US Army Corps
of Engineers ®
Nashville District

CENTER HILL LAKE
CE-QUAL-W2
WATER QUALITY MODEL

FINAL REPORT
February 20, 2001

CENTER HILL LAKE
CE-QUAL-W2
WATER QUALITY MODEL

Prepared for

U. S. Army Corps of Engineers
Nashville District

Under Contract
DACW 62-98-D-0002
Delivery Order No. 0011

Prepared by

FTN Associates, Ltd.
3 Innwood Circle, Suite 220
Little Rock, AR 72211

FINAL REPORT
February 20, 2001

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
20 February, 2001

3. REPORT TYPE AND DATES COVERED
Final Report

4. TITLE AND SUBTITLE
Center Hill Lake CE-QUAL-W2 Water Quality Model

5. FUNDING NUMBERS

6. AUTHOR(S)
Christina R. Lauren, Dennis E. Ford

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
FTN Associates, Ltd.
3 Innwood Circle, Suite 220
Little Rock, AR 72211

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U. S. Army Engineer District, Nashville
P. O. Box 1070
Nashville, TN 37202-1070

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The objective of this study was to provide a calibrated temperature and water quality model for Center Hill Lake suitable for addressing management related issues. CE-QUAL-W2 (Version 2.05), a two-dimensional, longitudinal and vertical hydrodynamic and water quality model, was chosen as the model for this application. Modifications to the model included the use of three algal compartments instead of one, addition of silica as a water quality constituent affecting algal productivity, and addition of an algorithm to create an output file to be used by the Animation and Graphics Portfolio Manager (AGPM) pre- and post-processor.

The model was calibrated to three years (1973, 1988 & 1996) representing dry, wet and average hydrologic conditions. The study included the development of boundary conditions for the major inflows through regression analyses.

The calibrated model was used to evaluate the impacts of point source discharges on water quality conditions in Center Hill Lake.

14. SUBJECT TERMS
CE-QUAL-W2, Eutrophication, Dissolved Oxygen, Model, Temperature, Center Hill Lake

15. NUMBER OF PAGES
77

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

TABLE OF CONTENTS

TABLE OF CONTENTS (CONTINUED)

TABLE OF CONTENTS (CONTINUED)

LIST OF APPENDICES

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (CONTINUED)

LIST OF FIGURES (CONTINUED)

1.0 INTRODUCTION

Center Hill Lake water quality modeling was performed for US Army Corps of Engineers Nashville District (District) under Contract Number DACW62-98-D-002, Delivery Order No. 0011. The objective of this modeling effort is to provide the District with a calibrated CE-QUAL-W2 model of Center Hill Lake that is suitable for evaluating existing water quality conditions and temporal trends, and predicting water quality conditions in the reservoir under various management scenarios.

The CE-QUAL-W2 water quality model was selected for use because of its applicability in addressing concerns related to the District projects. This report describes model calibration, confirmation, and simulation of management scenarios. Results of these activities and the dominant physical, chemical, and biological processes affecting Center Hill Lake water quality are specifically highlighted in the report.

The report sections are arranged in chronological order with respect to steps initiated in the modeling procedure. It should be noted that steps involved in the modeling procedure are interdependent and may be repeated as part of an iterative process.

This report is organized as follows:

- Section 2.0 describes the general characteristics of Center Hill Lake and its watershed.
- Section 3.0 describes the development of the reservoir bathymetry file, including branches, tributaries, and outlet configuration.
- Section 4.0 describes procedures for the calibration of the water budget, hydrodynamics, temperature and water quality.
- Section 5.0 describes simulation of modified point source contributions.
- Section 6.0 lists references.

2.0 BACKGROUND

2.1 Reservoir and Watershed System

Center Hill Lake is a U.S. Army Corps of Engineers multi-purpose reservoir located in central Tennessee (Figure 2.1). It is part of the Cumberland Basin flood control system. The reservoir is the result of impounding the Caney Fork River at river mile 26.6. The reservoir became operational in 1951. Morphometric characteristics of the reservoir are summarized in Table 2.1. Project purposes include flood control, power generation, recreation, water supply (Cities of Cookeville and Smithville, TN), water quality, and fish and wildlife conservation.

The majority of the Center Hill Lake watershed (77%) drains to the Caney Fork and Collins Rivers. These rivers are impounded by the Great Falls Dam located just upstream of Center Hill Lake at Caney Fork river mile 91.1. Great Falls Reservoir is managed by the Tennessee Valley Authority (TVA) for power generation.

Table 2.1. Morphometric characteristics of Center Hill Lake.

	English Units	Metric Units
Volume, V	1.33 x 10^6 ac-ft	1.64 x 10^8 m^3
Length, L	63.6 mi	102.4 km
Surface area, SA	18,220 ac	73.7 km^2
Mean width, W (A/L)	0.45 mi	0.72 km
Max. depth, Zm	156 ft	48 m
Mean depth, Z (V/A)	73 ft	22.2 m
Hydraulic residence time, t (V/Q)	0.46 yr	0.46 yr
Watershed area, DA	2,174 mi^2	5,631 km^2
Normal pool elevation range	30 ft	9 m
Average inflow, Q	3,954 cfs	112 m^3/sec
Range of inflow	19 to 210,000 cfs	0.5 to 5,947 m^3/sec
Outlet elevations (invert elev.)	538/496/648 ft msl	164.0/ 151.2/ 197.5 m msl

Notes:
1) All reservoir dimensions are based on a water surface elevation of 648 ft.
2) Range of inflow is based on 1911-1994 USGS Station downstream of Great Falls Dam (03422500).
3) Average inflow is based on center Hill releases from 1973, 1988, and 1996.
4) Outlet elevations are for penstocks/sluices/spillway.

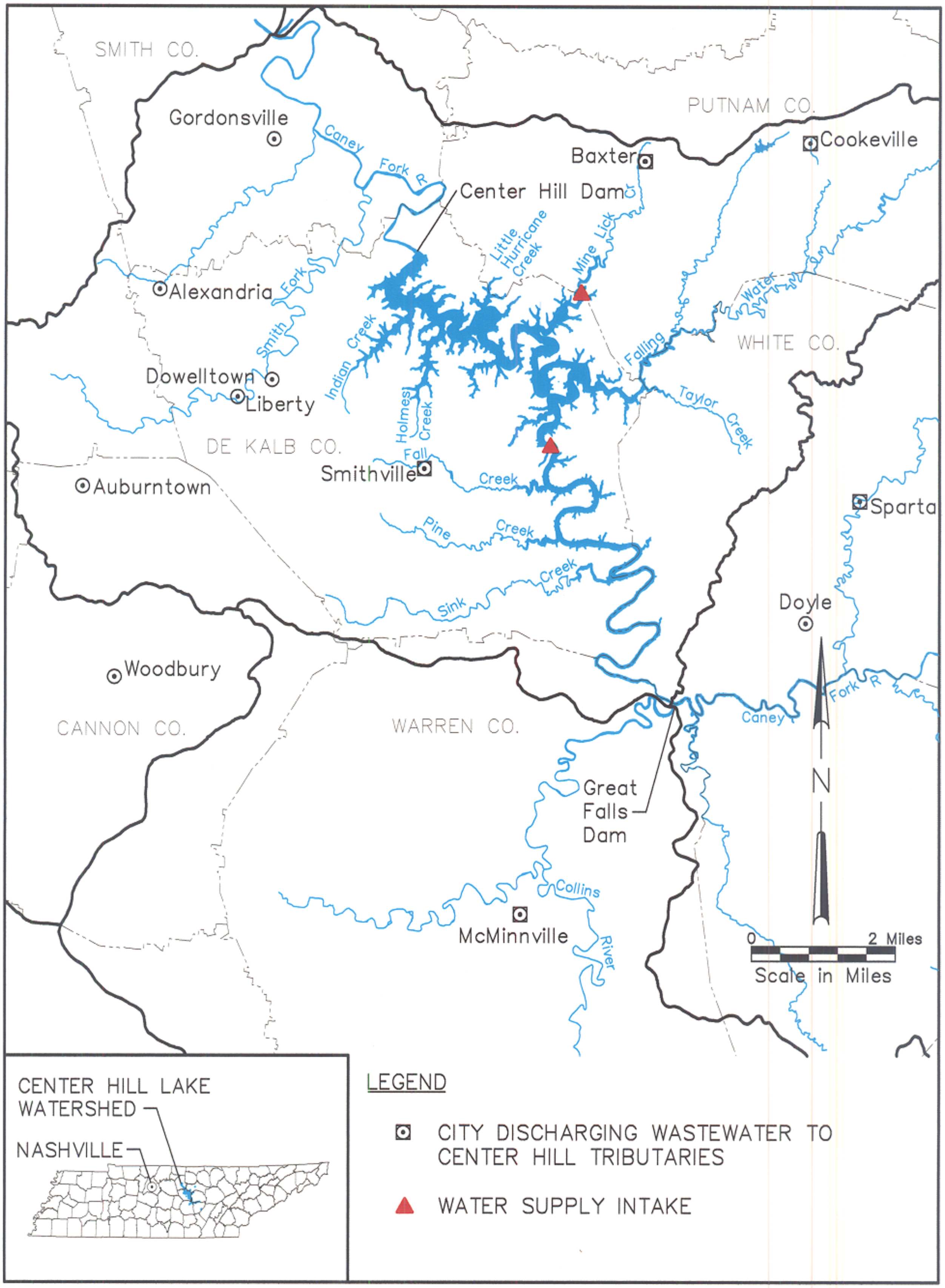


Figure 2.1 Site location map of Center Hill Lake

The watershed is fairly evenly split between agricultural land uses (48%) and forested land (49%) (Tennessee Wildlife Resources Agency, 2000). Tobacco, corn, soybeans, hay and wheat are the primary crops grown in the watershed. Cattle, poultry, and hogs are also raised in the watershed.

The largest town in the watershed is Cookeville, TN with a 1989 estimated population of approximately 25,000 people (US Census Bureau). There are a number of towns that discharge treated wastewater to Center Hill Lake tributaries. These towns are indicated on Figure 2.1 by a box around the town marker. There are also a number of businesses that discharge wastewater in the watershed. These discharges are not shown on the map. However, a list of NPDES permitted discharges in the watershed is included as Appendix A.

2.2 Reservoir Water Quality

Center Hill Lake is monomictic with summer temperature stratification and complete mixing in the winter period. Thermal stratification begins in March and continues through November until the onset of fall overturn. The water column is completely mixed from November until the start of spring stratification.

The District monitors water quality in the reservoir by collecting in situ measurements and water quality samples at a series of stations in the reservoir and five reservoir tributaries. The locations of the stations are shown in Figure 2.2. Samples are typically collected twice a year. Samples are analyzed for nutrients and chlorophyll *a*, among other parameters.

Table 2.2 lists characteristic values of several indicator parameters that are associated with three trophic states. Historical ranges of these indicator parameters measured in Center Hill Lake are also listed. Comparing the Center Hill Lake ranges to those for the various trophic states, results in a meso-eutrophic classification for the reservoir. Center Hill Lake water quality is similar in some respects to that of a mesotrophic system, and in other respects is similar to a eutrophic system.

In 1988, an intensive water quality study was performed on Center Hill Lake to determine the nutrient load to the reservoir and its trophic state. This study concluded that the main body of

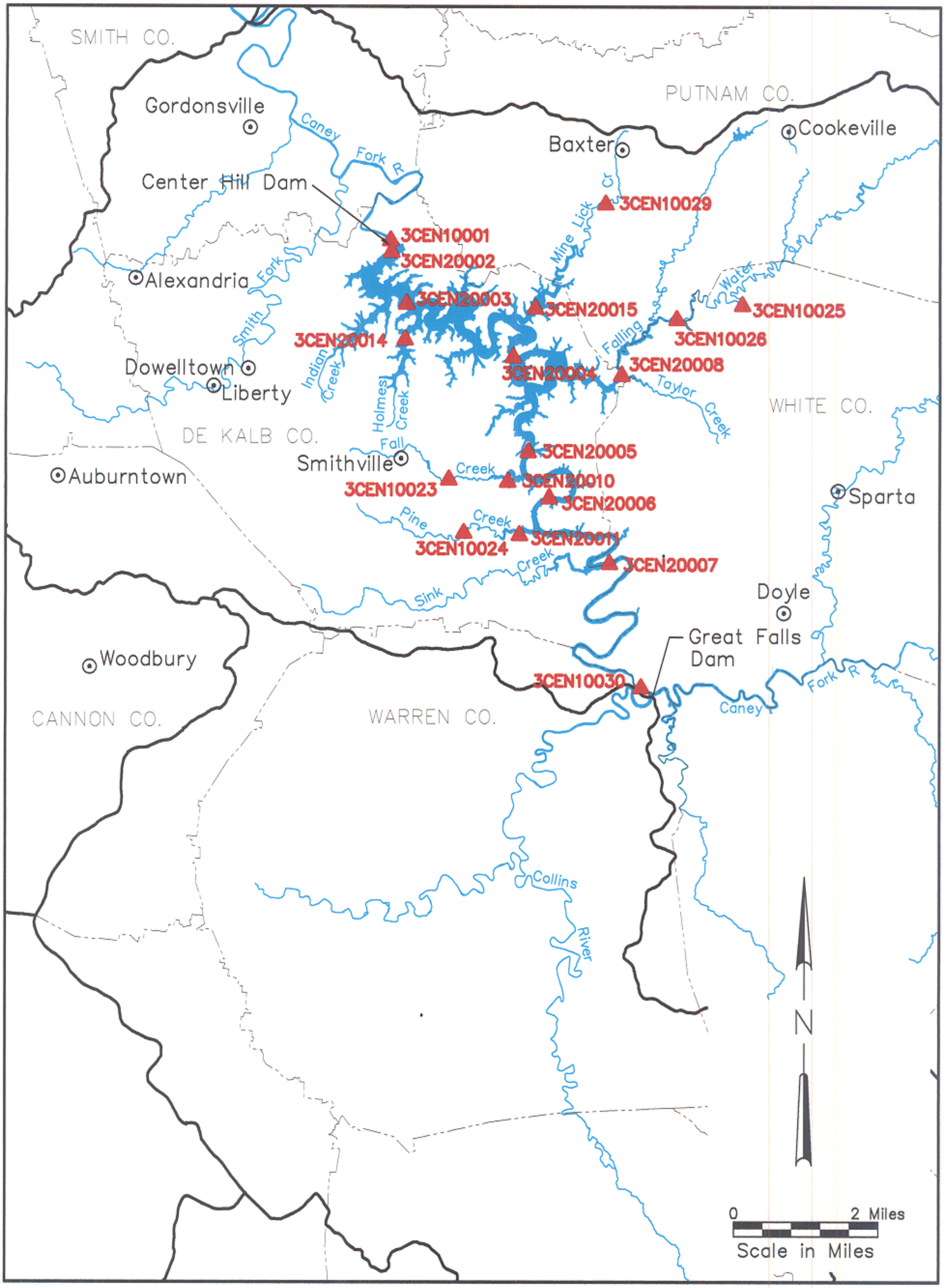


Figure 2.2 District water quality monitoring stations for Center Hill Lake

the reservoir was mesotrophic, while embayments tended to be eutrophic (S.J. Pucker et al. 1989). 1976 and 1979 reports on the reservoir water quality classify it as eutrophic (USAE Nashville District 1976, J.A. Gordon 1979). Pucker et al. stated that algae blooms were neither an aesthetic nor a water supply treatment problem in the reservoir. There has not been a record of algal blooms occurring in the reservoir (Personal communication with personnel at Center Hill Lake). The 1976 water quality report did mention occasional algal and fecal coliform problems at the City of Cookeville water treatment plant. Pucker et al. indicated that nutrient levels in Center Hill Lake were lower in 1988 than those reported in the 1976 report indicating improvement in the reservoir water quality. Improved waste water treatment and changes in watershed land uses were cited as likely causes for the reduction in nutrients.

Table 2.2. Trophic status indicators and Center Hill Lake status[1].

Indicator	Trophic State Mean and Range			
	Oligotrophic	Mesotrophic	Eutrophic	Center Hill Lake (1970 - 1999)
Summer Oxygen Distribution (mg/L)	Orthograde, Hypo. DO>2	Hypo. DO>0 to Anoxic	Clinograde, Anoxic	Clinograde, Anoxic
Total Phosphorus (μg/L)	8 3–18	27 11–96	84 16–386	50 10-520
Total Nitrogen (μg/L)	660 300–1,630	750 360–1,390	1875 390–6,100	680 100-1800
Secchi Depth Transparency (m)	10 5.5–28.5	4 1.5–8	2.5 1–7	2.28 0.80-5.00
Average Summer Chlorophyll *a* (μg/L)	1.5 0.3–4.5	5 3–10	15 3–75	5.1 0.5-32

[1] Modified after Wetzel (1983)

2.3 Great Falls Effect

The Great Falls Dam, which is located on the Caney Fork River at river mile 91.1, controls the majority of the flow coming into Center Hill Lake. 77% of the Center Hill Lake watershed is upstream of the Great Falls Dam and releases from Great Falls, on average, account for 80% of the inflow to Center Hill Lake. Therefore, releases from Great Falls have the potential to significantly affect Center Hill Lake water quality. Releases from Great Falls are primarily from its power generation facility located downstream of the dam at river mile 90.6. In general, releases from impoundments have the potential to have cooler temperatures, lower dissolved oxygen (DO) concentrations and greater dissolved nutrient concentrations than natural streams if the impoundments stratify and releases come from the hypolimnion.

There is limited water quality data available for Great Falls reservoir. Temperature and DO profiles measured in Great Falls reservoir during 1969-1970 are included in Appendix B. Temperature profiles taken at Great Falls Dam during July, August, and September 1969 show that the Great Falls reservoir does stratify. DO profiles measured at the dam at the same time show that the hypolimnion does become anoxic. However, releases at the dam come only from the spillway (crest elevation 791.2 ft) so cooler, low DO water at the dam would not typically be released downstream.

Water for the Great Falls turbine generators is pulled from the Collins River approximately 1.7 miles upstream of Great Falls Dam. No summer water quality profiles were available near the intake. Profiles were measured during the summer of 1969 in Collins River at river mile 0.2 (approximately 0.4 miles upstream of Great Falls Dam) and river mile 5.3 (approximately 5.5 miles upstream of Great Falls Dam). Profiles at Collins River mile 0.2 show temperature stratification and some low hypolimnetic DO concentrations. Profiles at Collins River mile 5.3 do not show temperature stratification nor low DO concentrations. It would seem possible that the reservoir does stratify at the intake and may experience low hypolimnetic DO concentrations since this occurs at Collins River mile 0.2. The invert elevation of the intake is 753.7 ft. Normal operating pool elevations for Great Falls range from 805 ft to 785 ft. The historical median pool elevation in July through September is about 800 ft. Therefore, if the reservoir did stratify and/or become anoxic at the intake, cooler, low DO water could be released downstream.

Figure 2.3 shows box and whisker plots comparing water temperature, DO, dissolved ortho-phosphorus (OP), ammonia-N, and nitrate + nitrite-N historical data (1987 – 1999) at the five tributary monitoring stations (see Figure 2.2). Box and whisker plots are a convenient way to summarize and compare data. The notch in the box indicates the sample median and 95 % confidence interval about the median. When notches in boxes do not overlap, the samples

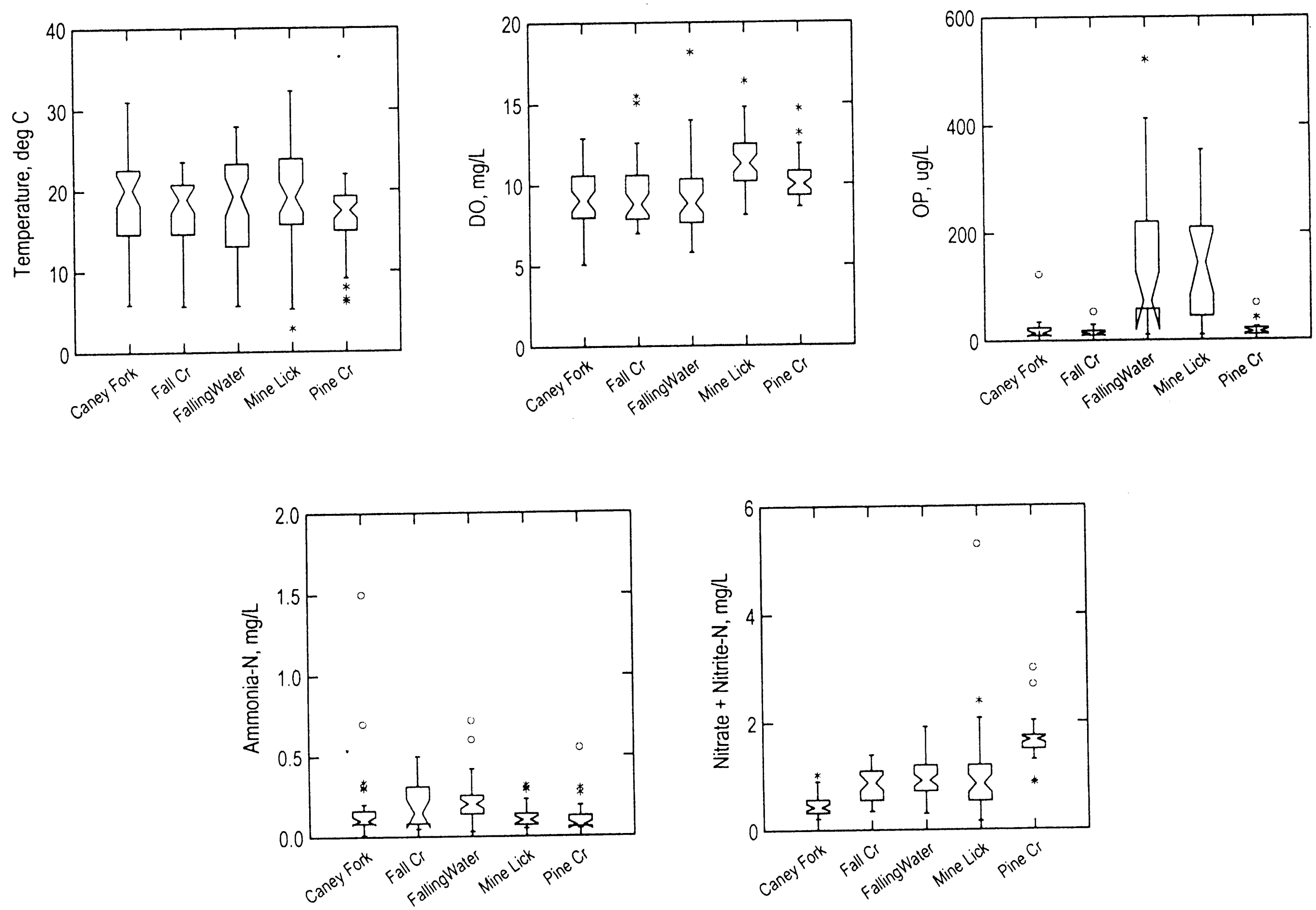


Figure 2.3. Box and whisker plots of historical water quality at Center Hill tributary monitoring stations. The Great Falls release quality is shown as the Caney Fork tributary to Center Hill.

represented by the boxes are statistically different from each other. When the notches do overlap, the samples represented by the boxes are not statistically different from each other.

Caney Fork River water temperatures measured downstream of Great Falls Dam are not statistically different from the water temperatures observed in the other tributaries. DO concentrations in Caney Fork River downstream of Great Falls Dam are similar to those in Falling Water River and Fall Creek. Both of these streams receive discharge from municipal wastewater treatment plants (WWTPs), and are statistically different from DO concentrations in Pine Creek, which does not receive discharge from WWTPs. Since DO downstream of Great Falls Dam is lower than DO in Pine Creek, the Great Falls reservoir is probably affecting downstream DO, perhaps as a result of releasing water with lower DO concentrations. However, the effect is similar to what is occurring in tributaries receiving WWTP discharge. OP concentrations in Caney Fork River downstream of Great Falls are similar to those in Pine Creek. It does not appear that Great Falls reservoir is resulting in greater phosphorus loads to Center Hill Lake than would occur naturally. Ammonia-N concentrations in Caney Fork River downstream of Great Falls Dam are similar to those measured in the other tributaries, except for Falling Water River, which had higher concentrations than the other tributaries. Nitrate + nitrite-N concentrations downstream of the dam are statistically lower than the concentrations found in the other tributaries.

Overall, the Great Falls project does not appear to be adversely affecting the quality of water that is released into Center Hill Lake. Temperature, DO, and nutrient concentrations downstream of the Great Falls Dam are for the most part similar to those found in the other tributaries to Center Hill Lake.

2.4 Land Use Effect

One of the objectives of this project was to investigate land use information to determine if an increase in nonpoint source pollution could be contributing to observed declines in Center Hill Lake hypolimnetic DO conditions over the past 25 years. Initially, land use information obtained from the Tennessee Wildlife Resource Agency for 1992 was compared with historic land use information from the EPA BASINS database representing conditions in 1975. The results are summarized in Table 2.3.

Table 2.3. Change in Center Hill Lake land use.

Land Use	1975 (m^2)	1992 (m^2)	Percent Change
Urban/developed	243,900,000 (4.1)*	42,500,000 (0.7)	-82.6%
Agriculture	2,238,200,000 (37.4)	2,817,850,000 (47.5)	25.9%
Forest	3,320,810,000 (55.6)	2,907,710,000 (49.0)	-12.4%
Open Water	81,660,000 (1.4)	124,980,000 (2.1)	53.0%
Wetland	4,740,000 (0.1)	5,120,000 (0.1)	8.0%
Mines/Quarries	20,470,000 (0.3)	23,510,000 (0.4)	14.9%
Transitional	67,320,000 (1.1)	-	-
Undefined	-	5,910,000 (0.1)	-
Total	5,977,100,000	5,927,580,000	-0.8%

* Percent of Total

Review of the information indicates that the data sets may be incompatible. In each data set there are land use categories not present in the other. Although some land use categories were combined into more general categories for comparison, this was not possible with all of the land use categories, e.g. "Transitional" and "Undefined". Even so, most of the changes in land use indicated in Table 2.3 seem reasonable. The notable exception is urban/developed land use. The data in Table 2.3 indicate the developed area in the watershed has decreased over 80% in the period from 1975 to 1992. However, the impression is that development is increasing in the area. As a check, populations reported for counties in the Center Hill Lake watershed were compared over the same period. Table 2.4 shows that county populations have increased from 1975 to

1992. This result does not support the dramatic decrease in developed land use shown in Table 2.3. It therefore appears that historical comparison of land use information in Table 2.3 is not valid because different methods were used to classify the land uses. It is not possible to make any statements about trends in land use change over the last 25 years. The 1992 land use data should be considered representative of the basin.

Table 2.4. County population percent difference for selected counties in Tennessee.

County	1975	1992	Percent Change
Cumberland	24,400	36,700	50%
DeKalb	12,500	14,600	17%
Grundy	12,500	13,500	8%
Putnam	41,900	53,300	27%
Van Buren	4,200	4,900	17%
Warren	29,900	33,500	12%
White	18,100	20,500	13%
Total	143,500	177,000	23%

Note: 1975 population numbers obtained from US Census Bureau, http://www.census.gov/population/www/estimates/countypop.html The 1992 population numbers are estimates of population obtained from The Government Information Sharing Project, http://givinfo.orst.edu/. The numbers were rounded to the nearest hundred.

2.5 Model

A modified version of CE-QUAL-W2 version 2.05 was used for this study. Modifications to CE-QUAL-W2 version 2.05 included use of three algal compartments instead of one, addition of silica as a water quality constituent affecting algal productivity, and addition of an algorithm to create an output file to be used by the Animation and Graphics Portfolio Manager (AGPM) pre- and post-processor (Loginetics Inc. 1998). The multiple algal compartments and silica algorithms were based on algorithms developed by Tom Cole and used in later versions of CE-QUAL-W2. The AGPM output algorithm was provided by Loginetics Inc. Appendix C includes printouts of these algorithms. Modifications to the model resulted in changes in the control file and in the constituent input files. Appendix C also includes a print out of the control file with the modified sections highlighted. The revised constituent order for input files is noted in Table 2.5. The constituents incorporated into CE-QUAL-W2 and their interactions are shown on Figure 2.4. Not all of these constituents were simulated for Center Hill Lake (see Section 4.4).

Table 2.5. CE-QUAL-W2 input order for water quality constituents.

1.	Tracer	13.	Sediment
2.	Suspended Solids	14.	Inorganic Carbon
3.	Coliform	15.	Alkalinity
4.	Dissolved Solids	16.	pH
5.	Labile DOM	17.	Carbon Dioxide
6.	Refractory DOM	18.	Bicarbonate
7.	Silica	19.	Carbonate
8.	Detritus	20.	Age of Water
9.	Phosphorus	21.	CBOD
10.	Ammonia	22.	Diatoms
11.	Nitrate-Nitrite	23.	Greens
12.	Dissolved Oxygen	24.	Cyanobacteria

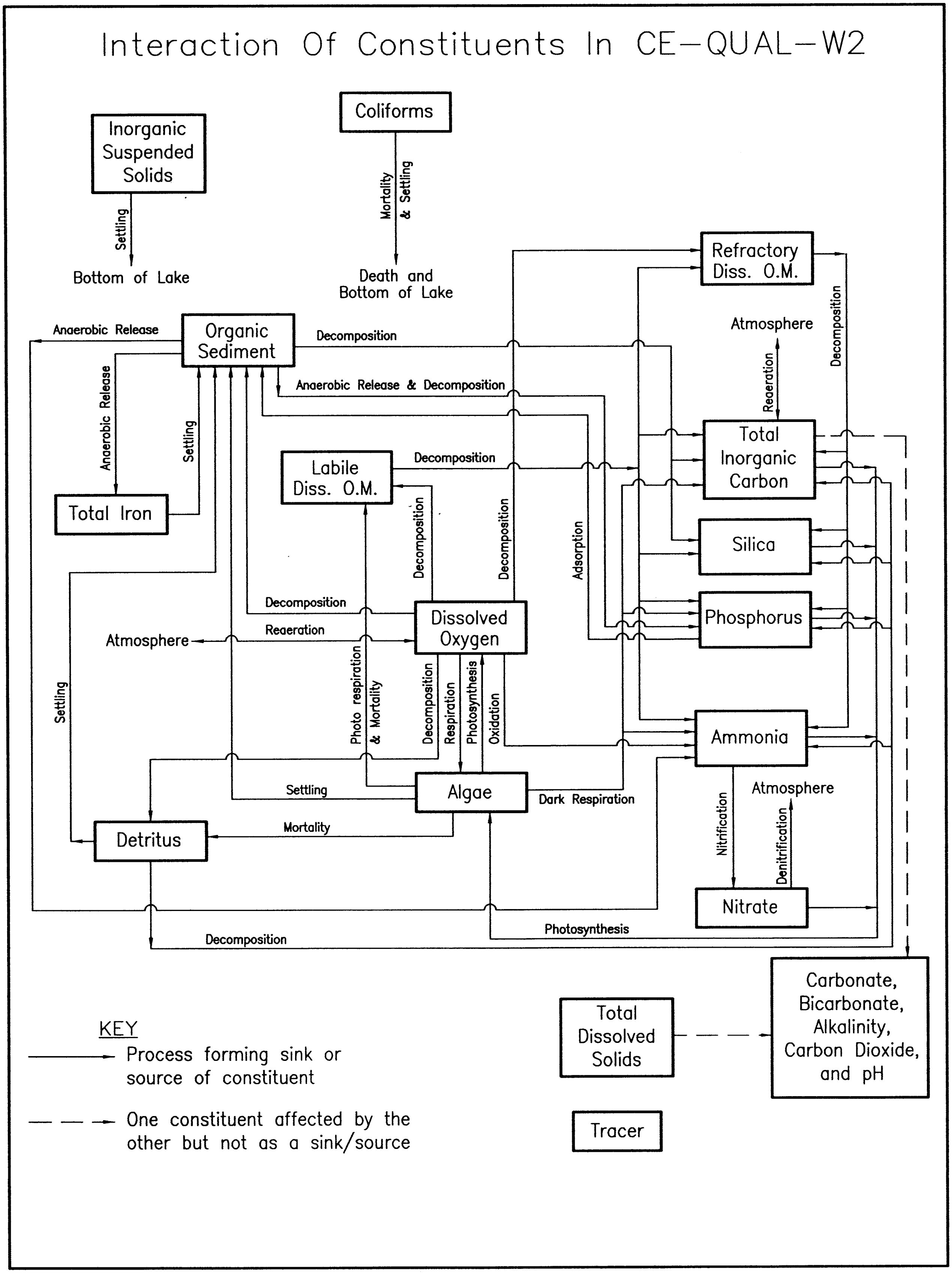


Figure 2.4. Interaction of constituents in CE-QUAL-W2.

3.0 RESERVOIR CONFIGURATION AND BATHYMETRY

A bathymetry plan was submitted to the District and approved (Appendix D). However, during the calibration process the bathymetry was modified. Therefore, the bathymetry described in this section differs from that described in the plan. A printout of the CE-QUAL-W2 bathymetry input file is included in Appendix E.

3.1 Physical Configuration

CE-QUAL-W2 conceptually represents a water body as a two-dimensional array of cells with each cell extending across the width of the water body. This "grid" of cells is determined by the longitudinal segment lengths (Δx) and layer thickness (Δz) specified by the user. The grid for Center Hill Lake used segment lengths (Δx) of 0.6 to 3.0 mi and a layer thickness (Δz) of 1.0 m (3.3 ft). A plan view of the segments is shown in Figure 3.1. Side views of the branch grids are shown in Figure 3.2. This grid will allow the simulation of both vertical (i.e. stratification) and longitudinal gradients in water quality constituents.

Figure 3.1 illustrates the model flow lines and conveyance channel through Center Hill Lake. The flow line locations were chosen based on previous studies and professional judgement. The main branch flow line indicates that water will move through the Narrows in the model. As a result, part of the Caney Fork meander loop around Davies Island was modeled as a continuation of the Falling Water River branch. The remainder of the Caney Fork meander loop around Davies Island was included in the model as a null embayment. The main branch flow line also cuts off a meander loop of the Caney Fork River at about mile 8.0, where the Little Hurricane Creek and Second Creek join it. The portion of that meander loop not included in the main branch of the model was modeled as a null embayment. These null embayments are shown on the model plan grid in Figure 3.3.

The bottom elevations along the flow line in the main branch at the Narrows and Little Hurricane Creek bend are deeper in the model than they are in the reservoir itself. Realistically modeling the bottom elevation along the flow line in the main branch would result in "weirs"

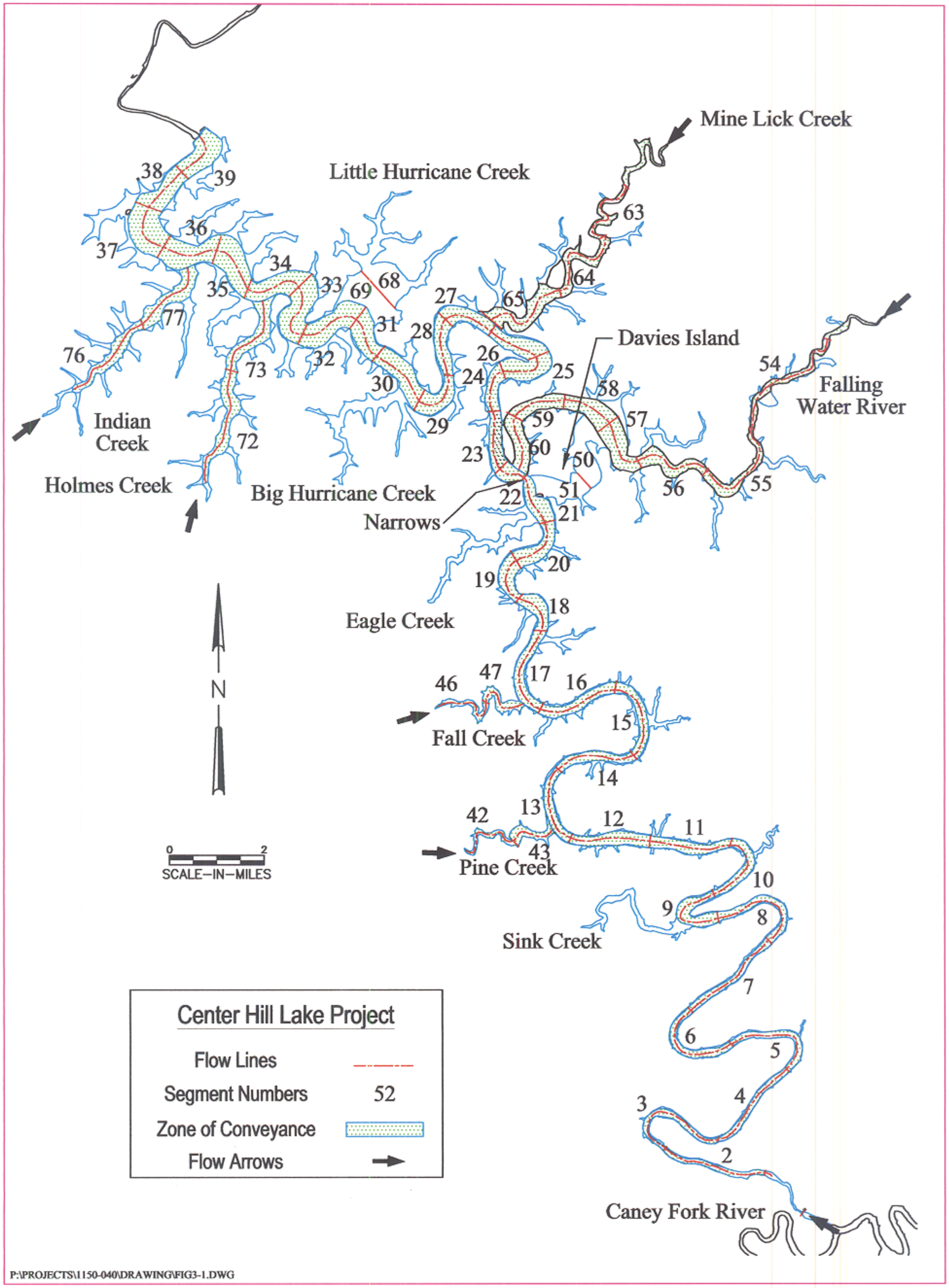


Figure 3.1 Plan view of Center Hill Lake Showing CE-QUAL-W2 segments

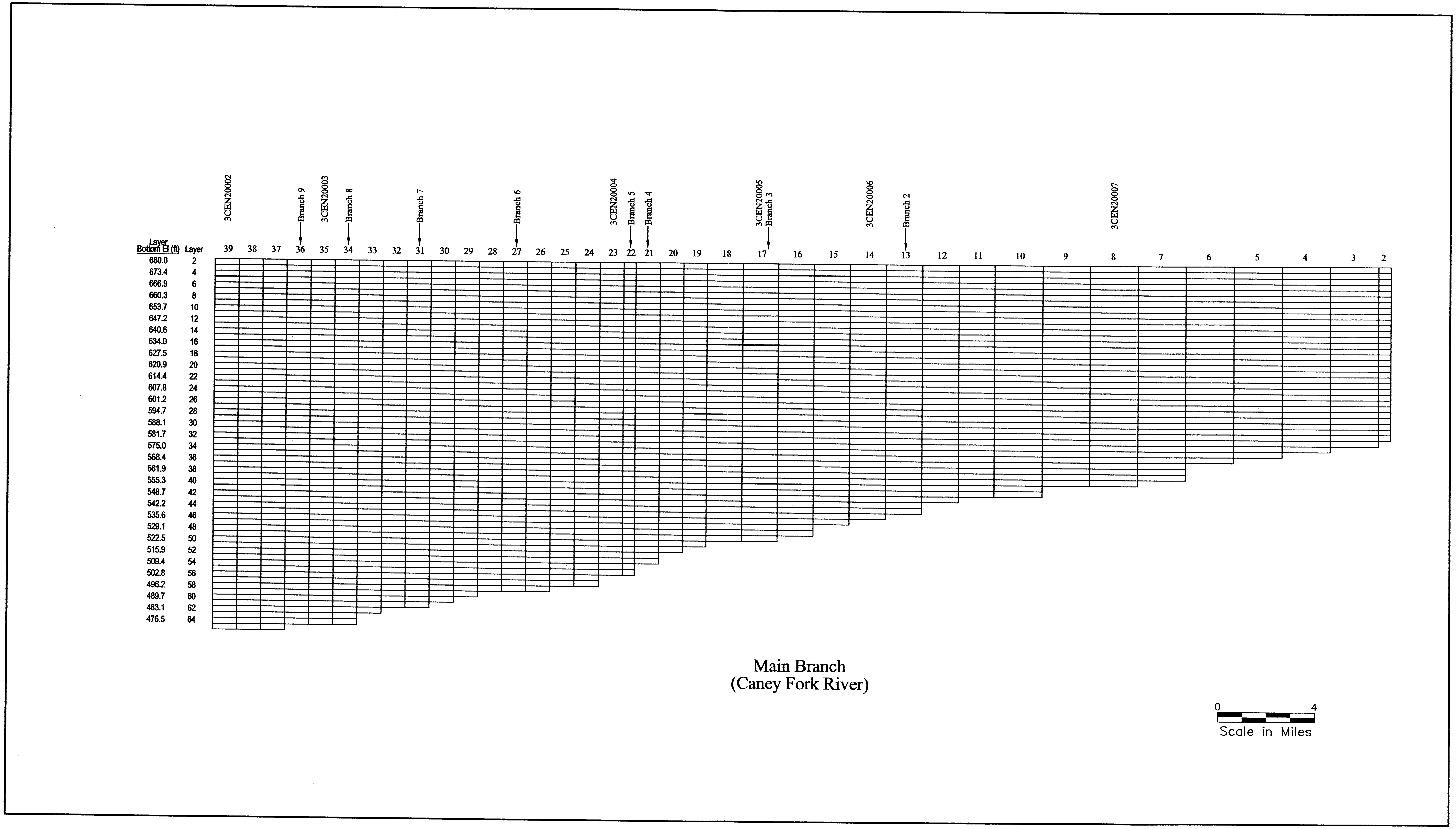


Figure 3.2. Center Hill Lake water quality model Main Branch Grid.

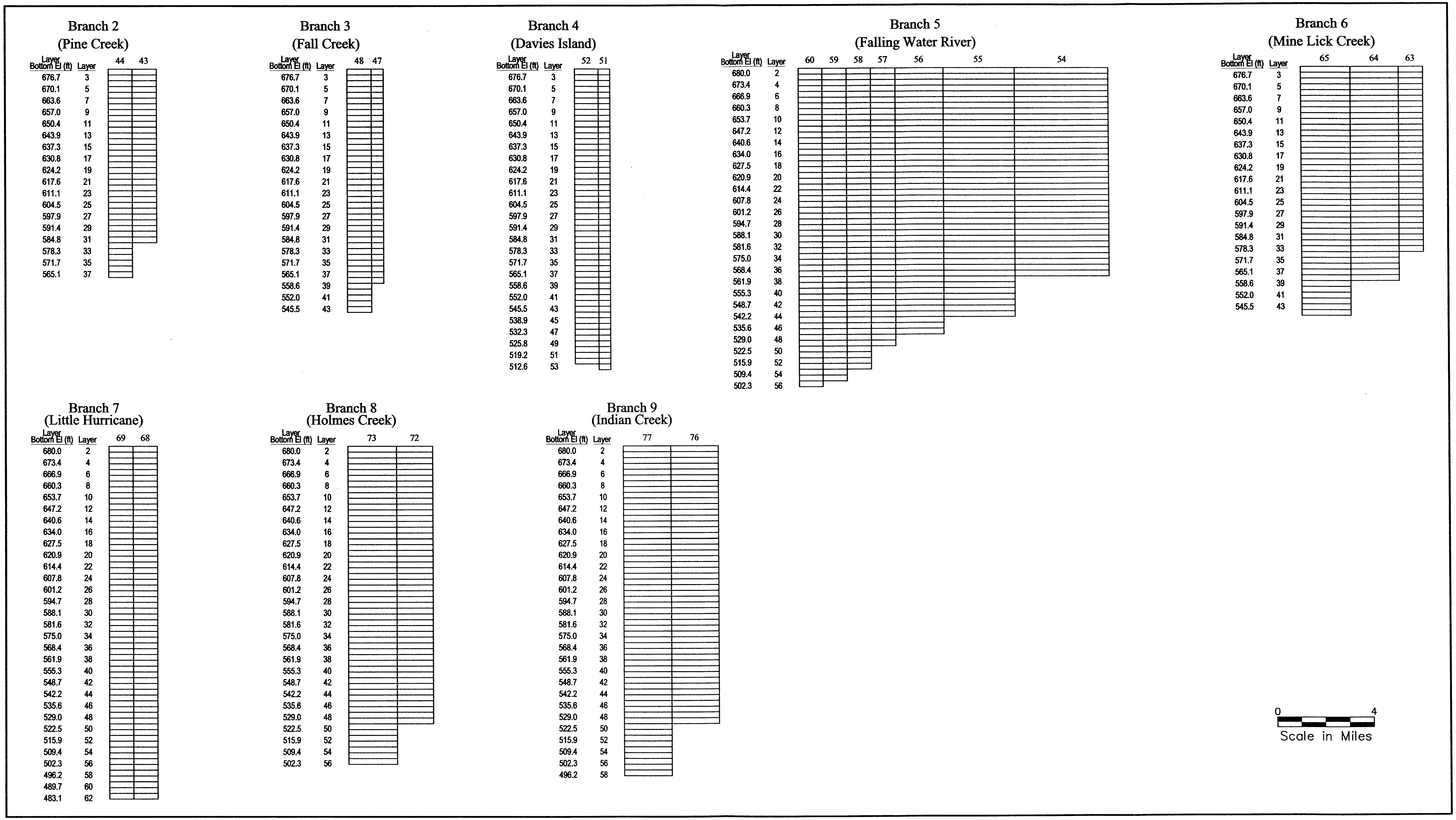


Figure 3.2. Continued

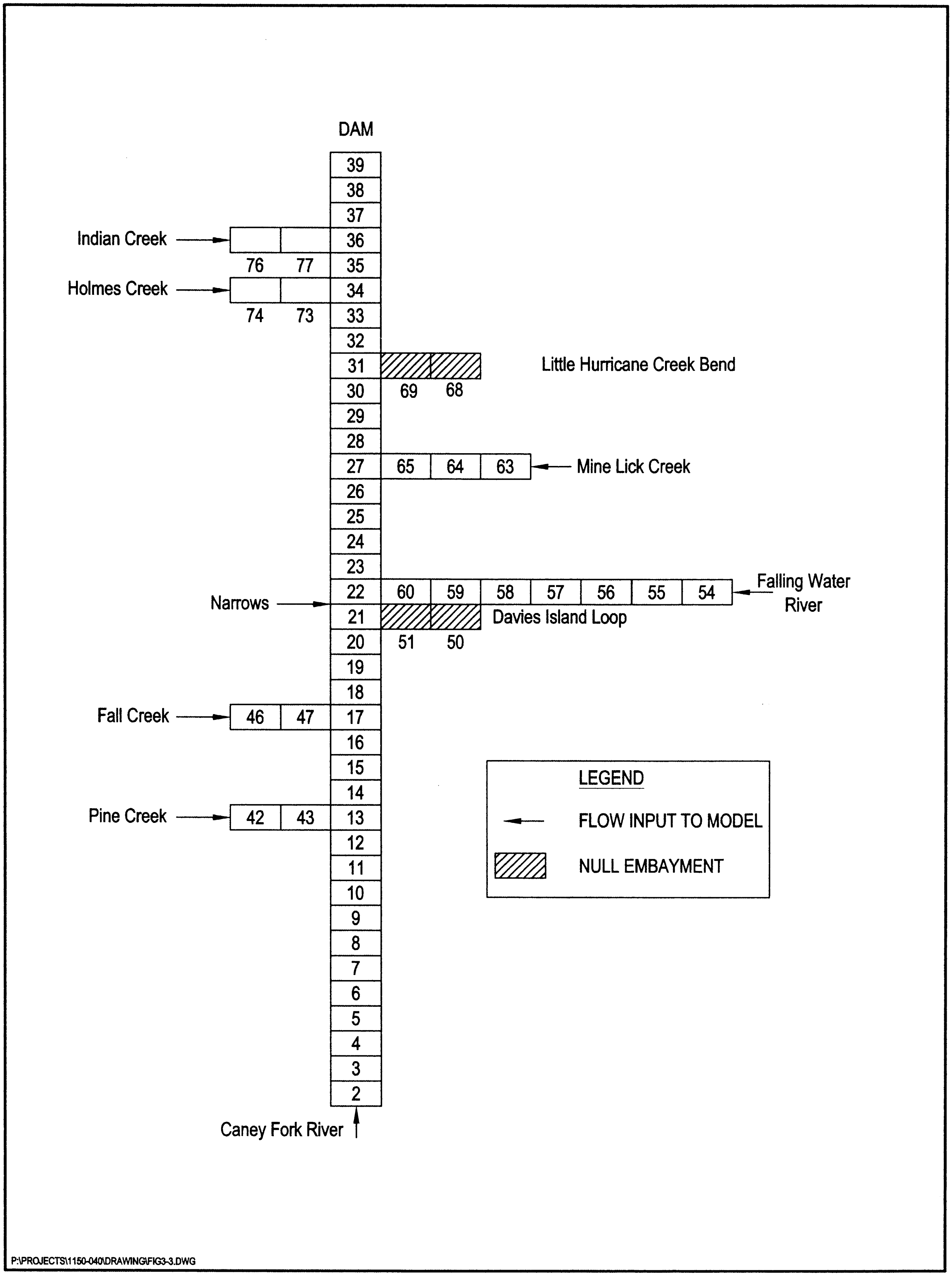


Figure 3.3 Center Hill Lake CE-Qual-W2 model plan grid

that would not allow underflows to move completely through the reservoir. As a result, the modeled hypolimnion flow line is shorter than the actual reservoir hypolimnion flow line, which follows the old stream channel. Based on available reservoir temperature data, underflows rarely occur, so they should not have much affect on the hypolimnion water quality. Generally, inflows to the reservoir would be expected to move as interflows or overflows. Therefore, hypolimnion volume should be more important than length of the hypolimnion flow line in affecting hypolimnion water quality.

3.2 Branches and Tributaries

The Center Hill Lake model consists of a main branch of 38 active segments with 6 embayments and 2 null embayments. Embayments are modeled as branches with inflows entering their upstream boundary. Null embayments are water storage areas and are modeled as branches with zero upstream flows. Main branch and embayment cells represent the conveyance channel of the main channel and important tributaries (shaded in Figure 3.1). Embayments were modeled at Indian Creek, Holmes Creek, Mine Lick Creek, Falling Water River, Fall Creek, and Pine Creek. Null embayments were modeled at Little Hurricane Creek and Davies Island.

Segments in the main branch are generally 1 mile long in the lower end of the reservoir and increase to 1.5 miles long above Fall Creek and to 2 miles long above Sink Creek, as the reservoir becomes narrower. Increasing the segment length for narrow segments keeps the residence time more similar to wider segments. Segment 22 at the Narrows is only 0.6 miles long. Segment lengths in the embayments and null embayments vary from 1 to 3 miles.

3.3 Average Widths

Cell widths were developed based on transects collected by the District. Transects were converted into HEC format and run through GEDA which computes volumes at specified intervals. Initial average widths for each cell were calculated from these volumes. The volume of the model bathymetry was then checked against the project elevation-capacity curve. Average

Previous experience with the CE-QUAL-W2 model has shown that small cell widths along the bottom of the reservoir can cause numerical instabilities during simulation. Therefore, any cell width that was less than 20 m was rounded to either zero or 20 m. The minimum cell width of 20 m has been used successfully in previous studies.

Figure 3.4 shows a comparison of the model elevation capacity curve to the District's elevation capacity curve for Center Hill Lake. Overall the model volume is 0.04% greater than the reported reservoir volume at elevation 676.9 ft msl.

3.4 Segment Orientation

Segment orientation was estimated to the nearest 10 degrees from the GIS map using a protractor. Segment orientation and wind direction affect hydrodynamics through longitudinal surface velocities and wind-generated shear stresses.

3.5 Outlet Configuration

Turbine releases were modeled as a point sink with a withdrawal centerline elevation of 556 ft msl (layer 40) and a lower withdrawal limit of 524 ft msl (layer 49). These elevations were based on the District's SELECT simulations (Appendix F). Sluice releases were also modeled as a point sink with a withdrawal centerline elevation of 499 ft msl (layer 58). Spillway releases were modeled as a line sink 470 ft wide with a withdrawal elevation of 648 ft msl (layer 12).

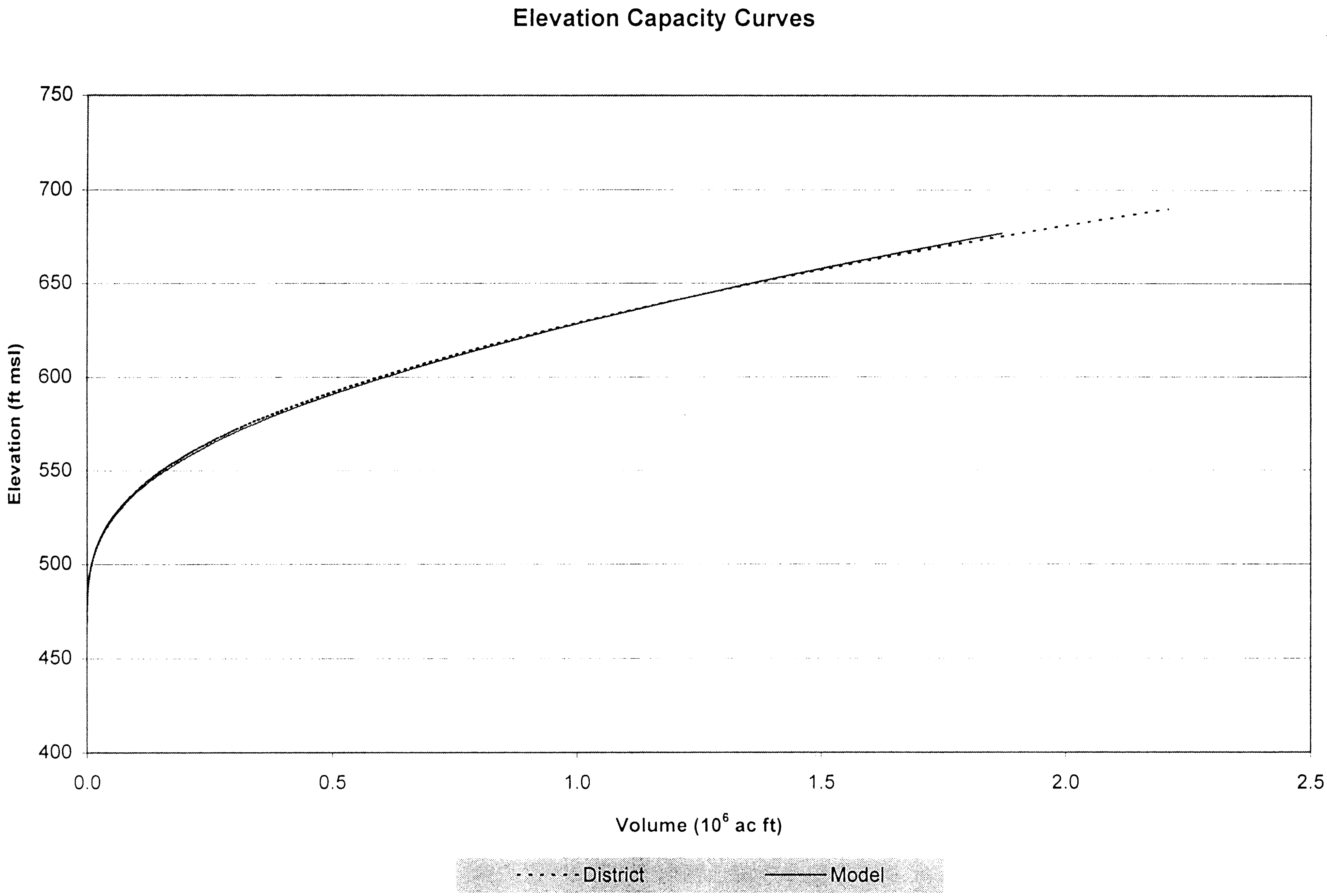


Figure 3.4. Comparison of model elevation capacity to District elevation capacity curve for Center Hill Lake.

4.0 MODEL CALIBRATION

The CE-QUAL-W2 model was calibrated using data from 3 years; 1973, 1988, and 1996. These three years were selected by the District to represent a range of hydrologic conditions, from dry (1988) to wet (1973) and average hydrologic conditions (1996). The method and rationale used to select these years is described in Appendix G.

The calibration process was similar to that recommended in the CE-QUAL-W2 User's Manual (Cole and Buchak, 1994). Once the reservoir bathymetry was developed, the water budget was checked by comparing computed and measured water surface elevations over time. Temperature was then calibrated to reflect heat budget computations and reservoir hydrodynamics. Temperature calibration was followed by calibration of the water quality parameters. Temperature and water quality parameters were calibrated by comparing measured data with model output for each parameter and then modifying model coefficients based on physiochemical phenomena to minimize differences. A printout of an example control file for the calibrated model of 1973 is included as Appendix H.

4.1 Water Budget

The Center Hill Lake water budget consisted of inflows from the watershed and releases from the reservoir. Evaporation was not modeled. Loss due to evaporation was implicit in the water budget since reservoir inflows used in the model were calculated by the District based on release flows and pool elevation.

4.1.1 Outflows

Average daily outflows during the model years for the turbines, sluice, and spillway at Center Hill Lake were obtained from the District daily operation records. Plots of outflows used in the model are included in Appendix I.

4.1.2 Inflows

Reservoir inflows that were included in the model were Caney Fork River, Pine Creek, Fall Creek, Falling Water River, Mine Lick Creek, Holmes Creek, and Indian Creek. These tributaries account for approximately 90% of the total watershed at the dam. In addition, a distributed inflow to the main branch was also modeled to account for smaller tributaries and direct inflow to the reservoir. Caney Fork River was the only tributary for which measured flow data were available. These data consisted of average daily Great Falls Dam releases which were obtained from the TVA. These Caney Fork River flows were subtracted from the average daily total inflows obtained from the District operation records. The remaining flow was divided among the embayments and distributed inflow based on watershed size (see Table 4.1 below).

Table 4.1. Center Hill Lake model subwatersheds.

Watershed	Area (sq mi)	%Total Drainage	%Drainage d/s Great Falls Dam
Caney Fork @ Great Falls Dam	1,675	77.0%	--
Pine Creek	23.2	1.1%	4.6%
Fall Creek	12.5	0.6%	2.5%
Falling Water River & Cane Creek	149.8	6.8%	29.8%
Mine Lick Creek	19.3	0.9%	3.8%
Holmes Creek	35.5	1.6%	7.1%
Indian Creek	35.5	1.6%	7.1%
Distributed	223.2	10.3%	42.7%
Total	2,174	100%	100%

4.1.3 Adjustments to Inflows

The inflow data provided by the District included negative flows because of the way it was computed. Subtracting the Great Falls Dam releases from Center Hill Lake total inflows at times resulted in negative flows for the remainder of the tributaries. The program HECUPD (USAE, 1991) was used to convert these negative inflows to a minimum value, while preserving the input water volume. The minimum value used in HECUPD was based on the 7Q10 flow

2.65 cfs reported for Falling Water River in BASINS (USEPA, 1996). The Falling Water River 7Q10 was converted to an areal flow by dividing by the corresponding watershed area. The areal flow (0.03 cfs/mi^2) was then multiplied by the sub-watershed areas for the tributaries and distributed inflow to estimate 7Q10 flows for these inputs. These 7Q10 flows were used as the minimum flow in the HECUPD runs. Plots of model inflows are included in Appendix I.

4.1.4 Evaluation of Water Budget and Adjustment of Inflows

A mass balance check was performed on the water budget for each study year. Cumulative values of inflow, outflow, and change in storage were calculated for each simulation period (approximately March through November of each year). For the mass balance, the cumulative inflow minus the cumulative outflow would equal the cumulative change in storage. The cumulative mass error was calculated as the deviation from this equality, or inflow minus outflow minus change in storage. To interpret the magnitude of the mass balance errors, the approximate difference in pool elevation that corresponds to each volume was calculated as shown in Table 4.2.

Table 4.2. Results of mass balance check on water budget for each study.

Year	Cumulative mass error during simulation period (ac-ft)	Difference in pool elevation due to cumulative mass error (ft)
1973	377	0.02
1988	292	0.02
1996	937	0.06

Original flows for 1996 resulted in elevations that were similar to measured elevations until the 1st of December when a large storm occurred. At this time the difference between calculated and measured water surface elevations was 4 ft. While investigating the model inflows to try to correct the difference, it was discovered that the Great Falls release flows appeared to be behind by one day. Large inflow events reported for Center Hill were matched by large releases from Great Falls dam the following day. This disparity was resulting in a large number of negative tributary inflows when Great Falls releases were subtracted from Center Hill inflows. The disparity appeared to start sometime in early March. Therefore, the Great Falls release reported for March 3, 1996 was deleted and the rest of the reported flows moved up one day. The results of the mass balance check with these modified inflows are shown in Table 4.2.

Although the calculated water balances reproduced measured water surface elevations well, model water surface elevations did not match so well, especially in 1988 and 1996 models (see Figure 4.1). The 1988 and 1996 tributary inflows (excluding Caney Fork River at Great Falls) were adjusted to allow the model to better reproduce measured water surface elevations. For 1988, 2 m^3/s were subtracted from the total of the tributary inflows when they were greater than 2 m^3/s starting on day 75. For 1996 the total of the tributary inflows were increased by 10% (multiplied by 1.1) starting on day 220. In addition, 250 m^3/s of flow was added on days 335 through 337 (November 30 through December 2) because the model still did not reproduce the measured water surface elevations during the storm. Plots of the modeled and measured pool elevations are shown on Figure 4.2.

4.2 Hydrodynamic and Temperature Calibration

4.2.1 Input Data Assimilation and Synthesis

Required input data for a hydrodynamic and temperature simulation with the CE-QUAL-W2 model include:

1) Bathymetric and hydrologic inputs (Sections 3.0 and 4.1),
2) Initial reservoir temperature data,
3) Inflow temperatures for the simulation period,
4) Meteorologic data for the simulation period, and
5) Values of selected physical coefficients.

4.2.2 Initial Temperatures

Simulations were started in early March. Temperature profiles were not available for the starting dates. Based on available historical temperature profiles, the reservoir was assumed to be

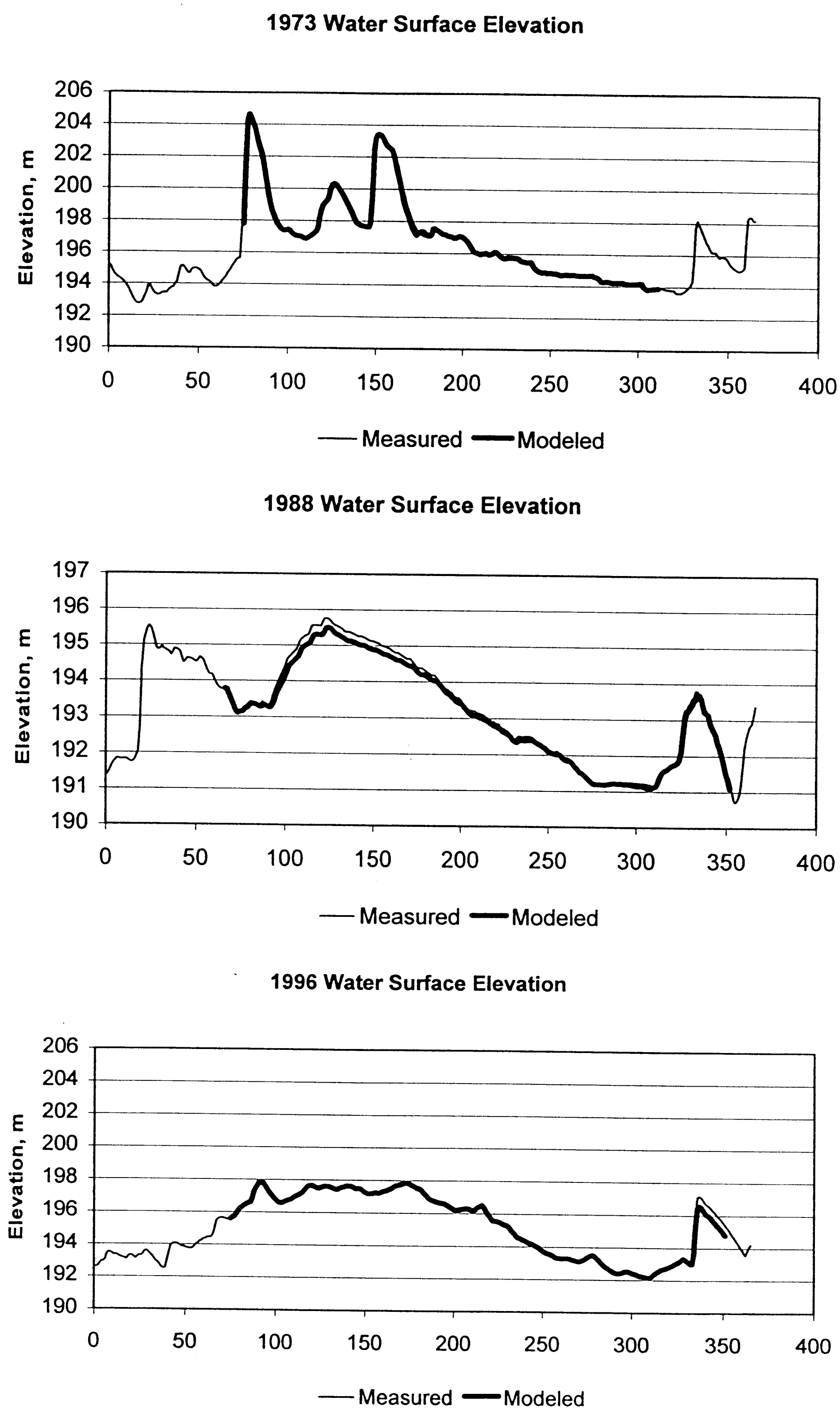


Figure 4.1. Modeled and measured Center Hill Lake pool elevations.

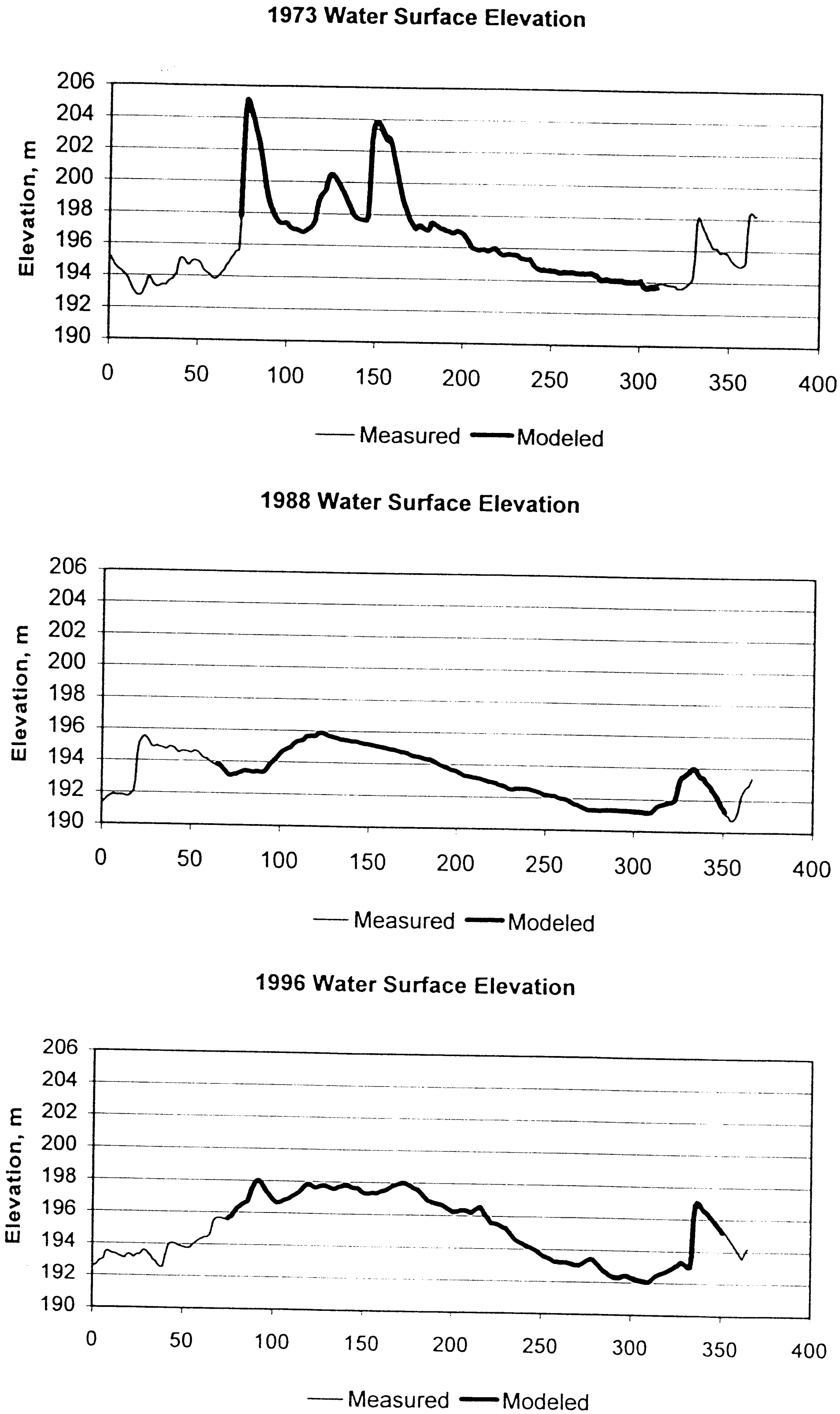


Figure 4.2. Comparison of final modeled and measured Center Hill Lake pool elevations.

simulations the initial temperature was adjusted to 9°C based on 1973 observed temperature data and the temperature calibration.

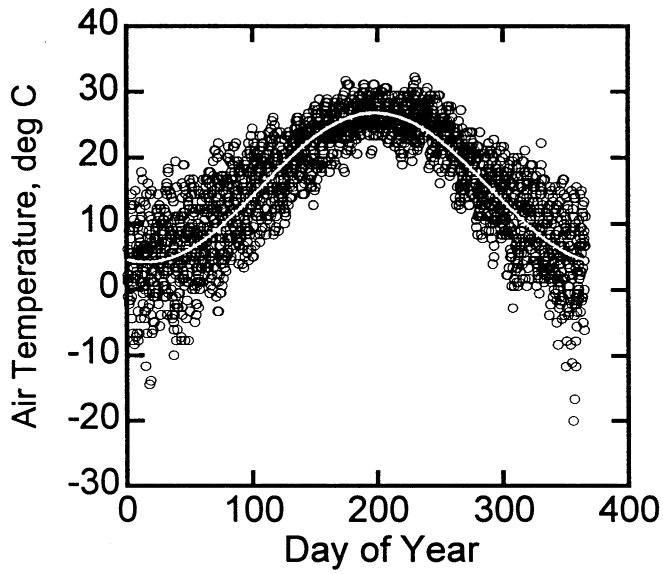
4.2.3 Inflow Temperatures

Inflow temperature is an important part of the temperature calibrations for simulating the proper vertical placement of inflows in the reservoir. Based upon experience, the use of daily inflow temperatures is recommended. Daily observed water temperatures were not available for the Center Hill Lake inflows included in the model. Water temperatures were measured on Caney Fork downstream of Great Falls Dam, Fall Creek, Pine Creek, Falling Water River, and Mine Lick Creek. Pine Creek water temperatures were used to represent water temperatures for Holmes Creek, Indian Creek, and the distributed tributary, because it is the least disturbed tributary (i.e., no impoundments nor WWTPs) for which temperature data was collected.

Because stream temperatures fluctuate in response to meteorological forces it was possible to estimate daily inflow temperatures based on variations in daily air temperatures using regression analyses. The first step was to estimate the seasonal temperature cycles for the year. This was done by fitting a sine curve to the observed temperature data for each tributary. An example is given on Figure 4.3, which shows the sine curves representing the seasonal temperature cycles estimated from the observed data for air temperatures from Nashville Airport and water temperatures for Fall Creek. For each day on which there was an observed value, a residual was calculated as the difference between the observed value and the seasonal cycle value. Then a regression analysis was performed using the observed water temperature residual as the dependent variable and the air temperature residuals and daily streamflow rates as independent variables. Because of its greater heat capacity, water responds more slowly than air to changes in meteorological conditions; therefore, the regression analysis included air temperature residuals from preceding days. The equation developed is shown below:

$$WT(t) = T(t) + a * ATR(t) + b * ATR(t-1) + c * ATR(t-2) + d * Q(t)$$

Where: WT(t) = water temperature for day t (°C)
T(t) = seasonal water temperature for day t (°C)
ATR(t) = air temperature residual for day t (°C)



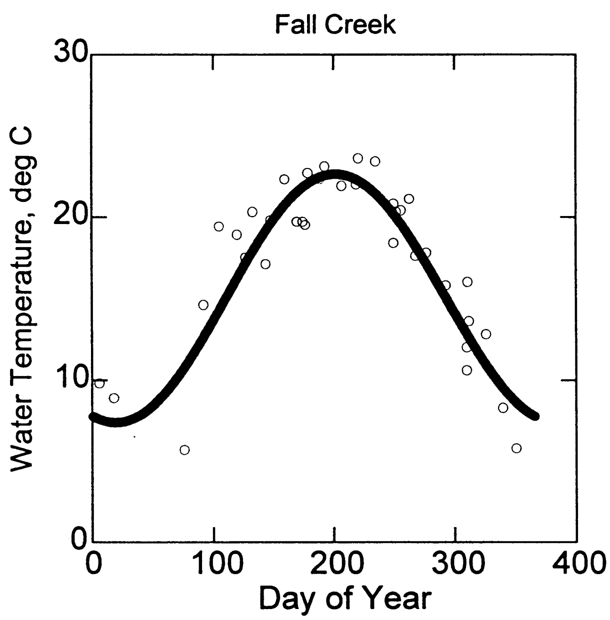


Figure 4.3. Seasonal temperature curves for air and Fall Creek water.

ATR(t-1) = air temperature residual for day t-1 (°C)
ATR(t-2) = air temperature residual for day t-2 (°C)
Q(t) = average stream flow for day t (cfs)
a,b,c,d = coefficients

The equations developed from our analysis are shown in Table 4.3. The flow component was omitted from the final equations because including flow did not improve the R^2 of the equation.

Table 4.3. Water temperature estimates.

Stream	Station	Equations	R^2
Caney Fork	CEN10030	T(t) = 15.6-11.631*sine (0.0172 * DAY + 7.563) WT(t) = T(t) + 0.095*ATR(t) + 0.009 ATR(t-l) + 0.009 ATR(t-2)	R^2=0.875 R^2=0.027
Pine Creek	CEN10024	T(t) =14.0-6.326*sine(0.0172*DAY+1.180) WT(t)=T(t)+0.207*ATR(t)+0.072*ATR(t-1)-0.08*ATR(t-2)	R^2=0.791 R^2=0.208
Fall Creek	CEN10023	T(t)=15.0-7.618*sine(0.0172 DAY+1.233) WT(t)=T(t)+0.267 ATR(t)+0.034 ART(t-l)+0.043*ATR(t-2)	R^2=0.841 R^2=0.912
Falling Water River	CEN10026	T(t)=16.0-8.987*sine (0.0172*DAY+1.191) WT(t)=T(t)+0.166 ATR(t)+0.223 ATR(t-l)-0.014*ATR(t-2)	R^2=0.912 R^2=0.515
Mine Lick	CEN10029	T(t)=15.0-10.681*sine(0.0172*DAY+1.167) WT(t)=T(t)+0.145 ATR(t)+0.506 ATR(t-l)-0.285*ATR(t-2)	R^2=0.761 R^2=0.186

The daily temperatures estimated using this procedure appeared to match measured water temperatures well. However, during the calibration process it became apparent that some modification of the estimated inflow temperatures was necessary to match measured temperature profiles. Inflows did not appear to be entering the reservoir at the correct depth. Spring inflow temperatures were of primary concern, since they affect the development of stratification. Caney Fork River inflow temperatures were of greatest impact. Caney Fork River inflow temperatures were adjusted to match measured temperatures by adding the difference between the measured and estimated temperatures to the estimated temperatures for that day and all of the days following, until the next temperature measurement. For the most part, when measured temperatures were frequent, the temperature adjustment for a period was constant. However, in cases where using a constant value resulted in a dramatic change in temperature (such as when a positive difference was followed by a negative difference), or when measured temperatures were not frequent, the adjustment for each day was linearly interpolated between the differences from consecutive measurements. Plots of estimated daily inflow temperatures are included in Appendix J. Measured water temperatures are included on the plots.

4.2.4 Meteorologic Data

The meteorologic input data used by CE-QUAL-W2 consists of air temperature, dew point temperature, wind speed, wind direction, and cloud cover. The meteorologic data utilized in the model were obtained from the Nashville Metro Airport Station, which is located about 50 miles west of the reservoir. Hourly data for the Nashville station for 1973 and 1988 were obtained from a CD-ROM (EarthInfo, 1996) that contains data retrieved from the National Oceanic and Atmospheric Administration (NOAA). Hourly data for the Nashville station for 1996 were not available on the CD and were obtained from NOAA.

The elevation of the Nashville station is 590 ft. Elevations of meteorological data stations are relevant because significant differences can sometimes be observed between data from two stations that are in the same region but are at significantly different elevations. During calibration, the model was predicting water surface temperatures that were too warm. Since the surface of the reservoir is at a higher elevation than Nashville (648 ft), and since Nashville is a metropolitan area, it is likely that Nashville temperatures are warmer than the surrounding countryside. Average daily air temperatures were available for Smithville, which is about 10 miles west of the reservoir. A comparison of the Nashville and Smithville temperatures showed the Smithville air temperatures were cooler than the Nashville air temperatures (Figure 4.4). The average difference in daily air temperatures from Nashville and Smithville during the model years was 1.9°C. Therefore, the hourly input air temperatures were adjusted

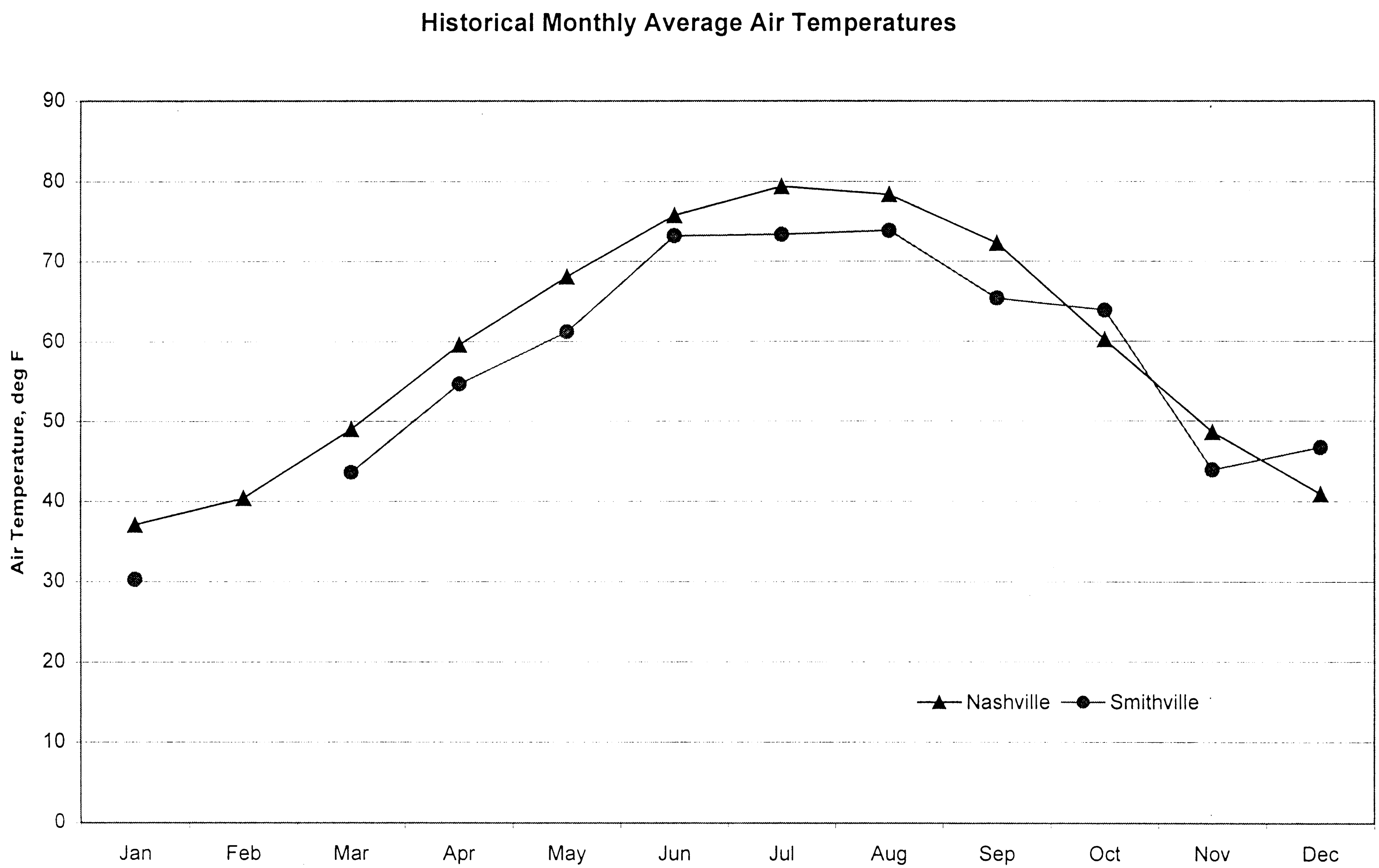


Figure 4.4. Comparison of air temperatures at Nashville and Smithville.

using the difference between the average daily temperatures at Nashville and Smithville. Dew point temperatures were also adjusted. The percent relative humidity was estimated as the ratio of Nashville dew point temperatures to Nashville air temperatures. The adjusted dew point temperature was estimated by multiplying this ratio with the adjusted air temperature.

4.2.4.1 Physical Coefficients

The CE-QUAL-W2 coefficients used to calibrate the temperature and hydrodynamic algorithms are shown in Table 4.4. AX and DX are the horizontal dispersion coefficients for momentum and temperature/constituents, respectively. The CHEZY coefficient is used in calculating boundary friction. The values used for AX, DX, and CHEZY were model default values and were not changed during calibration. Values used for other coefficients are discussed in the following sections of this report.

Table 4.4. Physical coefficients used in hydrodynamic/temperature calibrations.

Mnemonic Name	Description	Initial Value	Final Value
AX	Longitudinal eddy viscosity	1.0 m^2/sec	1.0 m^2/sec
DX	Longitudinal eddy diffusivity	1.0 m^2/sec	1.0 m^2/sec
CHEZY	Chezy coefficient	70 $m^{0.5}$/sec	70 $m^{0.5}$/sec
WSC	Wind sheltering coefficient	1.0	0.65
BETA	Fraction of solar radiation absorbed at surface	0.50	0.48
EXH2O	Extinction coefficient for pure water	0.45 m^{-1}	0.45 m^{-1}
EXINOR	Extinction coefficient for inorganic solids	0.01 m^{-1}	0.09 m^{-1}
EXORG	Extinction coefficient for organic solids	0.20 m^{-1}	0.11 m^{-1}
CBHE	Coefficient of bottom heat exchange	3.5E-7 m^2/sec	7.0E-8 m^2/sec
TSED	Sediment temperature	10.6 °C	15.0 °C

4.3 Temperature Calibration Results

4.3.1 Temperature Profiles

Measured and modeled temperature profiles at the dam are shown on Figures 4.5 through 4.7. Model temperatures show conditions at noon. Measured and modeled temperature profile

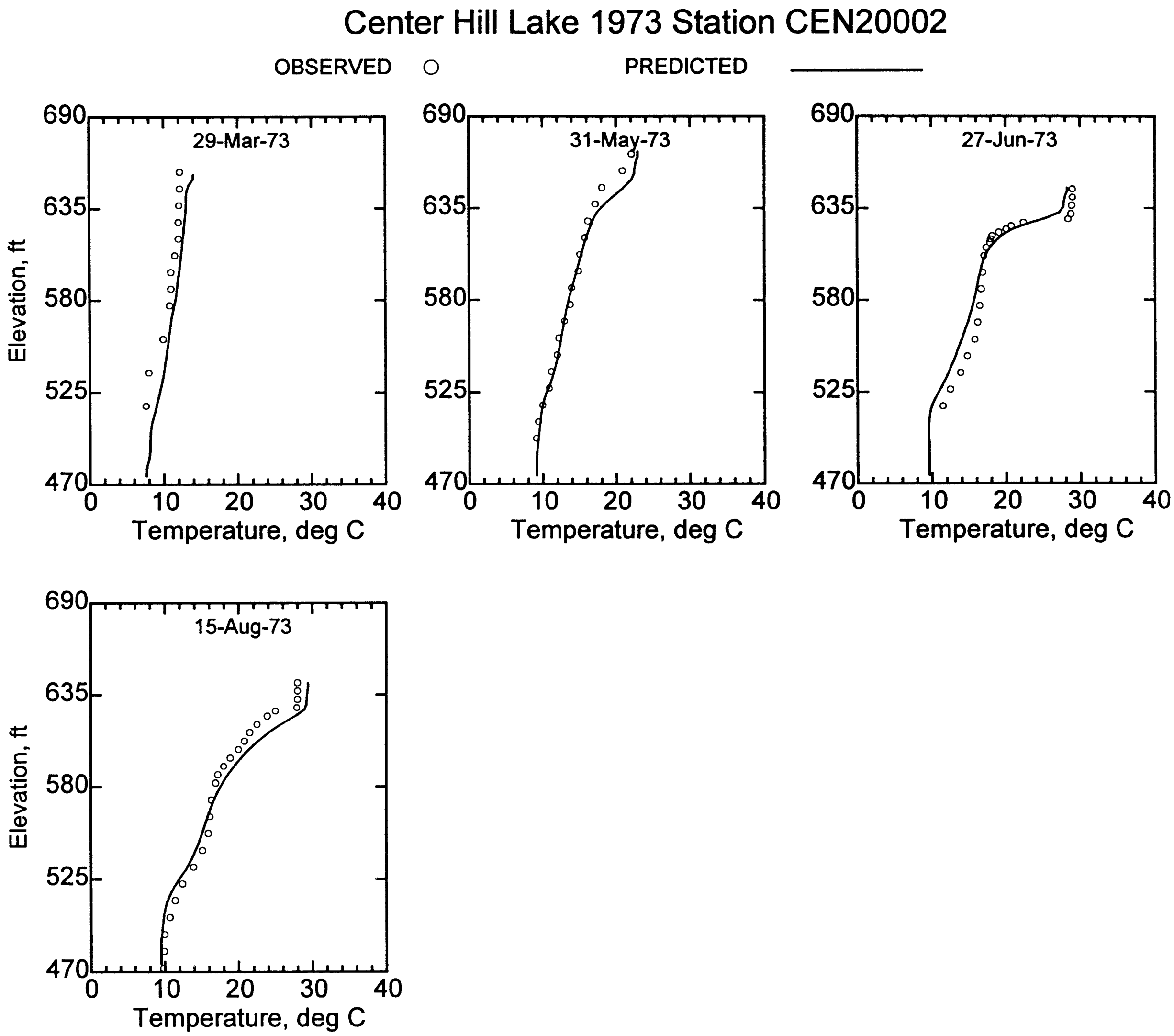


Figure 4.5. Comparison of 1973 measured temperature profiles at Center Hill Dam to modeled temperatures for noon.

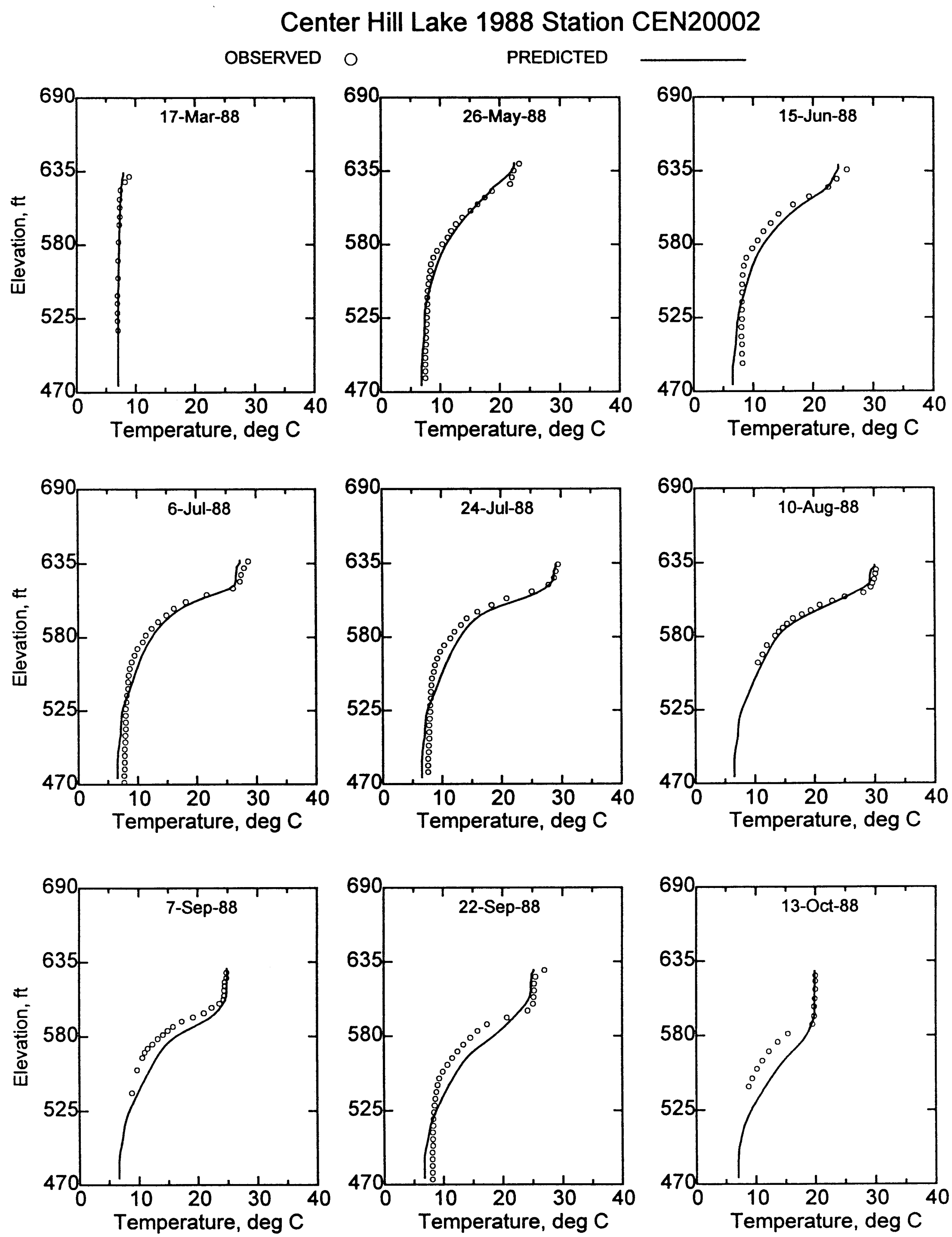


Figure 4.6. Comparison of 1988 measured temperature profiles at Center Hill Dam to modeled temperatures for noon.

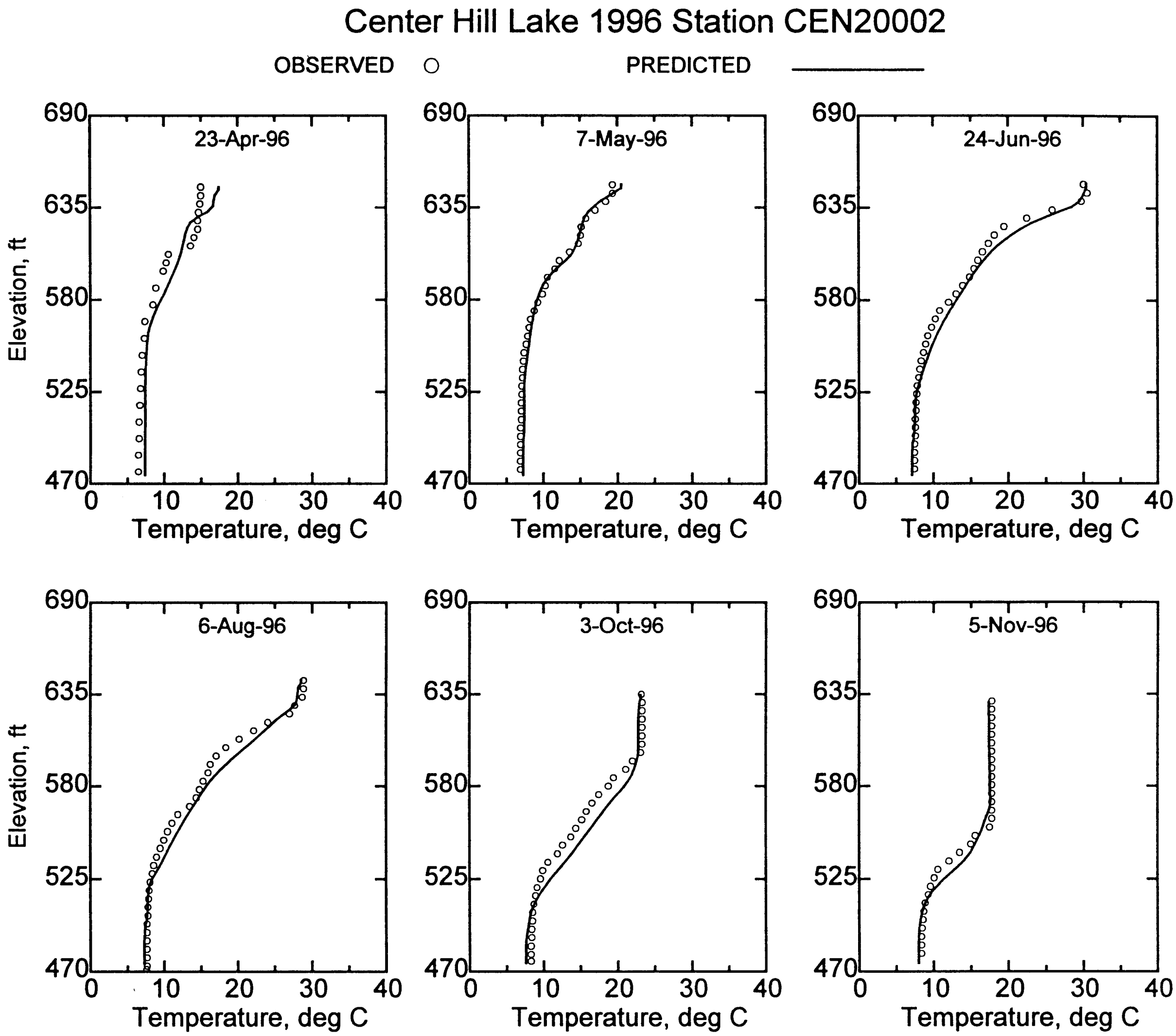


Figure 4.7. Comparison of 1996 measured temperature profiles at Center Hill Dam to modeled temperatures for noon.

plots for the remaining reservoir water quality monitoring stations are included in Appendix K. For the most part, the model reproduced the overall shape of the temperature profiles and correctly predicted the timing of the onset of stratification.

Modeled temperatures for 1996 (average year) show the best match to measured temperatures. The 1988 (dry year) modeled temperature profiles also seem to match measured temperatures well for most of the year. However, starting with the September profile, the modeled metalimnion temperatures are warmer than measured at all stations. As a result, modeled overturn is earlier than it should be in 1988. The 1973 (wet year) modeled temperature profiles generally match the shape of the measured temperature profiles. The modeled hypolimnion temperatures tend to be lower than measured at some of the mid-reservoir stations. This is probably a result of the estimated inflow temperatures, and possibly flows, for some of the tributaries. Based on the profiles at station 3CEN20007, it appears that the Caney Fork River inflow temperatures are satisfactory. However, profiles at the downstream stations do not match as well. This seems to indicate that some of the tributary inputs are not quite right. Since there is no measured temperature data for the tributaries (other than Caney Fork River) from 1973, it was not possible to check and correct the 1973 inflow temperatures as was done for 1988 and 1996. Because of the volume of inflow during wet years, these models can be more sensitive to problems in the inflow inputs than the average and dry year models. Since the last measured temperature profile is in August, it is unknown if the model correctly predicts fall overturn for 1973.

4.3.2 Surface Temperatures

Plots of surface temperature at the dam are shown on Figure 4.8. For all years, the modeled noon temperatures are within 2°C of measured temperatures. This indicates that the meteorologic data and resulting heat budget adequately reproduces conditions at the reservoir.

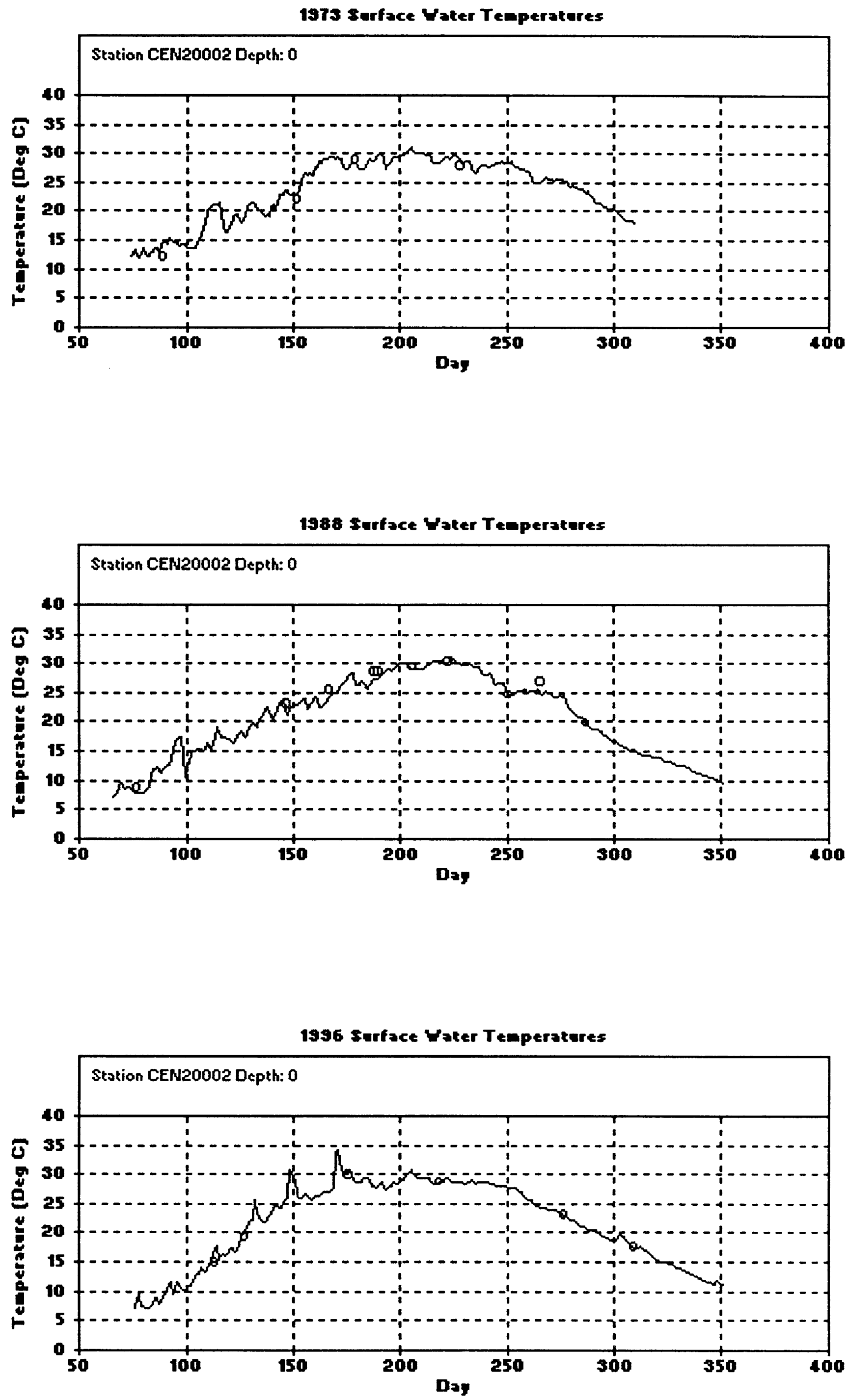


Figure 4.8. Comparison of measured surface temperatures at Center Hill Dam to modeled temperatures for noon.

4.3.3 Outflow Temperatures

Modeled noon release temperatures and measured temperatures downstream of Center Hill Dam were plotted to ensure that the withdrawal algorithm in the model was properly configured. These plots are shown on Figure 4.9. The modeled outflow temperatures follow the general trends of the measured outflow temperatures. For the most part, modeled outflow temperatures are within 2 to 3 °C of measured temperatures. Differences between modeled and measured outflow temperatures appear to be the result of differences between modeled and measured temperature profiles in the lake at the dam. Thus, modeled outflow temperatures are warmer than measured temperatures when the modeled temperature profile at the dam is warmer than the measured profile at the withdrawal elevation. Modeled outflow temperatures are cooler than measured temperatures when the modeled temperature profile at the dam is cooler than the measured profile at the withdrawal elevation.

4.3.4 General Conclusions

The calibrated temperature model reproduced the patterns in the measured in-lake and release temperatures and was generally within 1 to 2°C. The current calibrated model is considered adequate to evaluate various reservoir management alternatives or various watershed land use management alternatives. The model calibration exercise also has provided additional insight into the processes influencing inflow and reservoir water quality.

4.4 Water Quality Calibration

Water quality constituents of interest for this modeling effort were DO, nutrients, and algae. The approach for calibrating reservoir water quality was to (1) prepare the input data required for the model; (2) compile the coefficient and parameter distributions based on existing water quality, and scientific literature for similar systems; and (3) use these coefficient and parameter distributions to initiate the calibration process for the 1973, 1988, and 1996 study years.

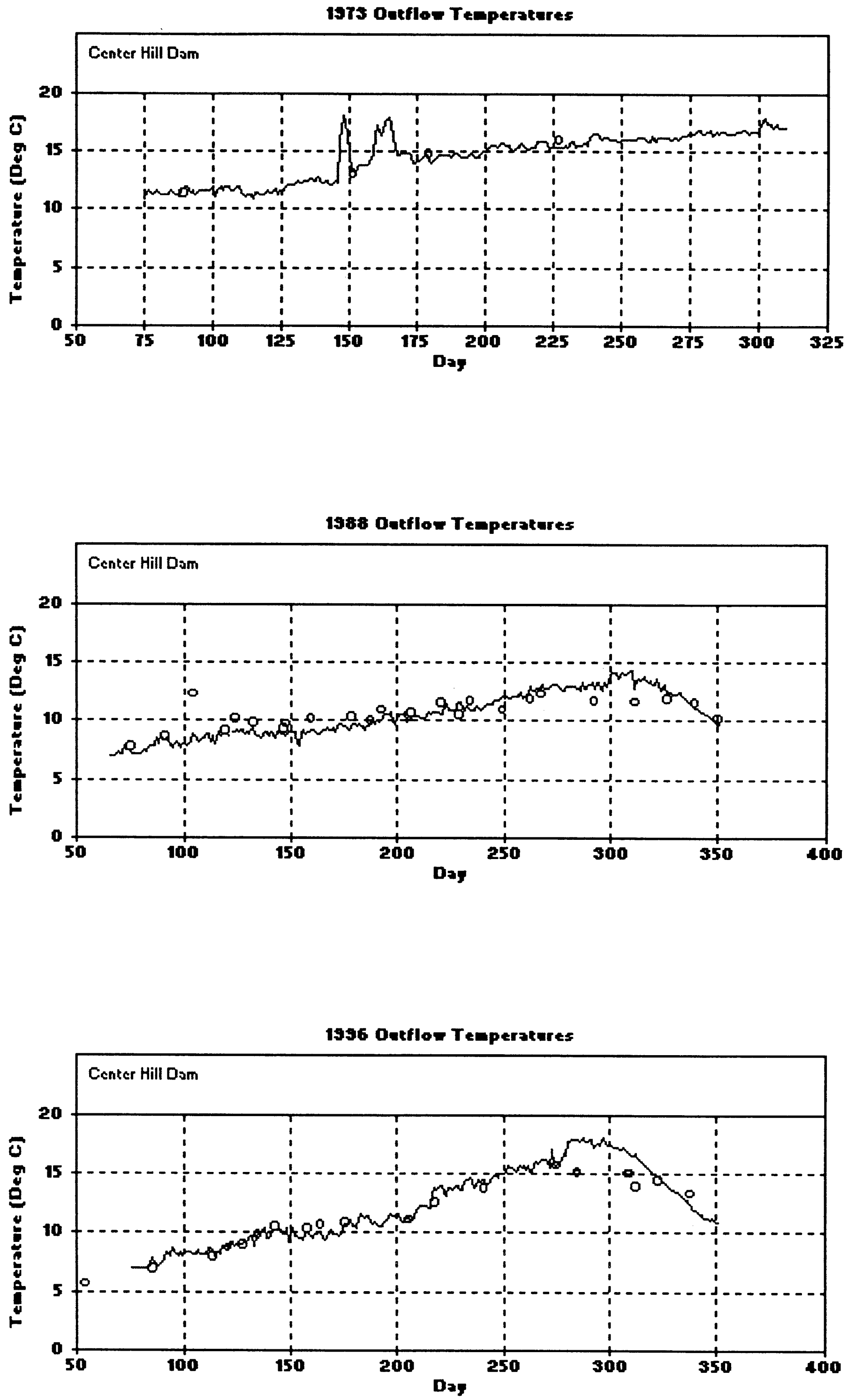


Figure 4.9. Comparison of measured temperatures downstream of Center Hill Dam to modeled Center Hill Dam release temperatures at noon.

4.4.1 Input Constituents

Inflowing constituents loadings from seven tributaries and direct runoff were required to simulate Center Hill Lake water quality. The tributaries were Caney Fork River, Pine Creek, Fall Creek, Falling Water River, Mine Lick Creek, Holmes Creek, and Indian Creek. Measurements of DO, TDS, dissolved organic matter (labile and refractory DOM), silica, detritus, ammonia-N, nitrate+nitrite-N (hereafter referred to as nitrate-N), and dissolved phosphorus were required for the reservoir inflows included in the model. At one point CBOD was also included in the model, but has been converted to LDOM in the calibrated model.

Temperature inputs were discussed in Section 4.2.3. Water quality constituents were measured by the District in Caney Fork River, Pine Creek, Fall Creek, Falling Water River, and Mine Lick Creek during 1988 and 1996. Water quality measurements were not collected in the tributaries during 1973. Water quality constituent inputs for Holmes Creek, Indian Creek, and the distributed tributary were set to the values determined for Pine Creek.

In general, measurements of the inflow constituents of interest were available for 1988 and 1996. The exception was organic matter. DOC (DOM), was not measured in the tributaries any time during the period of record. TOC was measured only a few times. In addition, detritus has never been a monitored water quality constituent in the tributaries. Therefore, refractory DOM and detritus inflow inputs were estimated. Labile DOM was initially assumed to be negligible in inflows, so that constituent was set to zero in the inflow concentration files. A method for estimating detritus and refractory DOM from TKN, ammonia, and TOC data was used. Particulate organic nitrogen for a stream was estimated by subtracting the historical mean of ammonia from the historical mean of TKN. Particulate organic carbon was estimated from this particulate organic nitrogen using the Redfield Ratio of C:N:P = 40:7:1 on a mass basis. This results in a C:N ratio of 5.7:1. Therefore, particulate organic carbon was estimated as 5.7 * particulate organic nitrogen. This particulate organic carbon was assumed to represent detritus. Refractory DOM was calculated as TOC minus detritus. Plots of the estimated refractory DOM and detritus values used for model inputs are located in Appendix L.

CBOD was not originally included as an input to the Center Hill Lake model. However, model results during calibration indicated that more than algae could be contributing to the metalimnetic DO minimum apparent in the measured DO profiles. When modeled chlorophyll *a* concentrations were similar to measured, the model did not reproduce the metalimnetic DO minimum. Decreasing detritus settling did not improve the DO profiles much. Another source of oxygen demanding material seemed likely. Therefore, CBOD was added as an input constituent for the Center Hill Lake model. CBOD was not measured in the tributaries, so initially input CBOD was set constant at 2 mg/L for all of the tributary inputs. The CBOD concentrations for the tributaries were then adjusted iteratively until the modeled DO profiles were similar to the measured profiles. These CBOD concentrations were then converted to LDOM at the request of the District. Plots of the input LDOM concentrations are also included in Appendix L.

Although the model can be run with inflow concentrations specified at any time interval (e.g., weekly, monthly, etc.), the use of daily DO values was important for modeling reservoir DO. Therefore, daily values had to be estimated for all of the constituents.

In 1988 measurements of dissolved orthophosphorus, ammonia-N, nitrate-N, and DO were taken approximately every 2 weeks in each of the monitored tributary streams. These measurements were frequent enough to use as-is. Daily input values for these parameters were estimated for the 1988 model by linearly interpolating between measured values.

The remainder of the model water quality constituents for 1988, and all of the water quality inputs for 1973 and 1996 had to be estimated. Estimated daily water quality concentrations were based on historical data from the tributary monitoring stations. Historical water quality data were evaluated to determine if relationships between water quality and flow or water temperature, or seasonal variability were evident. Initially, the data were examined by plotting the historical data from each monitoring station versus day of year, flow, and water temperature, untransformed and log transformed. If linear or non-linear relationships were evident in the plots, they were tested for statistical significance using regression analysis. When no significant relationship could be determined for a parameter at a monitoring station, the model input value was set to a constant value. Usually, this constant value was the historical mean concentration. When there were one or two values that skewed the mean, the historical median was used. Estimated values were examined for reasonableness and input values were modified to eliminate the influence of outliers. Table 4.5 shows the equations used to estimate daily values of water quality inputs. When appropriate, the R^2 of an equation is also listed. Most of these equations are based primarily on 1988 water quality since a large portion of the historical data was collected that year. Plots of the input concentrations are included in Appendix L. Measured concentrations are also shown on the plots.

4.4.2 Model Coefficients

Model coefficients for the thermal simulations were discussed in Section 4.2. This section discusses the water quality coefficients, parameters, and constants. These water quality coefficients can be categorized as:

- Biological Coefficients (e.g., algal growth rates);
- Chemical Coefficients (e.g., nitrification rates, SOD, etc.);
- Rate Modifiers (e.g., temperature factors, Q10 factors, etc.); and
- Stoichiometric Constants (e.g., oxygen required to oxidize 1 mole of NH_3 to 1 mole of NO_3).

Coefficient values were compiled from the water quality literature for reservoirs with similar hydrologic, physical, water quality, and biological characteristics as Center Hill Lake. The initial coefficient values used to initiate model calibration were taken from these coefficient compilations. If necessary, this initial coefficient rate was then modified to reduce the deviation between observed and predicted values during calibration. The coefficients, rate modifying parameters, and stoichiometric constants for the water quality variables simulated in Center Hill Lake are listed in Table 4.6 and discussed below.

4.4.2.1 Biological Coefficients

The original Version 2.05 CE-QUAL-W2 model had only one algal compartment. Because algae are of particular interest in most reservoirs. The Version 2.05 model was modified

Table 4.5. Equations for estimating water quality input.

Tributary	Station	Water Quality Estimate
Caney Fork	CEN10030	TSS = 11 mg/L TDS = 104 mg/L Labile DOM = 0-1.54 mg/L Refractory DOM = 0.91 mg/L Detritus = 1.96 mg/L Silica = 2 mg/L Ammonia-N = 0.10 mg/L Nitrate-N = 0.47 mg/L Phosphorus = 0.022 mg/L DO = 7.03227 + 0.00047 * (flow, cfs); R^2 = 0.888 when flow <10,000 cfs DO = $[\exp^{(7.7117 - 1.314 * \ln(\text{temperature, °C} + 45.93))}] * [1-(0.198 \div 44.3)]^{5.25}$ when flow>10,000 cfs
Pine Creek	CEN10024	TSS = $10^{(0.079+0.270*\text{Log10(flow, cfs)})}$; R^2 = 0.254 TDS = 103 mg/L Labile DOM = 0 –2.67 mg/L Refractory DOM = 0.57 mg/L Detritus = 6.9 mg/L Silica = 2 mg/L Ammonia-N = 1.67 mg/L Nitrate-N = 1.67 mg/L Phosphorus = 0.017 mg/L DO = 14.109 – 0.235 * (temperature, °C); R^2 = 0.552
Fall Creek	CEN10023	TSS = 45 mg/L TDS = 125 mg/L Labile DOM = 0 – 6.62 mg/L Refractory DOM = 0.45 mg/L Detritus = 10.655 mg/L Silica = 2 mg/L Ammonia-N = 0.20 mg/L Nitrate-N = 1.0 mg/L Phosphorus = 0.017 mg/L DO = 14.827 – 0.312 * (temperature, °C); R^2 = 0.595

Table 4.5. Continued.

Tributary	Station	Water Quality Estimate
Falling Water River	CEN10026	TSS = 15 mg/L TDS = 192 mg/L Labile DOM = 0 – 5.03 mg/L Refractory DOM = 1.37 mg/L Detritus = 1.43 mg/L Silica = 2 mg/L Ammonia-N = 0.22 mg/L Nitrate-N = 0.97 mg/L Phosphorus = 0.159 mg/L $DO = 0.98 * [exp^{(7.7117-1.314* \ln(\text{temperature, °C} + 45.93))}] * [1 - (0.198 \div 44.3)]^{5.25}$
Mine Lick Creek	CEN10029	TSS = 4 mg/L TDS = 183 mg/L Labile DOM = 0 – 8.32 mg/L Refractory DOM = 1.08 mg/L Detritus = 2.75 mg/L Silica = 2 mg/L Ammonia-N = 0.13 mg/L Nitrate-N = 1.3 mg/L Phosphorus = 0.154 mg/L $DO = [108 + 17 * \sin(0.0172 * JDAY - 14.6)) \div 100] * [exp^{(7.7117-1.314 * \ln(\text{temperature, °C}) + 45.93))}] * [1 - (0.198 \div 44.3)]^{5.25}$

Table 4.6. CE-QUAL-W2 parameters and coefficients.

Name	Description	Initial Value	Modified Value
AGROW	Algal growth rate, day^{-1}	2.08, 1.95, 1.45	1.20, 0.95, 1.00
AMORT	Algal mortality rate, day^{-1}	0.03, 0.03, 0.03	0.03, 0.03, 0.03
AEXCR	Algal excretion rate, day^{-1}	0.0, 0.0, 0.0	0.0, 0.0, 0.0
ARESP	Algal dark respiration rate, day^{-1}	0.1, 0.1, 0.1	0.07, 0.05, 0.04
ASETL	Algal settling rate, day^{-1}	0.42, 0.25, 0.10	0.35, 0.15, 0.08
ASATUR	Saturation intensity at maximum photosynthetic rate, Wm^{-2}	40, 42.6, 48.5	125, 120, 135
ALGT1	Lower temperature for algal growth, ℃	0, 0, 0	5, 5, 10
ALGT2	Lower temperature for maximum algal growth, ℃	5, 5, 10	12, 10, 25
ALGT3	Upper temperature for maximum algal growth, ℃	15, 15, 20	22, 25, 38
ALGT4	Upper temperature for algal growth, ℃	34, 34, 34	35, 30, 42
AGK1	Fraction of algal growth rate at ALGT1	0.1, 0.1, 0.1	0.1, 0.1, 0.1
AGK2	Fraction of maximum algal growth rate at AGLT2	0.98, 0.98, 0.98	0.98, 0.98, 0.98
AGK3	Fraction of maximum algal growth rate at ALGT3	0.98, 0.98, 0.98	0.98, 0.98, 0.98
AGK4	Fraction of algal growth rate at ALGT4	0.1, 0.1, 0.1	0.1, 0.1, 0.1, 0.1
LABDK	Labile DOM decay rate, day^{-1}	0.3	0.3
LRFDK	Labile to refractory decay rate, day^{-1}	0.003	0.001
REFDK	Maximum refractory decay rate, day^{-1}	0.003	0.001
DETDK	Detritus decay rate, day^{-1}	0.28	0.06
DSETL	Detritus settling rate, day^{-1}	0.35	0.05
OMT1	Lower temperature for organic matter decay, ℃	0	4
OMT2	Lower temperature for maximum organic matter decay, ℃	15	20
OMK1	Fraction of organic matter decay rate at OMT1	0.1	0.1
OMK2	Fraction of organic matter decay rate at OMT2	0.98	0.98
SEDDK	Sediment decay rate, day^{-1}	0.01	0.06
SOD	Sediment oxygen demand (SOD) for each segment, gm^{-2} day^{-1}	0.05	0.75 to 5.0
PO4REL	Sediment release rate (fraction of SOD)	0.015	0.007
PARTP	Phosphorus partitioning coefficient for suspended solids	0.1	0.1
AHSP	Algal half-saturation constant for phosphorus, gm^{-3}	0.017, 0.003, 0.008	0.012, 0.010, 0.015

Table 4.6. Continued.

Name	Description	Initial Value	Modified Value
NH3REL	Sediment release rate of ammonia (fraction of SOD)	0.035	0.035
NH3DK	Ammonia decay rate, day^{-1}	0.25	0.013
PARTN	Ammonia partitioning coefficient for suspended solids	0.01	0.01
AHSN	Algal half-saturation constant for ammonia, gm^{-3}	0.068, 0.09, 0.05	0.06, 0.06, 0.10
AHSSI	Algal half-saturation constant for silica, gm^{-3}	0.1, 0.0, 0.0	0.1, 0.0, 0.0
NH3T1	Lower temperature for ammonia decay, °C	0.0	0.1
NH3T2	Lower temperature for maximum ammonia decay, °C	15	20
NH3K1	Fraction of nitrification rate at NH3T1	0.1	0.1
NH3K2	Fraction of nitrification rate at NH3T2	0.98	0.98
NO3DK	Nitrate decay rate, day^{-1}	0.1	0.1
NO3T1	Lower temperature for nitrate decay, °C	5.0	5.0
NO3T2	Lower temperature for maximum nitrate decay, °C	20.0	20.0
NO3K1	Fraction of denitrification rate at NO3T1	0.1	0.1
NO3K2	Fraction of denitrification rate at NO3T2	0.98	0.98
SIREL	Silica release rate (fraction of sediment oxygen demand)	0.01	0.01
CO2REL	Sediment carbon dioxide release rate (fraction of sediment oxygen demand)	0.1	0.1
O2NH3	Oxygen stoichiometric equivalent for ammonia decay	3.43	3.43
O2ORG	Oxygen stoichiometric equivalent for decay of organic matter	1.4	1.4
O2RESP	Oxygen stoichiometric equivalent for dark respiration	1.2	1.2
O2ALG	Oxygen stoichiometric equivalent for algal growth	1.1	1.4
BIOP	Stoichiometric equivalent between organic matter and phosphorus	0.004	0.004
BION	Stoichiometric equivalent between organic matter and nitrogen	0.067	0.067
BIOSI	Stoichiometric equivalent between organic matter and silica	0.0	0.0
BIOC	Stoichiometric equivalent between organic matter and carbon	0.5	0.1
O2LIM	DO concentration at which anaerobic processes begin, gm^{-3}	0.2	0.2

*Sets of 3 values represent values for the 3 algal groups (diatoms, greens, and cyanobacteria) to have three algal compartments. This modification was patterned on the algal compartments used in Version 3.0 of CE-QUAL-W2. Data on the species composition of the algal community were available from 1981 through 1984 and 1996 through 1998. The three algal communities specified for the Center Hill Lake model are diatoms plus golden-brown algae (referred to as diatoms), green algae, and blue-green bacteria (cyanobacteria). Table 4.7 is a list of the dominant phytoplankton species from each of these communities enumerated in all samples collected from Center Hill Lake.

Table 4.7. Dominant phytoplankton observed in Center Hill Lake grouped by taxonomic assemblage.

Diatoms	Golden-Brown Algae	Green Algae	Blue-Green Bacteria
Centrales	Dinobryon	Tetraedron	Arthrospira
Achnanthes	Mallomas	Chlamydomonas	Oscillatoria
Pennales		Actinastrum	Anacystis
Synedra		Scenedesmus	Lyngbya
Fragillaria		Ankistrodesma	Anabaena
Stephanodisc			
Melosira			

Literature values for rate coefficients were compiled for each of these algal communities and used to develop frequency distributions. An example of algae growth rate frequency distributions is shown on Figure 4.10. The median value was used initially. Algal coefficient values are required for growth (gross production), mortality, excretion, respiration, and settling rates. In addition, parameter values are required for the fraction of algal biomass that is converted to detritus, and for phosphorus, nitrogen, silica (diatoms only) and light half-saturation parameters. Algal production in the model is not limited by carbon, so half-saturation values for this constituent are not required.

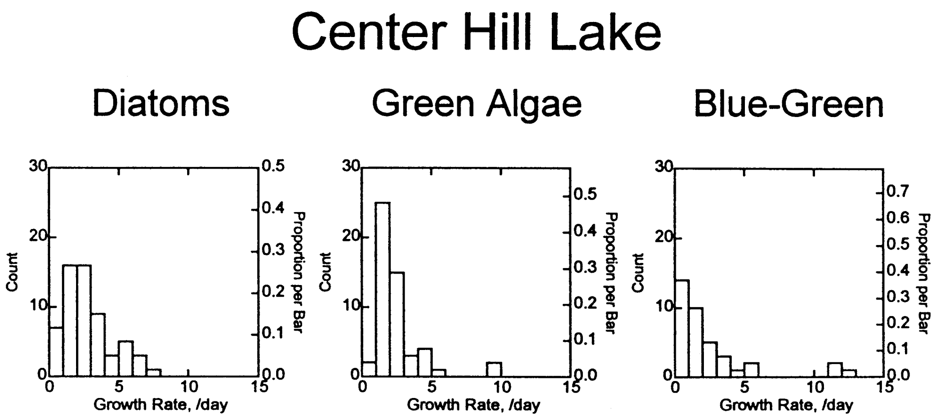


Figure 4.10. Frequency distributions of literature values for algal growth rates for three modeled algal communities.

In general, values for these algal related parameters and coefficients were obtained from Bowie et al. (1985), Cole (1995), Jorgensen (1979), Harris (1986), and Mills et al. (1985). A literature review was conducted for species that were not adequately represented in these manuals, and additional information was obtained, for example, from Baines and Pace (1994), Canale and Vogel (1974), Cobelas and Rojo (1994), del Giorgio and Peters (1993, 1994), Eppley (1972), Eppley et al. (1969), Elser et al. (1990), Guy et al. (1994), Harris and Lott (1973), Hecky et al. (1993), Jewell and McCarty (1971), Marshall and Peters (1989), Mazunder (1994), Megard et al. (1979), Morris and Lewis (1988), Reuter and Axler (1992), Reynolds (1984, 1988), Shapiro (1973), Smits (1980), Sterner and Hessen (1994), Tilman et al. (1982), and Toetz et al. (1973). In general, there are a greater number of studies on green algae and blue-green bacteria than there are on diatoms. This is the case, in part, because the problem algal species typically found in eutrophic lakes and reservoirs are green algae and blue-green bacteria.

4.4.2.2 Chemical Coefficients

Chemical rate coefficients include dissolved (DOM) and particulate (detritus) organic matter decay rates, SOD, and nitrification rates. DOM has two components: (1) a labile, easily metabolized fraction, and (2) a refractory, slowly metabolized fraction. Detritus also has an associated settling rate in addition to a decay rate. These rates were obtained from the

CE-QUAL-W2 manual and literature cited above. Initial SOD rates were estimated by calculating the DO depletion over time, 1 m above the bottom, at Station CEN20002 in Center Hill Lake. Nitrification rates represent the combined processes of nitritification (ammonia conversion to nitrite) and nitratification (nitrite conversion to nitrate) because the model considers nitrate-N as one compartment.

4.4.2.3 Rate Modifiers

The primary rate modifiers used in the model modify the maximum specified rates as a function of temperature. The temperatures for the various processes reflect the temperature regime observed in Center Hill Lake.

4.4.2.4 Stoichiometric Constants

Stoichiometric constants for grams of oxygen respired per gram of carbon, grams of oxygen produced per gram of carbon, C:N:P ratios, oxygen required to oxidize 1 mole of NH_3 to 1 mole of NO_3, C:Si ratio, and grams of oxygen respired per gram of organic matter were obtained from the CE-QUAL-W2 User's Manual. These have been verified in other applications and laboratory studies and reflect the formulations used in the model to represent biochemical processes.

4.4.3 Initial Conditions

The CE-QUAL-W2 model was used to model temperature, TSS, TDS, DOM (refractory and labile), detritus, DO, ammonia-N, nitrate-N, phosphorus, and algae in Center Hill Lake. The in-pool concentrations of these constituents at the beginning of the simulation period (March) are defined in the model control file. Initial temperatures were discussed in Section 4.2.2. Initial concentrations for the remaining modeled parameters are discussed below.

Most of the modeled parameters were measured in the reservoir during late March 1973 and early April 1988. Initial concentrations of TSS, TDS, DO, ammonia-N, nitrate-N, and phosphorus were set to the average of these early measured concentrations for the 1973 and 1988 models. DO was measured in April 1996, so the initial DO concentration for the 1996 model was set to the average of the April DO measurements. Initial concentrations for parameters that were not measured in the reservoir were set to the weighted average of the branch inflow concentrations on the model starting date. The average was weighted by the tributary watershed size.

Initial diatom, green algae, and blue-green bacteria concentrations were calculated from District chlorophyll *a* measurements. There were only two sets of spring chlorophyll *a* measurements taken in April 1976 and March 1983. The average of all chlorophyll *a* measurements taken at the lake stations for each depth was used as an average chlorophyll *a* profile for the reservoir. The 1976 data was used to develop initial algal concentration profiles for the 1973 model. A combination of the 1983 surface chlorophyll *a* concentrations and the 1973 chlorophyll *a* concentrations from greater than 15 feet deep, was used to develop initial algal concentration profiles for the 1988 and 1996 models.

In the CE-QUAL-W2 User's Manual, a multiplier of 65 is recommended to convert chlorophyll *a* concentration to algal biomass. Once the initial chlorophyll *a* concentration had been converted to algal biomass, the biomass was split among the three algal groups represented in the model based on the proportions of diatoms, green algae, and blue-green bacteria reported in the March 1983 algal enumerations. 1983 was the only year early spring algal enumerations were performed.

4.4.4 Water Quality Calibration Results

Because of the questions being asked about Center Hill Lake water quality, the primary emphasis during the calibration process was on DO, nutrients, and chlorophyll *a* (as a surrogate for algae). At times during the calibration other parameters such as TSS and Secchi disk depth were also examined. This section discusses the results from the calibration process for these constituents. Plots of modeled and measured concentrations of these parameters at the reservoir water quality monitoring stations are included in Appendix M.

4.4.4.1 Dissolved Oxygen

DO integrates many of the water quality processes occurring within the reservoir and provides more information about the conditions of a lake or reservoir than any other single constituent (Hutchinson 1957). Since there is concern about DO in downstream releases at Center Hill Lake, the primary concern regarding modeled DO is how it looks at the dam. Figures 4.11 through 4.13 show measured DO with noon modeled DO profiles at the dam during the 3 model years. Plots of measured and modeled DO profiles at the other water quality monitoring stations are included in Appendix M.

The modeled DO profiles do exhibit low concentrations in the metalimnion, similar to the minima evident in the measured profiles. Several sources have suggested that the metalimnetic DO minimum is likely the result of algal activity. However, even with modeled chlorophyll *a* concentrations often similar to measured (see Section 4.4.4.4), the modeled DO was not as low as that measured in the metalimnion. This led us to suspect that another oxygen demand may be acting in the reservoir and prompted the inclusion of LDOM as a parameter in the model. It is also interesting to note that even with LDOM inputs in the model, the metalimnetic DO minimum at the dam was still not as marked as in the measured profiles until the Holmes Creek and Indian Creek bays were changed from null embayments to embayments in the model. Oxygen demand from the tributaries to the upper reservoir was not making it down to the dam.

Modeled DO profiles for 1988 match the measured profiles better than the other 2 years. Since this is the dry year and would not be much influenced by inflow water quality, these results probably indicate how well the model is reproducing the reservoir processes. So, the model seems to be doing a good job reproducing the reservoir processes.

The Animation and Graphics Portfolio Manager (AGPM) program was used to try to determine the cause of some of the differences between the measured and modeled profiles. During 1973 a pocket of lower DO water occurred at about elevation 525 ft. AGPM profile animation of the main branch and some of the embayments indicate that this water is coming from the Hurricane Creek null embayment. A small constant flow (0.0002 m^3/s) was added for Little Hurricane Creek along with water quality (the same as Pine Creek) in an effort to get DO

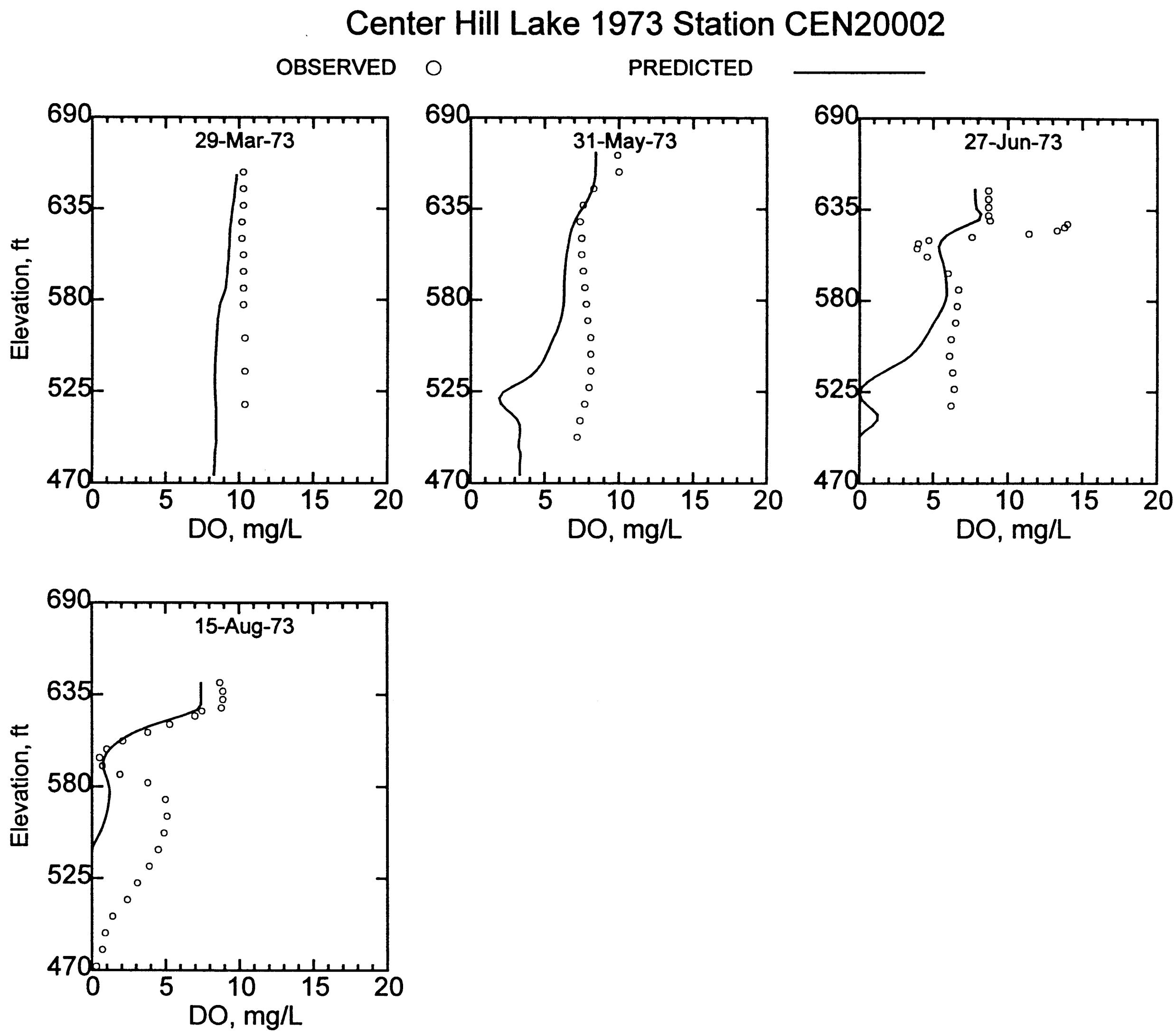


Figure 4.11. Comparison of 1973 measured DO profiles at Center Hill Dam to modeled DO at noon.

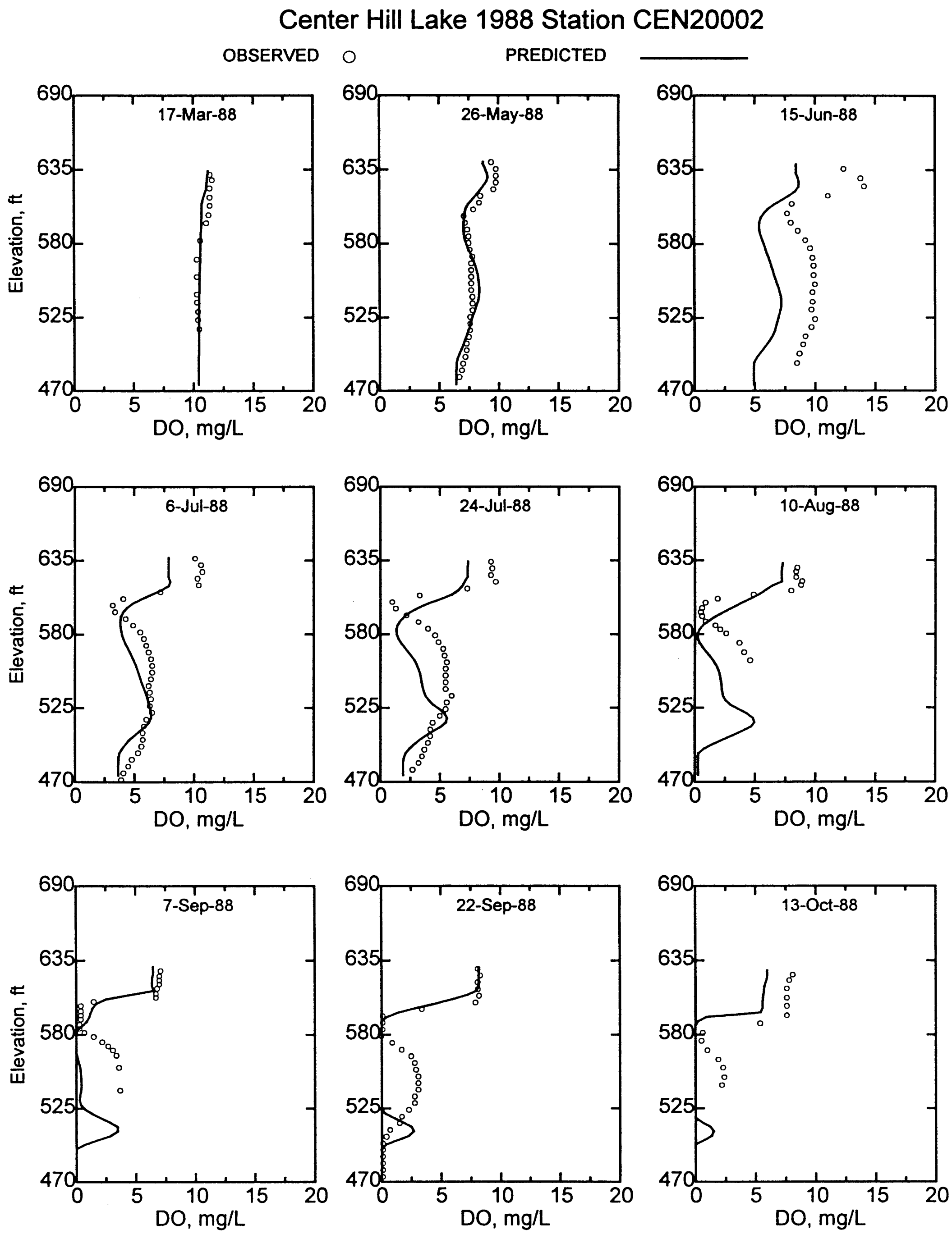


Figure 4.12. Comparison of 1988 measured DO profiles at Center Hill Dam to modeled DO at noon.

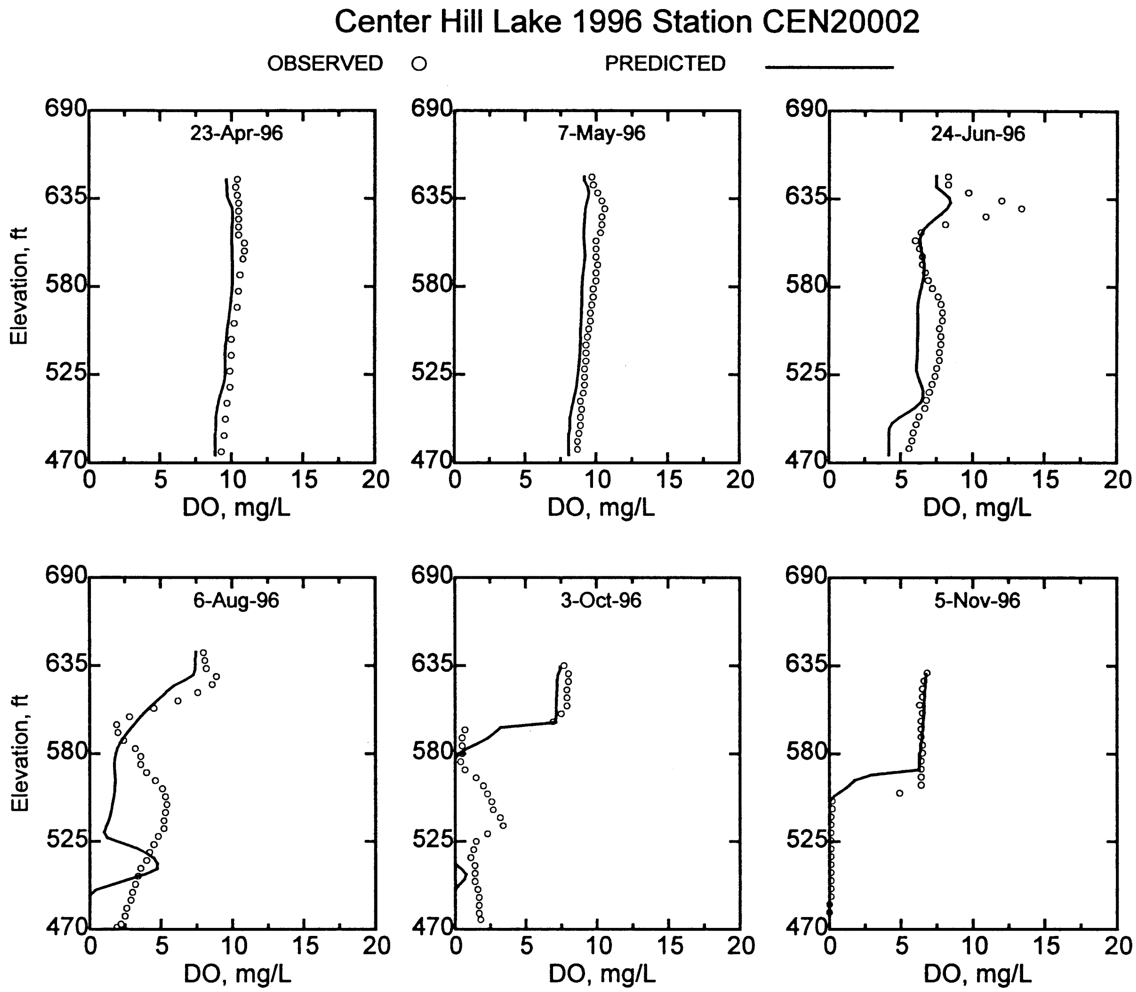


Figure 4.13. Comparison of 1996 measured DO profiles at Center Hill Dam to modeled DO at noon.

concentrations in the Hurricane Creek embayment to match those in the main branch. Attempts to get DO concentrations in the Hurricane Creek null embayment to match the reservoir were unsuccessful.

The 1988 and 1996 models exhibited a pocket of water with higher DO concentrations at approximately elevation 515 ft. The DO concentrations in this pocket are usually similar to the measured DO concentrations at that elevation. Based on the AGPM animation it appears that low DO water from Holmes Creek and/or Indian Creek branches is entering the main branch of the model at the dam in the metalimnion and the upper hypolimnion. Model DO profiles in the Holmes Creek and Indian Creek branches do show lower DO concentrations than those measured (see Appendix M stations CEN20013 and CEN20014). Active exchange between the branches does not extend down into the lower hypolimnion because flows are entering the reservoir at the metalimnion and epilimnion. There is little water mixing below elevation 524 ft at the dam because that has been set as the lower limit for the withdrawal zone (see Section 3.5). The too low modeled DO concentrations in the upper hypolimnion at the dam may also be partly the result of incorrect placement of the Holmes and Indian Creek inflows. Model temperature profiles in the Holmes and Indian Creek bays do show warmer metalimnion temperatures than measured (see Appendix K), so the inflows probably are not going where they should.

Another element of the DO profiles that should be noted is that modeled epilimnion DO concentrations are often less than those measured. This is because the CE-QUAL-W2 model is not able to maintain supersaturated DO conditions. When the measured DO profiles show supersaturated DO concentrations as a result of algal activity, the modeled DO profiles will not match those DO concentrations.

Figure 4.14 shows modeled release DO concentrations with measured DO concentrations downstream of Center Hill Dam. In the spring and summer the model tends to predict release DO concentrations lower than those measured. This underprediction of tailwater DO concentrations is not surprising, even for a hydropower project. The model does not assume any reaeration through the dam, nor between the dam and the downstream monitoring location. It is interesting to note however, that as fall overturn occurs in October and November, the match between measured downstream DO and the model release DO becomes quite good.

4.4.4.2 Phosphorus

Measurements of orthophosphorus (1973 and 1996) and total phosphorus (1988) in the reservoir are most often less than detection. Phosphorus profiles indicate that phosphorus release from sediments does occur during extended periods of anoxia. Model phosphorus profiles are similar to the measured profiles for the model years. The best phosphorus input data was from 1988, when inflow orthophosphorus was measured about once every 2 weeks. The model orthophosphorus profiles for 1988 show responses to variability in the orthophosphorus load similar to those displayed in the measured total phosphorus profiles (orthophosphorus was not measured in the reservoir during 1988).

4.4.4.3 Nitrogen

Reservoir ammonia-N concentrations are often less than detection. Ammonia-N profiles indicate that ammonia-N may be released from sediments when the hypolimnion is anoxic. The model ammonia-N concentrations are similar to measured and exhibit increases in hypolimnion concentrations due to sediment releases. The model ammonia-N profiles are similar to measured ammonia-N profiles.

Measured reservoir nitrate-N concentrations can be pretty high in the spring and summer, but usually by late summer or fall concentrations are at detection. Modeled nitrate-N profiles match spring and summer profiles pretty well. The model doesn't reproduce some of the higher reservoir concentrations that are probably the result of storm run off. This is to be expected since the input concentrations are constant. During late summer and fall modeled nitrate-N concentrations stay fairly constant while measured concentrations decrease. This may be a function of the input concentrations also.

4.4.4.4 Chlorophyll *a* (algae)

Algae are represented by three model compartments: 1) diatoms, 2) green algae, and 3) blue-green bacteria. While the model maintains a mass balance on algal carbon, the typical field measurement of algae is one of the algal pigments, usually chlorophyll *a*. Chlorophyll *a*

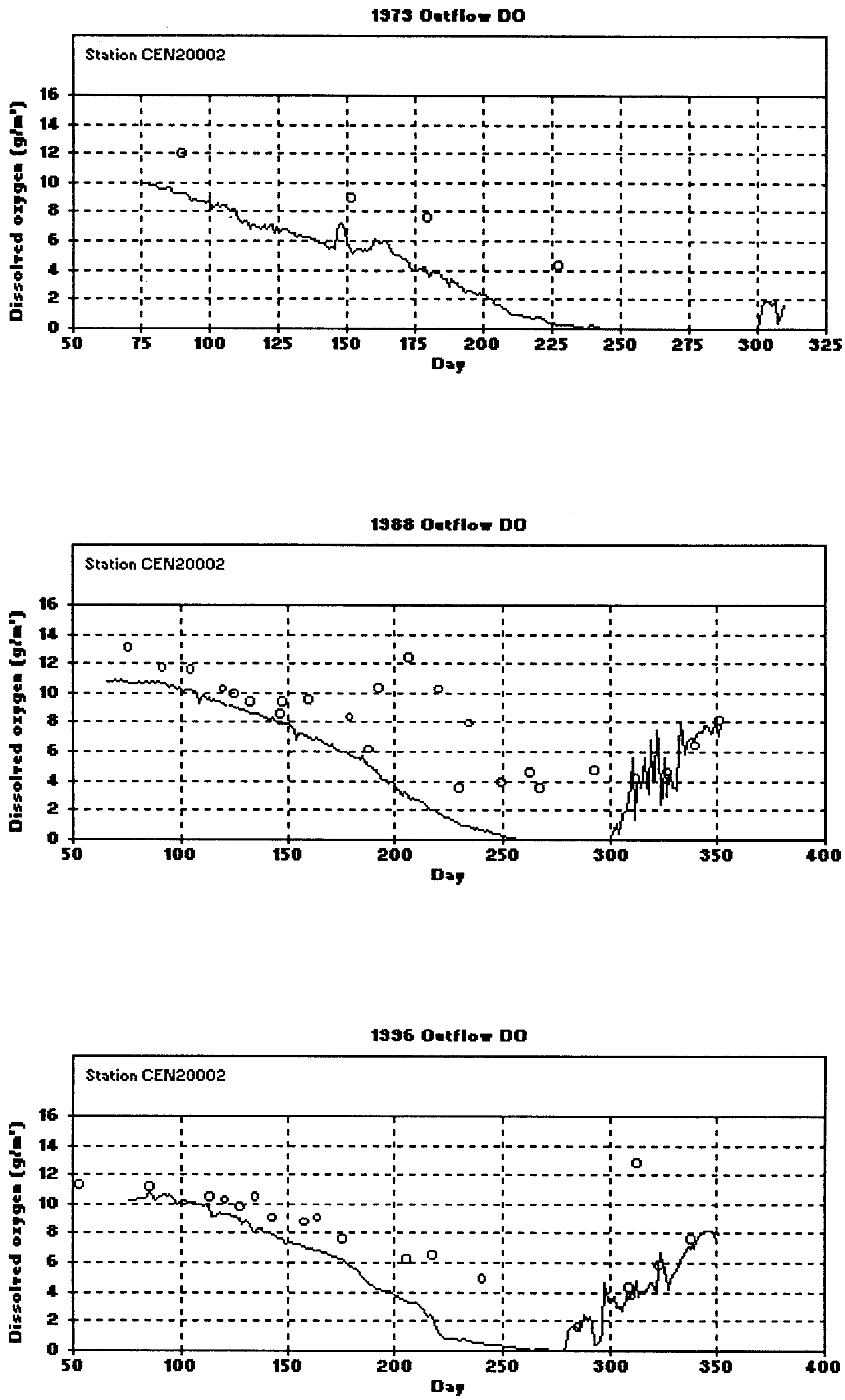


Figure 4.14. Comparison of measured DO downstream of Center Hill Dam to modeled Center Hill Dam release DO at noon.

measurements were not taken in the reservoir during 1973, but chlorophyll *a* was measured in the reservoir during 1988 and 1996. The model algal carbon concentrations were converted to chlorophyll *a* by dividing the concentrations by 65. The sum of the estimated chlorophyll *a* concentrations for the three algal groups was compared to measured chlorophyll *a* concentrations. Because of spatial patchiness, chlorophyll *a* has a relatively high variance in field samples, averaging around ± 15 μg/L (APHA 1995). Plots of modeled and measured chlorophyll *a* profiles are included in Appendix M.

1996 modeled chlorophyll *a* profiles are similar in magnitude and shape to measured profiles throughout the year in the lower reservoir stations (CEN20002 and CEN20003). At stations farther up the reservoir the modeled spring algae exhibit inhibition that is not evident in the measured profiles. Model output indicates the algae at all of the stations are limited by phosphorus. It would seem more likely however, that algae may experience inhibition from lack of light in the spring as a result of suspended solids entering the reservoir during the spring rains. Late summer and fall modeled chlorophyll *a* is similar to measured at all stations. Despite the differences noted, modeled chlorophyll *a* measurements are within 15 μg/L of measured concentrations.

1988 modeled chlorophyll *a* profiles tend to exhibit similar shape to measured profiles. However, spring modeled chlorophyll *a* concentrations tend to be greater than measured concentrations. In some cases the difference between measured and observed chlorophyll *a* concentrations is greater than 15 μg/L. Modeled chlorophyll *a* exhibited inhibition in the spring only at the station farthest upstream (CEN20007). Modeled chlorophyll *a* profiles in late summer and fall are closer to measured chlorophyll *a* concentrations.

There is not measured chlorophyll *a* data to compare the 1973 model results to. The model chlorophyll *a* profiles have similar shapes to the modeled and measured chlorophyll *a* profiles for the other model years. The model for 1973 predicts greater chlorophyll *a* concentrations than observed or modeled for the other two years. The maximum modeled chlorophyll *a* concentration output for 1973 (27 μg/L) is, however, less than the reported historical maximum of 32 μg/L (see Table 2.2).

Time series plots of the predicted concentrations for the three algal groups are also informative (see Figure 4.15). These plots show the relative abundance and dominance succession for the three algal groups. The accepted model of algal succession proceeds with diatoms dominating in the winter and early spring when water temperatures are cool, followed by green algae in the late spring and early summer, then blue-green bacteria in the late summer, and diatoms becoming dominant again in the fall with cooler water temperatures. The model results at the dam generally follow this pattern. Algal identification and enumeration is conducted at the reservoir water quality monitoring stations fairly often. However, the enumeration results are not consistently available for all depths, so it is difficult to determine if algal succession in Center Hill Lake follows the accepted model.

4.4.4.5 Conclusions

The calibration exercise indicates that the model predicts the general patterns and seasonal changes expected in reservoir water quality, generally agrees with measured water quality, and represents the appropriate limnological processes. The calibrated Center Hill Lake model appears to reproduce processes affecting nutrient concentrations well. Problems with DO calibration evident in the profiles at the dam are likely the result of difficulties with the temperature calibration. During DO calibration it became apparent that low DO concentrations at the dam may not be the effect of just algal productivity. Organic matter from another source may be contributing. It also became apparent that organic matter inputs close to the dam have a significant affect on DO concentrations at the dam. Calibration of algae is difficult. Although our calibration is not as good as we would like, model chlorophyll *a* concentrations are generally within the range of analysis variability from measured concentrations. This calibrated model is a viable tool for evaluating different reservoir and watershed management alternatives.

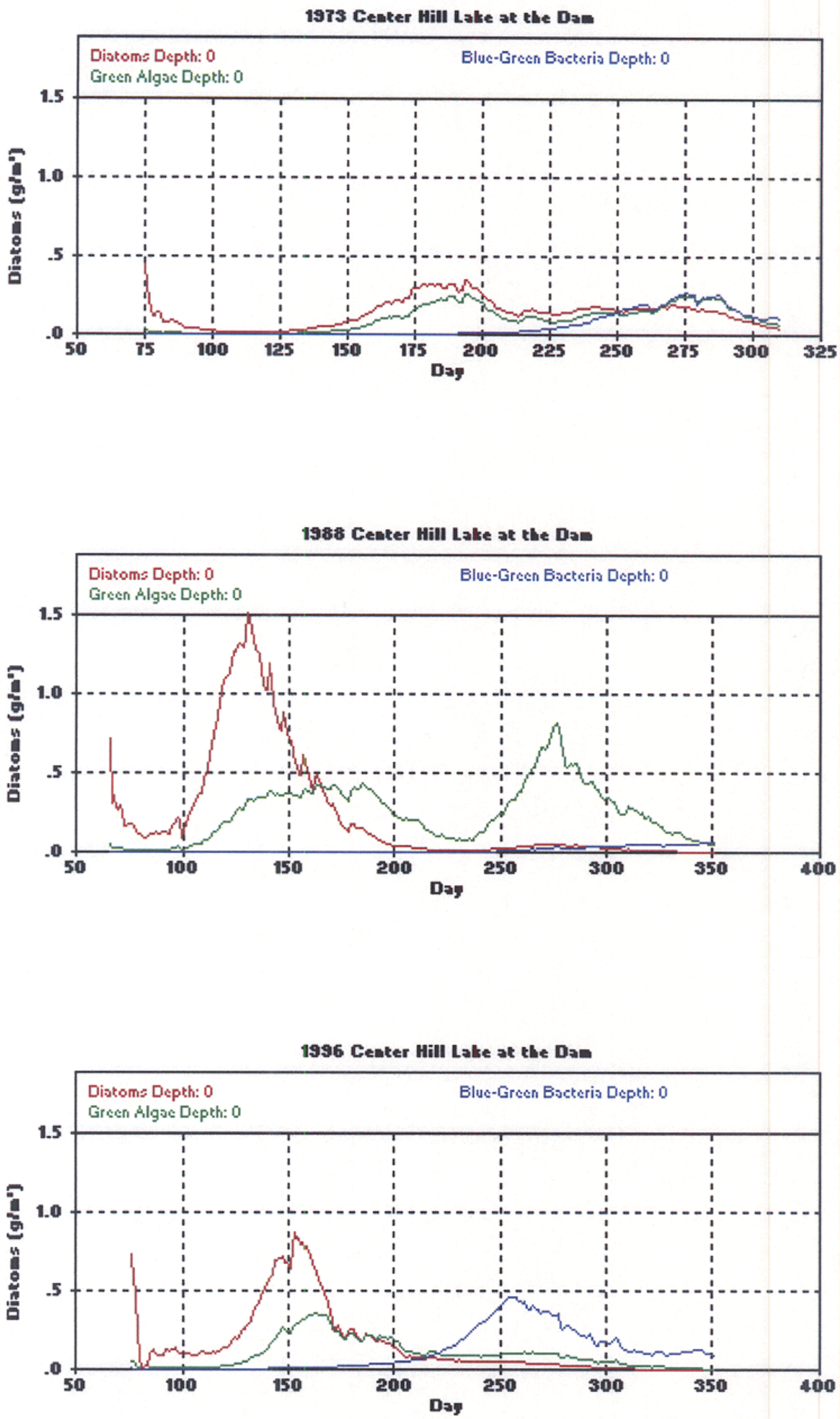


Figure 4.15. Time series of surface concentrations of the three algal types at Center Hill Dam for the three model years.

5.0 SCENARIO SIMULATION

The calibrated model was used to evaluate the impacts of point source dischargers on Center Hill Lake water quality. The scenario involved removing the inputs to the reservoir from all existing WWTPs discharging to Center Hill Lake tributaries. This scenario was simulated for the dry year (1988) only.

5.1 Inputs

The tributary water quality monitoring stations used to develop input water quality for the Center Hill Lake model were located downstream of the WWTPs discharging in the watershed (see Figure 2.2) except on Fall Creek. Therefore, the model water quality inputs include the contributions from these point source dischargers.

During 1988 (the dry year), an intensive water quality study was conducted in the Center Hill Lake watershed. During this study water, quality samples were collected at the wastewater treatment plants in Sparta, McMinnville, Smithville, Cookeville, and Baxter.

Annual nutrient loads calculated from these data, as well as stream water quality data, were included in a report on nutrient loading to Center Hill Lake (Pucker et al. 1989). To get a feeling for the contribution of point sources to the nutrient load, the point source loads were divided by the stream loads (Table 5.1). Fall Creek sampling station was upstream of the Smithville WWTP discharge so the Fall Creek proportion was calculated by dividing the Smithville load by the sum of the Smithville and Fall Creek loads. The Great Falls proportion was calculated by dividing the sum of the Sparta and McMinnville loads by the Great Falls load. Some of the proportions calculated in this manner were greater than one. Apparently, there was some loss of nutrient load as the WWTP discharges traveled downstream. The ammonia-N from Cookeville and Baxter WWTPs was probably converted to nitrate-N by the time it reached the water quality sampling stations. OP from Cookville WWTP may have been trapped by Burgess Falls Lake.

Table 5.1. Nutrient loads from Pucker et al, 1989.

Source	Nitrate-N (lbs)	Ammonia-N (lbs)	OP (lbs)
Fall Creek	20468	17832	4353
Smithville	4201	15476	4100
Proportion	0.17	0.46	0.48
Falling Water	171683	26214	15992
Cookeville	61415	52727	24412
Proportion	0.36	2.01	1.53
Mine Lick	16704	2019	2154
Baxter	1369	3324	1378
Proportion	0.08	1.64	0.64
Great Falls	1893334	364173	70757
Sparta	1776	23173	6499
McMinnville	11638	18637	3769
Proportion	0.70	0.12	0.14

Stream nutrient concentrations without WWTP discharges were estimated by multiplying the original concentrations by one minus the load proportion, in essence subtracting the WWTP nutrient load. When the load proportion was greater than one, we used 0.9. Considering the distance between the WWTPs and the stream sampling stations, the nutrient contributions to Center Hill Lake from the WWTPs were probably overestimated using this method. In addition to reducing nutrients, LDOM concentration were set to zero in streams receiving WWTP discharge. Other parameter concentrations were not changed for this simulation.

5.2 Results

The effect of removing point source loads to the reservoir was evaluated by comparing simulation DO profiles at the dam to the calibrated model profiles (Figure 5.1). The profiles indicate that existing WWTPs do not have much affect on DO at the dam. This is because the WWTPs are mostly in the upper end of the reservoir. The DO calibration exercise indicated that

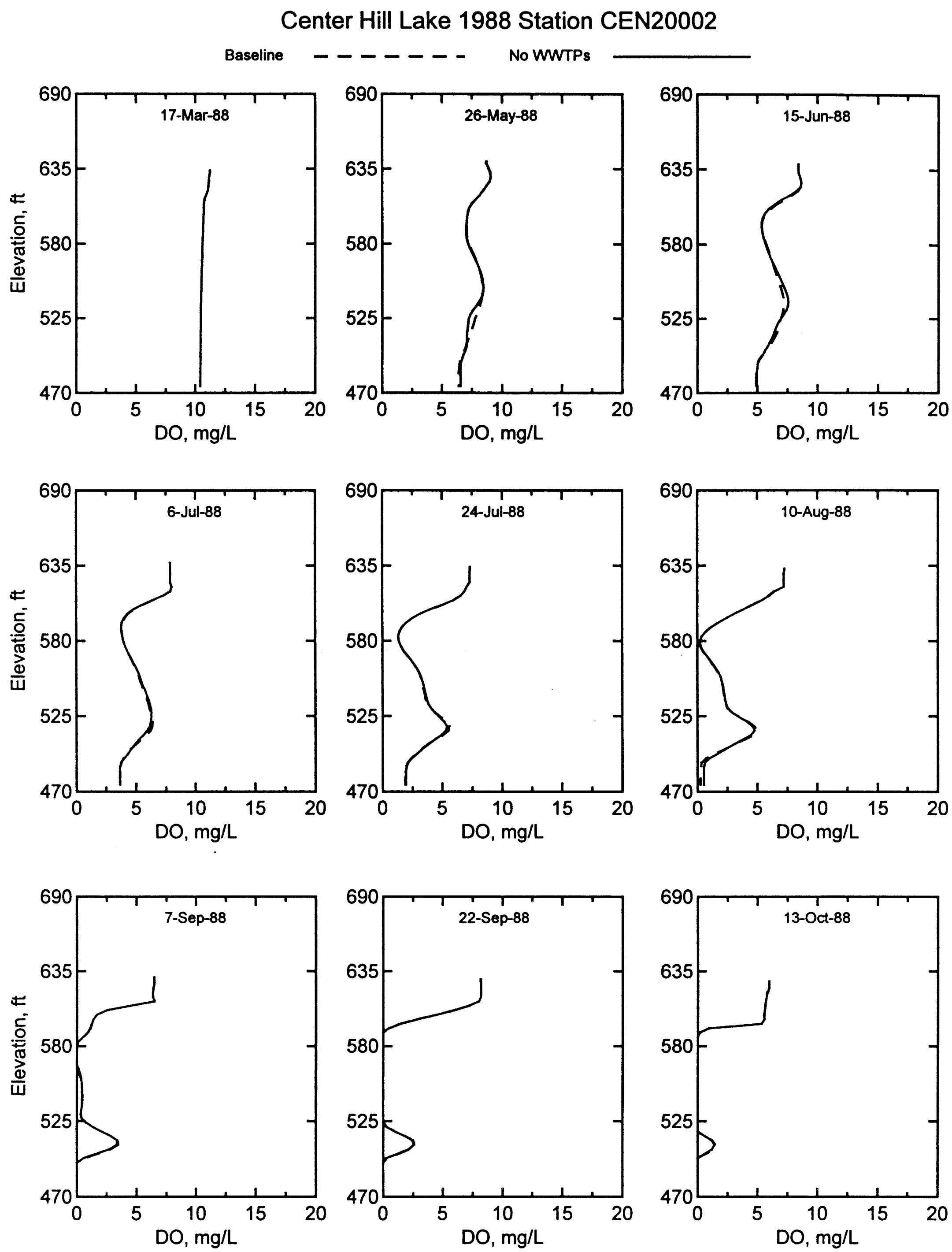


Figure 5.1. Comparison of simulation and calibration DO profiles at Center Hill Dam.

sources of oxygen demand originating closer to the dam are contributing significantly to low DO conditions at the dam. It would appear that non-point sources are the source of the problem.

Since algal productivity is suspected to be the cause of the low DO in the metalimnion, chlorophyll *a* profiles at the dam from the simulation were also compared to the calibrated model profiles (Figure 5.2). There was little change in chlorophyll *a* concentrations either.

5.3 Conclusions

Removing WWTP nutrient and DOM contributions from Center Hill Lake inputs had little effect on DO concentrations at the dam. It appears that WWTPs are not significantly contributing to the problems with low DO in Center Hill releases.

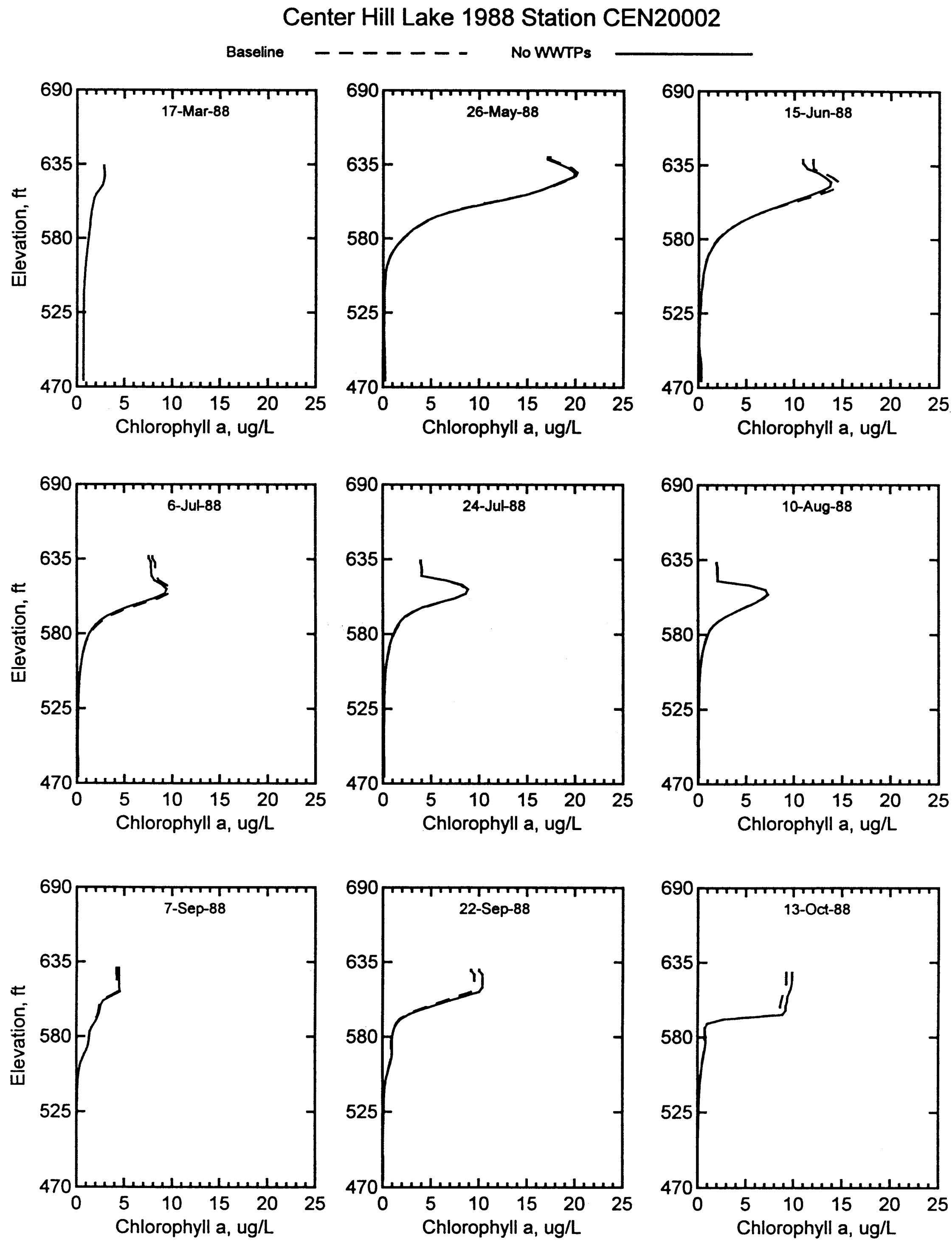


Figure 5.2. Comparison of simulation and calibration chlorophyll *a* profiles at Center Hill Dam.

6.0 REFERENCES

Baines, S.B. and M.L. Pace. 1994. Relationships between suspended particulate matter and sinking flux along a trophic gradient and implications for the fate of planktonic primary production. Can. Jour. Fish Aquat. Sci. 51:25–36.

Bowie, G.L., W.B. Mills, D.B. Porcella, C.L. Campbell, J.R. Pagenkopf, S.A. Gherini, and C. Chamberlain. 1985. Rates, constants, and kinetic formulations in surface water quality modeling. 2nd edition. EPA/600/3-85/040. US Environmental Protection Agency. Athens, GA.

Canale, R.P. and A.H. Vogel. 1974. Effects of temperature on phytoplankton growth. J. Env. Engr. ASCE. 100(EE1):231–241.

Cobelas, M.A. and C. Rojo. 1994. Factors influencing the shape of planktonic diatoms in lakes. Algological Studies. 74: 73–104.

Cole, T.M. 1995. CE-QUAL-W2: A two-dimensional, laterally averaged, hydrodynamic and water quality model. Version 2.0. User Manual. Instruction Report EL-95-1. US Army Corps of Engineer Waterways Experiment Station. Vicksburg, MS.

Cole, T.M. and E.M. Buchak. 1994. CE-QUAL-W2: A two-dimensional, laterally averaged, hydrodynamic and water quality model. Version 2.0. Draft User's Manual. US Army Corps of Engineers Waterways Experiments Station. Vicksburg, MS.

del Giorgio, P.A. and R.H. Peters. 1993. Balance between phytoplankton production and plankton respiration in lakes. Can. Jour. Fish Aquat. Sci. 50:282–289.

del Giorgio, P.A. and R.H. Peters. 1994. Patterns in planktonic P:R ratios in lakes: Influence of lake trophy and dissolved organic carbon. Limnol. Oceanogr. 39:772–787.

EarthInfo. 1996. Surface airways data on CD-ROM. EarthInfo, Inc., Boulder, CO.

Elser, J.J., E.R. Marzolf, and C.R. Goldman. 1990. Phosphorus and nitrogen limitation of phytoplankton growth in the freshwaters of North America: A review and critique of experimental enrichments. Can. Jour. Fish Aquat. Sci. 47:1468–1477.

Eppley, R.W. 1972. Temperature and phytoplankton growth in the sea. Fish. Bull. 70(4):1063–1085.

Eppley, R.W., J.N. Rogers, and J.J. McCarthy. 1969. Half-saturation constants for uptake of nitrate and ammonia by marine phytoplankton. Limnol. Oceanogr. 14:912–920.

Guy, M., W.D. Taylor, and J.C.H. Carter. 1994. Decline in total phosphorus in the surface waters of lakes during summer stratification, and its relationship to size distribution of particles and sedimentation. Can. Jour. Fish Aquat. Sci. 51:1330–1337.

Harris, G.P. 1986. Phytoplankton ecology. Chapman and Hall. New York. 372 pp.

Harris, G.P. and J.N.A. Lott. 1973. Light intensity and photosynthetic rates in phytoplankton. Jour. Fish. Res. Board Canada. 30:1771–1778.

Hecky, R.E., P. Campbell, and L.L. Hendzel. 1993. The stoichiometry of carbon, nitrogen, and phosphorus in particulate matter of lakes and oceans. Limnol. Oceanogr. 38:709–724.

Jewell, W.J. and P.L. McCarty. 1971. Aerobic decomposition of algae. Env. Sci. Tech. 5:1023–1031.

Jirka, B.H. and D.R.F. Harleman. 1979. Cooling impoundments: Classification and analyses. ASCE Jour. Hyd. Div. 106:701–715.

Jorgensen, S.E. ed. 1979. Handbook of environmental data and ecological parameters. Pergamon Press. New York.

Marshall, C.T. and R.H. Peters. 1989. General patterns in the seasonal development of chlorophyll for temperate lakes. Limno. Oceanogr. 34:856–867.

Mazunder, A. 1994. Phosphorus-chlorophyll relationships under contrasting herbizory and thermal stratification: Predictions and patterns. Can. Jour. Fish. Aquat. Sci. 51:390–400.

Megard, R.O., W.S. Combs, Jr., P.D. Smith, and A.S. Knoll. 1979. Attenuation of light and daily integral rates of photosynthesis attained by planktonic algae. Limnol. Oceanogr. 24:1038–1050.

Mills, W.B., D.B. Porcella, M.J. Ungs, S.A. Gherini, K.V. Summers, Ling Fung Mok, G.L. Rupp, G.L. Bowie, and D.A. Haith. 1985. Water quality assessment: A screening procedure for toxic and conventional pollutants in surface and groundwater - Part I. EPA/600/6-85/002a. US Environmental Protection Agency. Athens, GA.

Morris, D.D. and W.M. Lewis, Jr. 1988. Phytoplankton nutrient limitation in Colorado mountain lakes. Freshwat. Biol. 20:315–327.

Pucker, S.J., J.A. Gordon, and H.T. Andrews. 1989. Water Quality Survey of Nutrient Loadings to Center Hill Lake from the Caney Fork River Basin. US Army corps of Engineers. Nashville, TN.

Reynolds, C.S. 1984. Phytoplankton periodicity: The interactions of form, function and environmental variability. Freshwat. Biol. 14:111–142.

Reynolds, C.S. 1988. The concept of ecological succession applied to seasonal periodicity of freshwater phytoplankton. Vert. Int. Veroin. Limnol. 23:683–691.

Reuter, J.E. and R.P. Axler. 1992. Physiological characteristic of inorganic nitrogen uptake by spatially separate algal communities in a nitrogen-deficient lake. Freshwa. Bio. 27:227–236.

Shapiro, J. 1973. Blue-green algae: Why they become dominant. Science 179:382–384.

Smits, T. 1980. Respiration and Mineralization Rates. Delft Hydraulic Institute. Report 80–2.

Sterner, R.W. and D.O. Hessen. 1994. Algal nutrient limitation and the nutrition of aquatic herbivores. Ann. Rev. Ecol. System. 24:1–29.

Tennessee Wildlife Resources Agency. 2000. Center Hill Watershed Detailed Land Cover. Land use and land cover digital data based on satellite imagery (1990-1993) and videography (1995). Tennessee Wildlife Resources Agency, Geographic Information System. Nashville, TN.

Thornton, K.W. and A.S. Lessem. 1978. A temperature algorithm for modifying biological rates. Trans. Am. Fish Soc. 107(2):284–287.

Tilman, D., S.S. Kilham, and P. Kilham. 1982. Phytoplankton community ecology: The role of limiting nutrients. Ann. Rev. Ecol. System. 13:349–372.

Toetz, D., L. Varga, and D. Loughran. 1973. Half-saturation constants for uptake of nitrate and ammonia by reservoir plankton. Ecol. 54(4):903–908.

USGS. 1986. Land use and land cover digital data from 1:250,000- and 1:100,000-scale maps: data users guide 4. Department of the Interior. US Geological Survey, National Mapping Program. Reston, VA.

US Army Corps of Engineers. 1991. HECUPD.

US Army Corps of Engineers Nashville District. 1976. Water Quality Conditions in Center Hill Lake. US Army Corps of Engineers. Nashville, TN.

US Census Bureau. 1999. Website, http://www.census.gov/population/www/estimates/countypop.html. September 6, 2000.

US Environmental Protection Agency. 1996. BASINS Version 1.0 Region 4 EPA-823-C-96-004. US Environmental Protection Agency, Office of Water, Office of Science and Technology. Washington, DC.

Wetzel, R.G. 1983. Limnology, 2nd edition. Saunders College Publishing. Chicago, IL.