RESERVOIR OPERATIONS MODELING WITH HEC-RESSIM

Joan D. Klipsch, Thomas A. Evans, PhD.
Hydrologic Engineering Center, U.S. Army Corps of Engineers
Davis, CA. 530-756-1104
joan.d.klipsch@usace.army.mil
thomas.a.evans@usace.army.mil

Abstract: The Hydrologic Engineering Center (HEC) of the U.S. Army Corps of Engineers has developed a new reservoir simulation model, HEC-ResSim, as the successor to the well-known HEC-5. Designed to simulate reservoir operations for flood management as well as flow augmentation, HEC-ResSim represents a significant advancement in the decision support tools available to water managers.

HEC-ResSim uses an original rule-based approach to mimic the actual decision-making process that reservoir operators must use to meet operating requirements for flood control, power generation, water supply, and environmental quality. Parameters that may influence flow requirements at a reservoir include time of year, hydrologic conditions, water temperature, and simultaneous operations by other reservoirs in a system. The reservoirs designated to meet the flow requirements may have multiple and/or conflicted constraints on their operation. HEC-ResSim describes these flow requirements and constraints for the operating zones of a reservoir using a separate set of prioritized rules for each zone. Basic reservoir operating goals are defined by flexible at-site and downstream control functions and multi-reservoir system constraints. As HEC-ResSim has evolved, advanced features such as outlet prioritization, scripted state variables, and conditional logic have made it possible to model more complex systems and operational requirements. The graphical user interface makes HEC-ResSim easy to use and the customizable plotting and reporting tools facilitate output analysis.

INTRODUCTION

Large man-made reservoirs are constructed and operated for multiple purposes. Reservoir operators must simultaneously meet requirements for many needs, including flood control, power generation, recreational use of the reservoir pool, environmental quality downstream of the reservoir, and the safety and structural integrity of the dam itself. Each of these needs imposes constraints on the storage and release of water from the reservoir, and the needs and constraints often conflict with one another. Setting a schedule of reservoir releases that fulfils the purpose of a reservoir, meets operating constraints, and is physically possible is not a simple task, and engineers have created reservoir simulation models to help develop those release schedules.

HEC-ResSim is one such reservoir simulation model. It has been developed by the Hydrologic Engineering Center of the US Army Corps of Engineers to aid engineers and planners in predicting the behavior of reservoir systems in water management studies, and to help reservoir operators plan releases in real time during day-to-day and emergency operations.

HEC-ResSim is unique among reservoir simulation models because it attempts to reproduce the decision making process that human reservoir operators must use to set releases. The program represents the physical behavior of reservoir systems with a combination of hydraulic computations for flows through control structures, and hydrologic routing to represent the lag and attenuation of flows through segments of streams. It represents operating goals and constraints with an original system of rule-based logic that has been specifically developed to represent the decision-making process of reservoir operation.

This paper describes the purposes and development of HEC-ResSim and identifies the unique features of its rule-based operating logic. The program has progressed through three major versions, and its decision logic has grown more complex to meet user requirements, and presently addresses operation of multi-reservoir systems, operation to meet power-generation goals, and operation of pump-back systems. Inevitably, HEC-ResSim will grow still more complex as its users attempt to find solutions to still more reservoir operation problems.

ORIGIN AND GOALS OF HEC-RESSIM

HEC-ResSim is the successor to HEC-5 as the Corps's reservoir simulation model. The development of HEC-ResSim follows the path established by HEC with the introduction of HEC-RAS and HEC-HMS as successors to the river hydraulics model HEC-2 and the hydrology model HEC-1. Although it serves similar purposes to those of HEC-5, HEC-ResSim, like HEC-RAS and HEC-HMS, is an original program, sharing no code with its predecessor.

HEC began developing HEC-ResSim in the mid 1990's by surveying water management and regulatory personnel of the Corps to determine what the field believed was needed in a modern reservoir modeling program. The results of the survey were compiled into a requirements document that detailed the physical and operational elements necessary to an effective reservoir simulation program. That requirements document has provided the foundation for the design and development of HEC-ResSim. The two primary requirements were: it must be physically realistic and it must be capable of representing a complex set of operational goals and constraints.

THE PHYSICAL RESERVOIR SYSTEM

HEC-ResSim represents a system of reservoirs as a network composed of four types of elements: junctions, routing reaches, diversions, and reservoirs. Each element is defined with enough information to be physically realistic without requiring excessive detail that would bog down computation time.

By combining reservoirs, reaches, junctions, and diversions, a HEC-ResSim user is able to build a network capable of representing anything from a single reservoir on a single stream to a highly developed and interconnected system like that of California's central valley. The program's user interface allows the user to draw the network either as a stick figure, or as a map drawn over geo-referenced graphics (see Figure 1).

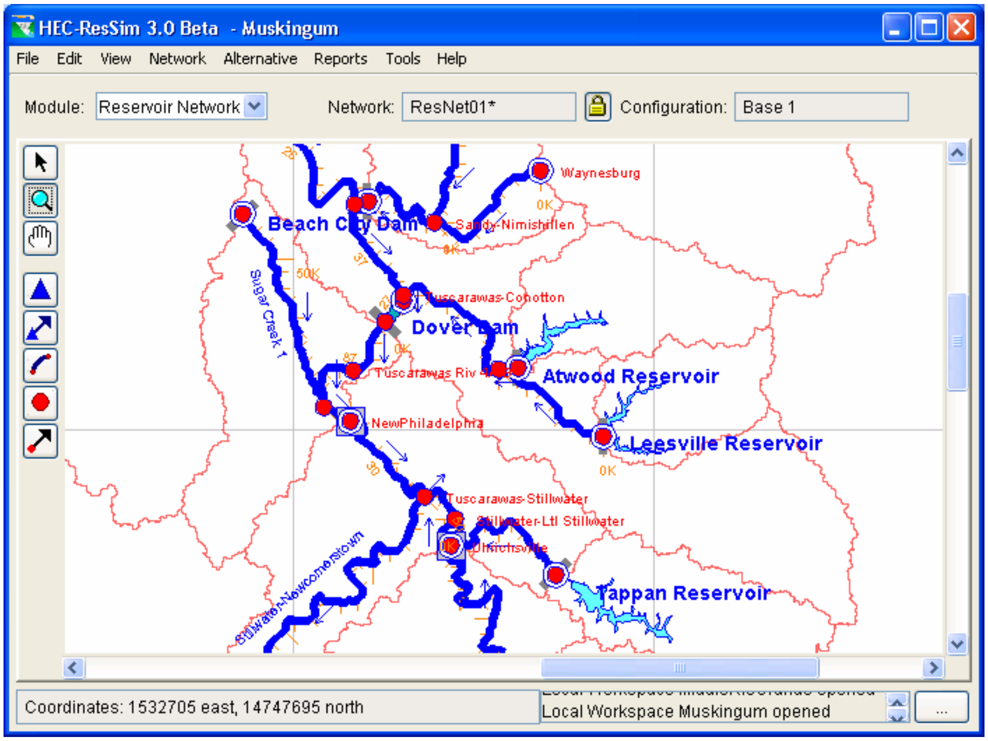

Figure 1 Reservoir Network Schematic

The simplest element type is the junction. Junctions represent stream confluences or points where external flows enter the system. Since HEC-ResSim does not calculate runoff, all local flows must be introduced at junctions as external flows. The flow out of a junction is simply the sum of the flows into the junction. Flows at junctions can be converted to stages through the use of rating curves.

Routing reaches represent the natural streams in the system, and the lag and attenuation of flow in a reach is computed by one of a variety of available standard hydrologic routing methods, such as Muskingum, Modified Puls, Coefficient, or Muskingum-Cunge. Losses through seepage can be specified for each routing reach.

A diversion is a more complex element. It represents a "withdrawal" of water from the natural stream. The quantity of the withdrawal can be specified as a constant amount or as a function of some parameter such as time or flow. Some or all of the diverted water can be routed and returned by a diversion or it can be removed from the system entirely.

A reservoir is the most complex element of the reservoir network and is composed of a pool and a dam. HEC-ResSim assumes that the pool is level (i.e., it has no routing behavior) and its hydraulic behavior is completely defined by an elevation-storage-area table. The real complexity of HEC-ResSim's reservoir network begins with the dam.

The dam is the root of an outlet hierarchy or "tree" which allows the user to describe the different outlets of the reservoir in as much detail as is deemed necessary. There are two basic and two advanced outlet types. The basic outlet types are *controlled* and *uncontrolled*. An uncontrolled outlet can be used to represent an outlet of the reservoir, such as an overflow spillway, that has no control structure to regulate flow. Controlled outlets can be used to represent any outlet, such as a gate or valve, capable of regulating flow. The advanced outlet types are *power plant* and *pump*, both of which are controlled outlets with additional features to represent their special purposes. The power plant adds the ability to compute energy production to the standard controlled outlet. The pump is an even more specialized controlled outlet. Its flow direction is opposite that of the other outlet types, and it can draw water up into the reservoir from the pool of another reservoir. The pump outlet type was added to enable the user to model pump-back operation in hydropower systems.

FLEXIBLE OPERATIONS DEFINITION

HEC-ResSim uses an original rule-based approach to mimic the operational decision-making process that reservoir operators follow in setting release schedules. Just as operators must, the HEC-ResSim release decision-making process for a reservoir takes into account time of year, hydrologic conditions, water temperature, and simultaneous operations by other reservoirs in a system.

<u>Basic Decision Logic:</u> At most reservoirs, flow requirements and constraints vary depending on the state of the reservoir pool. That is, the rules change depending on the amount of water stored in the reservoir. HEC-ResSim describes this dependency by dividing the pool into elevation bands, called zones, and applying a different set of prioritized rules to each operating zone in the reservoir. An operating zone is described by a water elevation curve representing the top of the zone. When the water level in the pool exceeds the top (or bottom) of a zone, its rules no longer apply to release decisions. The top-of-zone elevation curve can be a constant or can vary seasonally.

A reservoir in HEC-ResSim must have a target elevation. A reservoir's target elevation, represented as a function of time, is called its *Guide Curve*. It is the dividing line between the upper zones of the reservoir (typically called the flood-control pool) and the lower zones (typically called the conservation pool).

The release decision logic in HEC-ResSim starts and ends with the guide curve. When the reservoir's pool elevation is above the guide curve ("in flood control"), the reservoir wants to release more water than is entering the pool; when below guide curve ("in conservation"), the reservoir wants to release less water than is entering the pool. All operating rules and physical limitations act as constraints upon the reservoir's ability to meet the goal of returning the pool to its guide curve elevation. Without rules, the reservoir will be constrained only by physical capacity of the outlets to get to and stay at the guide curve elevation.

Each reservoir operating goal is described by a flexibly-defined rule that, when evaluated, specifies a minimum or maximum limit on the release from the reservoir or outlet. The rules are placed in a prioritized list in one or more reservoir zones. As each rule is evaluated, its calculated minimum and/or maximum flow is applied to an evolving "allowable range of release”. At the start of the release decision process, HEC-ResSim sets the allowable release range to the physical limits of the dam or outlet: the maximum of the range is the total maximum capacity of the outlets for the current pool elevation, the minimum of the range is the minimum release capacity of the outlets, usually zero. As a rule is applied, it may narrow the allowable release range. If a rule does not either raise the minimum allowable release or lower the maximum, then that rule will have no effect on the range. Once all rules have been evaluated and applied to the range, the allowable range is considered complete and the “desired guide curve release” is computed. The desired guide curve release is the release the reservoir would make if it were not constrained by any “limits”. The final release is the closest value to the desired guide curve release that falls inside the allowable range.

Complex Operation Plans: Although only a small variety of rule types are available in HEC-ResSim, when combined with one another and the conditional (IF-Then-Else) rule usage logic, the user can describe very complex operation schemes. Some examples are given below to illustrate the flexibility of the rules and operation scheme definition in HEC-ResSim. (Note: These are merely examples and are NOT to be taken as representative of the actual regulations on these systems or any models that may currently be in use as real-time decision support tools.)

Example 1: Flood Operation for Multiple Downstream Locations: Evaluating operations of a reservoir for a downstream goal or limit is the primary objective for most HEC-ResSim models. When a downstream control rule is evaluated during a time step, HEC-ResSim sums all contributing flows to the downstream control point, compares that sum to the limit at the control point, and routes the difference back to the controlling reservoir. That difference is often referred to as the “available space” at the control point. The *back-routed* space represents the limit on the release that the controlling reservoir can make.

The operation set illustrated in Figure 2 includes downstream control rules for three downstream locations – Vida, Albany, and Salem. HEC-ResSim evaluates each downstream control rule independently, producing a maximum limit for each rule. It might seem that because the rule at

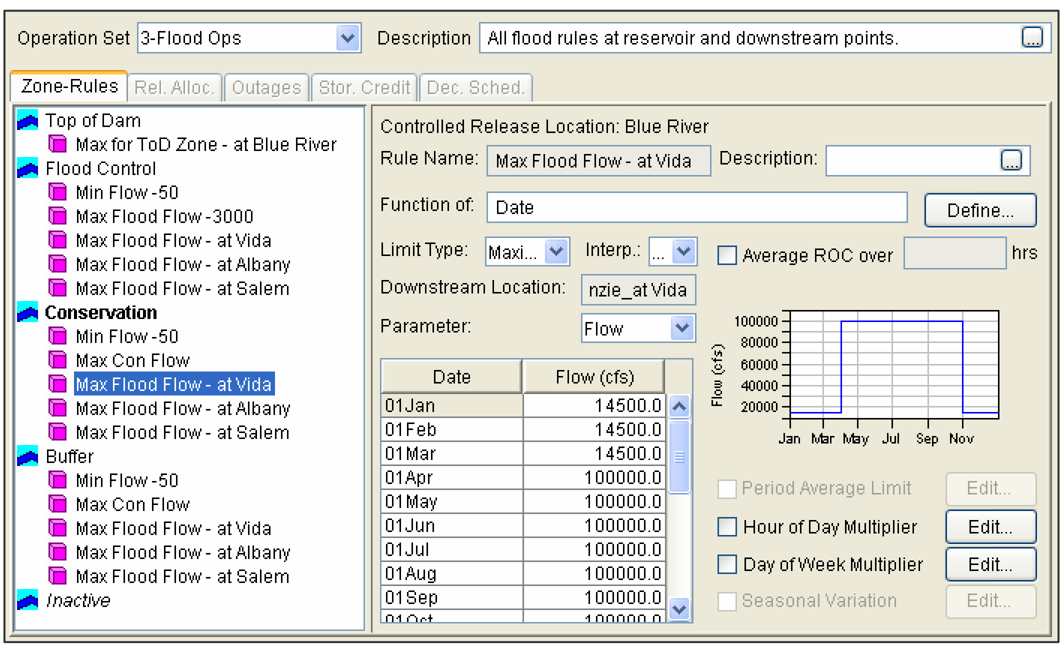

Figure 2 Specifying Multiple Downstream Controls

Vida is the highest priority, then Albany and Salem would suffer violations of their limits. In fact, each rule has the opportunity to apply its limit to the allowable range of releases and none of the three will be violated as long as the reservoir has some control over the downstream flow. So, if the maximum limit at Salem produces a lower limit on the release than the limit at Vida or Albany, then the allowable range of release for this reservoir will simply be narrowed further – the limit at Vida or Albany will not be violated, it simply will not have its entire available space filled by this reservoir.

Example 2: Multiple Reservoirs Operating For a Common Objective: It is not unusual for more that one reservoir in a basin to be assigned the objective of controlling flow at a downstream location. In this example, both reservoirs illustrated Figure 3, Cochiti and Jemez Canyon, contribute flow to and operate for the control point at Albuquerque.

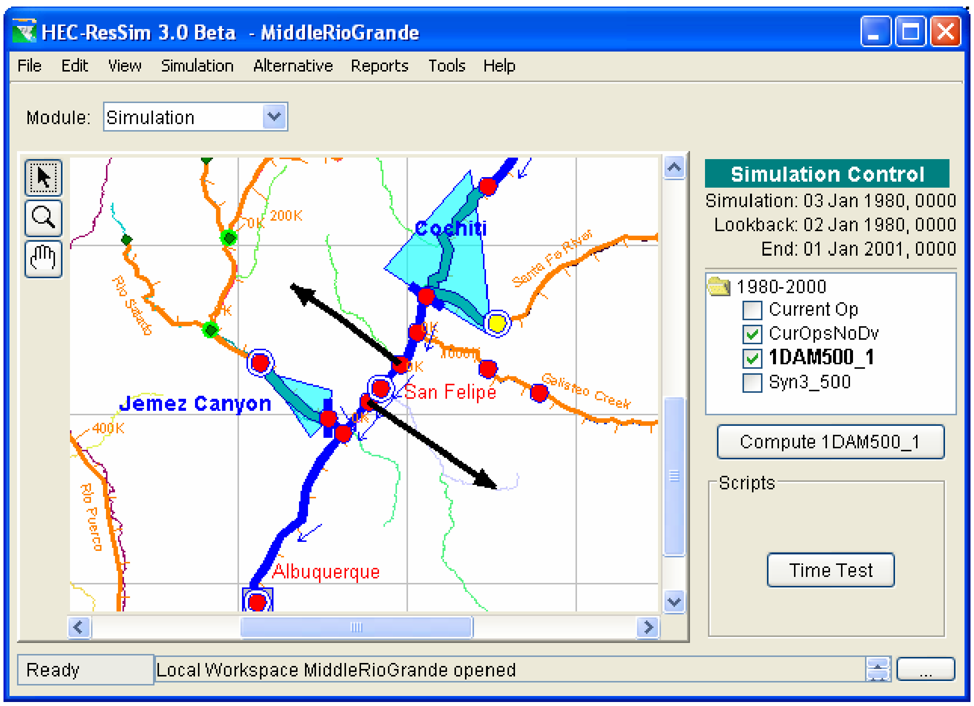

Figure 3 Two Reservoir Contributing to a Downstream Control Point

In HEC-ResSim, multi-reservoir system constraints are orchestrated using a storage balancing approach. The system storage balance specifies the weighting or allocation of the total release from all the reservoirs to each reservoir in the system. By default, HEC-ResSim will try to maintain an even percent-of-storage balance between the reservoirs that are operating as a system. This default balance is referred to as the *implicit* storage balance. If the implicit balance is not appropriate, the user can enter an *explicit* description of the storage balance between the reservoirs.

Several factors including relative size of the reservoirs and the proximity to the control point make it in inappropriate for the reservoirs in this system to balance evenly to meet the constraints at Albuquerque. For this reason, an explicit storage balance was specified. The purpose of the explicit system storage balance illustrated in Figure 4 is to force the larger and more distant reservoir, Cochiti, to fill first, allowing the smaller and nearer reservoir, Jemez Canyon, to stay empty as long as possible when operating for flood control.

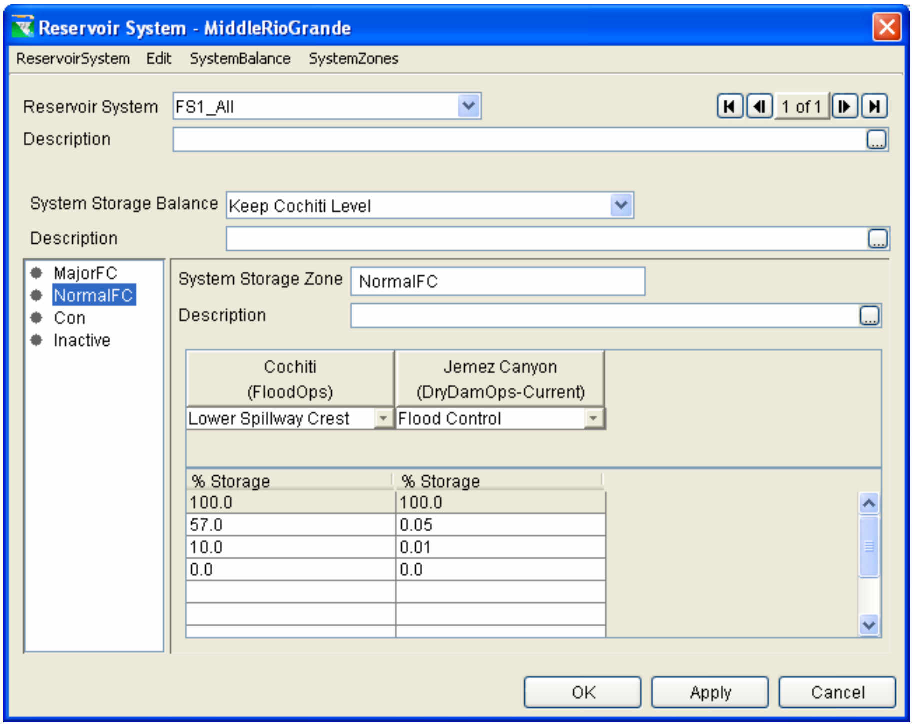

Figure 4 Explicit System Storage Balance

Example 3: Conditional Constraints : In this example, an upstream reservoir, Atwood, watches the pool elevation at a downstream reservoir, Dover. When Dover exceeds a specified pool elevation, the release at Atwood is reduced to almost zero so as not to contribute to the

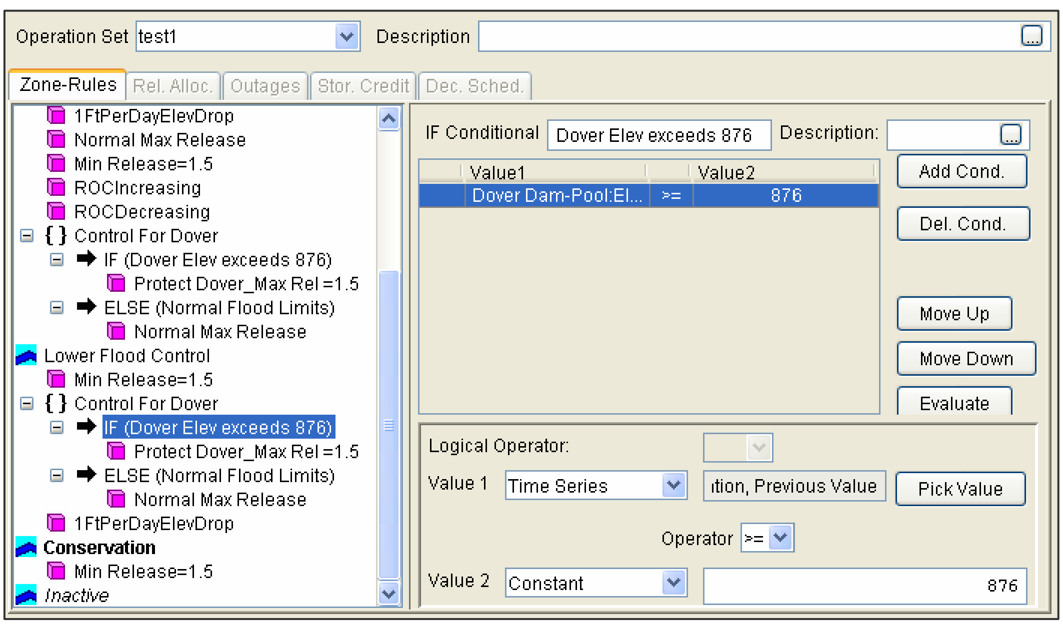

Figure 5 Using If Blocks to Add Conditional Constraints

flows entering Dover reservoir. The standard zone and rules do not allow for the state of one reservoir to influence the operation at another reservoir. With the use of the If-Block illustrated in Figure 5, this conditional operation is easily defined.

FUTURE OUTLOOK

Version 3.0 of HEC-ResSim is expected to be released by the end of December 2005. Further developments are already in progress to enhance the water supply modeling capabilities of HEC-ResSim. The first target of the new development is an enhanced network traversal algorithm for the release decision logic. This is needed to handle the complex and often non-dendritic flow networks that are fairly common in water supply systems. It is anticipated that the new algorithm will not only enable HEC-ResSim to represent more complex flow networks, but it will also speed up computation time and improve the simulation of existing models.

Several other important features will also be added. The first is an option that was requested and funded by HEC’s real-time water management partners at the Lower Colorado River Authority. This new option will allow HEC-ResSim to use a projected pool elevation to base its current release decisions on rather than using the current pool elevation.

Through an expected inter-agency partnership with the National Weather Service, additional features are being anticipated. Among these are new options for emergency gate operations and extensions to the downstream control operation to respect rate of change constraints. Also, this partnership will provide HEC-ResSim with the ability to execute in a batch mode so that it can be utilized within the National Weather Service’s River Forecasting System.

CONCLUSION

HEC-ResSim is a generalized reservoir simulation program that has been (and continues to be) developed to provide watershed managers an effective tool for real-time decision support and use in planning studies. The generalized nature of HEC-ResSim, its flexible scheme for describing reservoir operations, and its powerful new features make it applicable for modeling almost any single- or multi-purpose reservoir system.