Prepared in cooperation with the

Arkansas Game and Fish Commission

SIMULATION OF HYDRODYNAMICS, TEMPERATURE, AND DISSOLVED OXYGEN IN BULL SHOALS LAKE, ARKANSAS, 1994-1995

Water-Resources Investigations Report 03-4077

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

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By Joel M. Galloway and W. Reed Green

U.S. GEOLOGICAL SURVEY
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Little Rock, Arkansas
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U.S. DEPARTMENT OF THE INTERIOR
GALE A. NORTON, Secretary

U.S. GEOLOGICAL SURVEY
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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
hectare (ha)	2.471	acre
square meter (m^2)	10.76	square foot (ft^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
liter (L)	0.2642	gallon (gal)
cubic meter (m^3)	35.31	cubic foot (ft^3)
gram (g)	0.03527	ounce (oz)
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:
$°C = 0.55(°F – 32)$

In this report vertical coordinate information is referenced to the National Geodetic Vertical datum of 1929 (NGVD of 1929). Horizontal coordinate information is referenced to North American Datum of 1983 (NAD 83).

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

SIMULATION OF HYDRODYNAMICS, TEMPERATURE, AND DISSOLVED OXYGEN IN BULL SHOALS LAKE, ARKANSAS, 1994-1995

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ABSTRACT

Outflow from Bull Shoals Lake and other White River reservoirs supports a cold-water trout fishery of substantial 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 Bull Shoals 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 Bull Shoals 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 4.6 cubic meters per second (the existing minimum flow) to 22.6 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 initial water-surface elevation of 1.5 meters in Bull Shoals Lake on outflow temperatures and dissolved-oxygen concentrations.

The increased minimum flow simulation (without increasing initial water-surface elevation) increased the water temperature and dissolved-oxygen concentration in the outflow. Conversely, the increased minimum flow and increased initial water-surface elevation (1.5 meters) simulation decreased outflow water temperature and dissolved-oxygen concentration through time. However, results from both scenarios for water temperature and dissolved-oxygen concentration were within the boundaries of the error between measured and simulated water column profile values.

INTRODUCTION

Bull Shoals Lake (fig. 1) is a large, deep-storage reservoir located on the White River on the border of Arkansas and Missouri. Bull Shoals Lake dam was completed in 1951 and operated by the U.S. Army Corps of Engineers (USACE) for the purposes of flood control and hydroelectric power. In addition to aforementioned uses, the reservoir is used for fish and wildlife habitat, recreation, and water supply. The outflows from Bull Shoals Lake, and other White River reservoirs, also support a cold-water trout fishery of substantial 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 Bull Shoals 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 Bull Shoals 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 Bull Shoals Lake and the effects of increased minimum flow.

Bull Shoals Lake is the most downstream in a chain of major reservoirs on the White River mainstem. Upstream from Bull Shoals are Lake Taneycomo, Table Rock Lake, and Beaver Lake. Norfork Lake is located downstream on the North Fork River, a tributary to the White River (fig. 1). A study was conducted by the U.S. Geological Survey (USGS) in cooperation with the AGFC to characterize the hydrodynamics, temperature, and dissolved-oxygen concentrations in Bull Shoals Lake and to simulate the effect of reservoir operations on temperature and dissolved-oxygen concentrations in

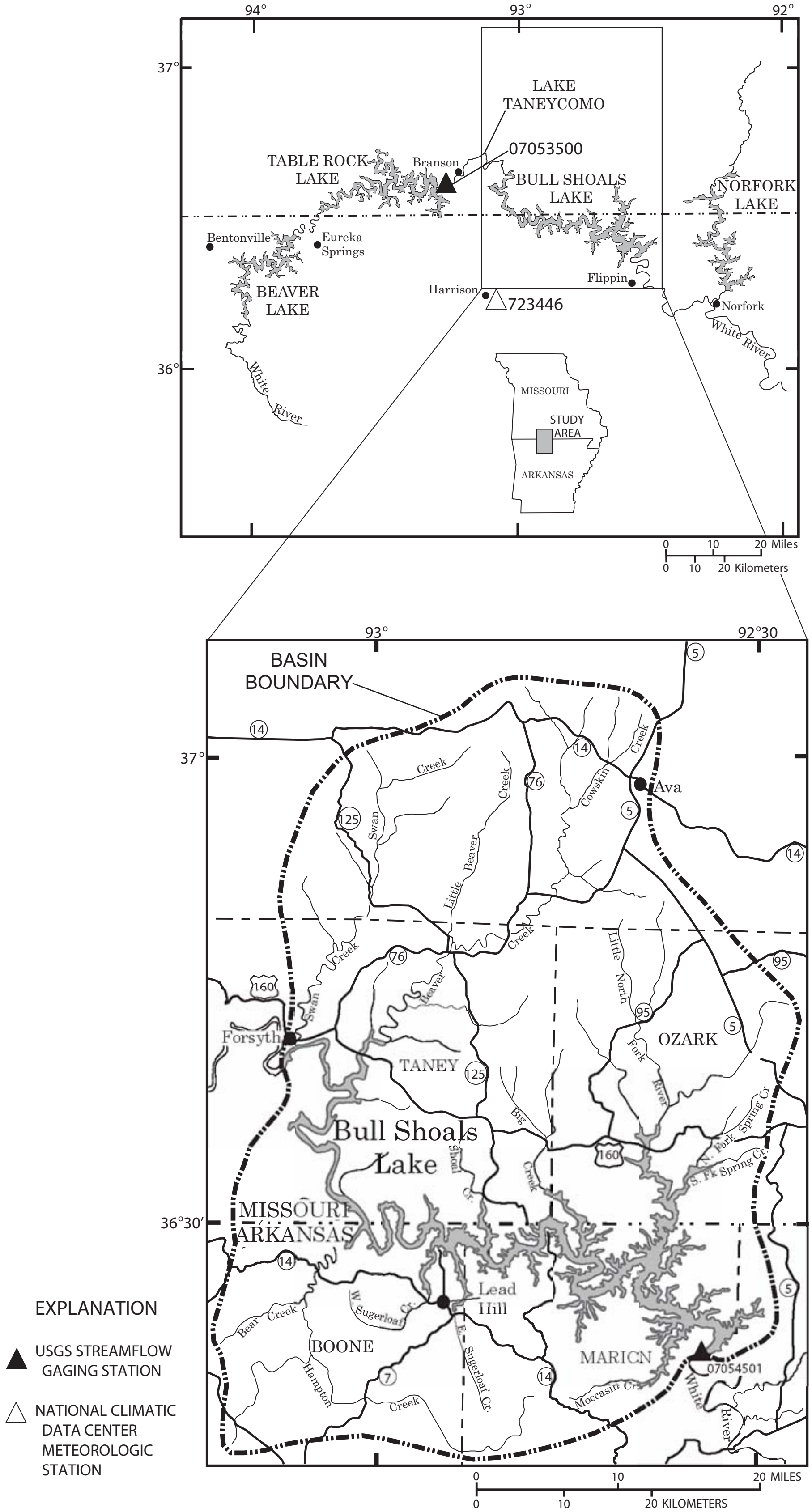


Figure 1. Location of Bull Shoals Lake and the White River Basin in Arkansas and Missouri.

the reservoir and outflow. A hydrodynamic model of Bull Shoals 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 Norfork (Galloway and Green, 2002), Table Rock, and Beaver Lakes (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 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 Bull Shoals 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

Bull Shoals Lake was impounded in 1951 on the White River, southeast of the city of Branson, Missouri. The primary inflows into Bull Shoals Lake are Little North Fork River, Beaver Creek, and the White River; several smaller tributaries also flow into the reservoir (fig. 1). The watershed has a drainage area of 15,675 km^2 at the Bull Shoals Lake dam. Bull Shoals Lake contains 4,194 million m^3 of water at the elevation of the current conservation pool (199.3 m above NGVD of 1929) and the surface area is 184 km^2. The length of the reservoir is 130 km from the Lake Taneycomo dam to the Bull Shoals Lake dam. The depth of the reservoir at the dam at conservation pool elevation is about 63 m, and the average depth through the reservoir is 23 m. On average, the hydraulic retention time of Bull Shoals Lake is about 0.75 year (Green, 1996).

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 BULL SHOALS LAKE

A two-dimensional, laterally averaged, hydrodynamic, temperature, and dissolved-oxygen model using CE-QUAL-W2 was developed for Bull Shoals Lake and calibrated based on hydrologic records and vertical profiles of temperature and dissolved oxygen measured near the Bull Shoals 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 Bull Shoals 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 (fig. 2) that numerically represents the space and volume of the reservoir. The model extends 130 km from the upstream boundary (Lake Taneycomo dam) to the downstream boundary (Bull Shoals 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). Sixty-two computational segments exist along the mainstem of the White River in Bull Shoals Lake, whereas, 10 segments are in the Little North Fork River and 4 segments are in the Big Creek and Shoal Creek branches. In addition, five other embayments (branches), including Bear Creek, West Sugarloaf Creek, East Sugarloaf Creek, Spring Creek, and Moccasin 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.

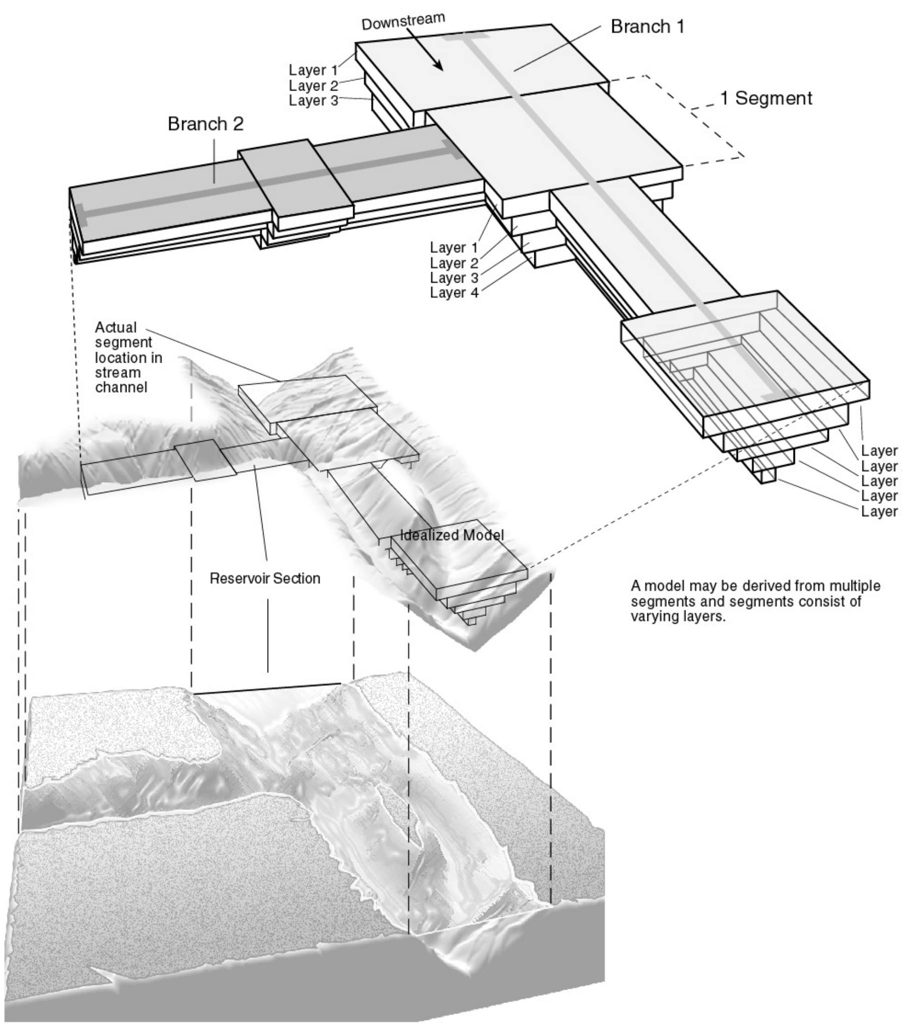


Figure 2. Idealized model segments, layers, and branches for the CE-QUAL-W2 reservoir model.

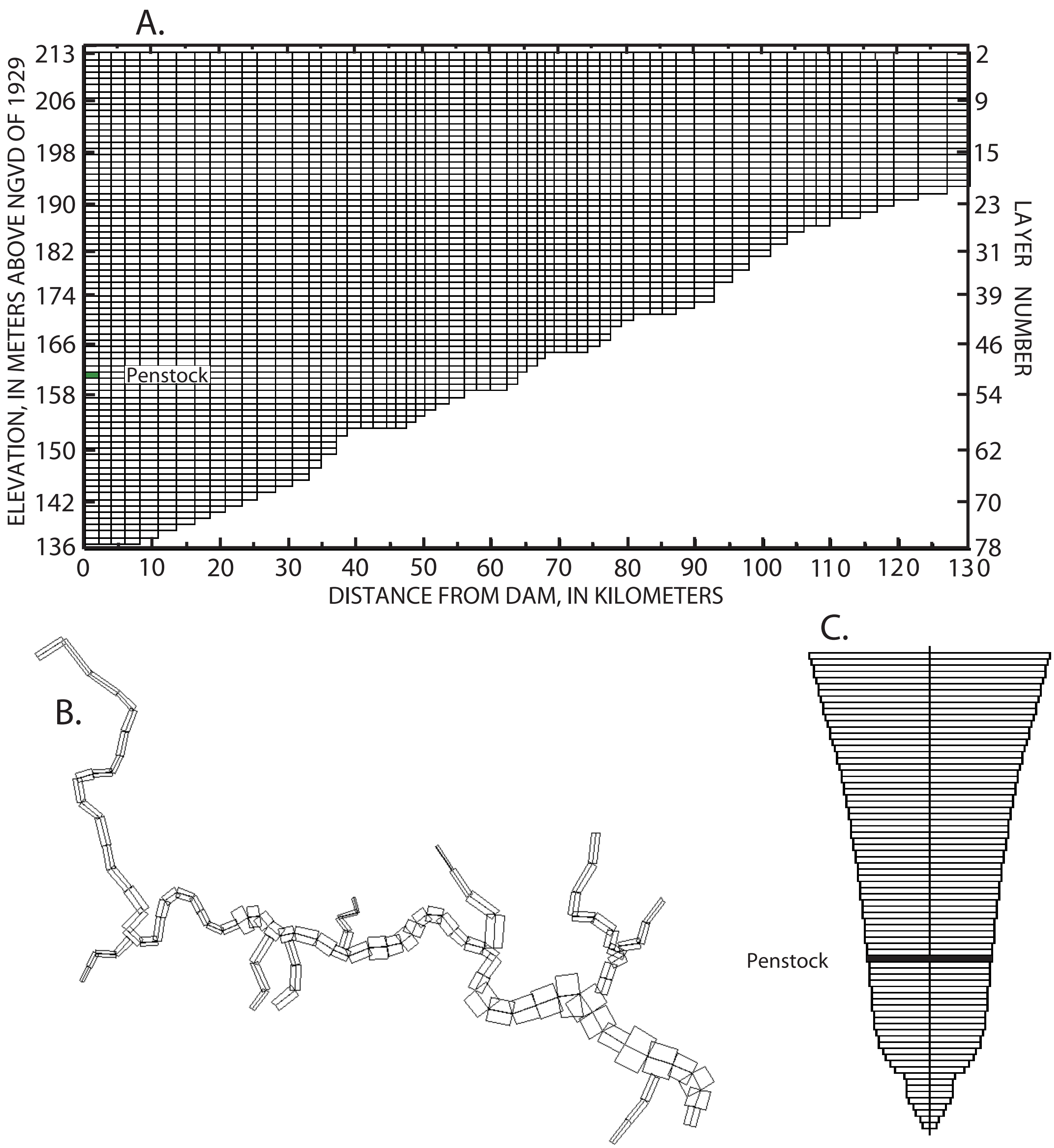


Figure 3. Side view (A), top view (B), and face view from the dam (C) of the computational grid of Bull Shoals Lake used in CE-QUAL-W2.

Segment geometry varied along the upstream-downstream gradient (fig. 3). Segment length was based in part on segment width. Segments ranged in length from 1,208 to 4,446 m, and orientation of the longitudinal axis relative to north was determined for each segment. Segment widths at the reservoir surface ranged from 264 m in the headwaters to more than 4,400 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 19 m at the upstream boundary to 76 m near Bull Shoals Lake dam. Relations between water-surface elevation and volume and surface area in the Bull Shoals Lake model grid were similar to USACE preimpoundment data (U.S. Army Corps of Engineers, 1960) (fig. 4).

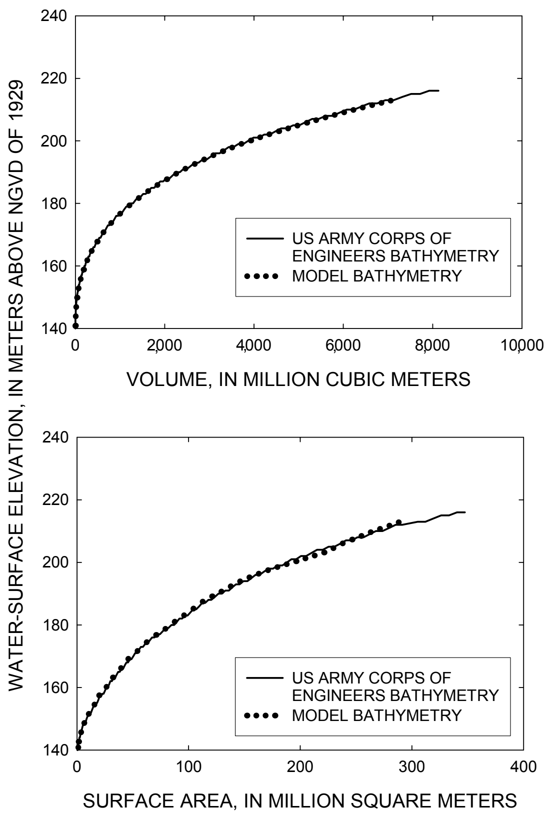


Figure 4. Relation between water-surface elevation and volume and water-surface elevation and surface area in Bull Shoals Lake.

Boundary and Initial Conditions

Hydraulic, thermal, and chemical boundary conditions are required in CE-QUAL-W2. The boundaries of the Bull Shoals Lake model included the reservoir bottom, the shoreline, tributary streams, the upstream boundary (Lake Taneycomo dam), the downstream boundary (Bull Shoals Lake dam), and the water-surface elevation of the reservoir. Initial water-surface elevation of the reservoir, water temperature, and selected water-quality 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 resistance 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 7.0 °C was used in the Bull Shoals 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-surface elevation.

Table 1. Hydraulic and thermal input parameters specified for Bull Shoals 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	7.0 °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 Branson, Missouri (station number 07053500; fig. 1), on the White River indicates that inflow to Bull Shoals Lake during the 1994 and 1995 modeling time period was above average (fig. 5). Annual mean streamflow for the White River from 1952 through 1995 ranged from 23.7 to 234.7 m^3/s. The average annual mean streamflow for this time period was 110.4 m^3/s. Annual mean streamflow for the 1994 and 1995 modeling time period was 149.3 and 149.0 m^3/s, respectively (Reed and others, 1995; Hauck and others, 1996, 1997).

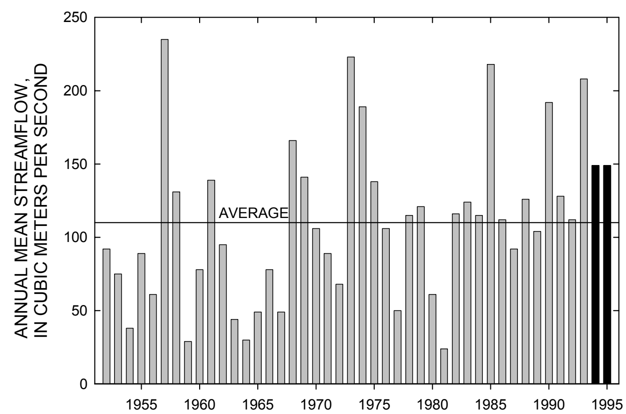


Figure 5. Annual mean streamflow for the White River near Branson, Missouri, upstream from Bull Shoals Lake, 1952-1995.

Daily reservoir inflows used in the model (fig. 6) were calculated by the USACE (John Kielczewski, U.S. Army Corps of Engineers, written commun., 1999) based on daily average outflows and changes in reservoir water-surface elevations. The daily inflow was distributed into one major branch (White River) and eight minor branches according to drainage area Daily reservoir inflows used in the model (fig. 6) were calculated by the USACE (John Kielczewski, U.S. Army Corps of Engineers, written commun., 1999) based on daily average outflows and changes in reservoir water-surface elevations. The daily inflow was distributed into one major branch (White River) and eight minor branches according to drainage area size. Approximately 70 percent of the inflow was distributed to the White River, 23 percent was evenly distributed along the reservoir shoreline, and 7 percent was distributed among the eight smaller branches. Total mean reservoir inflow from January 1, 1994, through December 31, 1995, was estimated to be 208.7 m^3/s, whereas, the estimated median reservoir inflow for the same period was 162.4 m^3/s. The estimated reservoir inflow exceeded 514 m^3/s 10 percent of the time.

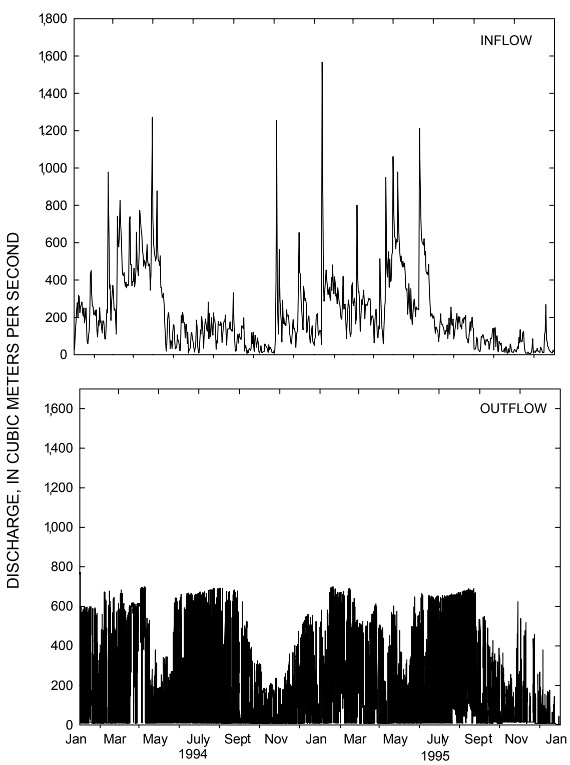


Figure 6. Daily inflow (top) and hourly outflow (bottom) for Bull Shoals Lake, January 1994 through December 1995. Inflow and outflow data provided by the U.S. Army Corps of Engineers.

The downstream boundary for the Bull Shoals Lake model consists of the outflow from Bull Shoals Lake dam. Hourly outflow data (fig. 6) were calculated by the USACE (John Kielczewski, U.S. Army Corps of Engineers, written commun., 1999) using stage-discharge relations and hourly power generation records. The mean and median reservoir outflow for the modeling period (January 1994 to December 1995) was 210.6 and 126.6 m^3/s, respectively. The reservoir outflow exceeded 597 m^3/s 10 percent of the time for the modeling period. The vertical extent and distribution of flow in the release zone near the Bull Shoals 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 163 m above NGVD of 1929, model layer 51 (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; fig. 1), 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 segments. 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 Bull Shoals 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 dataset, 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 Bull Shoals 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 for all tributaries and branches included dissolved oxygen, ammonia as nitrogen, nitrite plus nitrate as nitrogen, total phosphorus, and a conservative tracer concentrations. Because of the small amount of available water-quality data, annual average concentrations were estimated based on similar values reported from the White River 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 NGVD of 1929, 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 Bull Shoals 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 (table 1). Other parameters such as Chezy resistance, bottom-water heat exchange, bottom temperature, and wind-sheltering coefficients were discussed previously (table 1). 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.

Sixty-one chemical and biological 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 Bull Shoals Lake model

[m, meters; *, dimensionless; d, day; Q_{10}, temperature correction factor; m/d, meters per 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	0.24/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	0.24*
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	1.5/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 ^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	15.0^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	35.0 ^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

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

[m, meters; *, dimensionless; d, day; Q_{10}, temperature correction factor; m/d, meters per 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
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	0.2*
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 ^{o}C
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 ^{o}C
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 ^{o}C
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 ^{o}C
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	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	0.1 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. Bull Shoals 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 $\pm$ 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:

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

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

Hydrodynamics and Temperature

Simulated water-surface elevations in Bull Shoals Lake were adjusted to the measured water surface for the model period January 1994 to December 1995 (fig. 7). The water-surface elevations were corrected to the measured values by adjusting the unmeasured inflow into the lake that was distributed to all the segments within a branch. Inflow was either added or subtracted so that the simulated water-surface elevation reflected the measured water-surface elevation. By correcting the distributed inflow, the thermodynamics could be calibrated without the uncertainty incurred with having differences between simulated and measured elevations.

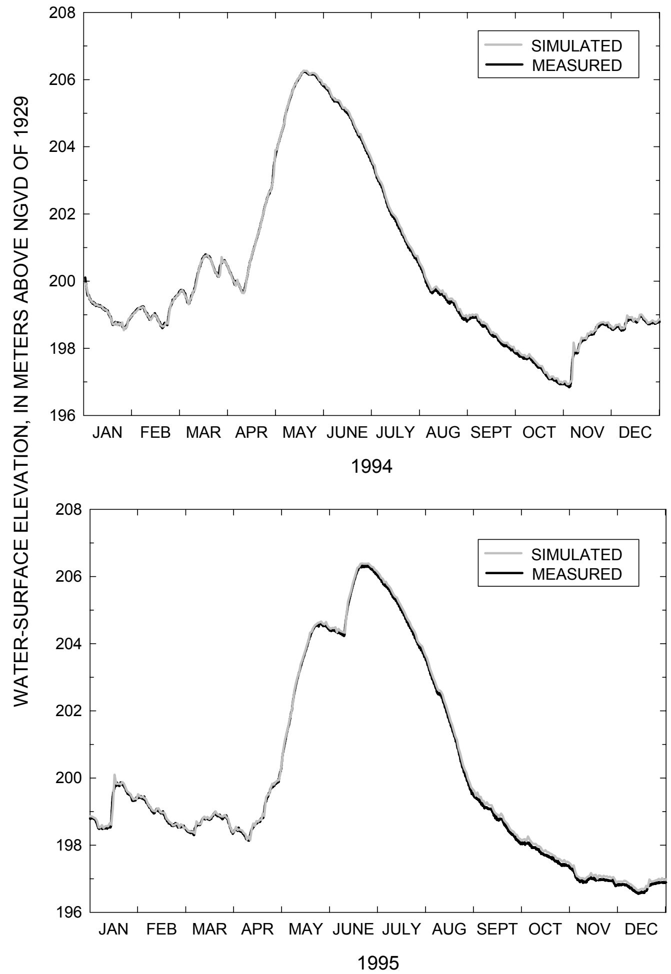


Figure 7. Simulated and measured water-surface elevations near the Bull Shoals Lake dam, January through December 1994 and January through December 1995.

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, and 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.

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 Bull Shoals Lake dam during June through November in 1994 and 1995.

All simulated water temperatures (711) in 1994 were compared with corresponding measured temperatures near the Bull Shoals Lake dam (Evans and others, 1995; Porter and others, 1996). 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 5.7 to 28.0 °C, whereas measured water temperatures ranged from 5.9 to 28.4 °C. Simulated water temperatures in the vertical profile generally (79 percent) were within 1 °C of measured temperatures. The AME and RMSE between simulated and measured water temperature were 0.67 and 0.89 °C, respectively. The difference between simulated and measured temperature ranged from -2.2 to 4.0 °C, and the average and median differences both were -0.2 °C.

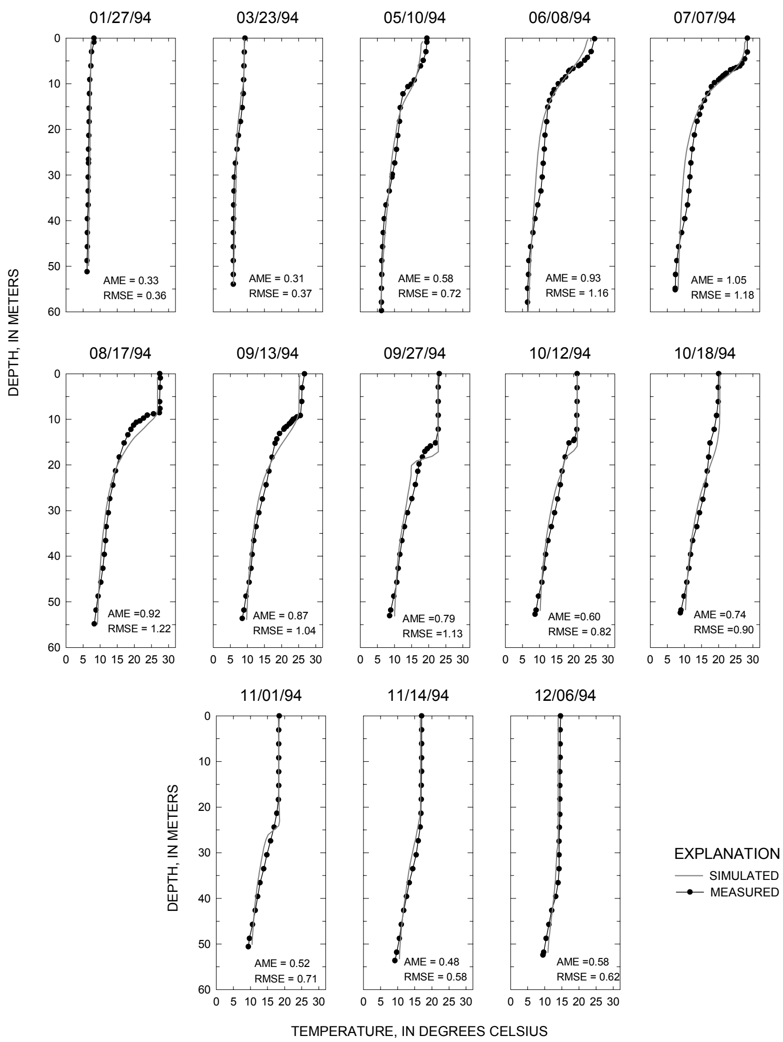


Figure 8. Relation between simulated and measured water temperatures in the water column near the Bull Shoals Lake dam, January through December 1994.

Although the calibrated model closely simulated water temperature near the Bull Shoals Lake dam in 1994, with most simulated temperatures within 1° C of the measured temperatures, the accuracy and precision of simulated temperatures varied with temperature, season, and depth (fig. 9). Simulated water temperatures were less than measured temperatures more often when measured temperatures were less than 17 °C. Conversely, simulated water temperatures were greater than measured temperatures more often when measured temperatures were greater than approximately 17 °C. Error in simulated water temperatures was greater during the thermal stratification season (May through November). Simulated temperatures generally were less than measured temperatures at all depths, except between depths of 46 to 54 meters where simulated temperatures tended to be greater than measured temperatures.

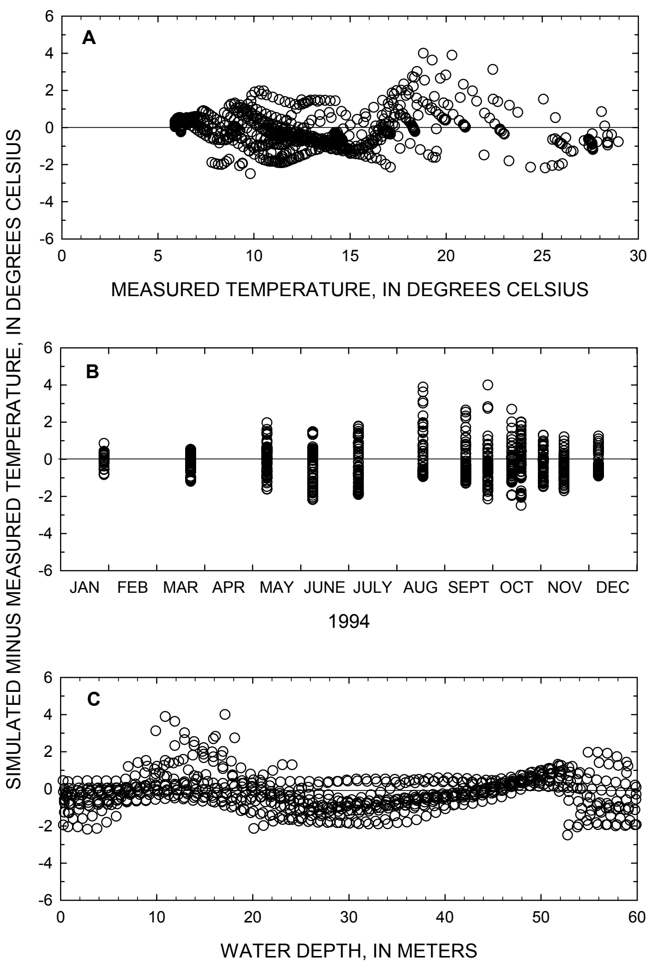


Figure 9. Relation of difference between simulated and measured water temperatures near the Bull Shoals Lake dam to (A) measured water temperature, (B) sampling date, and (C) water depth, January through December 1994.

All simulated temperatures (654) in 1995 were compared with corresponding measured temperatures (Porter and others, 1996; 1997) (fig. 10). Simulated water temperatures ranged from 5.8 to 29.1 °C, whereas measured water temperatures ranged from 6.7 to 30.5 °C. Simulated water temperatures generally (58 percent) were within 1° C of measured temperatures. The AME and RMSE between simulated and measured water temperature were 0.94 and 1.13 °C, respectively. The difference between simulated and measured temperatures ranged from -2.4 to 4.0 °C, and the average and median differences were -0.4 and -0.6 °C, respectively.

Simulated water temperatures were similar to measured temperatures in 1995 (fig. 11). Simulated water temperatures during 1995 were less than measured temperatures more often when measured temperatures were less than 18 °C, and were greater than measured temperatures when temperatures were greater than 18 °C. From January 1995 through the stratification season (May to November), simulated water temperatures generally were less than measured water temperatures. Near the end of the stratification season, simulated water temperatures were greater than measured water temperatures. Simulated water temperatures generally were less than measured temperatures below depths of 20 m 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 Bull Shoals 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 Bull Shoals Lake.

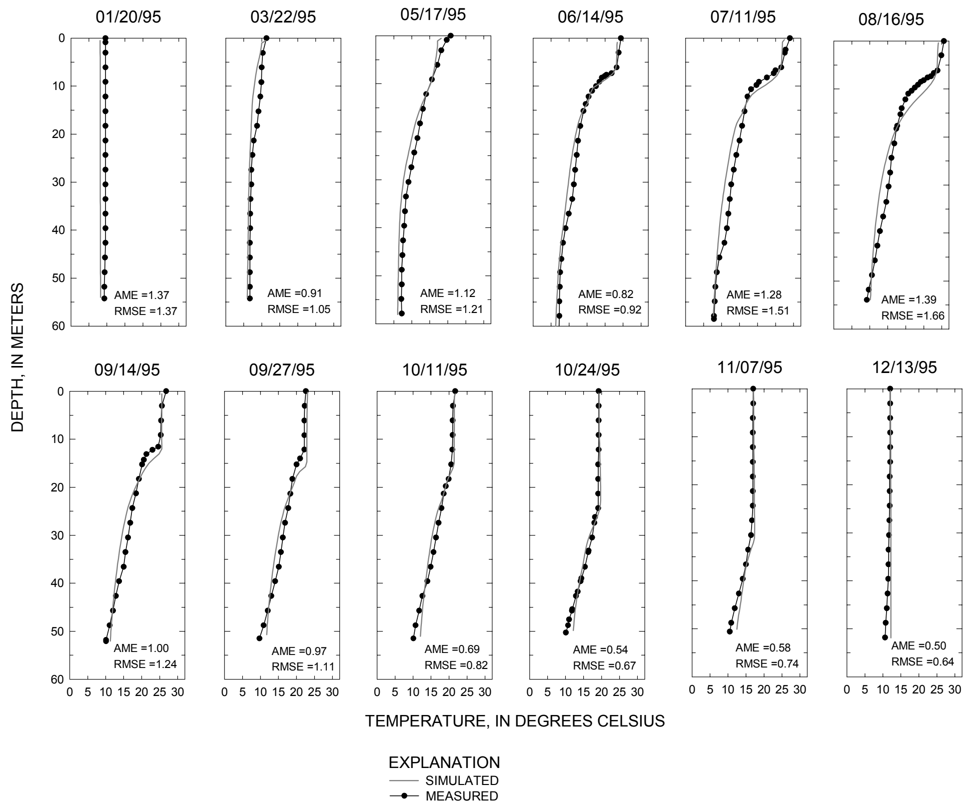


Figure 10. Relation between simulated and measured water temperatures in the water column near the Bull Shoals Lake dam, January through December 1995.

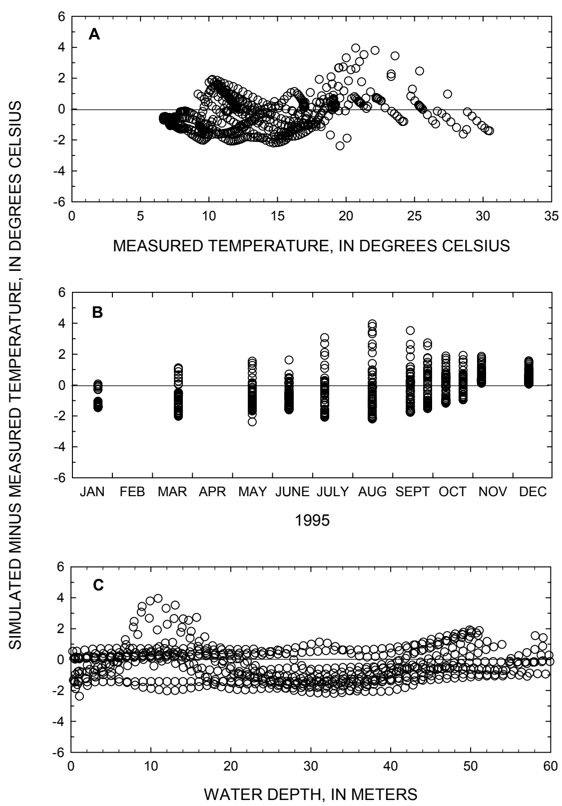


Figure 11. Relation of difference between simulated and measured water temperatures near the Bull Shoals Lake dam to (A) measured water temperature, (B) sampling date, and (C) water depth, January through December 1995.

Simulated dissolved-oxygen concentrations near the Bull Shoals Lake dam exhibited the same general patterns and magnitudes as measured concentrations (fig. 12). All simulated dissolved-oxygen concentrations (711) for 1994 were compared to corresponding measured concentrations (Evans and others, 1995; Porter and others, 1996). Simulated dissolved-oxygen concentrations ranged from 0.0 to 11.4 mg/L, whereas, measured dissolved-oxygen concentrations ranged from 0.1 to 11.1 mg/L. Simulated dissolved-oxygen concentrations in the vertical profile generally (61 percent) were within 1 mg/L of measured concentrations. The AME and RMSE between simulated and measured dissolved-oxygen concentrations were 1.13 and 1.71 mg/L, respectively. The difference between simulated and measured concentrations ranged from -8.6 to 7.6 mg/L, and the average and median differences were -0.2 and -0.1 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 concentrations less than 5 mg/L and greater than measured values at concentrations greater than 5 mg/L. Errors in simulated dissolved-oxygen concentration were greater near the end of the thermal stratification season (September-November) and during turnover (December). Simulated dissolved oxygen concentrations generally were less than measured concentrations at all depths.

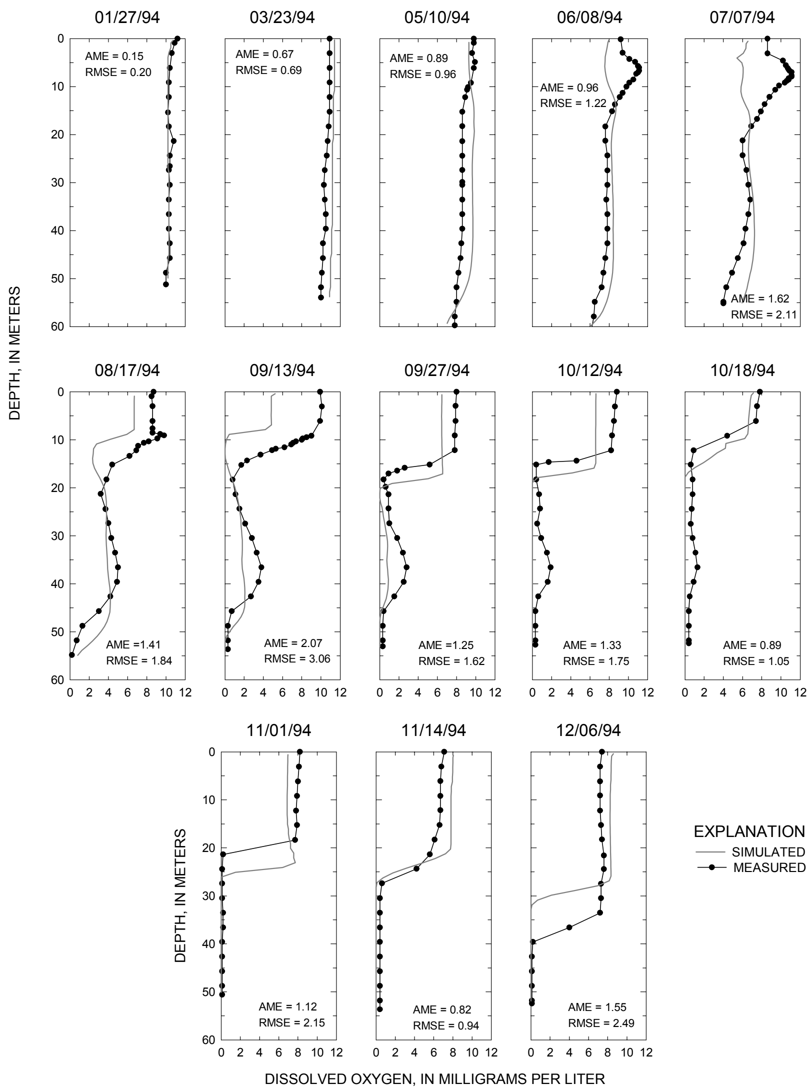


Figure 12. Relation between simulated and measured dissolved-oxygen concentrations in the water column near the Bull Shoals Lake dam, January through December 1994.

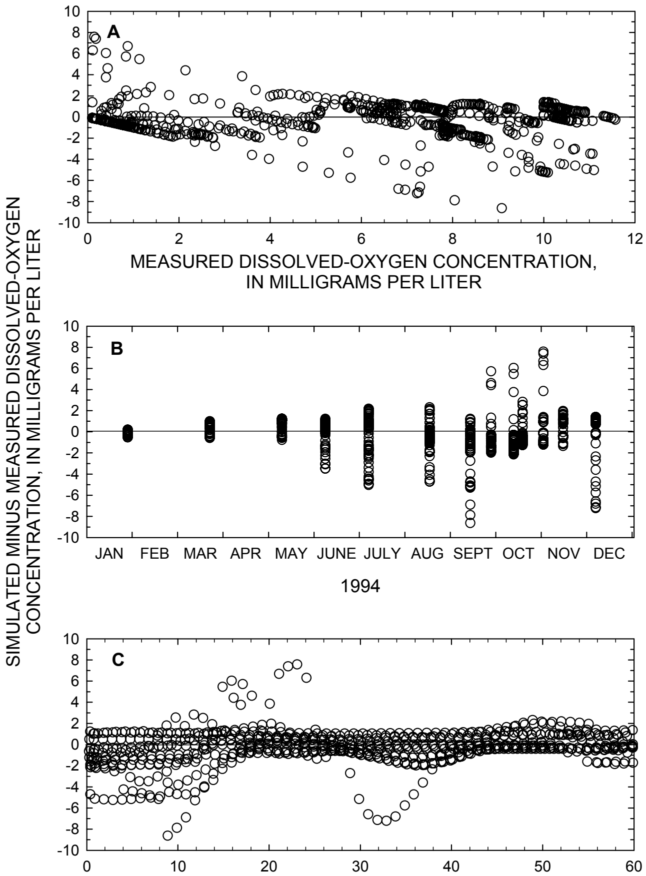


Figure 13. Relation of difference between simulated and measured dissolved-oxygen concentrations near Bull Shoals Lake dam to (A) measured dissolved-oxygen concentrations, (B) sampling date, and (C) water depth, January through December 1994.

Simulated dissolved-oxygen concentrations were similar to measured dissolved-oxygen concentrations in 1995 (fig. 14), but differences were somewhat less 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 (654) were compared with corresponding measured concentrations near the Bull Shoals Lake dam (Porter and others, 1996, 1997). Simulated values ranged from 0.0 to 11.1 mg/L whereas, measured dissolved-oxygen concentrations ranged from 0.0 to 13.1 mg/L. Simulated dissolved-oxygen concentrations in the vertical profile generally (67 percent) were within 1 mg/L of measured concentrations. The AME and RMSE between simulated and measured dissolved-oxygen concentrations were 0.94 and 1.37, respectively. The difference between simulated and measured dissolved-oxygen concentrations ranged from -6.9 to 6.7 mg/L, and the average and median differences were -0.2 and -0.1 mg/L, respectively.

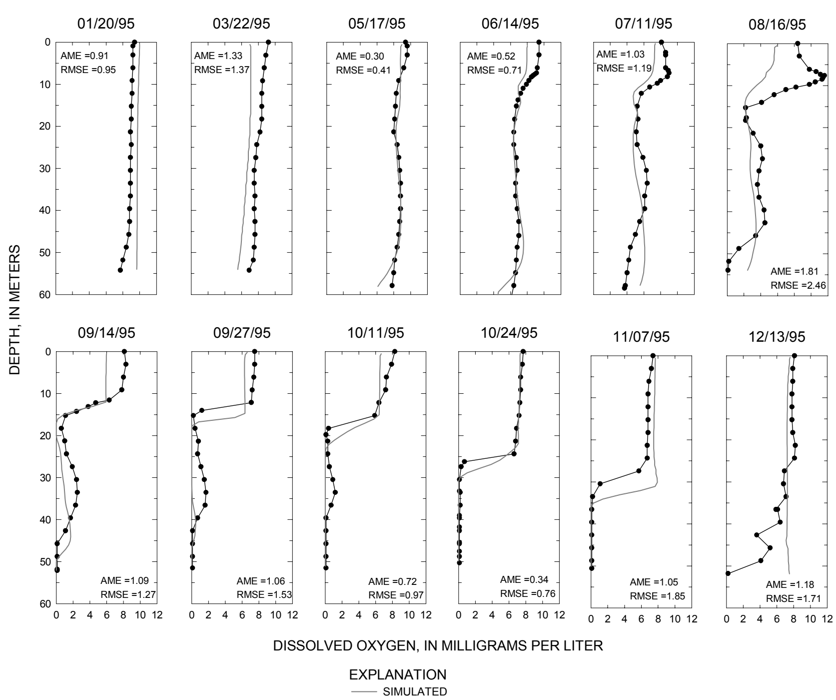


Figure 14. Relation between simulated and measured dissolved-oxygen concentrations in the water column near the Bull Shoals Lake dam, January through December 1995.

On average, simulated dissolved-oxygen concentrations in 1995 were less than measured concentrations (fig. 15). Simulated dissolved-oxygen concentrations were less than measured concentrations through most of the stratification season. Near the end of the stratification season and during turnover, simulated concentrations were typically greater than measured concentrations. Simulated dissolved-oxygen concentrations often were less than measured concentrations near the water surface and greater than measured concentrations near the lake bottom. Despite these tendencies, simulation of dissolved-oxygen concentration in the vertical profile near the Bull Shoals Lake dam followed the same general patterns as measured concentrations.

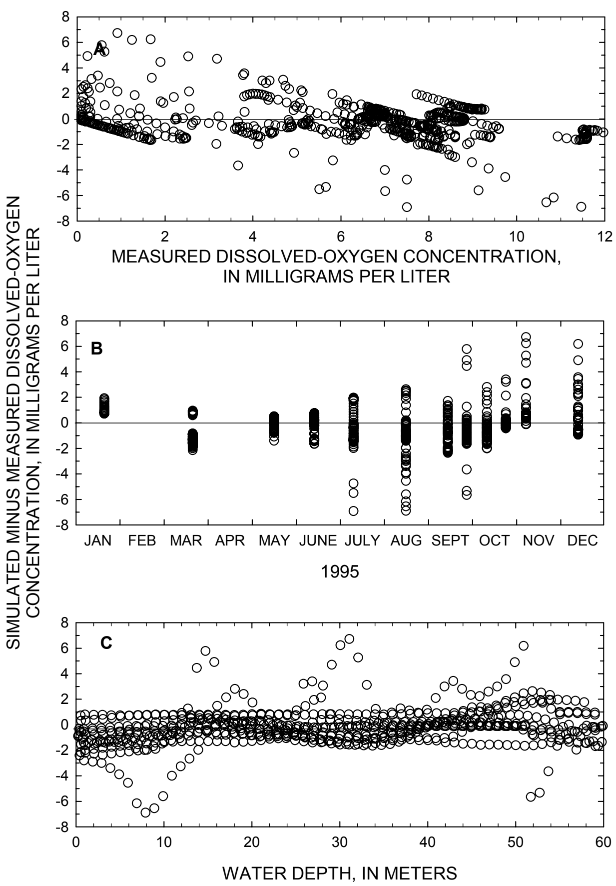


Figure 15. Relation of difference between simulated and measured dissolved-oxygen concentrations near Bull Shoals Lake dam to (A) measured dissolved-oxygen concentrations, (B) sampling date, and (C) water depth, January through December 1995.

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 Bull Shoals Lake model was not conducted because the Bull Shoals 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 Bull Shoals Lake model was most sensitive to changes in the WSC, α, and inflow water temperature (fig. 16). Wind speed in the calibrated Bull Shoals 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. During thermal stratification, more vertical mixing was simulated when the WSC was increased (1.0) and less vertical mixing was simulated 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 also affected vertical water temperature profiles near the dam during stratification. Surface-water temperatures were not impacted as much by changes in inflow water temperatures as was the position of the thermocline and hypolimnetic temperatures. 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 Bull Shoals Lake near the dam.

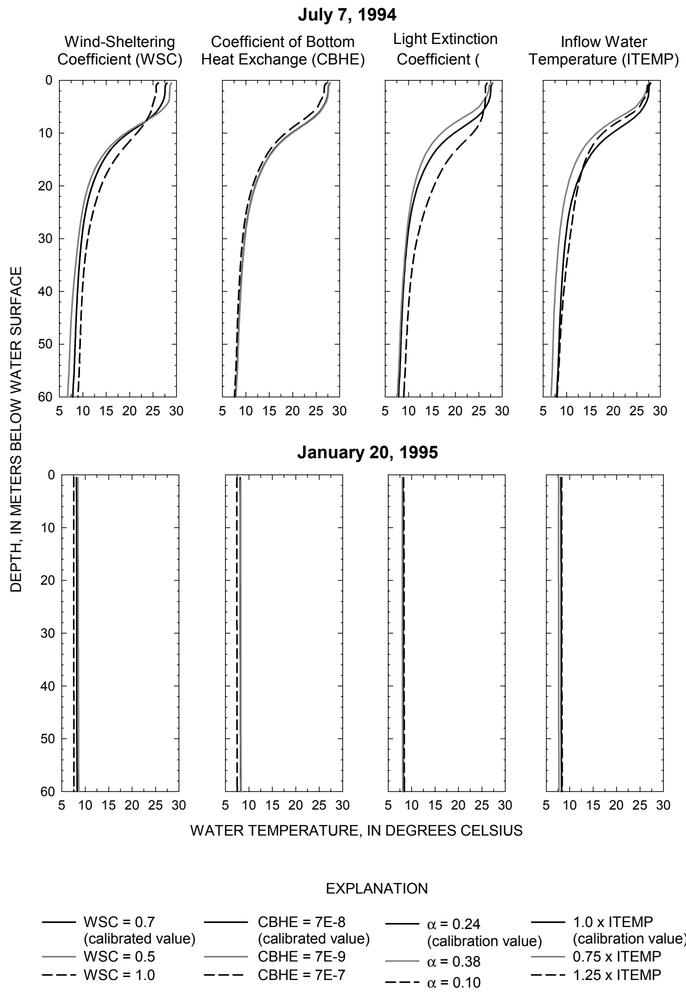


Figure 16. Vertical temperature distributions near the Bull Shoals Lake dam on July 7, 1994 (top), and January 20, 1995 (bottom), showing calibrated model profiles and profiles as a result of differing model parameters.

In the Bull Shoals Lake model, dissolved-oxygen concentrations were most affected by changes in the WSC 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. Changes in α and inflow dissolved-oxygen concentrations had little effect on vertical distribution of dissolved oxygen near the dam.

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 Bull Shoals Lake dam.

Model Applications

The calibrated Bull Shoals 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 Bull Shoals Lake outflow waters. Two scenarios were simulated, including (1) an increase in the outflow of Bull Shoals Lake dam from the existing minimum flow of 4.6 m^3/s to 22.6 m^3/s, and (2) an increase in water-surface elevation of Bull Shoals Lake of 1. 5 m to correct for the volume displaced by the additional minimum flow.

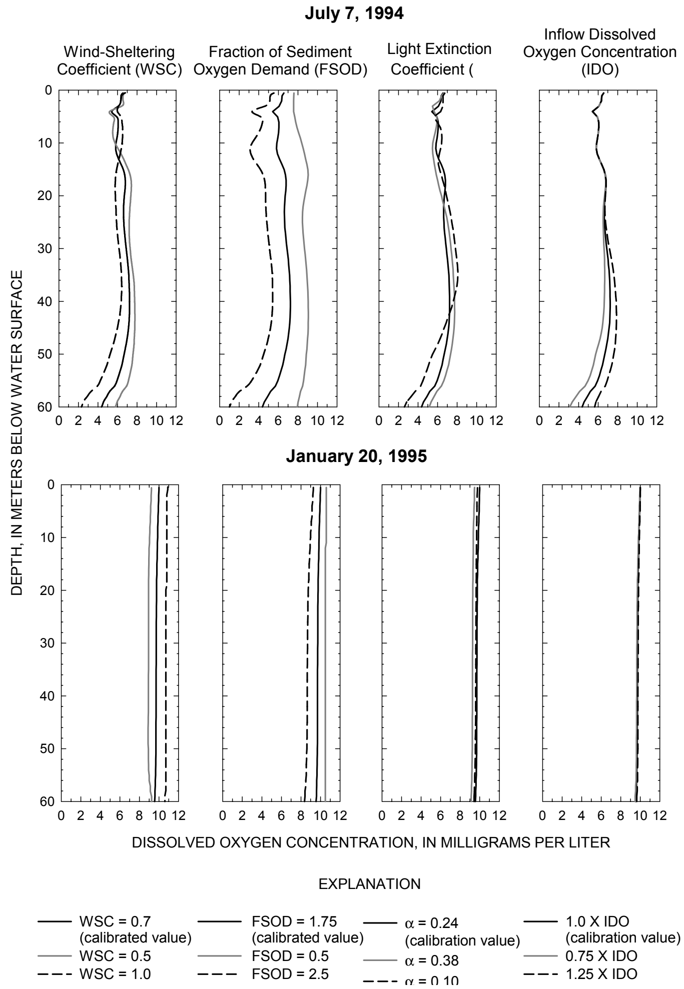


Figure 17. Vertical dissolved-oxygen concentration distributions near the Bull Shoals Lake dam on July 7, 1994 (top), and January 20, 1995 (bottom), showing calibrated model profiles and profiles as a result of differing model parameters.

When 22.6 m^3/s was applied as the minimum amount of outflow (increased minimum flow scenario), mean annual outflow increased from 210.6 to 215.1 m^3/s, about a 2 percent increase. Approximately 37 percent of the hourly outflow data required an increase to 22.6 m^3/s. Average annual outflow increased from 6,641 to 6,782 million m^3, which is equivalent to 141 million m^3 per year increase, or about 3.4 percent of reservoir volume at conservation pool elevation. The water-surface elevation at the end of 1994 was reduced 0.79 m and at the end of 1995 was reduced about 1.5 m (figs. 18 and 19) from the initial elevation on January 1, 1994 (168.79 m). When 1.5 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 0.77 m greater than the calibrated model without the increased minimum flow and by the end of 1995 only 0.04 m greater than the calibrated model (fig. 19).

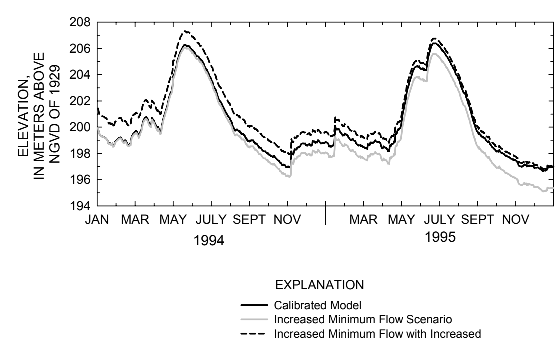


Figure 18. Simulated water-surface elevations resulting from increased minimum flow scenarios.

Simulated temperature in the outflow water differed little between 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 3.03 °C and between the increased minimum flow with increased water-surface elevation and the calibrated model was 1.03 °C. The maximum temperature differences occurred at the end of the stratification season in November 1994 and 1995. This could be attributed to the difference in the timing of turnover, when the lake goes from a stratified condition to a well-mixed condition. Turnover occurs within a short time period and the timing could be affected by the difference in flow conditions from the calibrated model to the minimum flow scenarios. Overall, 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 07054501) (fig. 21). Water temperature in the dam outflow increased slightly (less than 0.2 °C, on average) with increased minimum flow. Conversely, with the increase in water-surface elevation plus the increased minimum flow, water temperature in the dam outflow decreased slightly (less than 0.1 °C, on average) through time during the stratification season.

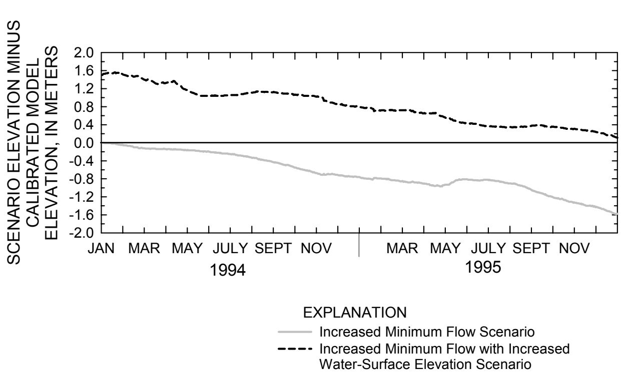


Figure 19. Relation of difference between water-surface elevations predicted from increased minimum flow scenarios and calibrated model water-surface elevation with time.

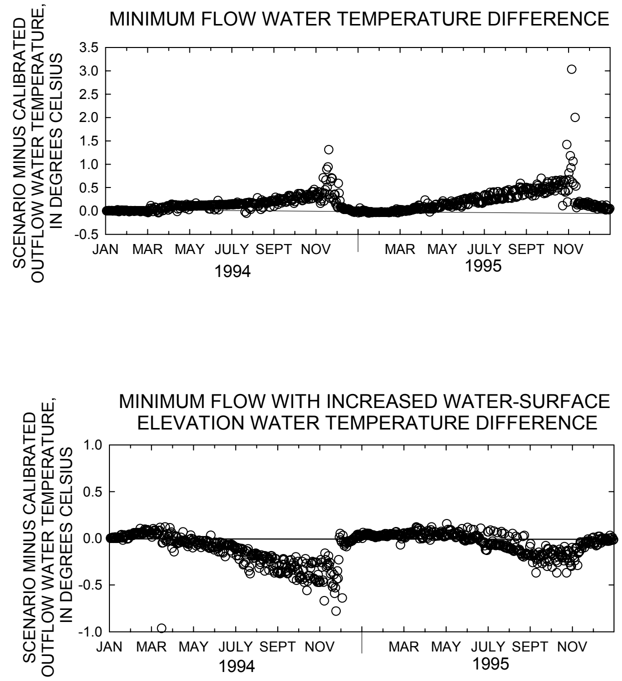


Figure 20. Simulated water temperature differences between increased minimum flow scenarios and the calibrated model.

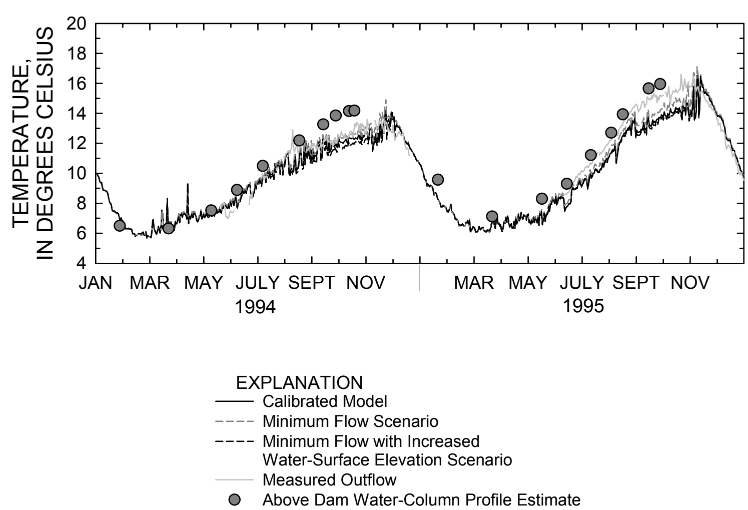
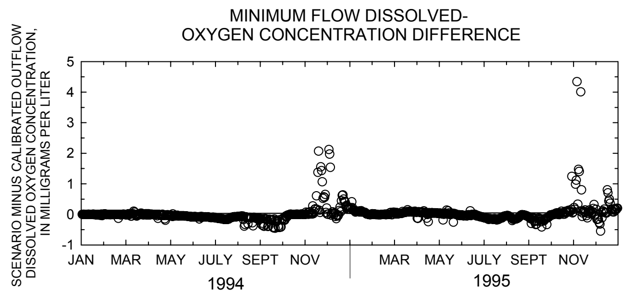


Figure 21. Simulated and estimated water temperatures in Bull Shoals Lake outflow and measured temperatures downstream from Bull Shoals Lake dam.

Simulated dissolved-oxygen concentrations in the outflow water differed little between 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 4.34 mg/L and between the increased minimum flow with increased water-surface elevation and the calibrated model was 2.02 mg/L. The maximum dissolved-oxygen concentration differences occurred at the end of the stratification season in November 1994 and 1995. The differences could be attributed to the difference in timing of the turnover, caused by the changes in flow condition from the calibrated model to the minimum flow scenarios. Overall, dissolved-oxygen concentration differences for both scenarios generally 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) (fig. 23). Simulated dissolved-oxygen concentrations in the dam outflow increased slightly with the addition of increased minimum flow (less than 0.05 mg/L, on average). Conversely, with the increase in water-surface elevation and the increased minimum flow, simulated dissolved-oxygen concentrations in the dam outflow decreased slightly (less than -0.05 mg/L, on average) during the simulation period.

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 concentrations determined for model calibration.



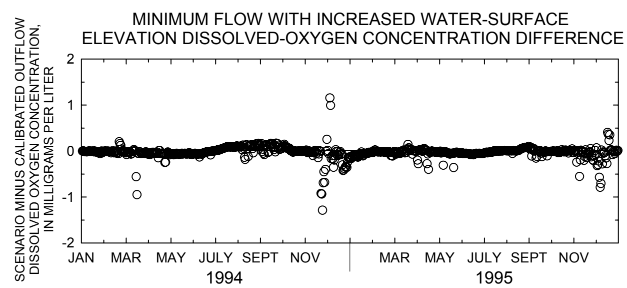


Figure 22. Simulated dissolved-oxygen concentration differences between increased minimum flow scenarios and calibrated model.

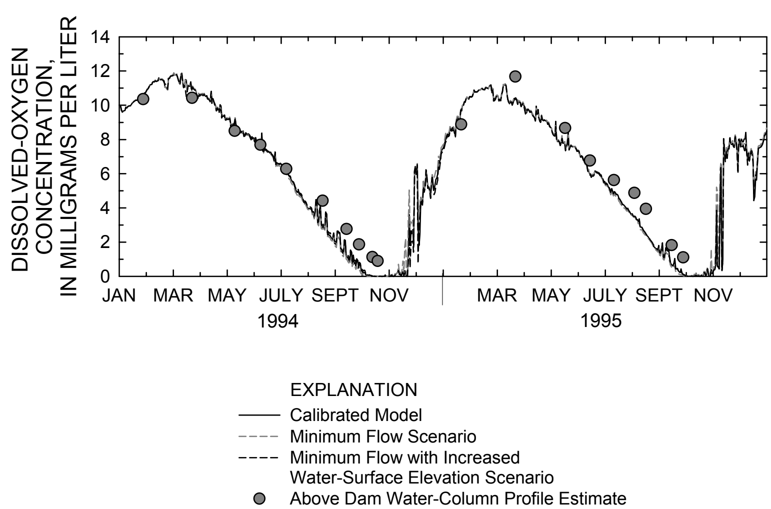


Figure 23. Simulated and estimated dissolved-oxygen concentrations in Bull Shoals Lake outflows.

SUMMARY

Outflow from Bull Shoals Lake and other White River reservoirs support a cold-water trout fishery of substantial 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 Bull Shoals 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. 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 Bull Shoals 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 Bull Shoals Lake, Arkansas. The model was calibrated using hydrologic records and vertical profiles of temperature and dissolved oxygen measured in or near Bull Shoals Lake from January 1994 through December 1995. The model simulates water-surface elevation, water temperature, and dissolved-oxygen concentration. The model simulated temperatures generally within 1 °C of the measured temperatures. The AME and RMSE between simulated and measured water temperature for 1994 were 0.67 and 0.89, respectively, and for 1995 were 0.94 and 1.13, respectively. The model simulated dissolved-oxygen concentrations generally within 1 mg/L of the measured concentrations. The AME and RMSE between simulated and measured dissolved-oxygen concentrations for 1994 were 1.13 and 1.71, respectively, and for 1995 were 0.94 and 1.37, respectively.

The Bull Shoals Lake model was developed to assess the impacts of proposed increases in minimum flows from 4.6 m^3/s (the existing minimum flow) to 22.6 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 1.5 m greater than the initial water-surface elevation on outflow temperatures and dissolved-oxygen concentrations. With the increased minimum flow, water temperatures and dissolved oxygen concentrations increased in the outflow. Conversely, increased minimum flow with increased water-surface elevation decreased the outflow water temperature and dissolved-oxygen concentrations. However, these results were within the boundaries of the error between simulated and measured water temperature and dissolved-oxygen concentrations for the calibrated model.

This model provides the basis and framework for future water-quality modeling of Bull Shoals 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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