USING HEC-RESSIM FOR COLUMBIA RIVER TREATY FLOOD CONTROL

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Abstract In the 1950s, the Corps of Engineers (COE) and the National Weather Service (NWS) jointly developed the Streamflow Synthesis And Reservoir Regulation (SSARR) computer model. SSARR was used to evaluate Columbia River system development alternatives, and subsequently to regulate the developed system. SSARR was used both as the streamflow forecasting tool and as the real-time reservoir regulation tool. In the early 1990s the NWS modernized its streamflow forecasting tool set, dropping SSARR. The COE continues to use SSARR as its primary system flood control planning model and has been updated to automate the input/output protocols and greatly reduce the elapsed simulation time for a period-of-record flood control planning study. The current version of SSARR and its front-end (AUTOREG) can simulate a daily time step, full period (80 years), Columbia system operation in less than five minutes. Unfortunately, AUTOREG/SSARR has a limited life span because the model developers and maintainers are no longer available. However over the past few years, the streamflow routing algorithms have been migrated to the HEC's ResSim model. This paper describes the challenges and strategies to completely migrate the AUTOREG/SSARR model to ResSim. The two most significant success metrics associated with this effort are elapsed simulation time and replication of regulated flows. Replicating regulated flows implies that all the provisions of the current Columbia River Treaty Flood Control Operating Plan (FCOP) must be migrated to ResSim. The new model must be flexible enough to accommodate FCOP strategy changes because the current FCOP terms and conditions expire in 2024**.** For more information on the genesis of the Columbia River Treaty flood regulating plan see Nelson and Rockwood (1971).

INTRODUCTION

The intent of this paper is to present the technical challenges, strategy used, measures of success, and results of model migration. The idea of migrating models has been discussed before. See Modini (2003). This work was done for Columbia Basin Water Management, Northwestern Division, Corps of Engineers.

Technical Challenges From a technical standpoint, knowledge of the Columbia Basin System and ResSim were crucial. For the Columbia Basin, a working knowledge of system hydrology, Treaty FCOP, and AUTOREG/SSARR were necessary. Team members from HEC and Columbia Basin Water Management had many years of combined experience in these areas. Leveraging this knowledge, team members developed a list of AUTOREG functions to be migrated to ResSim. These functions reflect procedures in the FCOP and were primary objectives. These procedures reflect two distinct periods defined in the FCOP, drawdown of reservoir storage and refill during the runoff period. An optional capabilities list was added as secondary objective. This list was to account for hand regulation and visualization features of AUTOREG/SSARR. Next an in-depth look at ResSim capabilities was performed. Both lists were then cross-referenced with ResSim capabilities to determine the strategy for model migration.

Strategy The strategy for model migration was to maximize ResSim capabilities while using Jython scripting to migrate the more complex operations (algorithms) of AUTOREG. Jython is an implementation of Python in a Java (object oriented programming) environment. A work plan was developed based on this strategy.

Success Metrics The yardsticks for success would be a quick elapsed simulation time, model verification, and model flexibility. The current version of AUTOREG/SSARR can simulate a daily time step, full period (80 years), very basic Columbia system operation in about five minutes. Comparing regulated flows from both models ensures model verification. Providing Columbia Basin Water Management (CBWM), a new institutionally certified and supported model to be used for all post-2024 flood control planning studies and for and flood control evaluation studies prior to 2024 ensures flexibility.

It is also hoped that this ResSim model and future variants will serve the U.S Army Corps of Engineers and stakeholders in the Northwest as superbly as SSARR. In this way, it is a tribute to the fine public servants who developed the SSARR model in years past.

Having defined the technical challenges, strategy, and metrics of success, next is a presentation of AUTOREG/SSARR, ResSim, and model migration.

AUTOREG/SSARR

AUTOREG was developed by the Hydrologic Engineering Branch of Water Management (CBWM) in the early 1990’s. AUTOREG is a graphical user interface (GUI) for the SSARR program. AUTOREG was written in C++ while SSARR was written in FORTRAN. AUTOREG utilizes UNIX graphics libraries. It runs on a UNIX platform. AUTOREG/SSARR can be accessed and executed from a PC via a console terminal.

AUTOREG utilizes HEC's Data Storage System (HECDSS). DSS was developed to meet needs for data storage and retrieval for water resource studies. The system enables efficient storage and retrieval of time series data and other data types for which storage in blocks of contiguous data elements was most appropriate. Included in DSS are auxiliary programs such as DSSMATH (data manipulation), REPGEN (Report Generator), and DSPLAY (Graphics Utility). These auxiliary programs are utilized extensively by AUTOREG.

AUTOREG/SSARR Model The Columbia SSARR model consists of a P-card list and Model Characteristics file. The P-card list defines the reservoir network and routing reaches. The Model Characteristics files contains all the physical data for the projects, routing reaches, and definitions of headwater inflow and local flows. Other files include initial conditions, project operating limits, and model setup files that interface with AUTOREG.

AUTOREG/SSARR Flexibility AUTOREG was designed to perform flood control simulations for planning studies in an efficient manner. At the most basic level, it is a hand regulation model based on the FCOP and the modeler must have that knowledge. The positive is that it automates data input requirements and, based on hand regulation, makes iterative executions to achieve predetermined Columbia River regulation objectives such as controlling flows to non-damaging levels.

The real flexibility of AUTOREG/SSARR is easy run control and quick simulations. Basic upper rule curve (URC's) multi-year simulations would take on the order of 2 – 4 minutes. However, for complex studies, extensive hand regulation was often required and resulted in increased simulation times.

Besides basic project regulation, algorithms were developed for complex operations such as International Joint Commission (IJC) requirements at Cora Linn on Kootenay Lake. Another algorithm was the combined operation of Grand Coulee Dam on the Columbia River and Arrow Dam on the Upper Columbia River commonly known as the Synthetic Reservoir Operation. Without the use of these algorithms, detailed arduous hand regulation would have to be performed. See U.S. Army Corps of Engineers (1999) Charts #3 and #6.

AUTOREG/SSARR Enhancements The first version interfaced with an existing SSARR model of the Columbia River system. The AUTOREG GUI was used for model setup, execution, and analysis of output. Later, SSARR algorithms were directly incorporated into AUTOREG so that non-headwater projects could be simulated and more accurate iterative solutions could be accomplished. Many features and algorithms were developed to make for more efficient simulations. Trace files were added for specific algorithms to track the computation process. Warning files were also added that reflected violation of flood objectives. These are used to assist in hand regulating projects to meet these objectives.

AUTOREG/SSARR Setup In AUTOREG, a system of menus is used to assist the modeler in the study process. The system of menus provides the flexibility to maintain overall control of the simulation process from preparing study inputs all the way through execution of the study and final acceptance of results. It is very efficient.

In system setup, basic inputs include historic streamflow data. Other operational criteria consist of project upper rule curves, seasonal runoff volumes, and special operating procedures that guide day-to-day changes in outflow from certain projects during all or certain periods of the year. These inputs are utilized by AUTOREG to regulate 20 projects to desired regulated flows at eight downstream control points. The main menu system and a Columbia Basin Schematic are shown in Figure 1.

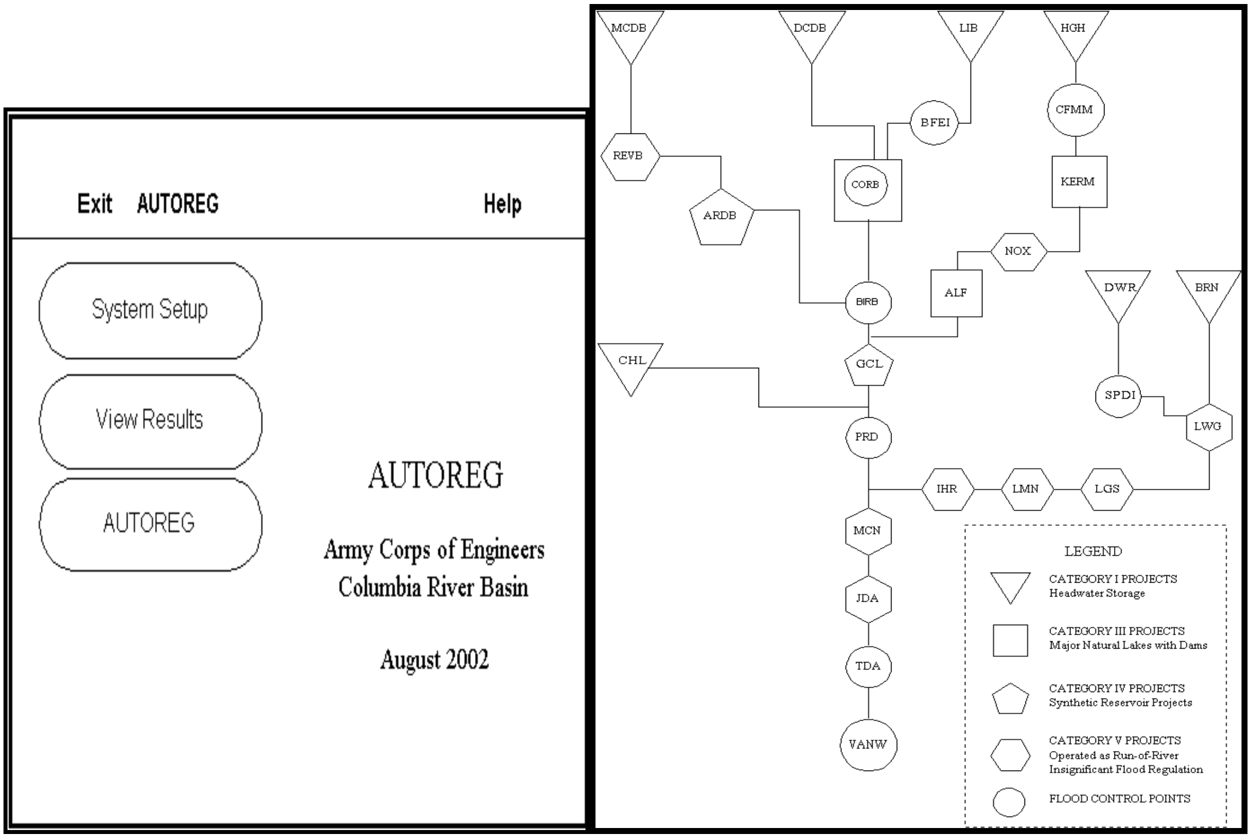

Figure 1. AUTOREG Main Menu and Columbia Basin Schematic

AUTOREG utilizes a predetermined set of streamflows. These are specified for each headwater reservoir's inflow and downstream local inflows. For the Columbia, inflows are expressed as mean-daily values.

Projects that are modeled by AUTOREG are the Category I (headwater), Category III (Natural Lakes), Category IV (Synthetic Reservoir), and selected Category V (Run-of-River) projects referenced in Table 1 of the FCOP. Category II and some Category V projects are not included because they have only minor effect on main stem Snake and Columbia River streamflows. For reference see U.S. Army Corps of Engineers (1999).

AUTOREG/SSARR Master Control File In the regulation menu of AUTOREG, a modeler builds a Master Control File (MCF) which provides operating instructions (codes) for each project in a highly efficient way. Note, this is the hand regulation of the model. System knowledge must come from the modeler and be reflected in specifying the correct operations codes. Operations codes can be global or project specific and must include specified time period. The model attempts to regulate to the operations codes while subject to physical constraints, operating constraints, and streamflows. Multiple simulations are then performed. The modeler analyzes the results, specifies additional operations codes, and re-simulates until the water year is complete. An example of an MCF is shown in figure 2.

PROJECT	START TIME	END TIME	OPERATION CODE
*	01OCT72	30SEP77	MPO
MCDB	20NOV73	25FEB74	QPHC
MCDB	05JAN75	15FEB75	QPHC +/- 10000
MCDB	06MAR75	17MAR76	QMIN
MCDB	18MAR76	30APR76	QMIN + 12500
LIB	07JAN74	14JAN74	MPO + 10000
LIB	15JAN74	20JAN74	HOLD
LIB	21JAN74	31JAN74	MPO + 5000
LIB	01FEB74	28FEB74	MPO + 6000
CORB	01OCT72	30SEP77	URC
CORB	01MAY73	31MAY73	URC +/- 10
CORB	01JUN73	30SEP73	HOLD=1743.32
CORB	01MAY74	31JUL74	URC +/- 10
CORB	01AUG74	30SEP74	HOLD+1743.32
CORB	01MAY75	30JUN75	URC +/- 10
CORB	01JUL75	30SEP75	HOLD=1743.32
CORB	01MAY76	01JUL76	URC +/- 10
CORB	01AUG76	30SEP76	HOLD=1743.32
CORB	01MAY77	31MAY77	URC +/- 10
CORB	01JUN77	30SEP77	HOLD=1743.32
REVB	01OCT72	30SEP77	HOLD
NOX	01OCT72	30SEP77	HOLD
JDA	01OCT72	30SEP77	HOLD
BRN	01OCT72	30SEP77	MPE
GCL	01MAY74	31JUL74	HOLD
GCL	01OCT72	30SEP77	MPE

Figure 2. AUTOREG Master Control File

As an example, the URC operations code attempts to regulate projects to the upper limit for flood control. URCs are based on a water supply forecast and storage reservation diagram and are pre-processed. The QPHC operations code attempts to regulate projects to power house capacity. The IJC operations code regulates Libby and Duncan projects to meet IJC requirements at Cora Linn on Kootenay Lake. The SYNRES operation code automates the combined operation of Grand Coulee Dam on Arrow Dam, commonly known as the Synthetic Reservoir Operation in the FCOP. Mathematical operators are also applicable to some operations codes.

AUTOREG/SSARR Simulation Run control for simulations as shown in figure 3 allows for specification of the MCF file, simulation period, what parts of the system to simulate, and execution.

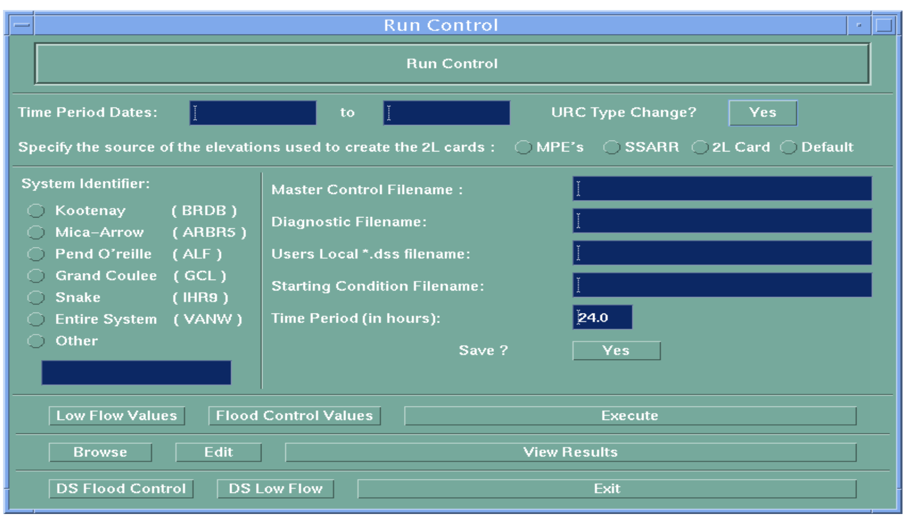

Figure 3. AUTOREG Run Control Menu

AUTOREG/SSARR Post-Processing and Visualization Features After building an initial MCF and performing a simulation, the modeler uses the post-processing features of AUTOREG to analyze operations, make adjustments to the MCF, and complete the simulations. Figure 4 shows an actual plot of project operations.

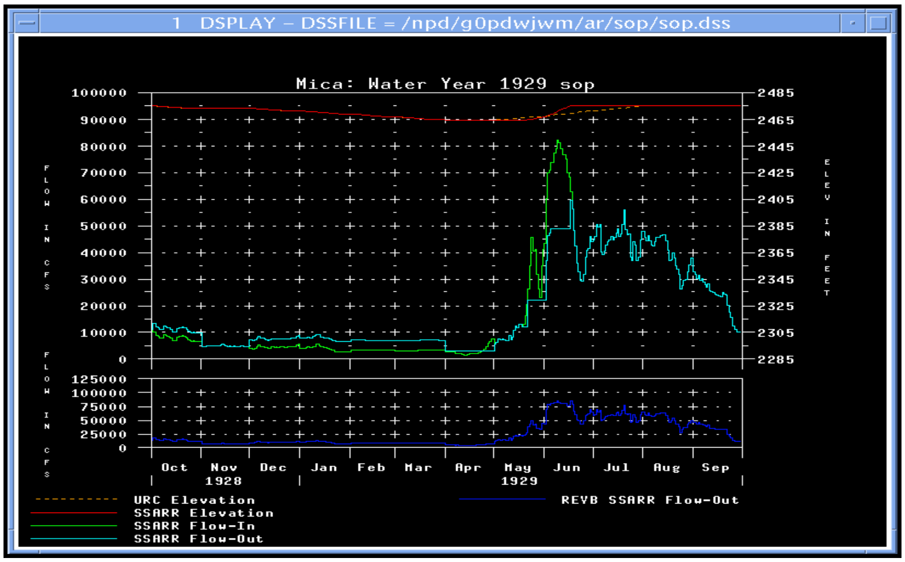

Figure 4. AUTOREG Plot of Project Operations

HEC-ResSim

Capabilities of HEC-ResSim will now be presented. The U.S. Army Corps of Engineers' Hydrologic Engineering Center's Reservoir System Simulation, ResSim, model is a computer program comprised of a graphical user interface (GUI) and a computational engine to simulate reservoir operations and river routing. Included are data storage and management capabilities including graphics and reporting facilities. HEC-DSSVUE is used for storage and retrieval of input and output time series data.

HEC-ResSim Modules ResSim offers three separate sets of functions called Modules that provide access to specific types of data within a ResSim model. These modules are Watershed Setup, Reservoir Network, and Simulation. Each module has a unique purpose and an associated set of functions accessible through menus, toolbars, and schematic elements. Please see Klipsch and Hurst (2007) for more details. Figure 5 presents the module concepts.

HEC-ResSim Watershed Setup Module The watershed module is used to create the stream alignment and configure where projects and computation points (stream junctions and control points) are placed. It is important that considerable thought be given to creation of the stream alignment and configuration of projects since this is the foundation for creating a reservoir network and possibly used for future model expansion.

HEC-ResSim Reservoir Network Module The reservoir network is developed here. More than one network can be created. Physical data for reservoirs, routing reaches, diversions, and junctions are defined. Operational rules (parameters) for reservoirs and control points are also created. More than one set of operational rules can be created. Alternatives based on different reservoir networks and operations sets are also created in this module. An alternative must be specified for a simulation.

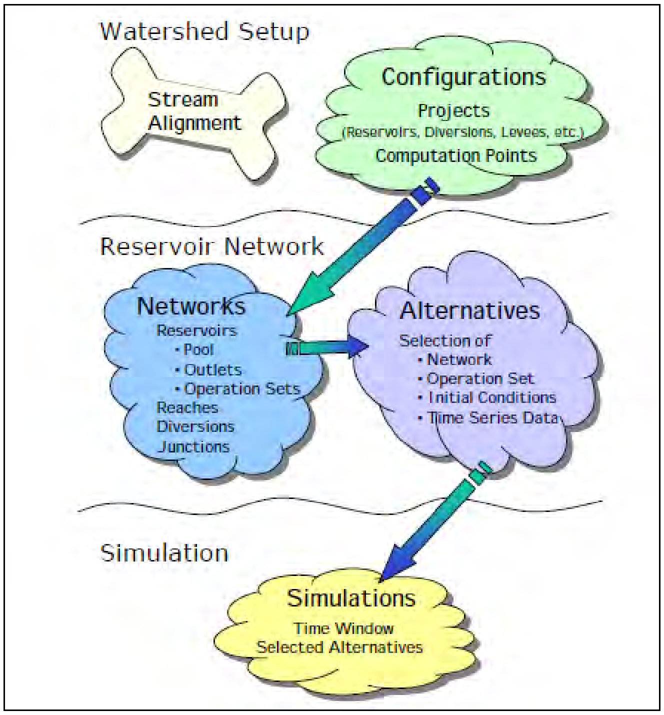

Figure 5. HEC-ResSim Module Concepts

HEC-ResSim State Variables In addition to these operational parameters, state variables (objects) that belong to the network and represent the state or status of an element in the system can be used to develop release decision rules. These state variables are globally accessible and can be used in more than one operating rule and in more than one reservoir. State variables can either be user defined or internal model variables like pool elevation that are stored in a times series object for each time step and available for use with operational rules. The type of rules can be created are release and downstream control function rules, IF-THEN-ELSE conditional rules logic, and scripted operating rules.

HEC-ResSim Jython Scripting Also in the reservoir network module, Jython scripts can be written to compute state variables and scripted rules. The script may perform calculations referencing any TimeSeries Object in the Network, including all model variables and other State Variables.

HEC-ResSim Simulation Module
In this module, reservoir operations can be simulated based on selected alternatives and a specified time window. Here the user has many ways to view model output. This can be accomplished by clicking on displayed objects, using HEC-DSSVUE, or utilizing a user created

visual interface. Scripts developed in this module and packaged in a GUI can be used to post-process model output and create custom plots similar to those in AUTOREG.

Model Migration

Model migration was handled in two steps. The first step was to develop a base ResSim model to ensure physical project data, basic operating constraints, and routing criteria were correctly input. The second step was to develop a more complex model according to the primary and secondary objectives.

Before commencing model migration, the first challenge was to determine which version of ResSim to use. It decided to use a development version, ResSim 3.2 DEV which has the latest model improvements.

Model Migration: Base Model The first step was data collection**.** AUTOREG/SSARR simulations were provided to verify the model migration for both steps. An existing ResSim model and all AUTOREG/SSARR model files were provided. It was decided to build a new model leveraging usable physical and operational data in the existing ResSim model and AUTOREG/SSARR files.

In the Watershed Module a new stream alignment and model configuration was created. Care was taken to create contigious stream elements to reflect main stem, tributary, and local streams which was physically and hydrologically consistent. A configuration of projects and computation points for routing reaches were then created. The main reference for projects and routing reaches was the SSARR P-Card list. It should be noted that SSARR is not tied to a physical stream alignment as ResSim. Therefore a few extra routing reaches were created in ResSim that used Null Routing (no attenuation). These would have no effect on routing of flows.

Next, a reservoir network was created by defining routing reaches and connecting the network. Physical and operation data were defined using the existing ResSim model and SSARR model characteristics. Data included storage tables, capacity curves, SSARR routing reach criteria, rating curve data, and basic project operating constraints. Where applicable, ResSim wizards were utilized to import some data from the existing ResSim model. Some data was manually entered. Table 1 shows the breakout of projects, junctions, and reaches. Figure 6 shows the new Stream Alignment/Configuration and Reservoir Network.

Base Model	Projects	Junctions	Reaches
New Network	**22**	**61**	**38**

Table 1. Reservoir Network

An alternative called URC was created that references the reservoir network. Initial conditions were specified in the alternative editor for the first water year. All model inputs to include historic streamflow data ,URC's, seasonal runoff volumes, and streamflows were mapped to DSS files, Additionally a script was developed to compute the stage at Bonner's Ferry on the

Kootenay River based on a three variable relationship. Figures 7 shows a portion of the Jython script for this three-variable relationship.

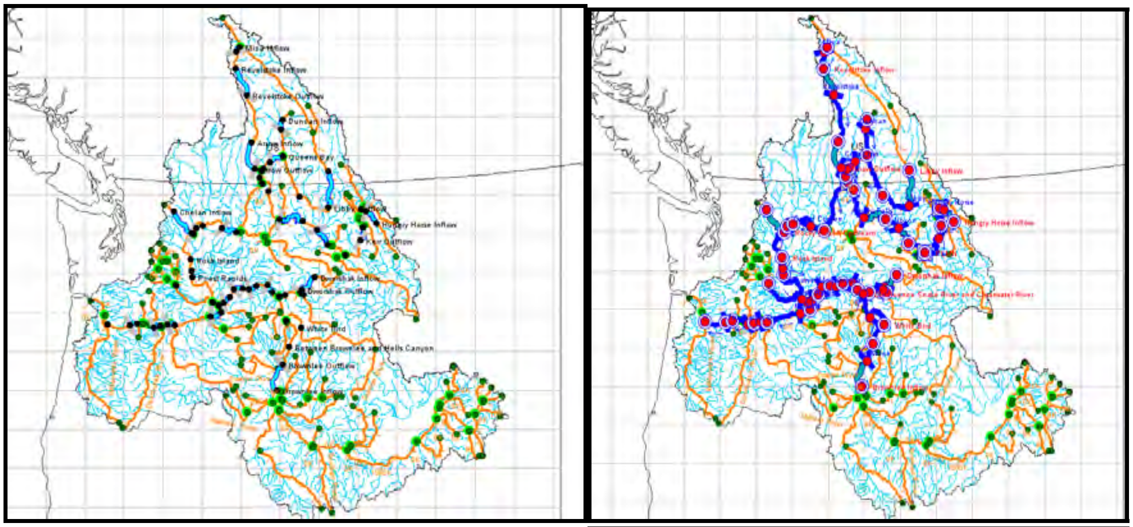

Figure 6. HEC-ResSim Stream Alignment/Configuration and Reservoir Network

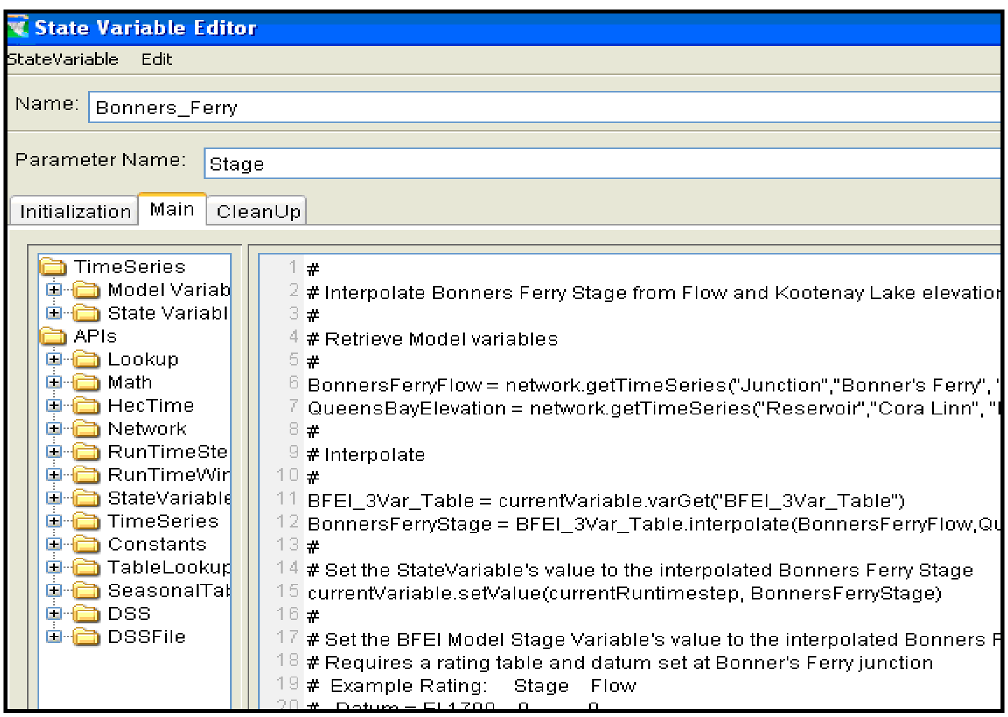

Figure 7 State Variable Editor- Jython Script for Three-Variable Lookup

Next in the simulation module, a simulation was created for the period 1928-1999 using the newly created URC alternative. Initial conditions for ensuing water years were specified in a release overrides DSS file. This allows ResSim to reinitialize the model at the beginning of each water year. A simulation was then executed. The elapsed time for simulation was 4.5 minutes.

Model Migration: Base Model Calibration and Verification Base model calibration was completed by performing quality control checks on all physical and operational data by cross referencing with legacy model data.

In order to perform model verification, AUTOREG/SSARR regulated flows were compared to ResSim regulated flows. In this case, AUTOREG/SSARR was run to the URC for 1928-1999. The same model input was used in ResSim. ResSim was then run to a URC guide curve operation. Spot checks of inflows, local flows, initial conditions, and URCs were made to ensure accuracy of input data. Checks of regulated flows indicated satisfactory verification of the Base Model. Figure 8 shows a plot of Bonner's Ferry stage and flow.

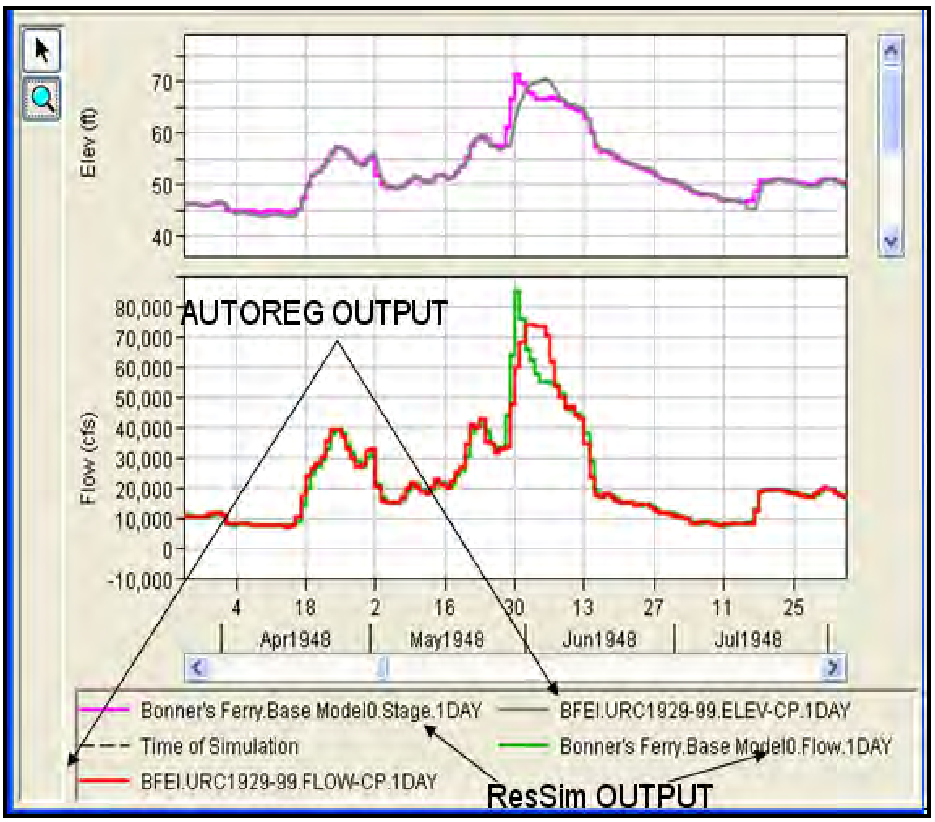

Figure 8. Plot of Bonner's Ferry Regulated Stages and Flows

Model Migration: Complex Model For the more complex model development, the goals were to meet the primary and secondary objectives of model migration. The primary objectives were the list of AUTOREG functions to be migrated. The secondary objectives were to automate those procedures requiring extensive hand regulation and to provide similar post-processing and visualization features as in AUTOREG. It should be noted that most of the post-processing and visualization features could be accomplished while utilizing the inherent capabilities of ResSim and DSSVUE. Hand regulation procedures to be automated depending on priorities included: a Lake Lowering Formula, meeting flood stage objectives for local and system requirements, flood control refill curve computations, natural lake regulation restrictions, computation of variable flow flood control requirements, variable minimum flows for some projects, filling transitions curves or similar refill procedures, priority setting with respect to trapped flood control storage, capability to override computed releases efficiently, and an On-call Treaty Storage option.

Model Migration: Complex Model Calibration and Verification A number of State variable scripts and scripted rules were developed to handle the primary and secondary objectives of the complex modeling phase. Some important lessons were learned regarding scripting state variables and scripted rule,

Regarding state variables, to utilize available virtual memory on the resident machine effectively, HEC-ResSim breaks up long simulation periods into time blocks. An effective way to write scripts was needed to leverage this. Fortunately, a new development version of ResSim provides a scripting environment, application programming interface, for state variables which includes initialization, main, and cleanup sections. The initialization section of the script is executed only once before the time block simulation begins. Therefore, the initialization section is also a good place to prepare data that can be defined once and be used over and over in the main script section. The mechanism for passing data from the initialization to the main sections of the script, is to create local variables and local time series which are attached to the script and remain in memory between script executions. Reducing the amount of times the database must be accessed helps reduce overall simulation time.

Another key point is the actual execution of a state variable main script. Selecting the always compute check box on the script editor will specify execution after each time step. Using the state variable in a reservoir rule will cause the main script to be executed for every reference of the rule. This can happen as a result of iterative solutions for location specific rules or by the number of passes specified for each compute time step. Given the number of times the main script can be called, it is wise to keep the script to a minimum. It's also judicious to release memory reserved by initialization script by writing reports to logs.

The cleanup script is also executed only once at the end of a simulation time block.

Another type of script is the scripted rule which resides in the Reservoir Editor. A key point regarding scripted rules is that the results of a scripted rule are a reservoir release this is either a maximum, minimum, or specified. This type of rule has two sections defined as the initialization and main. However, the scripted rule editor currently does not have separate tabs. Script in these sections are defined as Jython functions. Applying the same principles for the initialization and main sections as for state variables can result in reducing the amount of simulation time.

Model calibration during this phase consisted of understanding the underlying processes to be scripted. Model verification consisted of comparing AUTOREG/SSARR regulated flows to those of ResSim. Note that not all scripts had a comparable feature in AUTOREG/SSARR. In this case, CBWM personnel performed verification of results.

Discussion of Results

Considering the technical challenges, the strategy of maximizing ResSim capabilities and using the power of Jython scripting for complex operations was applied. To the extent possible, primary and secondary objectives for model migration were met. This model has also achieved a level of automation not available with AUTOREG/SSARR.

Additionally the yardsticks of success of quick simulation time, model verification, and model flexibility were met. Actual simulation time for a daily time step full period of record run took on the order of 4.5 minutes. This was comparable to AUTOREG/SSARR. During model verification, both phases of the model migration provided good results by replicating regulated flows. Regarding flexibility, Columbia Basin Water Management (CBWM) was provided, a new institutionally certified and supported model that can used for all post-2024 flood control planning studies and for and flood control evaluation studies prior to 2024.

The user now has a model that is readily supported, more transparent, and easier to modify if necessary.

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