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Simulation of Hydrodynamics, Temperature, and Dissolved Oxygen in Table Rock Lake, Missouri, 1996–1997

Water-Resources Investigations Report 03–4237

Prepared in cooperation with the
Missouri Department of Conservation

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

Cover Photograph: Table Rock Lake Dam, June 1987. Photograph by Wayne R. Berkas, U.S. Geological Survey.

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By W. Reed Green, Joel M. Galloway, Joseph M. Richards, and Edwin A. Wesolowski

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2003

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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)

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29). **Altitude,** as used in this report, refers to distance above or below NGVD 29. NGVD 29 can be converted to the North American Vertical Datum of 1988 (NAVD 88) by using the National Geodetic Survey conversion utility available at URL **http://www.ngs.noaa.gov/TOOLS/Vertcon/vertcon.html.**

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Simulation of Hydrodynamics, Temperature, and Dissolved Oxygen in Table Rock Lake, Missouri, 1996–1997

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Abstract

Outflow from Table Rock Lake and other White River reservoirs support a cold-water trout fishery of substantial economic yield in south-central Missouri and north-central Arkansas. The Missouri Department of Conservation has requested an increase in existing minimum flows through the Table Rock Lake Dam from the U.S. Army Corps of Engineers to increase the quality of fishable waters downstream in Lake Taneycomo. Information is needed to assess the effect 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, CE-QUAL-W2, was developed and calibrated for Table Rock Lake, located in Missouri, north of the Arkansas-Missouri State line. The model simulates water-surface elevation, heat transport, and dissolved-oxygen dynamics. The model was developed to assess the effects of proposed increases in minimum flow from about 4.4 cubic meters per second (the existing minimum flow) to 11.3 cubic meters per second (the increased minimum flow). Simulations included assessing the effect of (1) increased minimum flows and (2) increased minimum flows with increased water-surface elevations in Table Rock Lake, on outflow temperatures and dissolved-oxygen concentrations.

In both minimum flow scenarios, water temperature appeared to stay the same or increase slightly (less than 0.37 °C) and dissolved oxygen appeared to decrease slightly (less than 0.78 mg/L) in the outflow during the thermal stratification season. However, differences between the minimum flow scenarios for water temperature and dissolved-oxygen concentration and the calibrated model were similar to the differences between measured and simulated water-column profile values.

INTRODUCTION

Table Rock Lake (fig. 1) is a large, deep-storage reservoir located on the White River in Missouri north of the border of Arkansas and Missouri. Table Rock Lake Dam was completed in 1958 and is operated by the U.S. Army Corps of Engineers (USACE) for the purposes of flood control and hydroelectric power. Table Rock Lake is downstream from Beaver Lake. Downstream from Table Rock Lake are Lake Taneycomo and Bull Shoals Lake (fig. 1). The U.S. Geological Survey (USGS) monitors streamflow and water quality at various sites in and around Table Rock Lake (table 1). Today, in addition to aforementioned uses, the reservoir is used for fish and wildlife habitat, recreation, and water supply. The outflows from Table Rock Lake, and other White River reservoirs, also support a cold-water trout fishery of substantial economic yield in south-central Missouri and north-central Arkansas. The Missouri Department of Conservation (MDC) has requested an increase in minimum flows through Table Rock Lake Dam to increase the quality of fishable waters downstream in Lake Taneycomo. Proposed

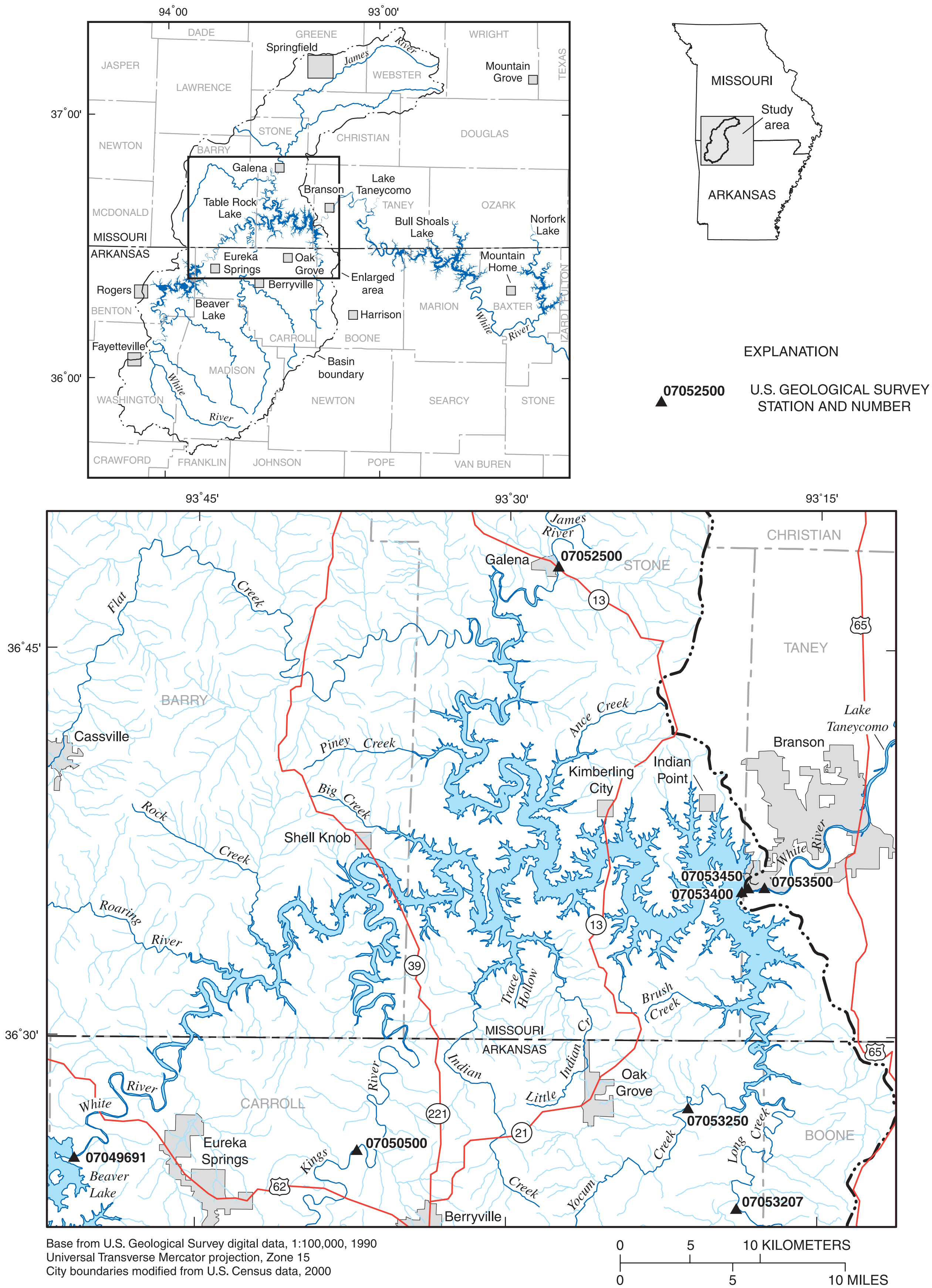

Figure 1. Location of Table Rock Lake Basin in Missouri and Arkansas.

Table 1. Streamflow-gaging station and water-quality sampling site locations in and around Table Rock Lake

[Temp and DO, water temperature and dissolved-oxygen concentration monitor; Q, discharge recording station; QW, water-quality sampling station]

USGS station number (fig. 1)	Name	Type	Latitude	Longitude
07049691	White River at Beaver Dam near Eureka Springs, Arkansas	Temp and DO	362515	935050
07050500	Kings River near Berryville, Arkansas	Q and QW	362536	933715
07053207	Long Creek at Denver, Arkansas	Q only	362323	931901
07053250	Yocum Creek near Oak Grove, Arkansas	Q and QW	362717	932121
07053400	Table Rock Lake near Branson, Missouri (Table Rock Lake Dam)	Temp and DO	363546	931835
07052500	James River at Galena, Missouri	Q only	364819	932741
07053450	White River below Table Rock Dam near Branson, Missouri	Temp and DO	363542	931832
07053500	White River near Branson, Missouri	Q only	363551	931742

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 Table Rock Lake. Increases in water temperature and decreases in dissolved oxygen could have potential negative effects on the cold-water trout fisheries in the downstream outflow. Comprehensive information is needed to address temperature and dissolved-oxygen dynamics of Table Rock Lake and the effects of increased minimum flow.

In July 1999, a study was initiated by the USGS in cooperation with the MDC to characterize the hydrodynamics, temperature, and dissolved-oxygen concentration in Table Rock Lake, and to simulate the effect of reservoir operations on temperature and dissolved-oxygen concentration in the reservoir and outflow. A hydrodynamic model of Table Rock 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 effects of reservoir operations on temperature and dissolved-oxygen concentration in Beaver, Norfork, and Bull Shoals Lakes (Galloway and Green, 2002; 2003; and Haggard and Green, 2002). 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 and system 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. Effects of upstream reservoir management on downstream reservoirs also could be tested.

Purpose

The purpose of this report is to describe the simulation of hydrodynamics, temperature, and dissolved oxygen in Table Rock Lake and outflows for January 1996 through December 1997. Surface-water elevation, water temperature, and dissolved-oxygen concentration results from model applications simulating several proposed minimum flow scenarios are presented and compared to a calibrated, base condition. Data collected at the sites listed in table 1 were used in the model calibration. Simulated water temperature and dissolved-oxygen concentrations were calibrated to measured water-column profiles of water temperature and dissolved-oxygen concentrations collected at 07053400, Table Rock Lake near Branson, Missouri, hereafter referred to as near Table Rock Lake Dam.

Description of Study Area

Table Rock Lake was impounded in 1958 on the White River, west of the city of Branson, Missouri. The primary inflows into Table Rock Lake are the James River, Kings River, Long Creek, and White River; several smaller tributaries also flow into the reservoir (fig.

1, table 1). The watershed has a drainage area of 10,412 km^2 at the Table Rock Lake Dam. Table Rock Lake contains 3,330 million cubic meters of water at the elevation of the current conservation pool (278.9 m above NGVD 29) and the surface area is 174 km^2. The length of the reservoir is 96 km from the Beaver Lake Dam to the Table Rock Lake Dam. The depth of the reservoir at the dam at conservation pool elevation is about 62 m, and the average depth through the reservoir is 19 m. On average, the hydraulic retention time of Table Rock Lake is about 0.8 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 TABLE ROCK LAKE

A two-dimensional, laterally averaged, hydrodynamic, temperature, and dissolved-oxygen model using CE-QUAL-W2 was developed for Table Rock Lake and calibrated based on hydrologic records and vertical profiles of temperature and dissolved oxygen measured near the Table Rock Lake Dam from January 1996 through December 1997 (Porter and others, 1997; 1998; 1999). 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 report.

Model Implementation

Implementation of the CE-QUAL-W2 model for Table Rock 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 are given in this section.

Computational Grid

The computational grid is the geometric scheme (figs. 2 and 3) that numerically represents the space and volume of the reservoir. The model extends 96 km from the upstream boundary (Beaver Lake Dam) to the downstream boundary (Table Rock Lake Dam). The grid geometry (fig. 3) 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. Twenty-eight computational segments exist along the main stem of the White River in Table Rock Lake. Three segments are in the Kings River branch, 18 segments are in the James River branch, and 6 segments are in the Long Creek branch. In addition, 10 other embayments (branches) are included containing two or three segments each. Volumes of the smaller embayments not included in the computational grid were added to associated main-stem segments so that reservoir volume was preserved. Segment geometry varied along the upstream-downstream gradient (fig. 3). Segment length was based in part on segment width. Segments ranged in length from 1,273 to 15,332 m, and orientation of the longitudinal axis relative to north was determined for each segment. Segment widths at the reservoir surface ranged from 316 m at the upstream White River boundary to 1,730 m further downstream. Each segment was divided vertically into 1-m layers. Depth from the elevation of the top of the flood-control pool (284 m) to the reservoir bottom ranged from 24 m at the upstream boundary to 68 m near Table Rock Lake Dam. Relations between water-surface elevation and volume and surface area in the Table Rock Lake model grid were similar to USACE pre-impoundment data (fig. 4).

Boundary and Initial Conditions

Hydraulic, thermal, and chemical boundary conditions are required in CE-QUAL-W2. The boundaries of the Table Rock Lake model included the reservoir

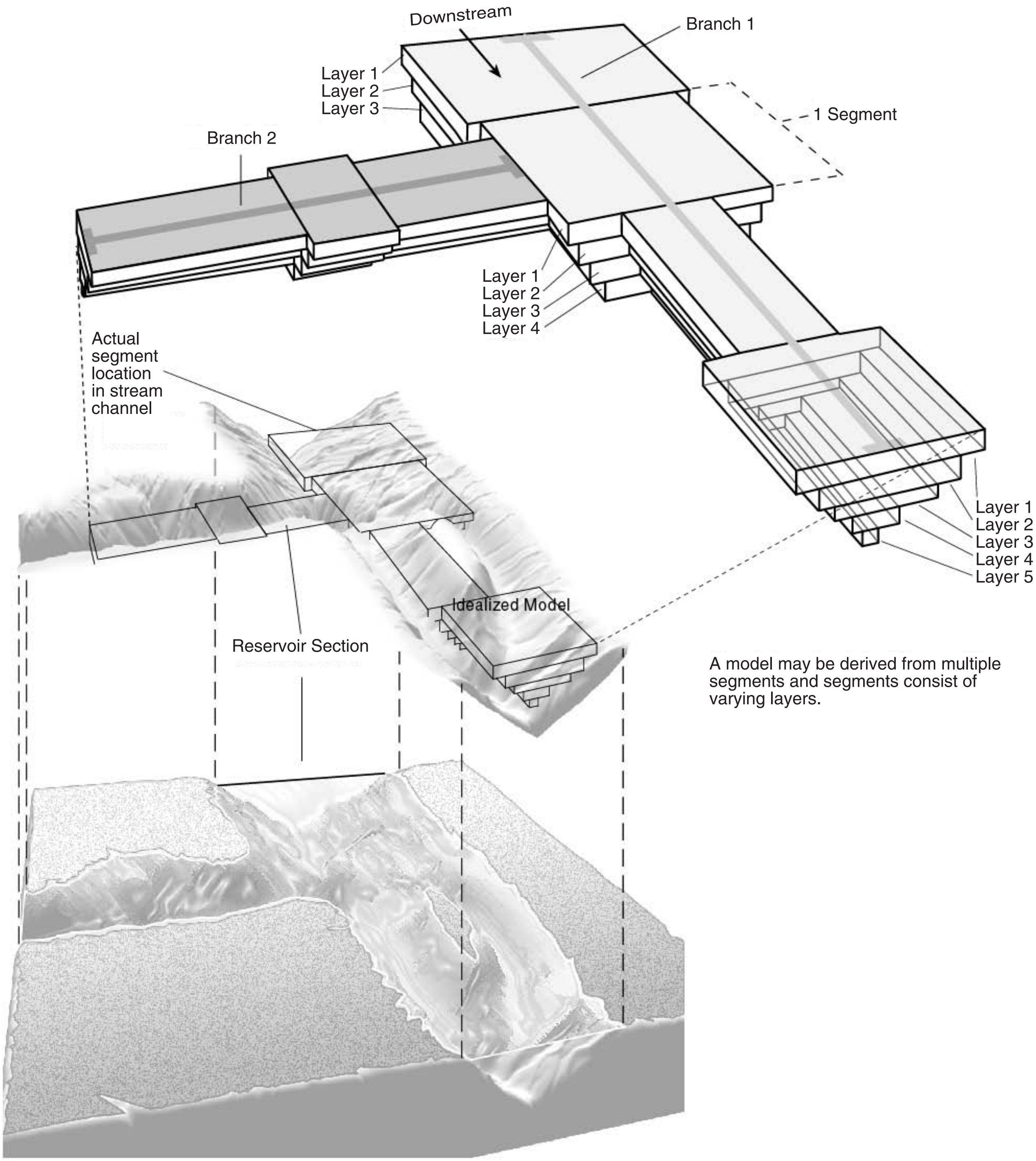

Figure 2. Idealized model segment, layers, and branches for the CE-QUAL-W2 reservoir model.

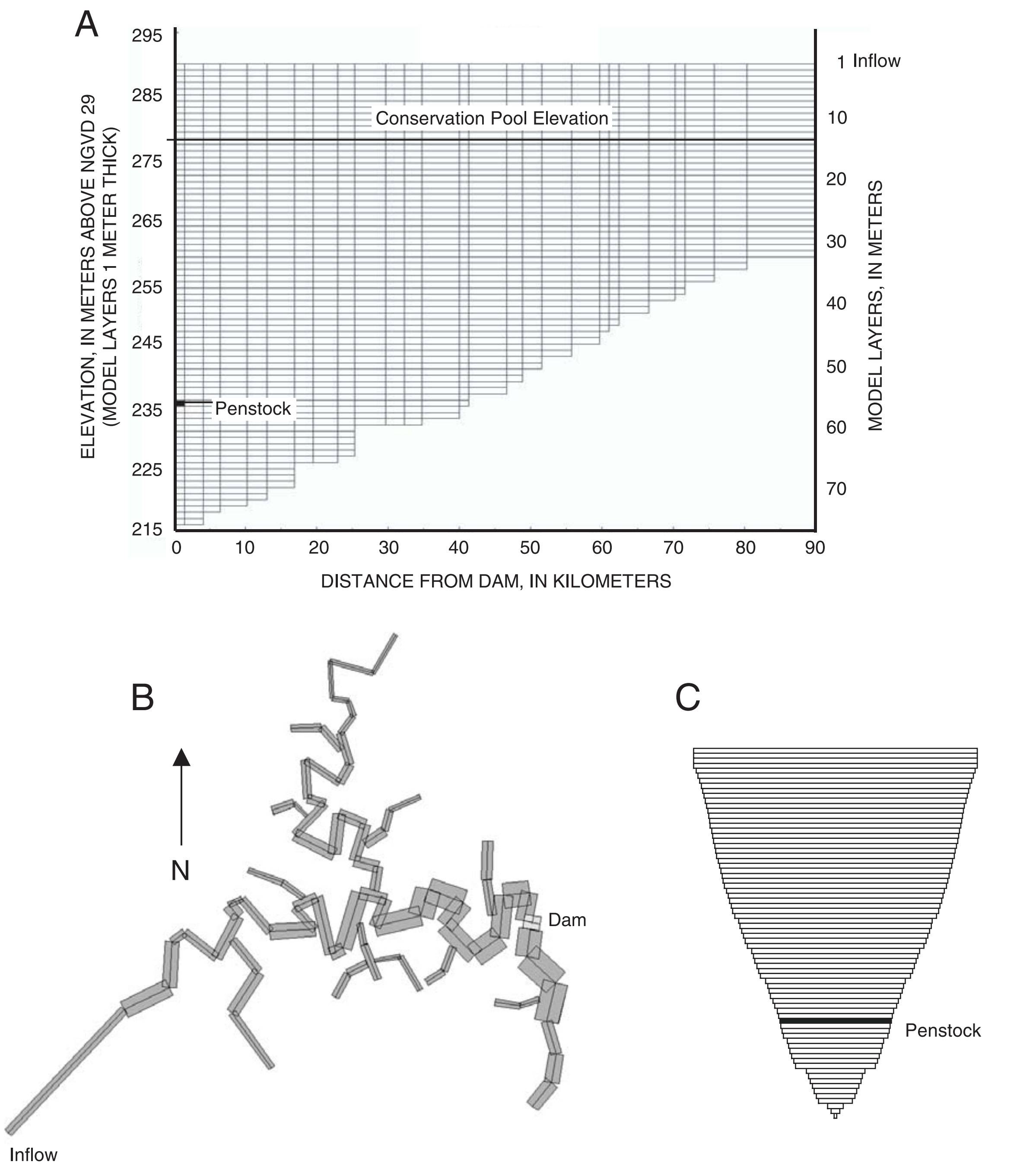

Figure 3. Side view (A), top view (B), and face view from the dam (C) of the computational grid of Table Rock Lake used in CE-QUAL-W2.

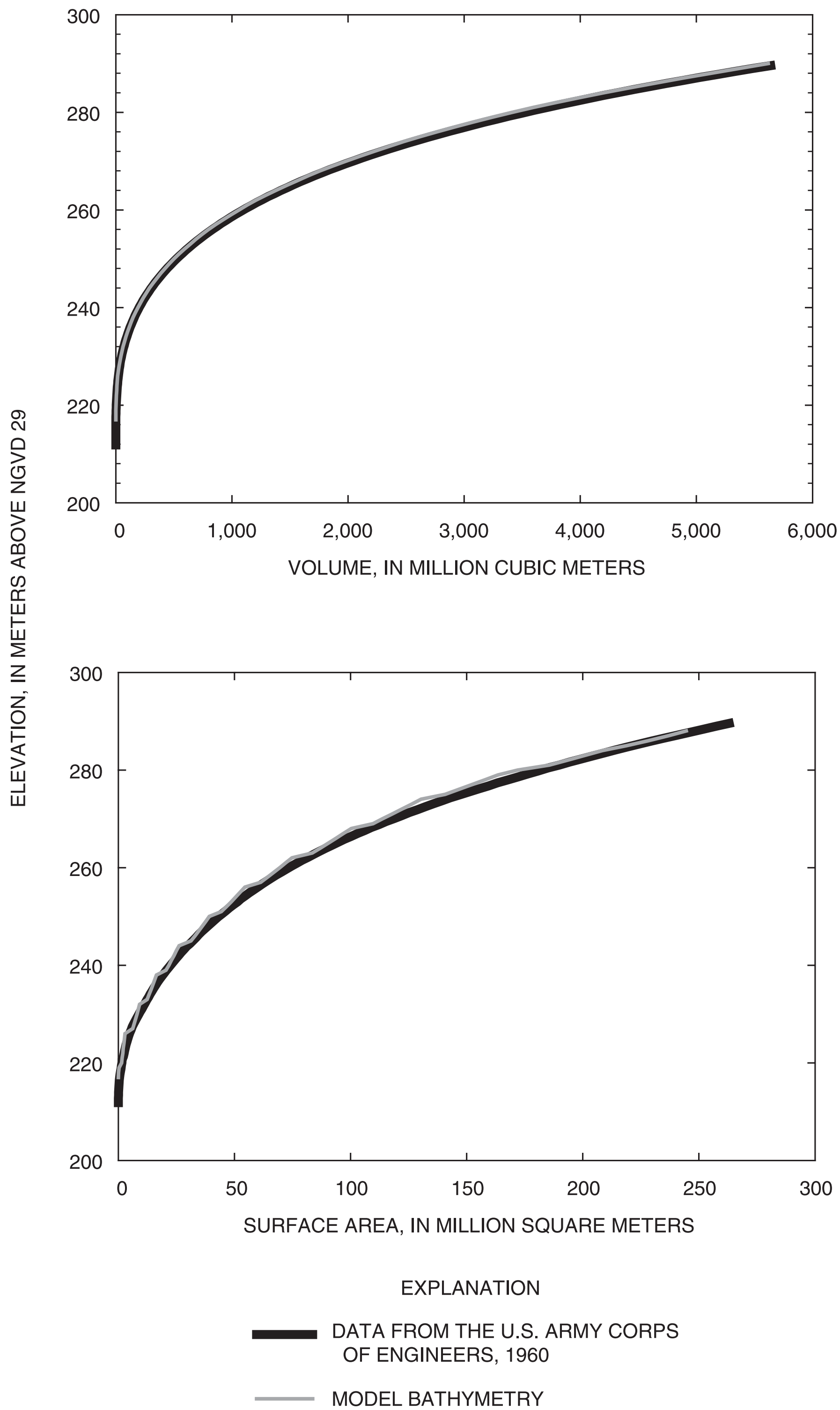

Figure 4. Relation between water-surface elevation and volume and water-surface elevation and surface area in Table Rock Lake.

bottom, the shoreline, tributary streams, the upstream boundary (Beaver Lake Dam), 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 ground-water 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 2).

Heat exchange between the reservoir bottom and the overlying water column is computed from (1) the sediment temperature (table 2), (2) bottom-water heat exchange coefficient (table 2), and (3) the simulated temperature of the overlying water. 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 8.0 °C was used in the Table Rock 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 as a result of changing water level and, therefore, cell layers.

Table Rock Lake receives water from the White River, which is regulated upstream at Beaver Lake Dam, from the James and Kings Rivers, and from many other tributaries (table 1). Other than the discharge from Beaver Lake (White River), the James River contributes the largest discharge into Table Rock Lake of all other tributaries. Annual streamflow recorded at the USGS streamflow-gaging station on the James River at Galena, Missouri (station number 07052500; fig. 1) indicates that inflow to Table Rock Lake during the 1996 and 1997 simulation time period was below average (fig. 5). Annual mean streamflow for the James River from 1958 through 1997 ranged from 10.3 to 63.27 m^3/s. The average annual mean streamflow during this time was 28.9 m^3/s. Annual mean streamflow for the 1996 and 1997 simulation time period was 26.2 and 20.9, respectively (Hauck and others, 1997; 1998; 1999).

Total daily reservoir inflow into Table Rock Lake was estimated by USACE (John Kielczewski, U.S. Army Corps of Engineers, written commun., 2000) based on measured outflow and change in reservoir water-surface elevations. Total mean reservoir inflow from January 1, 1996 through December 31, 1997, was estimated to be 113 m^3/s; whereas, the estimated median reservoir inflow for the same period was 65.1 m^3/s. The estimated inflow exceeded 269 m^3/s 10 percent of time.

Table 2. Hydraulic and thermal input parameters specified for Table Rock 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	7.0×10^{-8} (watts/m^2)/°C	Constant
Sediment temperature	Represents the reservoir bottom (sediment) temperature	8.0 °C	Constant
Wind–sheltering coefficient	Reduces wind speed to effective wind speed at water surface	0.8 (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

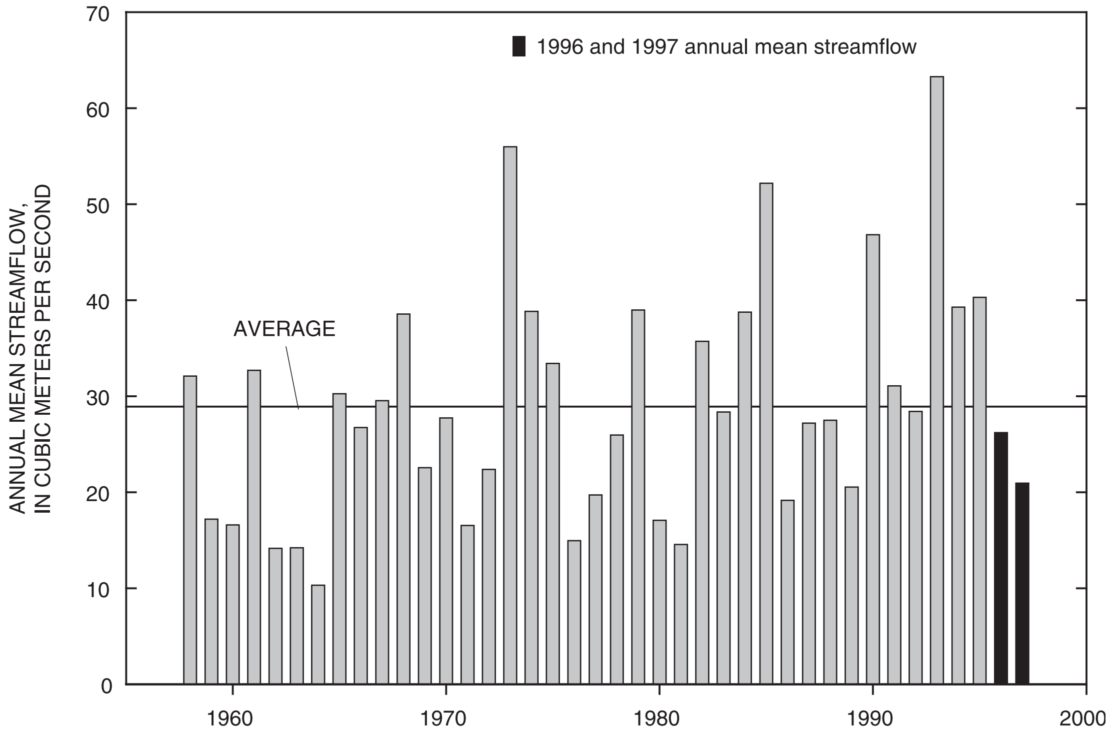

Figure 5. Annual mean streamflow for the James River upstream from Table Rock Lake, 1958 through 1997.

Gaged and areal-adjusted inflows used in the model were applied among 14 branches and 3 tributaries. Measured discharge from the White, James, and Kings Rivers, and Long Creek (fig. 6) made up about 75 percent of the total estimated inflow (White River, 35 percent; James River, 24 percent; Kings River, 12 percent; and Long Creek, 4 percent). The remaining 25 percent of inflow was divided up among smaller tributaries and branches and ungaged inflows were applied diffusely into the White River and James River branches as distributed inflow.

The downstream boundary for the Table Rock Lake model consists of the outflow from Table Rock Lake Dam. Outflow data (fig. 6) were produced by the USACE using stage-discharge relations and hourly power generation records. The mean and median reservoir outflow were 104 and 6.3 m^3/s, respectively. The reservoir outflow exceeded 370 m^3/s 10 percent of the time. The vertical extent and distribution of flow in the release zone near the Table Rock 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 about 20 m above the bottom at an elevation of 236.2 m above NGVD 29 in model layer 56 (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 (fig. 1; 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 2). 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 Table Rock 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 air temperatures, dewpoint temperatures, cloud covers, and wind speeds and directions measured

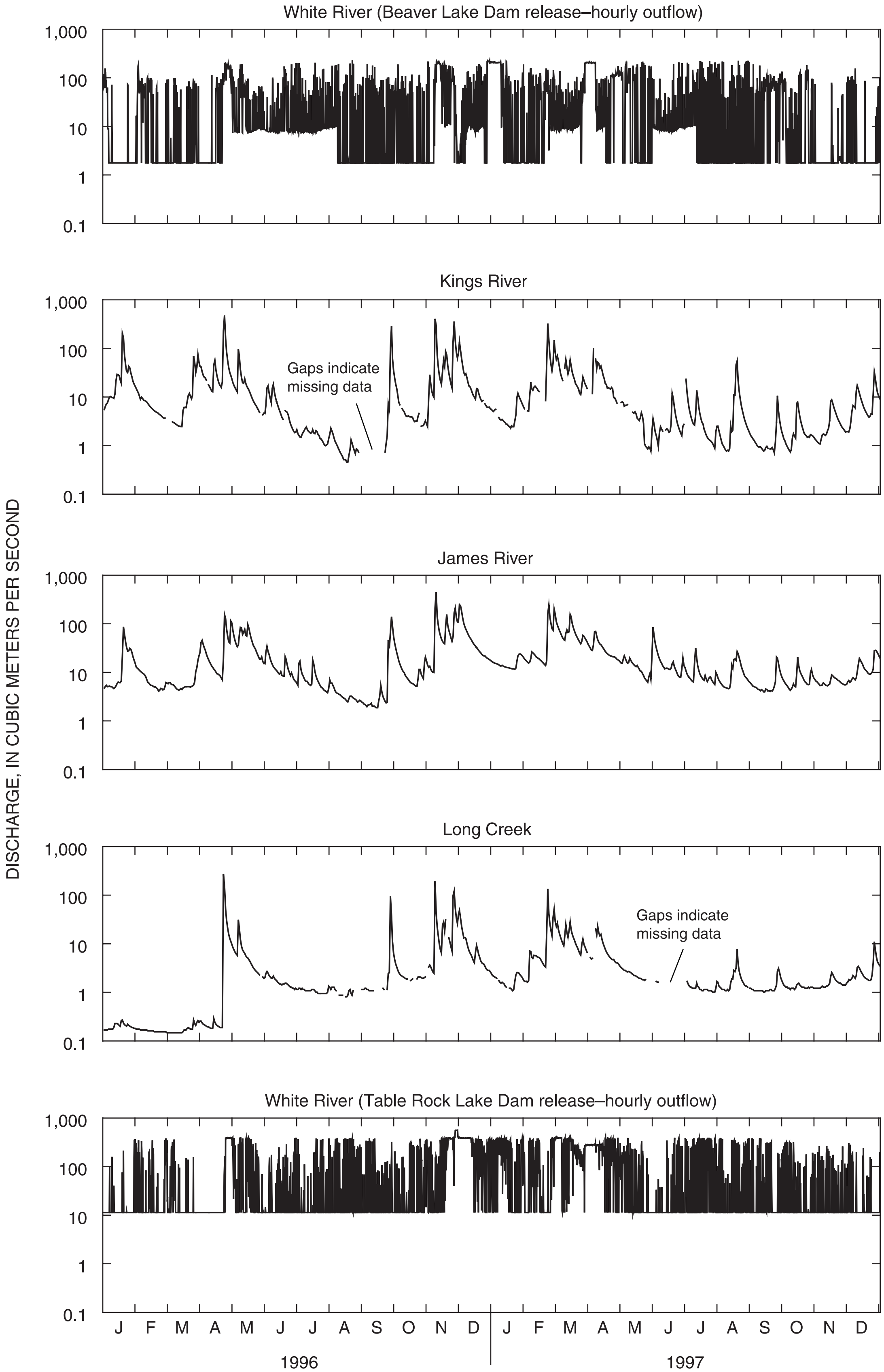

Figure 6. Daily inflow and hourly outflow for the Table Rock Lake Dam, Missouri, January 1996 through December 1997.

at Harrison, Arkansas. The simulated surface-water temperature and loss of heat through evaporation were included in the heat budget.

Chemical Boundary Conditions

Concentrations of selected constituents at all inflow boundaries are required for model operation. Boundary data in all tributaries and branches included hourly or daily concentrations of dissolved oxygen, ammonia as nitrogen, nitrite plus nitrate as nitrogen, total phosphorus, and a conservative tracer. Because of few available water-quality data, annual average concentrations were estimated based on similar values reported by Porter and others (1997; 1998; 1999) and Hauck and others (1997; 1998; 1999), and used for all inflow boundary constituents except dissolved oxygen. Dissolved-oxygen concentrations in the White River inflow were obtained from measured data at the Beaver Lake tailwater station 07049693 (Porter and others, 1997; 1998; 1999). Dissolved-oxygen concentrations at the remaining inflow tributary boundaries were set to the concentration for 80 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 NGVD 29, and the molecular diffusivity of oxygen gas. Atmospheric nutrient inputs were not included in this model, and nutrient constituent inputs from the reservoir bottom generally were computed within the model based on the value of selected parameters (table 3) 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 before initiating model simulation. Initial water-surface elevation was set to the value measured at the Table Rock Lake Dam on January 1, 1996. 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, 1995 (Porter and others, 1997).

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 (table 2). 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 3). 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 3. Rate coefficients used in water-chemistry and biological simulations and other parameters specified as input in the Table Rock Lake model

[m, meters; *, dimensionless; Q_{10}, temperature correction factor; m/d, meters per day; d, day; watts/m^2, watts per square meter; °C, 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	0.30/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	0.28*
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	2.0 m/d
Algal growth rate	Maximum gross algal production rate, uncorrected for respiration, mortality, excretion or settling; temperature dependent	1.5/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	500 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 °C
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	15.0°C
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	35.0 °C
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 °C
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

Table 3. Rate coefficients used in water-chemistry and biological simulations and other parameters specified as input in the Table Rock Lake model—Continued

Parameter/rate coefficient	Computational purpose	Value
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	3.0 $(g/m^2)/d$
5-day BOD decay rate	Effects of BOD loading on dissolved oxygen	2.0/d
BOD temperature rate coefficient	Adjusts 5-day BOD decay rate at 20^{o}C 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	0.015*
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	0.02*
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

Table 3. Rate coefficients used in water-chemistry and biological simulations and other parameters specified as input in the Table Rock Lake model—Continued

Parameter/rate coefficient	Computational purpose	Value
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	1.4*
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	0.5 mg/L

Model Calibration

Successful model application requires model calibration that includes comparing model (simulated) results with observed (measured) reservoir conditions. If possible, 2 or more years of water-quality data should be used for adequate model calibration. Table Rock Lake model calibration was achieved by adjusting model parameters and, in some cases, estimated input data, for the 2 years from January 1996 through December 1997.

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:

$$RMSE = \sqrt{\frac{\Sigma(Simulated\ Values - Measured\ Values)^2}{Number\ of\ Observations}} \qquad (2)$$

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 water-surface elevations in Table Rock Lake (fig. 7) were adjusted to the measured water surface for the simulation period January 1996 to December 1997 (John Kielczewski, written commun., 2000). The water-surface elevations were corrected to the measured values by adjusting the unmeasured inflow into the lake that was applied to all the segments within a branch segment. Inflow was either added or subtracted so that the simulated water-surface elevation reflected the measured water-surface elevation. By correcting the water budget, the thermodynamics could be calibrated without the uncertainty incurred with having differences between simulated and measured elevations (volumes).

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 (from Harrison, Arkansas: station number 723446, National Climatic Data Center, Asheville, North Carolina), sim-

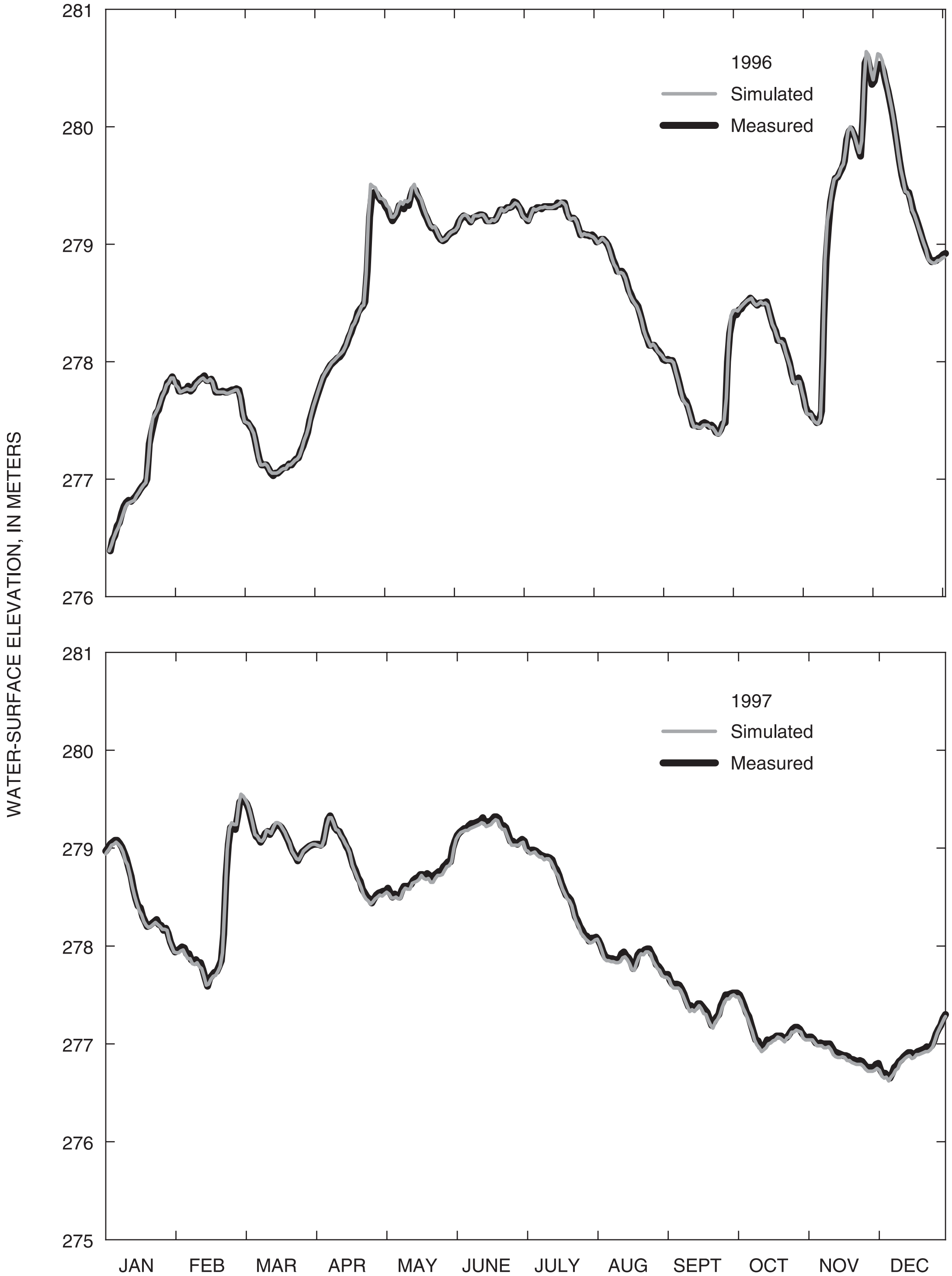

Figure 7. Simulated and measured water-surface elevations near the Table Rock Lake Dam (U.S. Geological Survey station 07053400), January 1996 through December 1997.

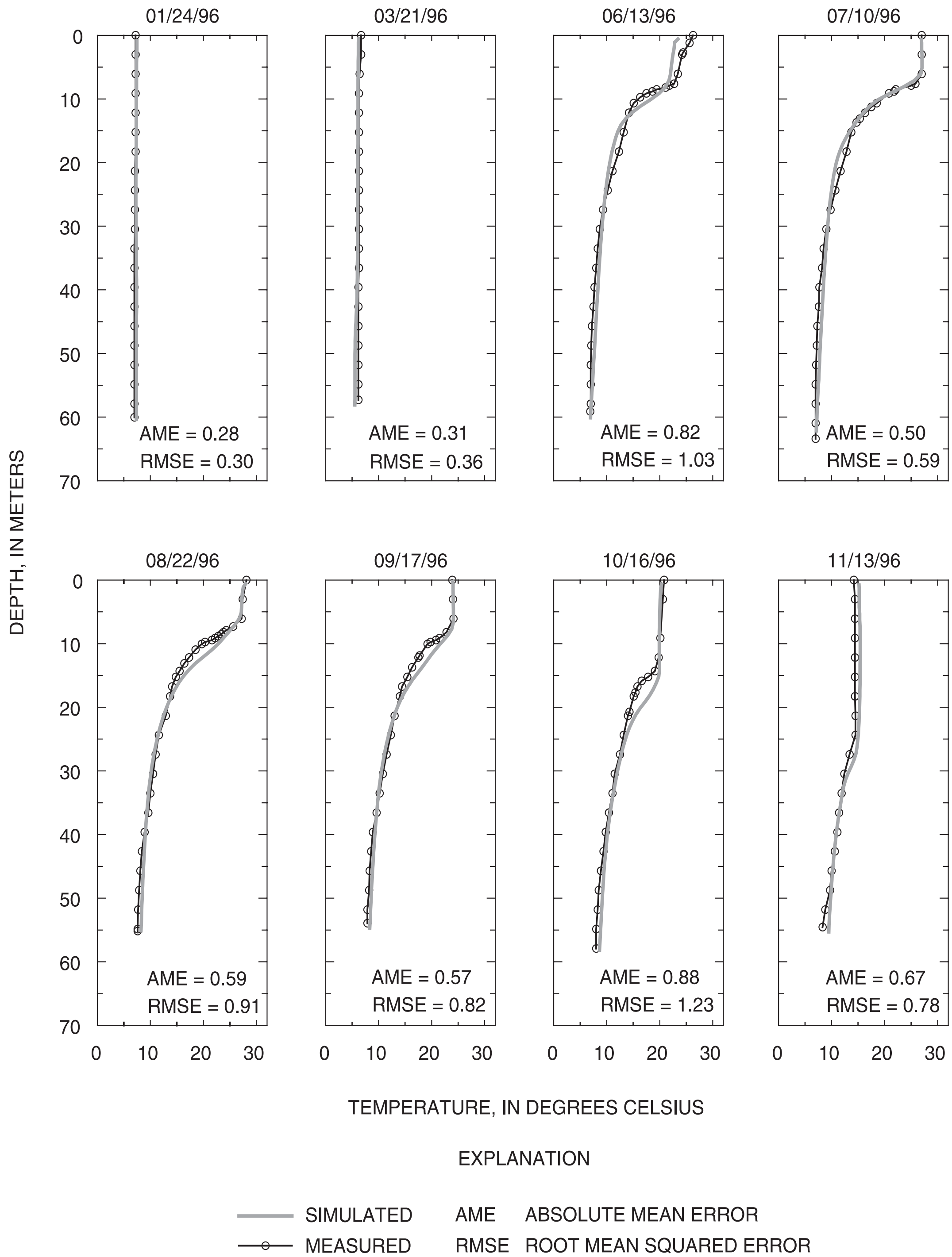

Figure 8. Relation between simulated and measured water temperatures in the water column near the Table Rock Lake Dam (U.S. Geological Survey station 07053400), January through November 1996.

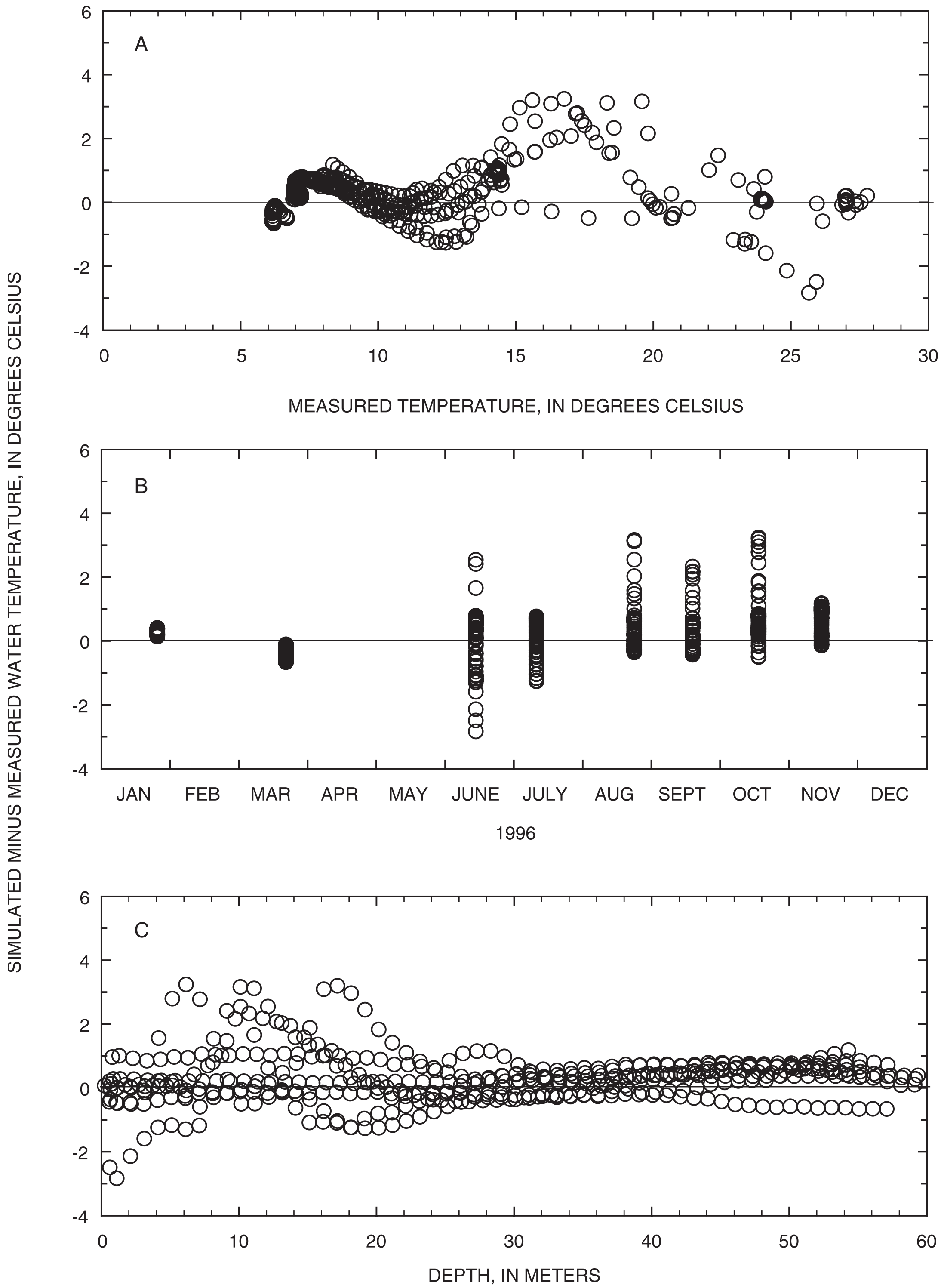

Figure 9. Relation of difference between simulated and measured water temperatures near the Table Rock Lake Dam (U.S. Geological Survey station 07053400) to (A) measured water temperature, (B) sampling date, and (C) water depth, January through November 1996.

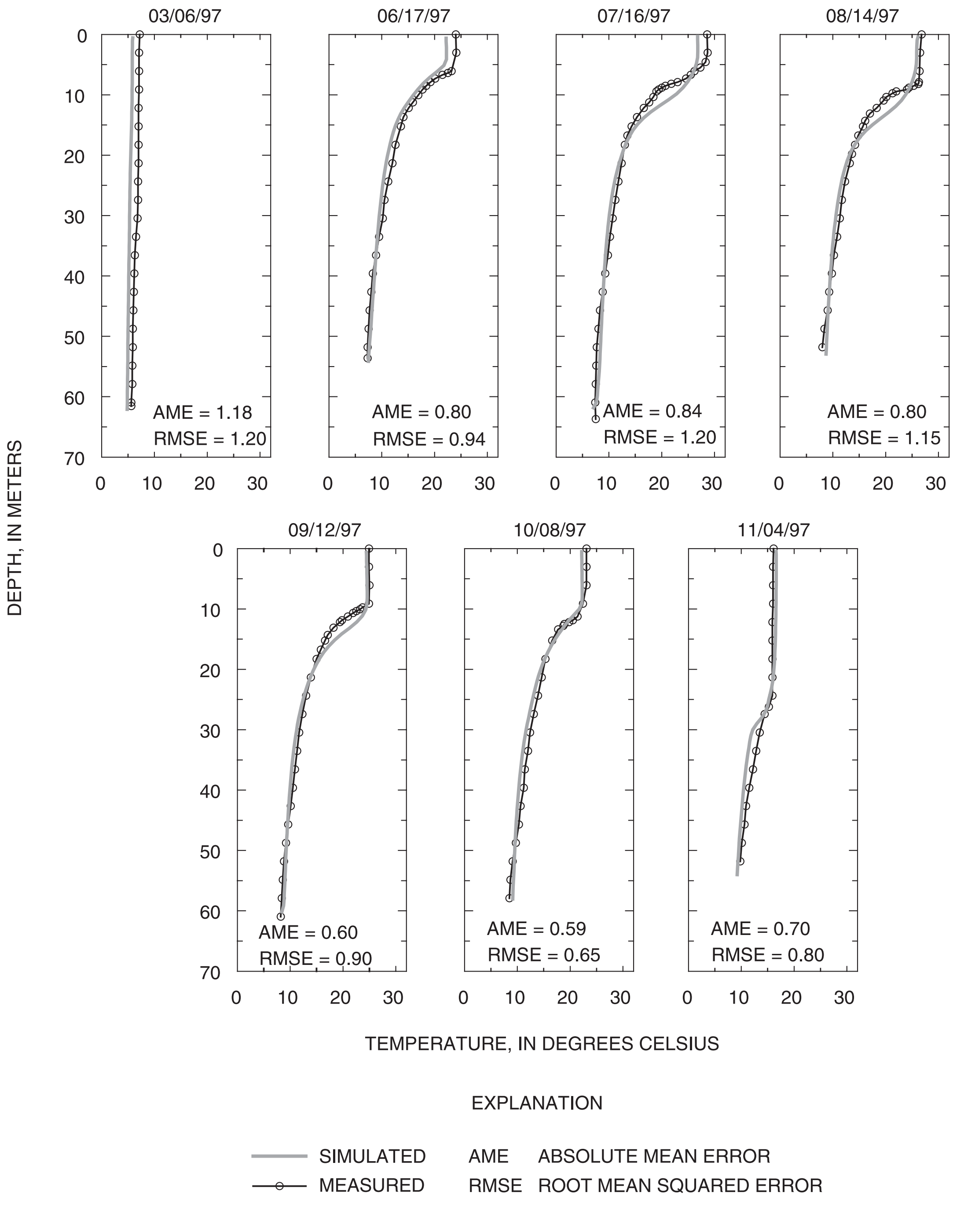

Figure 10. Relation between simulated and measured water temperatures in the water column near the Table Rock Lake Dam (U.S. Geological Survey station 07053400), March through November 1997.

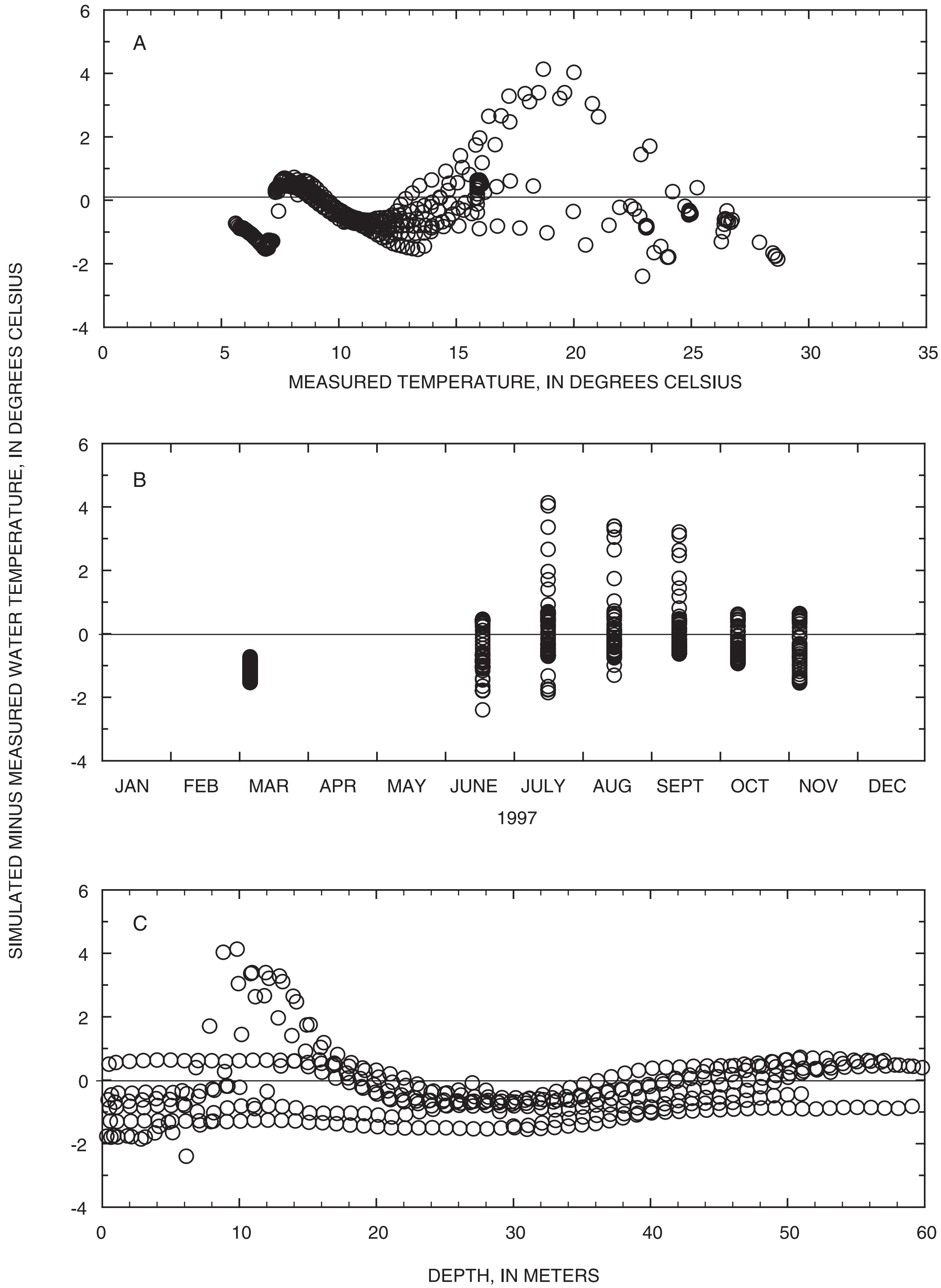

Figure 11. Relation of difference between simulated and measured water temperatures near the Table Rock Lake Dam (U.S. Geological Survey station 07053400) to (A) measured water temperature, (B) sampling date, and (C) water depth, March through November 1997.

Simulated dissolved-oxygen concentrations in 1996 near the Table Rock Lake Dam exhibited the same general patterns and magnitudes as measured concentrations (fig. 12). Selected simulated dissolved-oxygen concentrations for January through December 1996 were compared to 465 corresponding measured concentrations (Porter and others, 1997; 1998). Simulated dissolved-oxygen concentrations ranged from 0.0 to 11.8 mg/L, whereas, measured dissolved-oxygen concentrations ranged from 0.1 to 11.6 mg/L. Simulated dissolved-oxygen concentrations in the vertical profile were within 1 mg/L of measured concentrations 74 percent of the time. The overall AME and RMSE between simulated and measured dissolved-oxygen concentrations were 0.74 and 1.00 mg/L, respectively. The difference between simulated and measured concentrations ranged from -5.9 to 5.3 mg/L, and the median absolute difference was 0.42 mg/L.

Differences between simulated and measured dissolved-oxygen concentrations in 1996 were compared to corresponding measured dissolved-oxygen concentrations, sampling date, and the water depth (fig. 13). Simulated dissolved-oxygen concentrations typically were greater than measured values at lower concentrations. Errors in simulated dissolved-oxygen concentration were greater later in the thermal stratification season (September through November). The July 10, 1996, results had the greatest error near the lake bottom. Simulated dissolved-oxygen concentrations generally were less than measured values near the water surface.

Simulated dissolved-oxygen concentrations were similar to measured dissolved-oxygen concentrations in 1997 (fig. 14), but differences were somewhat greater in 1997 than in 1996. Seasonal variations in simulated dissolved-oxygen concentration were reproduced despite pronounced differences in the vertical distribution. Selected simulated dissolved-oxygen concentrations were compared to 402 corresponding measured concentrations (Porter and others, 1998; 1999) near the Table Rock Lake Dam. Simulated values ranged from 0.0 to 11.7 mg/L, whereas measured dissolved-oxygen concentrations ranged from 0.1 to 11.6 mg/L. Simulated dissolved-oxygen concentrations in the vertical profile were within 1 mg/L of measured concentrations 53 percent of the time. The overall AME and RMSE between simulated and measured dissolved-oxygen concentrations were 1.09 and 1.41, respectively. The difference between simulated and measured dissolved-oxygen concentrations ranged from -3.0 to 5.3 mg/L, and the median absolute difference was 0.90 mg/L.

On average, simulated dissolved-oxygen concentrations in 1997 were slightly greater than measured concentrations (fig. 15). The largest differences between simulated and measured dissolved-oxygen concentrations typically occurred at concentrations less than 4 mg/L. Simulated dissolved-oxygen concentrations consistently were greater than measured concentrations during thermally stratified conditions within the thermocline. Simulated dissolved-oxygen concentrations often were greater than measured concentrations regardless of depth except near the surface. Despite these tendencies, simulation of dissolved-oxygen concentration in the vertical profile near the Table Rock Lake Dam followed the same general patterns as measured concentrations.

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 Table Rock Lake model was not conducted because the model includes more than 60 parameters (tables 2 and 3). 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; Galloway and Green, 2002; 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), coefficient of bottom-water heat exchange coefficient (CBHE), light extinction coefficient (α), sediment-oxygen demand (SOD), and changes in inflow water temperature (ITEMP) and dissolved-oxygen concentrations was assessed.

Water temperature in the Table Rock Lake model was most sensitive to changes in the WSC and α (fig. 16). Wind speed in the calibrated Table Rock Lake model was adjusted (WSC = 0.8) from the meteorological data recorded at Harrison, Arkansas; that is, the effective wind speed was 80 percent of the recorded wind speed at Harrison. Surface-water temperatures were not affected as much by changes in WSC as was the position of the thermocline and hypolimnetic tem-

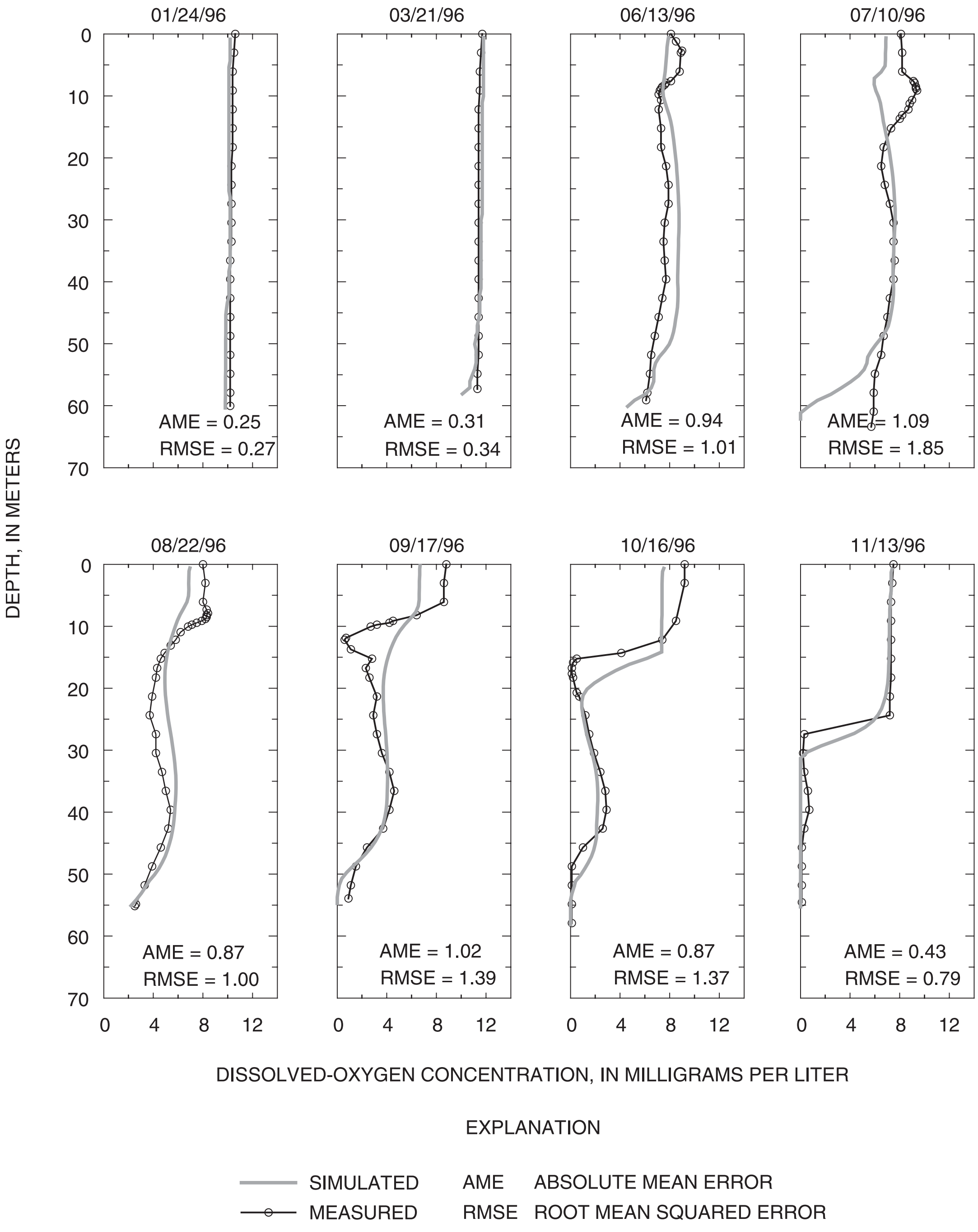

Figure 12. Relation between simulated and measured dissolved-oxygen concentrations in the water column near the Table Rock Lake Dam (U.S. Geological Survey station 07053400), January through November 1996.

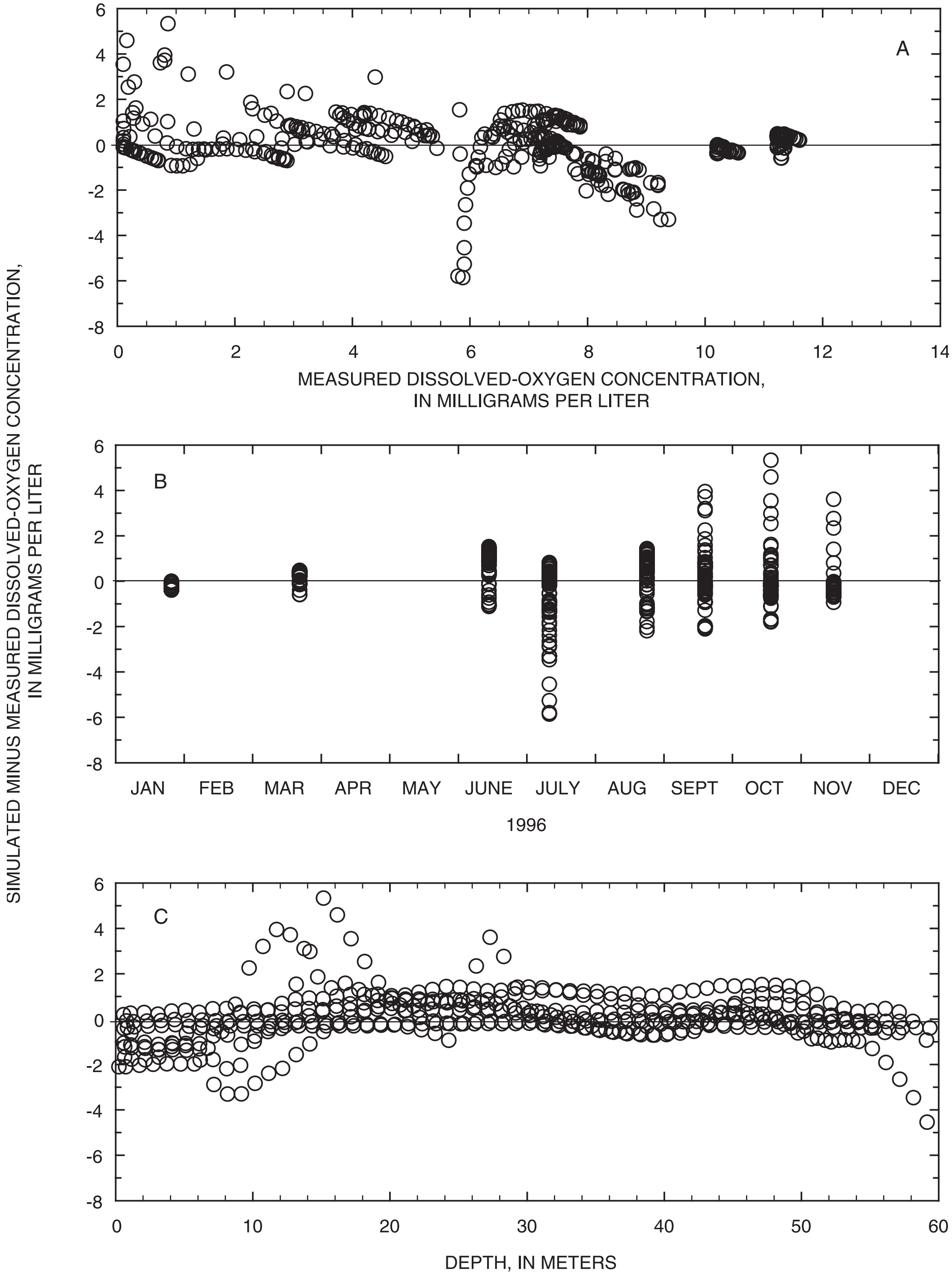

Figure 13. Relation of difference between simulated and measured dissolved-oxygen concentrations near the Table Rock Lake Dam (U.S. Geological Survey station 07053400) to (A) measured dissolved-oxygen concentrations, (B) sampling date, and (C) water depth, January through November 1996.

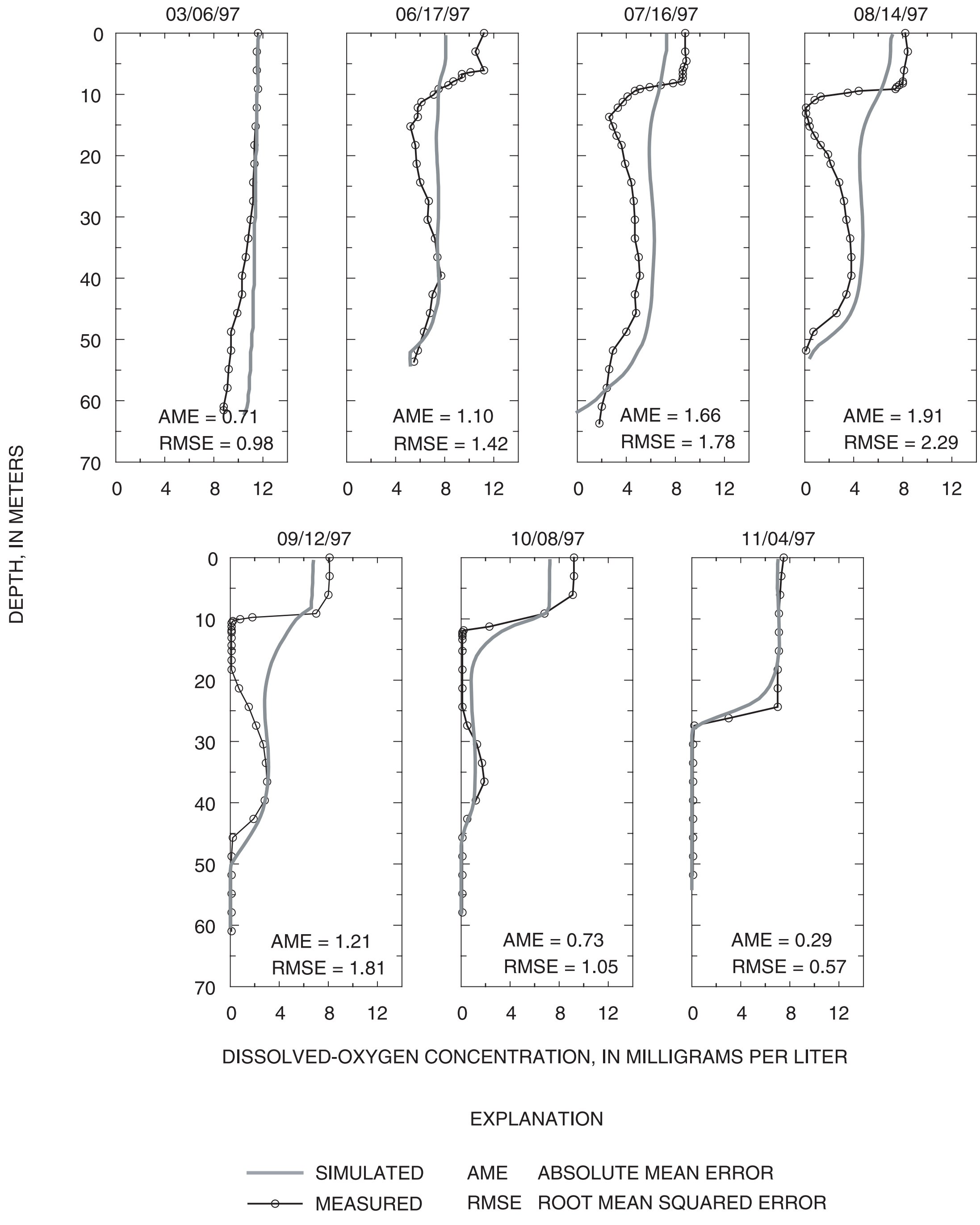

Figure 14. Relation between simulated and measured dissolved-oxygen concentrations in the water column near the Table Rock Lake Dam (U.S. Geological Survey station 07053400), March through November 1997.

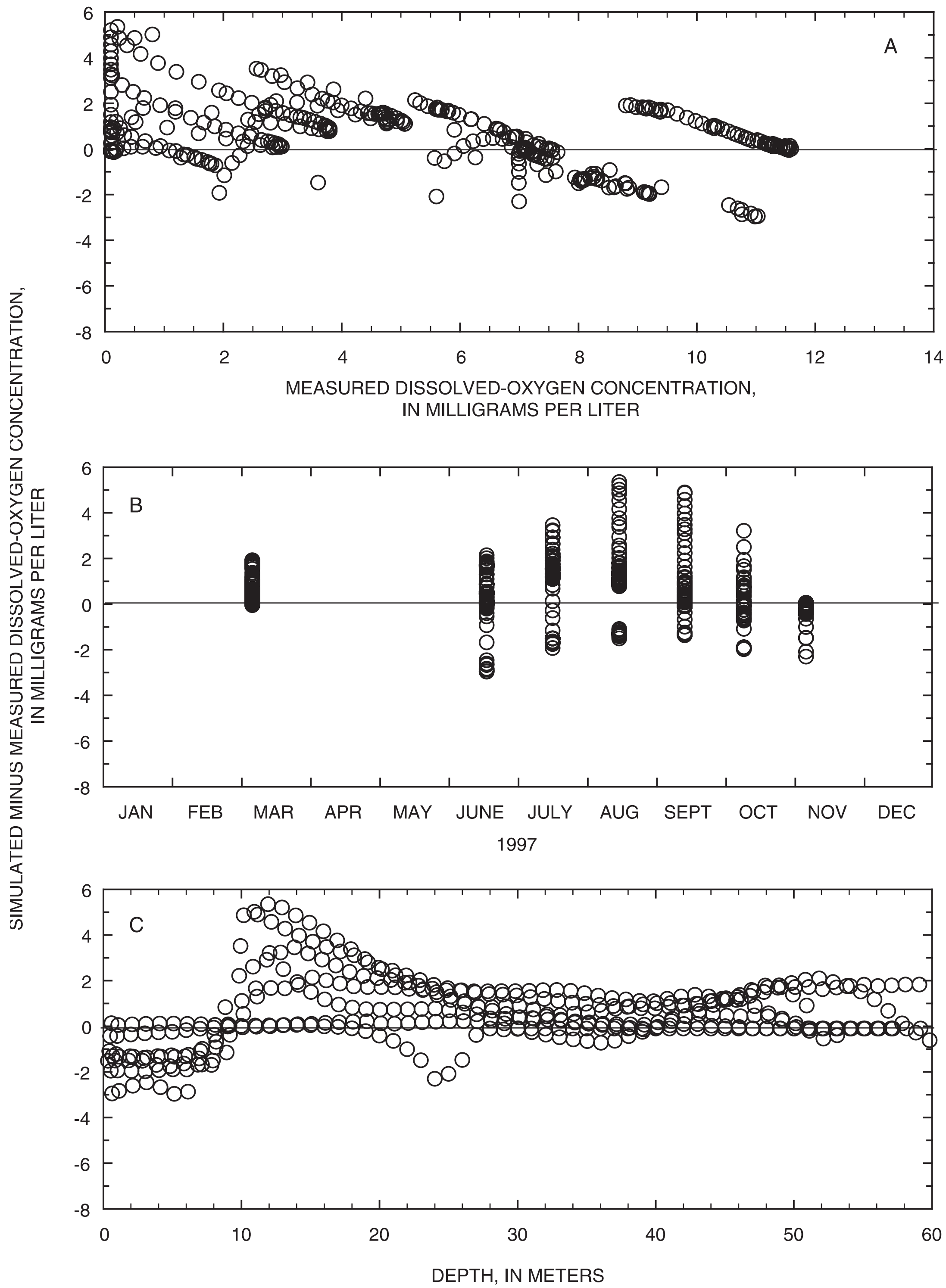

Figure 15. Relation of difference between simulated and measured dissolved-oxygen concentrations near the Table Rock Lake Dam (U.S. Geological Survey station 07053400), to (A) measured dissolved-oxygen concentrations, (B) sampling date, and (C) water depth, March through November 1997.

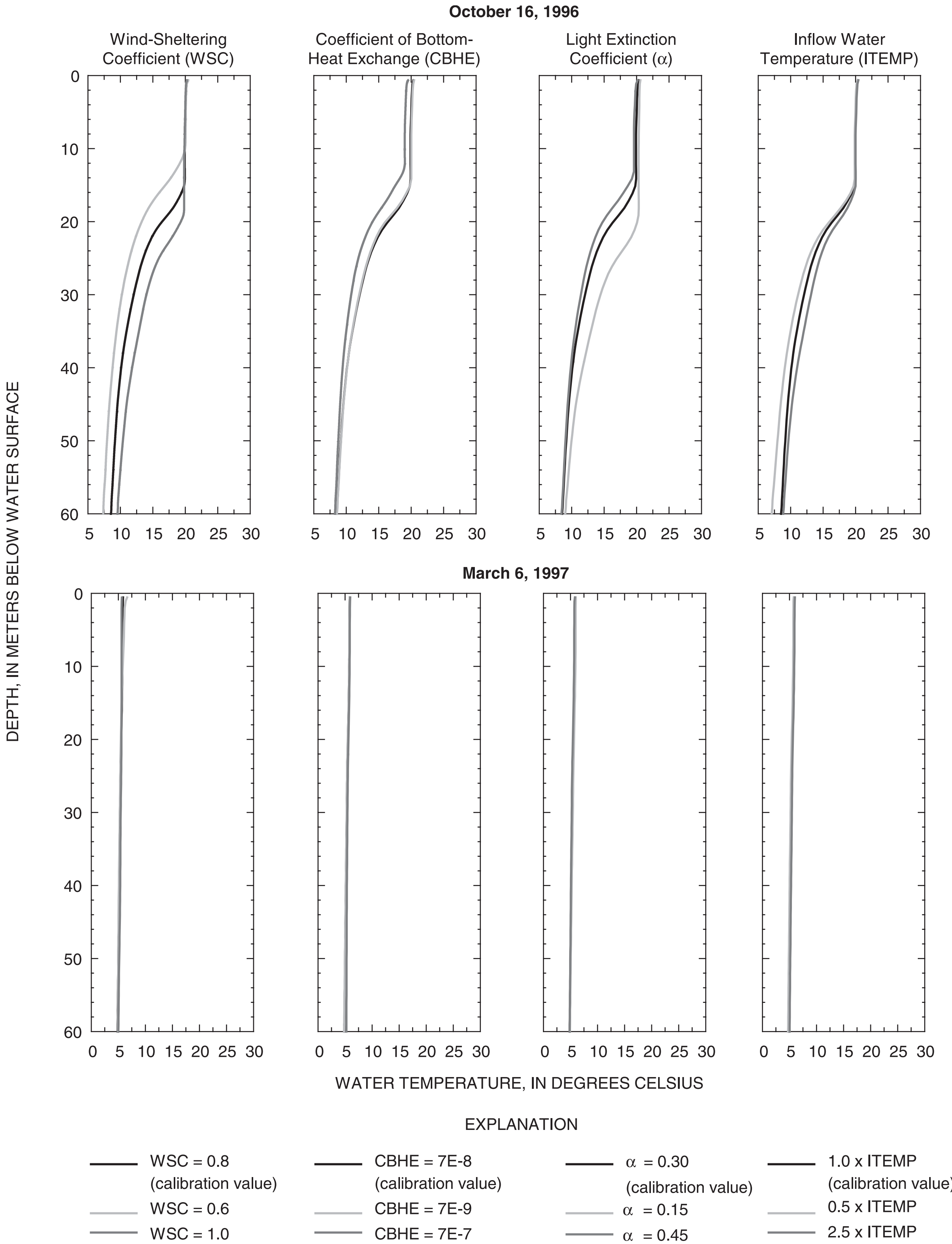

Figure 16. Vertical temperature distributions near the Table Rock Lake Dam (U.S. Geological Survey station 07053400) on October 16, 1996 (top), and March 6, 1997 (bottom), showing calibrated model profiles and profiles as a result of differing model parameters.

peratures. During thermal stratification, vertical mixing was over-predicted when the WSC was increased (1.0) and under-predicted when the WSC was decreased (0.6). 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 CBHE and inflow water temperature had a slight 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 Table Rock Lake near the dam.

In the Table Rock Lake model, dissolved-oxygen concentrations were most affected by changes in the WSC, α, and fraction of sediment-oxygen demand (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 affecting algal production. During thermal stratification, changes in α had the greatest effect on the position and configuration of the thermocline. Changes in the inflow dissolved-oxygen (IDO) concentrations had little effect on the vertical distribution of dissolved oxygen near the dam except near the bottom.

Many other parameters indirectly affect dissolved-oxygen concentrations through algal dynamics; however, examination of all of these parameters is beyond the scope of this report 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 Table Rock Lake Dam.

Model Applications

The calibrated Table Rock Lake model was used to assess the effects of increased minimum flow on water-surface elevation and on temperature and dissolved-oxygen concentrations in the Table Rock Lake outflow waters. Two scenarios were simulated: an increase in the outflow of Table Rock Lake Dam from the existing minimum flow of 4.36 to 11.33 m^3/s, and an increase in water-surface elevation of the existing operational plan by 0.61 m that included 11.33 m^3/s minimum flow.

When 11.33 m^3/s was applied as the minimum amount of outflow (increased minimum flow scenario) during 1996 and 1997, average annual outflow increased from 104.6 to 108.2 m^3/s, about a 3 percent increase. Approximately 55 percent of the measured hourly outflow data required an increase to simulate 11.33 m^3/s. Average annual outflow increased from 3,296 to 3,411 million cubic meters, which is equivalent to 115 million cubic meters per year increase, or about 3.5 percent of reservoir volume at summer conservation pool elevation (279.5 m).

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 07053450) (fig. 18). Temperature in the outflow water differed little between results from the increased minimum flow scenarios and the calibrated model (fig. 19). Absolute maximum difference in outflow water temperature between the increased minimum flow scenario and the calibrated model was 0.62 °C. The absolute mean and median differences were 0.14 and 0.10 °C, respectively. Temperature differences with and without additional minimum flow 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 dissolved-oxygen concentrations were similar to estimated outflow concentrations from water-column profiles measured upstream from the dam (George Robins, written commun., 2000) (fig. 20). Dissolved-oxygen concentrations in the outflow water differed little between results from the minimum flow scenario and the calibrated model (fig. 21). Absolute maximum difference in outflow dissolved oxygen between the increased minimum flow scenario and the calibrated model was 1.30 mg/L. The absolute mean and median differences were 0.16 and 0.09 mg/L, respectively. Dissolved-oxygen concentration differences with and without additional minimum flow 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.

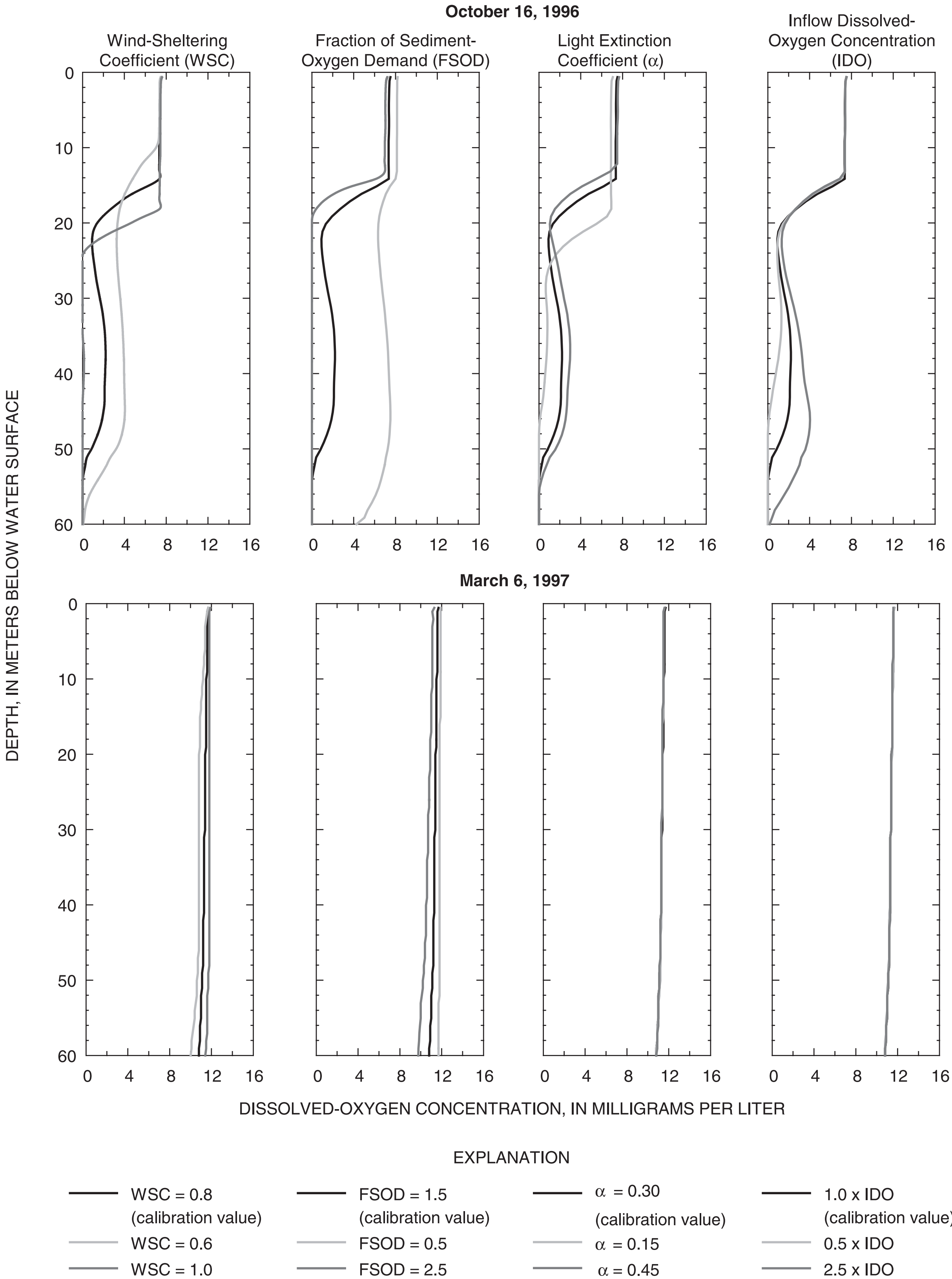

Figure 17. Vertical dissolved-oxygen concentration distributions near the Table Rock Lake Dam (U.S. Geological Survey station 07053400) on October 16, 1996 (top), and March 6, 1997 (bottom), showing calibrated model profiles and profiles as a result of differing model parameters.

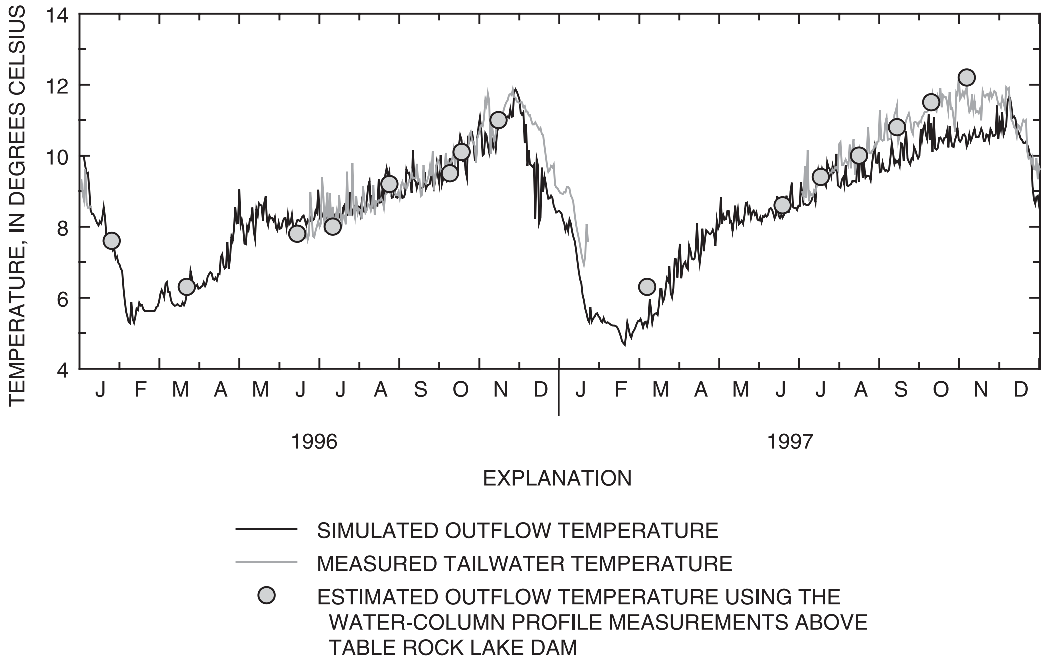

Figure 18. Simulated outlfow, measured tailwater, and estimated outflow temperatures.

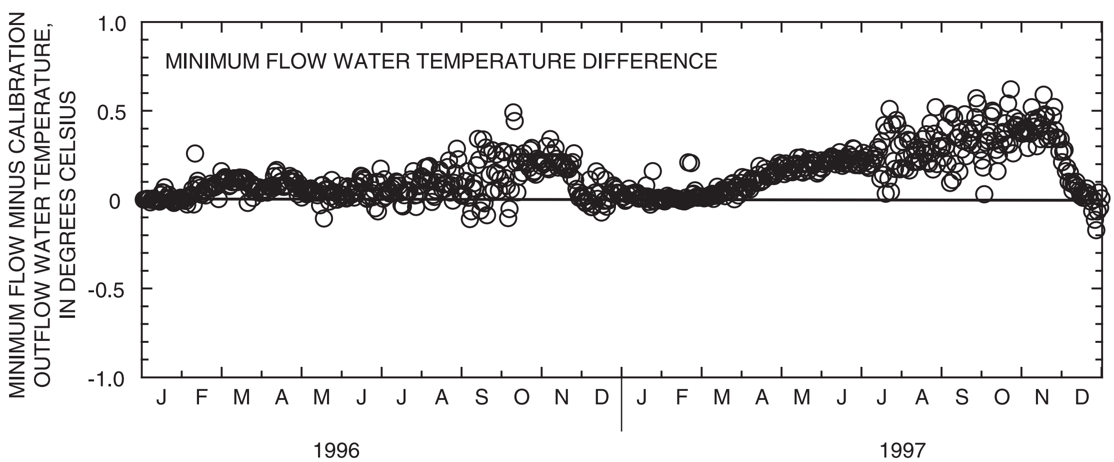

Figure 19. Simulated water temperature difference between the increased minimum flow scenario and the calibrated model.

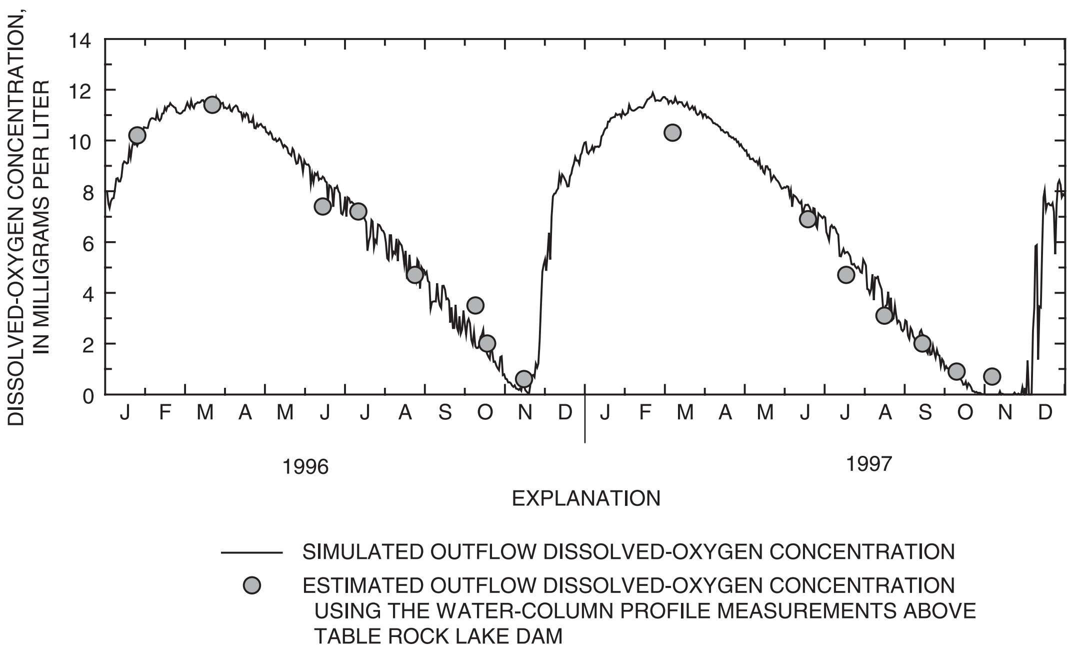

Figure 20. Simulated and estimated outflow dissolved-oxygen concentration.

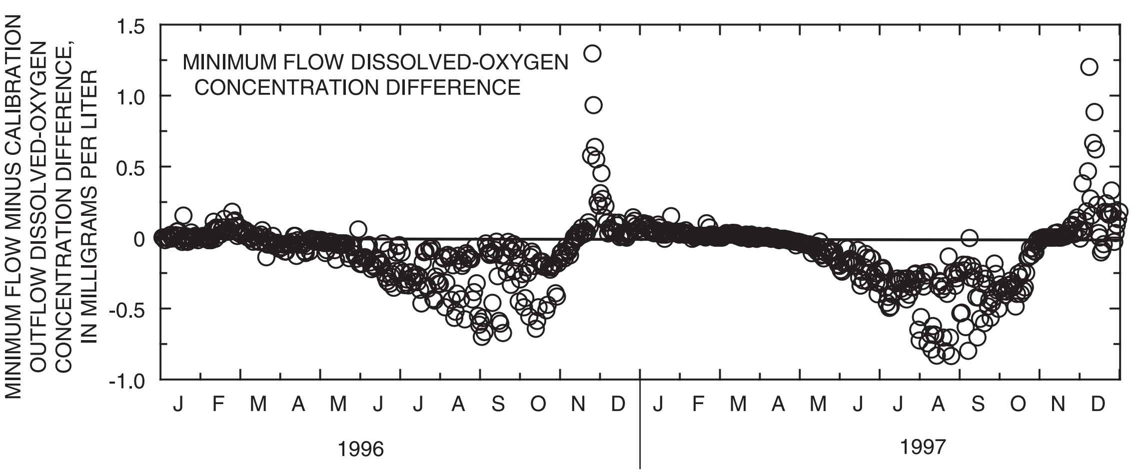

Figure 21. Simulated dissolved-oxygen concentrations between the increased minimum flow scenario and the calibrated model.

The existing operational plan for Table Rock Lake is to maintain a conservation pool at an elevation of 278.9 m between December 1 and April 30, and 279.50 m between May 1 and November 30. An increase in conservation pool of 0.6 m or 2 feet also is proposed along with the proposed increase in minimum flow. The potential water-surface elevation of the conservation pool would then be 279.5 m between December 1 and April 30, and 280.11 between May 1 and November 30. Two model simulations were developed to assess the temperature and dissolved-oxygen differences between the existing operational plan without increased minimum flow and the potential operational plan with increased pool elevation and increased minimum flow of 11.33 m^3/s.

The water budget in the calibrated model was modified by adding or subtracting discharge in the distributed tributary file so that pool elevation in the model matched the pool elevation of the existing operational plan and the proposed minimum flow plan (fig. 22). All other inflow and outflow files in the model remained unchanged with the exception of the outflow file that included the increase in minimum flow in the increased minimum flow simulation.

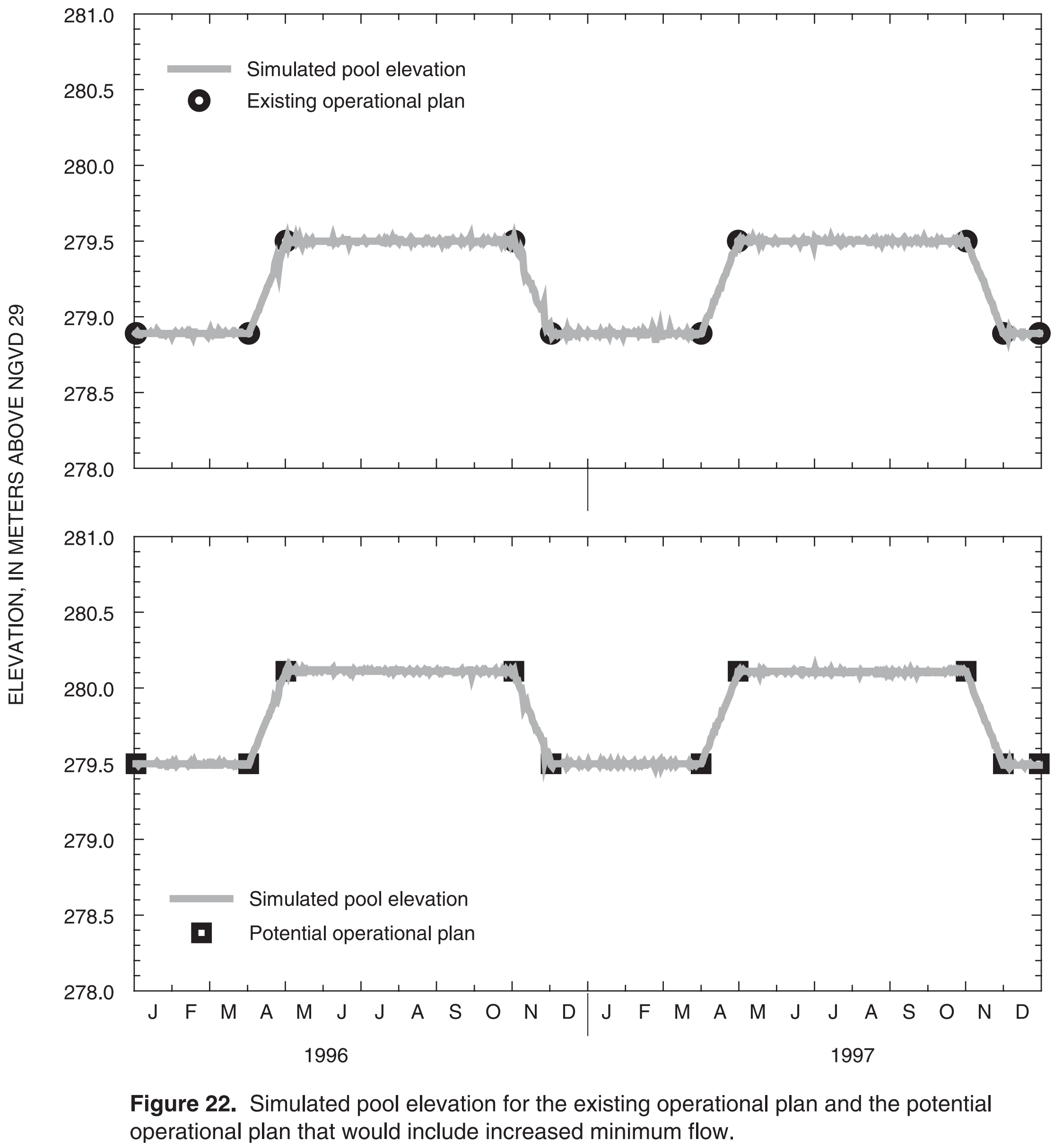

Figure 22. Simulated pool elevation for the existing operational plan and the potential operational plan that would include increased minimum flow.

Water temperature and dissolved-oxygen concentrations in the outflow differed little between the existing operational plan and the simulation containing the potential operational plan (figs. 23 and 24). Temperature differences ranged from -0.34 to 0.37 °C and dissolved-oxygen concentration differences ranged from -0.71 to 0.78 mg/L between the two simulations. Both, temperature and dissolved-oxygen differences were similar to the error between simulated and measured temperature and dissolved-oxygen concentrations in the model calibration.

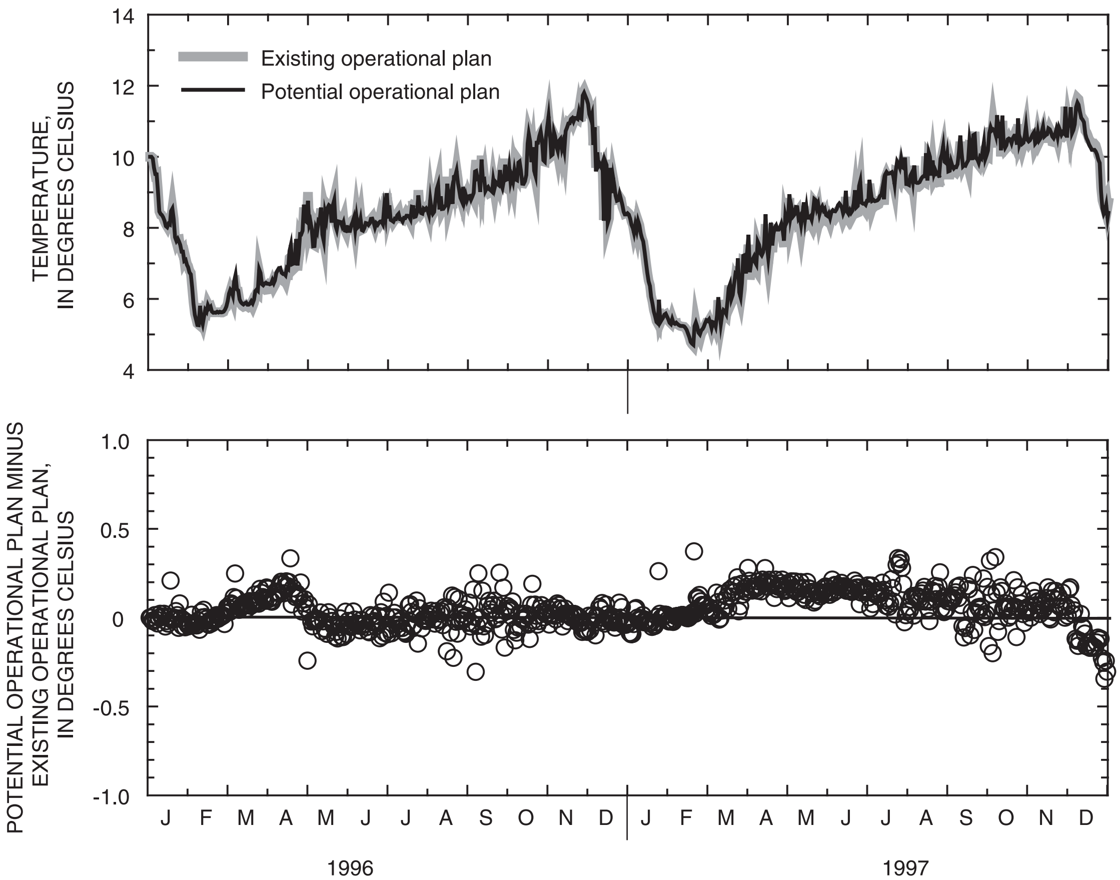

Figure 23. Simulated water temperature for Table Rock Lake Dam outflow using the existing operational plan and the potential operational plan of increased stage and minimum flow.

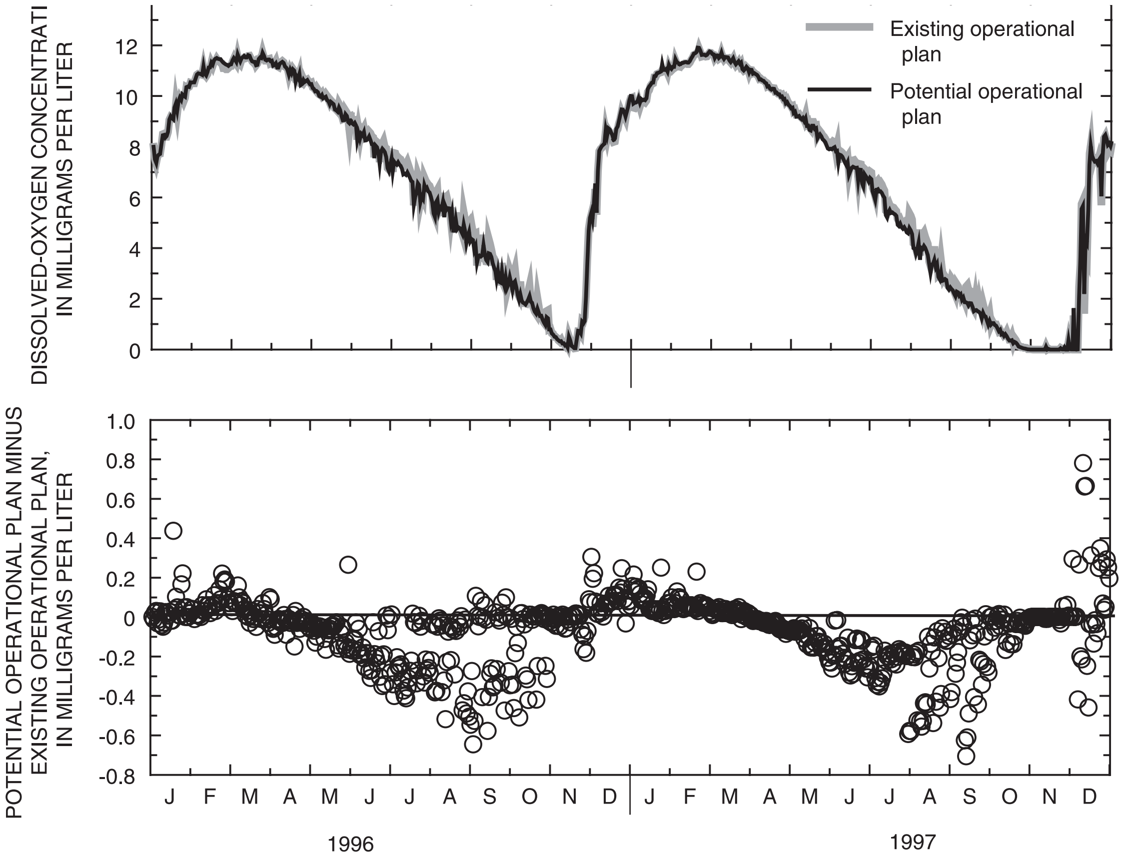

Figure 24. Simulated dissolved-oxygen concentrations for Table Rock Lake Dam outflow using the existing operational plan and the potential operational plan of increased conservation pool and minimum flow.

SUMMARY

Outflow from Table Rock Lake and other White River reservoirs support a cold-water trout fishery of substantial economic yield in south-central Missouri and north-central Arkansas. 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 Table Rock Lake. Increases in water temperature and decreases in dissolved oxygen potentially could have negative effects on the cold-water trout fisheries in the downstream outflow. Thus, the U.S. Geological Survey in cooperation with the Missouri Department of Conservation, conducted a study to assess the effects of additional minimum flows and increased water-surface elevations on the hydrodynamics, temperature, and dissolved-oxygen concentrations in Table Rock Lake and on temperature and dissolved-oxygen concentrations in the downstream outflow.

A two-dimensional, laterally averaged, hydrodynamic, temperature, and dissolved-oxygen model (CE-QWAL-W2) was developed for Table Rock Lake, Missouri. The model was calibrated using hydrologic records and vertical profiles of temperature and dissolved oxygen measured in or near Table Rock Lake from January 1996 through December 1997. The model simulates surface-water elevation, water temperature, and dissolved-oxygen concentration. The model simulated temperatures generally within 1 °C of the measured temperatures. The AME and RMSE for 1996 were 0.58 and 0.75, respectively, and for 1997 were

0.79 and 0.98, respectively. The model simulated dissolved-oxygen concentrations generally within 1 mg/L of the measured concentrations. The AME and RMSE for 1996 were 0.74 and 1.00, respectively. For 1997, the AME and RMSE were 1.09 and 1.41, respectively.

The Table Rock Lake model was developed to assess the effects of proposed increases in minimum flows from 4.36 m^3/s (the existing minimum flow) to 11.33 m^3/s (the increased minimum flow). Scenarios included assessing the effect of (1) increased minimum flows using the calibrated model as the basis for comparison and (2) creating a simulation of current operational plan and comparing results with a simulation including a potential increase in conservation pool elevation and increased minimum flow on outflow temperature and dissolved-oxygen concentrations. With the increased minimum flow in both scenarios, water temperature appeared to increase slightly (less than 0.37 °C) and dissolved oxygen appeared to decrease in the outflow during the thermal stratification season. However, results were similar to the differences between measured and simulated water-column profile values.

Water temperature and dissolved-oxygen concentrations in the outflow differed little between the existing operational plan and the simulation containing the potential operational plan. Temperature differences ranged from -0.34 to 0.37 °C and dissolved-oxygen concentration differences ranged from -0.71 to 0.78 mg/L between the two simulations. Both, temperature and dissolved-oxygen differences were similar to the error between simulated and measured temperature and dissolved-oxygen concentrations in the model calibration.

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