MODELING TEMPERATURE AND DISSOLVED OXYGEN IN THE CHEATHAM RESERVOIR WITH CE-QUAL-W2

By

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CHAPTER I

INTRODUCTION

Purpose of Study

The Nashville District of the U.S. Army Corps of Engineers (USACE) schedules and maintains ten water control projects (dams) on the Cumberland River. Of these ten projects, four are considered main stem projects, with the other six considered tributary storage projects to the Cumberland. Historically, the main uses of the Cumberland River Dam System were hydropower generation and navigation. An increased interest in water quality management has motivated the Nashville District to develop a system of tracking and modeling the water quality conditions of the Cumberland River and incorporate that information into their water control decisions.

The latest hydrologic model used by USACE for predicting flows and stages is the Corps Water Management System (CWMS). Initially developed to align all districts of the Corps of Engineers into a standardized water control model, CWMS incorporates many of the existing hydraulic and hydrologic models. These include the Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) and Hydrologic Engineering Center's Reservoir System Simulation (HEC-ResSim). The selected water quality model to be included in CWMS is CE-QUAL-W2 (U.S. Army Corps of Engineers, 2010).

The Nashville District is currently developing a CE-QUAL-W2 model for the entire Cumberland River. The initial plan is to model the portion of the river between each dam as a separate entity and then link all portions for a final model that enables improved understanding of impacts of water management decisions on individual and system-wide water quality. The Cheatham Model represents one portion of the overall plan and a diagram of the area of concern is shown in Figure 1-1. Included in this effort is the J. Percy Priest Reservoir, which flows to the Cheatham portion of the Cumberland through the J. Percy Priest Dam and the Stones River. The Stones River portion is included in this study to assist future linkage of the Cheatham Model to the J. Percy Priest Reservoir.

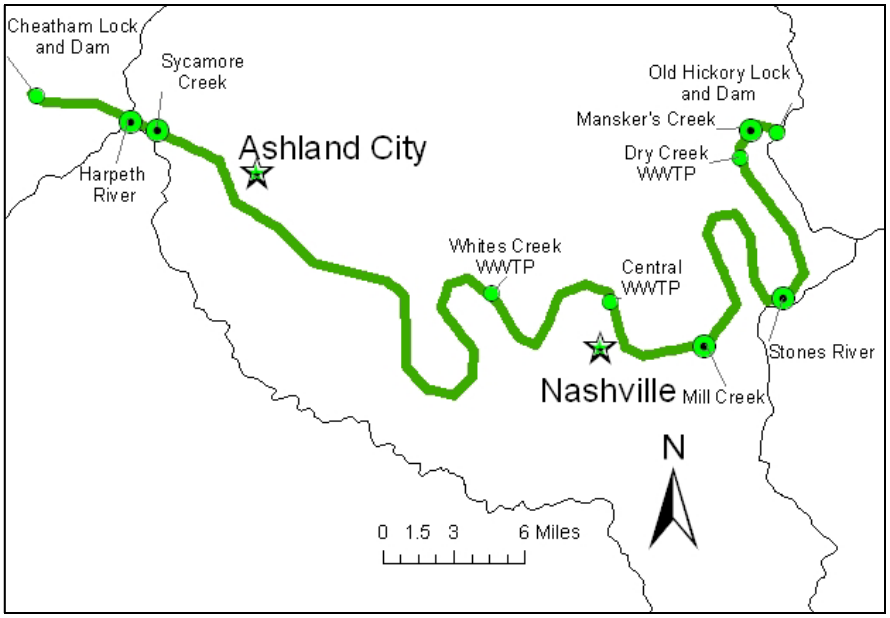


Figure 1-1. Cheatham Portion of the Cumberland River.

An additional effort being pursued is a Simulation and Optimization of Large-Scale Controlled Reservoir System Constituent Response to Power Generation Activities project at Vanderbilt University (LeBoeuf, et al., 2011). It is expected that the model in this report may be used in that project.

Literature Review

Mathematical modeling of riverine and reservoir water systems is thought to have begun in the early part of the 20th century (Orlob, 1983). The earliest water models consisted of differential equations that were solved analytically and used to model effects such as stratification (Orlob, 1983). These models included few hydrodynamic calculations. Little progress was made until the 1950's and the advent of computer systems. With these new tools, modelers had the ability to develop numerical solutions to differential equations that were more complex than the earlier versions (Orlob, 1983). The first models of river and lake systems were one-dimensional and eventually incorporated the advection-diffusion equation (Orlob, 1981). As computers progressed from mainframes to personal computers and speeds increased, more capable and complex models were developed.

Today, water quality models exist that address a variety of uses. One-, two-, and three-dimensional models are available from research institutions and commercial enterprises. Select examples of the most common models most relevant to this study are discussed below.

One-Dimensional Models

Minnesota Lake Water Quality Management Model (MINLAKE)

MINLAKE was developed in the 1980's to simulate lake stratification and water quality characteristics in shallow temperate lakes (Riley, et al., 1988). The model predicts these variables in response to weather, inflow, outflow, exchange processes, and in-lake processes (Riley, et al., 1988). MINLAKE uses advection-diffusion transport equations and addresses temperature, algae, phosphorus and nitrogen, detritus, zooplankton, inorganic suspended sediment, and dissolved oxygen (Riley, et al., 1988).

The model is one-dimensional (z-direction) and is suggested for use in lakes with small surface areas (50 to 100 km^2) that can be either deep or shallow (Riley, et al., 1988). The majority of the code is focused on algae predictions with sub-routines that address nutrient loading. It takes into account growth, diffusion, settling, respiration, mortality, and grazing of algae and zooplankton (Dorsel, 1998).

MINLAKE has been applied to a variety of lakes, mostly in the upper region of the United States. A 1992 study, by Stefan and Fang, used MINLAKE as an evaluation tool for 6 lakes in the Minnesota region. Statistical results for dissolved oxygen from that study are shown in Table 1-1.

Table 1-1. Dissolved Oxygen results for application of MINLAKE to 6 lakes in Minnesota (after Stefan, et al., 1994).

Lake	Year	R^2	Standard error (mg/l)
Calhoun	1981	0.96	0.91
Fish	1981	0.89	1.54
Fish	1982	0.82	1.59
Rebecca	1984	0.69	2.13
George	1981	0.38	2.29
Charley	1985	0.88	0.61
Cedar	1984	0.73	0.99

As can be seen, MINLAKE is capable of reproducing selected constituent data to a relatively high degree of accuracy but the model is best suited to northern lakes where there is little need to address the anaerobic tendency of the hypolimnion during the summer months (Herold, et al., 1999). For this reason, a 1999 model of the Roodeplaat Dam, in South Africa, included a MINLAKE model with a code modification to address the differences of using MINLAKE in a warmer climate to include differing biological rates of bacterial decomposition (Herold, et al., 1999).

The Roodeplaat Dam model was able to simulate the hydrodynamic behavior of the reservoir, as well as phosphate concentration change due to varying inputs. However, the model was not able to predict the change in chlorophyll-a, ammonia, or nitrate concentration resulting from the same types of input changes. This deficiency limited the use of this model to sensitivity predictions of differing nutrient inputs to the system. This information could then be used in the development of water quality standards for the land use of the area that affect nutrient loading of inflowing rivers (Herold, et al., 1999).

CE-QUAL-RIV1

CE-QUAL-RIV1 was developed for USACE using an original model developed at The Ohio State University (U.S. Army Engineer Waterways Experiment Station, 2011). It is a hydrodynamic and water quality model that contains separate sub-models for hydrodynamic and water quality calculations (Deas, 2005). The model uses the St. Venant equations to model flow. It also has the ability to address temperature, carbonaceous biochemical oxygen demand (CBOD), organic nitrogen, ammonia nitrogen, nitrate and nitrite nitrogen, dissolved oxygen, organic phosphorus, dissolved phosphates, algae, dissolved iron, dissolved manganese, and coliform bacteria (Deas, 2005).

This model is one-dimensional (laterally and vertically averaged) and is suited for rivers and run of the river reservoir projects (USGS, 2011). It is best applied to systems where axis-of-flow variations are important but lateral and vertical variations can be neglected (USGS, 2011). The water quality portion, written in FORTRAN, has the ability to be decoupled from the hydraulic portion and receive inputs from other models (USGS, 2011).

The Waterways Experiment Station of USACE was originally interested in the model because of its ability to reproduce flow and water quality data (U.S. Army Engineer Waterways Experiment Station, 2011). After selection, the Waterways Experiment Station contracted The Ohio State University to develop the additional ability to simulate control structures such as dams. Because of the incorporation of control structures and the fact that the model is best suited for river systems with highly irregular flows, steady-flow rivers may be better served by other one-dimensional models such as MINLAKE or ADYN and RQUAL (U.S. Army Engineer Waterways Experiment Station, 2011).

CE-QUAL-RIV1 has been applied to a variety of river systems and one example is a model developed for a portion of the Chattahoochee River, Georgia between Buford Dam and Peachtree Creek (Zimmerman, et al., 1989). In that study, CE-QUAL-RIV1 was applied to a peaking hydropower dam operated by USACE with a smaller hydropower dam within the modeled portion. Flows for this stretch of the river are highly irregular with variations from 16 to 240 $m^3 s^{-1}$ possible in the course of a day (Zimmerman, et al., 1989). Selected results for water elevation and temperature calibration are shown in Figure 1-2 and Figure 1-3.

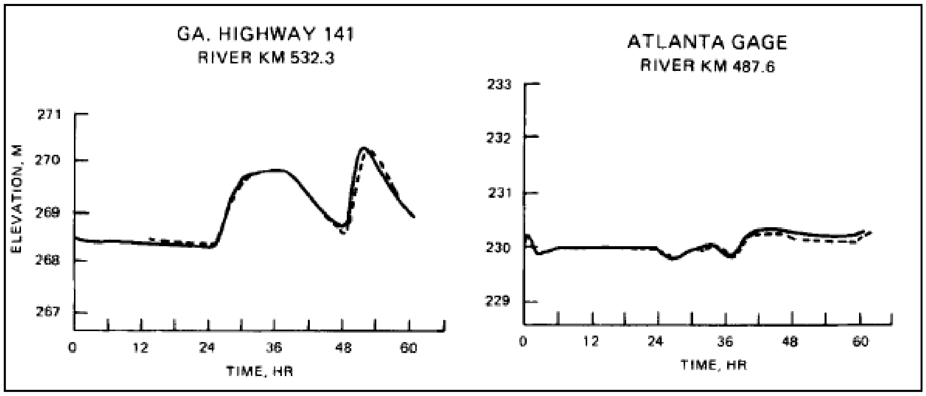


Figure 1-2. Stage Calibration for Chattahoochee River using CE-QUAL-RIV1 (after Zimmerman, et al., 1989).

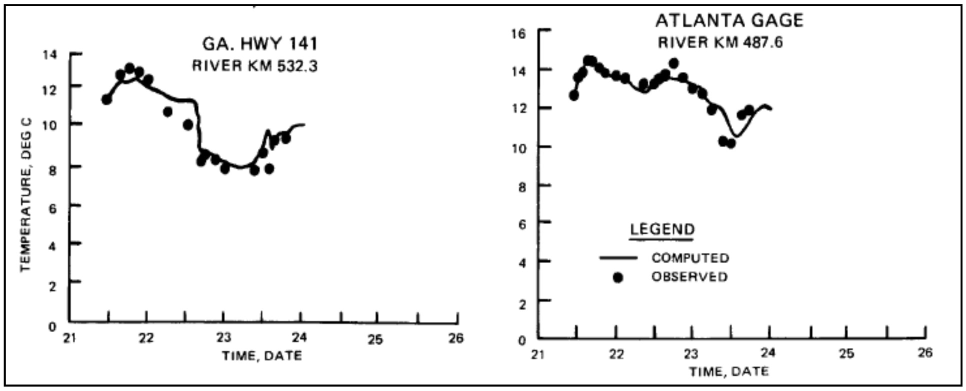


Figure 1-3. Temperature Calibration for Chattahoochee River using CE-QUAL-RIV1 (after Zimmerman, et al., 1989).

In Figure 1-2 and Figure 1-3, field measurements are represented with a dashed line and model results with a solid line. Figure 1-2 illustrates the capability of the model to predict stages due to unsteady flow. As shown in the Atlanta gauge plot, the model is able to predict low-flow stage. On the highway 141 gauge plot of the same figure, higher and more irregular flows are represented with good correlation between the model and field data. Although statistical evaluation was not included in the study, the shape and accuracy of the profiles illustrate the model's capability under varying circumstances. Using this same unsteady flow, the model produced the results shown in Figure 1-3, illustrating an example of the capability of the model to predict temperature. Temperature inflows to the model were based on monthly averages calculated from the period of record for that month and meteorological data included dew point and dry bulb temperature, atmospheric pressure, wind speed, and cloud cover (Zimmerman, et al., 1989). The fast response of the model to highly irregular temperature inputs is shown best in the Highway 141 Gauge location on day 22.5.

ADYN and RQUAL

ADYN and RQUAL were developed by the Tennessee Valley Authority (TVA) as a set of hydrodynamic and water quality models, with ADYN addressing the hydrodynamic open-channel free-surface flow attribute and RQUAL addressing the water quality component (Deas, 2005). ADYN uses conservation of mass and momentum equations while RQUAL uses the mass transport equation. RQUAL has the ability to model temperature, biochemical oxygen demand, nitrogenous oxygen demand, dissolved oxygen, and primary production (Deas, 2005).

A 2005 study of the Shasta River, in Northern California, used ADYN and RQUAL to model flow, temperature, and dissolved oxygen. A summary of the results of the study is shown in Table 1-2. These statistics represent the results from 3 different model periods ranging from 5 to 6 days each (Geisler, 2005). Because of limited sampling data, dissolved oxygen statistics were not included but were on the order of 1.5 milligram per liter AME.

Table 1-2. Selected sampling locations along the Shasta River (after Geisler, 2005).

	Location		
	Louie Rd. RM (33.92)	Anderson Grade RM (8.03)	Mouth RM (0.62)
AME Flow (cfs)	0.63	1.67	2.32
RMSE	0.81	1.95	2.79
AME Temperature (°C)	0.59	1.29	1.58
RMSE	0.73	1.56	1.93

ADYN and RQUAL are capable models for evaluation of the above parameters. Temperature statistics reveal the capability of the model over a range of conditions in late summer and early fall and over a range of rocky canyon terrain that radiates heat into the water, well into the evening hours (Geisler, 2005). The model is also able to be used for low-flow rivers. The Shasta River flow values ranged from 15 to 50 cubic feet per second during this study. This ability makes ADYN and RQUAL better choices for low-flow rivers than models such as CE-QUAL-W2, the focus of the current report, which may become unstable during the initial timesteps of a calibration or have segments run dry during a simulation (Cole, et al., 2008). An additional strength of ADYN and RQUAL is their ease of interface to other types of models such as FISH and RHAB, fish habitat and growth models, respectively, as described in a 2006 study of dissolved oxygen mitigation at hydropower dams (Bevelhimer, et al., 2006).

Two-Dimensional Models

Box Exchange Transport Temperature and Ecology (BETTER)

The BETTER model, developed by TVA, is a two-dimensional water quality model that uses flow, mixing, temperature, stratification, and residence time patterns to address nutrient and dissolved oxygen simulations (Brown, et al., 1989). The model is divided longitudinally and vertically into an array of cells. It attempts to replicate re-aeration, photosynthesis, respiration, inflowing BOD, and sediment oxygen demand to model temperature, dissolved oxygen and various nutrients including total phosphorus, surface carbon dioxide, pH, algae, and dissolved manganese (Brown, et al., 1989).

Though capable in years past, the BETTER model has not been updated to take advantage of modern computational abilities. The model uses daily averages for all input variables, rather than the more accurate (and common) hourly averages of current models. It is, however, useful for modeling systems where high resolution is not required. For example, in a 1989 model of the Cheatham Reservoir, the reservoir of interest in the current report, the 67.5 river mile stretch was divided into 19 columns and 9 layers, as compared to 273 columns and 23 layers of the current model. Of the points modeled, the results were mixed. Using correlation coefficients, where a value of 0 implies no linear correlation and 1 implies perfect replication of data, statistics for selected variables are illustrated in Table 1-3 (Brown, et al., 1989).

Table 1-3. Correlation Coefficients for BETTER Model of Cheatham Reservoir (after Brown, et al., 1989).

	Reservoir Location		
Parameter	Old Hickory	Stones River	Nashville
Temperature	0.996	0.994	0.994
Dissolved Oxygen	0.915	0.902	0.9
Suspended Solids	0.999	0.095	0.326
pH	0.241	0.404	0.427
Total Phosphorus	1.00	0.866	0.689

In this case, the BETTER Model provided an accurate representation of temperature and dissolved oxygen. However, suspended solids, pH, and total phosphorus appear to require more calibration. Discrepancies with field data may have been a cause of error in the nutrient portion of this study (Brown, et al., 1989). Even so, the BETTER Model is useful for modeling systems where lower resolution and shorter run times are required, such as well-mixed reservoirs with little stratification. This simulation, on an 80286 processor required approximately 17 minutes (Brown, et al., 1989).

CE-QUAL-W2

CE-QUAL-W2 was developed by USACE as a two-dimensional water quality model (Cole, et al., 2008). It has the ability to model hydrodynamics using the continuity and conservation of momentum equations. It can also model temperature and a variety of constituents. The U.S. Army Engineer Research and Development Center (ERDC) officials plan to incorporate CE-QUAL-W2 as the water quality model for CWMS since it is recognized as a state of the art water quality model and since most Districts of USACE already possess existing CE-QUAL-W2 Models (Cole, et al., 1997) (Tillman, et al., 2011). CE-QUAL-W2 is the model selected for use in this study and is described in more detail in Chapter III of this thesis.

Three-Dimensional Models

Water Quality Analysis Simulation Program (WASP)

WASP was developed by the Environmental Protection Agency (EPA) to help users predict and interpret water quality responses to natural phenomena and man-made pollution (Ambrose, et al., 1993). It uses time-varying processes of advection, dispersion, point and diffuse mass loading, and boundary exchange and users can examine systems in one, two, or three dimensions (Ambrose, et al., 1993). Similar to CE-QUAL-RIV1, WASP separates hydrodynamics from water quality calculations into two separate code elements. The water quality approach used by WASP is based on conservation of mass. It has the ability to model temperature, dissolved oxygen, sediment transport, algae, and many other constituents (Ambrose, et al., 1993).

The primary advantage of WASP is that it is able to be tailored to a variety of systems and complexities in one-, two-, or three-dimensions depending on the accuracy of the results required. By increasing accuracy, however, WASP can be hampered by large external hydrodynamic files and may not be suited to older computer systems. WASP is limited in its application to spill modeling, floodplain drying, simulation of photosynthesis, nutrients, and dissolved oxygen (Environmental Protection Agency, 2005). The main disadvantage of WASP lies in the complexity of the input files required and types of simulations available. Without extensive training and experience, users can become overwhelmed with the multitude of options available and are much better served with a less complex and more easily understandable model (Environmental Protection Agency, 2005).

CE-QUAL-ICM

CE-QUAL-ICM was initially developed by USACE to study eutrophication processes in the Chesapeake Bay (Cerco, et al., 1995). The code allows users to divide a model into discrete cells to which a mass-balance approach is used (Cerco, et al., 1995). It has the ability to model in one, two, or three dimensions and can predict 22 constituents, including algae, carbon, nitrogen, phosphorus, silica, and dissolved oxygen (Cerco, et al., 1995).

The largest limitation of this model is that it does not compute hydrodynamics (U.S. Army Engineer Waterways Experiment Station, 2011). Inflows to the model and hydrodynamic calculations must be read from an external source and may be entered through an ASCII file (U.S. Army Engineer Waterways Experiment Station, 2011).

CE-QUAL-ICM was used to model the eutrophication processes of the Chesapeake Bay in 2002. Statistical results, shown in Table 1-4, illustrate the model’s ability to reproduce field data on a large system. The Chesapeake Bay watershed is composed of 166,000 square kilometers with 94 sub-watersheds and the grid for model is made up of 13,000 cells (Cerco, et al., 2002). Other systems to which the model has been successfully applied include Inland Bays of Delaware, New York Bight, Newark Bay, New York - New Jersey Harbors and Estuaries, Lower Green Bay, Los Angeles - Long Beach Harbors, Cache River wetland, San Juan Bay and Estuaries, and Florida Bay (U.S. Army Engineer Waterways Experiment Station, 2011).

Table 1-4. Chesapeake Bay CE-QUAL-ICM Model Statistics (after Cerco, et al., 2002).

	Mainstem Bay	James	York	Rappahannock	Potomac	Patuxent
Surface Chorophyll, µg/l AME	5.01	9.29	4.71	8.22	7.45	8.15
Summer, Bottom Dissolved Oxygen mg/l AME	1.47	2.43	1.18	1.93	2.13	1.74
Light Attenuation 1/m AME	0.36	0.97	0.84	0.89	1.03	0.84
Salinity ppt AME	1.97	2.01	1.84	1.49	0.97	1.69
Total Nitrogen mg/l AME	0.17	0.42	0.23	0.26	0.61	0.43
Total Phosphorus mg/l AME	0.014	0.069	0.036	0.036	0.053	0.047

CHAPTER II

CHEATHAM RESERVOIR/STONES RIVER HISTORY

With the primary purposes of navigation and hydropower generation, the Cheatham Lock and Dam system was authorized in 1946 (U.S. Army Corps of Engineers, 1998). Construction began on 6 April, 1950 and the dam was closed on 19 November, 1953 (U.S. Army Corps of Engineers, 1998). Cheatham Lake stretches from river mile 148.7 (Cheatham Dam) to river mile 216.2 (Old Hickory Dam). At 67.5 miles, the lake is comprised mostly of a riverine section that flows into a reservoir section near the dam. Secondary purposes for the construction of Cheatham Dam, as authorized by Congress, include recreation, fish and wildlife protection, water quality, and water supply (U.S. Army Corps of Engineers, 1998).

Cheatham Dam is a concrete gravity structure with 7 spillway gates, totaling 495 feet across, and 3 low-head, adjustable blade turbines for electric power generation. Each of the generation units is rated at 12 megawatts. Cheatham Lock measures 800 feet long by 110 feet wide. As it was when the dam was built, navigation is still considered a high priority, and a channel depth of 9 ft is maintained by the water control managers to support this function (U.S. Army Corps of Engineers, 1998). This holds true even during drought conditions.

Cheatham Dam is one of three dams on the main stem of the Cumberland River that does not possess flood control capability. During periods of high water, the tailwater elevation approaches the headwater elevation and the spillway gates are opened, allowing free flow of the river. During periods of flood the Lock, Dam, and Powerhouse are designed to be overtopped, a capability used during the flood of 1-2 May 2010 (LeStourgeon, 2011).

The Cheatham Reservoir has multiple uses and water quality characteristics. The main commercial use is barge traffic that transports coal to the Cumberland Fossil Plant, west of the Cheatham Dam and the Gallatin Fossil Plant east of the Old Hickory Dam. Three different waste water treatment plants exist within the Cheatham Reservoir and a variety of city and commercial intakes and discharges. Water quality of the Cheatham Reservoir is characterized by low stratification, due to relatively high flows, with residence times generally between 2 and 10 days. Dissolved oxygen concentrations often border the state limit of 5 milligrams per liter in the summer months (Brown, et al., 1989).

The Stones River joins the Cheatham Reservoir just upstream of Nashville. Since the completion of the J. Percy Priest Dam in 1968, the Stones River is considered to be the 6.7 mile portion between the Cheatham Reservoir and the J. Percy Priest Dam (U.S. Army Corps of Engineers, 1998). The Stones River has historically been characterized by lower water quality than the other parts of the Cumberland River (U.S. Army Corps of Engineers, 2011). Reasons include high nutrient runoff from the Stones River basin coupled with the low summertime flows that are necessary to maintain the proper power generation and recreation pool levels. In addition, the Stones River is very susceptible to backwater effects when higher Cheatham Reservoir elevations exist (U.S. Army Corps of Engineers, 2011). To mitigate these water quality issues, a fixed-cone valve, described later in this report, has been installed in the J. Percy Priest Dam (U.S. Army Corps of Engineers, 2011).

CHAPTER III

CE-QUAL-W2

CE-QUAL-W2 is a 2-dimensional, laterally-averaged water quality model (Cole, et al., 2008). Because of the lateral averaging, it is best suited for water systems that are long and narrow (Cole, et al., 2008). Cheatham Reservoir is 67.5 river miles long with an average width of approximately 200 meters and fits the description of a long and narrow reservoir.

CE-QUAL-W2 originally was developed in 1975 as Laterally Averaged Reservoir Model (LARM) by Edinger and Buchak. LARM allowed for a single branch and was soon modified to allow multiple branches and renamed Generalized Longitudinal-Vertical Hydrodynamics and Transport Model (GLVHT). From there, the addition of water quality algorithms produced CE-QUAL-W2 version 1.0 that was released in 1986 (Cole, et al., 1995).

Code modifications to improve accuracy, efficiency, and many other updates resulted in the release of version 2.0 (Cole, et al., 1995). Continued updates in numerical solution schemes, water quality algorithms, multiple waterbody capabilities, multiple constituent capabilities, and other improvements led to the release of version 3.0 (Cole, et al., 2008).

The current version of CE-QUAL-W2 is version 3.6 (Cole, et al., 2008). Although there is a beta version 3.7, the project described in this thesis was calibrated using version 3.6, as that is the chosen version for the overall Cumberland River model that is currently under development.

Capabilities

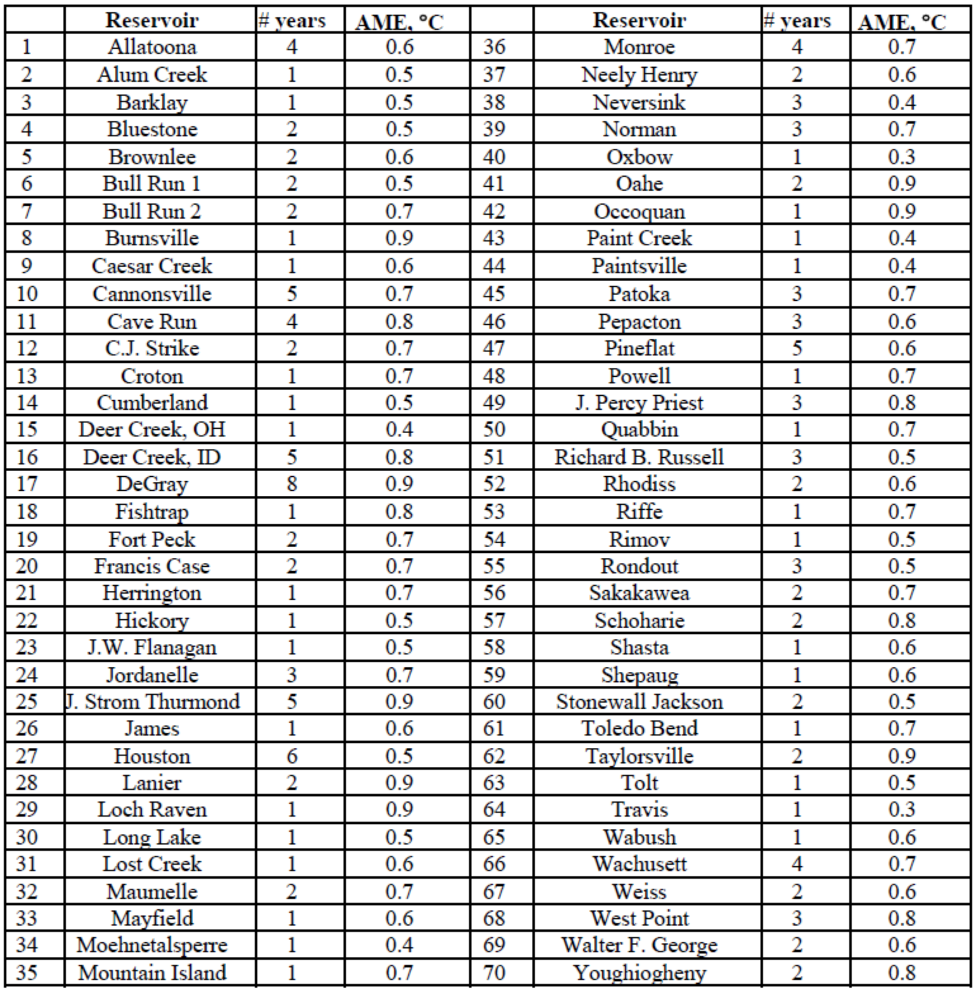
CE-QUAL-W2 is capable of accurately predicting water surface elevations, water velocities, temperatures, and many different combinations of constituents. Users can adapt the model to a variety of river, estuary, or reservoir systems by building the model with any number of waterbodies and any number of branches and tributaries. Once described, the minimum data needed to run a model include inflows, outflows, meteorological data, and initial conditions.

Since temperature has a large impact on overall hydrodynamic and water quality behavior, CE-QUAL-W2 requires temperature inputs and computes temperature predictions for all runs. However, the user has the option of disregarding the water quality data constituent calculations to increase computational speed. The water quality portion can include groups of inorganic suspended solids, groups of phytoplankton, groups of epiphyton, carbonaceous biochemical oxygen demand (CBOD), organic matter, and a variety of nutrients to include phosphorus, ammonia, and nitrate/nitrite.

The model is written in FORTRAN and version 3.6 was compiled with the Intel Visual FORTRAN V10.1 compiler (Cole, et al., 2008). The code for the model is open source and available on the CE-QUAL-W2 website (http://www.cee.pdx.edu/w2/). User's have the option of using the model as compiled or, if additional functionality is required, modifying the code and recompiling.

CE-QUAL-W2 has been applied to many different water systems throughout the world with varying degrees of success. Table 3-1, reproduced from the User's Manual, shows examples of completed models and associated error in water temperature calibrations.

Table 3-1. Reservoir Simulations (after Cole, et. al., 2008).



	Reservoir	# years	AME, °C		Reservoir	# years	AME, °C
1	Allatoona	4	0.6	36	Monroe	4	0.7
2	Alum Creek	1	0.5	37	Neely Henry	2	0.6
3	Barklay	1	0.5	38	Neversink	3	0.4
4	Bluestone	2	0.5	39	Norman	3	0.7
5	Brownlee	2	0.6	40	Oxbow	1	0.3
6	Bull Run 1	2	0.5	41	Oahe	2	0.9
7	Bull Run 2	2	0.7	42	Occoquan	1	0.9
8	Burnsville	1	0.9	43	Paint Creek	1	0.4
9	Caesar Creek	1	0.6	44	Paintsville	1	0.4
10	Cannonsville	5	0.7	45	Patoka	3	0.7
11	Cave Run	4	0.8	46	Pepacton	3	0.6
12	C.J. Strike	2	0.7	47	Pineflat	5	0.6
13	Croton	1	0.7	48	Powell	1	0.7
14	Cumberland	1	0.5	49	J. Percy Priest	3	0.8
15	Deer Creek, OH	1	0.4	50	Quabbin	1	0.7
16	Deer Creek, ID	5	0.8	51	Richard B. Russell	3	0.5
17	DeGray	8	0.9	52	Rhodiss	2	0.6
18	Fishtrap	1	0.8	53	Riffe	1	0.7
19	Fort Peck	2	0.7	54	Rimov	1	0.5
20	Francis Case	2	0.7	55	Rondout	3	0.5
21	Herrington	1	0.7	56	Sakakawea	2	0.7
22	Hickory	1	0.5	57	Schoharie	2	0.8
23	J.W. Flanagan	1	0.5	58	Shasta	1	0.6
24	Jordanelle	3	0.7	59	Shepaug	1	0.6
25	J. Strom Thurmond	5	0.9	60	Stonewall Jackson	2	0.5
26	James	1	0.6	61	Toledo Bend	1	0.7
27	Houston	6	0.5	62	Taylorsville	2	0.9
28	Lanier	2	0.9	63	Tolt	1	0.5
29	Loch Raven	1	0.9	64	Travis	1	0.3
30	Long Lake	1	0.5	65	Wabush	1	0.6
31	Lost Creek	1	0.6	66	Wachusett	4	0.7
32	Maumelle	2	0.7	67	Weiss	2	0.6
33	Mayfield	1	0.6	68	West Point	3	0.8
34	Moehnetalsperre	1	0.4	69	Walter F. George	2	0.6
35	Mountain Island	1	0.7	70	Youghiogheny	2	0.8

Users are cautioned early in the User's Manual of the complexity of the model's design and that the accuracy of results obtained are proportional to the effort exerted by the user (Cole, et al., 2008). One of the main capabilities of the model lies in the user's ability to tailor the model to each individual system and make judgment of which is more important, accuracy or speed.

Limitations

CE-QUAL-W2 is a mathematical representation of complex reservoir or river system. It solves hydrodynamic and transport differential equations numerically and, in doing so, is limited by the numerical stability of those equations. Because of this, there are a number of guidelines to which the user must adhere.

The developers of CE-QUAL-W2 used a mass and momentum balance approach in developing the governing equations for the code. The results are continuity and conservation of momentum equations in 3 dimensions as shown (Cole, et al., 2008):

$$\frac{\partial \bar{u}}{\partial x}+\frac{\partial \bar{v}}{\partial y}+\frac{\partial \bar{w}}{\partial z} = 0 \qquad \text{(1) Continuity}$$

$$\frac{\partial \bar{u}}{\partial t}+\bar{u}\frac{\partial \bar{u}}{\partial x}+\bar{v}\frac{\partial \bar{u}}{\partial y}+\bar{w}\frac{\partial \bar{u}}{\partial z}=g\ \sin\alpha-\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x}+\frac{1}{\rho}\left(\frac{\partial \tau_{xx}}{\partial x}+\frac{\partial \tau_{xy}}{\partial y}+\frac{\partial \tau_{xz}}{\partial z}\right) \qquad \text{(2) x-Momentum}$$

$$\frac{\partial \bar{v}}{\partial t}+\bar{u}\frac{\partial \bar{v}}{\partial x}+\bar{v}\frac{\partial \bar{v}}{\partial y}+\bar{w}\frac{\partial \bar{v}}{\partial z}=-\frac{1}{\rho}\frac{\partial \bar{p}}{\partial y}+\frac{1}{\rho}\left(\frac{\partial \tau_{yx}}{\partial x}+\frac{\partial \tau_{yy}}{\partial y}+\frac{\partial \tau_{yz}}{\partial z}\right) \qquad \text{(3) y-Momentum}$$

$$\frac{\partial \bar{w}}{\partial t}+\bar{u}\frac{\partial \bar{w}}{\partial x}+\bar{v}\frac{\partial \bar{w}}{\partial y}+\bar{w}\frac{\partial \bar{w}}{\partial z}=g\ \sin\alpha-\frac{1}{\rho}\frac{\partial \bar{p}}{\partial z}+\frac{1}{\rho}\left(\frac{\partial \tau_{zx}}{\partial x}+\frac{\partial \tau_{zy}}{\partial y}+\frac{\partial \tau_{zz}}{\partial z}\right) \qquad \text{(4) z-Momentum}$$

where: u = x-direction velocity
v = y-direction velocity
w= z-direction velocity
g = gravitational acceleration
τ = turbulent shear stress acting in (first subscript) direction on the (second subscript) face of control volume
α = angle of channel slope

The developers considered Coriolis acceleration to be negligible and it is not included (Cole, et al., 2008). The x and z momentum equations include a (g sin α) term that allows users to model a river with a constant slope. In the case of a reservoir, that term is set to zero.

In order to reduce the number of variables and simplify the model, two key assumptions are made. The first assumption is that the length of the system being modeled is much greater than the depth. This simplification limits the user from modeling any vertical acceleration that may be present. Thus, the z-momentum equation reduces to:

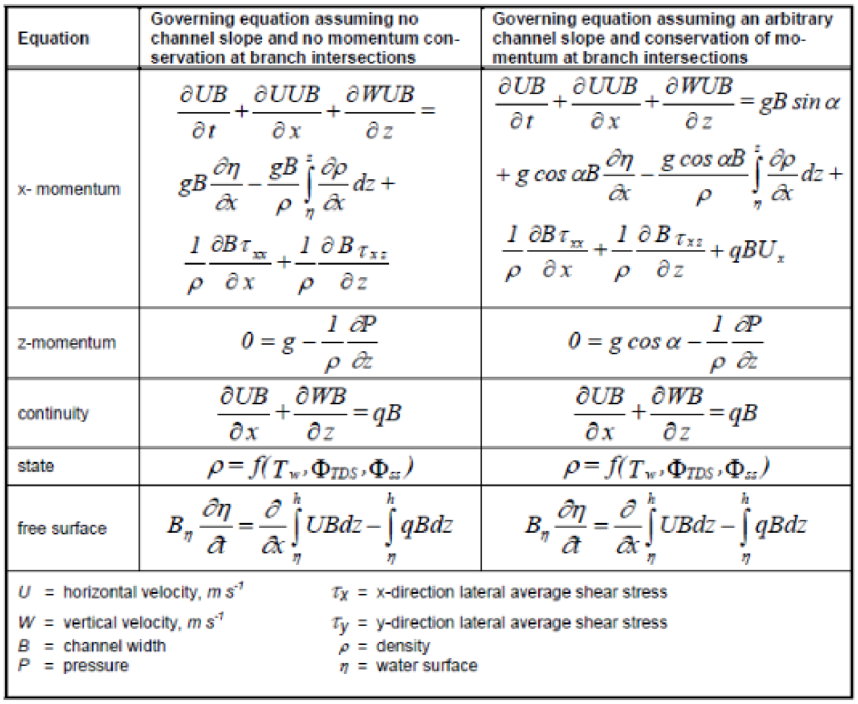
$$g\ \sin\alpha=\frac{1}{\rho}\frac{\partial \bar{p}}{\partial z} \qquad (5)$$

The second simplification is the use of lateral averaging. Lateral averaging is the main limitation of CE-QUAL-W2 and users must judge whether or not this is appropriate for their system. Since lateral variations in velocities, temperatures, and constituents are assumed small, CE-QUAL-W2 is best-suited to systems where the longitudinal variations far outweigh the lateral variations. For this reason, an ideal system for the model is one where length is much greater than width (Cole, et al., 2008). Lateral averaging allows the model to neglect the y-momentum equation altogether.

One additional limitation of CE-QUAL-W2 is the model's inability to represent accelerations that are due to atmospheric changes. This limitation was accepted in order to further simplify the model by considering the atmospheric portion of the total pressure term to be negligible (Cole, et al., 2008).

A summary of the governing equations used in CE-QUAL-W2, reproduced from the User's Manual is provided in Table 3-2 (Cole, et al., 2008).

Table 3-2. Governing Equations for CE-QUAL-W2 (after Table A-1, Cole, et al., 2008).



Equation	Governing equation assuming no channel slope and no momentum conservation at branch intersections	Governing equation assuming an arbitrary channel slope and conservation of momentum at branch intersections
x- momentum	$\frac{\partial UB}{\partial t}+\frac{\partial UUB}{\partial x}+\frac{\partial WUB}{\partial z}=$ $gB\frac{\partial \eta}{\partial x}-\frac{gB}{\rho}\int_{\eta}^{z}\frac{\partial \rho}{\partial x}dz+$ $\frac{1}{\rho}\frac{\partial B\tau_{xx}}{\partial x}+\frac{1}{\rho}\frac{\partial B\tau_{xz}}{\partial z}$	$\frac{\partial UB}{\partial t}+\frac{\partial UUB}{\partial x}+\frac{\partial WUB}{\partial z}=gB\sin\alpha$ $+g\cos\alpha B\frac{\partial \eta}{\partial x}-\frac{g\cos\alpha B}{\rho}\int_{\eta}^{z}\frac{\partial \rho}{\partial x}dz+$ $\frac{1}{\rho}\frac{\partial B\tau_{xx}}{\partial x}+\frac{1}{\rho}\frac{\partial B\tau_{xz}}{\partial z}+qBU_x$
z-momentum	$0=g-\frac{1}{\rho}\frac{\partial P}{\partial z}$	$0=g\cos\alpha-\frac{1}{\rho}\frac{\partial P}{\partial z}$
continuity	$\frac{\partial UB}{\partial x}+\frac{\partial WB}{\partial z}=qB$	$\frac{\partial UB}{\partial x}+\frac{\partial WB}{\partial z}=qB$
state	$\rho=f(T_w,\Phi_{TDS},\Phi_{ss})$	$\rho=f(T_w,\Phi_{TDS},\Phi_{ss})$
free surface	$B_\eta\frac{\partial \eta}{\partial t}=\frac{\partial}{\partial x}\int_{\eta}^{h}UBdz-\int_{\eta}^{h}qBdz$	$B_\eta\frac{\partial \eta}{\partial t}=\frac{\partial}{\partial x}\int_{\eta}^{h}UBdz-\int_{\eta}^{h}qBdz$

U = horizontal velocity, $m\ s^{-1}$
W = vertical velocity, $m\ s^{-1}$
B = channel width
P = pressure
τ_x = x-direction lateral average shear stress
τ_y = y-direction lateral average shear stress
ρ = density
η = water surface

There are 3 different numerical schemes included with CE-QUAL-W2 that address transport of temperature and constituents slightly differently. The QUICKEST scheme is the second oldest and reduces the excessive amount of numerical diffusion that was present in the original UPWIND scheme. The ULTIMATE scheme is the newest, and was developed to eliminate over/undershoots generated by the QUICKEST scheme (Cole, et al., 2008). For the purposes of this study, the ULTIMATE scheme was selected for use.

A consideration of any numerical solution scheme to a set of differential equations is numerical stability. CE-QUAL-W2 uses the following numerical stability criteria to calculate time-steps:

$$\Delta t \leq \frac{1}{2\left(\frac{A_x}{\Delta x^2}+\frac{A_z}{\Delta z^2}\right)+\frac{Q}{V}+\frac{\sqrt{\frac{\Delta \rho g H}{\rho \quad 2}}}{\Delta x}} \qquad (6)$$

where: Δt = timestep
A_x = longitudinal eddy viscosity
A_z = vertical eddy viscosity

Q = total flow into or out of a cell
V = cell volume
g = gravitational acceleration
H = maximum waterbody depth
ρ = water density
$\Delta\rho$ = surface to bottom water density difference

To ensure numerical stability, CE-QUAL-W2 includes an auto-stepping algorithm. The above equation is used to calculate the limits of stability; the results are then compared to the current time-step. If the time-step being used is outside the bounds of the calculated numerical stability, the model resets to the corresponding minimum or maximum time-step (values set by the user in the setup file) and sends an error message indicating the model may become unstable at that point (Cole, et al., 1995).

Output of the model is in the form of a text file and plotting software is not included. Users are encouraged to incorporate after-market plotting software to view their results. For this study, the post-processing capability of Animation and Graphics Portfolio Manager (AGPM), developed by Loginetics, Inc., was used (Hauser, 2011). In addition to the post-processing capability, AGPM includes a bathymetry viewer and an input file generator. The post-processing viewer provides the user the ability to generate time-series plots, animations, and profile-depth plots (Hauser, 2011).

CE-QUAL-W2 Layout

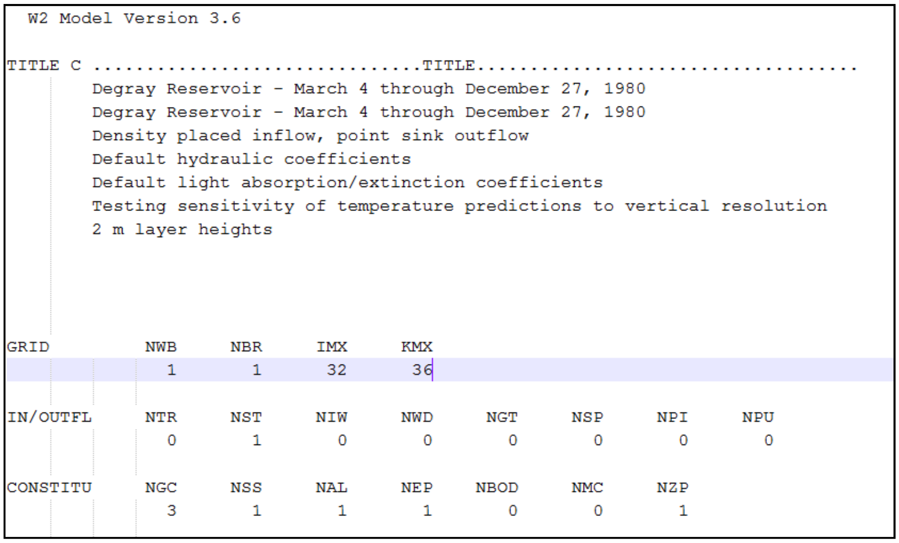
CE-QUAL-W2 uses various text-based input files that are read by the executable file when the model is run. The riverine or reservoir system is first divided into branches, tributaries, and waterbodies. Branches distinguish large bodies of water from one another. For example, the main stem of a river could be one branch with separate branches for storage reservoirs that feed the main stem. A branch must have associated bathymetry and its volume is added to the total volume calculation. CE-QUAL-W2 models must contain at least one branch. Additional branches that connect to the main branch could be used if a user wants to model some or all available parameters in that location. If modeling in a side location is not needed, another option is to use a tributary. A tributary is used to add flow to the main branch but will not add volume to the total volume calculations. Waterbodies are collections of branches to which a user wants to apply similar parameters. Like branches, every CE-QUAL-W2 model must contain at least one waterbody.

For every branch and/or tributary, CE-QUAL-W2 requires an associated input file for temperature, flow, and constituents. Data for these input files can come from a variety of sources. The best source would be actual gauge data, available from USACE, U.S. Geological Survey (USGS), or other similar agencies. Various options exist to generate data based on seasonal and annual averages, available air temperatures, and other methods.

Other assorted input files contain required and additional information. Branches, tributaries, constituents to be modeled, and other parameters are defined in the control file. Bathymetry, meteorological, shading, and wind sheltering information are all contained in their respective input files. All files are text-based, 8-space format and all files are organized into different sections of data. All data should be in metric units.

Input Cards

All input files begin with two lines for file identification. Each input file is then organized into different sections, called cards. Following the initial identification lines, each card consists of groups of three or more lines. The first line is blank for separation. The second, a title line, is not read by the executable. The third line, and subsequent lines if needed, contains the variables, in 8-space ASCII text widths. All input files are described in detail in the User's Manual. The standard example model that is included with the CE-QUAL-W2 model package is that of the Degray Reservoir in Arkansas (Cole, et al., 2008). Figure 3-1 illustrates the beginning of the control file depicting the file identification lines, title card, and the first three variable cards.



```
 W2 Model Version 3.6

TITLE C ..............................TITLE...................................
        Degray Reservoir - March 4 through December 27, 1980
        Degray Reservoir - March 4 through December 27, 1980
        Density placed inflow, point sink outflow
        Default hydraulic coefficients
        Default light absorption/extinction coefficients
        Testing sensitivity of temperature predictions to vertical resolution
        2 m layer heights




GRID         NWB     NBR     IMX     KMX
               1       1      32      36

IN/OUTFL     NTR     NST     NIW     NWD     NGT     NSP     NPI     NPU
               0       1       0       0       0       0       0       0

CONSTITU     NGC     NSS     NAL     NEP    NBOD     NMC     NZP
               3       1       1       1       0       0       1
```

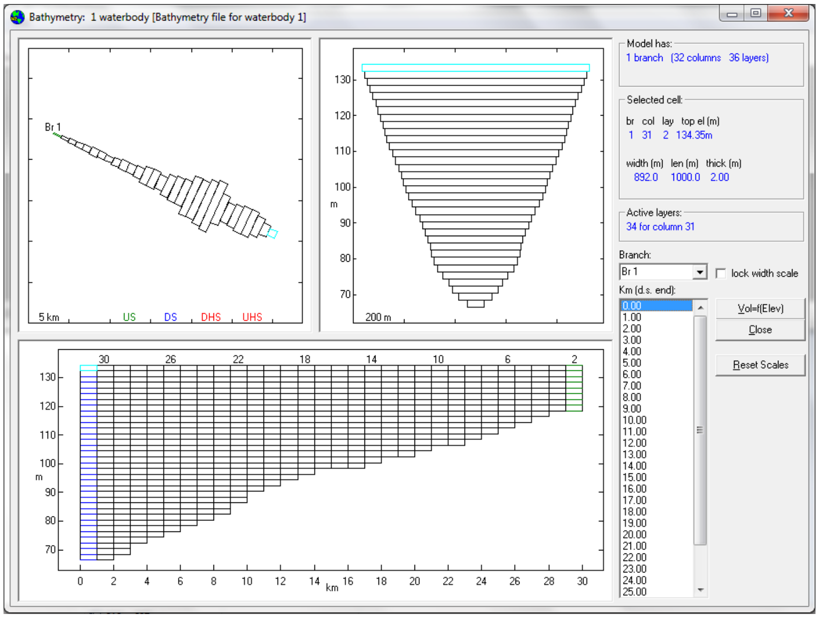
Figure 3-1. Sample Control File (after Cole, et al., 2008).

Control File

The control file represents the main file used in every CE-QUAL-W2 model. It contains all grid definitions, computation methods, initial conditions, variable coefficients, structure definitions, and many other options. File names for each of the input files are also defined in the control file. All cards in the control file are required, although they may be zeroed if not used (Cole, et al., 2008). Most of the changes made during model calibration are done within the control file.

Bathymetry

Development of a CE-QUAL-W2 model begins with bathymetry. Bathymetry is configured into what is known as a computational grid. Since it is a laterally-averaged model, the only lateral data needed is width. Longitudinally, CE-QUAL-W2 is divided into segments. Any number of segments with differing lengths is possible. It is up to the user to determine where segment boundaries should be designated, with more segments providing greater resolution but increased computation time. Like the longitudinal segments, vertically, the computational grid is divided into layers. Layers can also be of varying height with any number possible. Figure 3-2 shows a graphical representation of bathymetry for the Degray Reservoir using the bathymetry viewer included with the W2i package from Loginetics, Inc (Hauser, 2011).



Bathymetry: 1 waterbody [Bathymetry file for waterbody 1]

Model has:
1 branch (32 columns 36 layers)

Selected cell:
br col lay top el (m)
1 31 2 134.35m
width (m) len (m) thick (m)
892.0 1000.0 2.00

Active layers:
34 for column 31

Branch: Br 1

☐ lock width scale

Km (d.s. end):
0.00
1.00
2.00
3.00
4.00
5.00
6.00
7.00
8.00
9.00
10.00
11.00
12.00
13.00
14.00
15.00
16.00
17.00
18.00
19.00
20.00
21.00
22.00
23.00
24.00
25.00

Figure 3-2. Sample Bathymetry File (after Hauser, 2011).

The top-left square shows the north-up overhead view of the segments with the scale shown along the bottom. The top-right square shows the cross-section view of the channel with associated layer heights. The bottom rectangle shows the plan-form view of the segments from left to right and layers from top to bottom.

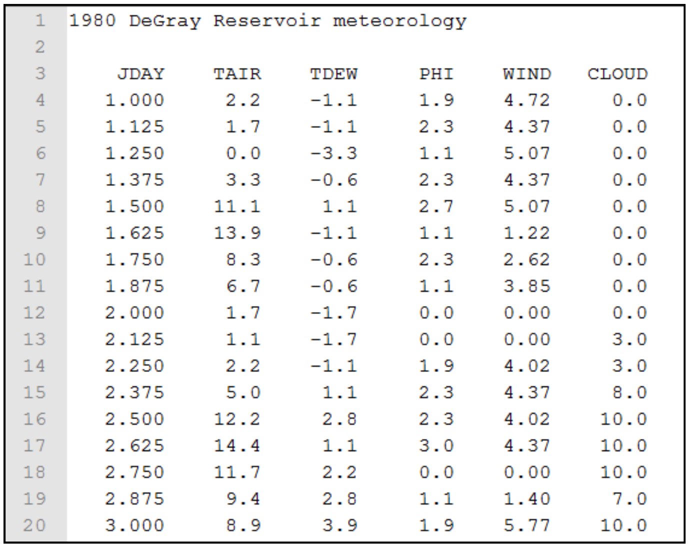
Inflow files

Inflow files are available for use for each branch and tributary in a project. Inflow files contain data for flow, temperature, and constituent loading in a chronological format. CE-QUAL-W2 uses a Julian day format, labeling each day of the year 1 through 365. Users can choose any time step, with hourly or daily being the most common. Irregular time steps are supported as well (Cole, et al., 2008).

Flow files for branches and tributaries contain Julian format time-steps followed by flow in cubic meters per second. Temperature files contain Julian time-steps followed by temperature values in Celsius. Constituent files contain Julian time-steps followed by various constituent values and must be in the same order as defined in the control file. Additional format information for is provided in the User's Manual (Cole, et al., 2008).

Meteorological, Wind Sheltering, and Shading files

A meteorological file is available that uses Julian time-steps, air temperature, dew point temperature, wind direction, wind speed, cloud cover, and short-wave solar radiation (Cole, et al., 2008). All temperatures are in degrees Celsius, wind direction is in radians from North, and wind speed is in meters per second. Cloud cover is in percent of sky covered with values ranging from 0 (no cloud coverage) to 10 (complete cloud coverage). Solar radiation is in Watts per meter squared. Meteorological data is available from many airports and other meteorological information sites. All values are required except solar radiation unless the SROC variable in the control file (the parameter that enables short-wave solar radiation to be read) is set to “ON”. An example meteorological file is shown in Figure 3-3.

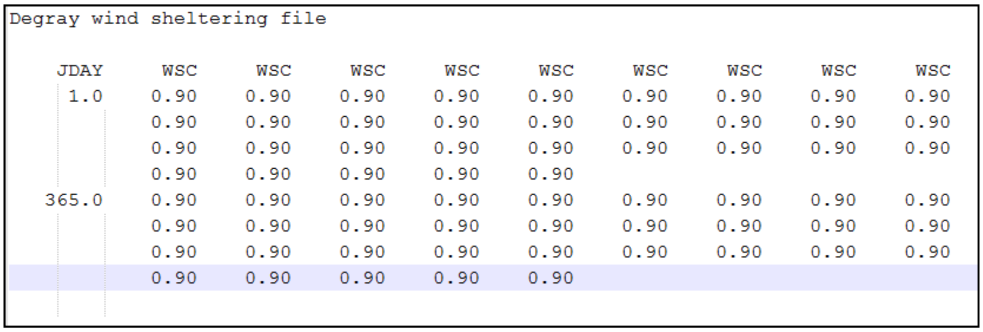


```
1980 DeGray Reservoir meteorology

    JDAY     TAIR     TDEW      PHI     WIND   CLOUD
   1.000      2.2     -1.1      1.9     4.72     0.0
   1.125      1.7     -1.1      2.3     4.37     0.0
   1.250      0.0     -3.3      1.1     5.07     0.0
   1.375      3.3     -0.6      2.3     4.37     0.0
   1.500     11.1      1.1      2.7     5.07     0.0
   1.625     13.9     -1.1      1.1     1.22     0.0
   1.750      8.3     -0.6      2.3     2.62     0.0
   1.875      6.7     -0.6      1.1     3.85     0.0
   2.000      1.7     -1.7      0.0     0.00     0.0
   2.125      1.1     -1.7      0.0     0.00     3.0
   2.250      2.2     -1.1      1.9     4.02     3.0
   2.375      5.0      1.1      2.3     4.37     8.0
   2.500     12.2      2.8      2.3     4.02    10.0
   2.625     14.4      1.1      3.0     4.37    10.0
   2.750     11.7      2.2      0.0     0.00    10.0
   2.875      9.4      2.8      1.1     1.40     7.0
   3.000      8.9      3.9      1.9     5.77    10.0
```

Figure 3-3. Sample Meteorological File (after Cole, et al., 2008).

The wind sheltering file uses Julian time-steps and a wind-sheltering coefficient as its only inputs but it requires a wind-sheltering coefficient value for each segment in a model. Values for each segment are listed as percentages with 0.0 representing 0% of the wind in the meteorological file used per segment and 1.0 representing 100% of the wind in the meteorological file used per segment. An example wind sheltering file is shown in Figure 3-4.

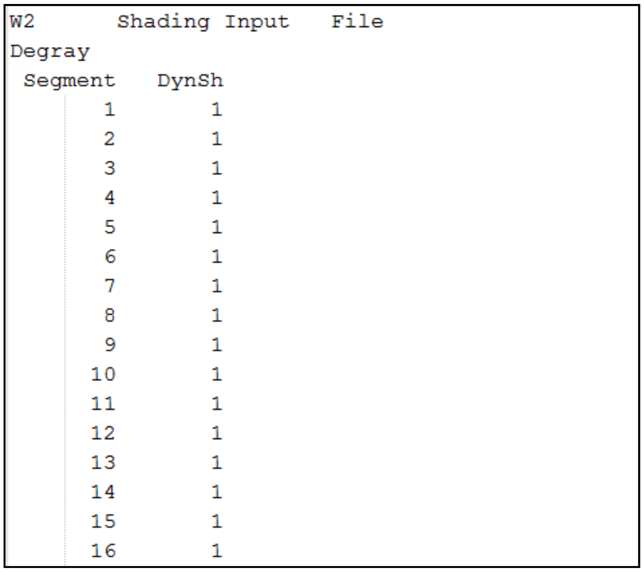


```
Degray wind sheltering file

    JDAY     WSC     WSC     WSC     WSC     WSC     WSC     WSC     WSC     WSC
     1.0    0.90    0.90    0.90    0.90    0.90    0.90    0.90    0.90    0.90
            0.90    0.90    0.90    0.90    0.90    0.90    0.90    0.90    0.90
            0.90    0.90    0.90    0.90    0.90    0.90    0.90    0.90    0.90
            0.90    0.90    0.90    0.90    0.90
   365.0    0.90    0.90    0.90    0.90    0.90    0.90    0.90    0.90    0.90
            0.90    0.90    0.90    0.90    0.90    0.90    0.90    0.90    0.90
            0.90    0.90    0.90    0.90    0.90    0.90    0.90    0.90    0.90
            0.90    0.90    0.90    0.90    0.90
```

Figure 3-4. Sample Wind Sheltering File (after Cole, et al., 2008).

The Shade input file allows users to adjust for vegetative and topographic shading with a variety of inputs. For the purposes of this study, the shading file was used for static shading with values for Julian date and a percentage, similar to wind sheltering. Values for static shading are applied to all segments and are listed as percentages with 0.0 representing 0% of the solar radiation reaching the water surface and 1.0 representing 100% of the solar radiation reaching the water surface. An example shade input file is shown in Figure 3-5.



```
W2      Shading Input   File
Degray
 Segment   DynSh
       1       1
       2       1
       3       1
       4       1
       5       1
       6       1
       7       1
       8       1
       9       1
      10       1
      11       1
      12       1
      13       1
      14       1
      15       1
      16       1
```

Figure 3-5. Sample Shade Input File (after Cole, et al., 2008).

CHAPTER IV

MODEL DEVELOPMENT

Previous Models

The first known numerical model of the Cheatham Reservoir was completed in 1989 for USACE. Known as BETTER, the model is a 2-dimensional water quality model that simulates flow, mixing, temperature, stratification, and residence time of reservoirs (Brown, et al., 1989).

Given the computing power available in 1989, the resolution of the BETTER model was limited. In the BETTER model, the entire Cheatham Reservoir was divided into 19 columns and 9 layers of differing measurements. Eight inflows and one outflow were included. What it lacked in resolution, the BETTER model made up for in processing speed. On an 80286 processor with a 10 MB hard drive and 640k RAM, a one-year simulation required between 15 and 17 minutes (Brown, et al., 1989).

In 2003, a CE-QUAL-W2 version 3.1 model was developed for use as part of a Spill Management Information System within the Cheatham Reservoir (Martin, 2003). This model's purpose was not for extensive evaluation of the Cheatham Reservoir, but to create a working CE-QUAL-W2 model from which to construct a spill management information system. For this reason, the bathymetry and other input files were a rough representation.

Current Model Development

The current model is based on the 2003 model developed in a thesis by Paul H. Martin (Martin, 2003). However, since that version's main use was to further develop a spill management system, it lacked some of the detail required for this model. For this reason, and because it was written in version 3.1, all input files for the current project were re-written. The purpose of this project is to model the Cheatham Reservoir as accurately as possible for follow-on use in the overall USACE Cumberland River model. Accordingly, the focus on setup and calibration, assumptions made, and methods to develop data for lacking areas are explained in detail.

To evaluate the accuracy of the results produced by the model, this report uses absolute mean error (AME) as the statistical method. Absolute mean error is computed as follows:

$$AME = \frac{\sum |Predicted - Observed|}{number\ of\ observations} \tag{7}$$

Although other methods are available, AME provides a good indication of model performance (Cole and Wells, 2008). An AME of 0.5 indicates data are, on average, within ± 0.5 of observed values. In addition to AME, root mean square (RMS) indicates how far the computed values deviate from the observed data (Cole, et al., 1997). RMS is defined as:

$$RMS = \sqrt{\frac{\sum (Predicted - Observed)^2}{number\ of\ observations}} \tag{8}$$

Cole and Tillman provided the example that an RMS error of 0.5 indicates that 67% of the predicted data are within ± 0.5 of the observed data (Cole, et al., 1997). These statistics are calculated and included in the results in this report.

Control File

The construction of the computational grid for the Cheatham system is defined in the control file. All branches, tributary connections, and structure connections are defined in the first portion. The remaining portions define computational parameters, initial conditions, and many constituent coefficients.

The main stem of the Cheatham Reservoir is defined as Branch 1. Similar to the 2003 model, the segment lengths for Branch 1 are 400 meters each. Therefore, 273 segments were required to model the river from Old Hickory Dam to Cheatham Dam. A link must be made to the J. Percy Priest Reservoir to be able to include this project into the overall Cumberland River project at a later date. Historically, the Stones River has been a focus of water quality improvement efforts by USACE (Gregory, 2011). Using a tributary to link these portions, however, would not allow modeling of water quality constituents. For these reasons, this portion of the Stones River must be modeled as a branch, with included bathymetry, and in this project it is defined as Branch 2. Branch 2 links to Branch 1 at Segment 41 and contains 17 segments. A view of the bathymetry is shown in Figure 4-1.

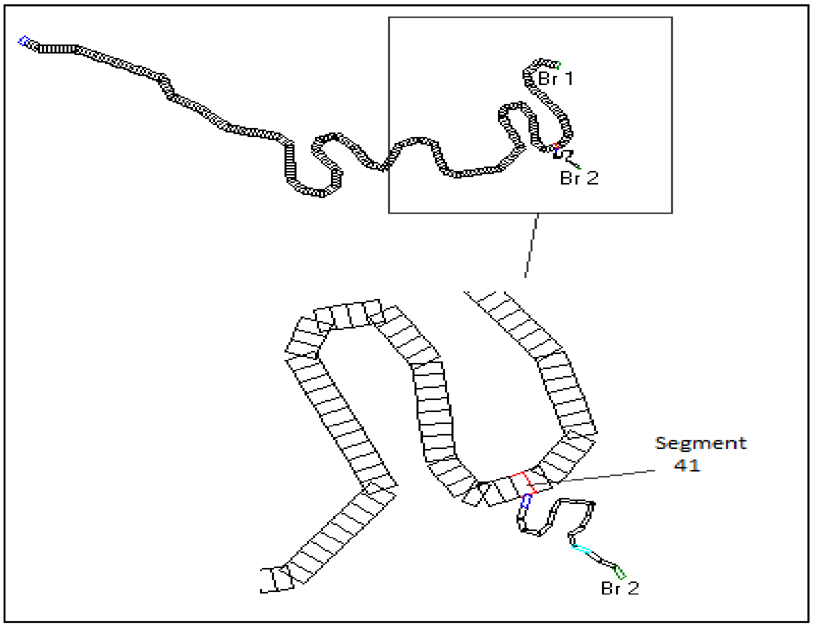


Figure 4-1. Cheatham Model Bathymetry

Branches 1 and 2 both use zero slope. Two options exist within CE-QUAL-W2 to model river slope. The first, and the method used in this project, is to model the slope within the bathymetry file. The second method is to define an average slope within the control file. If doing this, a second set of equations, shown in Table 3-2, are used to calculate momentum. This method has been used much less frequently and is still being developed (Cole, et al., 2008). Future versions of this model may use this option.

The main inflow to the Cheatham Reservoir is the outflow of the Old Hickory Dam. The Old Hickory Dam discharges water in two ways: by turbine generation and through the spillway gates. Turbine generation provides the majority of the volume released. Hourly flow values, supplied by USACE, were used in the Branch 1 flow input file, qin_br1. Releases from spillways represent less volume and are discharged from approximately 30 feet below the surface (U.S. Army Corps of Engineers, 1998). Although temperature data was available from a logger in the tailwater, and was used as inputs for temperature in this model, the constituent concentrations may be different because of the different discharge locations. Using a branch and tributary separately preserves the option to include different constituent files in the future. Hourly flow values for the spillway discharges were used in a tributary file to Branch 1, qtr_tr1.

Many different parameters are available to the user in the control file. Most of these were set to the defaults, described in the User's Manual (Cole, et al., 2008). However, select key parameters are described here.

PQC, part of the CALCULAT card, addresses inflow placement. The two options available are to distribute the inflow uniformly or to place inflows based on density. Initially this parameter was set to place inflows based on density but checked during calibration to examine its effect on temperature and constituent calibrations.

AFW is one of three variables used in the wind function shown below (Cole, et al., 2008):

$$f(W_z) = AFW + BFW\ W_z^{CFW} \tag{9}$$

BFW and CFW can be changed but AFW has the largest effect and can be thought of as evaporative cooling. Initially, this term was set to the default of 9.2 but was adjusted during the calibration phase.

WINDH is used to specify the height at which wind speed measurements were taken for the meteorological file. This number has a direct impact upon wind calculations that affect evaporation and temperature. The Nashville International Airport, the location used in this model, reports that wind height measurements are taken at 182.9 meters above mean sea level. The normal summer pool elevation of the Cheatham Reservoir is 385 ft (117.37 meters) above mean sea level. Considerable error may be induced with the use of WINDH because of the differences in elevation and because there is only one value available that is used across the entire reservoir. Initially this value was set to 2 meters but was adjusted during calibration.

AX and DX are used to specify the horizontal eddy viscosity and diffusivity. Default values for these variables were used initially and are both 1.0 m^2 sec^{-1}. These values were also adjusted during calibration.

TSED is used to set the sediment temperature and is used for all segments in a model. This term is used in the heat exchange calculation at the ground-water interface. The User's Manual states that this parameter can be approximated by the average air temperature in the area of the system to be modeled (Cole, et al., 2008). From the Nashville International Airport data for 2009, the average air temperature was calculated to be 14.8 °C and that was the value used in this model.

AZMAX is used to set the maximum value for vertical eddy viscosity. The User's Manual suggests setting a value of 1 m^2 s^{-1} for a river and this value was used initially (Cole, et al., 2008). However, during calibration it was adjusted to vary viscosity between layers.

STR ELEV, STR SINK, and STR WIDTH are used to specify the elevations, widths, and types of structures in a model (Cole, et al., 2008). For the Cheatham Reservoir, the structures to be modeled are the turbine and spillway gates at Cheatham Dam. These parameters have an impact on the temperature of water being released from the system and the overall system stratification. From the Cheatham Water Control Manual, supplied by USACE, the midpoint elevation of the turbine intakes is 362 ft (110.4 meters) above mean sea level (U.S. Army Corps of Engineers, 1998). The crest of the spillway gates is 359 ft (109.45 meters) above mean sea level (U.S. Army Corps of Engineers, 1998). These were used as the values for STR ELEV for the turbine and spillway gates respectively. STR SINK has two options: LINE and POINT. The User's Manual states LINE is used for structures that are wide in relation to the dam and POINT is used for structures that are narrow in relation to the dam (Cole, et al., 2008). For this model, a LINE was used for the spillway gates and a POINT was used for the turbine output. STR WIDTH only applies to LINE structures and the Cheatham Water Control Manual shows the seven spillway gates are each 60 feet (18.3 meters) giving a total of 420 feet (128 meters) (U.S. Army Corps of Engineers, 1998). STR WIDTH for the spillway gates was set to 128 meters.

Bathymetry

The first step in the development of the Cheatham Reservoir model was to develop bathymetry. USACE supplied, upon request, a River Analysis System (RAS) model for the Cheatham reach of the Cumberland River. Included in that model were data from past sediment surveys conducted by USACE (Moran, 2011).

In the 2003 model of the Cheatham Reservoir, the author used 400 meter segments and 1 meter layer heights. Early in the bathymetry development, the initial results showed a need for more resolution and the layer heights were changed to 0.5 meters. The run times for the model with 0.5 meter layer heights were approximately 12 hours. Upon closer examination of USACE sampling data, it was learned that the Cheatham Reservoir is a relatively well-mixed reservoir year-round. Because of this, and the long run times, the layer heights were reset to 1 meter and the run times returned to approximately 4 hours with little to no reduction in resolution.

The sediment survey data showed bathymetry information available approximately each river mile. From that data an initial bathymetry file was developed by replicating the sediment survey data for each 400 meter segment until the next set of data was available.

The Cheatham Reservoir Water Control Manual, supplied by USACE, provides daily operational requirements and restrictions on the operation of the Cheatham Reservoir (U.S. Army Corps of Engineers, 1998). It is used by the water managers to develop generation schedules for the reservoir that will comply with the pool restrictions set forth by USACE when the Cheatham Dam was constructed (U.S. Army Corps of Engineers, 1998). The manual also provides volumes per foot of elevation for the Cheatham drainage basin (U.S. Army Corps of Engineers, 1998). Since the volume data is listed in feet above mean sea level, a conversion to metric units was required. To aid in the conversion, the data was first changed to metric units and plotted.

Table 4-1 shows the values for volumes and the corresponding elevations for the Cheatham Reservoir (U.S. Army Corps of Engineers, 1998). For this study, elevations at 1 and 0.5 meter increments were required. In order to generate these values, the above data were plotted and fit to a fourth-order polynomial using Microsoft Excel. The equation for the trend-line and corresponding R^2 value are shown in Figure 4-2 (Microsoft, 2007).

Table 4-1. Cheatham Reservoir Volumes and Elevations.

El (ft)	El (m)	V(ac-ft)	V (Mm^3)
400	121.9512	299000	369.09446
399	121.6463	281000	346.87473
398	121.3415	262000	323.42056
397	121.0366	246000	303.66969
396	120.7317	229000	282.68439
395	120.4268	214000	264.16794
394	120.122	200000	246.88593
393	119.8171	186000	229.60391
392	119.5122	173000	213.55633
391	119.2073	161000	198.74317
390	118.9024	150000	185.16445
389	118.5976	139000	171.58572
388	118.2927	129000	159.24142
387	117.9878	120000	148.13156
386	117.6829	111000	137.02169
385	117.378	104000	128.38068
384	117.0732	96500	119.12246
383	116.7683	90000	111.09867
382	116.4634	84200	103.93898
381	116.1585	78600	97.026169
380	115.8537	73700	90.977464
379	115.5488	68700	84.805316
378	115.2439	64500	79.620712
377	114.939	60000	74.065778
376	114.6341	56100	69.251503
375	114.3293	52200	64.437227
374	114.0244	48400	59.746394
373	113.7195	44800	55.302448
372	113.4146	41200	50.858501
371	113.1098	38000	46.908326
370	112.8049	34700	42.834708
369	112.5	31800	39.254862
368	112.1951	28700	35.428131
367	111.8902	26000	32.095171
366	111.5854	23200	28.638768
365	111.2805	20500	25.305808
364	110.9756	18300	22.590062
363	110.6707	15900	19.627431
362	110.3659	13800	17.035129
361	110.061	11500	14.195941
360	109.7561	9800	12.09741

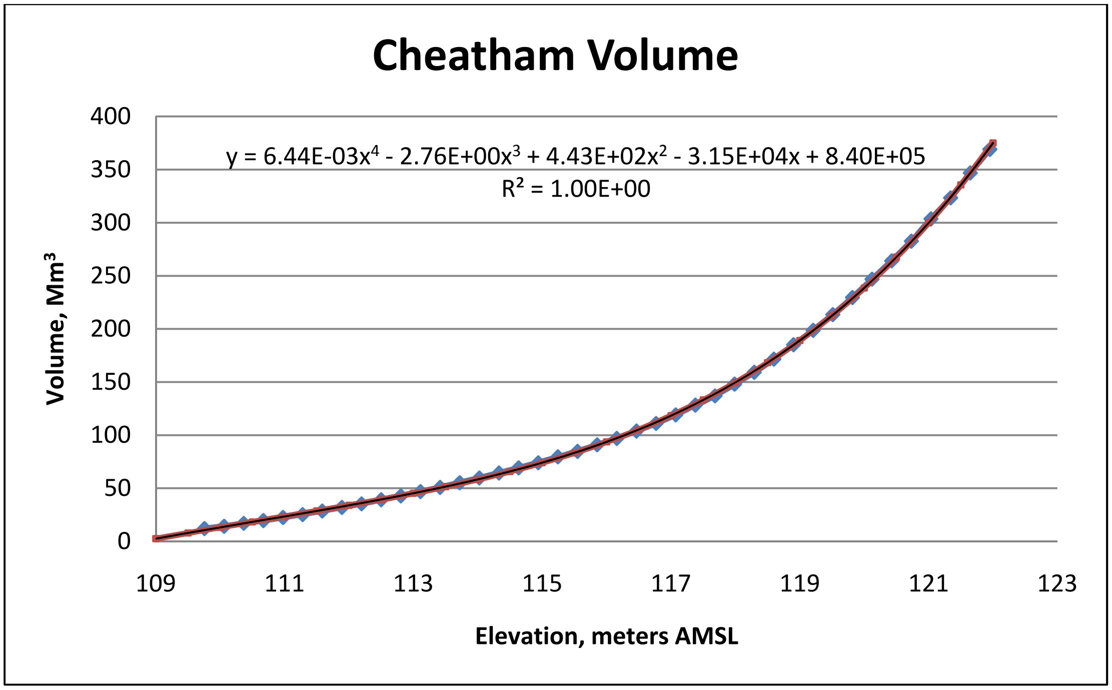


Figure 4-2. Volume trendline.

Using this equation, values for metric integer elevation were generated as illustrated in Table 4-2.

Table 4-2. Cheatham Reservoir Volumes.

El (m)	V (Mm^3)
122	375.088
121.5	335.595
121	299.858
120.5	267.603
120	238.567
119.5	212.495
119	189.143
118.5	168.277
118	149.671
117.5	133.110
117	118.389
116.5	105.311
116	93.689
115.5	83.349
115	74.121
114.5	65.849
114	58.385
113.5	51.591
113	45.339
112.5	39.509
112	33.994
111.5	28.692
111	23.515
110.5	18.382
110	13.223
109.5	7.977
109	2.592

To assist with bathymetry development, a second MS Excel spreadsheet was used that calculated the total volume of each 1 meter layer by multiplying each layer width by 400 meters and then summing the entire layer. To match the volumes, the bathymetry was adjusted by trial and error and compared to each layer volume calculated earlier. Closely matching the known volumes of the water control manual is important to complete the water balance as it has a great impact on model water temperatures (Cole, et al., 2008). Figure 4-3 shows a plot of elevation versus volume for the Water Control Manual and the Model. The Water Control Manual values are plotted with a diamond and the model values are plotted with circles.

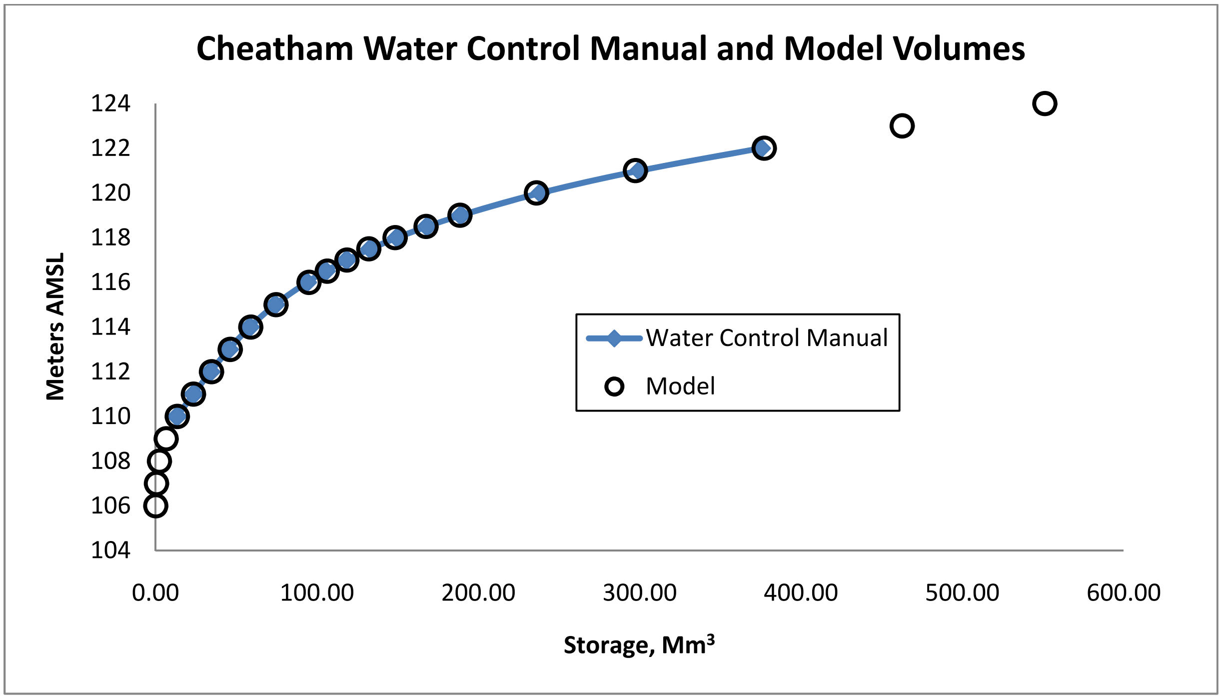


Figure 4-3. Water Control Manual and model volumes.

The bathymetry was adjusted until the circles matched the diamonds for each elevation. Values below 110 meter elevation and above 122 meter elevation are interpolated since the range of values in the Cheatham Water Control Manual lie within these bounds (U.S. Army Corps of Engineers, 1998). The model volumes match the Water Control Manual to within 0.59 Mm^3 AME.

Inflow Regression

Gauged data provides actual measured inflows and outflows at various locations and, thus, is used in the model whenever available. However, for some inflows, only partial records are available and, in some cases, no records are available. Possible options to fill in missing data include using stream data from similar sized streams where data is available or to use a regression technique to generate data. In the cases where flow data is incomplete, or non-existent, multiples of existing stream data, based on volume, were used. This technique is described in more detail in the Tributaries section. For incomplete or non-existent temperature or dissolved oxygen data, the technique used is described below.

The main inputs required for this model are flow, temperature and dissolved oxygen. Different methods have been developed to estimate stream temperatures and dissolved oxygen from available air temperatures. One method uses the concept of equilibrium temperature, a theoretical surface temperature at which the net rate of heat exchange is zero (Edinger, et al., 1968). Other methods have been developed for fish habitat studies which only require weekly averages or maximum daily or weekly averages (Mohseni, et al., 1998) (Caissie, et al., 2001). Still other methods generate weekly or daily temperatures (Stefan, et al., 1993).

USACE has developed a method to generate water temperature and dissolved oxygen values based on daily average air temperatures and has used it successfully in a CE-QUAL-W2 model of the Center Hill Reservoir near Nashville, TN (Gregory, 2011). This method uses known period of record air temperatures to calculate a yearly average and then calculates *air temperature residuals* that are regressed to generate daily water temperature values using a two-day delay.

Beginning with air temperature, a daily average was calculated in Julian day format from the period of record from 1948 to present, as shown in Figure 4-4, for Nashville, TN. The daily average was fit to an equation of the form

$$T(t) = \overline{T} + a\ \sin(\frac{2\pi}{365}t + \theta) \tag{10}$$

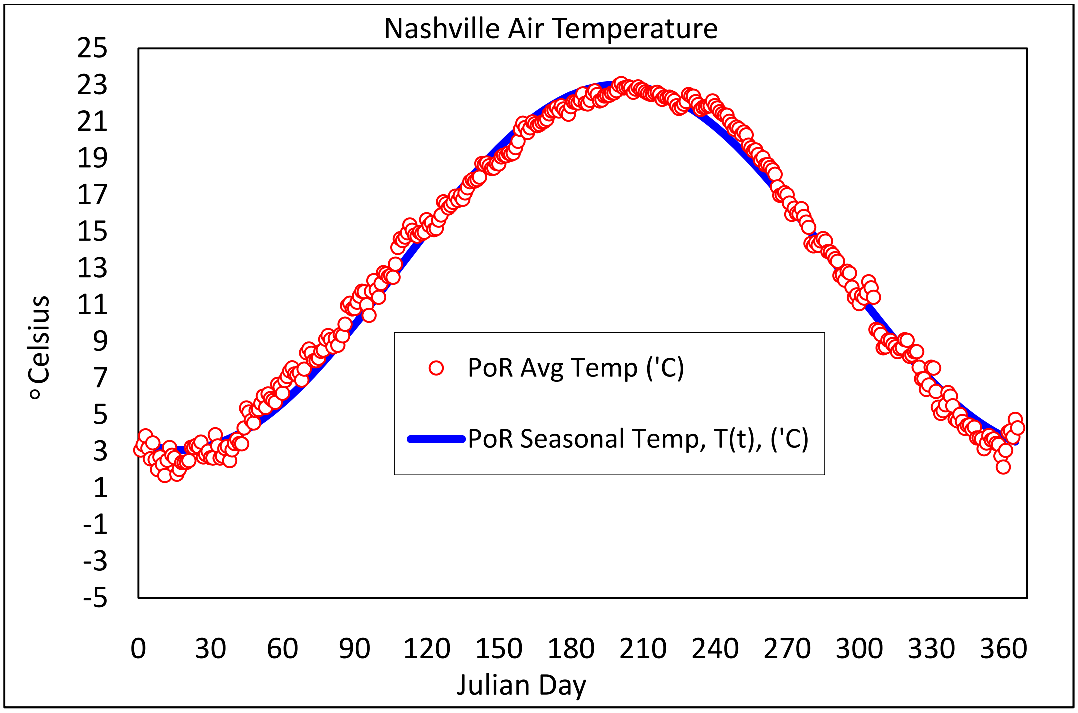


Figure 4-4. Nashville Daily Average Air Temperatures.

Values for the coefficients were obtained using the Solver function of MS Excel to minimize the RMS error (Microsoft, 2007). After substituting into equation 10, the Nashville average yearly air temperature was represented by the following:

$$T_a(t) = 13.05 + 9.96\ \sin\left(\frac{2\,\pi}{365}\ t - \ 1.87\right) \qquad (11)$$

RMS = 0.68

The next step is to apply this same process to water temperature records. For this example, Mill Creek temperature data was used. Again, MS Excel Solver was used to minimize the RMS error in the daily averages and calculate the coefficients. The following equation, using the calculated coefficients, represents the daily seasonal Mill Creek Water Temperature:

$$T_w(t) = 16.15 + 9.40\ \sin\left(\frac{2\,\pi}{365}\ t - \ 1.89\right) \qquad (12)$$

RMS = 1.71

The greater RMSE value results from fewer total sample values. A plot of the data and the line generated from the equation is shown in Figure 4-5.

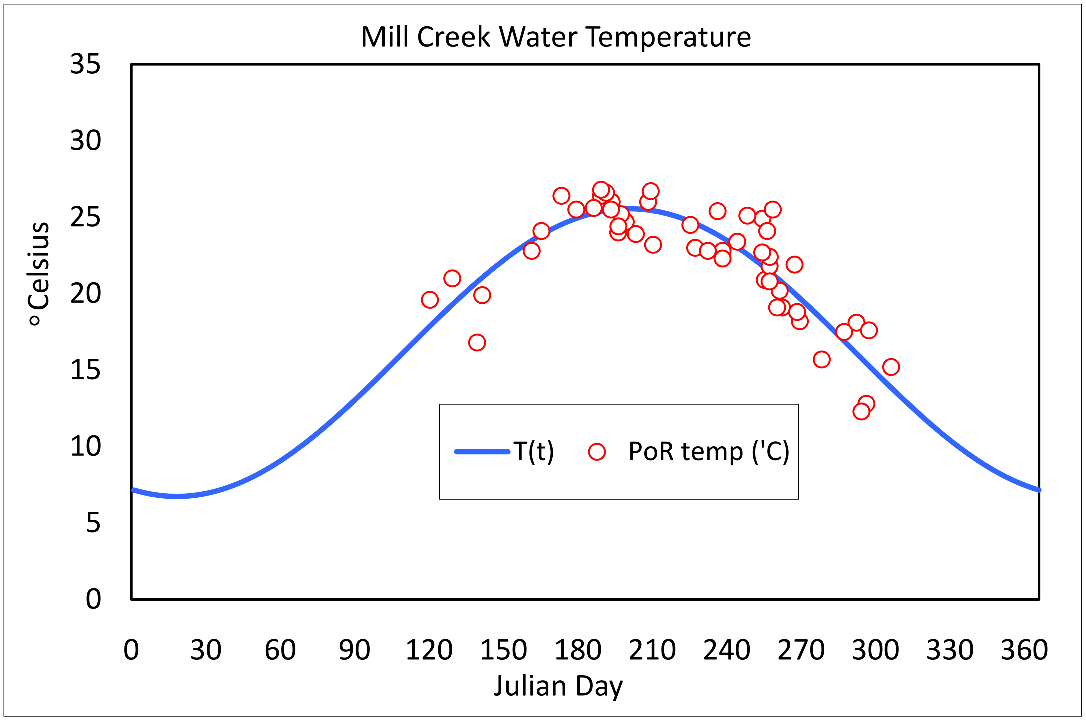


Figure 4-5. Mill Creek Daily Water Temperatures.

Next, an air temperature residual, ATR(t), was calculated for each Julian day of available sample data. This value represents the difference between the daily average air temperatures for the model year (2009 in this case) and the average air temperatures for the entire period of record. Similarly, a water temperature residual, WTR(t), was calculated for each day in 2009 in which sampling data was available.

A least squares line is a line that minimizes the sum of the squares of the residuals (Lay, 1998), and the following general equation (Lay, 1998),

$$y_{n=}\ \beta_0 + \beta_1 x_{1n} + \beta_2 x_{2n} \qquad (13)$$

can be represented in matrix form as (Lay, 1998):

$$y = \begin{bmatrix} y_1 \\ \vdots \\ y_n \end{bmatrix}, X = \begin{bmatrix} 1 & x_{1a} & x_{2a} \\ \vdots & \vdots & \vdots \\ 1 & x_{1n} & x_{2n} \end{bmatrix}, \beta = \begin{bmatrix} \beta_0 \\ \vdots \\ \beta_2 \end{bmatrix} \tag{14}$$

Applying this idea to the current system, for each period of record water sample, there is a corresponding seasonal water temperature. The difference between the two represents the water temperature residual. Therefore, the calculated water temperature residual from above can be represented as

$$\mathrm{WTR(t)} = \beta_0 + \beta_1 \mathrm{ATR(t)} + \beta_2 \mathrm{ATR(t-1)} + \beta_3 \mathrm{ATR(t-2)} \tag{15}$$

where:

$$\mathrm{y} = \begin{bmatrix} \mathrm{WTR(t)}_1 \\ \vdots \\ \mathrm{WTR(t)}_n \end{bmatrix}, \mathrm{X} = \begin{bmatrix} 1 & \mathrm{ATR(t)}_1 & \mathrm{ATR(t-1)}_1 & \mathrm{ATR(t-2)}_1 \\ \vdots & \vdots & \vdots & \vdots \\ 1 & \mathrm{ATR(t)}_n & \mathrm{ATR(t-1)}_n & \mathrm{ATR(t-2)}_n \end{bmatrix}, \beta = \begin{bmatrix} \beta_0 \\ \vdots \\ \beta_3 \end{bmatrix}$$

Solving this system of equations results in a single equation for seasonal water temperature residual and values for the coefficients β_0, β_1, β_2, β_3,, as shown:

$$WTR(t) = -2.04 + 0.09\, ATR(t) + 0.43\, ATR(t-1) + 0.03\, ATR(t-2). \tag{16}$$

Using equation 16, water temperature residuals were calculated for Julian days 1 through 365. Water temperature values for each Julian day can then be calculated using equation 17, where T_w is defined in equation 12.

$$WT(t) = T_w + WTR(t). \tag{17}$$

This approach approximates water temperature values based on known air temperature values. The effect is to mimic the slower change in water temperature as compared to air temperature, due to the difference in heat capacities. For Mill Creek, values are shown in Figure 4-6. The dashed line represents air temperature, the solid line represents water temperature, and the dots are plotted field samples.

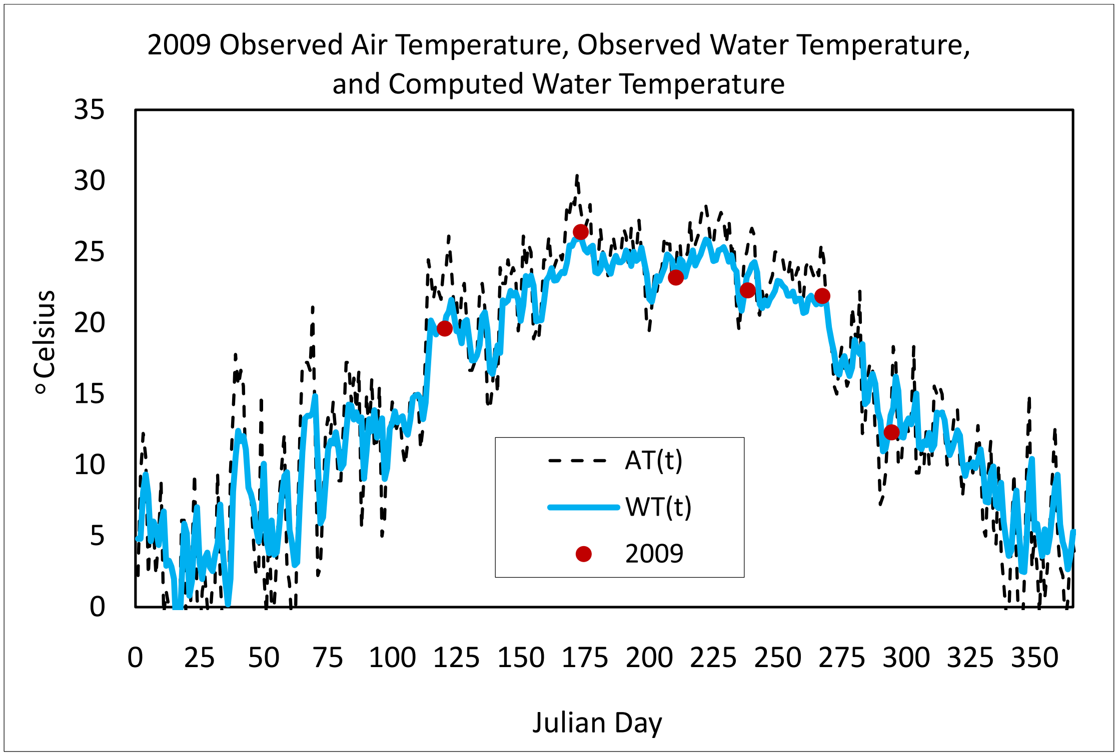


Figure 4-6. Mill Creek Water Temperatures versus Air Temperatures.

To approximate daily dissolved oxygen values, it was assumed that inflows ranged from 80% to 100% of saturation and a trial and error between those values can be applied to fit the field data. Saturation was calculated from Mortimer's formulation (Cole, et al., 2008):

$$\varphi_{O2Sat} = P_{alt}e^{(7.7117-1.31403[ln\{T+45.93\}])} \tag{18}$$

where: T = Water Temperature, °C

P_{alt} = altitude correction factor = $\left(1-\frac{H}{44.3}\right)^{5.25}$

H = elevation of the water body, km, above sea level

Calculated dissolved oxygen values for Mill Creek are shown in Figure 4-7.

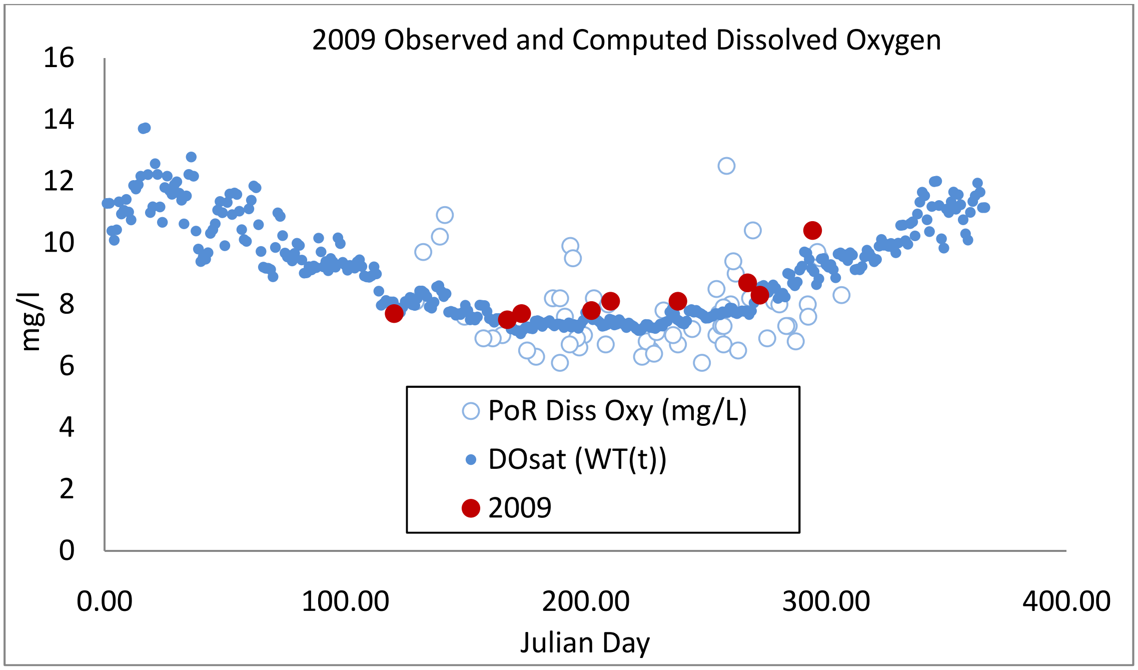


Figure 4-7. Mill Creek Dissolved Oxygen Values.

Actual temperature and dissolved oxygen gauge data were available from USGS Gauge No. 03431060 located at N36 07 03.06, W86 43 08.58. Regression data plotted with actual gauge data for 2009 is shown in Figure 4-8 and Figure 4-9. For this example, the regression method predicts stream values well, showing absolute mean error values of 1.59 °Celsius and 0.62 milligrams per liter, respectively.

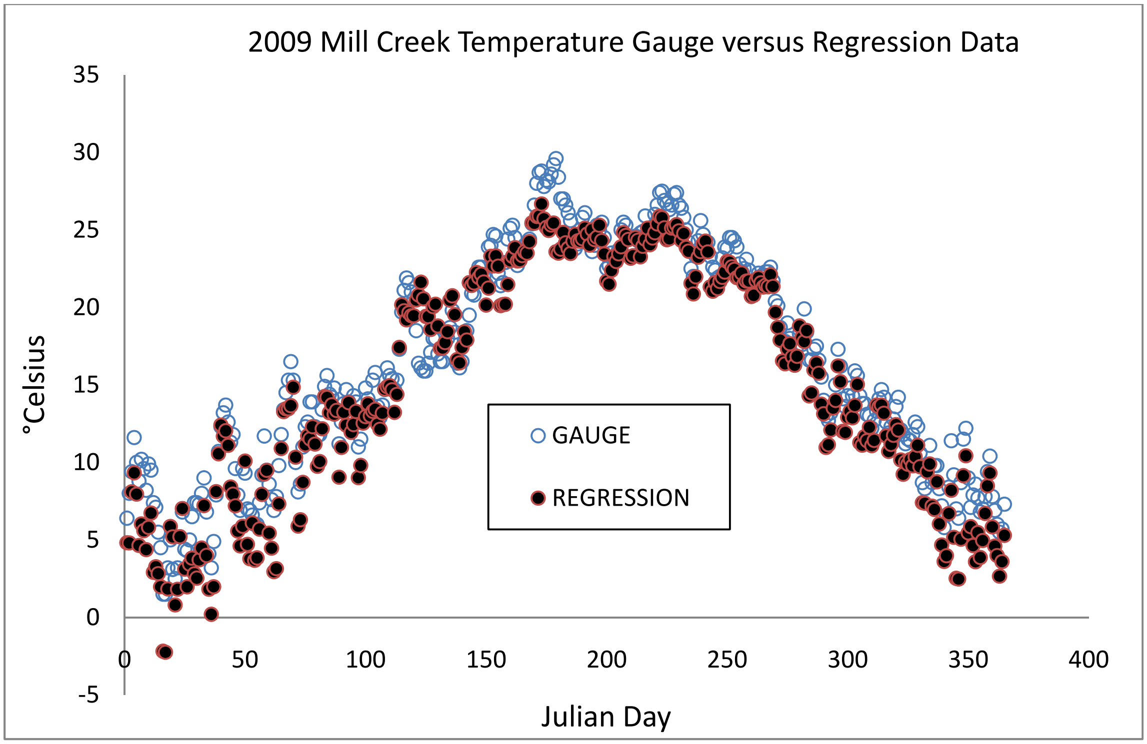


Figure 4-8. Mill Creek Temperature Gauge versus Regression Data.

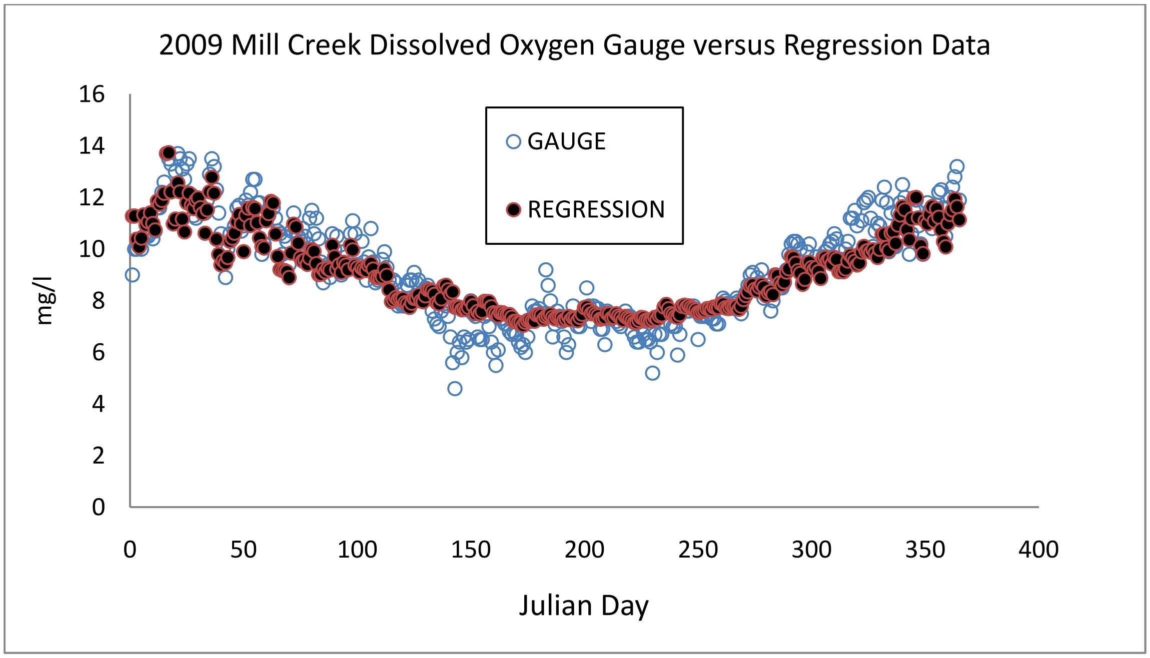


Figure 4-9. Mill Creek Dissolved Oxygen Gauge versus Regression Data.

Old Hickory Inflow

Hourly discharge data for Old Hickory turbines and spillway gates were provided by USACE. This data was converted from cubic feet per second to cubic meters per second and used directly. The QINIC variable in the INTERPOL card, in the control file, allows users to specify whether to use changes in inflow as step functions or to average their values over the given time-step. If data was available at a gauge, for example, interpolation would be used since the values do not actually change instantly (they are measured instantly) at each new timestep. Since the flows in this project are from a dam, and do change instantly at each timestep with gate or turbine changes, this variable was set to OFF.

Temperature data from Old Hickory was available in hourly increments from Julian Day 63 through 313. This data availability was viewed as adequate since the sampling days to which the model was calibrated begin on Julian day 120 and end on Julian day 294. However, to complete the remaining days with reasonable values, a regression was run, as described in the Inflow Regression Section, using Old Hickory tailwater sample data.

The overall focus of this modeling effort is to accurately predict temperature and dissolved oxygen for improved water quality modeling and more informed water management decisions. Equation (19) (reproduced from the User's Manual (after Cole, et al., 2008)) represents the method used by CE-QUAL-W2 to calculate dissolved oxygen.

$$
\begin{aligned}
S_{DO} = {} & \underbrace{\sum \left(K_{ag} - K_{ar}\right)\delta_{OMa}\,\Phi_{a}}_{\text{algal net production}} + \underbrace{\sum \left(K_{eg} - K_{er}\right)\delta_{OMe}\,\Phi_{e}}_{\text{epiphyton net production}} + \underbrace{A_{sur}\,K_{L}\left(\Phi'_{DO} - \Phi_{DO}\right)}_{\text{aeration}} \\
& - \underbrace{K_{RPOM}\,\delta_{OM}\,\gamma_{OM}\,\Phi_{RPOM}}_{\text{refractory POM decay}} - \underbrace{K_{LPOM}\,\delta_{OM}\,\gamma_{OM}\,\Phi_{LPOM}}_{\text{labile POM decay}} - \underbrace{K_{LDOM}\,\gamma_{OM}\,\delta_{OM}\,\Phi_{LDOM}}_{\text{labile DOM decay}} \\
& - \underbrace{K_{RDOM}\,\delta_{OM}\,\gamma_{OM}\,\Phi_{RDOM}}_{\text{refractory DOM decay}} - \underbrace{K_{s}\,\delta_{OM}\,\gamma_{OM}\,\Phi_{sed}}_{\text{1st-order sediment decay}} - \underbrace{SOD\,\gamma_{OM}\,\frac{A_{sed}}{V}}_{\text{0-order SOD}} \\
& - \underbrace{\sum K_{CBOD}\,R_{CBOD}\,\Theta^{T-20}\,\Phi_{CBOD}}_{\text{CBOD decay}} - \underbrace{K_{NH4}\,\delta_{NH4}\,\gamma_{NH4}\,\Phi_{NH4}}_{\text{nitrification}} + \underbrace{\sum \left(K_{mg} - K_{mr}\right)\delta_{OMmac}\,\Phi_{macro}}_{\text{macrophyte net production}} \\
& \underbrace{- \sum \gamma_{zoo}\,K_{zr}\,\delta_{OMzoo}\,\Phi_{zoo}}_{\text{zooplankton respiration}}
\end{aligned}
\tag{19}
$$

where:
δ*OMa* = oxygen stoichiometric coefficient for algal organic matter
δ*OMe* = oxygen stoichiometric coefficient for epiphyton organic matter
δ*OMmac* = oxygen stoichiometric coefficient for macrophyte organic matter
δ*OM* = oxygen stoichiometric coefficient for organic matter
δ*NH4* = oxygen stoichiometric coefficient for nitrification
δ*OMzoo*= oxygen stoichiometric coefficient for zooplankton
γ*NH4* = temperature rate multiplier for nitrification
γ*OM* = temperature rate multiplier for organic matter decay
γ*zoo* = temperature rate multiplier for zooplankton
RBOD = conversion from CBOD in the model to CBOD ultimate
Θ = BOD temperature rate multiplier
V = volume of computational cell
T = temperature
Ased = sediment surface area
Asur = water surface area
Kag = algal growth rate
Kar = algal dark respiration rate
Keg = epiphyton growth rate
Ker = epiphyton dark respiration rate
Kmg = macrophyte growth rate
Kmr = macrophyte dark respiration rate
Kzr = zooplankton respiration rate
KNH4 = ammonia decay (nitrification) rate
KLDOM = labile DOM decay rate
KRDOM = refractory DOM decay rate
KLPOM = labile POM decay rate
KRPOM = refractory POM decay rate
KBOD = CBOD decay rate
Ksed = sediment decay rate
SOD = sediment oxygen demand
KL = interfacial exchange rate for oxygen
Φ*NH4* = ammonia-nitrogen concentration
Φ*a* = algal concentration
Φ*e* = epiphyton concentration
Φ*zoo* = zooplankton concentration

$\Phi macr$ = macrophyte concentration
$\Phi LDOM$ = labile DOM concentration
$\Phi RDOM$ = refractory DOM concentration
$\Phi LPOM$ = labile POM concentration
$\Phi RPOM$ = refractory POM concentration
ΦBOD = CBOD concentration
Φsed = organic sediment concentration
ΦDO = dissolved oxygen concentration
$\Phi' DO$ = saturation DO concentration

Each of the concentrations in the equation need to first be included in the calculation and, second, be generated for each branch and tributary. In CE-QUAL-W2, users can turn on or off the water quality portion of the model with the CCC variable within the CST COMP card. Setting CCC to OFF will only generate temperature data, in addition to the hydraulic data. After setting CCC to ON, users must then set the active constituents by toggling each to ON within the CST ACTIVE card. Since this model is currently focused on temperature and dissolved oxygen, only total dissolved solids (TDS), inorganic suspended solids (ISS1), phosphate (PO_4), ammonia (NH_4), nitrate and nitrite (NO_x), total iron (TFE), labile dissolved organic matter (LDOM), refractory dissolved organic matter (RDOM), labile particulate organic matter (LPOM), refractory particulate organic matter (RPOM), total inorganic carbon (TIC), and alkalinity (ALK) were set to ON.

Constituent data from USACE, Nashville District Sampling Plan was available with information dating back to 1980. However, since the inflow values change over time due to many factors, including land use, a maximum of 10 years was used to generate values for use with this model. To generate constituent data for the inflow of Old Hickory Dam, all sampled values for the above parameters were averaged over the 10-year period. Those average values were used for all Julian days. For the branch 1 inputs, averages from the sampling location at the tailwater of Old Hickory Dam were used.

Cheatham Outflow

Hourly discharge data for Cheatham turbines and spillway gates were provided by USACE. Prior to use, this data was converted from cubic feet per second to cubic meters per second. The values for this data are based on the flow guide curve in the Water Control Manual (U.S. Army Corps of Engineers, 1998). There is no evidence that the guide curve used has been updated since it was initially derived, upon dam construction. Additionally, the water control managers at the Corps of Engineers use a correction factor of 6% when controlling the Cheatham discharges (LeStourgeon, 2011). To clarify, when a flow setting is changed on the Cheatham Dam, whether it is a turbine or spillway gate change, the effect is assumed to be 6% less flow than published. All turbine and spillway releases used in this model for Cheatham Dam were adjusted with a 1.06 correction factor.

Tributaries

The stream tributaries in this study include Sycamore Creek, Mill Creek, Mansker's Creek, Stones River, and Harpeth River. Of these, gauge data for temperature was available for Mill Creek, Harpeth River, and Stones River. Periodic sampling data was available for Sycamore Creek, allowing the developed regression technique to be used. Flow data was available for Mill Creek, Mansker's Creek, Sycamore Creek, Harpeth River, and Stones River. However, gauge location on these tributaries varies. Ideally, the gauges would be located at the confluence of each tributary and the Cheatham branch. Since, this is not the case, a ratio of the drainage area above each gauge to that below each gauge was used to account for the un-gauged portions between the gauge location and the Cheatham branch. These correction factors were applied to the values for flow. Temperature and all other constituents available at the gauge were used directly.

Mill Creek

Data for Mill Creek flow was available for Julian day 1 through 131 and 181 through 365. To complete data for the other dates, an approximation was made based on values from the Harpeth River. Available Mill Creek daily values were divided by corresponding daily Harpeth River values for the periods available and then averaged. This average multiplication factor was used with the available Harpeth values to estimate Mill Creek daily values. Comparing the available Mill Creek flow values with the calculated flow values for the same Julian days show an absolute mean error of 1.31 cubic meters per second.

The Mill Creek values were then corrected for gauge location. USACE supplied a Geographical Information System (GIS) representation of the Cheatham Basin that was subdivided into local basins. GIS-calculated area for the sub-basin containing Mill Creek, shown in Figure 4-10, is 107.9 mi^2. USGS Gauge No. 03431060 located at N36 07 03.06, W86 43 08.58 shows a drainage area of 93.4 mi^2. Therefore, to account for the un-gauged flow between the USGS gauge and the Cheatham Reservoir, the following equation was used:

$$\text{Mill Creek gauge} \times 107.9/93.4 = \text{Mill Creek gauge} \times 1.15 \qquad (20)$$

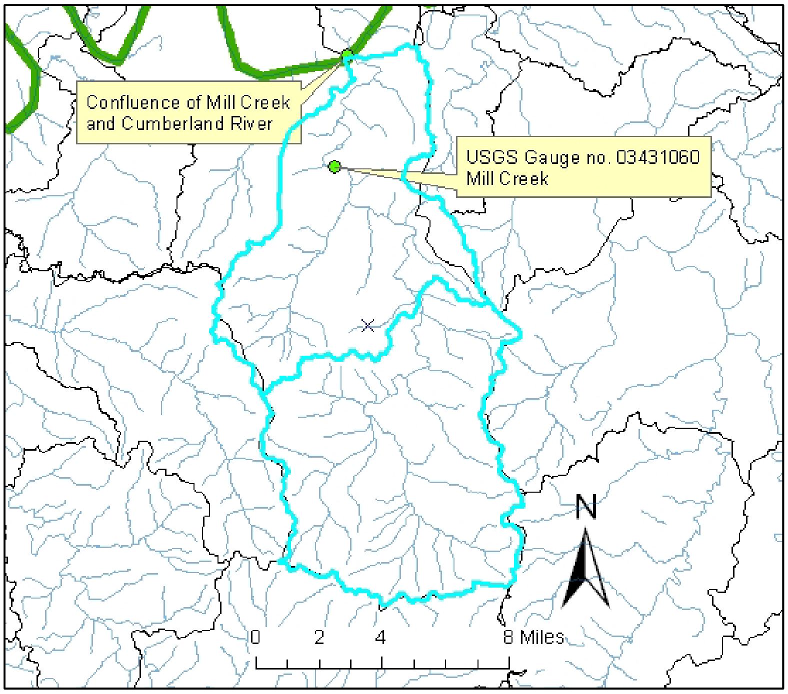


Figure 4-10. Mill Creek Basin.

Temperature and dissolved oxygen data for Mill Creek, shown in Figure 4-8 and Figure 4-9, were available for the entire year and used directly in the model.

Sycamore Creek

Data for Sycamore Creek flow was only available for Julian day 294 through 365. An approximation was made based on the Harpeth River values to provide data for missing dates. Available Sycamore Creek daily values were divided by corresponding daily Harpeth River values for the periods available and then averaged. This average multiplication factor was used with the available Harpeth values to estimate Sycamore Creek daily values. Comparing the available Sycamore Creek flow values with the calculated flow values for the same Julian days show an absolute mean error of 3.68 cubic meters per second. The larger absolute mean error than that of Mill Creek could be due to the fewer number of days of data available for Sycamore Creek.

The Sycamore Creek values were then corrected for gauge location. GIS-calculated area for the sub-basin containing Sycamore Creek, shown in Figure 4-11, is 131.3 mi^2. USACE NSWHB5 Gauge No. ACST1 located at N36 19 12, W87 03 04 drains an area of 97.4 mi^2. Therefore, to account for the un-gauged flow between the Corps gauge and the Cheatham Reservoir, the following equation was used:

Sycamore Creek gauge x 131.3/97.4 = Sycamore Creek gauge x 1.35. (21)

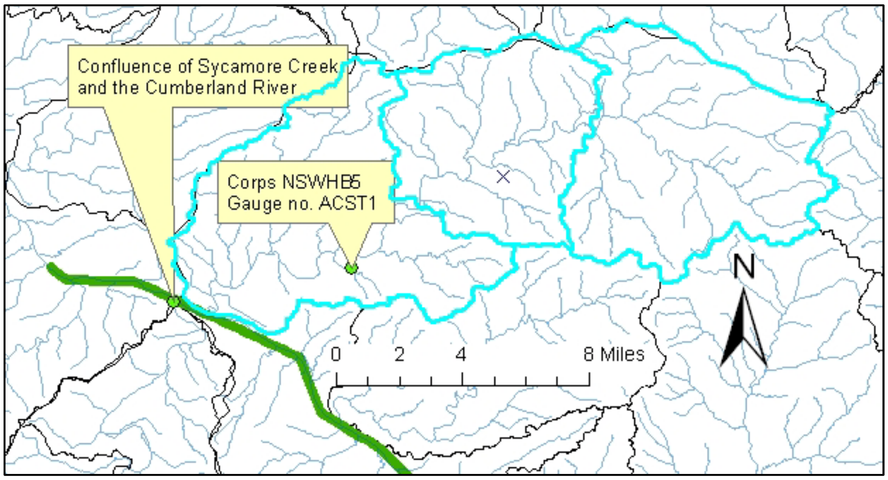


Figure 4-11. Sycamore Creek Basin.

Periodic temperature and dissolved oxygen sample data were provided by USACE (U.S. Army Corps of Engineers, 2011). Daily values for temperature and dissolved oxygen were derived from these values using the regression technique described in the Inflow Regression section.

Harpeth River

The Harpeth River is the largest, by volumetric flow rate, of the tributaries in this project. Because it is being modeled as a tributary, there is no associated bathymetry and only one possible daily input value for temperature, dissolved oxygen, and the other constituents. Since calibration of the Harpeth River model is beyond the scope of this project, this was viewed as sufficient. Although limiting, this simplification was made to decrease the complexity and increase the computational speed of the model. It is recommended that future versions of this model consider treating the Harpeth River as a branch.

To adjust the inflows for the Harpeth River for gauge location, the same procedure used for Mill Creek data was applied. GIS-calculated area for the sub-basin containing the Harpeth River, shown in Figure 4-12, is 867 mi^2. USGS Gauge No. 03434500 located at N36 07 19, W87 05 56 shows a drainage area of 681 mi^2. Therefore, to account for the un-gauged flow between the USGS gauge and the Cheatham Reservoir, the following equation was used:

Harpeth Gauge x 867/681 = Harpeth gauge x 1.27 (22)

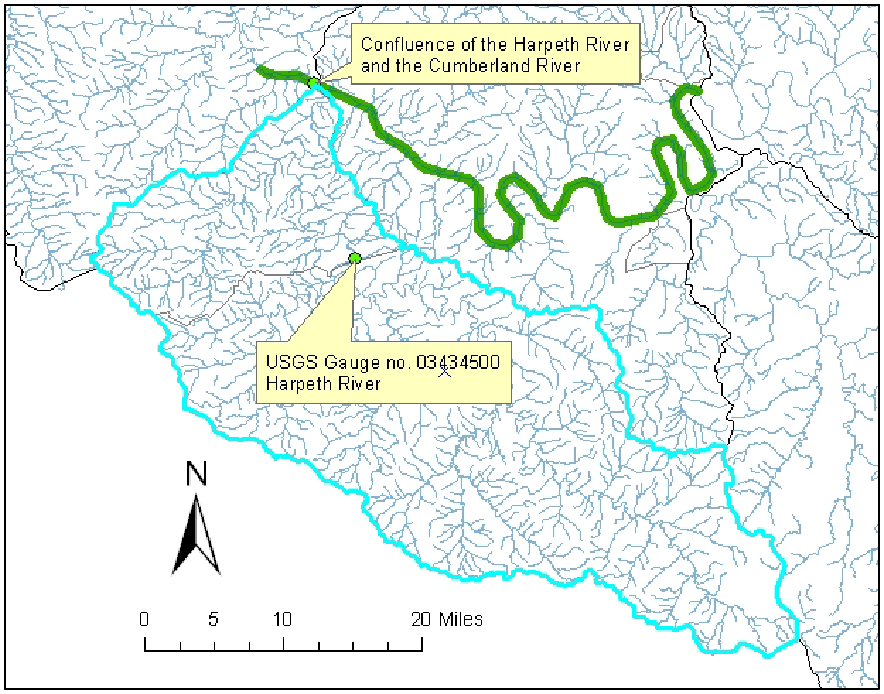


Figure 4-12. Harpeth River Basin.

Periodic temperature and dissolved oxygen sample data were provided by USACE (U.S. Army Corps of Engineers, 2011). Daily values for temperature and dissolved oxygen were derived from these values using the regression technique described in the Inflow Regression section.

Mansker's Creek

Early in the development of the Cheatham model, it was noted that water elevations at the Cheatham Dam were matching well, but the elevations at the tailwater of Old Hickory Dam were low. Upon further review, it was discovered that an input existed that was not represented in the model. Mansker's Creek flows into the Cheatham Reservoir approximately 1.5 km below Old Hickory Dam.

Data for Mansker's Creek gauge was available for Julian day 1 through 272. To complete data for the other dates, an approximation was made based on the Harpeth River values. Available Mansker's Creek daily values were divided by corresponding daily Harpeth River values for the periods available and then averaged. This average multiplication factor was used with the available Harpeth values to estimate Mansker's Creek daily values. Comparing the available Mansker's Creek flow values with the calculated flow values for the same Julian days show an absolute mean error of 0.97 cubic meters per second.

To adjust the inflows for the Mansker's Creek gauge location, the same procedure used for Mill Creek was applied. GIS-calculated area for the sub-basin containing Mansker's Creek, shown in Figure 4-13, is 46.7 mi^2. USGS Gauge No. 03426385 located at N36 20 20.32, W86 43 04.02 shows a drainage area of 27.7 mi^2. The following equation was used to account for the un-gauged flow between the USGS gauge and the Cheatham Reservoir,

$$\text{Mansker gauge} \times 46.7/27.7 = \text{Mansker gauge} \times 1.69 \qquad (23)$$

No sampling locations exist on Mansker's Creek, and since Mill Creek is of similar size and location, Mill Creek temperature and dissolved oxygen data were used.

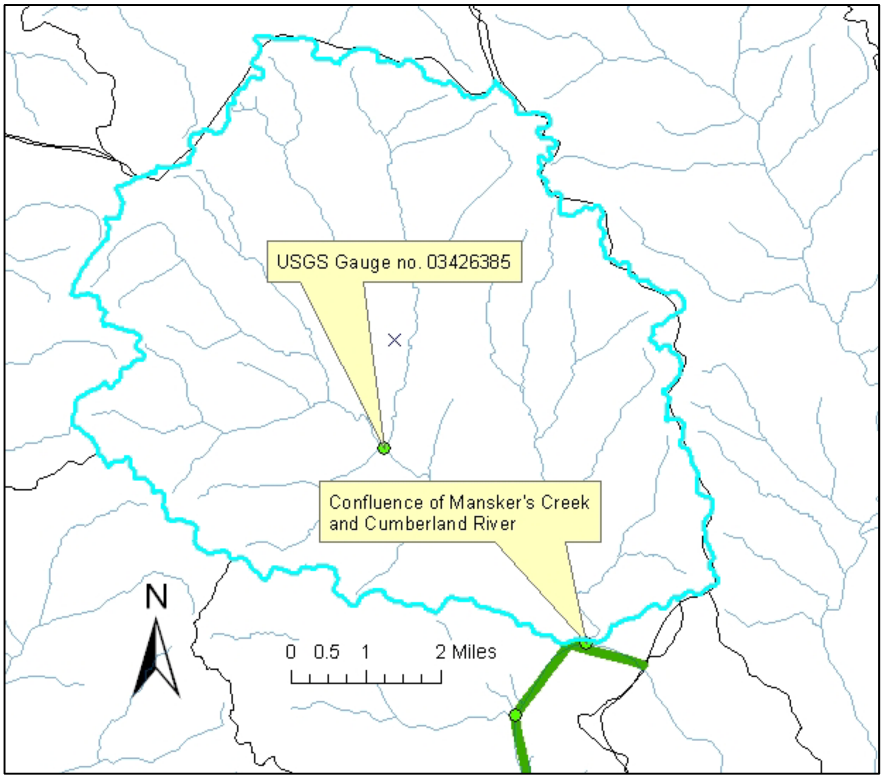


Figure 4-13. Mansker's Creek Basin.

Stones River

USACE plans to eventually link each element of the Cumberland River to produce an overall CE-QUAL-W2 model of the entire Cumberland River system. To facilitate this process, the Stones River was modeled as a branch with associated bathymetry. Like the Cheatham Reservoir, the starting point for developing the bathymetry needed for this model was the RAS 4.1 model, supplied by USACE (Moran, 2011). The sediment surveys included in the RAS 4.1 model, along with a site and depth survey helped generate the bathymetry for this portion of the model.

Hourly turbine and spill outputs from J. Percy Priest Dam, also supplied by USACE, were used for the flow inputs for the Stones River branch (U.S. Army Corps of Engineers, 2011). Outputs were available for the entire year.

Monthly sampling data, that included temperature and dissolved oxygen, were also available from USACE from the tailwater of J. Percy Priest Dam. Since sufficient numbers of data points were available to show a trend for temperature, a trendline in MS Excel was used to generate daily values. Figure 4-14 illustrates a plot of the temperature values for each Julian day, along with the trendline equation used to generate daily values and corresponding R^2 value (Microsoft, 2007). Dissolved oxygen data show a normal trend in the early part of the year but flattens out during the summer months. In 2009, USACE used spillway releases to help alleviate the historically low dissolved oxygen content during the summer months. That effect is shown in Figure 4-15 between days 150 and 275.

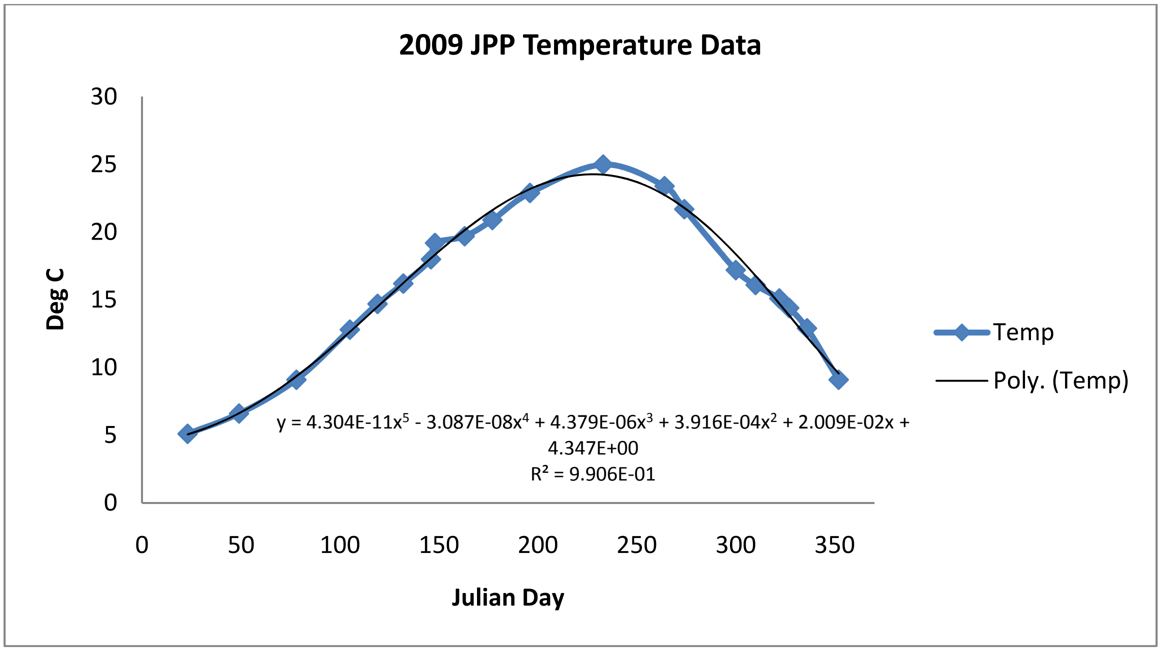


Figure 4-14. J. Percy Priest Temperature Data.

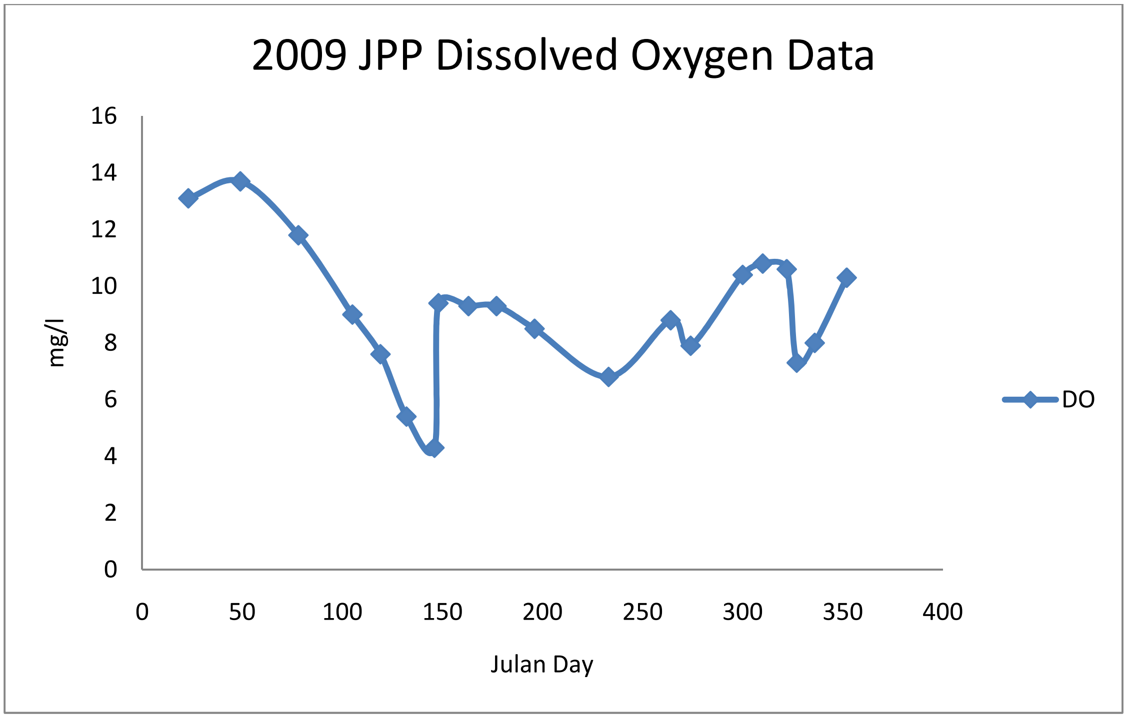


Figure 4-15. J. Percy Priest Dissolved Oxygen Data.

Since no trend exists due to the increased dissolved oxygen during the summer months, values for dissolved oxygen releases for J. Percy Priest were set to the sampled value for each day until the next sampled value was available.

Central Waste Water Treatment Plant

The Central Waste Water Treatment Plant is located at river mile 189.4, as illustrated in Figure 1-1. Monthly average discharge data for flow in million gallons per day was obtained from Metro Water Services in Nashville, TN for 2009 (Metro Water Services, 2009). This data was converted to cubic meters per second and used directly. Yearly averages for suspended solids, ammonia, dissolved oxygen, and pH were obtained as well. All other constituent values were set to zero.

Whites Creek Waste Water Treatment Plant

The Whites Creek Waste Water Treatment Plant is located at river mile 182.6, as illustrated in Figure 1-1. Monthly average discharge data for flow in million gallons per day was obtained from Metro Water Services in Nashville, TN for 2009 (Metro Water Services, 2009). This data was converted to cubic meters per second and used directly. Yearly averages for suspended solids, ammonia, dissolved oxygen, and pH were obtained as well. All other constituent values were set to zero.

Dry Creek Waste Water Treatment Plant

The Dry Creek Waste Water Treatment Plant is located at river mile 214, as illustrated in Figure 1-1. Monthly average discharge data for flow in million gallons per day was obtained from Metro Water Services in Nashville, TN for 2009 (Metro Water Services, 2009). This data was converted to cubic meters per second and used directly. Yearly averages for suspended solids, ammonia, dissolved oxygen, and pH were obtained as well. All other constituent values were set to zero.

Water Intakes

There are 3 main drinking water intakes from the Cheatham portion of the Cumberland River. Harrington Treatment Plant, located at river mile 205.9, Omohundro Treatment Plant, located at river mile 193.7, and Harpeth Valley Treatment Plant, located at river mile 172.4, account for the majority of the water taken from the Cheatham Reservoir. Yearly averages for flow were obtained from Metro Water Services and Harpeth Valley Utilities, Nashville, TN for

2009 (Metro Water Services, 2009) (Harpeth Valley Utilities, 2009). This data was converted to cubic meters per second and used directly.

Meteorological Data

The National Climatic Data Center, a division of the National Oceanic and Atmospheric Administration (NOAA), provided data via their Quality Controlled Local Climatological Data System. The data needed by CE-QUAL-W2 is Julian day, air temperature (^oC), dew point temperature (^oC), wind direction (radians), wind speed (meters per second), and cloud cover. The station selected was the Nashville International Airport, Nashville, TN that reports a gauge height of 182.9 meters above mean sea level. All data was available in hourly increments for the entire model year of 2009, except cloud cover.

The Nashville site in NOAA lists sky condition in Meteorological Aerodrome Report (METAR) format, followed by the altitude of the observation. The METAR data is provided by surface observations or an Automated Weather Observation System (AWOS). Terms used by airport stations divide the sky into eighths and represent the following estimated cover: OVC (overcast) 8/8 covered, BKN (broken) 5/8-7/8 covered, SCT (scattered) 3/8-4/8 covered, FEW 1/8-2/8 covered, and CLR (clear) 0/8 covered.

CE-QUAL-W2 uses a scale of 0 through 10 corresponding to cloud cover of 0% through 100%. For each line in the meteorological file, if OVC appeared, cloud cover was set to 9; if BKN appeared, cloud cover was set to 5; if SCT appeared, cloud cover was set to 3; and if FEW or CLR appear, cloud cover was set to 0.

CHAPTER V

Calibration

Calibration is an iterative process and in this project many simulation runs were made in an effort to calibrate the model within certain threshold requirements for water balance, temperature, and dissolved oxygen. There are many different variables available to users and the best method is to evaluate new systems for sensitivity to each variable. From there, selection of the most sensitive variables allows a user to get the best fit of data.

Generally, the goal of a mathematical model of a system is to be able to predict future conditions based on changing inputs. One approach is to calibrate to a set of data, generally a season or year, and then validate the model by using input data from a different year and checking the match of field data. This approach assumes the developed model to be useable under most circumstances once calibrated. An example of this is shown in a CE-QUAL-W2 model of the Tongue River. In that study, a model was developed of the Tongue River in Montana and Wyoming. The model was first calibrated to data from the year 2000. The next step used was to “validate” the model by running the same model with 2003 data inputs (U.S. Environmental Protection Agency, 2007).

A different approach is to consider the initial calibration of a model as a first step. Instead of using subsequent data sets as validation tools and making no adjustments, users should think of subsequent runs as ongoing calibration. This is the approach suggested in the CE-QUAL-W2 User’s Manual (Cole, et al., 2008). In that manual, the authors argue that good modelers will adjust coefficients, review assumptions made, and gather new data, if needed, thereby improving the results of not only the second set of data, but often times the first (Cole, et al., 2008). This is the better approach as it uses the model to develop an ongoing understanding of a water system that can and will change over time instead of a one size fits all description.

The first step in calibration was to determine the type and amount of data needed to describe a system. In a 2000 model of the J. Percy Priest Reservoir, upstream of the Stones River input to the Cheatham Reservoir, the authors analyzed a number of years of data and classified each year based on hydrologic conditions. From there they chose a minimum of four years with which to calibrate, using years classified as wet, dry, and normal (Martin, et al., 2000). A similar approach was used in this study, although due to time constraints, this model was calibrated to a single year. Continuation of this project in the future should include different years of differing hydrologic conditions.

USACE supplied a classification of years based on total inflows and outflows to the Cheatham Reservoir. This data is shown in Table 5-1, along with the total number of sampling profiles that included temperature, dissolved oxygen, specific conductivity, and pH at 5 foot depth increments. Since this model was only calibrated to one year, a classification of typical would have been preferred. However, of the four typical years within the last 20 years, the highest number of sample profiles within those years was two. Because the highest numbers of samples were available in 2009, that year was used for calibration of this model. The goals of this model were to reproduce water surface elevation to within an AME of 0.5 feet, water temperature to within 0.5 °Celsius, and dissolved oxygen concentration to within 1 milligram per liter.

Table 5-1. Basin Yearly Hydrologic Classification.

Year	Type	# Profiles
1990	Typical	2
1991	Wet	4
1992	Typical	1
1993	Typical	0
1994	Wet	3
1995	Dry	2
1996	Wet	3
1997	Wet	7
1998	Wet	2
1999	Dry	6
2000	Dry	2
2001	Dry	5
2002	Typical	2
2003	Wet	2
2004	Wet	3
2005	Dry	2
2006	Dry	2
2007	Dry	5
2008	Dry	4
2009	Wet	6

Water Balance

Even with the most accurate data available for water inflows, a natural system is very difficult to model. CE-QUAL-W2 is a very simplified representation of a river system when compared to the overall system itself. Many inaccuracies may be present in the form of storm-water runoffs not included in the model, base-flow that is not able to be measured, precipitation of differing volumes across the basin, man-made intakes and outputs that are not accurately measured, differing evaporation rates, and many others.

To adjust for these inaccuracies, CE-QUAL-W2 includes a distributed tributary file. A distributed tributary is available for use for each branch in a model. The flows in this input file are distributed through the model to each segment proportional to their surface area.

Once an initial set of input files are generated, users run the CE-QUAL-W2 program. From there, comparing model outputs to observed water surface elevations will show what adjustments should be made in the distributed tributary file. Included with the CE-QUAL-W2 package is a water balance program to help with this calibration. This water balance program was used extensively in this study. The use of this program is a good initial step but the user will eventually make smaller adjustments based on experience. Figure 5-1 shows the water surface elevations for the Cheatham model, data plotted in five day increments, just upstream of Cheatham Dam. Absolute mean error for the entire year was 0.45 feet (0.136 meters).

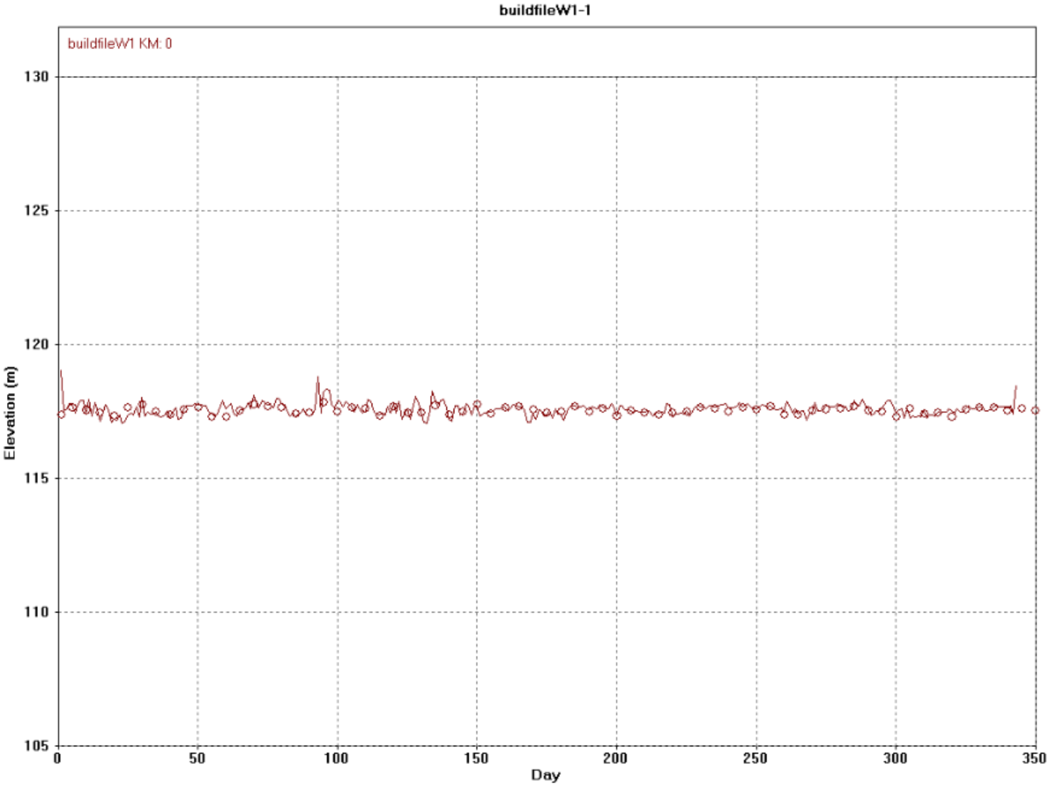


Figure 5-1. Water Surface Elevations, field data in circles, model data in line.

Bathymetry

The bathymetry for the Cheatham Reservoir was not well-defined in the initial model, written in 2003. As stated in Chapter IV, sediment surveys were available approximately every river mile. After configuring the initial bathymetry file and making multiple model runs with varying parameters, multiple observations were made.

First, the initial runs indicated pronounced stratification, suggesting the reservoir, as a whole, was not well mixed. Comparing these runs to the field data proved this to not be the case. Figure 5-2 illustrates an early plot of temperature calculations versus field observations. Days 210, 238, and 267 each show clear stratification compared to the observed values.

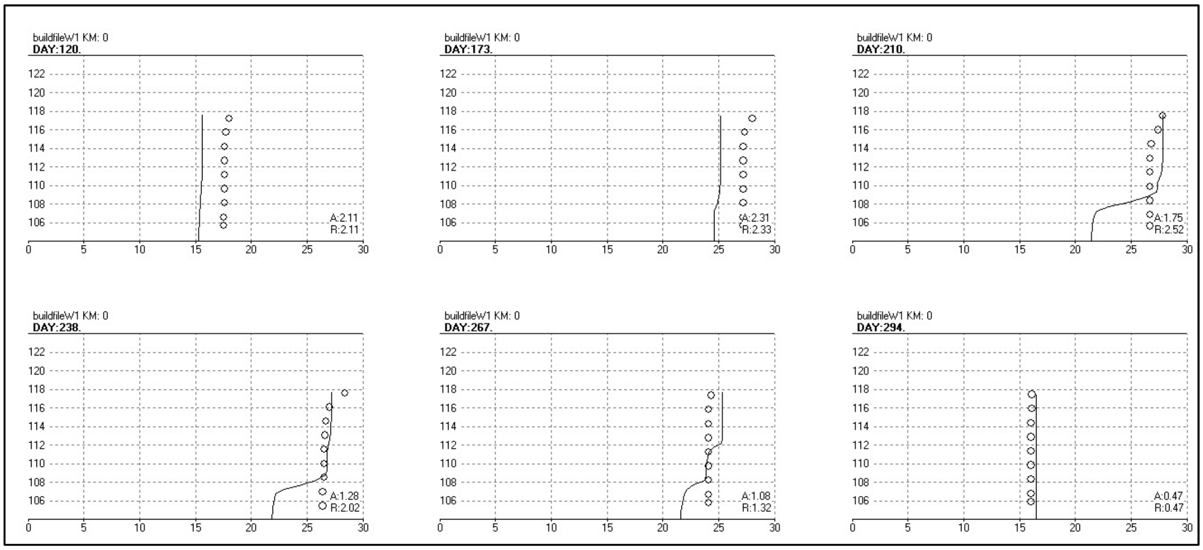


Figure 5-2. Early Temperature Profile Comparison.

In this figure and subsequent figures, field data is shown as circles and model data is shown as a line. The initial attempt at decreasing the stratification shown in the model was to increase the mixing within the water column. Two approaches were used for this. The first was to increase the bottom friction and the second was to increase the eddy viscosity and diffusivity.

The default value used for the CHEZY coefficient is 70, as specified in the User's Manual (Cole, et al., 2008). Bottom friction increases as CHEZY coefficients decrease, so a sensitivity value of 50 was run. After updating the water balance, the model predicted the results shown in Figure 5-3.

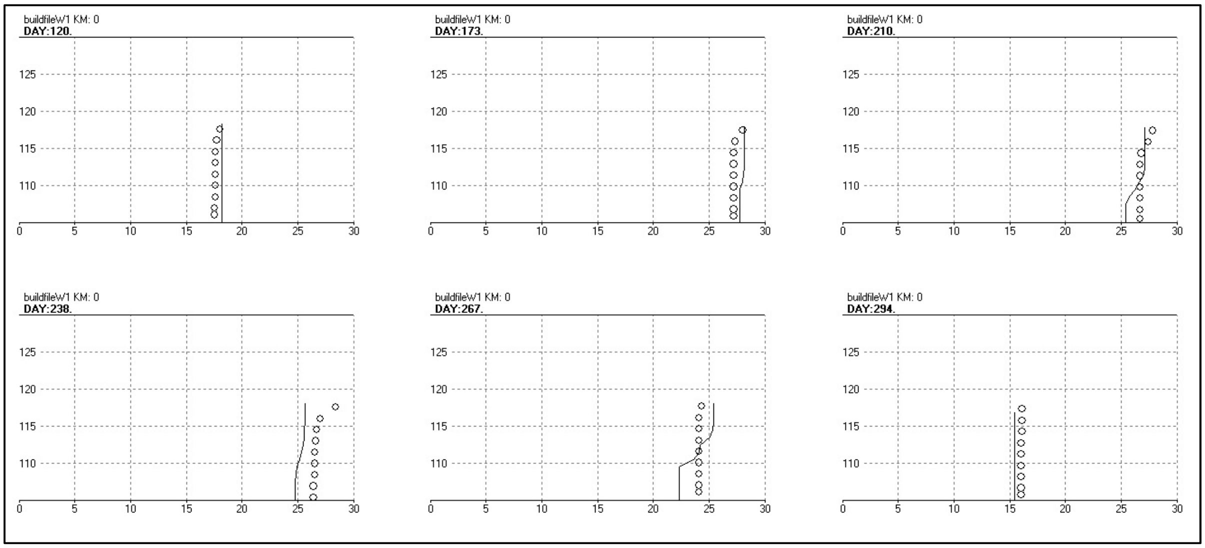


Figure 5-3. Early Temperature Profile Comparison.

Stratification decreased on days 210 and 238, but is still clearly present on day 267.

The horizontal eddy viscosity, AX, specifies dispersion of momentum in the longitudinal direction. The horizontal eddy diffusivity, DX, specifies dispersion of heat and constituents in the longitudinal direction (Cole and Wells, 2008). Default values for these variables are both 1.0 m^2 sec^{-1}. However, the User's Manual states that for rivers these values may be as high as 30 m^2 $sec^{-1}$and 100 m^2 sec^{-1}, respectively. After a sensitivity run to evaluate the effect of setting AX and DX to the highest values (small changes shown in Figure 5-4) it was decided to reconsider the bathymetry. A larger effect was needed to be able to reproduce the field data. By adjusting the bathymetry, the desire was to show a larger decrease in stratification. From there, the above variables were again adjusted to decrease the remaining error.

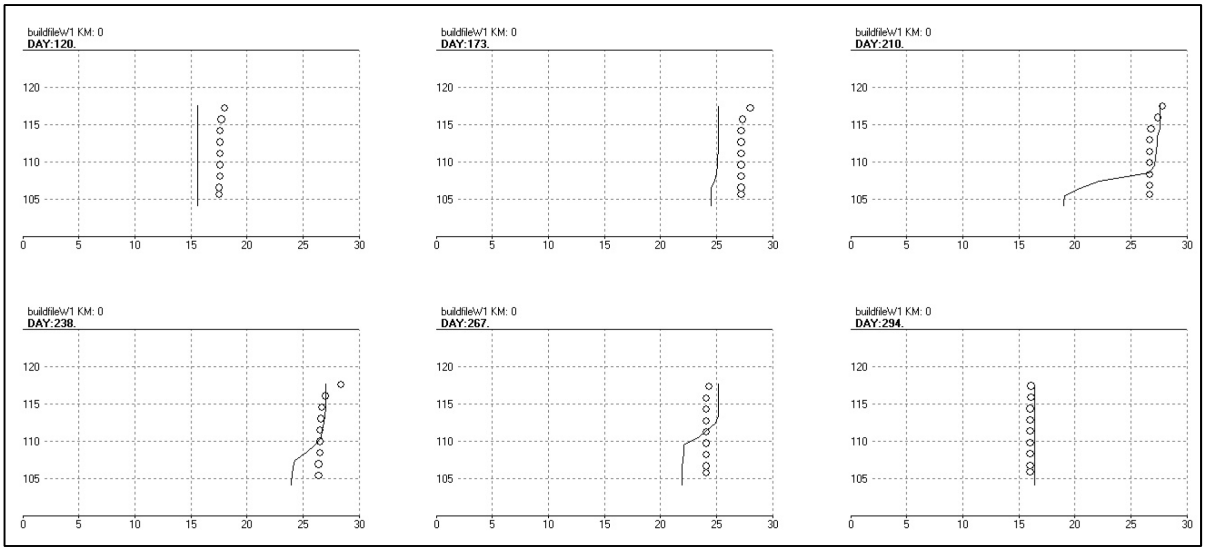


Figure 5-4. Temperature Comparison, new AX and DX values.

In a 1995 study of Lake Pepin , Upper Mississippi, it was found that in an 89 year period, the lake lost a total of 21% volume due to sedimentation. The study further showed the volume loss was distributed at 34%, 18%, and 14% corresponding to upper, middle, and lower portions of the lake (Maurer, et al., 1995). A 2009 USDA Natural Resources Conservation Service study estimated loss of volume from 6.6% to 28% for six different lakes in the Upper Missouri River Basin (USDA Natural Resources Conservation Service, 2009). Little information is available for sedimentation rates for the Cumberland River. The Tennessee River has had a robust sediment sampling program in the past but the Cumberland River has seen interest decline in previous decades (Carey, et al., 1988). Currently, the Cumberland River Compact is undertaking a sediment study of the Harpeth River Watershed, but no such study is available for the Cheatham Reservoir (Cumberland River Compact).

Given that the Cheatham Dam is 58 years old at the time of this report, it is reasonable to assume some sedimentation has occurred. Though the latest publication of the Cheatham Water Control Manual was in 1998, there is no evidence that the volumes have been updated since the initial survey. The field data show a well-mixed reservoir for the entire length. For this reason, coupled with the original sediment surveys being approximately one mile apart, the bathymetry for this project was used as one of the calibration tools.

The Cheatham Reservoir starts relatively narrow at the tailwater of the Old Hickory Dam and slowly widens throughout its length. Very near the Cheatham Dam, there is a more drastic widening. A rough estimate of volume loss due to sedimentation is shown in Figure 5-5. This figure shows the percentage loss applied to the bathymetry. The figure is shown in the plan-form view with Cheatham Dam located at the left boundary and Old Hickory Dam at the right boundary. The goal is to decrease the residence time of the water in Cheatham Reservoir to levels that will force the mixing required to match the field data.

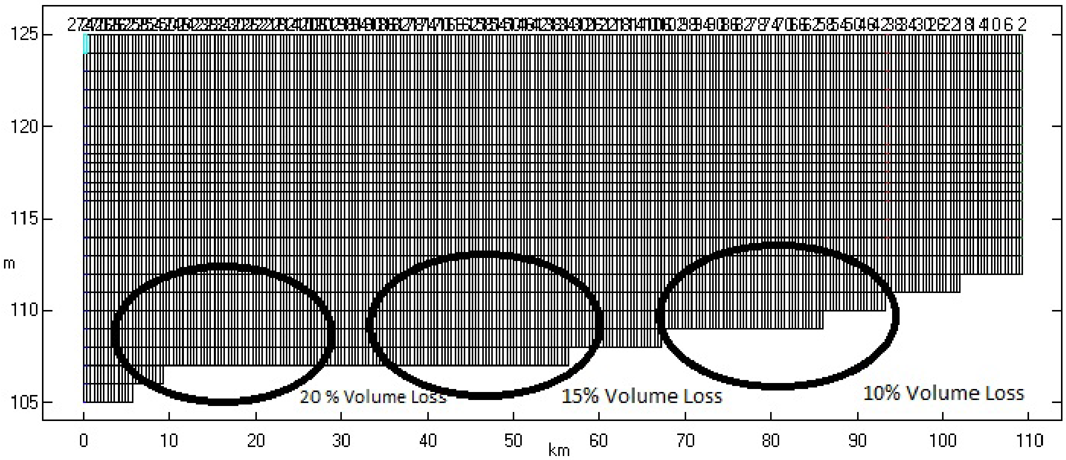


Figure 5-5. Volume loss due to sedimentation estimate.

After applying the above volume reductions, the updated water control manual and model volume comparison is shown in Figure 5-6. This estimate is based on the theory that as the reservoir widens and water velocity and energy decreases, the water column is less able to support sediment transport and more sediment will settle.

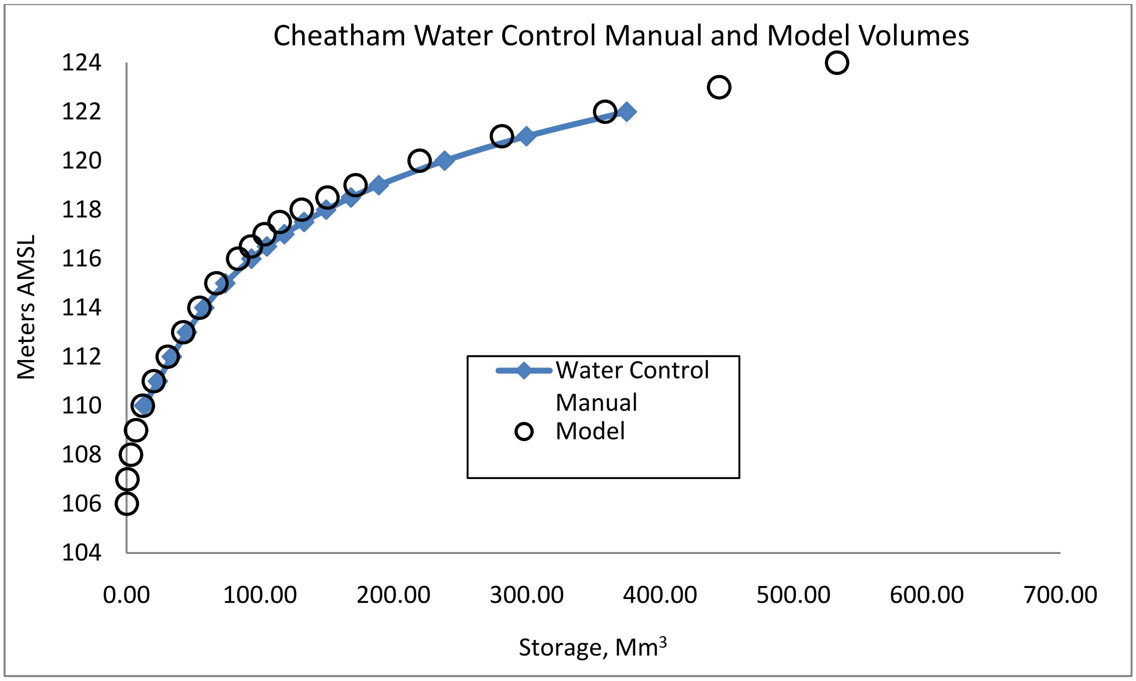


Figure 5-6. Comparison of Adjusted Volumes and Water Control Manual.

This reduction results in an overall 16% reduction in total volume with 75% of that reduction occurring in the bottom two layers. Because of the volume reduction, a new water balance was completed.

Figure 5-7 illustrates the temperature results after the volume reduction and water balance were completed.

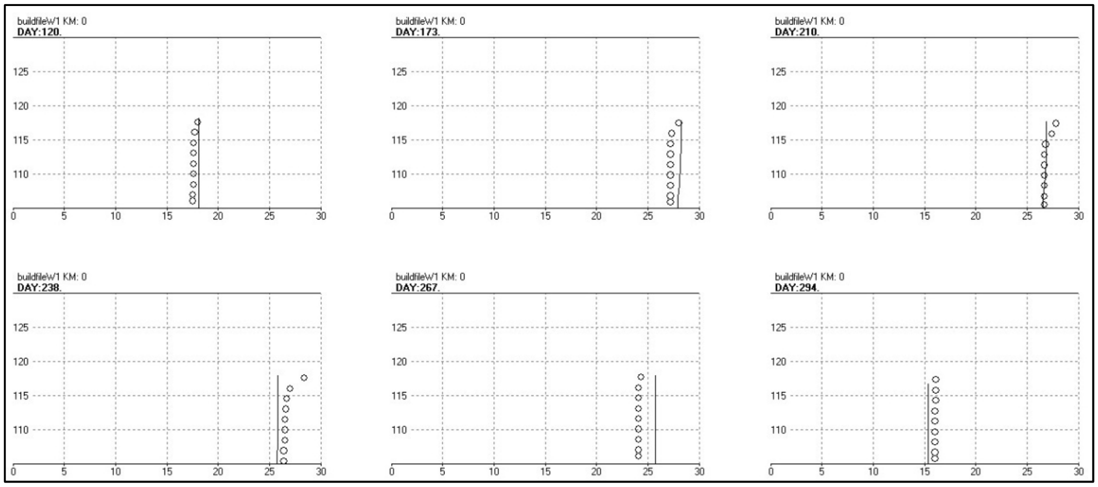


Figure 5-7. Temperature Plot After Volume Reduction.

Stratification is greatly reduced as a result of the changes in bathymetry.

Temperature

Three considerations to note when interpreting temperature results were outlined by Cole and Tillman in 1999. Observed data represent values at specific points in a reservoir, whereas model data are averaged over the length, height, and width of a cell. Meteorological data are measured at a specific point but applied by CE-QUAL-W2 across the entire model. Data for this model were measure at the Nashville International Airport, approximately 3 kilometers from the closest point on the Cheatham Reservoir and approximately 50 kilometers from the farthest point. Lastly, model temperatures are subject to large variations depending upon how rapidly inflows, outflows, and meteorological inputs are changing. The RMS can change more than one degree Celsius over a 24 hour period (Cole, et al., 1997).

Once the water balance results were within an acceptable range (0.5 feet is the goal of this study), the next step was calibration of temperature. This was an important point as it was found that improving this error from 1.0 feet to 0.8 feet affected predicted temperatures up to 1 degree Celsius. As stated earlier, there are numerous variables within the control file that can be used to calibrate temperature. Sensitivity analyses should be run on each to find the variables that have the most effect on individual systems.

Most of the variables that were adjusted during the temperature calibration were described in the Control File section. In a well-mixed reservoir, such as Cheatham, the wind sheltering coefficients and the shading coefficients have the most effect on temperature. Additionally, changing those values will generally move the entire temperature profile. Adjusting the profiles was needed, but the first attempt was to correct the shapes of each profile, similar to the effect seen by adjusting the volume earlier.

The profiles shown in Figure 5-7 depict surface heating in the field data that is not captured in the model, especially on days 173, 210, and 238. The main parameters adjusted to address the surface heating were WINDH, the height of meteorological measurements, AFW, the coefficient of evaporative cooling, AX and DX, the longitudinal eddy viscosity and diffusivity respectively, and AZMAZ, the vertical eddy viscosity. After many iterations with different variable values, it became clear that changes in these variables affected the shape of the profiles, but also warmed or cooled each profile as well. Therefore, the calibration process was extended to include the wind sheltering coefficient and shading files.

Dissolved Oxygen

As discussed in the Old Hickory Inflow section, the variables affecting dissolved oxygen within CE-QUAL-W2 are TDS, ISS1, PO_4, NH_4, NO_x, TFE, LDOM, RDOM, LPOM, RPOM, TIC, and ALK. To complete the input data sets for each of these, yearly averages for the previous 10 years were taken from the available sampling data and used for each Julian day of the year. Default values for all coefficients within the control file were used.

The initial results showed the model under-predicting dissolved oxygen for most dates. It was assumed that the algae concentrations had the most effect on the generation of dissolved oxygen and those concentrations were under-represented in the model. Algae concentrations were adjusted to reflect the yearly trend instead of the yearly average.

Sediment oxygen demand had a large effect on dissolved oxygen concentrations as well. Initially the default value of 0.5 g O_2 m^{-2} day^{-1} was used (Cole, et al., 2008). However, the User's Manual states that the acceptable range for sediment oxygen demand is 0.3-0.7 g O_2 m^{-2} day^{-1} and so 0.3 g O_2 m^{-2} day^{-1} was chosen to decrease the demand described above (Cole, et al., 2008).

The variable with the largest effect on dissolved oxygen was found to be the inflow concentrations, input from the Old Hickory Dam. Because some of the tributaries' concentrations entering the main stem were derived from the regression technique, described earlier, sensitivity analyses were run by doubling the inflow concentrations of each. Small, localized changes resulted and were considered to be negligible.

CHAPTER VI

RESULTS

There are ten water quality sampling sites along the Cheatham Reservoir where profiles were taken during 2009. Temperature and dissolved oxygen profiles from surface to bottom were available at each location. Figure 6-1 illustrates the relative position of each of these sites.

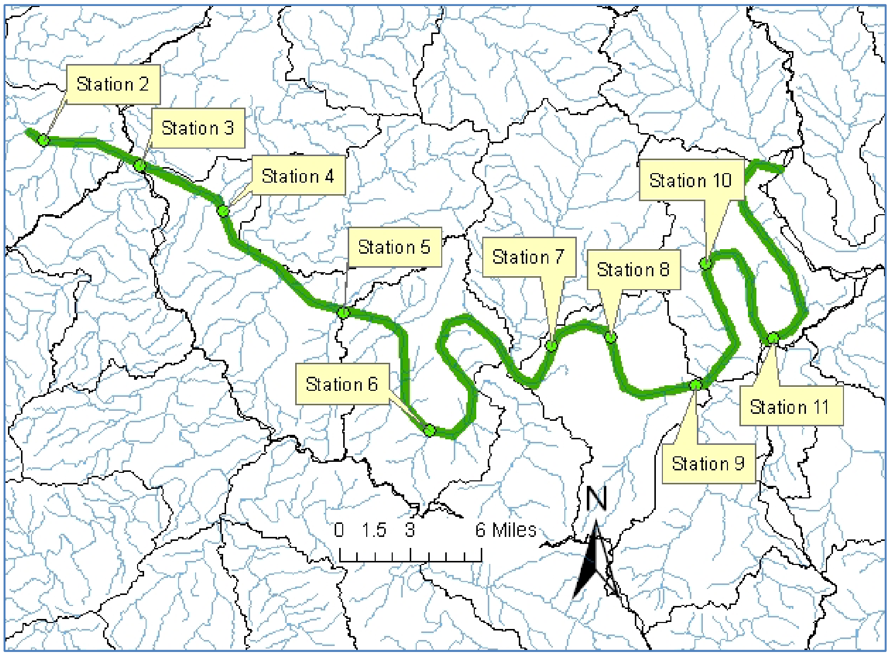


Figure 6-1. Water Quality Stations.

The results for the temperature calibration are shown in Figure 6-2 through Figure 6-11.

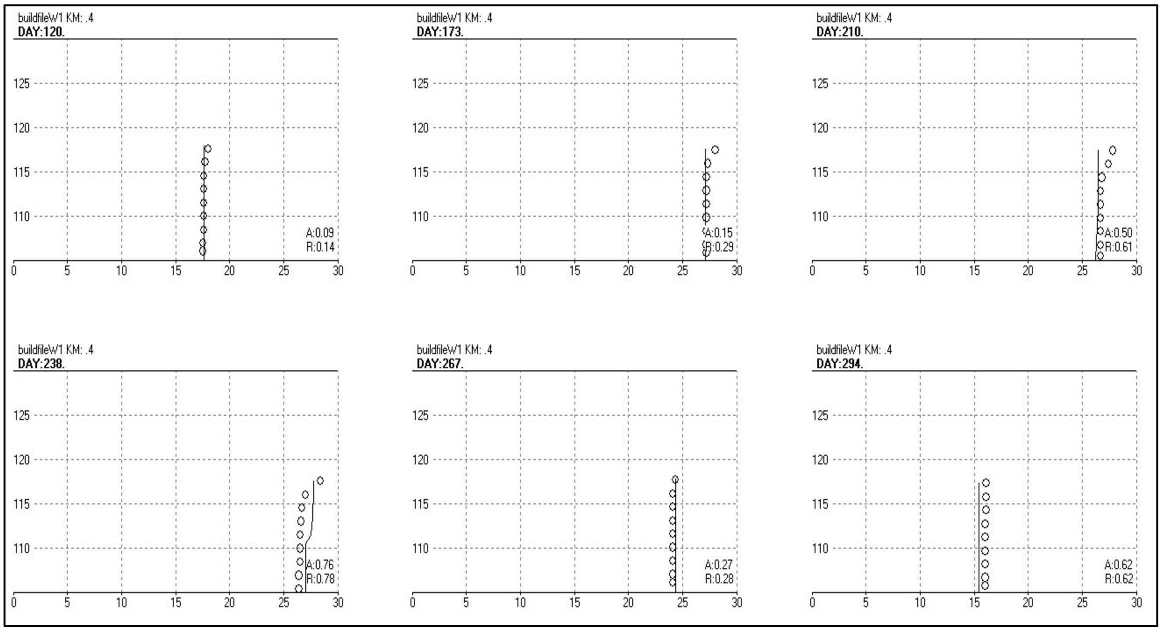


Figure 6-2. Station 2 Temperatures.

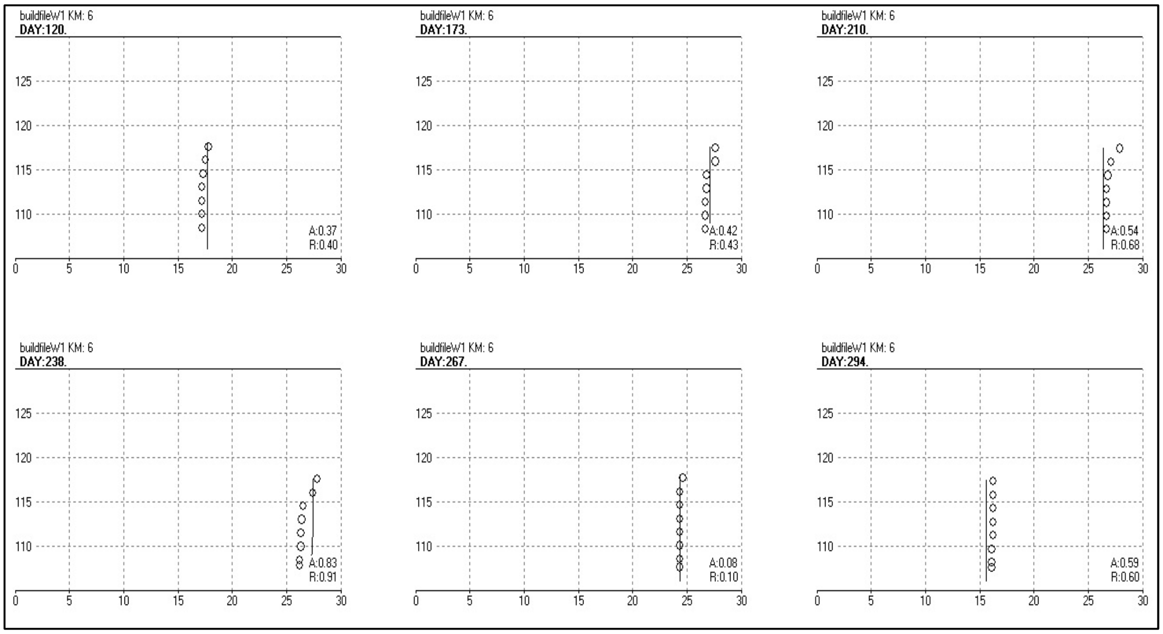


Figure 6-3. Station 3 Temperatures.

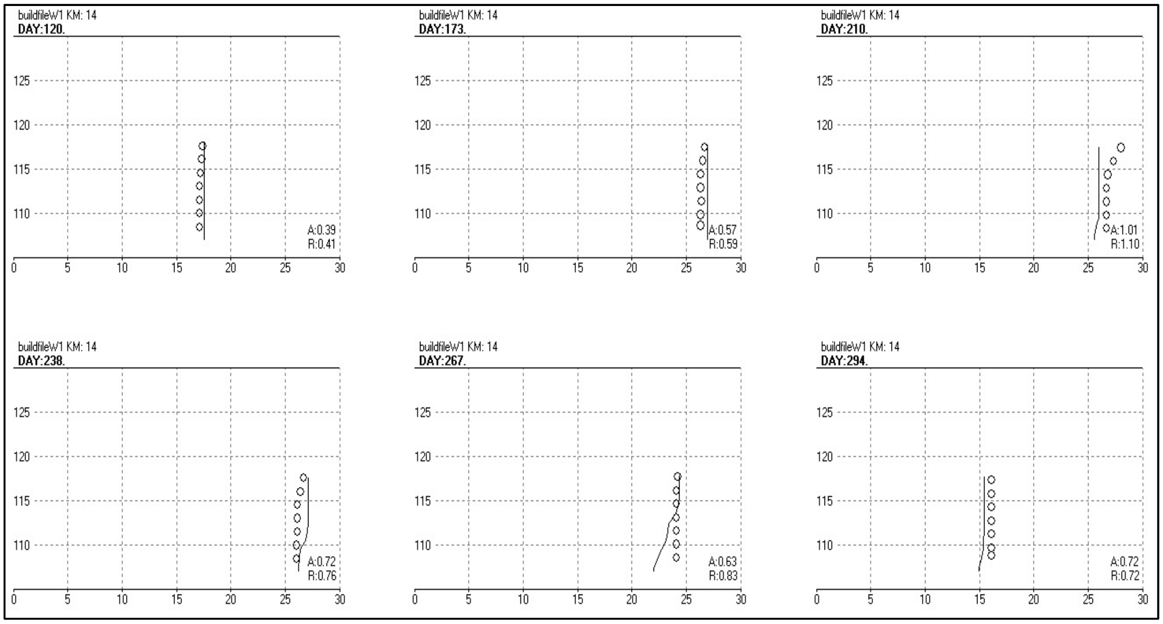


Figure 6-4. Station 4 Temperatures.

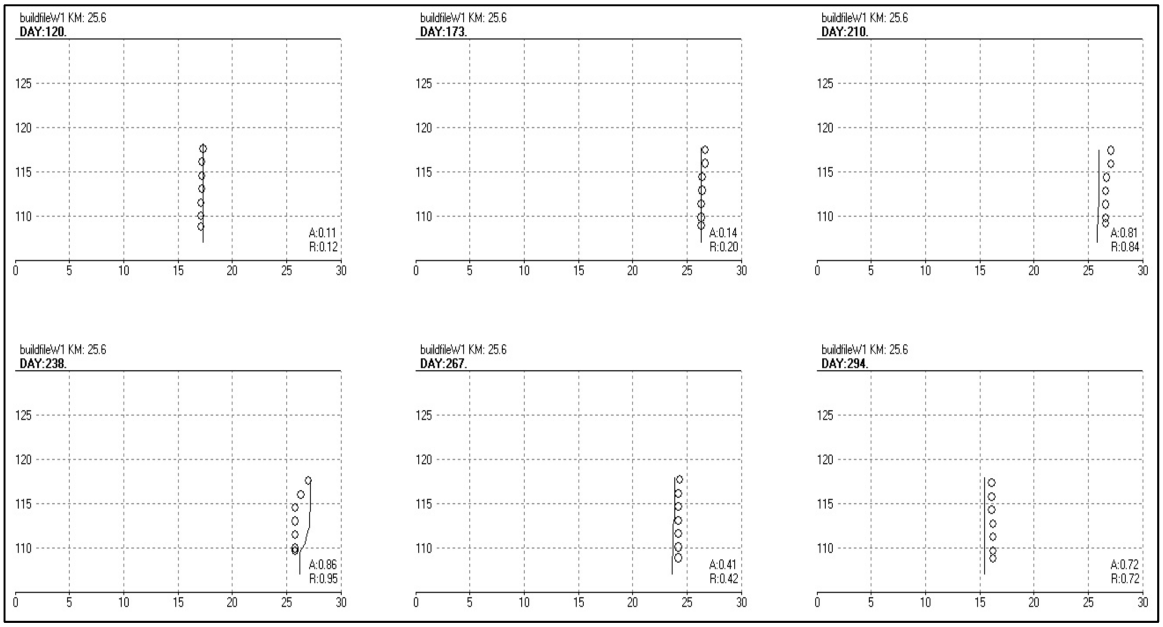


Figure 6-5. Station 5 Temperatures.

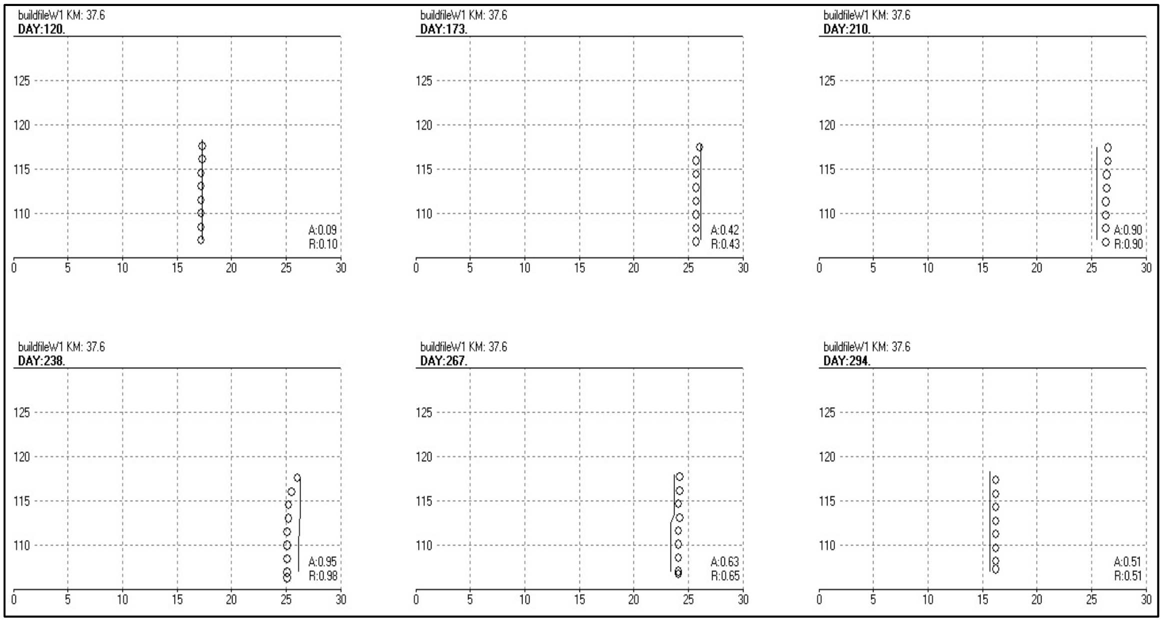


Figure 6-6. Station 6 Temperatures.

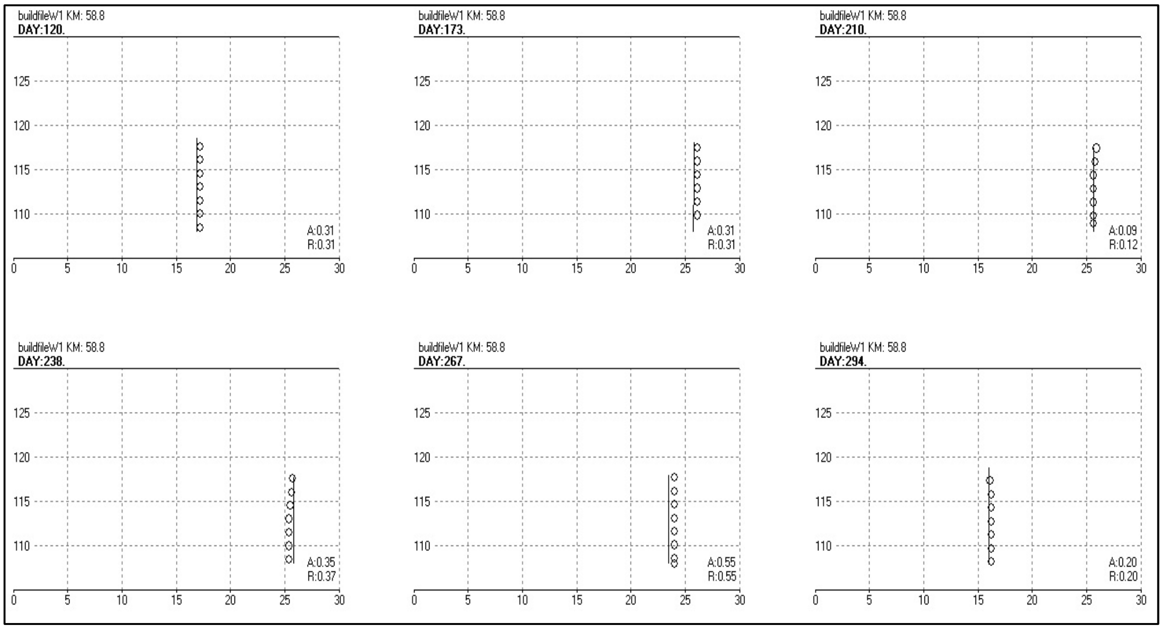


Figure 6-7. Station 7 Temperatures.

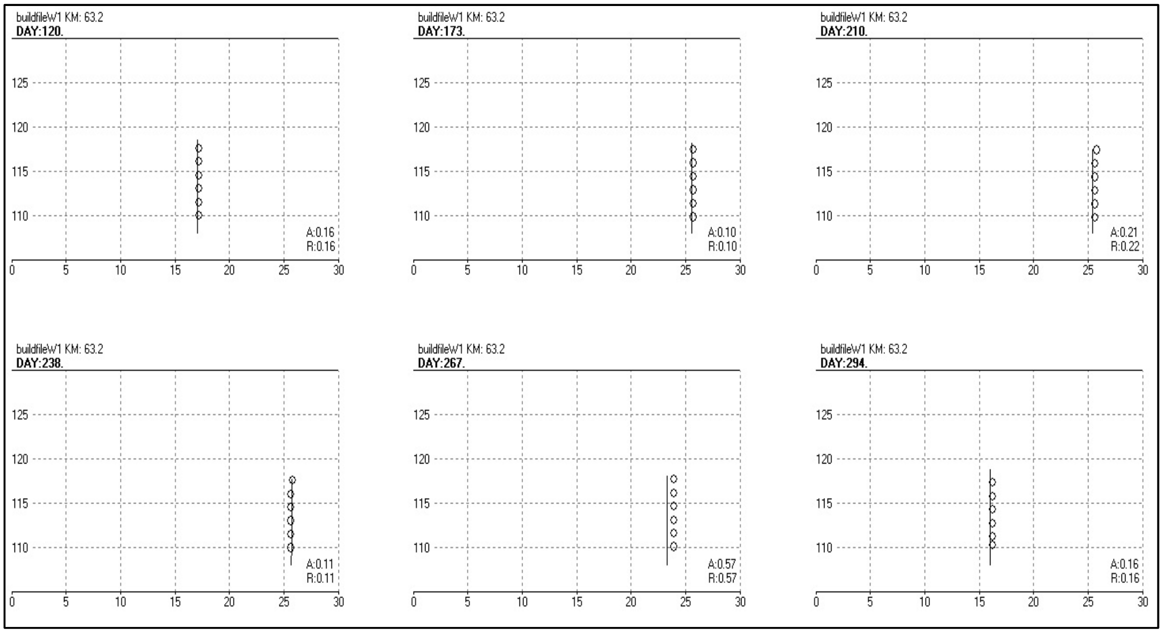


Figure 6-8. Station 8 Temperatures.

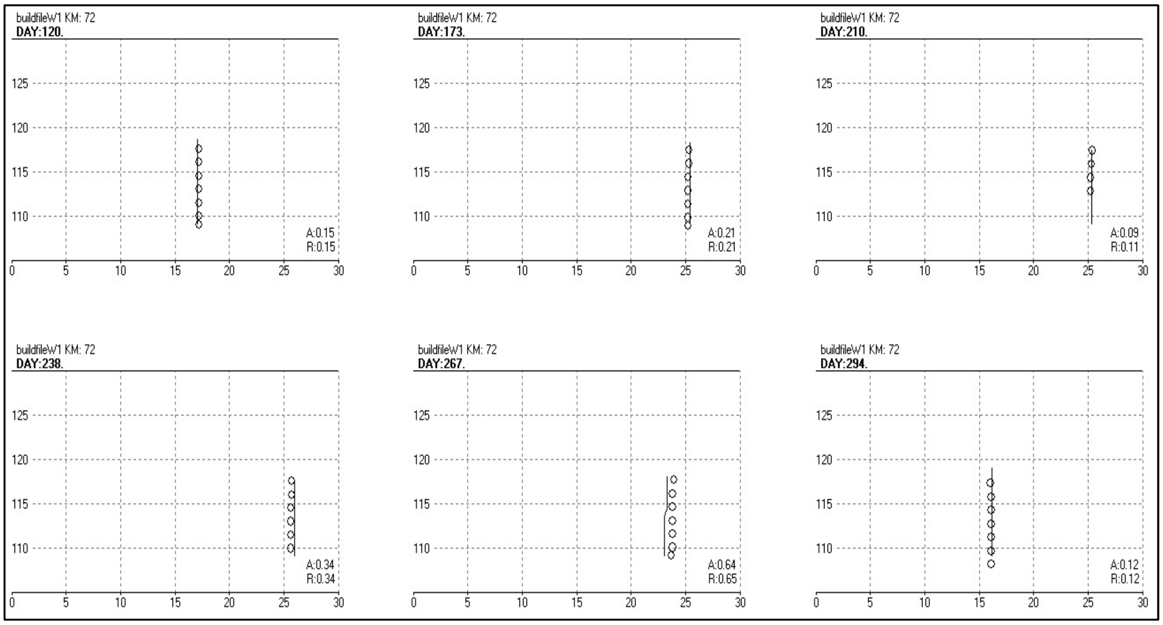


Figure 6-9. Station 9 Temperatures.

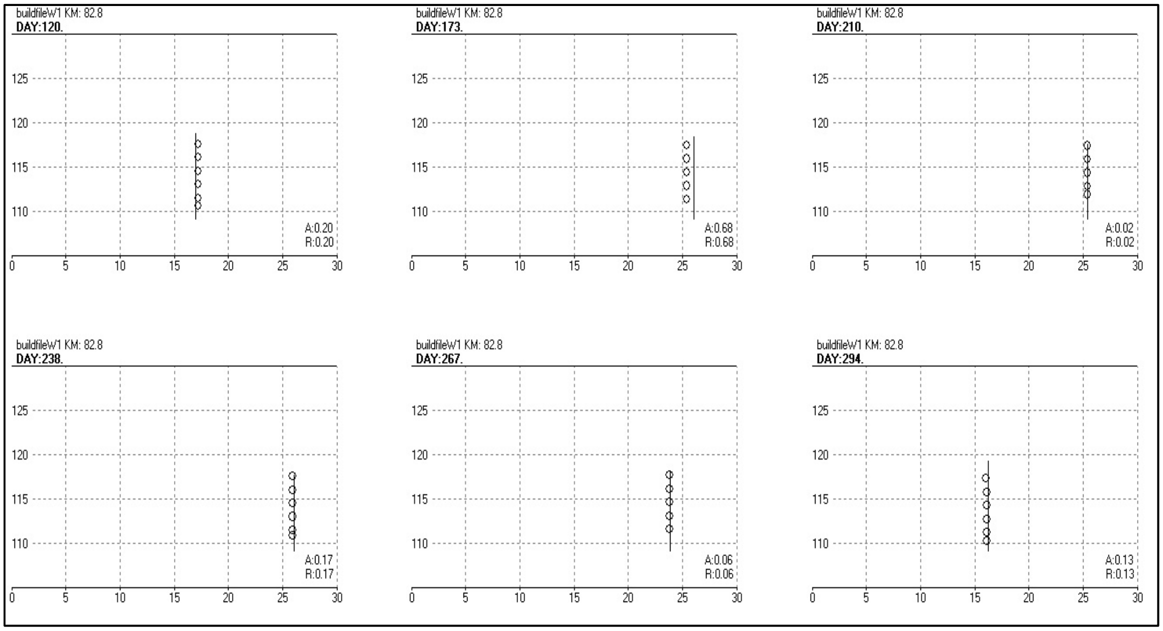


Figure 6-10. Station 10 Temperatures.

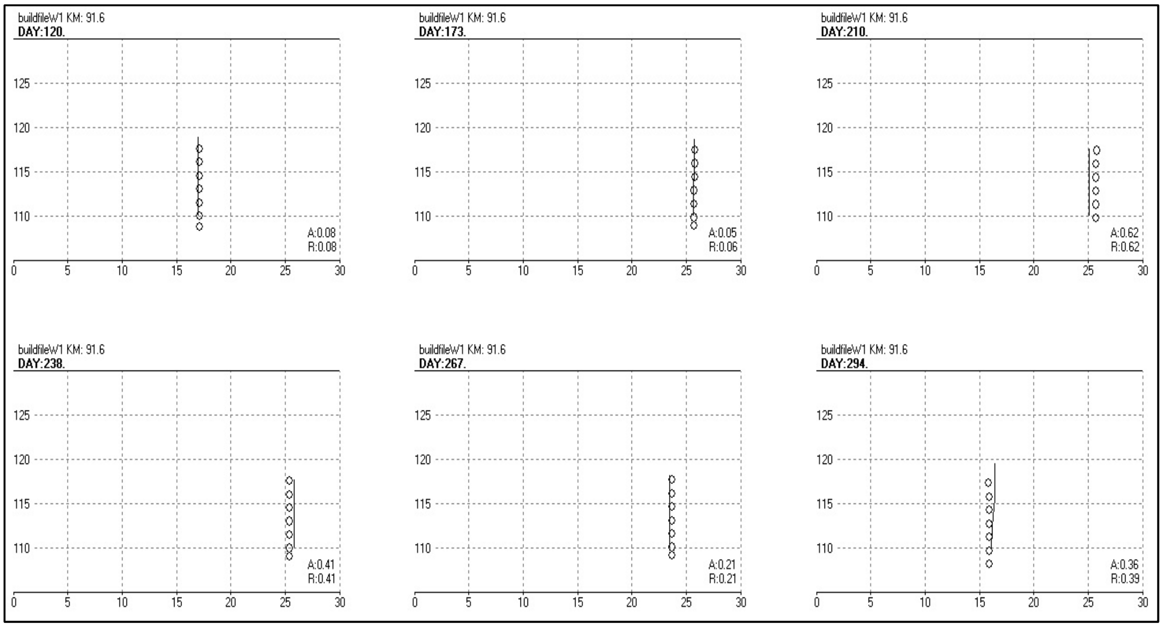


Figure 6-11. Station 11 Temperatures.

The results of the dissolved oxygen calibration are shown in Figure 6-12 through Figure 6-21.

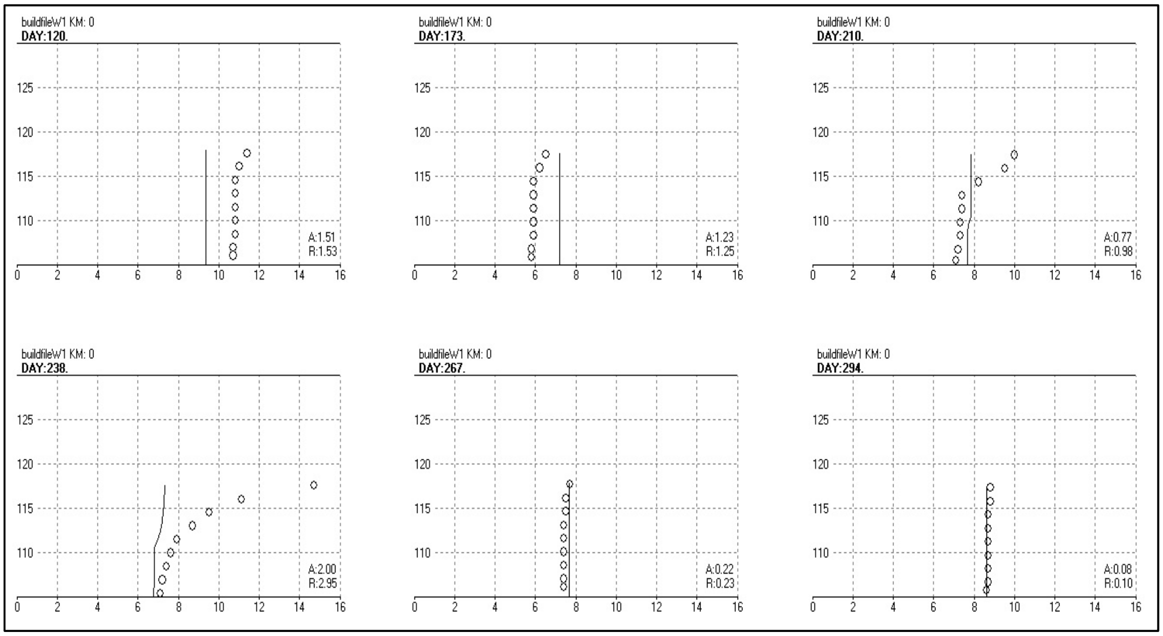


Figure 6-12. Station 2 Dissolved Oxygen.

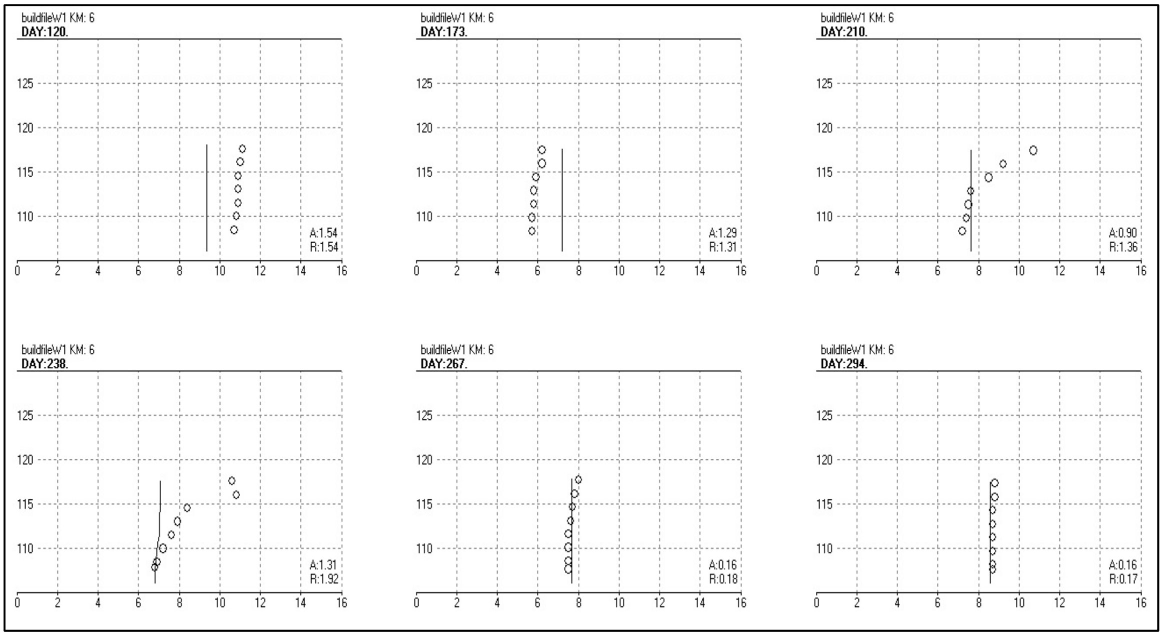


Figure 6-13. Station 3 Dissolved Oxygen.

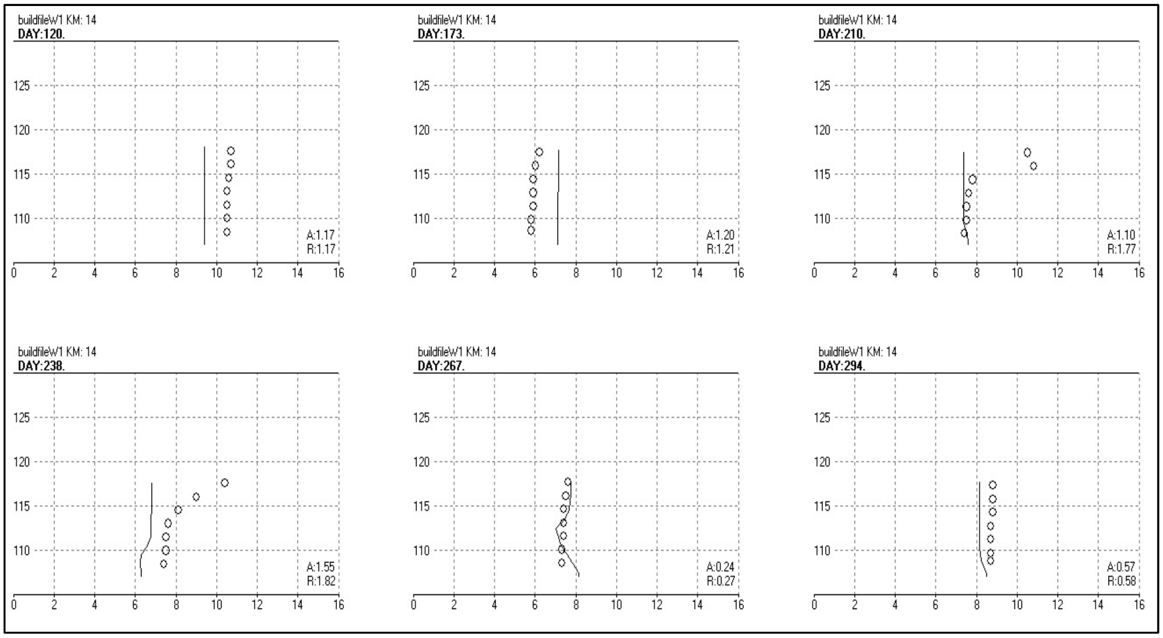


Figure 6-14. Station 4 Dissolved Oxygen.

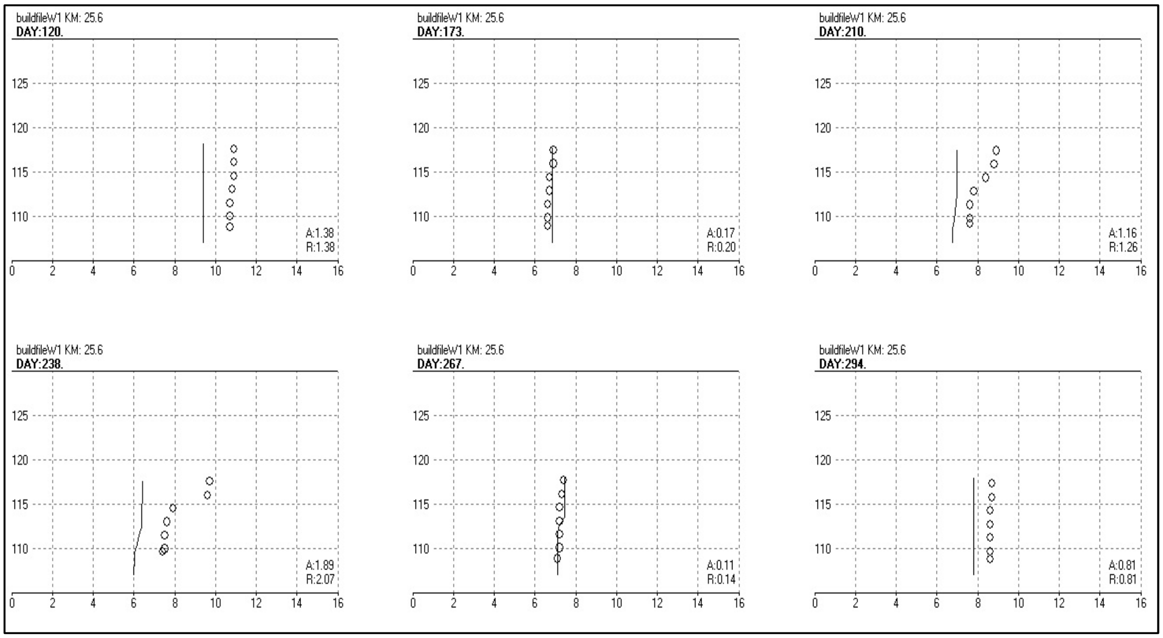


Figure 6-15. Station 5 Dissolved Oxygen.

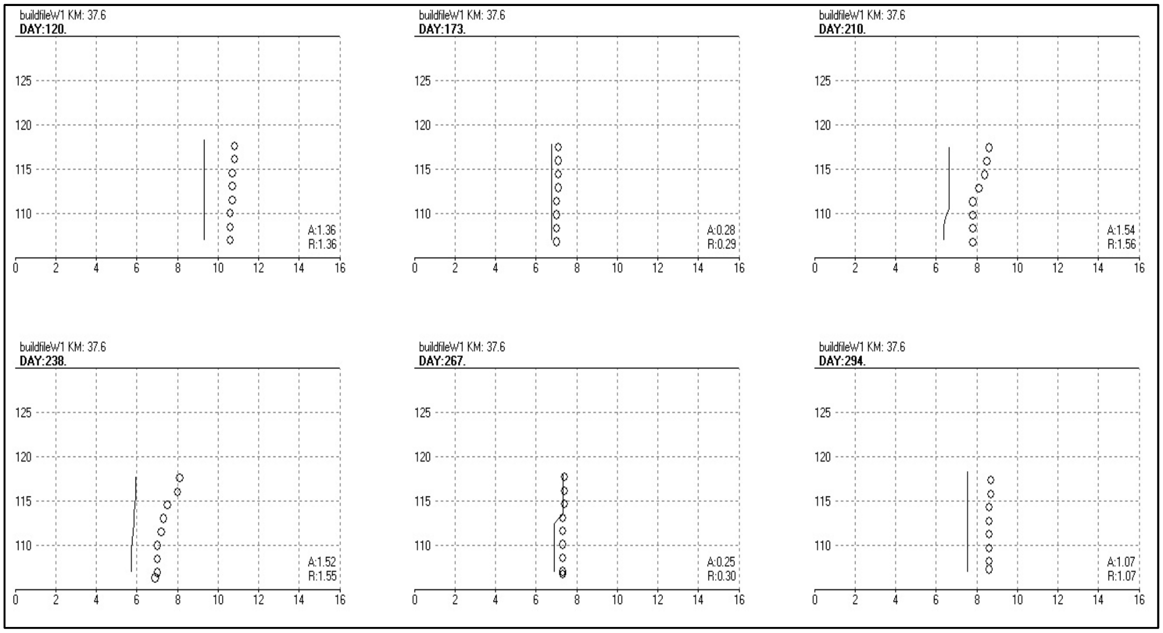


Figure 6-16. Station 6 Dissolved Oxygen.

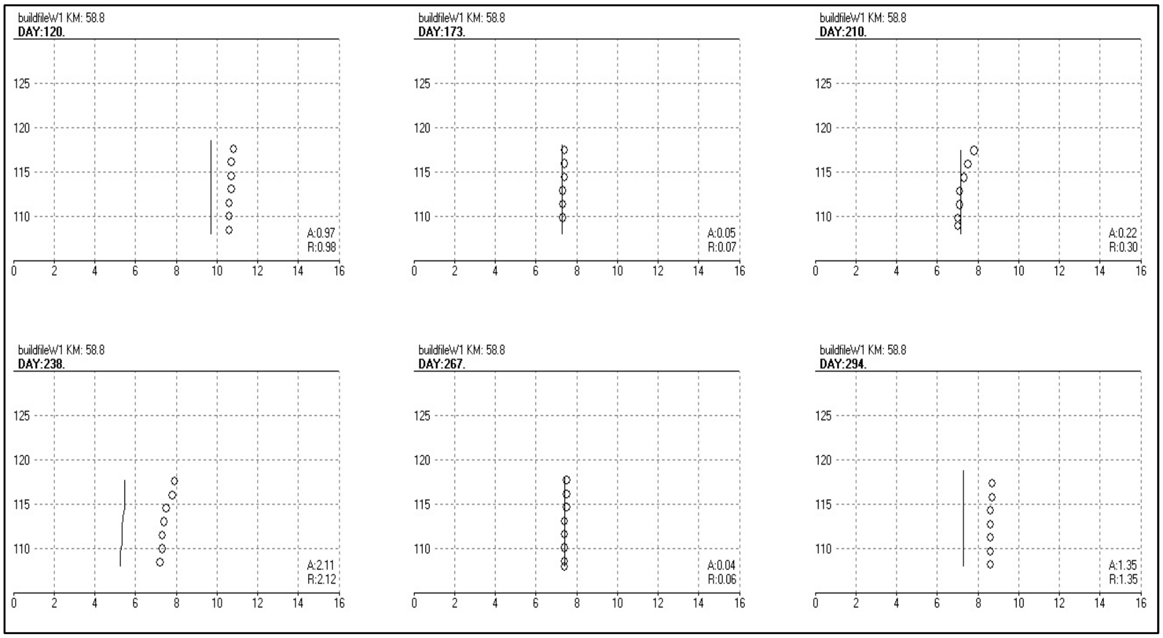


Figure 6-17. Station 7 Dissolved Oxygen.

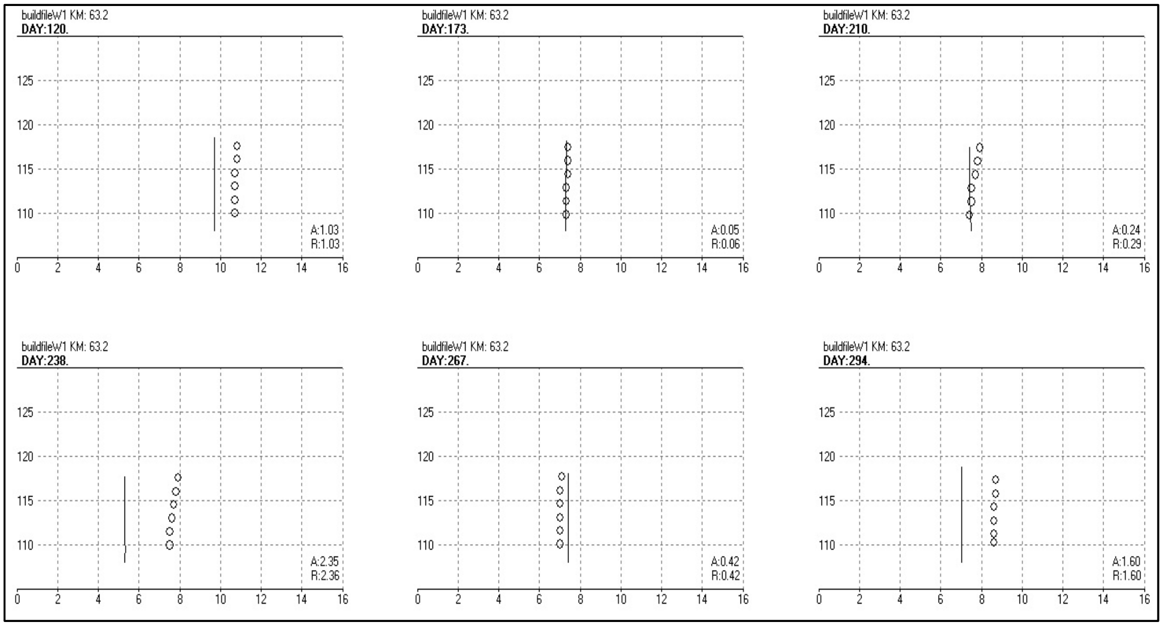


Figure 6-18. Station 8 Dissolved Oxygen.

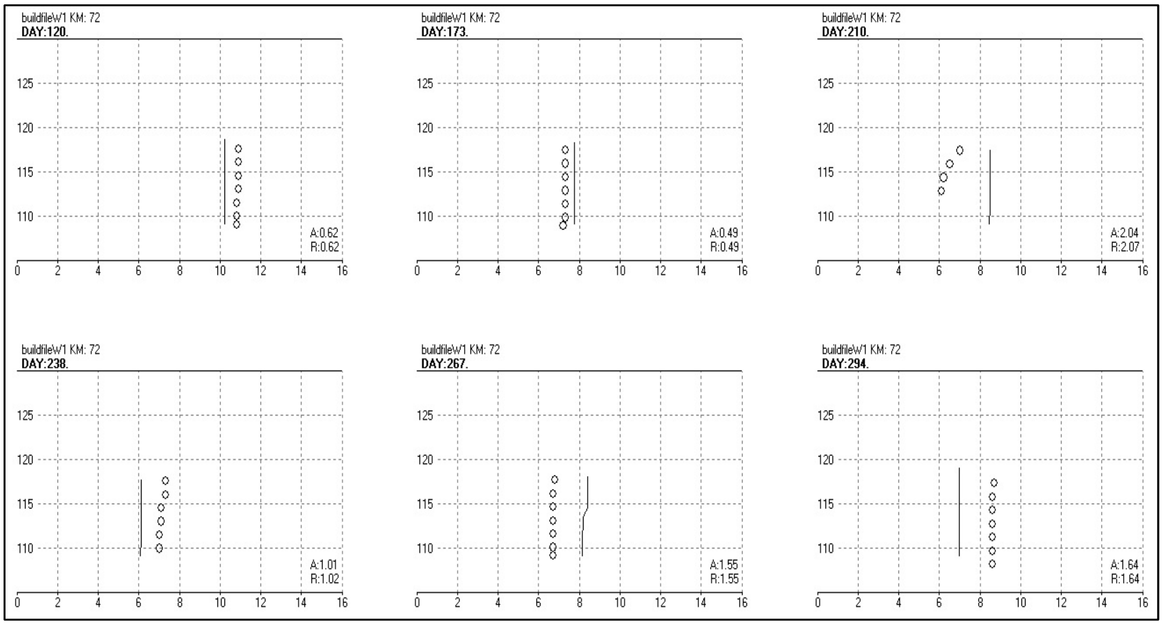


Figure 6-19. Station 9 Dissolved Oxygen.

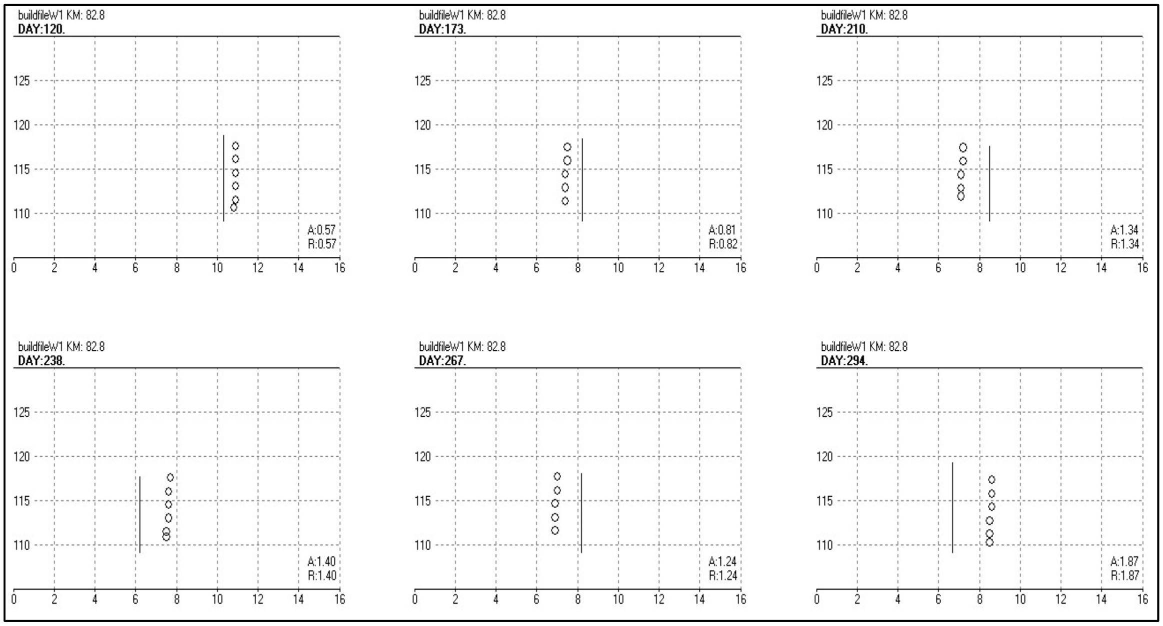


Figure 6-20. Station 10 Dissolved Oxygen.

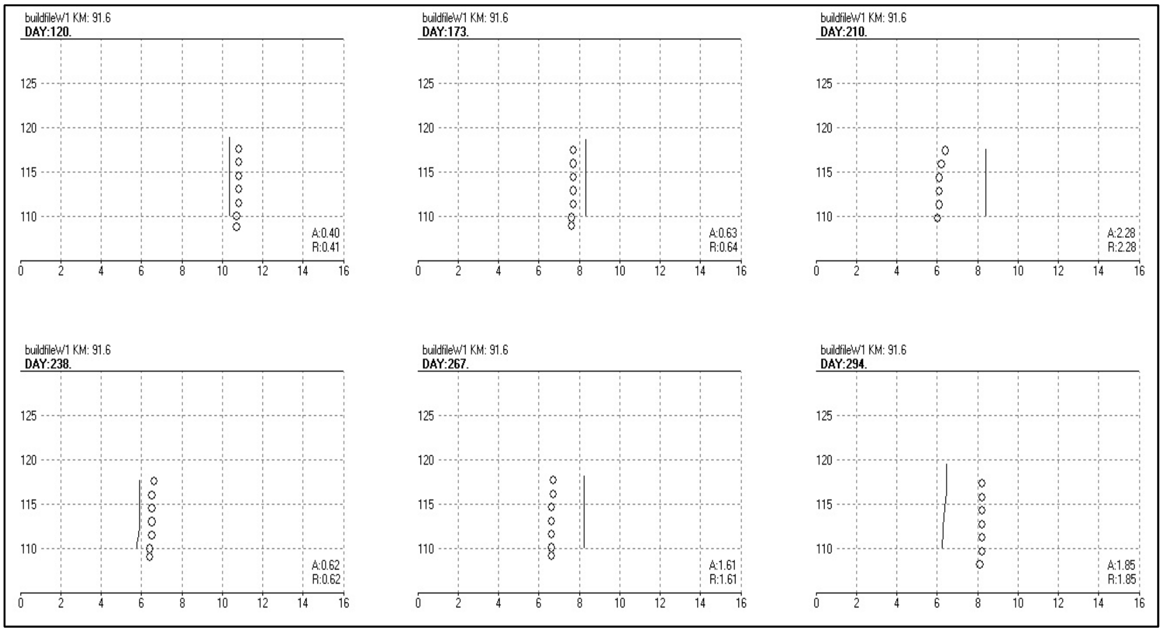


Figure 6-21. Station 11 Dissolved Oxygen.

A summary of the results and corresponding errors for temperature and dissolved oxygen are shown in Table 6-1 and Table 6-2, respectively.

Table 6-1. Station 2-11 Temperature Statistics (°C).

	Day						
Station	120	173	210	238	267	294	Overall
2 AME	0.09	0.15	0.5	0.76	0.27	0.62	0.398
RMS	0.14	0.29	0.61	0.78	0.28	0.62	0.509
3 AME	0.37	0.42	0.54	0.83	0.08	0.6	0.473
RMS	0.4	0.43	0.68	0.91	0.1	0.6	0.581
4 AME	0.39	0.57	1.01	0.72	0.63	0.72	0.673
RMS	0.41	0.59	1.1	0.76	0.83	0.72	0.766
5 AME	0.11	0.14	0.81	0.86	0.41	0.72	0.508
RMS	0.12	0.2	0.84	0.95	0.42	0.72	0.672
6 AME	0.09	0.42	0.9	0.95	0.63	0.51	0.583
RMS	0.1	0.43	0.9	0.98	0.65	0.51	0.595
7 AME	0.31	0.31	0.09	0.35	0.55	0.2	0.302
RMS	0.31	0.31	0.12	0.37	0.55	0.2	0.346
8 AME	0.16	0.1	0.21	0.11	0.57	0.16	0.218
RMS	0.16	0.1	0.22	0.11	0.57	0.16	0.273
9 AME	0.15	0.21	0.09	0.34	0.64	0.12	0.258
RMS	0.15	0.21	0.11	0.34	0.65	0.12	0.336
10 AME	0.2	0.68	0.02	0.17	0.06	0.13	0.210
RMS	0.2	0.68	0.02	0.17	0.06	0.13	0.295
11 AME	0.08	0.05	0.62	0.41	0.21	0.36	0.288
RMS	0.08	0.06	0.62	0.41	0.21	0.39	0.345
					Overall	AME:	0.391
						RMS:	0.472

Table 6-2. Station 2-11 Dissolved Oxygen Statistics (mg/l).

	Day						
Station	120	173	210	238	267	294	Overall
2 AME	1.51	1.23	0.77	2	0.22	0.08	0.968
RMS	1.53	1.25	0.98	2.95	0.23	0.1	1.173
3 AME	1.54	0.129	0.9	1.31	0.16	0.16	0.700
RMS	1.54	1.31	1.36	1.31	0.18	0.17	0.978
4 AME	1.17	1.2	1.1	1.55	0.24	0.57	0.972
RMS	1.17	1.21	1.77	1.82	0.27	0.58	1.137
5 AME	1.38	0.17	1.16	1.89	0.11	0.81	0.920
RMS	1.38	0.2	1.26	2.07	0.14	0.81	0.977
6 AME	1.36	0.28	1.54	1.52	0.25	1.07	1.003
RMS	1.36	0.29	1.56	1.55	0.3	1.07	1.022
7 AME	0.97	0.05	0.22	2.11	0.04	1.35	0.790
RMS	0.98	0.07	0.3	2.12	0.06	1.35	0.813
8 AME	1.03	0.05	0.24	2.35	0.42	1.6	0.948
RMS	1.03	0.06	0.29	2.36	0.42	1.6	0.960
9 AME	0.62	0.49	2.04	1.01	1.55	1.64	1.225
RMS	0.62	0.49	2.07	1.02	1.55	1.64	1.232
10 AME	0.57	0.81	1.34	1.4	1.24	1.87	1.205
RMS	0.57	0.82	1.34	1.4	1.24	1.87	1.207
11 AME	0.4	0.63	2.28	0.62	1.61	1.85	1.232
RMS	0.41	0.64	2.28	0.62	1.61	1.85	1.235
					Overall	AME:	0.996
						RMS:	1.073

The goal of this project was to model temperature to within 0.5 ˚Celsius AME and dissolved oxygen to within 1.0 milligram per liter AME. Temperature-wise, this goal was met overall but not at each individual sampling station. Additional effort should be focused on refining the shapes of the profiles. Surface cooling that is apparent in the field measurements is not captured well in the model. By decreasing the volume of the bathymetry (assumed due to sedimentation) stratification was decreased to more accurately represent the field data. In doing so, the residence time of the reservoir was increased, which is thought to increase mixing and decrease the model's ability to reproduce surface heating. It is believed that with further revision of the bathymetry a more accurate balance could be achieved between the two. Further fine tuning of wind sheltering and shading files would refine the calibration.

In addition to the bathymetry, a better representation and calibration of the phytoplankton life cycle would benefit the temperature calibration of this model. Phytoplankton growth has a direct effect on light extinction, which may be a dominant variable of surface heating. This information could be derived from existing Secchi Disk measurements, available from USACE, and incorporated into this model. This effect was not seen in the initial calibration of temperature (when the water quality component in CE-QUAL-W2 that includes algae calculations is turned off), but was apparent during the dissolved oxygen calibration.

Dissolved oxygen results, though within 1 milligram per liter AME goal overall, also require further refinement. Some effort was made in this model to adjust algae concentrations, algae coefficients, and nutrient loading, with some success. But, the dominant variable of dissolved oxygen was found to be inflow concentration. A major source of error in the inflow concentration of dissolved oxygen was noted to be in the actual gauge information at the tailwater of Old Hickory Dam. This gauge provided the hourly input to the model for dissolved oxygen, but it was found that, because of the location of the gauge, the data supplied to the model was not as accurate as desired. Nonetheless, this data source was still the best available for use in the model.

Figure 6-22 illustrates Old Hickory Dam, as viewed upstream. The temperature and dissolved oxygen gauge is located at the end of the lock wall, on the spillway gate side, as labeled. As can be seen from the figure, when the turbines and spillway gates are in use at the same time, water from the spillway gates blocks the majority of the water from the turbines from reaching the gauge. This is a source of error since the concentrations of dissolved oxygen can be quite different from each source. USACE routinely uses the spillway gates of reservoir dams to improve the dissolved oxygen content, downstream of the dam (U.S. Army Corps of Engineers, 2011). Spilling water through the gates effectively oxygenates the water to near saturation levels. Although turbine generation is the preferred method to release water, spilling is the only tool available, in this particular dam, to oxygenate the water. Other dams on the Cumberland River system employ oxygenation systems within the turbines but Old Hickory Dam is not so equipped (U.S. Army Corps of Engineers, 2011).

Figure 6-22. Old Hickory Lock and Dam.

Both the spillway gates and turbines draw water from approximately 30 feet below the surface of the Old Hickory Lake. During the summer months, oxygen depletion can occur at that depth and USACE will typically employ constant-flow releases, spread across the spillway gates to maximize aeration, designed to improve water quality downstream. During these constant-flow periods, turbine generation, and its associated negligible oxygenation, effectively lowers the dissolved oxygen concentration downstream (after mixing has occurred). From Figure 6-22 it is apparent that only the higher dissolved oxygen concentrations are represented in the data from the gauge on the lock wall. Furthermore, grab sample data, provided by USACE, shows periodic dissolved oxygen measurements taken on the turbine side, and again on the spillway side, of the channel with differences of up to 4 milligrams per liter during the summer months (U.S. Army Corps of Engineers, 2011). A better solution would be to determine a location, by analyzing sampling data, at which mixing between the turbine-released water and spillway-released water has occurred and move the gauge there.

Profile data for days 173, 210, and 267 were all measured during constant spill periods. The overall trend for those days is for the model to predict dissolved oxygen concentrations that are too high. Furthermore, as the profile locations move closer to the Old Hickory Dam, the difference between the model and the field data widens. At the tailwater of the Dam, the greatest discrepancy exists because of the gauge location described earlier. As the water moves downstream natural processes have an increasing effect and the dissolved oxygen concentration more closely reflects the field data.

As a final evaluation of this model, partial data from a different year (2008) was collected, formatted, and input to the current model. Inflow and outflow files were updated but all constituent coefficients remained unchanged. The summer portion of the year (between Julian day 153 and 274) was selected since water quality generally declines during that time. Again, a water balance was calibrated to within 0.5 feet AME. Figure 6-23 and Figure 6-24 illustrate the results for temperature and dissolved oxygen, respectively. The results shown are for Station 2, at the forebay of the Cheatham Dam.

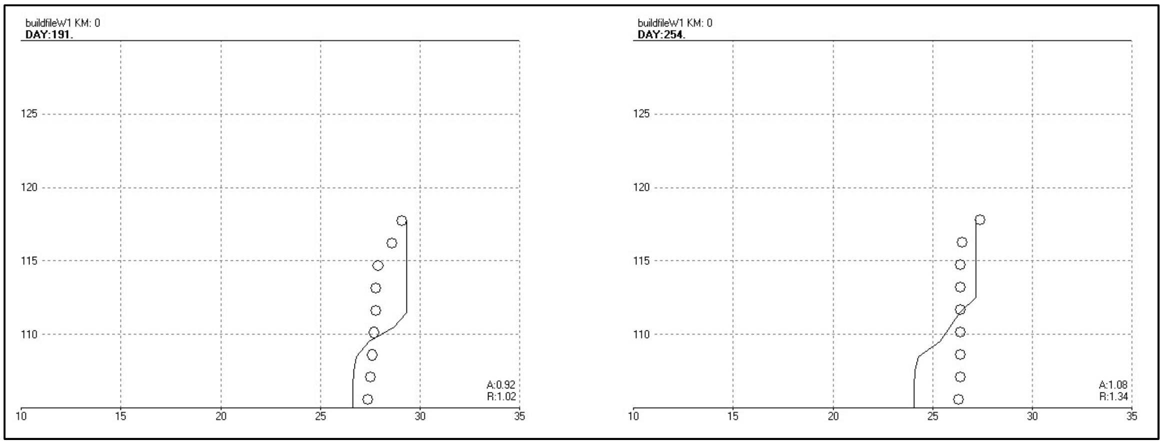


Figure 6-23. Station 2 Temperature results for the calibrated model with 2008 data.

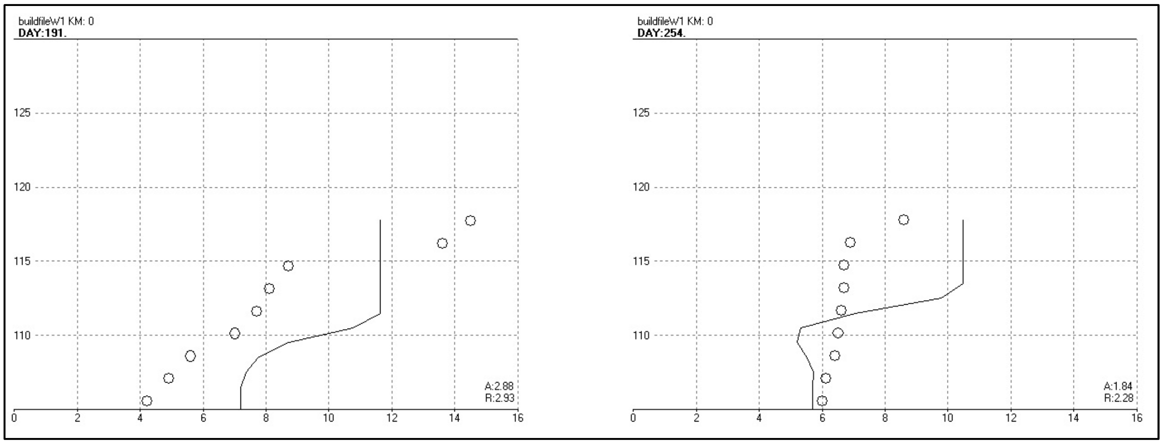


Figure 6-24. Station 2 Dissolved Oxygen data for the calibrated model with 2008 data.

As shown in the preceding figures, further calibration appears necessary. 2008 was a dry year, as defined in Table 5-1, and drought conditions were present during the summer months of that year (U.S. Army Corps of Engineers, 2011). The model predicts less pronounced temperature and dissolved oxygen stratification than the measured field data. Because 2008 was a dry year, stratification is more likely because of the lower associated flows. However, this field data still shows less stratification than the model. This data could be used as an additional calibration tool to adjust the bathymetry to a more refined balance between stratification and the surface heating described earlier. Day 191 and 254 of 2008 were both constant spill periods (U.S. Army Corps of Engineers, 2011). The model data again over-predicts the dissolved oxygen concentrations, consistent with the discussion above. This is believed to be the main source of error in this model.

CHAPTER VII

EXAMPLE USE OF MODEL

A potential use of this calibrated model is a performance analysis of the fixed-cone valve currently installed on the J. Percy Priest Dam. USACE has installed the fixed-cone valve to assist in oxygenating the water in the historically oxygen-deficient Stones River, between the J. Percy Priest Dam and the Cheatham Reservoir, shown in Figure 7-1 and Figure 7-2 (U.S. Army Corps of Engineers, 2011). A different option, used in the past, was to open the spillway gates already installed in the dam. This option was used in 2009, the calibration year of this model. This approach, illustrated in Figure 7-3, has been successful, as it has consistently increased the dissolved oxygen levels 4 to 5 milligrams per liter during the summer months. But, the spillway gate operator's ability to make small adjustments in the gates is limited since the motors that control the gates are analog-style motors that are specifically designed for larger-incremental adjustments. The installation of the fixed-cone valve will hopefully mimic or improve these results.

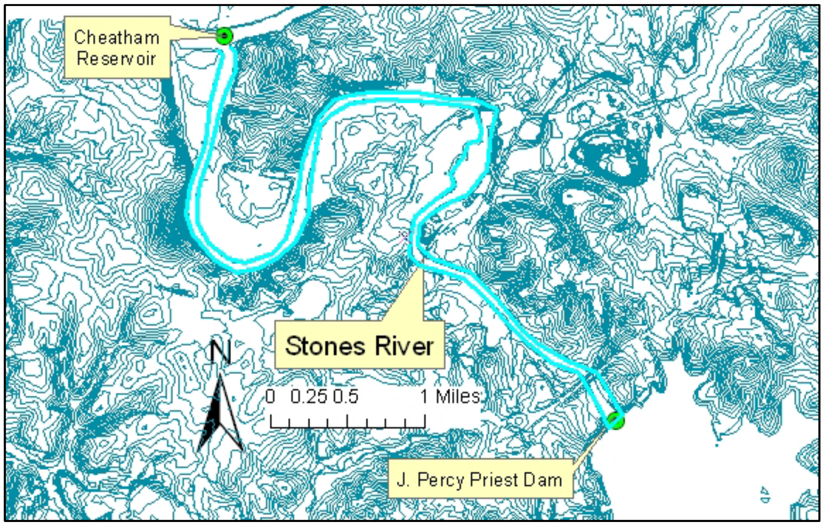


Figure 7-1. Stones River.

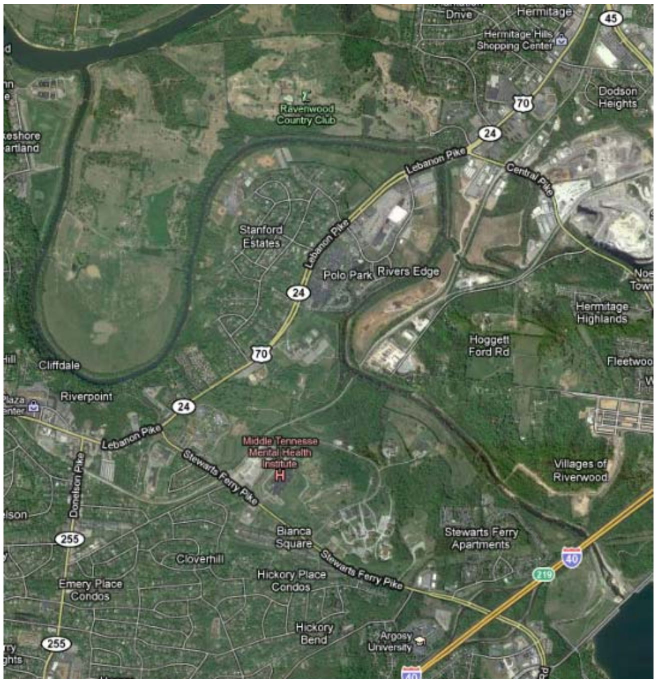


Figure 7-2. Satellite View of Stones River.

The fixed-cone valve functions by discharging water from below the surface of the reservoir into a fixed cone that sprays the water into the air. By misting the water into the atmosphere, the energy present in the water that causes erosion is dissipated, thereby maintaining the channel. That same misting oxygenates the water to levels greater than 80% saturation for the temperature which it was released (Elder, et al., 1969). An improvement over the spillway gate releases is possible since the water released from the fixed-cone valve originates from below the surface and is generally colder and has a higher saturation potential.

Understanding the details of how the output of this fixed cone valve is transferred downstream will provide a base of information as to how best to optimize its use. It will also add to the options available to USACE for improving Stones River water quality. This will benefit aquatic species downstream that rely on high water quality, specifically high dissolved oxygen content.

Figure 7-3 illustrates an average trend of the dissolved oxygen samples taken at the tailwater of J. Percy Priest Dam during the years 1995, 1996, and the values for 2009. Years 1995 and 1996 contained the largest number of samples during the period prior to institution of the minimum-flow requirements by USACE. The data from year 2009 illustrates the effect of the minimum flow releases from the spillway gates.

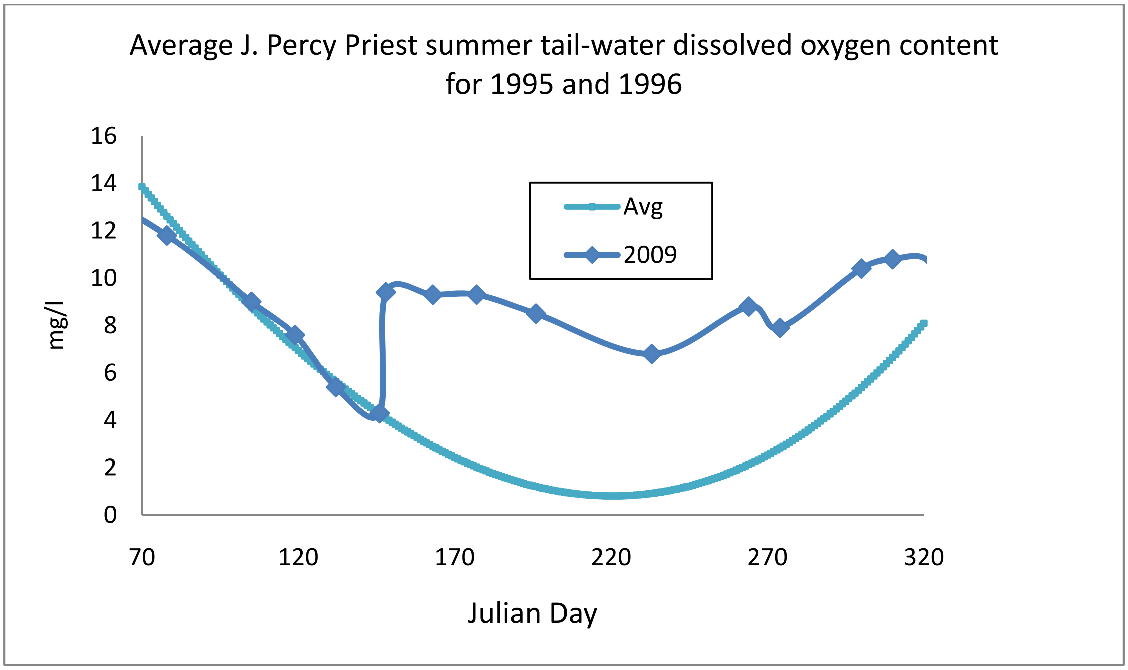


Figure 7-3. Average of 1995 and 1996 versus 2009 J. Percy Priest tailwater dissolved oxygen.

No turbine releases were made in 2009 between Julian day 147 (27 May) and 327 (23 November). To simulate the fixed-cone valve, a flow of 50 cubic feet per second (1.42 cubic meters per second) and 150 cubic feet per second (5.25 cubic meters per second) were used for the inputs of the model. Saturation values for this discharge were calculated by using the temperature of the water in the discharge and Mortimer's formula, shown in the Inflow Regression section. The intake elevation of the fixed-cone valve is 465.0 feet (141.77 meters) above mean sea level. Temperature data 25 feet (7.62 meters) below the normal summer pool elevation of 490 feet (149.39 meters) and a trendline and formula are shown in Figure 7-4.

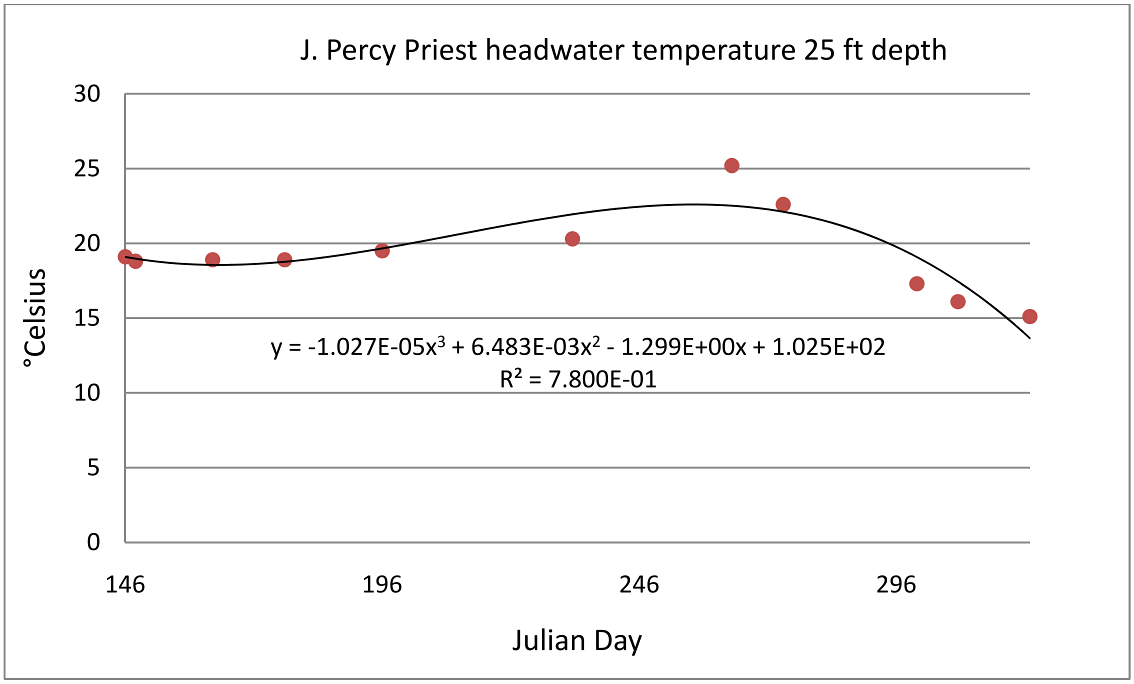


Figure 7-4. J. Percy Priest Headwater Temperature 25 ft Depth.

Using the equation shown, daily temperature data were generated for Julian days 147 through 327. Corresponding dissolved oxygen saturation values were also calculated. This data was used in place of the flow, temperature, and dissolved oxygen data for the calibrated model.

In order to provide an accurate simulation, water balances for each of the flow values were redone. No other changes were made to the existing model. Figure 7-5 shows the simulated dissolved oxygen content for the tailwater of J. Percy Priest during the summer months. This is theoretical since the low-flow requirements were actually in effect at that time. The five peaks on the left side are due to backwater effects from the Cumberland. The average trend illustrates the low dissolved oxygen seen in past years. Figure 7-6 shows the same location with 50 cubic feet per second discharge at saturation from the fixed-cone valve.

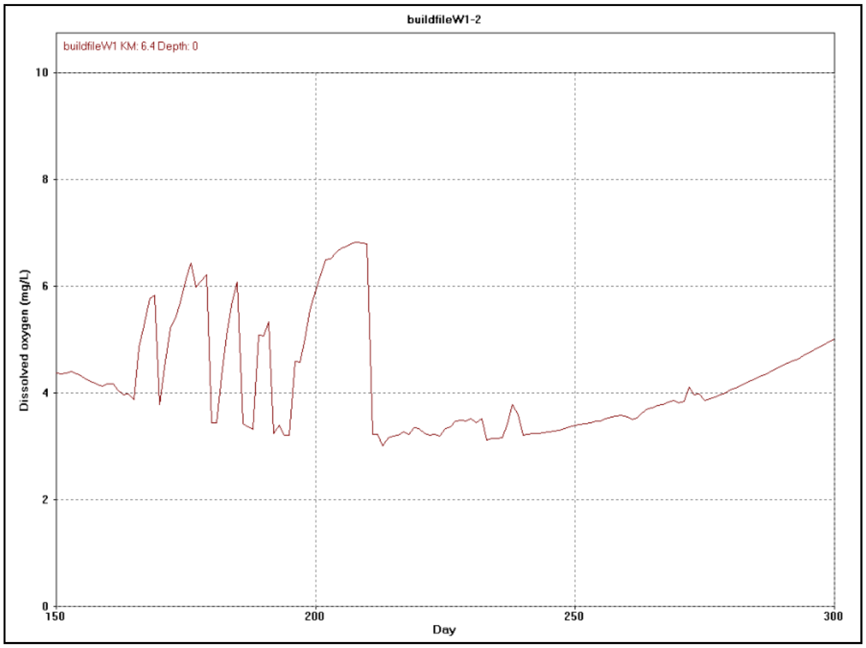


Figure 7-5. Dissolved oxygen at the tailwater of the J. Percy Priest Dam with no flow from fixed-cone valve.

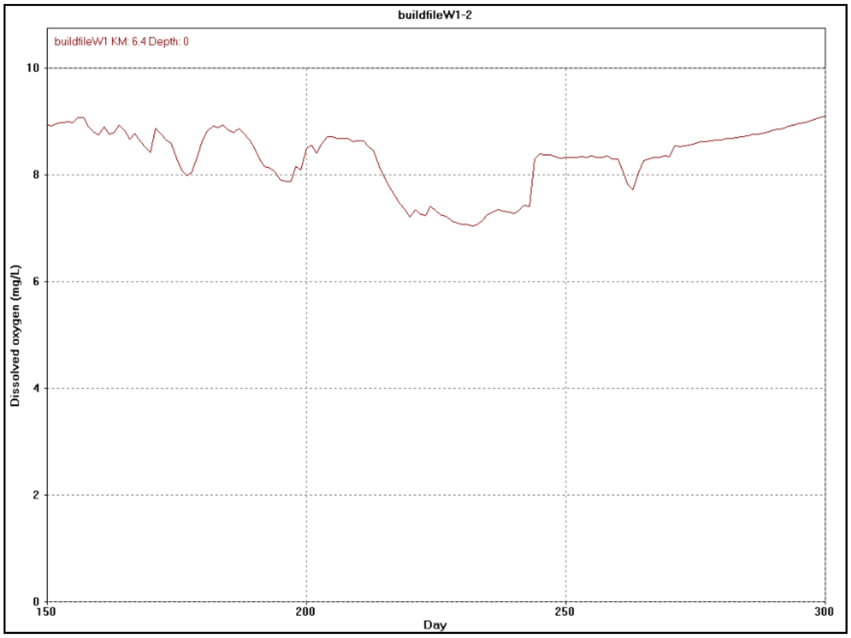


Figure 7-6. Dissolved oxygen at the tailwater of the J. Percy Priest Dam with 50 cubic feet per second from fixed-cone valve.

Figure 7-7 shows the result of no flow from the fixed-cone valve at the confluence of the Stones River and the Cheatham Reservoir. Figure 7-8 shows the effect of 50 cubic feet per second from the fixed-cone valve at the confluence of the Stones River and the Cheatham Reservoir. Thus, 50 cubic feet per second constant flow from the fixed-cone valve, assuming the discharge is at saturation, shows approximately 3 milligrams per liter dissolved oxygen improvement at the tailwater of the J. Percy Priest Dam. Furthermore, at the most distant point downstream of the Stones River, the valve produces an increase of approximately 2.5 milligrams per liter dissolved oxygen.

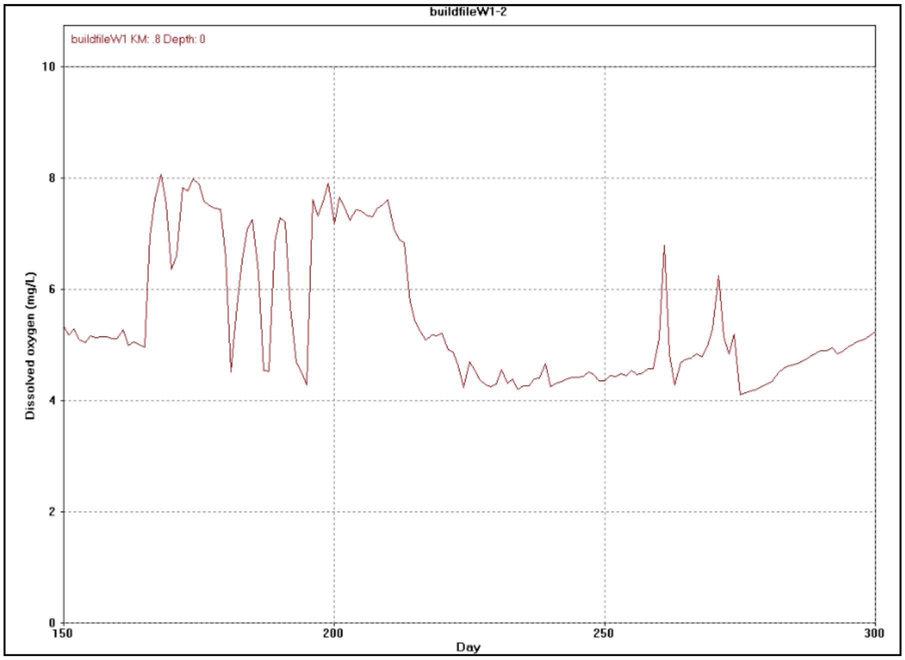


Figure 7-7. Dissolved oxygen at confluence of Stones River and Cheatham Reservoir with no flow from fixed-cone valve.

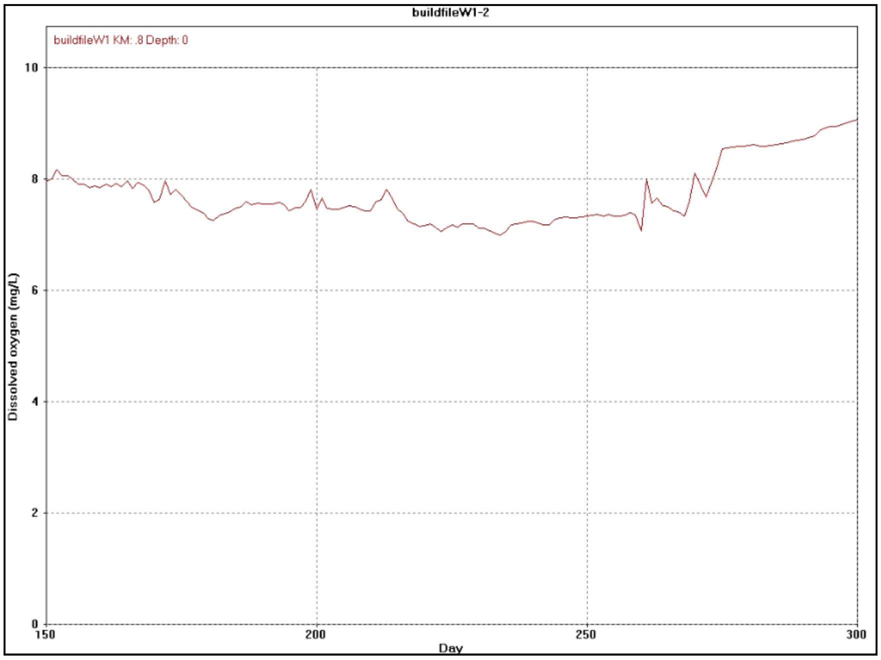


Figure 7-8. Dissolved oxygen at confluence of Stones River and Cheatham Reservoir with 50 cubic feet per second flow from fixed-cone valve.

As expected, more pronounced effects result from using 150 cubic feet per second discharge from the fixed-cone valve. At the most downstream point of the Stones River, the difference between 50 cubic feet per second and 150 cubic feet per second is shown in Figure 7-9.

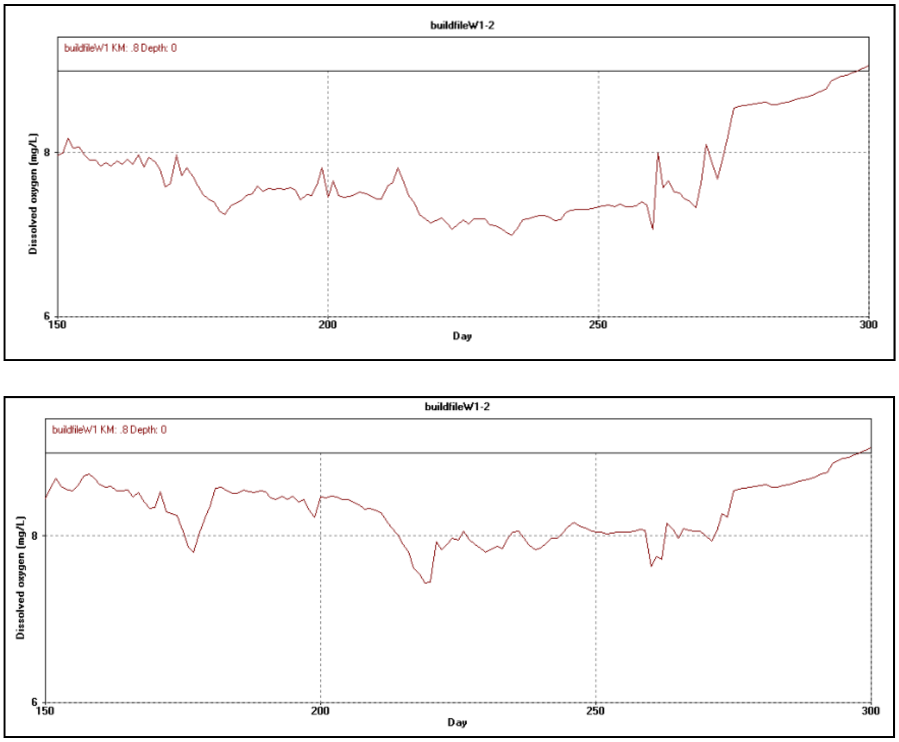


Figure 7-9. 50 cubic feet per second (upper diagram) versus 150 cubic feet per second (lower diagram)

Unfortunately, no field data exists to show the actual effect of use of the fixed-cone valve. Use of a calibrated model, however, can provide a useful means to examine the probable effects of fixed-cone valve operation more quickly and less expensively than regular field measurements. Not only do the example simulations above illustrate an improvement in dissolved oxygen content, but they are also able to provide water managers information on the relative impacts of reduced flow from the valve, a possible option during drought conditions. Of course, field data during fixed-cone valve operations are necessary to calibrate model parameters for the fix-cone valve aeration efficiency prior to more extensive use.

CHAPTER VIII

FUTURE

This CE-QUAL-W2 model possesses several useful attributes. First and foremost, this model may be used as a tool to better understand the complex hydrodynamic and water quality processes that occur within the Cheatham Reservoir. In addition, this model has the potential to be used to analyze different scenarios that may be of interest to water managers that make decisions on overall reservoir management, especially as it relates to water quality.

As one part of a larger system, this reservoir is impacted by the effects of water management decisions made upstream, and passes its effects to the next section of the river. On a broader scale, this model describes a section of a river that has significant impacts with respect to the environment, flood control, power generation, and navigation. As stated previously, this model represents an approximation of some of the natural processes occurring within this waterbody. However, a person using this model will develop an improved understanding of some of the interactions that occur, most notably the relationship between algae and associated nutrients that affect dissolved oxygen concentration, and the best means to describe these interactions mathematically.

In addition, this model will allow water managers at USACE to more quickly and accurately make decisions as to how to operate the river. Though hydraulic records are kept for each year and those records are analyzed to gain a better understanding of the consequences of different operational techniques, each year is different and a tool that is able to predict future outcomes based on current inputs is very useful. Even though subsequent years may be similar, each individual year possesses its own details that can offer challenges on a smaller level. A model with the ability to predict water temperatures to within 0.5 °C AME possesses significant value to the water managers that make environmental decisions affecting a number of water quality-related matters, including fish habitat and fossil steam plant efficiency on a daily, and sometimes hourly, basis.

This model provides a critical link between sections of the Cumberland and adds to the overall understanding of how the Cumberland affects downstream hydrodynamics and water quality, and how to best optimize its use on a system-wide scale. Further, this model expands upon earlier attempts at describing the Cheatham Reservoir. The 1989 BETTER Model of the Cheatham Reservoir, while useful at the time of its development, has given way to more capable models that possess an ability to solve more complex equations. The 2003 CE-QUAL-W2 model was updated to the current version 3.6 and calibrated in much more detail.

Although well calibrated to the 2009 flow record, the largest improvement that can be made to this model is to calibrate to additional years of data. A single year is a start, but, as mentioned in Chapter V, additional years of data calibration may even improve the first year. A small example of the added benefit of additional years of data was shown in the Chapter VI by using partial data from 2008. That data provided a glimpse of the model performance under a dry year. Examination of how this model responds to additional inputs of different types of years (wet, dry, and normal) would give more confidence that the model can predict an accurate outcome for a wider variety of inputs.

Another improvement that can be made in this model is with respect to the gauge location, discussed in Chapter VI. Though the hourly flow data available at the Old Hickory Tailwater Gauge is the best available, it is inducing unnecessary error into the model because of its location. With little sampling effort, a suitable location downstream could be determined by analyzing when mixing of the turbine water and spillway water has occurred and where an accurate reading could be made. As such, additional effort should be made to determine the effect of gauge location on other constituents. Currently, the model uses a yearly average for constituent loading that includes total dissolved solids, suspended solids, phosphorus, ammonia, nitrate/nitrite, iron, inorganic carbon, and alkalinity and uses the same values for the turbine-released and spillway-released water. By examining the differences in these variable locations, the calibration may be refined even further. A different approach may be to develop a correction factor for use when there is a significant difference between the values being released from the turbines and spillway gates.

Lastly, an improvement could be made in model efficiency. With all water quality calculations turned “On”, this model takes approximately 4 hours to complete a full year. Cheatham Reservoir is usually a well-mixed reservoir and using 400 meter segments most likely is not required. A sensitivity analysis should be run to ensure little to no loss in resolution would result from increasing the segment lengths. By doing this, the speed of the model could be increased considerably.

Overall, this model met the stated goals for accuracy when compared to available data, but there remain opportunities for improvement. Nonetheless, the model represents a significant improvement over other versions of models for the Cheatham Reservoir and thus should serve as an excellent representation of the Cheatham Reservoir section of the large, linked Cumberland River model being pursued by USACE.