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Meeting Water Quality and Water Control Objectives in River Basins with Multiple Reservoirs

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PURPOSE: This product provides simulation capabilities to allow water resource managers to meet operational and water quality objectives in a basin wide approach under the System-Wide Water Resources Program (SWWRP). This capability allows water management the ability to manage important parameters such as temperature and dissolved oxygen in complex systems. This tool can determine if temporal and spatial distribution of water quality is being met at the right place and time for an operational change. If not, adjustments to operations can be made to achieve the goal (e.g., a little warmer water temperature in the spring to conserve cooler water temperatures in the fall). Coupling ResSim and CE-QUAL-W2 (W2) provides a tool for the increasing demand of meeting water quality objectives in a reservoir and/or downstream to a critical location for improved habitat through changes in reservoir operations.

BACKGROUND: For many years, the Corps' reservoir modeling and operations community has relied on a number of reservoir tools. Each tool provides different capabilities. To illustrate, CE-QUAL-W2 and HEC-5Q provide water quality support while HEC-5 and HEC-ResSim provide reservoir simulation support for real-time water management and multi-objective planning studies. Recently, there has been an increasing demand to include water quality operating objectives for in-pool and riverine locations for real-time water management and in planning studies. The districts want to model the physical, chemical, and biological characteristics of water, and include the impact of water quality in reservoir operations system decision-making. As a result, integration of the capabilities of these models for use by the user community to evaluate a full suite of objectives in a coordinated fashion was begun under SWWRP in hopes to maximize benefits of the outcome of real-time operations and multi-object planning studies.

Engineers and scientists at the U.S. Army Engineer Research and Development Center (ERDC) and U.S. Army Corps of Engineers Hydrologic Engineering Center (HEC) have discussed a number of options on how best to combine the reservoir/riverine capabilities. The approach decided by the two groups was to couple the CE-QUAL-W2 water quality model (Cole and Wells, 2008) with the ResSim reservoir/riverine system operation model (Klipsch and Hurst, 2007), as opposed to developing a new product or making substantial revisions to either of the two existing models. By linking the two pieces of software, the user community receives the benefits of both without having to fund a major development effort. In addition, it was concluded that the districts that need the water quality capabilities have existing CE-QUAL-W2 models and have or will have HEC-ResSim models due to their involvement with the Corps Water Management System (CWMS).

APPROACH: As previously mentioned, the models selected for this endeavor were CE-QUAL-W2 and HEC-ResSim. CE-QUAL-W2 is a 2-dimensional water quality model developed and maintained in part by the U.S. Army Engineer Research and Development Center (ERDC). It has the capability of simulating surface water systems, including rivers, lakes, reservoirs and estuaries. W2 has been applied to over 1,000 different water bodies throughout the United States and abroad. In addition to computing water surface elevations, horizontal/vertical velocities, and temperature, the model can simulate many other water quality state variables including algal/nutrient/dissolved oxygen interactions. HEC-ResSim is a rule-based reservoir simulation model developed and maintained by the Hydrologic Engineering Center (HEC) of the Corps. It consists of a graphical user interface, a computational component for estimating reservoir operations, a data storage and management component, and pro-processing capabilities (i.e., graphics and report generating). There has been mutual interest by ERDC and HEC to integrate the capabilities of W2 and ResSim in order to improve the abilities of both tools to assess alternative water management scenarios. Combination of these two programs allows a more complete operational scenario to be simulated so that additional environmental parameters such as temperature, dissolved oxygen, and phosphorus can be considered in reservoir system decision-making.

The integration is envisioned as a two-phased approach with each successive phase integrating the tools in a more comprehensive manner. This technical note will cover the completion of Phase I and future development of Phase II. The two phases — “Sequential simulations” and “Parallel simulations for a user-defined season” — are briefly described below. Each description is followed by an example describing how that integration was or would be used to study reservoir operations for downstream water quality targets.

Phase I. This phase links W2 and ResSim such that the two models are simulated independently within the ResSim framework in the following sequence (Figure 1): 1) ResSim simulates first, which produces a set of reservoir elevations and outflows, 2) these data are prepared for use in W2 by converting DSS file format to W2 file format using the plug-in DSSIN, and then 3) W2 imports the data and simulates the water quality conditions in the reservoir and downstream resulting from the operational decisions of ResSim. Upon completion of the W2 simulation, criteria limits/goals are checked in ResSim by converting W2 output to DSS format using the plug-in DSSOUT and a decision is made to accept operations or if not accepted, sequence is reinitiated from the beginning with rules within ResSim adjusted (Figure 1) to meet downstream criteria. This is an iterative process until criteria are met.

Developing the Phase I sequential approach required that the models be able to exchange data between them. The method of sharing information between ResSim and W2 is through DSS (Data Storage System, HEC 1995 and 2006b) files. HEC-DSS is a file format used in many HEC programs and is part of the I/O of ResSim. W2 uses ASCII text file inputs and produces text file outputs. Hence, a method for translating file formats was necessary. To simplify this exchange, two plug-ins called DSSIN and DSSOUT were written to be able to receive data from ResSim and send back output data from a W2 simulation for analysis. Other modifications to W2 to communicate with ResSim were: 1) code to control W2-ResSim simulation parameters within W2, 2) code to adjust and write out new control file for W2 based on ResSim, and 3) code to read new boundary conditions from ResSim using HEC-DSS. These modifications are activated by the W2 parser FORTRAN program from within ResSim and are discussed below.

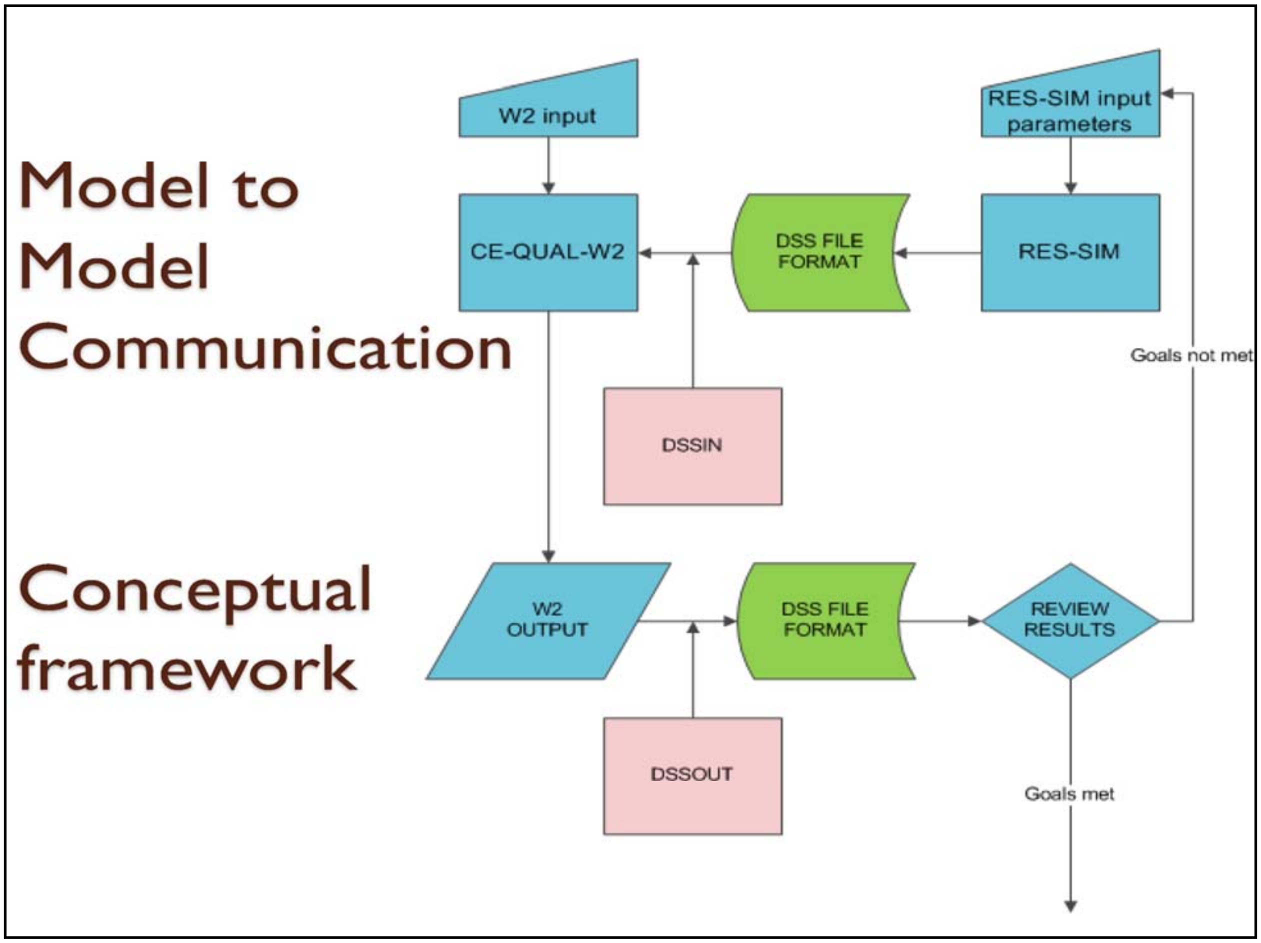

Figure 1. Conceptual framework of CE-QUAL-W2 and ResSim linkage.

An example to study water management for stream temperatures would be the sequential simulation of release water temperatures which would then be compared with temperature targets downstream of the project to see if any violations occurred. If so, the modeler would adjust user-specified rules or other parameters in ResSim to improve simulated outflows so that release water temperatures produce better agreement with the temperature targets downstream. Each ResSim modification would produce a new set of simulated results to be packaged and used in W2. A weakness of this integrated tool is that the models do not provide information to each other during simulations, which makes it difficult to know if the simulated reservoir decisions are making good use of the thermal resource within the reservoir. If the Districts have to meet downstream criteria during a critical period, a closer coupling would be beneficial. Several restart simulations may be necessary to adjust and test new operations to get through this period and still conserve enough water for other critical periods. Strength of this approach is that compute time is minimized. For many systems and for many time periods this level of detail may be sufficient to show that temperature violations are not likely to occur over a range of operational decisions, which may help identify critical periods and river reaches that require more detailed modeling.

Description of DSSIN plug-in. The program DSSIN.EXE converts DSS time series into a format that W2 can read. This executable reads a text input file (dssin.npt), reads a DSS file, and writes a text file input for W2. The dssin.npt file describes which DSS time series will be written to which W2 input for inflow or outflow boundary conditions. The W2 input must already have been specified in the w2_con.npt file. Hence, if there is an outflow time series produced by ResSim and that time series is in DSS format, the dssin.npt file describes where the DSS file is located and which time series to write out. The dssin.npt also tells it to which W2 file this time series corresponds. After using DSSIN, the W2 model is run. This takes place within the ResSim framework so the user is not responsible for the initiation of the program. They only have to prepare the dssin.npt and place it within the W2 directory.

Description of DSSOUT plug-in. To send information from a W2 run back to ResSim, the output text files produced by W2 are translated into DSS format using the program DSSOUT.EXE. The input file, dssout.npt, describes which W2 time series files to convert to DSS format. The model output specified in dssout.npt is then available for evaluation using plotting and tabulating capabilities in ResSim. The user specifies the contents of dssout.npt within the ResSim Alternative Editor (see Figure 2). This file then resides in the W2 directory to be initiated within the ResSim framework.

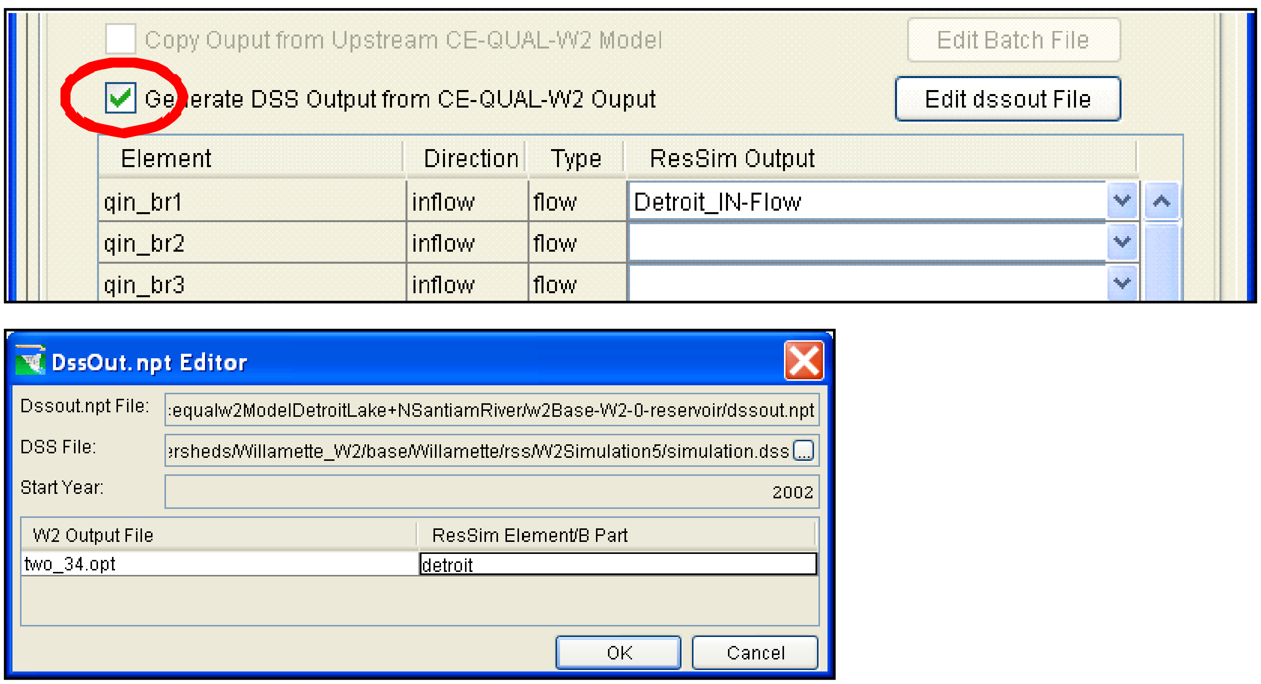

Figure 2. Specifying W2 output in DSS format is accomplished in the Alternative Editor.

Description of W2 parser plug-in. The W2 parser Fortran program called 'control_file_read_write.f90' reads the W2 version 3.6 control file for the project to be simulated and write outs a new control file after any desired changes have been made to the model input parameters within the ResSim plug-in. This new control file is run within the ResSim framework when the "run W2 option" is selected in the ResSim Alternative editor (Figure 3). The stand-alone program now also reads in new control file variables that are included in the most recent W2 version 3.6. Additionally after modifications, The W2 parser Fortran program performs a number of other duties: 1) parses model inflows and outflows, 2) writes out a backup control file of the original control file, and 3) reads a "changes" file that contains adjusted model parameters.

Two new control file parameters, NPROC and CLOSEC, were added to W2 version 3.6 and the W2 parser program has been altered to read and write these switches. NPROC specifies the number CPU's CE-QUAL-W2 executable will use to run in parallel or serial mode and CLOSEC allows the option to close the model interface at the end of a simulation. This allows other W2 models of different basin sections to be simulated sequentially in a batch run environment.

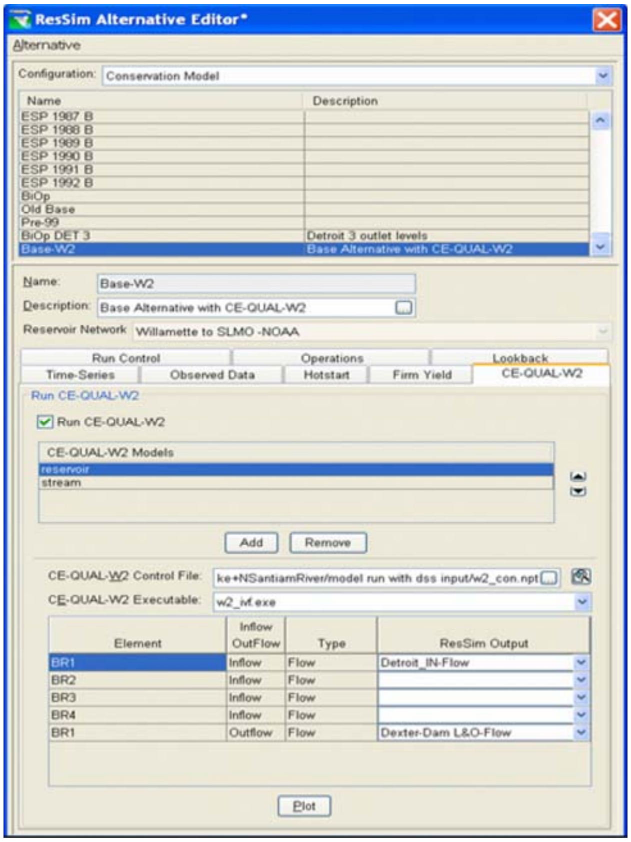

Figure 3a. Description of ResSim plug-in.

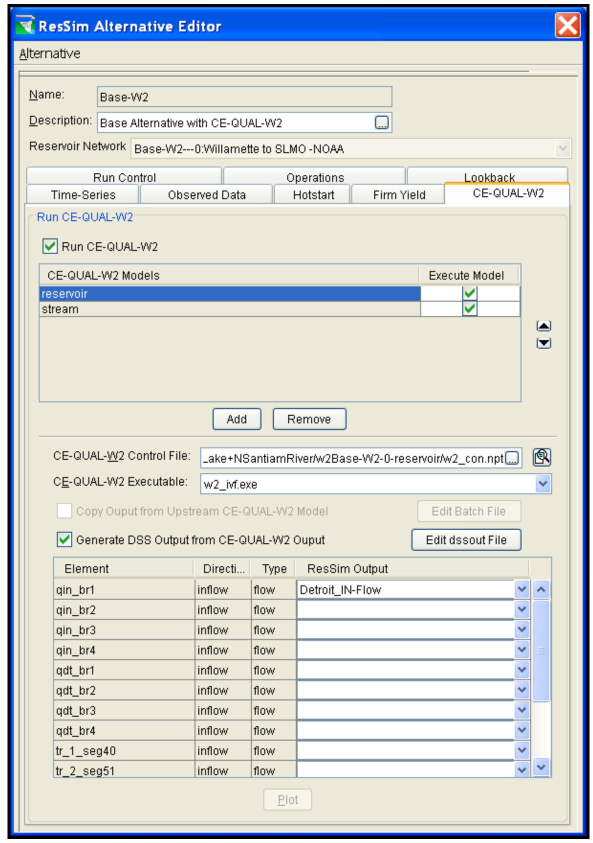

Figure 3b. ResSim alternative editor tab for W2 simulation.

Detroit Lake FY09 Phase I Demonstration: Detroit Lake, OR was chosen as the demonstration site for Phase I of the ResSim-W2 modeling package. It was completed in 1953 with the multipurpose of flood control, irrigation, power generation, downstream navigation improvement, and recreation. Both models had previously been set up for this Corps of Engineers project located in the Willamette River system. Figure 4 depicts the Willamette River system as set up in the ResSim model. For this test CE-QUAL-W2 is only set up for the Detroit Lake with a small portion of the downstream tailwater included. On the other hand, the ResSim model included the whole watershed as shown in Figure 4.

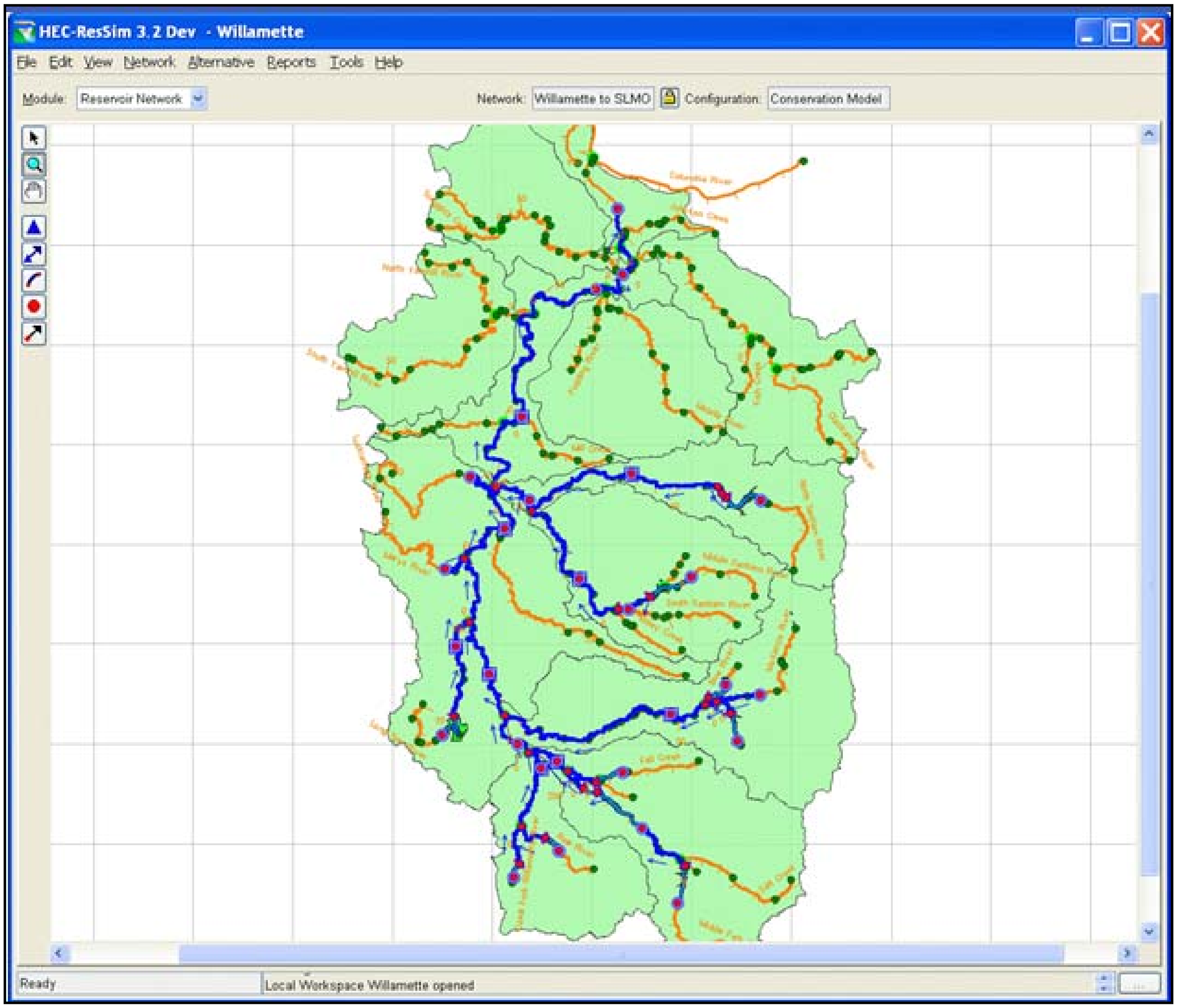

Figure 4. Screen shot of the ResSim model of the Willamette River system.

Since the original model developed for Detroit Reservoir was Version 3.1, the model was converted and updated to the latest Version 3.6 code. Before simulations were conducted, the W2 model was converted from Version 3.1 to 3.6. Both models were simulated for the periods of 1 January through 31 December 2002 and 1 December 2005 through 2 February 2006. The W2 Detroit Lake model grid (Figure 5) included four branches and 58 segments varying in length from 230 to 638 meters (m). One meter layers were evenly spaced with a total of 115 layers in the deepest segment (Figure 5). Inflows to the reservoir in the W2 run were set to the values used by the ResSim model instead of what was originally set up for the W2 runs. As a result, there were issues encountered running W2 with ResSim inputs. Namely water balance problems (Figure 6) were encountered in the reservoir, and predicted evaporation values did not match values used by the ResSim model. The main reason for water imbalance was attributed to using only one inflow from the ResSim model (Figure 7) while the original CE-QUAL-W2 model of Detroit Lake had 4 inflows from different inflow locations, 4 precipitation accretion flows, and 4 water distributed inflows. Lessons learned from this demonstration were that using boundary conditions from ResSim as input to W2 runs adds an extra step in the sequential path of the Phase I modeling sequence. After the initial W2 run using ResSim inflows, the water balance must be checked for flow inconsistencies using the water balance program distributed with CE-QUAL-W2 model. However, if both models use original inflow files from calibration or previous runs, this step will not be necessary.

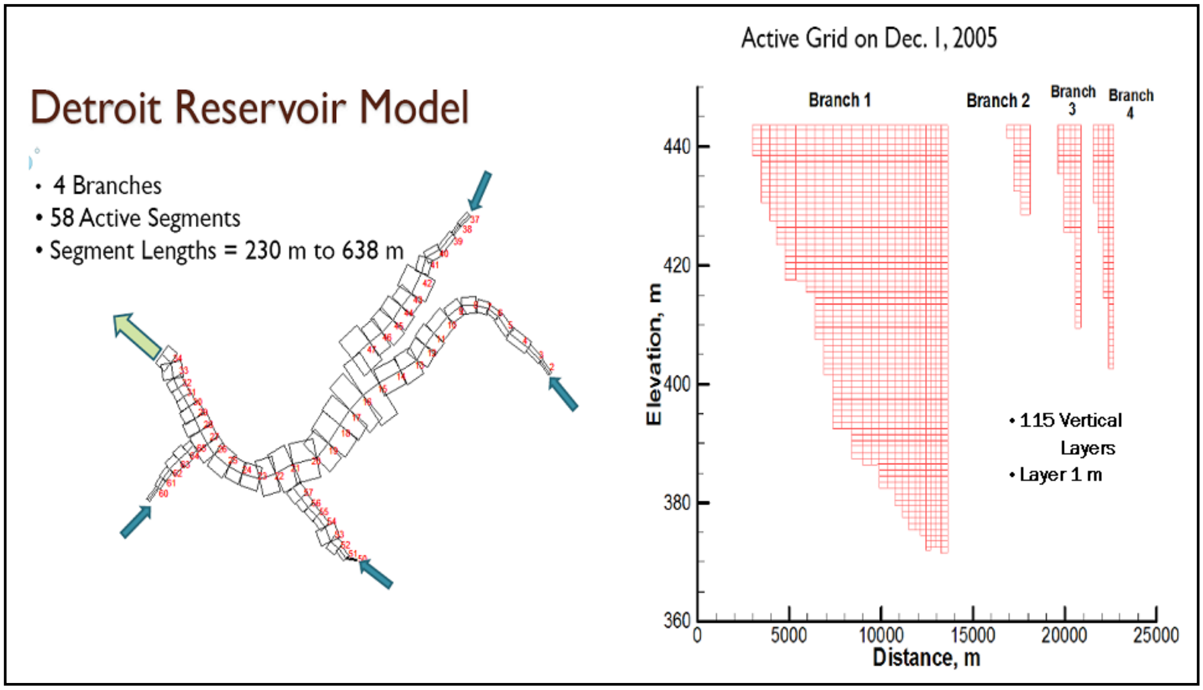

Figure 5. Plan view (segments) and vertical (layers) view of Detroit Lake W2 grid.

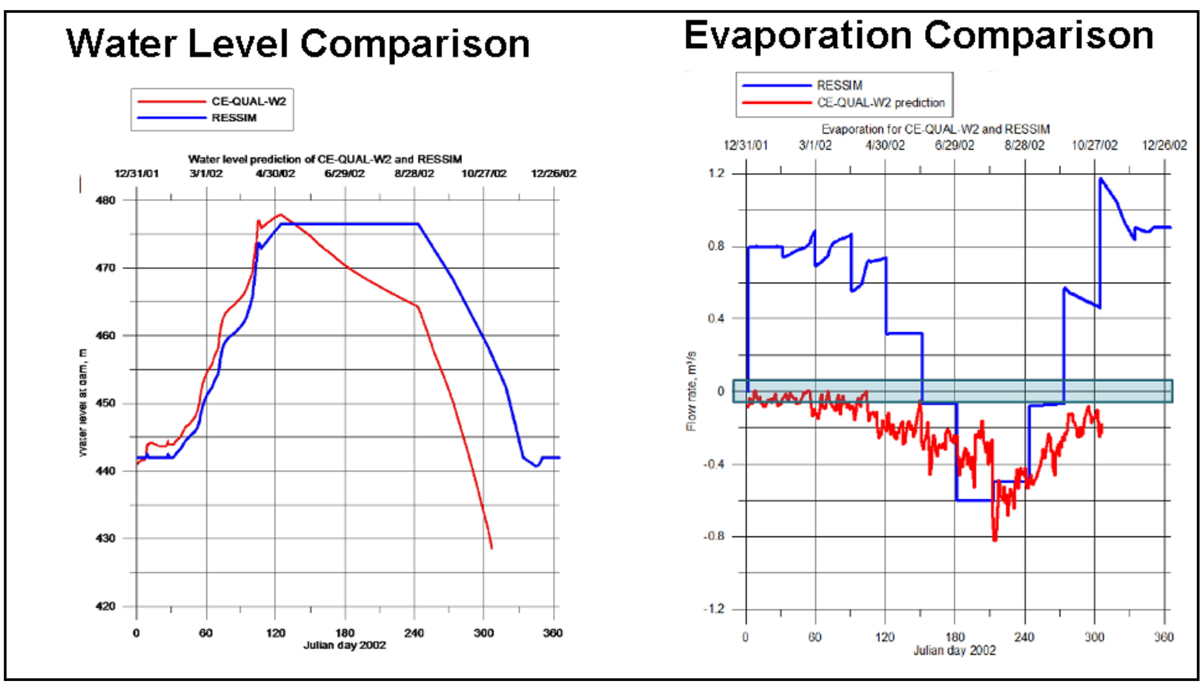

Figure 6. Water level and evaporation comparisons between ResSim and W2 output.

Flow inconsistencies were handled by adjusting inflows in the W2 run. Specifically, inflows to the main branch were adjusted to better match the ResSim inflows (Figure 6). As denoted in Figure 7, inflow adjustments greatly improved water levels.

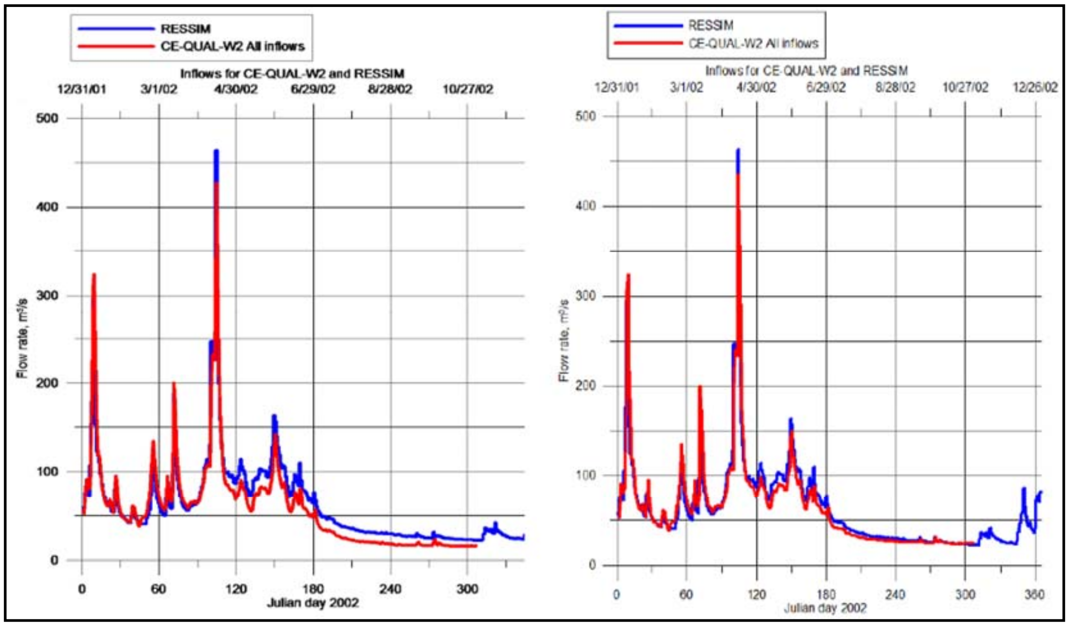

Figure 7a. Inflow comparisons of ResSim and W2 inputs before (left) and after (right) adjustments to W2 inflows.

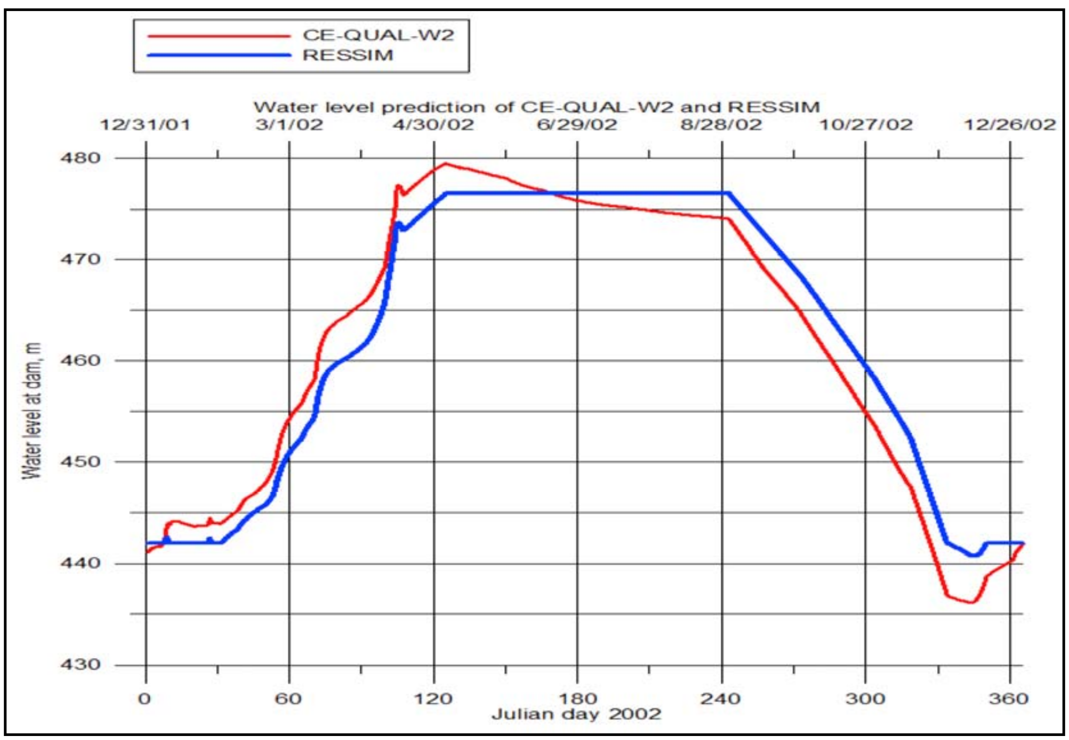

Figure 7b. Comparison of water levels (W2 results in red and ResSim results in blue) after inflow adjustments.

An advantage of running W2 within the ResSim framework is being able to display W2 output immediately after a run is completed. Examples of W2 time series output are shown in Figures 8 and 9. In Figure 8, plots of reservoir release temperatures and reservoir release temperatures displayed in the ResSim framework are displayed. Having the ability to display within the ResSim framework reduces post-processing time; thus, the user is able to determine whether to accept or test a new reservoir operation immediately. Figure 9 illustrates additional types of time series data that can be plotted within ResSim from W2 output.

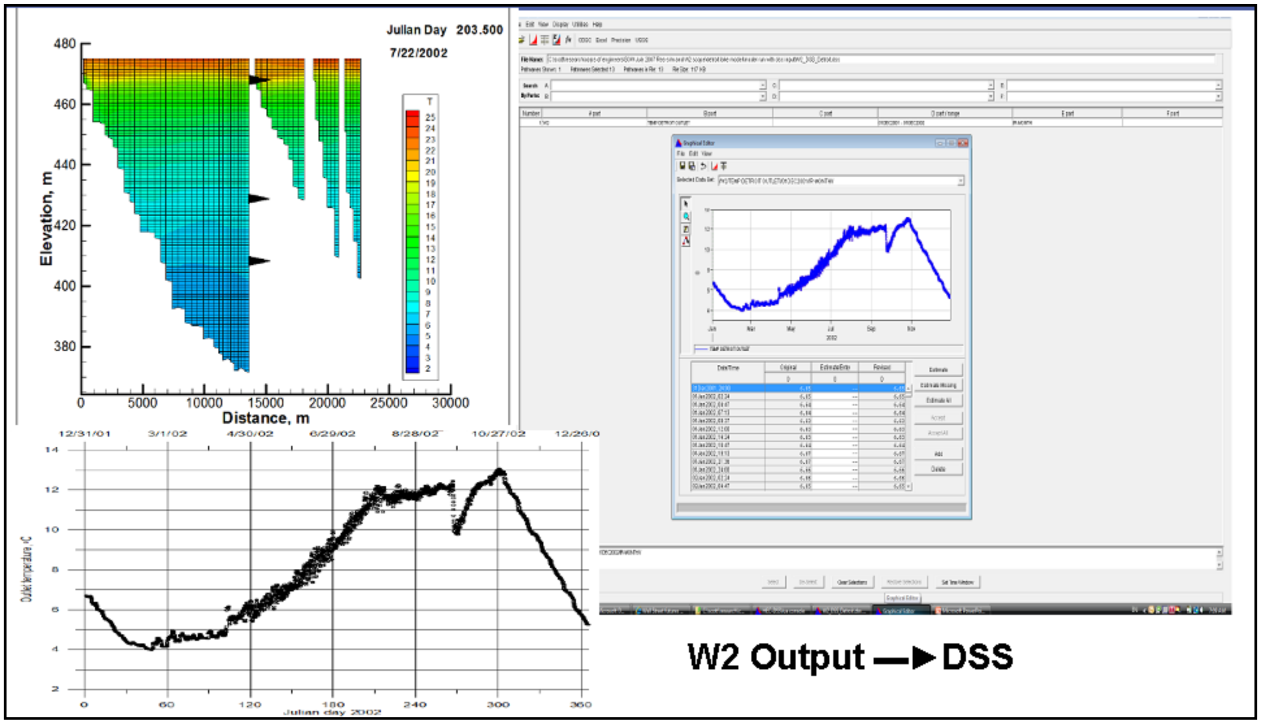

Figure 8. W2 release temperature time series output (bottom left) converted to DSS displayed within ResSim framework (right).

In addition to the Detroit Lake Demo, a ResSim-W2 model of the Alabama-Coosa-Tallapoosa/ Apalachicola-Chattahoochee-Flint basin (ACT/ACF) containing a Lake Lanier W2 application has been developed. Presently, only Lake Lanier can be included in the coupled system because no W2 applications have been developed for the ACT/ACF riverine sections. With this coupled model set-up, impacts to water quality resulting from operation changes in the reservoir and at the release can be studied at Lake Lanier, but impacts to downstream locations can only be studied when W2 applications are developed for those reaches. For future demonstrations, consideration is being given to the Delaware Basin where a ResSim model is being developed by HEC. Likewise, ERDC is developing W2 applications at F.E. Walter and Beltzville Reservoirs and approximately 60 miles of the Lehigh and Pohopoco Rivers contained in the Delaware basin. The Philadelphia District is considering operational changes to improve downstream temperatures for fisheries and recreation. Developing a coupled model for this project would be beneficial for analysis of multiple management considerations.

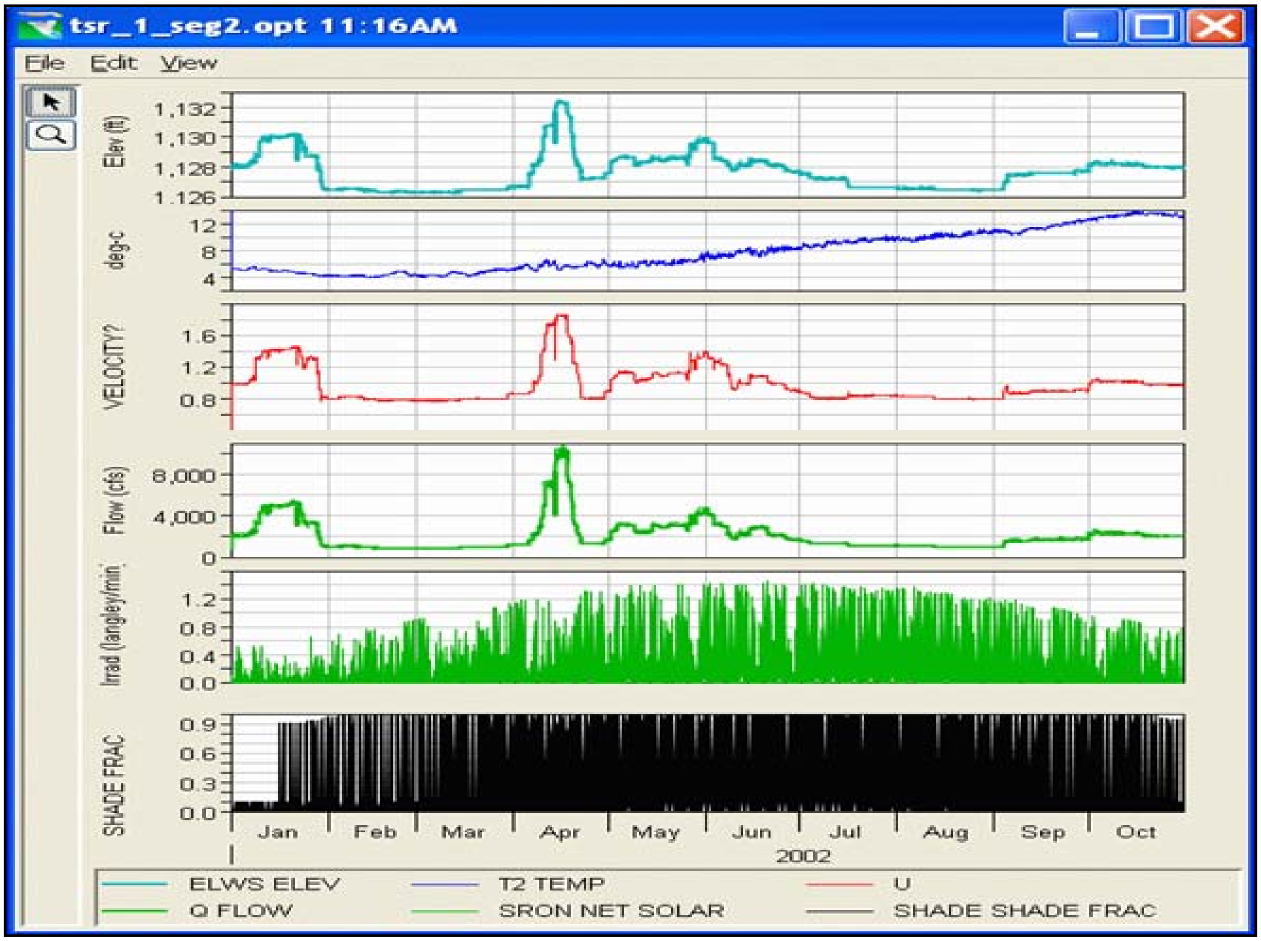

Figure 9. Example time series output from W2 run viewed in ResSim.

SUMMARY AND FUTURE DEVELOPMENT. Development of the integrated models ResSim and CE-QUAL-W2 has been completed with Version 1 of the software that was available fall of 2009. A demonstration of the linkage was tested on Detroit Lake in the Willamette River system. Issues with linkage were identified which were: 1) water balance problems from use of ResSim inflows instead of W2's inflows and 2) predicted evaporation values did not match values used by the ResSim model. Further investigation is on-going for solutions to these problems.

Ongoing development of the model integration package will allow closer coupling of ResSim and W2. This will entail iterative checks throughout the simulation for criteria deviations that would send the simulation back to a previous period for rule adjustments within ResSim. This would be based on 1) a user defined time period to check for criteria violations and 2) activate W2 decision making to determine new distribution of releases and feed back to ResSim. This function could be built to manage any potential shortages. Questions like "Can the severity of the violation be reduced if targets were missed earlier in the year?" could be addressed. The foresight of this approach would be equal to a user-defined time-period and/or other trigger condition, 3) enhancement of the W2 parser, DSSIN, DSSOUT plug-ins, and 4) refining the W2 model restart capabilities so that there can be tightly-coupled interaction with ResSim in running through multiple forecasting scenarios. Forecasted inflows and meteorological data would be required by both models (ResSim and W2) for the full simulation period, which allows the models to manage releases for a water quality resource or contaminant in accordance with objectives set by the user.

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> Tillman, D. H., G. C. Modini, and S. A. Wells. 2011. *Meeting water quality and water control objectives in river basins with multiple reservoirs.* SWWRP Technical Notes Collection. ERDC TN-SWWRP-11-2. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

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