	65,456.58	65,463.41	65,471.34	65,480.72	65,496.45	65,523.68	65,
Regulation Discharge	cfs	NaN	60,000.00	60,000.00	60,000.00	60,000.00	60,000.00	60,000.00	60,000.00	60,

Beaver.Pool Elevation [@ 4/29 23:00]

1 value: 1,128.73 [ft]

Figure 5. Sample SCT used to operate the White River

In the sample operation, the operator modifies the release in the "Release Override" slot on Beaver. These values are then applied to the reservoir object's Outflow by a rule. The operators start off with a small gate change and slowly open up in about 3 gate changes to 56,000 cfs. With this override set, the modeler reruns the RiverWare model by clicking "Compute" within the CAVI. The resulting outflow and elevations are shown in **Figure 3**.

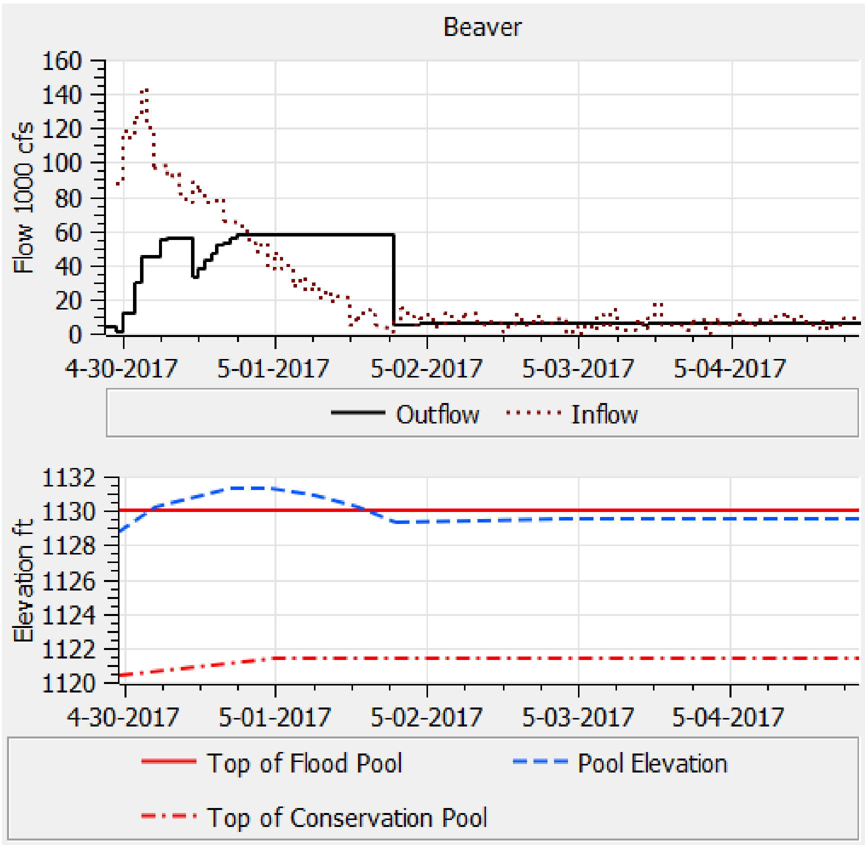


Figure 6. Plot of results from RiverWare after the first set of changes

After the overrides, the RiverWare rules shut back to around 35,000 cfs and then increase outflows back up to 60,000 cfs. This is because there is a rule executing to calculate the induced surcharge curve at Beaver. Part of the purpose for Beaver reservoir is to hold water and keep it out of Table Rock Lake. This reservoir is the last reservoir to empty on the White River and sometimes needs to hold water. The induced surcharge curve represents the flow that has to be released at this elevation. The operators typically like to make releases before this surcharge elevation, which will allow it to cut off the peak release. But the rule results show the operators how long they can hold flows at Beaver and what the peak release will be. In this operation, it is more beneficial to turn this rule off and rerun the model and see the results. **Figure 4** shows the results when turning off the induced surcharge rule and re-running the model.

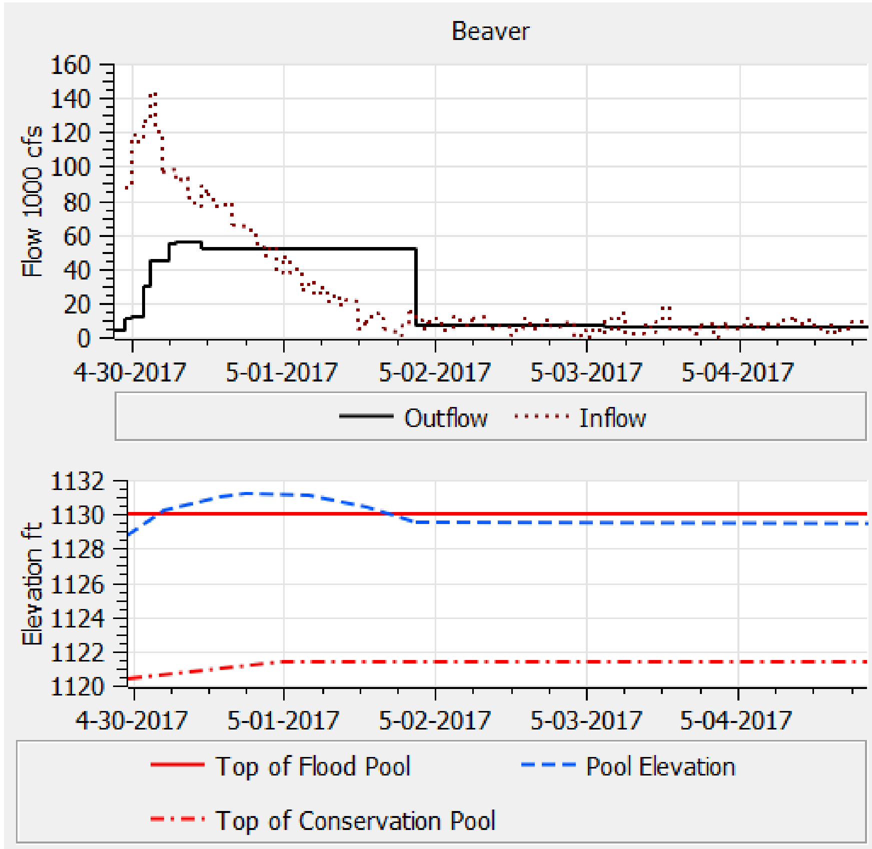


Figure 7. Plot of results from RiverWare after disabling the induced surcharge rule

With the initial opening overrides in place, the operations rules then hold the release until the pool is about 0.5 ft below the top of the flood pool, and then shut backs. This final shut back from 56,000 cfs to 11,500 cfs is still too dramatic. Additional rules were not added to refine the shut back because they are dependent on a variety of variables that engineering judgment is needed to evaluate. The final change is to put in small gate changes. This leads to an operation where the outflow is held at 56,000 cfs and then cut back in two gate changes to 11,500 cfs.

The final results are shown in **Figure 5**. The operations look reasonable and are provided to the dam operators who actually implement the change for the next few timesteps. During an extreme flood, the system is operated on a 24 hr basis, with the model run every few hours and gate changes made as frequently as needed. For smaller floods, the system is monitored and models are updated as necessary.

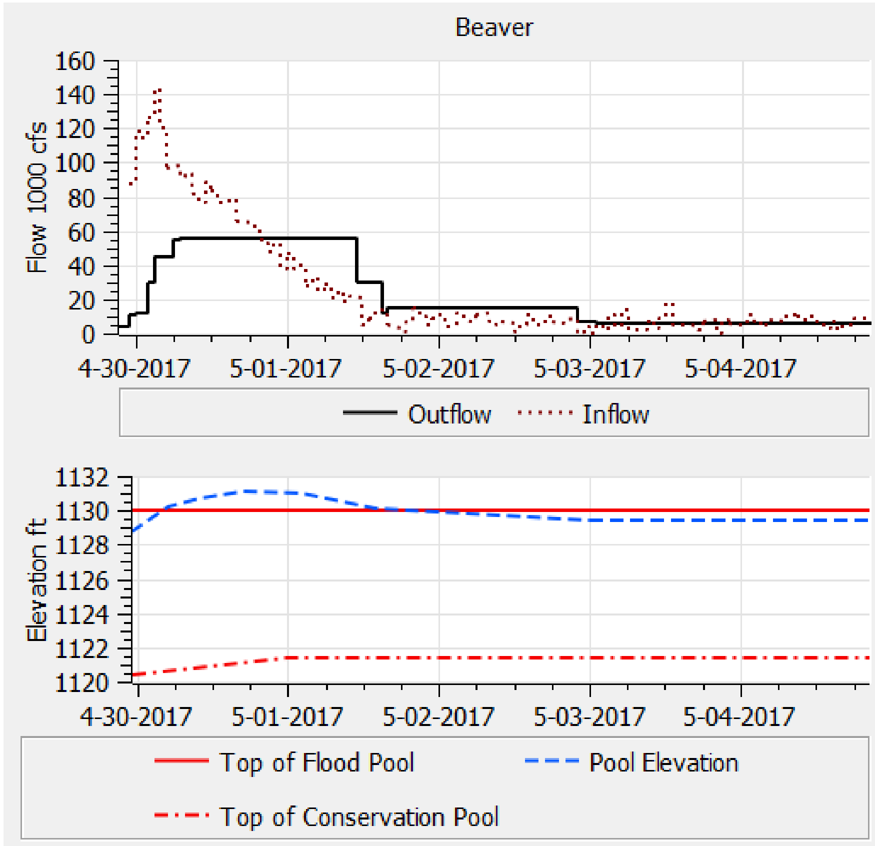


Figure 8. Plot of results from RiverWare after final overrides

Conclusions based on this operation: As we have shown, RiverWare and CWMS are tools to help make decisions. In a real time flood situation, these will never replace the engineering judgment required to operate a complex system like the White River. The benefit of having RiverWare in CWMS is that the operations process is much more automated and easy to use with nice graphical interfaces and stream-lined processes. RiverWare gives regulators a good starting point for a release plan, and reduces the time spent developing the release plan. It also allows them options to quickly compare different general release scenarios by turning rules on or off. With engineering judgment still needed to come up with the final plan. Now the operators can spend time making engineering decisions, not processing data and performing manual manipulation. Instead CWMS has automated many of these steps.

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