Modeling Interconnected Reservoirs with HEC-ResSim

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ABSTRACT

The USACE Hydrologic Engineering Center (HEC) reservoir simulation software, HEC-ResSim, is being used by reservoir modelers world-wide. HEC-ResSim can be used to simulate reservoir operations for multiple objectives including flood risk reduction, navigation, hydropower, and environmental support. ResSim uses a map-based schematic to represent the river and reservoir system. Reservoir operation is modeled through a set of operation rules that describe the operating goals and constraints. The Tioga-Hammond reservoir system, located in the Chemung River watershed at the headwaters of the Susquehanna River Basin, contains two parallel reservoirs, Tioga and Hammond, whose pools are joined by a connecting channel. The connecting channel contains a control structure with two gates and an overflow weir. Under normal operations, Hammond's pool is kept 5 feet higher than Tioga's and Hammond's excess inflows are released into Tioga by utilizing the gates in the connecting channel. During flood operations, the pools may rise and the 5 foot elevation difference may not be maintained. Under extreme events, one or both pools may exceed the elevation of the connecting channel's weir resulting in an uncontrolled exchange of flow between the reservoirs. HEC-ResSim was designed to represent only dendritic river systems so modeling the bi-directional flow of the Tioga-Hammond connecting channel posed a significant challenge. The solution involved the use of some special modeling techniques and the powerful scripting capability within ResSim. This presentation will describe the intricacies of this modeling effort within ResSim including how the network was constructed and how scripting was used to make it work.

INTRODUCTION

The HEC-ResSim software (USACE, Hydrologic Engineering Center Reservoir Simulation) represents a river-reservoir system as a georeferenced network of reservoir, reach, junction, and diversion elements. A model created with HEC-ResSim comprises data that characterizes both the physical and operational features of the system. Physical data includes reservoir elevation-capacity tables, outlet capacity curves, power-plant specifications, river-reach routing parameters, and the identification of inflows. Operational data is represented as zone-based rule stacks, which allow users to identify and prioritize multiple reservoir operation rules. The model supports local rules for at-site operations as well as system rules for downstream control and system hydropower generation.

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, environmental quality, and any other operating goals or constraints. Reservoir operating goals are defined by flexible at-site and downstream control function rules and multi-reservoir system rules and storage balancing objectives. Each reservoir may have multiple and/or conflicting goals and constraints on its operation and these objectives may vary depending on the operating zone of the reservoir. In ResSim, each reservoir operating zone has a separate set of prioritized rules defined by the user. As HEC-ResSim has evolved, advanced features such as outlet prioritization, scripted state variables, and conditional logic have made it possible to represent more complex systems and operational requirements.

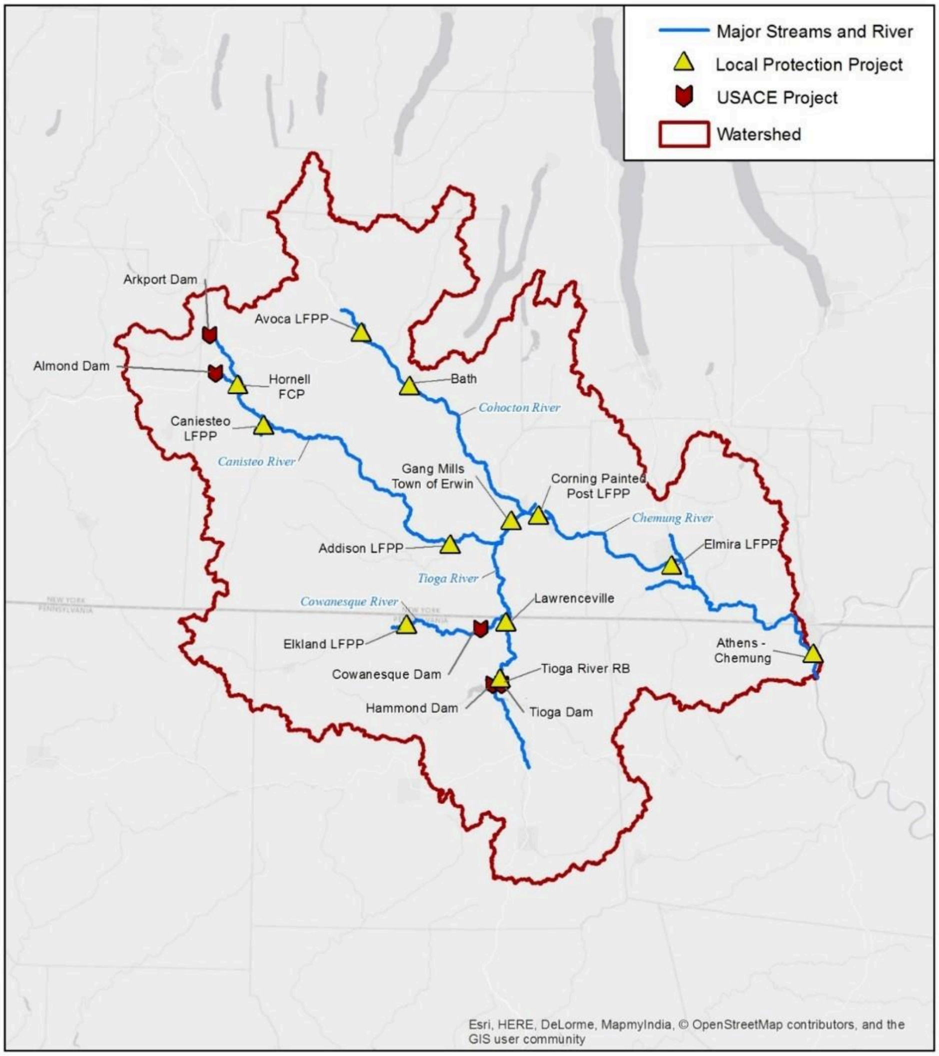

Figure 1. Chemung Watershed.

WATERSHED/MODELING

The Chemung River Basin is located within the states of Pennsylvania and New York in the Baltimore District of the U.S. Army Corps of Engineers (USACE). Of the 2,595 square miles that make up the basin, approximately 1,742 square miles or 67 percent of the basin is in New York with the remaining 853 square miles or 33 percent within Pennsylvania. The Chemung River watershed is illustrated in Figure 1. Tioga, Canisteo, Cowanesque and Cohocton Rivers are the head waters of the Chemung River; Cowanesque and Canisteo are tributaries to the Tioga which joins with the Cohocton to form the Chemung which flows into the Susquehanna River. There are five USACE dams in the basin: Almond Dam located on Canacadea Creek, a tributary to the Canisteo River; Arkport Dam located on the Canisteo River; Cowanesque Dam located on the Cowanesque River; Tioga Dam located on the Tioga River; and Hammond Dam located on Crooked Creek, a tributary to the Tioga River.

The general topography of the Chemung River watershed is predominately rural. The Chemung River watershed has a humid continental climate with no dry season. The area experiences thunderstorms concentrated in the warm months and major snow storms in the winter. On average, this watershed receives approximately 35 inches of rainfall annually, with higher precipitation typically occurring in the summer. The average annual snowfall is about 38 inches.

The Amec Foster Wheeler engineering team, as part of the USACE CWMS modeling team, developed HEC-RAS, HEC-ResSim, and HEC-FIA models for the Chemung River watershed. The HEC-HMS model was developed by the Baltimore District and calibrated to simulate rainfall-runoff processes within the watershed. The Amec Foster Wheeler team then combined the models into a CWMS watershed using the CWMS CAVI. The final CWMS watershed is shown in Figure 2.

The HEC-ResSim model was designed to provide potential release rates and the resultant potential reservoir elevation levels during forecast simulations for the reservoirs in the Chemung River watershed. The model results will supplement the Baltimore District water manager's release-decision making process.

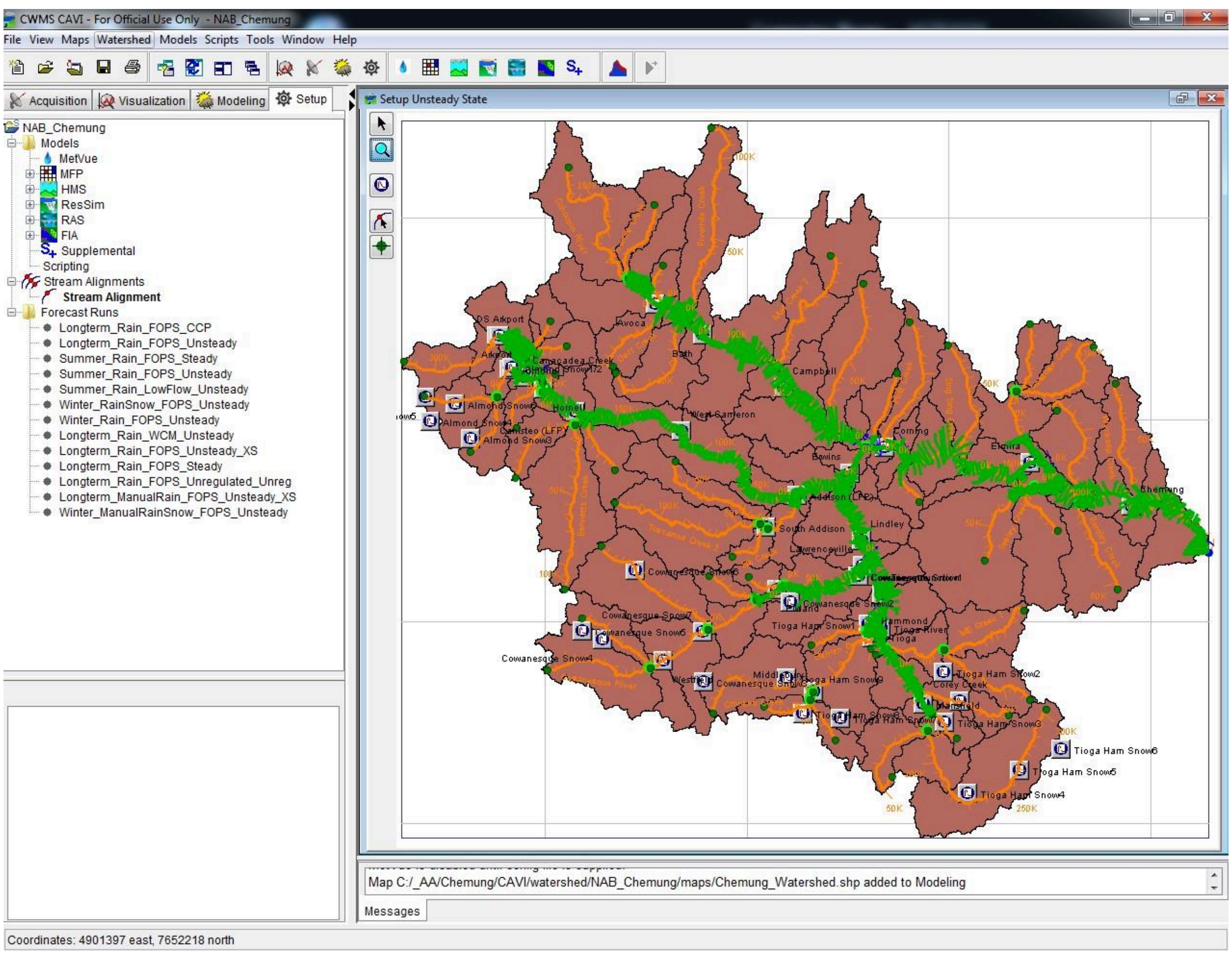

Figure 2. Corp Water Management System in CAVI.

Figure 3. Connecting Channel between Hammond and Tioga, Looking from Tioga toward Hammond.

TIOGA – HAMMOND SPECIAL SITUATION

The Tioga-Hammond Lakes project, completed in 1978, consists of two distinct reservoirs, joined by a 2700 foot long connecting channel in the ridge between the lakes. This unique feature allows surplus storage capacity in one reservoir to be used when floodwaters begin to fill the other reservoir. The primary purpose of the Tioga-Hammond Lakes project is to provide flood damage reduction for communities along the Tioga, Chemung, and Susquehanna Rivers as far downstream as Wilkes-Barre, PA. Secondary purposes include water quality control and recreation.

The Tioga and Hammond reservoirs are located near Tioga, PA, just upstream from the confluence of Crooked Creek and the Tioga River. Tioga Dam is a rolled earth and rockfill embankment located on the Tioga River about 1.7 miles upstream from the Crooked Creek confluence and about 0.8 miles upstream from Tioga Borough. Tioga dam is 2710 feet long and 140 feet tall with a top width of 25 feet and a top of the dam elevation of 1170 feet. Hammond Dam is also a rolled earth and rockfill embankment and is located on Crooked Creek about 3.3 miles upstream from the confluence, and just west of the Tioga damsite. Hammond dam is 6450 feet long and 122 feet tall with a top width of 25 feet and a top of dam elevation of 1169 feet.

The primary outlet works serving both reservoirs are located in Tioga Dam and consists of two 7 ft × 21 ft service gates and two 2 ft x 5 ft low flow/water quality gates. An uncontrolled spillway, also serving both reservoirs, is located in the left abutment of Hammond Dam. The spillway crest is at elevation 1131.0 ft with a design discharge capacity of 218,000 cubic feet per second (CFS); the estimated frequency of reaching spillway elevation is about once every 70 years. To date, spillway flow has not occurred. Hammond Dam also has a small outlet works through the dam that maintains a continuous discharge to Crooked Creek.

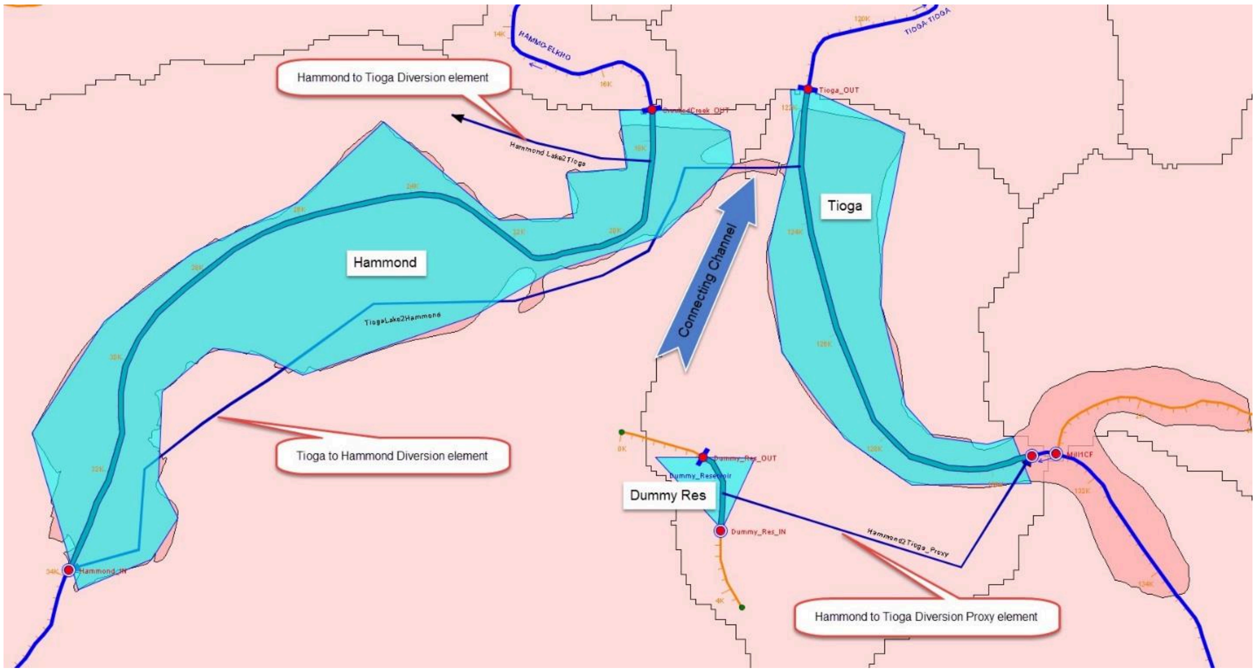

Figure 4. Schematics of Tioga/ Hammond and Diversion elements.

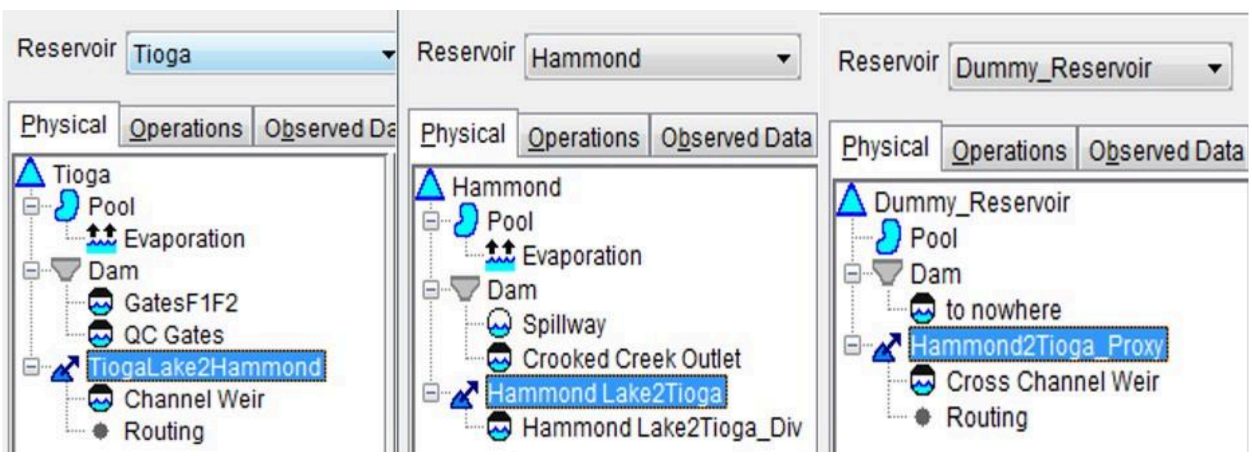

Figure 5. Diverted Outlet representation in the Reservoirs' Physical data.

At the normal conservation pool elevation 1081.0 feet Tioga Lake covers 498 acres and stores 9945 acre-feet of water. The normal conservation pool for Hammond Lake is elevation 1086.0 feet, covering 685 acres and storing 8625 acre-feet of water.

The connecting channel is cut through the ridge separating Hammond and Tioga Lakes, Figure 3. The channel is about 2700 feet long with a maximum depth of cut of approximately 230 feet. The outlet works in the connecting channel, adjacent to Tioga Lake, includes an overflow weir and gate structure located between a plunge pool on the Hammond (west) side and a stilling basin on the Tioga (east) side. There are two 8.5 ft x 11.5 ft hydraulically operated service gates in the structure. The weir is 230 long (including the gate section) and has a crest elevation of 1101.0 feet. The purpose of the connecting channel outlet works is to maintain the two distinct reservoir pools and to control the flow of water between them. Under normal conditions, the outlet works are operated to keep Hammond Lake at a higher elevation (1086 feet) than Tioga Lake (1081 feet), and to permit Hammond water with higher water quality to drain by gravity into Tioga Lake whose water quality is somewhat degraded by acid mine drainage. This arrangement keeps degraded water in Tioga Lake from entering Hammond Lake and dilutes and improves the water quality of Tioga releases, at least until the water elevation in Tioga Lake exceeds the weir crest.

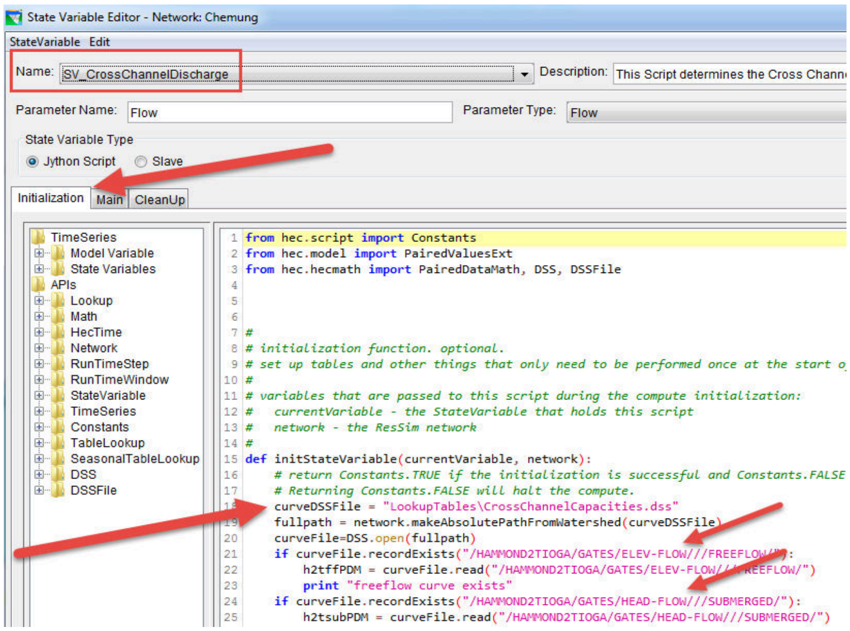

Figure 6. Creation of variables in Initialization tab.

TIOGA – HAMMOND SPECIAL MODELING IN RESSIM

The unique situation of Tioga-Hammond as two parallel reservoirs with a bi-directional connecting channel requires the use of special modeling techniques in HEC-ResSim. Currently, HEC-ResSim cannot directly represent two parallel reservoirs with a connecting channel because:

1. HEC-ResSim does not have a two-way flow element that can connect two reservoirs.
2. HEC-ResSim does not have a tailwater-dependent outlet type that can describe the discharge characteristics based on the head differential between the reservoirs.
3. HEC-ResSim does not allow two reservoirs to divert flow to one another’s inflow (such a connection results in a circular flow path).

To overcome these restrictions in the Chemung HEC-ResSim model, the Tioga-Hammond connectivity was configured as shown in Figure 4. Instead of connecting the two reservoirs directly, a third virtual reservoir (here called Dummy Reservoir) was used as a source/sink object for the volume of water that is discharged from one reservoir to the other. This volume is sent to the receiving reservoir by one of the diverted outlets depending on the direction of the flow that is determined based on pool elevations at the end of the previous time step.

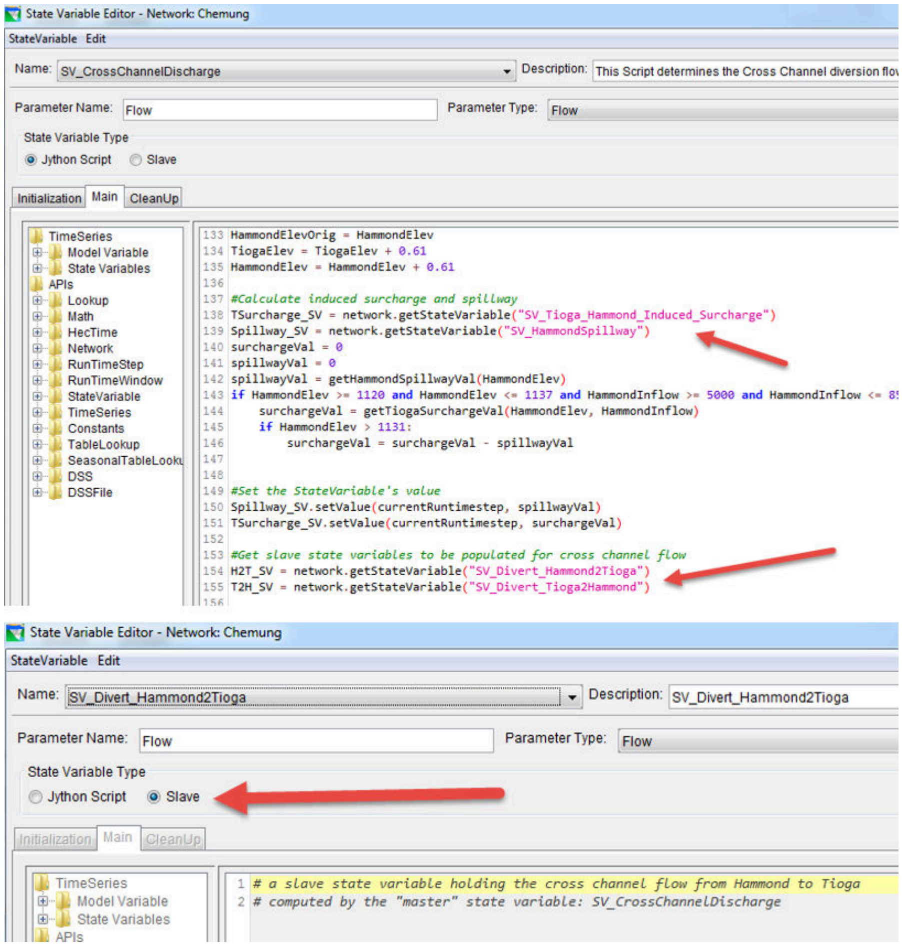

Figure 7. Master SV and Slave SV. In Master SV script, the Slave SV is populated.

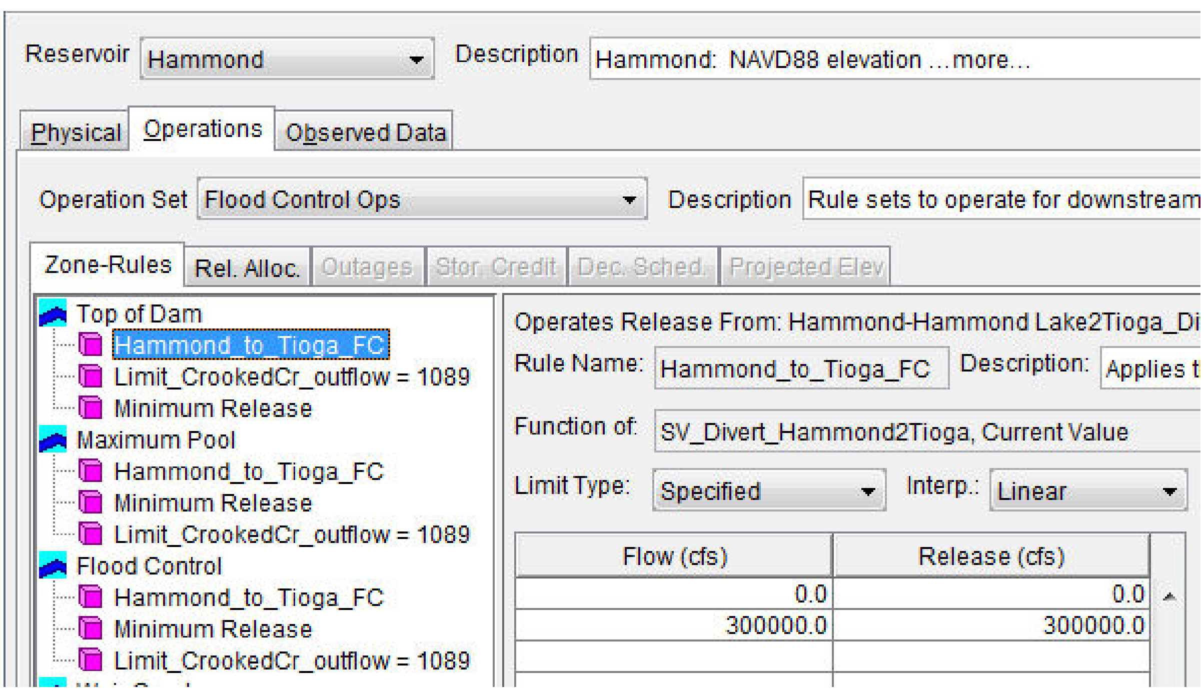

Figure 8.Hammond, diverted flow to Tioga (slave variable)

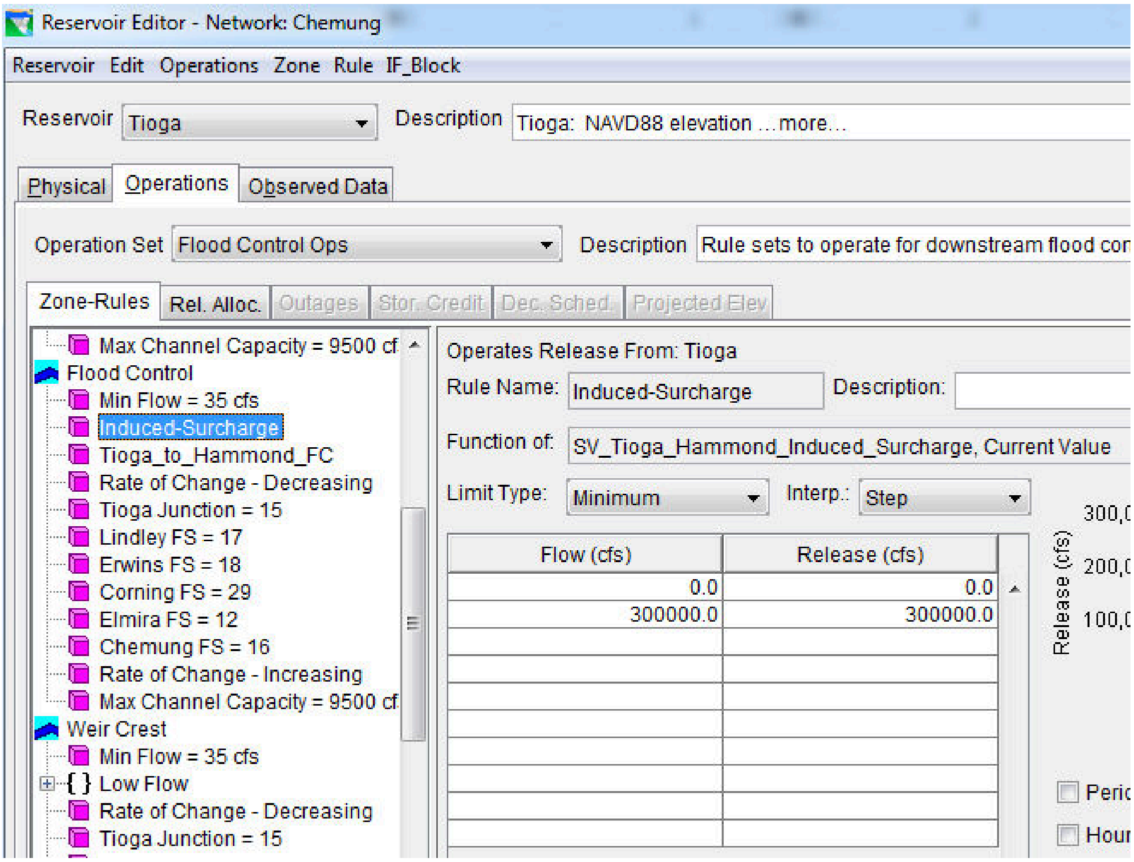

Figure 9. Tioga induced surcharge (slave variable)

A “master” state variable script, “SV_CrossChannelDischarge”, handles all the flow exchange calculations between the two reservoirs and is computed at the Dummy Reservoir. This script assigns the computed cross channel flow to one of two “slave” state variables, “SV_Divert_Hammond2Tioga” and “SV_Divert_Tioga2Hammond”, depending on the computed flow direction. By using the slave state variables in the rules controlling the diverted outlets at Tioga (TiogaLake2Hammond), Hammond (HammondLake2Tioga), and the Dummy Reservoir (Hammond2TiogaProxy), the connecting channel operation can be modeled without violating the ResSim’s connectivity rules and one-directional flow constraint. The volume in the Dummy Reservoir is inconsequential to the script calculations so the elevation-storage definition of the Dummy Reservoir is very large and all inflow is zeroed out. Figure 5 shows the inclusion of the diverted outlets at each of the three reservoirs.

MASTER STATE VARIABLE SCRIPT DESCRIPTION; SV_CROSSCHANNELDISCHARGE

The cross channel discharge script is used to calculate the flow between the Hammond and Tioga reservoirs. The script populates several state variables which are used in modeling to set the flow between the reservoirs and the induced surcharge. The Water Control Manual describes the discharge and flow exchange between the two reservoirs as a series of rating curves and tables. These along with the reservoir elevation-storage tables/curves were digitized and lookup tables were created and stored in a HECDSS file. The master state variable’s Initialization script is used to create and load a set of internal variables that represent these tables/curves. This is an important step in expediting the ResSim run time. The Initialization tab of the state variable editor is shown in Figure 6. The slave state variables are populated and pointed to in the main section of the master state variable script, illustrated in Figure 7. Figure 7 also provides an illustration of a slave state variable; this illustration shows that the slave state variable itself does not contain any code. Each slave state variable receives its values during the execution of the master state variable.

To calculate the cross-channel flow, the master state variable script uses the inflow to and starting pool elevations of Hammond and Tioga reservoirs. The Master script also utilizes the results from two other state variable scripts – SV_Tioga_Hammond_Induced_Surcharge and SV_Hammond_Spillway. Since these scripts are dependencies of the master state variable script, the modeler must be sure they are computed before the master script by placing rules that are a function of these state variables at a higher priority than the rule that requires the master state variable. Once the script has gathered these variables, it calculates the flow in the channel between the reservoirs based on the rating curves. To the extent possible, the script attempts to keep Hammond's elevation 5 ft. higher than Tioga's. Free flow occurs over the weir when either pool elevation exceeds 1101.0 feet.

The logic for calculating cross channel flow is as follows:

- First the script calculates the maximum flow for the given scenario (freeflow, submerged, or above weir).
- Then it estimates the target elevation of Hammond (5 ft. above Tioga) or of Hammond and Tioga (equal elevation in both reservoirs if above the weir).
- Next it calculates the amount of flow needed to reach the target elevation based on the pool storage (i.e. How much water do we need to release to reach the target elevation?). This is the target flow. If Hammond pool elevation is above the weir (within 1.5 ft.) and Tioga pool elevation is below the weir (over 5 ft. below), then target flow is the sum of Hammond flow over the weir plus Hammond submerged flow to a 5 ft. above Tioga target.
- Finally the script sets the cross channel flow to either the target flow or the maximum flow, whichever is smaller.

Figures 8 to 11 show the reservoir operating rules that launch the computation of the (master) state variables and control the diverted outlets release with the slave state variables.

SUMMARY

Tioga-Hammond reservoirs located in Chemung basin, a tributary to Susquehanna River, are two parallel reservoir that are connected through a connecting channel/weir/gate system. Their storage at times may become one and direction of flow can alternate. Although normal operational Rules in ResSim cannot handle the interdependency of connected reservoirs as such, ResSim's powerful State Variable scripting capability enables operational rules to be described as a function of the scripted variable. The network schematic was carefully constructed to include a diverted outlet from Hammond to Tioga to represent the "normal" connecting channel flow, an unconnected diverted outlet from Tioga to represent the "reversed" connecting channel flow and to remove it from the Tioga pool, and a virtual reservoir with a diverted outlet to Hammond to represent the "reversed" Tioga to Hammond flow and get it into Hammond. Then a state variable script was written to determine the flow in the connecting channel and its direction based on the current pool elevations, inflows, release capacity of the connecting channel's gates and weir, and the reservoir operating objectives. This volume is subsequently diverted to the receiving reservoir depending on the direction of the flow that is determined based on pool elevations. The methodology and schema setup for modeling is presented and described in this paper.

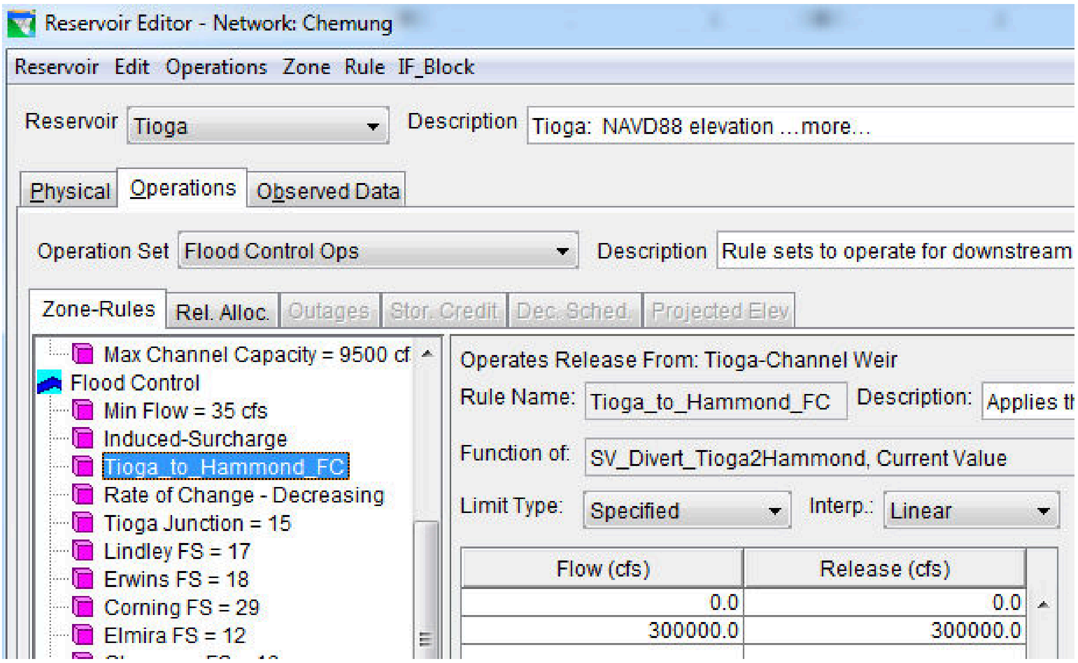

Figure 10. Tioga to Hammond diverted flow (slave variable).

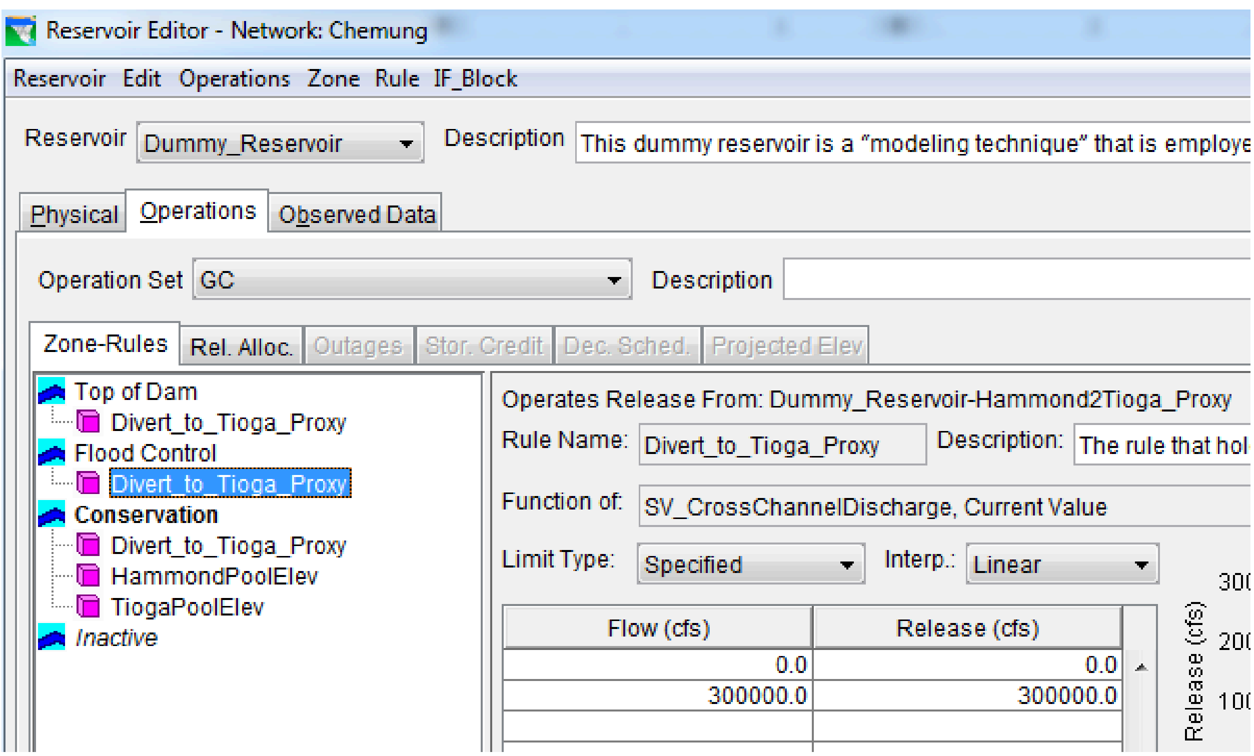

Figure 11. Dummy reservoir that holds the master script variable.