Prepared in cooperation with the

**Arkansas Game and Fish Commission**

# SIMULATION OF HYDRODYNAMICS, TEMPERATURE, AND DISSOLVED OXYGEN IN NORFORK LAKE, ARKANSAS, 1994-1995

## Water-Resources Investigations Report 02-4250

**U.S. Department of the Interior**
**U.S. Geological Survey**

Front Cover:
Photograph of Norfork Dam by Alan P. Hall, U.S. Geological Survey.

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Little Rock, Arkansas
2002

**U.S. DEPARTMENT OF THE INTERIOR**
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**U.S. GEOLOGICAL SURVEY**
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Denver Federal Center
Denver, Colorado 80225

# CONTENTS

## ILLUSTRATIONS

## TABLES

## CONVERSION FACTORS AND VERTICAL DATUM

| Multiply | By | To obtain |
|---:|---|---|
| centimeter (cm) | 0.3937 | inch |
| millimeter (mm) | 0.03937 | inch |
| meter (m) | 3.281 | foot |
| kilometer (km) | 0.6214 | mile (mi) |
| hectare (ha) | 2.471 | acre |
| square meter ($m^2$) | 10.76 | square foot |
| square kilometer ($km^2$) | 0.3861 | square mile |
| liter (L) | 0.2642 | gallon (gal) |
| cubic meter ($m^3$) | 35.31 | cubic foot |
| gram (g) | 0.03527 | ounce |
| kilogram (kg) | 2.205 | pound (lb) |

Degrees Celsius (° C) may be converted to degree Fahrenheit (° F) by using the following equation:
° F = 1.8(° C) + 32

Degrees Fahrenheit (° F) may be converted to degree Celsius (° C) by using the following equation:
° C = 0.55(° F – 32)

**Sea level**: In this report 'sea level' refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929) – a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

**Constituent concentrations** in water are in milligrams per liter (mg/L).

# SIMULATION OF HYDRODYNAMICS, TEMPERATURE, AND DISSOLVED OXYGEN IN NORFORK LAKE, ARKANSAS, 1994-1995

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## ABSTRACT

Outflow from Norfork Lake and other White River reservoirs support a cold-water trout fishery of significant economic yield in north-central Arkansas and south-central Missouri. The Arkansas Game and Fish Commission has requested an increase in existing minimum flows through the Norfork Lake dam to increase the amount of fishable waters downstream. Information is needed to assess the impact of increased minimum flows on temperature and dissolved-oxygen concentrations of reservoir water and the outflow.

A two-dimensional, laterally averaged, hydrodynamic, temperature, and dissolved-oxygen model was developed and calibrated for Norfork Lake, located on the Arkansas-Missouri State line. The model simulates water-surface elevation, heat transport, and dissolved-oxygen dynamics. The model was developed to assess the impacts of proposed increases in minimum flow from 1.6 cubic meter per second (the existing minimum flow) to 8.5 cubic meters per second (the increased minimum flow). Simulations included assessing the impact of (1) increased minimum flows and (2) increased minimum flows with increased water-surface elevation of 1.1 meter in Norfork Lake on outflow temperatures and dissolved-oxygen concentrations.

The increased minimum flow simulation (without increasing initial water-surface elevation) appeared to increase the water temperature and decrease dissolved-oxygen concentration in the outflow. Conversely, the increased minimum flow and initial increase in water-surface elevation (1.1 meter) simulation appeared to decrease outflow water temperature and increase dissolved-oxygen concentration through time. However, results from both scenarios for water temperature and dissolved-oxygen concentration were within the boundaries or similar to the error between measured and simulated water column profile values.

## INTRODUCTION

Norfork Lake (fig. 1) is a large, deep-storage reservoir located on the North Fork River in the White River Basin on the border of Arkansas and Missouri. Norfork Lake dam was completed in 1944 and operated by the U.S. Army Corps of Engineers (USACE) for the purposes of flood control and hydroelectric power. Today, in addition to aforementioned uses, the reservoir is used for fish and wildlife habitat, recreation, and water supply. The outflows from Norfork Lake, and other White River reservoirs, also support a cold-water trout fishery of significant economic yield in north-central Arkansas and south-central Missouri. The Arkansas Game and Fish Commission (AGFC) has requested an increase in minimum flows through Norfork Lake dam to increase the amount of fishable waters downstream. Proposed changes in reservoir operations such as increased minimum flows through the dam and increased water storage, have caused concerns about the sustainability of cold water temperature and dissolved oxygen in the bottom water (hypolimnion) of Norfork Lake. Increases in water temperature and decreases in dissolved oxygen could have potential negative impacts on the cold-water trout fisheries in the downstream outflow. Comprehensive information is needed to address temperature and dissolved-oxygen dynamics of Norfork Lake and the effects of increased minimum flow.

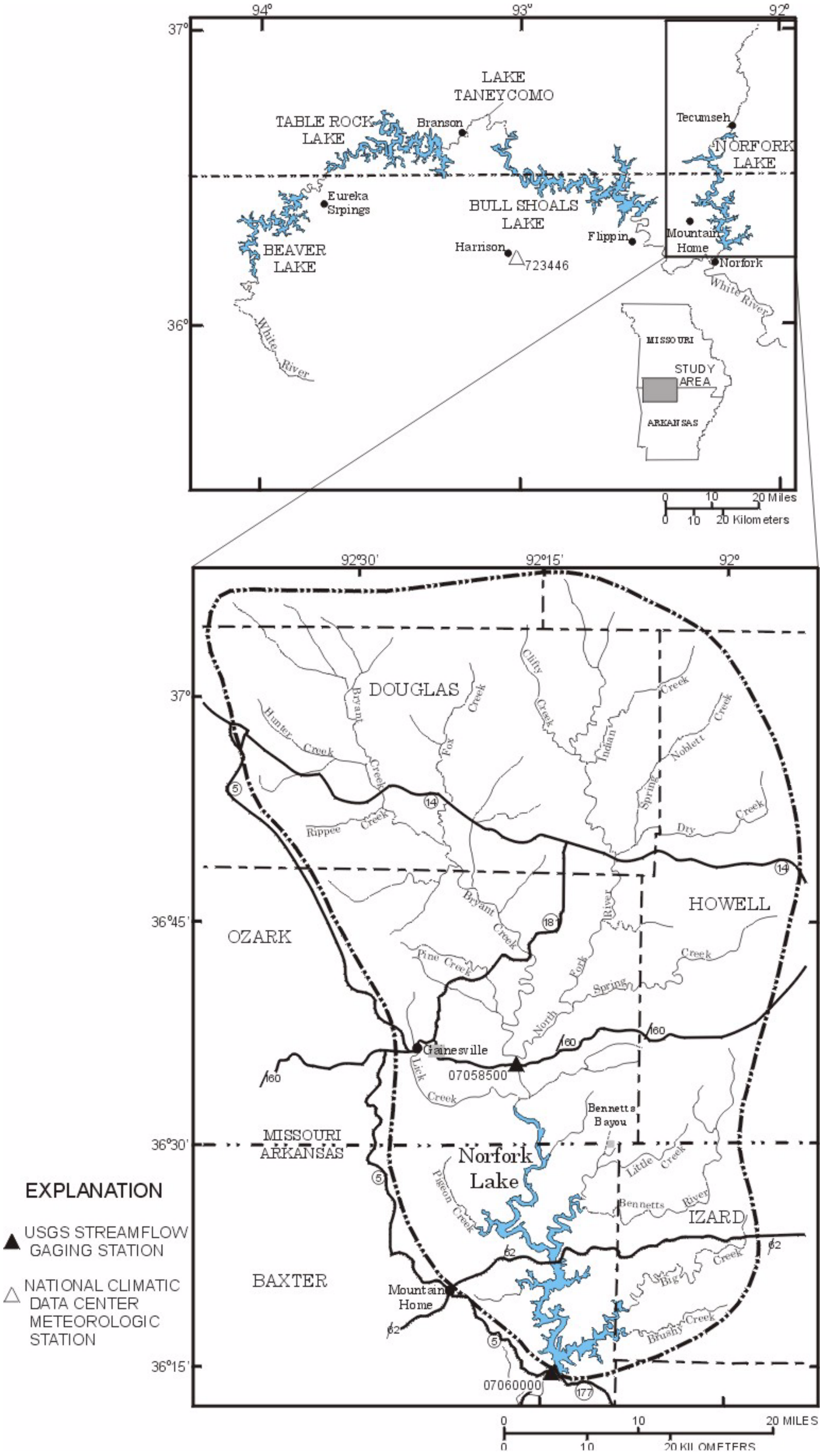

**Figure 1.** Location of Norfork Lake and the North Fork River Basin in Arkansas and Missouri.

Norfork Lake is located on the North Fork River, a tributary to the White River. Upstream from the North Fork River, on the main stem of the White River, are Bull Shoals Lake, Lake Taneycomo, Table Rock Lake, and Beaver Lake (fig. 1). In July 1999, a study was conducted by the U.S. Geological Survey (USGS) in cooperation with the AGFC to characterize the hydrodynamics, temperature, and dissolved-oxygen concentration in Norfork Lake and to simulate the effect of reservoir operations on temperature and dissolved-oxygen concentration in the reservoir and outflow. A hydrodynamic model of Norfork Lake was developed using the USACE CE-QUAL-W2 software program (Cole and Buchak, 1995) to simulate the expected minimum flow scenarios.

This study was conducted in conjunction with other studies evaluating the impacts of reservoir operations on temperature and dissolved-oxygen concentration in Bull Shoals, Table Rock, and Beaver Lakes. These studies will provide a better understanding of the hydro- and water-quality dynamics within each reservoir system. In addition, calibrated models developed for these studies will provide the basis and framework for future water-quality modeling. As more data are collected in both the reservoirs and tributaries, the calibrated models can be modified to assess the nutrient assimilative capacity of the reservoir, nutrient limitations, and the effect of increases in nutrient loading on reservoir trophic status.

## Purpose

The purpose of this report is to describe a model of hydrodynamics, temperature, and dissolved oxygen in Norfork Lake for the simulation period of January 1994 through December 1995. Water temperature and dissolved-oxygen concentration results from model applications simulating two proposed minimum flow scenarios are presented and compared to a calibrated, base condition.

## Description of Study Area

Norfork Lake was impounded in 1944 on the North Fork River, east of the city of Mountain Home, Arkansas. The primary inflows into Norfork Lake are Pigeon Creek, Bennetts River, and the North Fork River; several smaller tributaries also flow into the reservoir (fig. 1). The watershed has a drainage area of 4,683 km$^2$ at the Norfork Lake dam. Norfork Lake contains 1,540 million m$^3$ of water at the elevation of the current conservation pool (169 m above sea level) and the surface area is 89 km$^2$. The length of the reservoir is 57 km from the North Fork River at the Highway 160 bridge to the Norfork Lake dam. The depth of the reservoir at the dam at conservation pool elevation is about 57 m, and the average depth through the reservoir is 17 m. On average, the hydraulic retention time of Norfork Lake is about 0.9 year.

## Acknowledgments

Edward Buchak and Rajeev Jain of J.E. Edinger Associates, Inc., Jerad Bales of the USGS, and Tom Cole of the USACE provided valuable guidance on model development and applications. John Kielczewski of the USACE provided much of the inflow and outflow and water-surface elevation data used to develop and calibrate the model.

# SIMULATION OF HYDRODYNAMICS, TEMPERATURE, AND DISSOLVED OXYGEN IN NORFORK LAKE

A two-dimensional, laterally averaged, hydrodynamic, temperature, and dissolved-oxygen model using CE-QUAL-W2 was developed for Norfork Lake and calibrated based on hydrologic records and vertical profiles of temperature and dissolved oxygen measured near the Norfork Lake dam from January 1994 through December 1995. The CE-QUAL-W2 model simulates water-surface elevation and vertical and longitudinal gradients in water-quality constituents. The model includes routines for temperature, dissolved oxygen, and more than 20 other parameters, including algae, carbon dioxide, coliform bacteria, detritus, inorganic carbon, iron, labile and refractory dissolved organic matter, nitrite plus nitrate as nitrogen, pH, phosphorus, sediment, suspended solids, total dissolved solids, and a conservative tracer (Cole and Buchak, 1995). Calibration and simulation of water-quality parameters other than water temperature and dissolved oxygen, such as nitrogen, phosphorus, algal production, and organic matter, are beyond the scope of this study.

## Model Implementation

Implementation of the CE-QUAL-W2 model for Norfork Lake included development of the computational grid, specification of boundary and initial conditions, and preliminary selection of model parameter values. Model development and associated assumptions in the selection of boundary and initial conditions are described, and specific values of model parameters given.

### Computational Grid

The computational grid is the geometric scheme (fig. 2) that numerically represents the space and volume of the reservoir. The model extends 57 km from the upstream boundary (U.S. Highway 160 bridge) to the downstream boundary (Norfork Lake dam). The grid geometry was developed by digitizing pre-impoundment elevation contours of the land surface or reservoir bottom from USGS 7.5-minute and 15-minute quadrangle maps (fig. 3). Twenty-five computational segments exist along the mainstem of the North Fork River in Norfork Lake, whereas, 9 segments are in the Little Creek branch and 5 segments are in the Big Creek branch. In addition, three other embayments (branches), including Pigeon Creek, Bennetts River, and Brushy Creek, are modeled with three computational segments each. Volumes of the smaller embayments not included in the computational grid were added to associated mainstem segments so that reservoir volume was preserved.

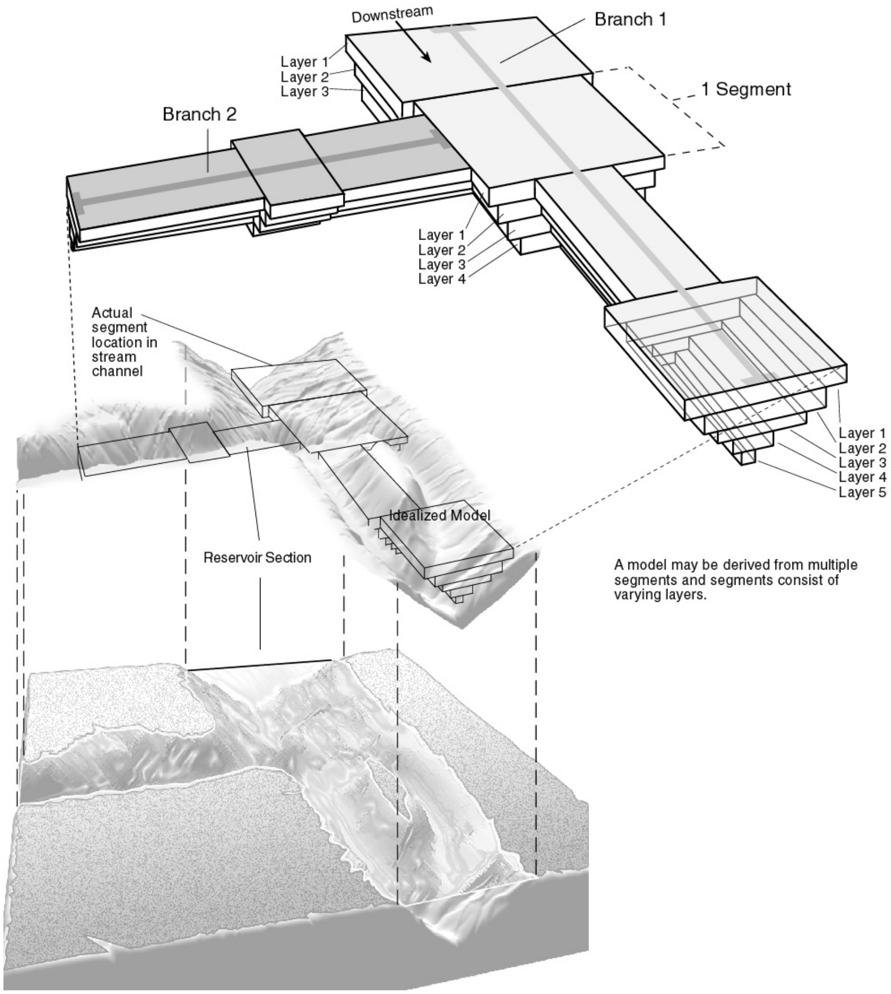

**Figure 2.** Idealized model segments, layers, and branches for the CE-QUAL-W2 reservoir model.

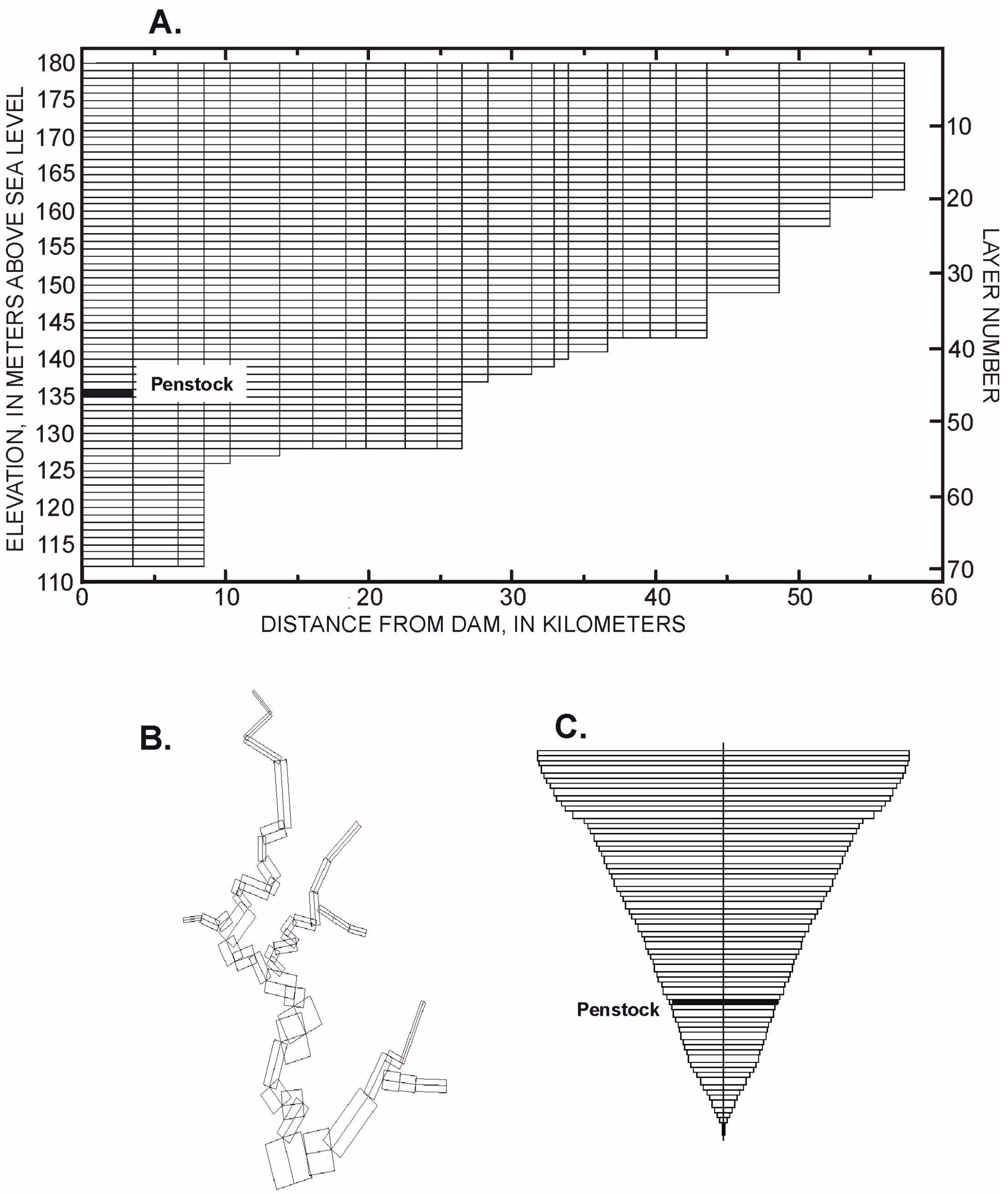

**Figure 3.** Side view (A), top view (B), and face view from the dam (C) of the computational grid of Norfork Lake used in CE-QUAL-W2.

Segment geometry varied along the upstream-downstream gradient (fig. 3). Segment length was based in part on segment width. Segments ranged in length from 926 to 5,097 m, and orientation of the longitudinal axis relative to north was determined for each segment. Segment widths at the reservoir surface ranged from 265 m in the headwaters to more than 3,300 m. Each segment was divided vertically into 1-m layers. Depth from the elevation of the top of the flood-control pool to the reservoir bottom ranged from 14 m at the upstream boundary to 65 m near Norfork Lake dam. Relations between water-surface elevation and volume and surface area in the Norfork Lake model grid were similar to USACE preimpoundment data (fig. 4).

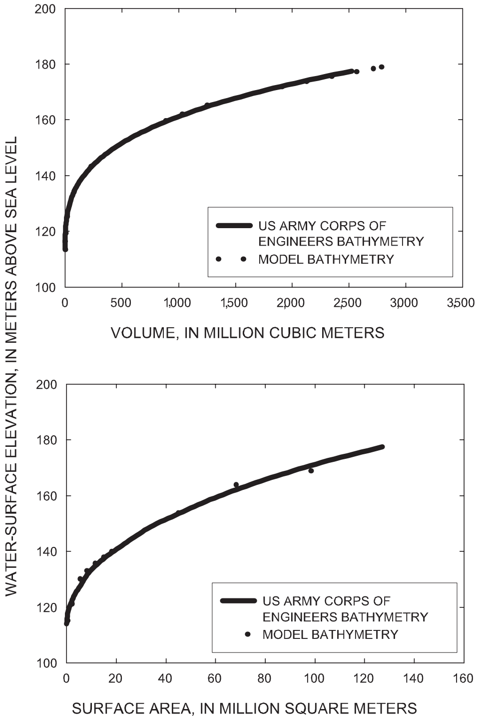

**Figure 4.** Relation between water-surface elevation and volume and water-surface elevation and surface area in Norfork Lake.

## Boundary and Initial Conditions

Hydraulic, thermal, and chemical boundary conditions are required in CE-QUAL-W2. The boundaries of the Norfork Lake model included the reservoir bottom, the shoreline, tributary streams, the upstream boundary (U.S. Highway 160 bridge), the downstream boundary (dam), and the water-surface elevation of the reservoir. Initial water-surface elevation of the reservoir, water temperature, and selected constituent concentrations also are required.

### Hydraulic and Thermal Boundary Conditions

The reservoir bottom is assumed to be an immobile and impermeable boundary. That is, the bottom sediments are stationary and not resuspended by flow, and groundwater discharge to the reservoir or recharge from the reservoir to ground water is negligible. The reservoir bottom extracts energy from water movement by causing resistance to water flow; this phenomenon varies with the magnitude of flow. A single, empirical coefficient (Chezy coefficient) is applied to the reservoir bottom in all computational segments (table 1). Heat exchange between the reservoir bottom and the overlying water column is computed from (1) the sediment temperature, (2) the simulated temperature of the overlying water, and (3) bottom-water heat exchange coefficient (table 1). The sediment temperature and the exchange coefficient are assumed to be temporally and spatially constant. A reasonable estimate of sediment temperature is the annual average water temperature near the sediment-water interface; a value of 10.0 °C was used in the Norfork Lake model. In general, heat exchange from the reservoir bottom is about two orders of magnitude less than surface heat exchange (Cole and Buchak, 1995).

The reservoir shoreline is defined as a boundary across which there is no flow. The exact position of the shoreline changes during model simulation because of changing water level.

**Table 1.** Hydraulic and thermal input parameters specified for Norfork Lake model

[$m^{0.5}$/s, meter to the one-half power per second; (watts/$m^2$)/° C, watts per square meter per degree Celsius; ° C, degrees Celsius; $m^2$/s, square meter per second]

| Parameter | Computational purpose | Value | Constant or time variable |
|---|---|---|---|
| Chezy resistance coefficient | Represents turbulent exchange of energy at the reservoir bottom | 70 $m^{0.5}$/s | Constant |
| Bottom – water heat exchange coefficient | Computes heat exchange between reservoir bottom and overlying water | $7.0 \times 10^{-8}$ (watts/$m^2$)/° C | Constant |
| Sediment temperature | Represents the reservoir bottom (sediment) temperature | 10 ° C | Constant |
| Wind – sheltering coefficient | Reduces wind speed to effective wind speed at water surface | 0.7 (dimensionless) | Constant |
| Horizontal eddy viscosity | Represents laterally averaged longitudinal turbulent exchange of momentum | 1 $m^2$/s | Constant |
| Horizontal eddy diffusivity | Represents laterally averaged longitudinal turbulent mixing of mass and heat | 1 $m^2$/s | Constant |

Annual streamflow recorded at the USGS streamflow-gaging station near Tecumseh, Missouri, (station number 07058500; fig 1) on the North Fork River indicates that inflow to Norfork Lake during the 1994 and 1995 modeling time period was slightly above average (fig. 5). Annual mean streamflow for the North Fork River from 1945 through 1995 ranged from 8.70 to 43.2 $m^3$/s. The average annual mean streamflow for this time period was 21.4 $m^3$/s. Annual mean streamflow for the 1994 and 1995 modeling time period was 28.0 and 23.3 $m^3$/s, respectively (Evans and others, 1995; Porter and others, 1996, 1997).

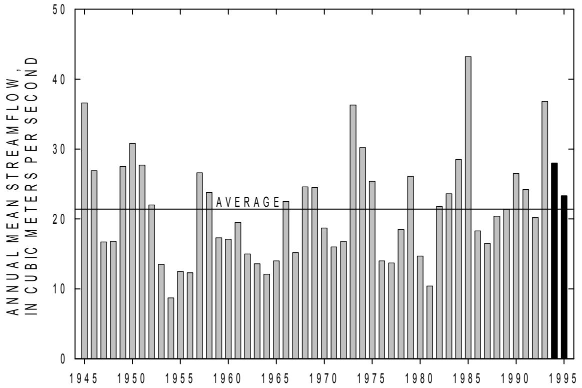

**Figure 5.** Annual mean streamflow for the North Fork River upstream from Norfork Lake, 1945-1995.

Daily reservoir inflows used in the model (fig. 6) were calculated by the USACE based on daily average outflows and changes in reservoir water-surface elevations. The daily inflow was distributed into one major branch (North Fork River) and five minor branches according to drainage area. Approximately 62 percent of the inflow was distributed to the North Fork River, 27 percent was evenly distributed along the reservoir shoreline, and 11 percent was distributed among the five smaller branches. Total mean reservoir inflow from January 1, 1994, through December 31, 1995, was estimated to be 70.2 $m^3$/s, whereas, the estimated median reservoir inflow for the same period was 44.3 $m^3$/s. The estimated reservoir inflow exceeded 142 $m^3$/s 10 percent of the time.

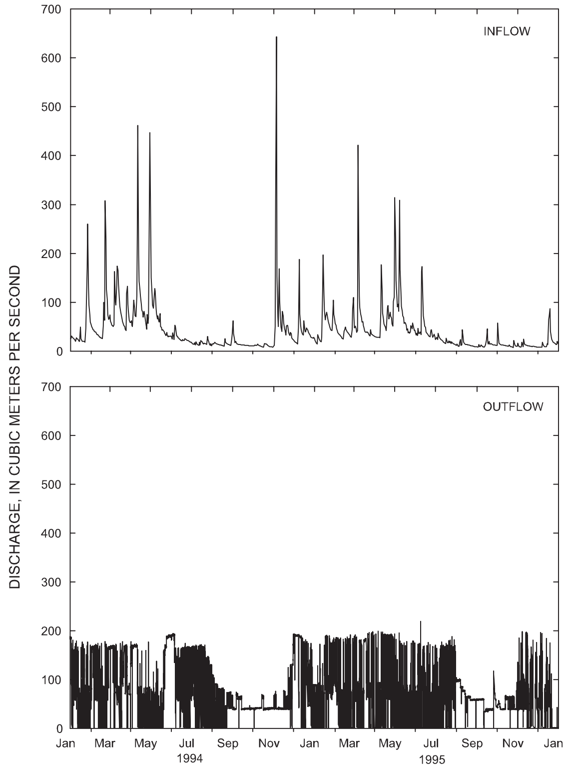

**Figure 6.** Daily inflow (top) and hourly dam outflow (bottom) for Norfork Lake, Arkansas, January 1994 through December 1995.

The downstream boundary for the Norfork Lake model consists of the outflow from Norfork Lake dam. Hourly outflow data (fig. 6) were produced by the USACE using stage-discharge relations and hourly power generation records. The mean and median reservoir outflow was 70.3 and 60.5 $m^3$/s, respectively. The reservoir outflow exceeded 168 $m^3$/s 10 percent of the time. The vertical extent and distribution of flow in the release zone near the Norfork Lake dam (downstream boundary) were simulated using penstock (point) dam release flow, the outflow rate, and the simulated density gradient upstream from the dam in the reservoir. The release structure was simulated as a point release, and the middle of the structure was at an elevation of 136.4 m above sea level, model layer 46 (fig. 3).

Hydraulic input parameters at the water surface included evaporation, wind stress, and surface heat exchange. All meteorological data required for these computations were measured at Harrison, Arkansas (station number 723446, National Climatic Data Center, Asheville, North Carolina), and generally were recorded at hourly intervals. Evaporation in the model was computed from a time series of water-surface temperatures, dewpoint temperatures, wind speeds, surface layer widths, and length of the segment. Wind stress was computed from a time series of wind speeds and directions, the orientation of the computational segment, and a wind-sheltering coefficient (table 1). The wind-sheltering coefficient is time variable and reduces the effect of wind on the reservoir because of topographic or vegetative sheltering; however, in the Norfork Lake model this coefficient was held constant. Surface heat exchange was computed in the model from reservoir latitude and longitude, and from a time series of measured air temperatures, dewpoint temperatures, cloud covers, and wind speeds and directions. In the original meteorological data, cloud cover was recorded as clear (CLR), scattered (SCT), broken (BKN), and overcast (OVC). The model requires cloud cover to be entered as a number ranging from 0.0 to 10.0. In the Norfork Lake model, cloud cover was recorded as: CLR = 0.0, SCT = 1.0, BKN = 3.6, and OVC = 7.8. The simulated surface-water temperature and loss of heat through evaporation were included in the heat budget.

### Chemical Boundary Conditions

A time series of concentrations of selected constituents at all inflow boundaries is required for model operation. Boundary data in all tributaries and branches included dissolved oxygen, ammonia as nitrogen, nitrite plus nitrate as nitrogen, total phosphorus, and a conservative tracer. Because of the limited amount of available water-quality data, annual average concentrations were estimated based on similar values reported by Evans and others (1995) and Porter and others (1996, 1997) and used for all inflow boundary constituents except dissolved oxygen. Dissolved-oxygen concentrations at the inflow boundaries were set to the concentration for 100 percent saturation for the given water temperature.

Exchange of dissolved oxygen occurs at the water surface of the reservoir and is affected by wind speed and direction, water temperature, water-surface elevation above sea level, and the molecular diffusivity of oxygen gas. Atmospheric nutrient inputs were not included in this model, and constituent inputs from the reservoir bottom were generally computed within the model based on the value of selected parameters (table 2) and the constituent concentrations in the overlying waters.

### Initial Conditions

Initial water-surface elevation and velocity, temperature, and constituent concentrations for each computational segment are required prior to initiating model simulation. Initial water-surface elevation was set to the value measured at the Norfork Lake dam on January 1, 1994. Initial velocities were assumed to be zero. The water was assumed to be isothermal throughout the reservoir and equal to the water temperature measured near the dam (10.0 °C). Initial constituent concentrations also were assumed to be uniform throughout the reservoir and equal to values measured near the dam on December 30, 1993 (Evans and others, 1995).

## Model Parameters

Parameters are used to describe physical and chemical processes that are not explicitly modeled and to provide chemical kinetic rate information for the model. Many parameters cannot be measured directly and often are adjusted during the model calibration process until simulated values agree with measured observations.

Most of the relevant hydrodynamic and thermal processes are modeled in CE-QUAL-W2; thus, relatively few hydraulic and thermal parameters are adjustable. The horizontal eddy viscosity describes turbulent exchange of momentum, and the horizontal eddy diffusivity describes turbulent mixing of mass and heat. Other parameters such as resistance, bottom heat exchange, bottom temperature, and wind-sheltering coefficients were discussed previously. In general, reservoir models are relatively insensitive to changes in the horizontal eddy viscosity and diffusivity. However, the thermal processes are relatively sensitive to changes in bottom-heat exchange and temperature, and the wind-sheltering coefficient.

About 60 biological and chemical rate coefficients and other parameters are required for the application of CE-QUAL-W2 (table 2). Most of the parameter values were based on suggestions given in the CE-QUAL-W2 manual (Cole and Buchak, 1995), and all the parameters are temporally and spatially constant. Some of the parameters have suggested ranges, and selected parameters were adjusted, within reasonable limits, until simulated values agreed with measured observations (calibration).

## Other Model Options

The maximum computational time step (interval) was limited to 1 hour because the input data were sometimes supplied at this interval. The model-selected computational interval generally was about 5 minutes. Model calculations occurred at time steps smaller than the boundary conditions that were provided, and linear interpolation occurred between values for all input conditions except meteorological data. The meteorological data were assumed to remain constant between measured values. The ‘QUICKEST’ numerical scheme (Leonard, 1979) was used for solving the transport equations, and a Crank – Nicholson scheme (Roache, 1982) was used to solve the vertical advection equation.

**Table 2.** Rate coefficients used in water-chemistry and biological simulations and other parameters specified as input in the Norfork Lake model

[m, meters; *, dimensionless; $Q_{10}$, temperature correction factor; m/d, meters per day; d, day; watts/$m^2$, watts per square meter; $^oC$, degrees Celsius; (g/$m^2$)/d, grams per square meter per day; BOD, biochemical oxygen demand; mg/L, milligrams per liter]

| Parameter/rate coefficient | Computational purpose | Value |
|---|---|---|
| Light extinction coefficient for water | Amount of solar radiation absorbed in the surface layer | 0.48/m |
| Light extinction coefficient for organic solids | Amount of solar radiation absorbed in the surface layer | 0.01/m |
| Light extinction coefficient for inorganic solids | Amount of solar radiation absorbed in the surface layer | 0.01/m |
| Fraction of incident solar radiation absorbed at water surface | Amount of solar radiation absorbed in the surface layer | 0.42* |
| Coliform decay rate | Decay rate for coliforms, temperature dependent | 1.4/d |
| Coliform decay rate temperature coefficient | A $Q_{10}$ formulation modifies coliform decay rate | 1.04* |
| Suspended solids settling rate | Settling rates and sediment accumulation in reservoir | 2 m/d |
| Algal growth rate | Maximum gross algal production rate, uncorrected for respiration, mortality, excretion or settling; temperature dependent | 1.0/d |
| Algal mortality rate | Maximum algal mortality rate; temperature dependent | 0.01/d |
| Algal excretion rate | Maximum algal photorespiration rate, which becomes labile dissolved organic matter | 0.01/d |
| Algal dark respiration rate | Maximum algal dark respiration rate | 0.02/d |
| Algal settling rate | Representative settling velocity for algal assemblages | 0.14 m/d |
| Saturation light intensity | Saturation light intensity at maximum algal photosynthesis rate | 300 watts/$m^2$ |
| Fraction of algal biomass lost by mortality to detritus | Detritus and dissolved organic matter concentrations; remaining biomass becomes labile dissolved organic matter | 0.8* |
| Lower temperature for algal growth | Algal growth rate as a function of water temperature | 1.0 $^oC$ |
| Fraction of algal growth at lower temperature | Algal growth rate as a function of water temperature | 0.10* |
| Lower temperature for maximum algal growth | Algal growth rate as a function of water temperature | 25.0$^oC$ |
| Fraction of maximum growth at lower temperature | Algal growth rate as a function of water temperature | 0.99* |
| Upper temperature for maximum algal growth | Algal growth rate as a function of water temperature | 30.0 $^oC$ |
| Fraction of maximum growth at upper temperature | Algal growth rate as a function of water temperature | 0.99* |
| Upper temperature for algal growth | Algal growth rate as a function of water temperature | 40.0 $^oC$ |
| Fraction of algal growth at upper temperature | Algal growth rate as a function of water temperature | 0.10* |
| Labile dissolved organic matter decay rate | Dissolved-oxygen loss and production of inorganic carbon, ammonia, and phosphate from algal decay; temperature dependent | 0.12/d |
| Labile to refractory decay rate | Transfer of labile to refractory dissolved organic matter | 0.001/d |
| Maximum refractory dissolved organic matter decay rate | Dissolved-oxygen loss and production of inorganic carbon, ammonia, and phosphate from decay of refractory dissolved organic matter; temperature dependent | 0.001/d |
| Detritus decay rate | Dissolved-oxygen loss and production of inorganic carbon, ammonia, and phosphate from decay of particulate organic matter, temperature dependent | 0.06/d |
| Detritus settling velocity | Loss of particulate organic matter to bottom sediment | 0.35 m/d |
| Lower temperature for organic matter decay | Organic matter decay as a function of temperature | 5.0 $^oC$ |
| Fraction of organic matter decay at lower temperature | Organic matter decay as a function of temperature | 0.10* |
| Lower temperature for maximum organic matter decay | Organic matter decay as a function of temperature | 30.0 $^oC$ |
| Fraction of maximum organic matter decay at lower temperature | Organic matter decay as a function of temperature | 0.99* |
| Sediment decay rate | Decay rate of organic matter in bed sediments | 0.08/d |
| Sediment oxygen demand | Zero-order sediment oxygen demand for each computational segment | 3.5 (g/$m^2$)/d |

**Table 2.** Rate coefficients used in water-chemistry and biological simulations and other parameters specified as input in the Norfork Lake model--Continued

[m, meters; *, dimensionless; $Q_{10}$, temperature correction factor; m/d, meters per day; d, day; watts/$m^2$, watts per square meter; $^oC$, degrees Celsius; $(g/m^2)/d$, grams per square meter per day; BOD, biochemical oxygen demand; mg/L, milligrams per liter]

| Parameter/rate coefficient | Computational purpose | Value |
|---|---|---|
| 5-day BOD decay rate | Effects of BOD loading on dissolved oxygen | 0.1/d |
| BOD temperature rate coefficient | Adjusts 5-day BOD decay rate at $20^oC$ to ambient temperature | 1.047* |
| Ratio of 5-day BOD to ultimate BOD | Effects of BOD loading on dissolved oxygen | 1.85* |
| Release rate of phosphorus from bottom sediments | Phosphorus balance; computed as a fraction of sediment oxygen demand | 0.05* |
| Phosphorus partitioning coefficient | Describes sorption of phosphorus on suspended solids | 1.2* |
| Algal half-saturation constant for phosphorus | The phosphorus concentration at which the uptake rate is one-half the maximum uptake rate; upper concentration at which algal growth is proportional to phosphorus concentration | 0.005 mg/L |
| Release rate of ammonia from bottom sediments | Nitrogen balance; computed as a fraction of the sediment oxygen demand | 0.08* |
| Ammonia decay rate | Rate at which ammonia is oxidized to nitrate | 0.12/d |
| Algal half-saturation constant for ammonia | Nitrogen concentration at which the algal uptake rate is one-half the maximum uptake rate; upper concentration at which algal growth is proportional to ammonia concentration | 0.014 mg/L |
| Lower temperature for ammonia decay | Ammonia nitrification as a function of temperature | 5.0 $^oC$ |
| Fraction of nitrification at lower temperature | Ammonia nitrification as a function of temperature | 0.1* |
| Lower temperature for maximum ammonia decay | Ammonia nitrification as a function of temperature | 20.0 $^oC$ |
| Fraction of maximum nitrification at lower temperature | Ammonia nitrification as a function of temperature | 0.99* |
| Nitrate decay rate | Rate at which nitrate is denitrified; temperature dependent | 1.0/d |
| Lower temperature for nitrate decay | Denitrification as a function of temperature | 5.0 $^oC$ |
| Fraction of denitrification at lower temperature | Denitrification as a function of temperature | 0.1* |
| Lower temperature for maximum nitrate decay | Denitrification as a function of temperature | 20.0 $^oC$ |
| Fraction of maximum denitrification at lower temperature | Denitrification as a function of temperature | 0.99* |
| Iron release from bottom sediments | Iron balance; computed as a fraction of sediment oxygen demand | 0.5* |
| Iron settling velocity | Particulate iron settling velocity under oxic conditions | 2.0 m/d |
| Oxygen stoichiometric equivalent for ammonia decay | Relates oxygen consumption to ammonia decay | 4.57* |
| Oxygen stoichiometric equivalent for organic matter decay | Relates oxygen consumption to decay of organic matter | 1.4* |
| Oxygen stoichiometric equivalent for dark respiration | Relates oxygen consumption to algal dark respiration | 1.4* |
| Oxygen stoichiometric equivalent for algal growth | Relates oxygen production to algal growth | 3.0* |
| Stoichiometric equivalent between organic matter and phosphorus | Relates phosphorus release to decay of organic matter | 0.011* |
| Stoichiometric equivalent between organic matter and nitrogen | Relates nitrogen release to decay of organic matter | 0.08* |
| Stoichiometric equivalent between organic matter and carbon | Relates carbon release to decay of organic matter | 0.45* |
| Dissolved-oxygen limit | Dissolved-oxygen concentration below which anaerobic processes such as nitrification and sediment nutrient releases occur | 0 mg/L |

## Model Calibration

Successful model application requires model calibration that includes comparing model (simulated) results with observed (measured) reservoir conditions. If possible, two or more years of water-quality data should be used for adequate model calibration. Norfork Lake model calibration was achieved by adjusting model parameters and, in some cases, estimated input data, for the 2-year period of January 1994 through December 1995.

Two statistics were used to compare simulated and measured water-surface elevation, water temperature, and dissolved-oxygen concentration. The absolute mean error (AME) indicates the average difference between simulated and measured values and is computed by equation 1:

$$AME = \frac{\Sigma|Simulated\ Value - Measured\ Value|}{Number\ of\ Observations} \qquad (1)$$

An AME of 0.5 °C means that the simulated temperatures are, on average, within ± 0.5 °C of the measured temperatures. The root mean square error (RMSE) indicates the spread of how far simulated values deviate from the measured values and is computed by equation 2:

$$RMSE = \sqrt{\frac{\Sigma(SimulatedValues - MeasuredValues)^2}{Number\ of\ Observations}} \qquad (2)$$

An RMSE of 0.5 °C means that 67 percent of the simulated temperatures are within 0.5 °C of the measured temperatures.

### Hydrodynamics and Temperature

Simulated and measured water-surface elevations near the Norfork Lake dam followed similar patterns for January through December 1994 (fig. 7). The AME and RMSE between simulated and measured water-surface elevations was 0.34 and 0.40 m, respectively. The difference between simulated and measured water-surface elevations ranged from –0.47 to 0.74 m. Overall, there was good agreement between simulated and measured water-surface elevations in 1994.

Agreement between simulated and measured water-surface elevations in Norfork Lake improved in 1995 compared to 1994 (fig. 7). The AME and RMSE between simulated and measured water-surface elevations for January through December 1995, were 0.20 and 0.24 m, respectively. The difference between individual simulated and measured water-surface elevations ranged from -0.52 to 0.25 m.

The heat budget in the model is computed from inflow water temperature, air-water surface heat exchange (determined from air and dew-point temperature, cloud cover, wind speed and direction, organic and inorganic solids concentration) and bottom-water heat exchange. Organic and inorganic solids indirectly affect heat distribution by reducing light penetration. Thus, water temperature calibration cannot be performed independently from water chemistry computations, but water temperature can still be simulated neglecting the effects of solids on heat distribution.

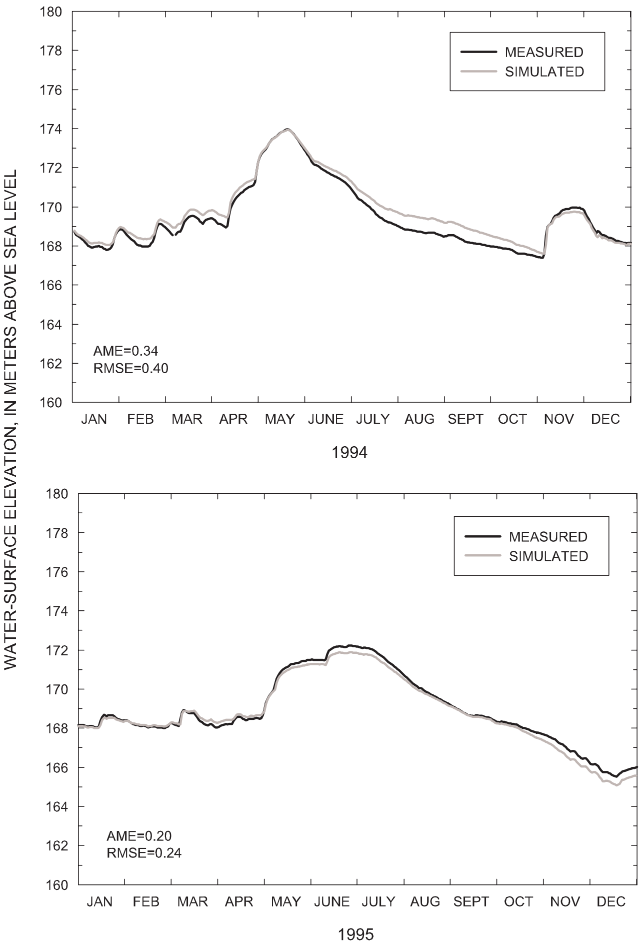

**Figure 7.** Simulated and measured water-surface elevations near the Norfork Lake dam, January through December 1994 and January through December 1995.

Vertical distribution of water temperature affects vertical mixing of dissolved and suspended materials and can be used to define the general location of the epilimnion and hypolimnion of the reservoir. During the thermal stratification season (May-November) the epilimnion and hypolimnion typically are separated by a thermocline, in which there is a relatively large change in temperature over a small change in depth. A strong thermocline existed near the Norfork Lake dam during June through November in 1994 and 1995. The model simulations agreed quite closely with the measured thermocline, but the changes were not as distinct because the model simulates temperature (and water chemistry) in homogeneous 1-m-thick layers within each computational segment. Hence, simulated changes in temperature near the thermocline would be more gradual than measured changes.

All simulated water temperatures (664) in 1994 were compared with corresponding measured temperatures near the Norfork Lake dam (Evans and others, 1995) (fig. 8). Simulated water temperatures reproduced seasonal variations observed in the water column near the dam (fig. 8), even for complex temperature profiles. Simulated water temperatures ranged from 5.2 to 28.9 ° C whereas measured water temperatures ranged from 6.2 to 29.0 ° C. Simulated water temperatures in the vertical profile generally were (67 percent) within 1° C of measured temperatures. The AME and RMSE between simulated and measured water temperature were 0.82 and 0.98 ° C, respectively. The difference between simulated and measured temperature ranged from -1.9 to 2.4 ° C, and the average and median differences were 0.3 and 0.2 ° C, respectively.

Although the calibrated model closely simulated water temperature near the Norfork Lake dam, with most simulated temperatures within 1° C of the measured temperatures, the accuracy and precision of simulated temperatures varied with temperature, season, and depth. Simulated water temperatures were greater

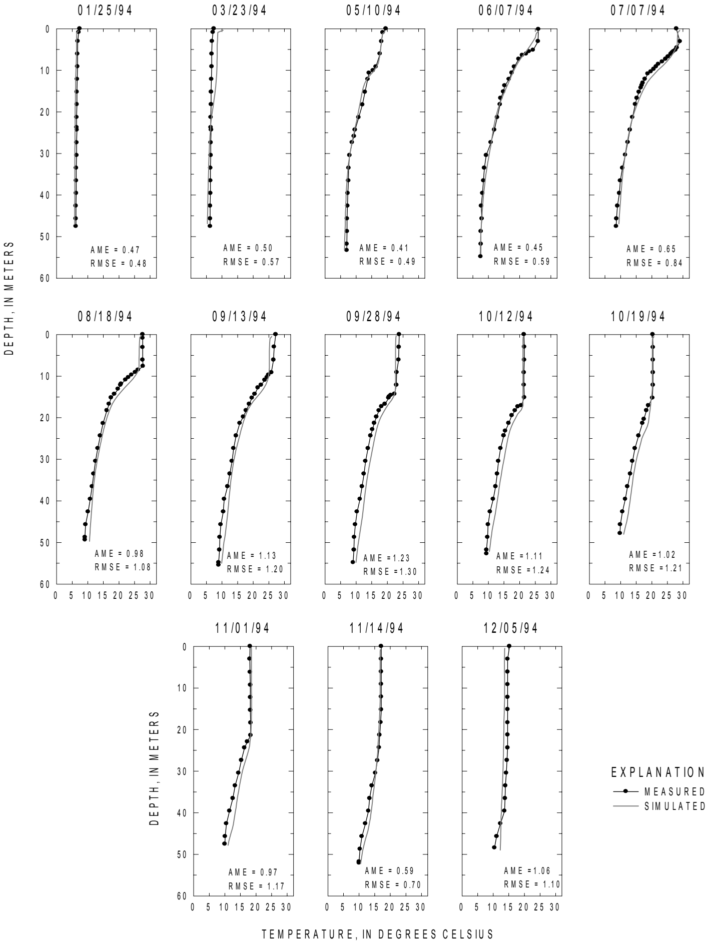

**Figure 8.** Relation between simulated and measured water temperatures in the water column near the Norfork Lake dam, January through December 1994.

than measured temperatures more often when measured temperatures were less than 20 ° C (fig. 9). On the other hand, simulated water temperatures were less than measured temperatures when measured temperatures were greater than approximately 20 ° C. Near-surface simulated temperatures were generally less than measured temperatures, whereas at greater depths, simulated temperatures tended to be greater than measured temperatures. Error in simulated water temperatures was greater during the thermal stratification season.

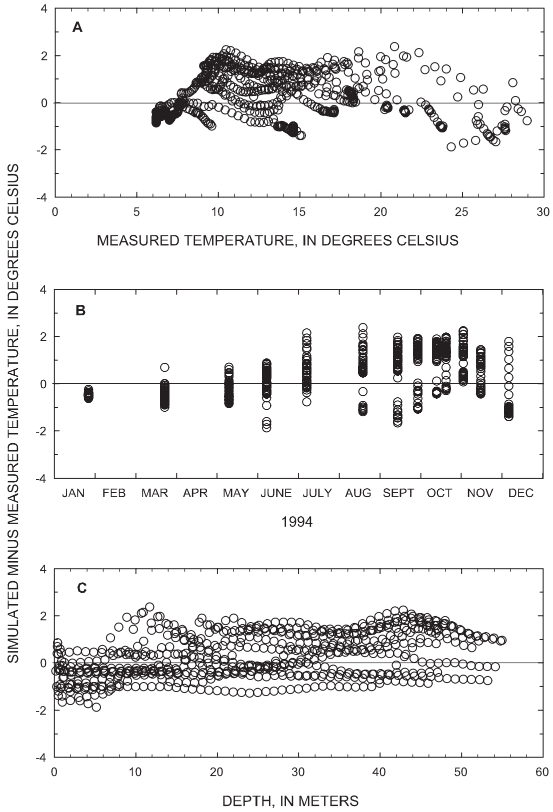

**Figure 9.** Relation of difference between simulated and measured water temperatures at Norfork Lake dam to (A) measured water temperature, (B) sampling date, and (C) water depth, January through December 1994.

Simulated water temperatures were similar to measured temperatures in 1995 (fig. 10). All simulated temperatures (613) in 1995 were compared with corresponding measured temperatures (Porter and others, 1996). Simulated water temperatures ranged from 5.1 to 30.0 ° C, whereas measured water temperatures ranged from 7.0 to 31.1 ° C. Simulated water temperatures were generally (58 percent) within 1° C of measured temperatures. The AME and RMSE between simulated and measured water temperature were 0.98 and 1.26 ° C, respectively. The difference between simulated and measured temperatures ranged from -3.0 to 2.6 ° C, and the average and median differences were -0.5 and -0.2 ° C, respectively.

Errors in simulated water temperatures were distributed differently during 1995 when compared to 1994 (fig. 11). Simulated water temperatures during 1995 were generally under-predicted when measured temperatures were less than 10 ° C or exceeded 25 ° C. During January and March 1995, simulated water temperatures were consistently less than measured temperatures, and errors were evenly distributed during the thermal stratification season indicating no tendency to over- or under-predict water temperature. Simulated water temperatures were generally less than measured temperatures near the reservoir bottom and near the water surface. However, as in 1994, most (58 percent) simulated temperatures were within 1 ° C of the measured temperature.

### Dissolved Oxygen

Simulation of the complex biochemical reactions affecting chemical and physical transport processes in the Norfork Lake model are expressed in part within the simulated dissolved-oxygen results. The supply of nitrogen, phosphorus, and light, regulates algal growth and the production of oxygen; photosynthesis is the only internal source of oxygen in the water-chemistry computations. Boundary sources of oxygen include the dissolved-oxygen concentration in the reservoir inflows and oxygen exchange at the air-water interface. Several sinks of oxygen exist including nitrification (conversion of ammonia to nitrate), algal and microbial respiration, organic matter decay (for example, detritus, labile and refractory dissolved organic matter), and sediment oxygen demand. These processes combined with the water-chemistry computations are used to simulate the complex vertical profiles of dissolved oxygen in Norfork Lake.

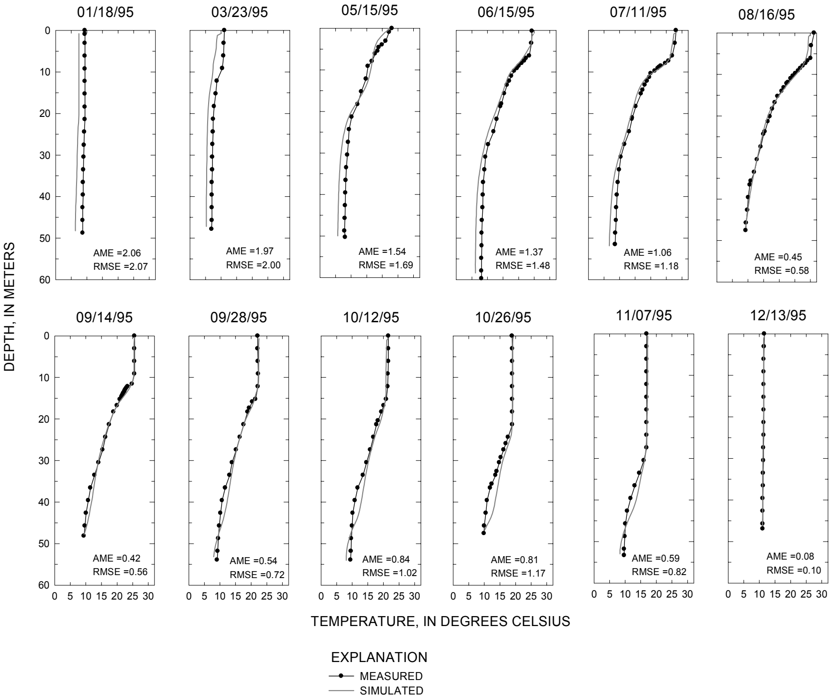

**Figure 10.** Relation between simulated and measured water temperatures in the water column near the Norfork Lake dam, January through December 1995.

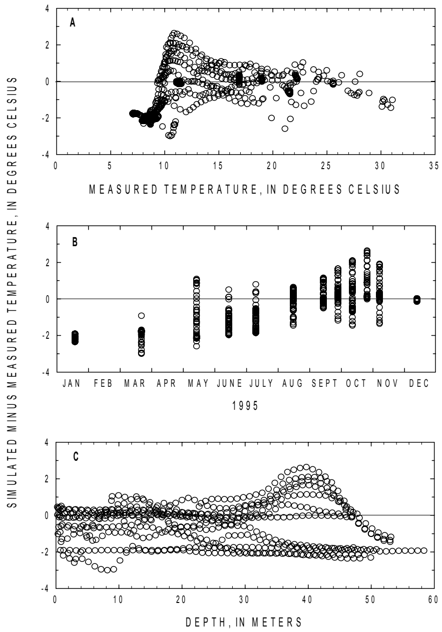

**Figure 11.** Relation of difference between simulated and measured water temperatures near Norfork Lake dam to (a) measured water temperature, (B) sampling date, and (C) water depth, January through December 1995.

Simulated dissolved-oxygen concentrations near the Norfork Lake dam exhibited the same general patterns and magnitudes as measured concentrations (fig. 12). All simulated dissolved-oxygen concentrations (664) for January through December 1994 were compared to corresponding measured concentrations (Evans and others, 1995). Simulated dissolved-oxygen concentrations ranged from 0.0 to 12.8 mg/L, whereas, measured dissolved-oxygen concentrations ranged from 0.1 to 11.6 mg/L. Simulated dissolved-oxygen concentrations in the vertical profile generally (71 percent) were within 1 mg/L of measured concentrations. The AME and RMSE between simulated and measured dissolved-oxygen concentrations were 0.87 and 1.24 mg/L, respectively. The difference between simulated and measured concentrations ranged from -4.9 to 5.8 mg/L, and the average and median absolute differences were 0.1 and -0.2 mg/L, respectively.

Differences between simulated and measured dissolved-oxygen concentrations were compared to corresponding measured dissolved-oxygen concentrations, sampling date, and the water depth (fig. 13). Simulated dissolved-oxygen concentrations typically were less than measured values at lower concentrations. Errors in simulated dissolved-oxygen concentration were greater near the end of the thermal stratification season (October-November) and during turnover (December). The December 5, 1994, results had the greatest differences between simulated and measured dissolved-oxygen concentrations. Thermal destratification was occurring during this time and the model simulated turnover occurring slightly earlier than it actually occurred. Simulated dissolved oxygen concentrations generally were under-predicted near the water surface and over-predicted near the lake bottom.

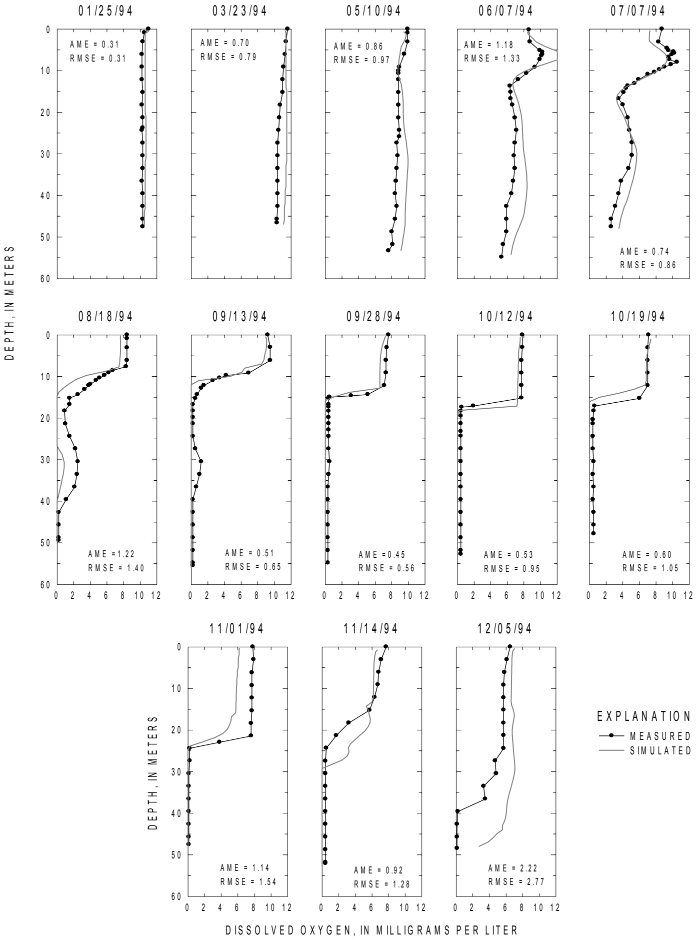

**Figure 12.** Relation between simulated and measured dissolved-oxygen concentrations in the water column near the Norfork Lake dam, January through December 1994.

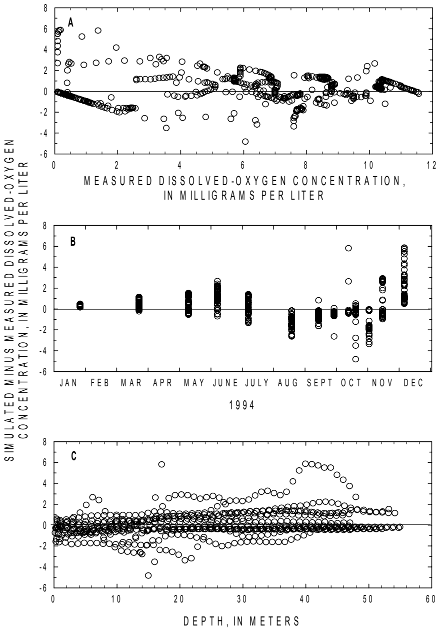

**Figure 13.** Relation of difference between simulated and measured dissolved-oxygen concentrations near Norfork Lake dam to (A) measured dissolved-oxygen concentrations, (B) sampling date, and (C) water depth, January through December 1994.

Simulated dissolved-oxygen concentrations were similar to measured dissolved-oxygen concentrations in 1995 (fig. 14), but differences were somewhat greater in 1995 than in 1994. Seasonal variations in simulated dissolved-oxygen concentration were reproduced despite pronounced differences in the vertical distribution. All simulated dissolved-oxygen concentrations (613) were compared with corresponding measured concentrations near the Norfork Lake dam. Simulated values ranged from 0.0 to 13.0 mg/L whereas, measured dissolved-oxygen concentrations ranged from 0.0 to 11.3 mg/L. Simulated dissolved-oxygen concentrations in the vertical profile generally were (67 percent) within 1 mg/L of measured concentrations. The AME and RMSE between simulated and measured dissolved-oxygen concentrations were 0.95 and 1.41, respectively. The difference between simulated and measured dissolved-oxygen concentrations ranged from -6.9 to 4.3 mg/L, and the average and median differences were -0.13 and 0.1 mg/L, respectively.

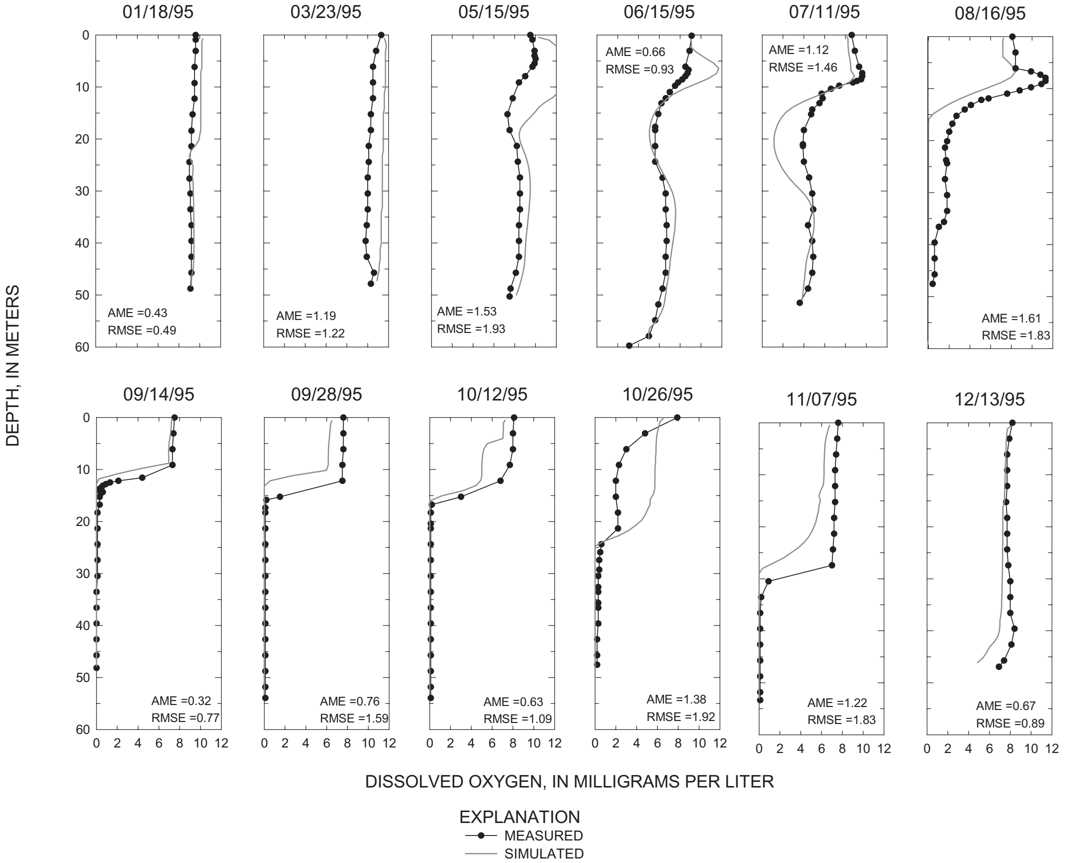

**Figure 14.** Relation between simulated and measured dissolved-oxygen concentrations in the water column near the Norfork Lake dam, January through December 1995.

On average, simulated dissolved-oxygen concentrations were slightly under-predicted when compared to measured concentrations (fig. 15). The largest differences between simulated and measured dissolved-oxygen concentrations typically occurred at concentrations greater than 5 mg/L. The model consistently over-predicted dissolved-oxygen concentrations during isothermal conditions, and typically under-predicted concentrations during the stratification season. Simulated dissolved-oxygen concentrations often were less than measured concentrations regardless of depth. Despite these tendencies, simulation of dissolved-oxygen concentration in the vertical profile near the Norfork Lake dam followed the same general patterns as measured concentrations.

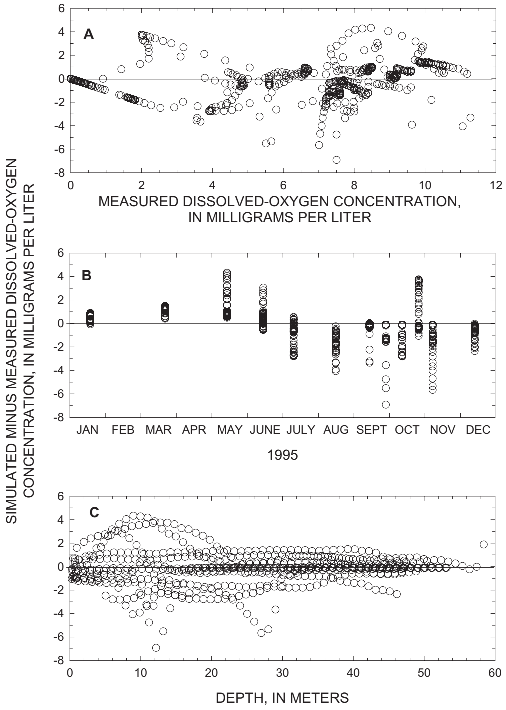

**Figure 15.** Relation of difference between simulated and measured dissolved-oxygen concentrations near Norfork Lake dam to (A) measured dissolved-oxygen concentrations, (B) sampling date, and (C) water depth, January through December 1995.

### Sensitivity Analysis

Sensitivity analysis is the determination of the effects of small changes in calibrated model parameters and input data on model results. A complete sensitivity analysis for all model parameters in the Norfork Lake model was not conducted because the Norfork Lake model includes more than 60 parameters (tables 1 and 2). However, many hydrodynamic, temperature, and dissolved-oxygen simulations were conducted as a component of model development and calibration. Results from these simulations and information from previous modeling studies (Bales and Giorgino, 1998; Giorgino and Bales, 1997; Green, 2001; Haggard and Green, 2002) in other reservoirs were used to identify several parameters for evaluation in the sensitivity analysis. The sensitivity of simulated water temperature and dissolved-oxygen concentration near the dam to changes in the wind-sheltering coefficient (WSC), bottom-water heat exchange coefficient (CBHE), light extinction (α), sediment-oxygen demand (SOD), and changes in inflow temperature and dissolved-oxygen concentrations was assessed.

Water temperature in the Norfork Lake model was most sensitive to changes in the WSC and α (fig 16). Wind speed in the calibrated Norfork Lake model was adjusted (WSC = 0.7) from the meteorological data recorded at Harrison, Arkansas; that is, the effective wind speed was 70 percent of the recorded wind speed at Harrison. Surface-water temperatures were not impacted as much by changes in WSC as was the position of the thermocline and hypolimnetic temperatures. During thermal stratification, vertical mixing was over-predicted when the WSC was increased (1.0) and under-predicted when the WSC was decreased (0.5). Changes in the α affected vertical water temperature profiles during stratification. Increasing α slightly elevated the thermocline and decreasing α lowered the thermocline. Changes in inflow water temperature had little affect on vertical water temperature profiles near the dam. The combination of WSC and α appear to be the driving factors in the model responsible for the development, duration, and vertical location of the thermocline in Norfork Lake near the dam.

In the Norfork Lake model, dissolved-oxygen concentrations were most affected by changes in the WSC, α, and FSOD (fig. 17). FSOD is the fraction of the zero-order SOD rate and is applied to adjust SOD equally among all segments. Changes in the WSC and FSOD had the greatest effect on dissolved-oxygen concentrations near the thermocline and throughout the hypolimnion. The α regulates the amount of light penetrating the water, indirectly affecting dissolved-oxygen concentrations by influencing algal production. During thermal stratification, changes in α had the greatest affect on the position and configuration of the thermocline. Changes in the inflow dissolved-oxygen concentrations had little effect on the vertical distribution of dissolved oxygen near the dam.

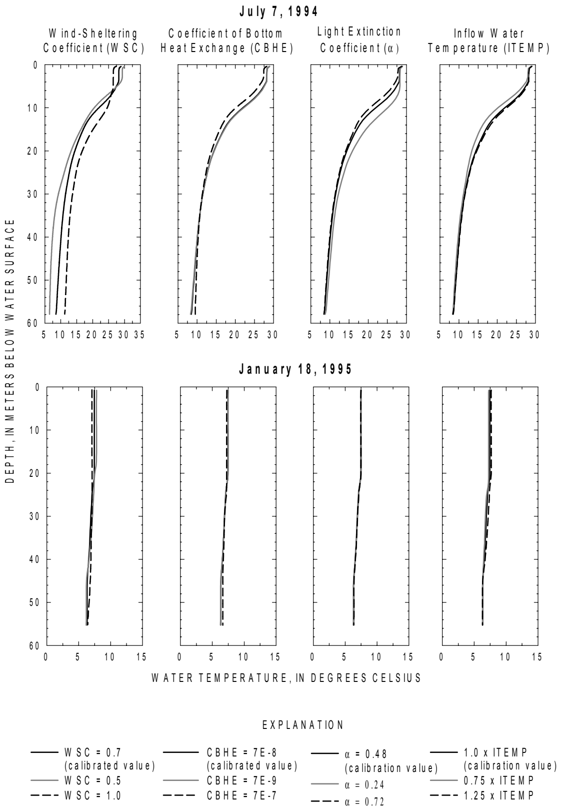

**Figure 16.** Vertical temperature distributions near the Norfork Lake dam on July 7, 1994 (top), and January 18, 1995 (bottom), showing calibrated model profiles and profiles as a result of differing model parameters.

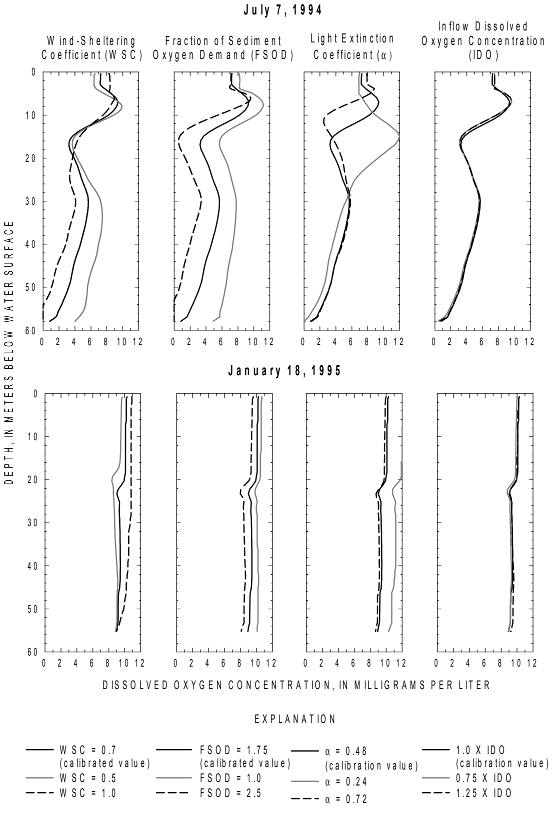

**Figure 17.** Vertical dissolved-oxygen concentration distributions near the Norfork Lake dam on July 7, 1994 (top), and January 18, 1995 (bottom), showing calibrated model profiles and profiles as a result of differing model parameters.

Many other parameters indirectly affect dissolved-oxygen concentrations through algal dynamics; however, examination of all of these parameters is beyond the scope of this study given that so many assumptions were made in evaluating dissolved-oxygen concentrations near the dam. Regardless, algal dynamics play a substantial role in the dissolved-oxygen conditions near the Norfork Lake dam.

## Model Applications

The calibrated Norfork Lake model was used to assess the impacts of increased minimum flow on water-surface elevation and on temperature and dissolved-oxygen concentrations in the Norfork Lake outflow waters. Two scenarios were simulated, including (1) an increase in the outflow of Norfork Lake dam from the existing minimum flow of 1.6 $m^3/s$ to 8.5 $m^3/s$, and (2) an increase in water-surface elevation of Norfork Lake to correct for the volume displaced by the additional minimum flow.

When 8.5 $m^3/s$ was applied as the minimum amount of outflow (increased minimum flow scenario), average annual outflow increased from 70.32 to 71.74 $m^3/s$, about a 2 percent increase. Approximately 23 percent of the hourly outflow data required an increase to 8.5 $m^3/s$. Average annual outflow increased from 2,218 to 2,262 million $m^3$, which is equivalent to 44 million $m^3$ per year increase, or about 2.8 percent of reservoir volume at conservation pool elevation. The water-surface elevation at the end of 1994 was reduced 0.41 m and at the end of 1995 was reduced about 1.1 m (figs. 18 and 19) from the initial elevation on January 1, 1994 (168.79 m). When 1.1 m of water was applied to the initial elevation (increased minimum flow with increased water-surface elevation scenario), the difference by the end of 1994 was 0.68 m greater than the calibrated model without the increased minimum flow and by the end of 1995 only 0.17 m greater than the calibrated model (fig. 19).

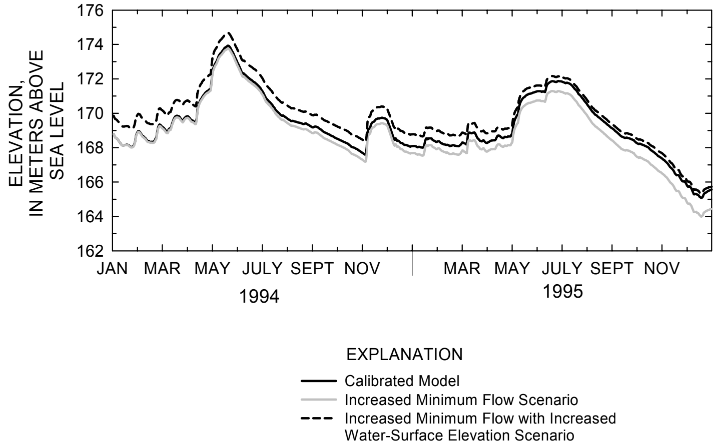

**Figure 18.** Simulated water-surface elevations resulting from increased minimum flow scenarios.

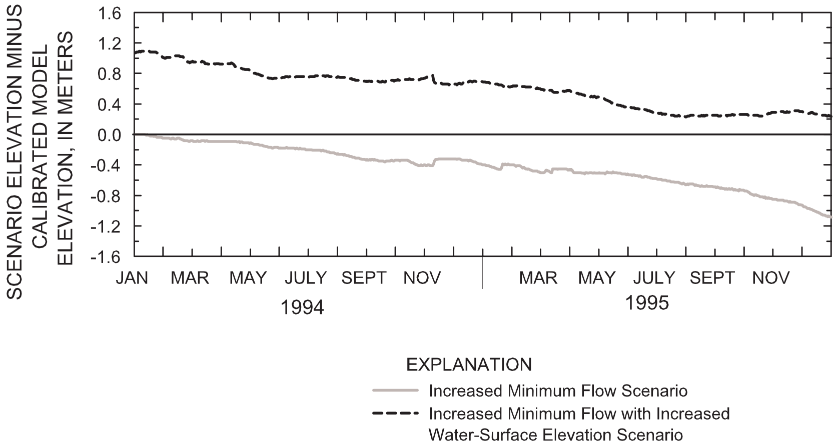

**Figure 19.** Relation of difference between water-surface elevations predicted from increased minimum flow scenarios and calibrated model water-surface elevation with time.

Temperature in the outflow water differed little between results from the increased minimum flow scenarios and the calibrated model (figs. 20 and 21). Absolute maximum difference in outflow water temperature between the increased minimum flow scenario and the calibrated model was 0.79 °C and between the increased minimum flow with increased water-surface elevation and the calibrated model was 1.08 °C. Temperature differences for both scenarios were within the AME and RMSE between simulated and measured water-column profile temperature differences reported in the Model Calibration section of this report. Simulated outflow temperatures were similar to estimated outflow temperatures from water-column profiles measured upstream from the dam (George Robins, Southwestern Power Administration, written commun., 2000) and to measured downstream outflow temperatures (USGS station number 07060000) (fig. 21). Water temperature in the dam outflow increased slightly with the addition of increased minimum flow. Conversely, with the increase in water-surface elevation plus the increased minimum flow, water temperature in the dam outflow decreased slightly through time.

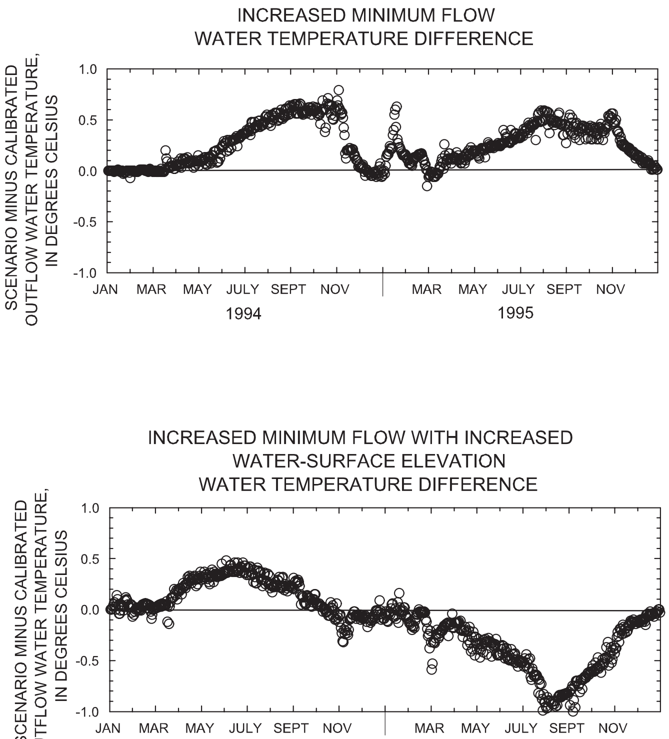

**Figure 20.** Simulated water temperature differences between increased minimum flow scenarios and the calibrated model.

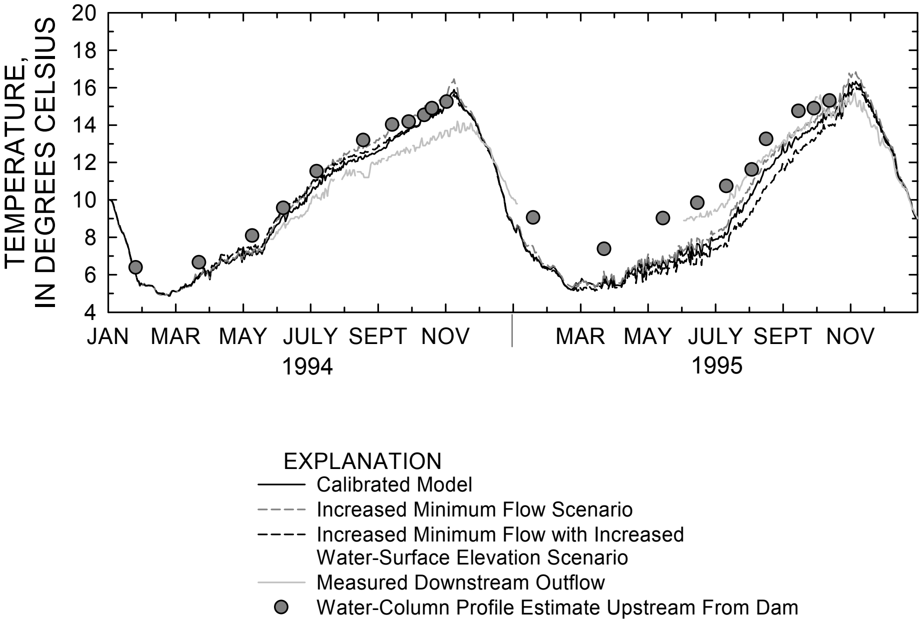

**Figure 21.** Simulated and estimated water temperatures in Norfork Lake outflow and measured temperatures downstream from Norfork Lake dam.

Dissolved-oxygen concentrations in the outflow water differed little between results from the two increased minimum flow scenarios and the calibrated model (figs. 22 and 23). Absolute maximum difference in outflow dissolved oxygen between the increased minimum flow scenario and the calibrated model was 0.81 mg/L and between the increased minimum flow with increased water-surface elevation and the calibrated model was 1.59 mg/L. Dissolved-oxygen concentration differences for both scenarios were about the same as the AME and RMSE between simulated and measured water-column profile dissolved-oxygen differences reported in the Model Calibration section of this report. Simulated outflow dissolved-oxygen concentrations were similar to estimated outflow concentrations from water-column profiles measured upstream from the dam (George Robins, Southwestern Power Administration, written commun., 2000) and to measured downstream outflow concentrations (USGS station number 07060000) (fig. 23). Dissolved-oxygen concentrations in the dam outflow decreased slightly through time with the addition of increased minimum flow. Conversely, with the increase in water-surface elevation and the increased minimum flow, dissolved-oxygen concentrations in the dam outflow increased slightly through time.

Small changes in water temperature and dissolved-oxygen concentration compared to the calibrated, base condition were simulated for the two increased minimum flow scenarios. However, the changes were similar to the error between simulated and measured temperature and dissolved-oxygen con-

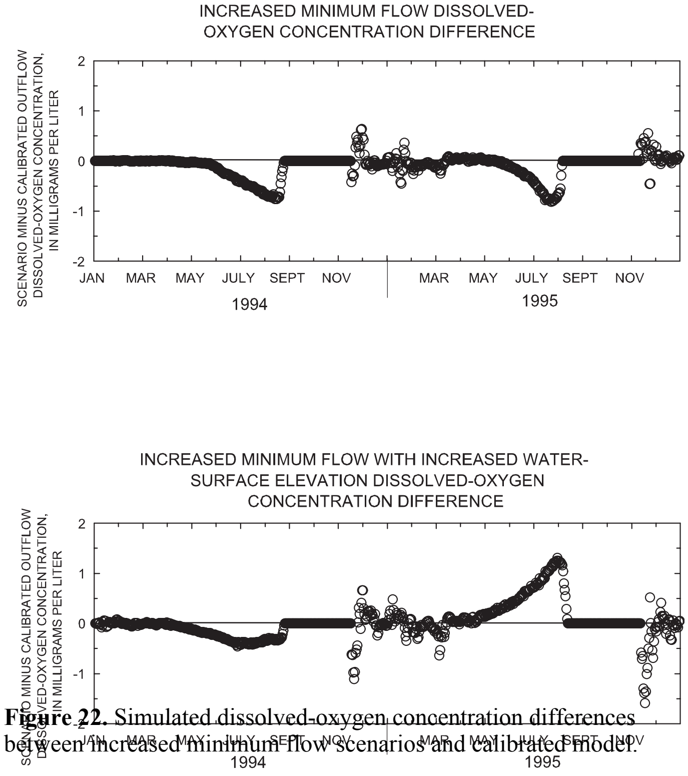

**Figure 22.** Simulated dissolved-oxygen concentration differences between increased minimum flow scenarios and calibrated model.

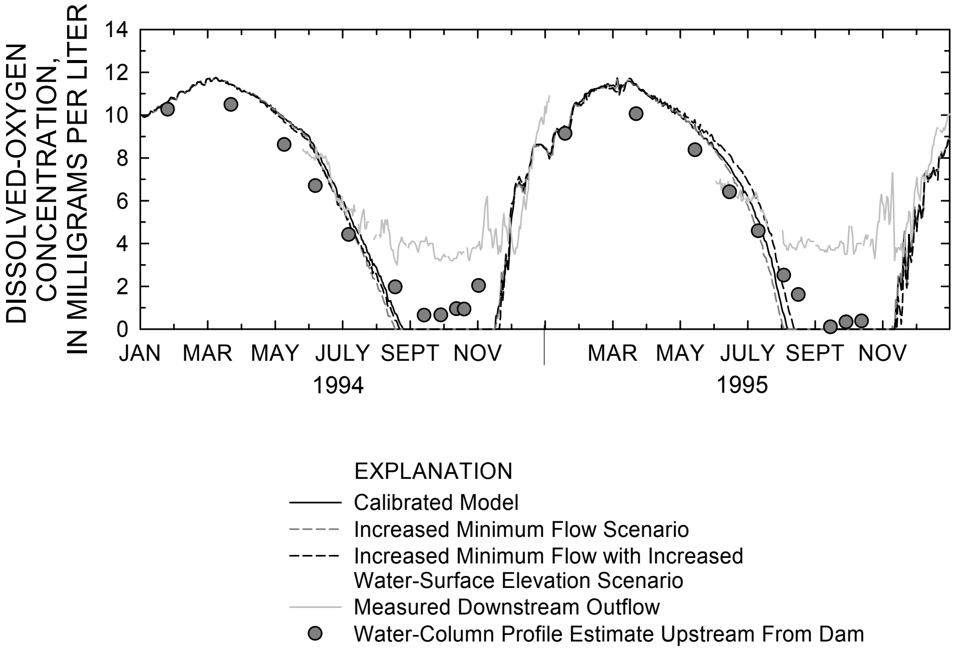

**Figure 23.** Simulated and estimated dissolved-oxygen concentrations in Norfork Lake outflows and measured dissolved-oxygen concentrations downstream from Norfork Lake dam.

## SUMMARY

Outflow from Norfork Lake and other White River reservoirs support a cold-water trout fishery of significant economic yield in north-central Arkansas and south-central Missouri. Proposed increases in minimum flows released from the dam have caused concerns about the sustainability of cold-water temperature and dissolved oxygen in the bottom water of Norfork Lake. Increases in water temperature and decreases in dissolved oxygen could have potentially negative impacts on the cold-water trout fisheries in the downstream outflow. Thus, the U.S. Geological Survey in cooperation with the Arkansas Game and Fish Commission, conducted a study to assess the impact of additional minimum flows on the hydrodynamics, temperature, and dissolved-oxygen concentrations in Norfork Lake and on temperature and dissolved-oxygen concentrations in the downstream outflow.

A two-dimensional laterally averaged, hydrodynamic, temperature, and dissolved-oxygen model was developed for Norfork Lake, Arkansas. The model was calibrated using hydrologic records and vertical profiles of temperature and dissolved oxygen measured in or near Norfork Lake from January 1994 through December 1995. The model simulates surface-water elevation, water temperature, and dissolved-oxygen concentration. The model predicted temperatures generally within 1 °C of the measured temperatures. The AME and RMSE for 1994 were 0.82 and 0.98, respectively, and for 1995 were 0.98 and 1.26, respectively. The model predicted dissolved-oxygen concentrations generally within 1 mg/L of the measured concentrations. The AME and RMSE for 1994 were 0.87 and 1.24, respectively. For 1995, the AME and RMSE were 0.95 and 1.41, respectively.

The Norfork Lake model was developed to assess the impacts of proposed increases in minimum flows from 1.6 $m^3/s$ (the existing minimum flow) to 8.5 $m^3/s$ (the increased minimum flow). Scenarios included assessing the impact of (1) increased minimum flows and (2) increased minimum flows with increased water-surface elevation of 1.1 m greater than the initial water-surface elevation on outflow temperatures and dissolved-oxygen concentrations. With the increased minimum flow, water temperatures increased and dissolved oxygen decreased in the outflow. Conversely, increased minimum flow with increased water-surface elevation lowered the outflow water temperature and increased dissolved-oxygen concentrations. However, these results were similar to the error between simulated and measured water temperature and dissolved-oxygen concentrations.

This model provides the basis and framework for future water-quality modeling of Norfork Lake. As additional data are collected in the reservoir and tributaries, the calibrated model can be modified to assess the nutrient assimilative capacity of the reservoir, nutrient limitation, and the effect of increases in nutrient loading on reservoir trophic status.

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