Prepared in cooperation with the

**Arkansas Game and Fish Commission,** the **Arkansas Soil and Water Conservation Commission** and the **Beaver Water District**

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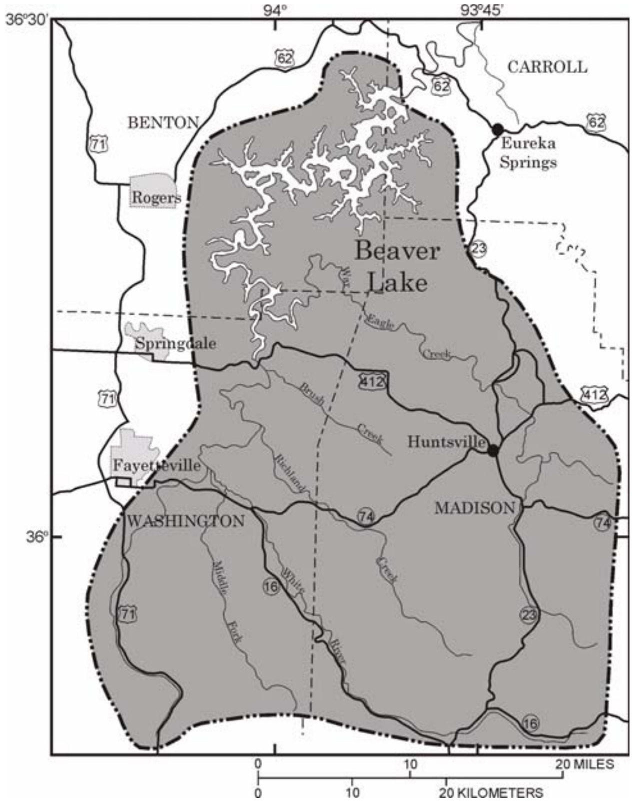
# SIMULATION OF HYDRODYNAMICS, TEMPERATURE, AND DISSOLVED OXYGEN IN BEAVER LAKE, ARKANSAS, 1994-1995

## Water-Resources Investigations Report 02-4116




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

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

Brian E. Haggard and W. Reed Green

**U.S. GEOLOGICAL SURVEY**
**Water-Resources Investigations Report 02-4116**

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**Arkansas Game and Fish Commission,** the **Arkansas Soil and Water Conservation Commission,** and the **Beaver Water District**

Little Rock, Arkansas
2002

**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 |
| 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)

**Water Year:** October 1 through September 30

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

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

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

By Brian E. Haggard and W. Reed Green


## ABSTRACT

The tailwaters of Beaver Lake and other White River reservoirs support a cold-water trout fishery of significant economic yield in northwestern Arkansas. The Arkansas Game and Fish Commission has requested an increase in existing minimum flows through the Beaver Lake dam to increase the amount of fishable waters downstream. Information is needed to assess the impact of additional minimum flows on temperature and dissolved-oxygen qualities of reservoir water above the dam and the release water.

A two-dimensional, laterally averaged hydrodynamic, thermal and dissolved-oxygen model was developed and calibrated for Beaver Lake, Arkansas. The model simulates surface-water elevation, currents, heat transport and dissolved-oxygen dynamics. The model was developed to assess the impacts of proposed increases in minimum flows from 1.76 cubic meters per second (the existing minimum flow) to 3.85 cubic meters per second (the additional minimum flow). Simulations included assessing (1) the impact of additional minimum flows on tailwater temperature and dissolved-oxygen quality and (2) increasing initial water-surface elevation 0.5 meter and assessing the impact of additional minimum flow on tailwater temperatures and dissolved-oxygen concentrations.

The additional minimum flow simulation (without increasing initial pool elevation) appeared to increase the water temperature (<0.9 degrees Celsius) and decrease dissolved oxygen concentration (<2.2 milligrams per liter) in the outflow discharge. Conversely, the additional minimum flow plus initial increase in pool elevation (0.5 meter) simulation appeared to decrease outflow water temperature (0.5 degrees Celsius) and increase dissolved oxygen concentration (<1.2 milligrams per liter) through time. However, results from both minimum flow scenarios for both water temperature and dissolved oxygen concentration were within the boundaries or similar to the error between measured and simulated water column profile values.


## INTRODUCTION

Beaver Lake (fig. 1) is a large, deep-storage reservoir located in the White River Basin in northwestern Arkansas. This impoundment was completed in 1963 and operated by the U.S. Army Corps of Engineers (USACE) for the purposes of flood control, hydroelectric power, and water supply. Today, in addition to aforementioned uses, the reservoir is used for fish and wildlife habitat, recreation, and waste assimilation. The tailwaters of Beaver Lake, and other White River reservoirs, also support a cold-water trout fishery of significant economic yield in northwestern Arkansas. Proposed changes in reservoir operations such as increased minimum flows through the dam and increased water storage have produced concerns about the sustainability of cold water temperature and dissolved oxygen in the bottom water (hypolimnion) above the Beaver Lake dam. Increases in water temperature and decreases in dissolved oxygen could have potential impacts on the cold-water trout fisheries in the downstream tailwater. Comprehensive information is needed to address thermal and dissolved-oxygen dynamics of this reservoir and the effect of increasing minimum flow.

Beaver Lake is the most upstream and youngest in a chain of major reservoirs on the White River mainstem. Downstream from Beaver Lake are Table Rock Lake, Lake Taneycomo, and Bull Shoals Lake, and Norfork Lake is located on the North Fork River, a tributary to the White River (fig. 1). In January 2000, a study was undertaken by the U.S. Geological Survey

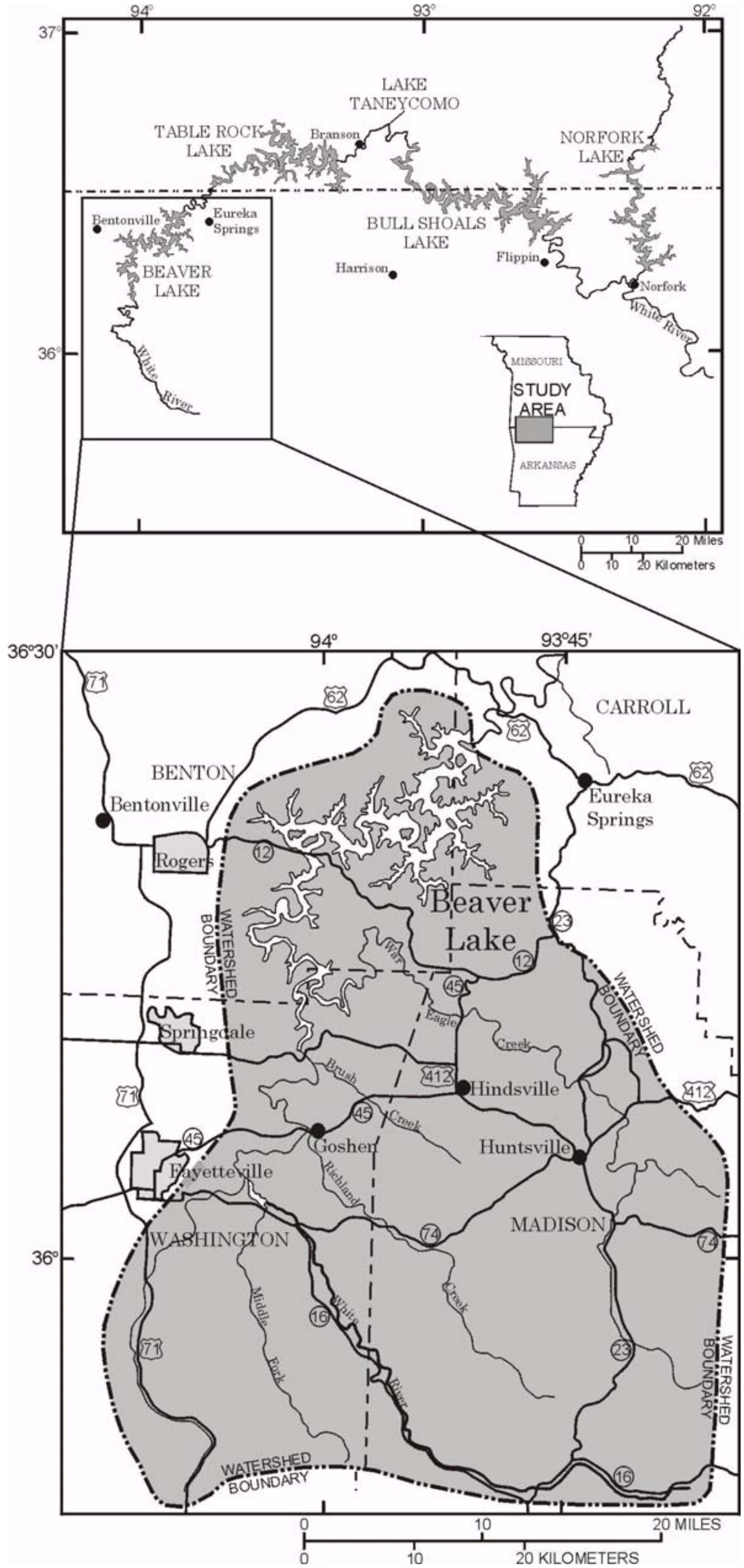


**Figure 1.** Location of Beaver Lake and the White River Basin in Arkansas and Missouri.

(USGS) in cooperation with the Arkansas Game and Fish Commission, the Arkansas Soil and Water Conservation Commission, and the Beaver Water District, to characterize the hydrodynamics, and thermal and dissolved-oxygen dynamics in Beaver Lake and to simulate the effect of reservoir operations on temperature and dissolved-oxygen qualities in the reservoir and release water. A hydrodynamic model of Beaver Lake was developed using the U.S. Army Corp of Engineers (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 releases in Table Rock, Bull Shoals, and Norfork Lakes. These studies will provide a better understanding of the hydro- and water-quality dynamics within each reservoir system. In addition, these models will provide the basis and framework for future water-quality modeling.

## Purpose

The purpose of this report is to describe a model of hydrodynamics, temperature, and dissolved oxygen in Beaver Lake, Arkansas, for the simulation period 1994 through 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

Beaver Lake was impounded in 1963 on the White River, northeast of the city of Fayetteville, Arkansas, and in 1968 the reservoir reached conservation-water supply capacity. The primary inflows into Beaver Lake are Richland Creek, War Eagle Creek and the White River; several smaller tributaries also flow into the reservoir (fig. 1). The watershed has a drainage area of 3,087 $km^2$ at the Beaver Lake dam. Beaver Lake contains 2,040 million $m^3$ of water at the top of the current conservation pool (341.4 m above sea level) and the surface area is 114 $km^2$. The length of the reservoir is 80 km from the White River at the Highway 45 bridge to the Beaver Lake dam. The depth of the reservoir at the dam at conservation pool elevation is about 60 m, and the average depth through the reservoir is 18 m. On average, the hydraulic retention time of Beaver Lake is about 1.5 years.

In addition to the purposes of flood-control and hydroelectric generation, Beaver Lake contains water allocated for drinking-water supply. Beaver Water District, the largest of four utilities withdrawing water, supplies an average 144,000 cubic meters (38 million gallons) of water daily.

Beaver Lake is impacted both by point and nonpoint sources of contamination. The city of Fayetteville discharges about one-half of its sewage effluent into the White River immediately upstream from backwater of the reservoir (Highway 45). Nutrients, sediment, pathogenic bacteria, and other constituents enter Beaver Lake through its tributaries and around its shoreline. Agriculture is a major land use in the Beaver Lake watershed. As a result of all the impacts, there is much concern about the current and future water quality in Beaver Lake.

Eutrophication and water-quality trends, that were assessed for the period 1974 to 1994 at the Beaver Lake dam, suggest that eutrophication may be decreasing in the reservoir (Green, 1996; Green, 1998). Whereas temporal fluctuations in water quality and trophic condition may not be as pronounced near the dam, the trophic conditions of the lotic or upper end of Beaver Lake were eutrophic, and the level of eutrophy in this area of the reservoir may have increased in the last 10 years (Haggard and others, 1999). The trophic conditions of the lacustrine zone can be considered mesotrophic (Green, 1998; Haggard and others, 1999); however, increases in nutrient loading, both externally and internally, may alter the trophic condition from mesotrophic to eutrophic conditions in the lacustrine zone of Beaver Lake.

## 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 reservoir elevation data used to develop and calibrate the model.

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

A two-dimensional, laterally averaged, hydrodynamic, temperature, and dissolved-oxygen model using CE-QUAL-W2 Version 2.11 was developed for Beaver Lake and calibrated based on hydrologic records and vertical profiles of temperature and dissolved oxygen measured near the Beaver Lake dam in 1994 and 1995. The CE-QUAL-W2 model simulates vertical and longitudinal gradients in water-quality constituents and 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, nitrate plus nitrite nitrogen, pH, phosphorus, sediment, suspended solids, total dissolved solids, and a conservative tracer (Cole and Buchak, 1995). Calibration and simulation of other water-quality constituents besides water temperature and dissolved oxygen, such as nitrogen, phosphorus, algal production. and organic matter are beyond the scope of this investigation. However, the Beaver Lake model presented in this report could be modified in the future to calibrate nutrient and algal dynamics if the appropriate data become available to do so.

### Model Implementation

Implementation of the Beaver Lake model 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 summarized, and specific values of model parameters given.

#### Computational Grid

The computational grid is the geometric scheme (fig. 2) that numerically represents the space and volume of the reservoir. The model extends 80 km, from the Highway 45 bridge on the White River to the

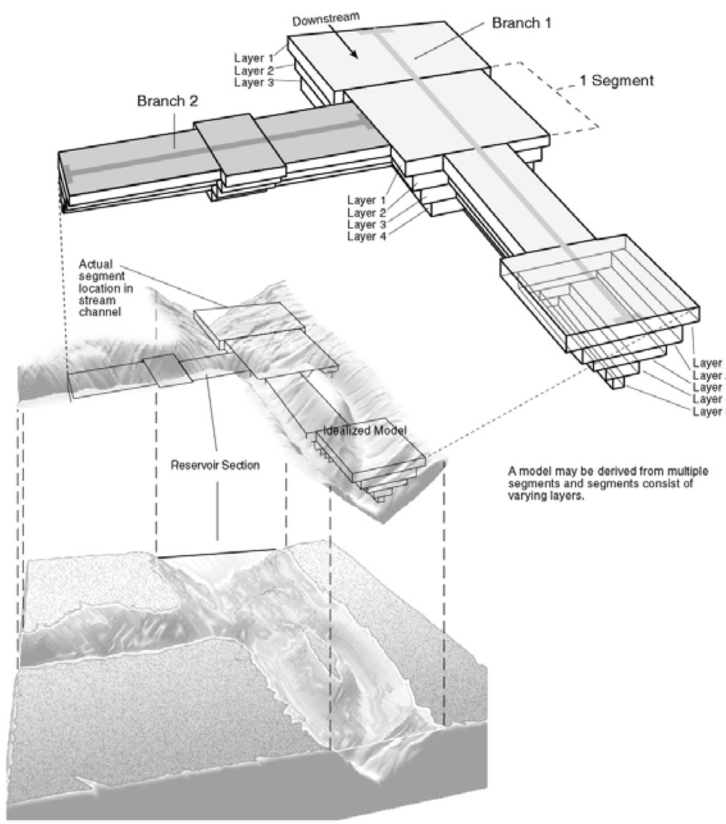


**Figure 2.** Idealized model segments, layers, and branches for Beaver Lake.

Beaver Lake dam. The grid geometry was developed using pre-impoundment elevation contours of the land surface or reservoir bottom (fig. 3). Thirty-five computational segments exist along the mainstem of the White River in Beaver Lake whereas 12 computational segments are in War Eagle Creek. In addition, four other embayments (branches) farther down-reservoir are modeled with three computational segments each. Volumes of the smaller embayments not included in the computational grid were simply added to associated mainstem 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 710 to 5,060 m, and orientation of the longitudinal axis relative to north was determined for each segment. Segment widths at the surface ranged from 243 m in the headwaters to more than 5,000 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 10 m at the upstream end to 60 m near the reservoir dam. Depth-and-volume and depth-and- surface area relations in the Beaver Lake model grid were similar to USACE preimpoundment data (fig. 4).

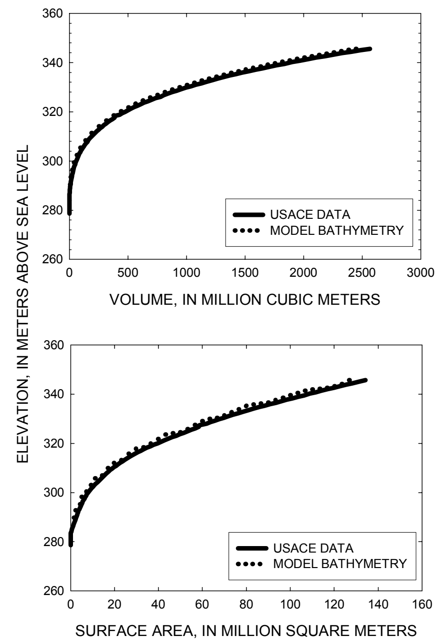


**Figure 4.** Relation between depth and volume and depth and surface area in Beaver Lake.

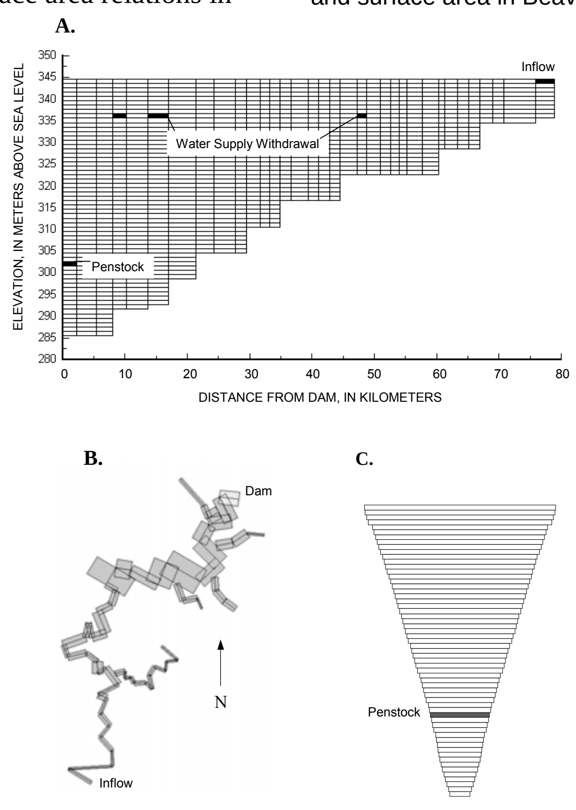


**Figure 3.** Side view (A), top view (B), and face view from the dam (C) of the computational grid of Beaver Lake used in CE-QUAL-W2.

## Boundary and Initial Conditions

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

### Hydraulic and Thermal Boundary Conditions

The reservoir bottom is assumed to be an immobile and impermeable boundary. That is, the bottom sediments are stationary and not resuspended by flow, and groundwater discharge to the reservoir or recharge from the reservoir is assumed to be negligible. The reservoir bottom extracts energy from water movement by causing resistance to water flow; this phenomenon varies with the magnitude of flow. A single, empirical coefficient (Chezy coefficient) is applied to the reservoir bottom in all computational segments (table 1).

**Table 1.** Hydraulic and thermal input parameters specified for Beaver 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 | Purpose | Value | Constant or time variable |
|---|---|---|---|
| Chezy resistance coefficient | Represents turbulent exchange of energy at the reservoir bottom | 70 $m^{0.5}$/s | Constant |
| Sediment – water heat exchange coefficient | Computes heat exchange between reservoir bottom and overlying water | $7.0 \times 10^{-8}$ (watts/$m^2$)/°C | Constant |
| Sediment temperature | Represents the reservoir bottom (sediment) temperature | 8.0 °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 transport of momentum | 1 $m^2$/s | Constant |
| Horizontal eddy diffusivity | Represents laterally averaged longitudinal turbulent transport of mass and heat | 1 $m^2$/s | Constant |

Heat exchange between the reservoir bottom and the overlying water column is computed from (1) the reservoir bottom temperature, (2) the simulated temperature of the overlying water, and (3) a coefficient of sediment-water heat exchange (table 1). The exchange coefficient and reservoir bottom temperature are assumed to be temporally and spatially constant. A reasonable estimate of reservoir bottom temperature is the annual average water temperature near the sediment-water interface; a value of 8.0 °C was used in the Beaver Lake model. In general, heat exchange from the reservoir bottom is about two orders of magnitude less than surface heat exchange.

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

Inflow conditions for Beaver Lake during the 1994 and 1995 modeling time period were slightly above normal (fig. 5). Annual mean streamflow from 1964 through 1995 ranged from 4.39 to 33.9 $m^3/s$. The average annual mean streamflow for this time period was 16.1 $m^3/s$. Annual mean streamflow for the 1994 and 1995 modeling time period was 17.7 and 18.8 $m^3/s$, respectively.

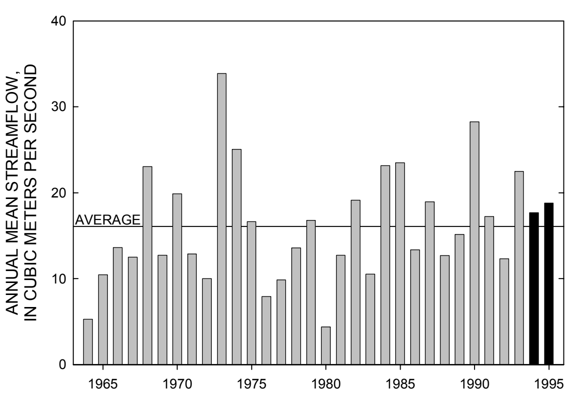


**Figure 5.** Annual mean streamflow for the White River upstream from Beaver Lake, 1964-1995.

Daily reservoir inflow was distributed on a drainage area basis into two major branches (White River and War Eagle Creek) and one tributary (Richland Creek). Approximately 91 percent of the inflow was distributed between Richland Creek (15 percent), War Eagle Creek (34 percent) and the White River (42 percent), and the remaining portion (9 percent) was evenly distributed between the four smaller branches and the surrounding shoreline. Total mean reservoir inflow from January 1, 1994, through December 31, 1995, was estimated to be 43.7 $m^3/s$, whereas the median reservoir inflow was 14.2 $m^3/s$. The reservoir inflow exceeded 100 $m^3/s$ 10 percent of the time.

Outflows (fig. 6) from the Beaver Lake dam were obtained from USACE records of hourly power generation based on a stage-discharge relation. The mean and median reservoir outflow was 42.6 and 8.5 $m^3/s$, respectively. The reservoir outflow exceeded 139 $m^3/s$ 10 percent of the time. The vertical extent and distribution of flow in the release zone near the Beaver Lake dam were simulated using penstock (point) dam release flow, the outflow rate, and the simulated density gradient upstream in the reservoir. The release structure was simulated as a point release, and the middle of the structure was at an elevation of 302.2 m above sea level, model layer 45 (fig. 3).

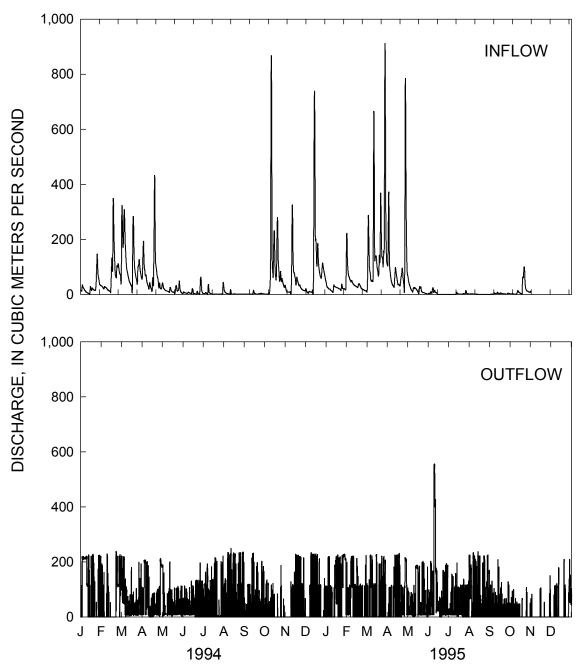


**Figure 6.** Daily inflow (top) and dam release flow (bottom) for Beaver Lake, Arkansas, January 1994 through December 1995.

Other hydraulic boundary conditions included water withdrawal by several municipal drinking water supply districts (Beaver Water District, Carroll – Boone County Water District, and Madison County Water District) (fig. 3). The Beaver Water District withdrawal rate was approximately 1.5 $m^3/s$ during the study period, whereas Carroll – Boone County Water and Southwest Boone County Water District withdrawal rates were considerably less (0.3 and 0.003 $m^3/s$, respectively). Withdrawal rates for each water district were variable by month and based on reported 1994 through 1995 monthly intakes (Terry Holland, U.S. Geological Survey, written commun., May 2000).

Hydraulic boundary conditions at the water surface included evaporation, wind stress, and surface heat exchange. All meteorological data required for these computations were measured at Harrison, Arkansas (station number 723446, National Climatic Data Center, Asheville, North Carolina), and generally were recorded at hourly intervals. Evaporation in the model was computed from a time series of water-surface temperature, dewpoint temperature, wind speed, width of the surface layer, and length of the segment. Wind stress was computed from a time series of wind speed and direction, 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 Beaver Lake model this coefficient was held constant. Surface heat exchange was computed from reservoir latitude and longitude, and from a time series of measured air temperature, dewpoint temperature, cloud cover, and wind speed and direction. In the original meteorological data, cloud cover was recorded as clear (CLR), scattered (SCT), broken (BKN), and overcast (OVC). The model requires cloud cover to be entered as a number ranging from 0.0 to 10.0. In the Beaver 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. In addition to temperature, concentrations of the following constituents were simulated for Beaver Lake: algae, ammonium nitrogen, carbonaceous biological oxygen demand, coliform bacteria, detritus, dissolved oxygen, labile and refractory dissolved organic matter, nitrate-nitrite nitrogen, phosphate phosphorus, and a tracer. Boundary data in all tributaries and branches included carbonaceous biological oxygen demand, dissolved oxygen, ammonium nitrogen, nitrate-nitrite nitrogen, total phosphorus, and a tracer. Due to the limited amount of available water-quality data, annual average concentrations from Haggard (1997) were used for all inflow boundary constituents except dissolved oxygen and carbonaceous biological oxygen demand (CBOD). These data (Haggard, 1997) were collected at the upstream model boundary between August 1993 and July 1995. Dissolved-oxygen concentrations were estimated at 80 percent saturation for the given water temperature. A wastewater treatment plant (WWTP) exists about 10 km upstream. Data reported by Haggard (1997) at the upstream boundary include WWTP contributions.

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

### Initial Conditions

Initial water level 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 Beaver 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 (9.0 °C). Initial constituent concentrations also were assumed to be uniform throughout the reservoir and equal to measured values near the dam. All initial values near the dam were obtained from triennial measurements (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. Many parameters cannot be measured directly and are often adjusted during the model calibration process until simulated values agree with measured observations.

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

[m, meters; $(m^3/m)/g$, cubic meter per meter per gram; *, dimensionless; m/d, meters per day; d, day; watts/$m^2$, watts per square meter; $^oC$, degrees Celsius; $(g/m^2)/d$, grams per square meter per day; BOD, biochemical oxygen demand; g/m, grams per meter; mg/L, milligrams per liter]

| Parameter | Computational purpose | Value |
|---|---|---|
| Light extinction coefficient for water | Amount of solar radiation absorbed in the surface layer | 0.35/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 | 0.32* |
| Coliform decay rate | Decay rate for coliforms, temperature dependent | 1.1/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 | 0.02/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 | 0.15 m/d |
| Saturation light intensity | Saturation light intensity at maximum algal photosynthesis rate | 325 watts/$m^2$ |
| Fraction of algal biomass lost by mortality to detritus | Detritus and dissolved organic matter concentrations; remaining biomass becomes labile dissolved organic matter | 0.8* |
| Lower temperature for algal growth | Algal growth rate as a function of water temperature | $1.0^oC$ |
| Fraction of algal growth at lower temperature | Algal growth rate as a function of water temperature | 0.10* |
| Lower temperature for maximum algal growth | Algal growth rate as a function of water temperature | $25^oC$ |
| 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 | $35^oC$ |
| 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 | $40^oC$ |
| 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* |

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

[m, meters; $(m^3/m)/g$, cubic meter per meter per gram; *, dimensionless; m/d, meters per day; d, day; watts/$m^2$, watts per square meter; $^oC$, degrees Celsius; $(g/m^2)/d$, grams per square meter per day; BOD, biochemical oxygen demand; g/m, grams per meter; mg/L, milligrams per liter]

| Parameter | Computational purpose | Value |
|---|---|---|
| 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 | 0.875-5.25 $(g/m^2)/d$ |
| 5-day BOD decay rate | Effects of BOD loading on dissolved oxygen | 0.05/d |
| BOD temperature rate coefficient | Adjusts 5-day BOD decay rate at $20^oC$ to ambient temperature | 1.047* |
| Ratio of 5-day BOD to ultimate BOD | Effects of BOD loading on dissolved oxygen | 1.85* |
| Release rate of phosphorus from bottom sediments | Phosphorus balance; computed as a fraction of sediment oxygen demand | 0.015* |
| 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 | $5.0^oC$ |
| 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 | $20^oC$ |
| Fraction of maximum nitrification at lower temperature | Ammonia nitrification as a function of temperature | 0.99* |
| Nitrate decay rate | Rate at which nitrate is denitrified; temperature dependent | 1.0/d |
| Lower temperature for nitrate decay | Denitrification as a function of temperature | $5.0^oC$ |
| Fraction of denitrification at lower temperature | Denitrification as a function of temperature | 0.1* |
| Lower temperature for maximum nitrate decay | Denitrification as a function of temperature | $20.0^oC$ |
| Fraction of maximum denitrification at lower temperature | Denitrification as a function of temperature | 0.99* |
| Iron release from bottom sediments | Iron balance; computed as a fraction of sediment oxygen demand | 0.5* |
| Iron settling velocity | Particulate iron settling velocity under oxic conditions | 2.0 m/d |
| Oxygen stoichiometric equivalent for ammonia decay | Relates oxygen consumption to ammonia decay | 4.5* |
| Oxygen stoichiometric equivalent for organic matter decay | Relates oxygen consumption to decay of organic matter | 2.8* |
| Oxygen stoichiometric equivalent for dark respiration | Relates oxygen consumption to algal dark respiration | 2.8* |
| Oxygen stoichiometric equivalent for algal growth | Relates oxygen production to algal growth | 4.0* |
| Stoichiometric equivalent between organic matter and phosphorus | Relates phosphorus release to decay of organic matter | 0.011* |
| Stoichiometric equivalent between organic matter and nitrogen | Relates nitrogen release to decay of organic matter | 0.08* |
| Stoichiometric equivalent between organic matter and carbon | Relates carbon release to decay of organic matter | 0.45 |
| Dissolved-oxygen limit | Dissolved-oxygen concentration below which anaerobic processes such as nitrification and sediment nutrient releases occur | 0.05 mg/L |

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

There exist about 60 biological and chemical rate coefficients required for application of CE-QUAL-W2 (table 2). Most of the coefficients were based on suggestions given in the CE-QUAL-W2 manual (Cole and Buchak, 1995), and all of the coefficients 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 was limited to 1 hour because the boundary 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.

## Model Calibration

Successful model application requires model calibration that includes comparing model (simulated) results with observed (measured) in-pool water quality. If possible, two or more years of water-quality data should be used to confirm or verify model calibration. Beaver Lake model calibration was achieved by adjusting model parameters and, in some cases, estimated input data, for the 2-year period of January 1, 1994 through December 31, 1995.

Two statistics were used to compare simulated and measured pool elevation, water temperature, and dissolved-oxygen concentration. The absolute mean error (AME) indicates how far, on average, computed values are from observed values and is computed according to the following equation:

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

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 data and is given by the following equation:

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

### Hydrodynamics and Temperature

Measured and simulated surface elevations near the Beaver Lake dam followed similar patterns between January 1 and December 31, 1994 (fig. 7).

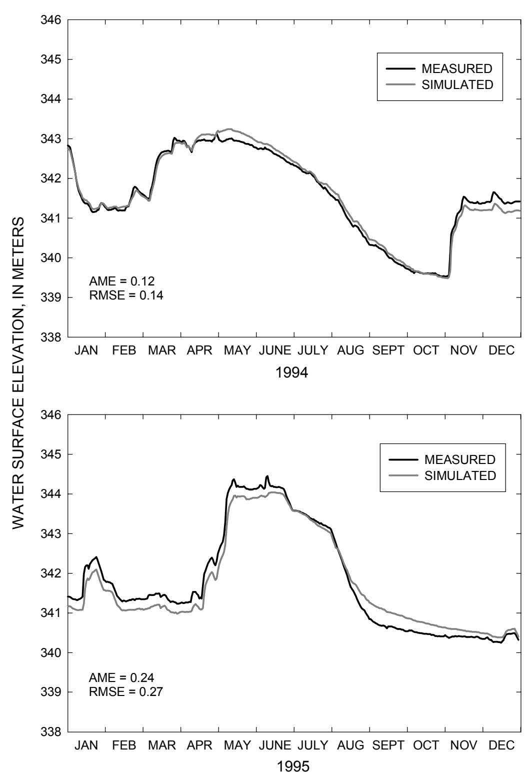


**Figure 7.** Measured and simulated water-surface elevation near the Beaver Lake dam, January through December 1994 and January through December 1995.

The AME and RMSE between measured and simulated water levels in 1994 was 0.12 and 0.14 m, respectively. The difference between measured and simulated values ranged from –0.29 to 0.31 m. Overall, there was good agreement between measured and simulated values in 1994.

Agreement between measured and simulated water levels in Beaver Lake in 1995 differed from 1994, but overall the simulated values matched the pattern of observed water levels despite larger absolute differences between the two (fig. 7). The AME and RMSE between measured and simulated water levels in 1995 was 0.24 and 0.27 m, respectively. The difference between measured and simulated values ranged from -0.75 to 0.80 m. The tendency in simulated water levels to be less than observed water levels in the spring of 1995 may reflect the fact that the model neglected some inflow or outflow from the reservoir such as ground-water recharge.

The heat budget in the model is computed from inflow water temperature, air-water surface heat exchange (air and dew-point temperature, cloud cover, wind speed and direction, organic and inorganic solids concentration) and heat exchange at the sediment-water interface. 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. 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 Beaver Lake dam during August through November in 1994 and 1995. The model simulations agreed quite closely with the observed thermocline, but the changes were not as distinct because the model simulates temperature (and water chemistry) in homogeneous 1-m-thick layers within each computational segment. Hence, simulated changes in temperature near the thermocline would be more gradual than observed changes.

All simulated water temperatures (553) in 1994 were compared with corresponding measured values near the Beaver Lake dam (Evans and others, 1995). Simulated water temperatures reproduced seasonal variations observed in the water column near the dam (fig. 8), even for complex temperature profiles.

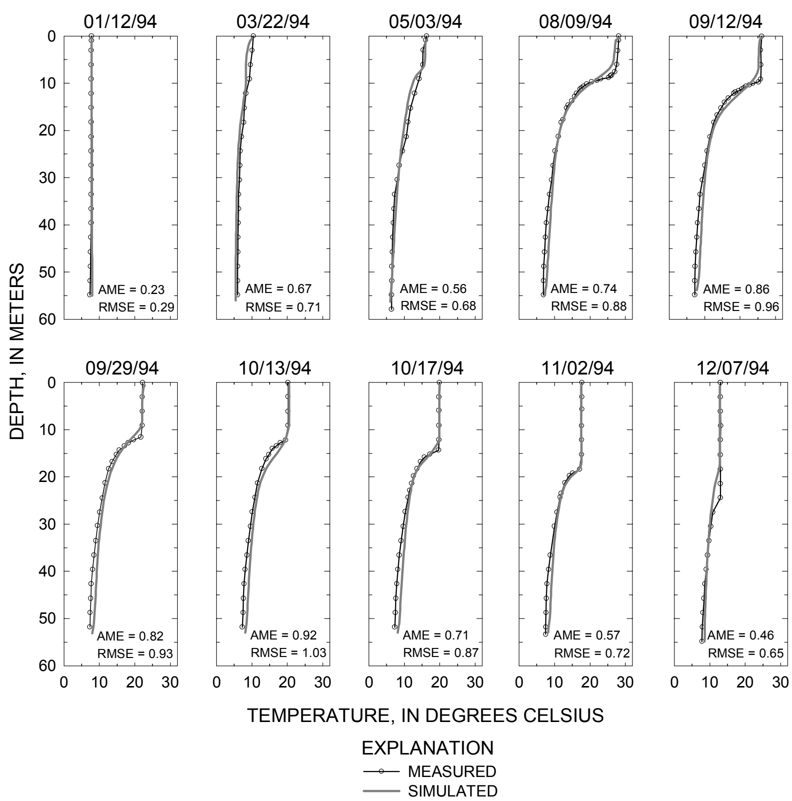


**Figure 8.** Relation between measured and simulated water temperatures in the water column near the Beaver Lake dam, January through December 1994.

Measured water temperatures ranged from 6.0 to 28.1°C whereas simulated water temperatures ranged from 5.4 to 28.2 °C. Simulated water temperatures in the vertical profile were generally (74 percent) within 1°C of measured values. The AME and RMSE between measured and simulated water temperature were 0.65 and 0.80 °C, respectively. The difference between measured and simulated values ranged from -2.5 to 2.3 °C, and the average and median absolute differences were 0.3 and 0.6 °C, respectively.

Although the calibrated model closely simulated water temperature near the Beaver Lake dam, with most simulated values within 1°C of the actual value, the accuracy and precision of simulated temperatures varied with temperature, season, and depth. Simulated water temperatures were greater than measured temperatures more often when measured temperatures were less than 10 °C (fig. 9). On the other hand, simulated water temperatures were less than measured temperatures when measured temperatures were greater than approximately 20 °C. Near-bottom simulated temperatures tended to be greater than measured values whereas near-surface simulated temperatures were less than measured values. Error in simulated water temperatures was greater during thermal stratification.

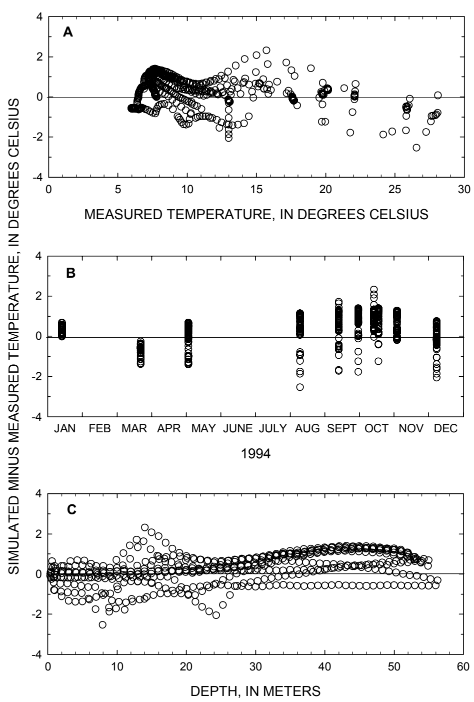


**Figure 9.** Relation of difference between measured and simulated water temperatures at Beaver Lake dam to (A) measured water temperature, (B) data, and (C) water depth, January through December 1994.

Simulated water temperatures in 1995 were very similar to 1995 measured temperatures (fig. 10). All simulated temperatures (560) in 1995 were compared with corresponding measured values (Porter and others, 1996). Measured water temperatures ranged from 7.0 to 30.7 °C whereas simulated water temperatures ranged from 5.1 to 30.7 °C. Simulated water temperatures were generally (58 percent) within 1°C of measured values. The AME and RMSE between measured and simulated water temperature were 0.83 and 1.04 °C, respectively. The difference between measured and simulated values ranged from -2.6 to 3.5 °C, and the average and median absolute differences were -0.1 and 0.6 °C, respectively.

Errors in simulated water temperatures were better distributed during 1995 when compared to 1994 (fig. 11). Simulated water temperatures during 1995 were generally under-predicted when measured temperatures exceeded 25 °C. During January and March 1995, simulated water temperatures were consistently less than measured values, and errors were evenly distributed during the stratification season suggesting no tendency to over- or under-predict water temperature. Simulated water temperatures were generally less than measured values near the reservoir bottom but were similar near the water surface. In general, the second (1995) year of simulation provided similar results as the first (1994) with most simulated values being within 1 °C of the measured value.

## Dissolved Oxygen

Simulation of the complex biochemical reactions affecting chemical and physical transport processes in the Beaver Lake model are expressed in part within the simulated dissolved-oxygen results. The supply of nitrogen, phosphorus, and light regulate algal growth and the production of oxygen; photosynthesis is the only internal source of oxygen in the water-chemistry computations. Other boundary sources 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 ammonium to nitrate), algal and microbial respiration, organic matter decay (for example, detritus, labile and refractory dissolved organic matter), and sediment oxygen demand. These processes interact in water-chemistry computations to simulate the complex vertical profiles of dissolved oxygen in Beaver Lake.

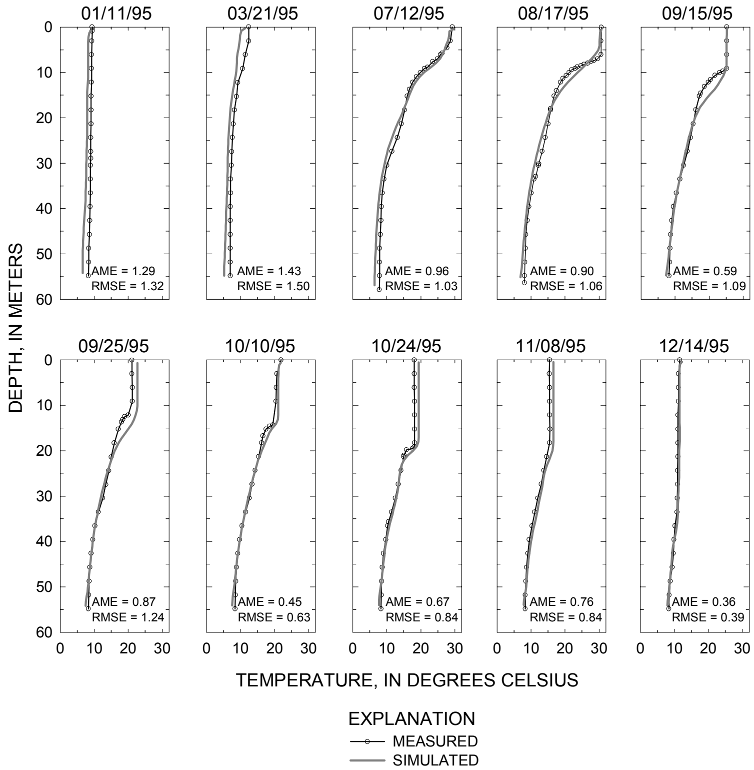


**Figure 10.** Relation between measured and simulated water temperatures in the water column near the Beaver Lake dam, January through December 1995.

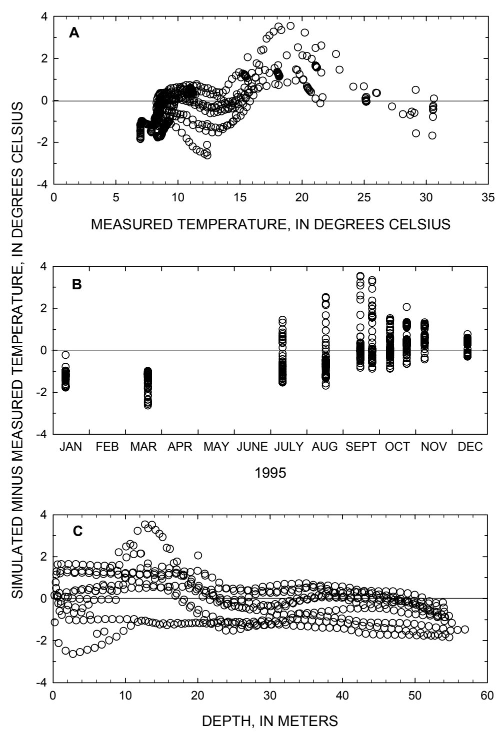


**Figure 11.** Relation of difference between measured and simulated water temperatures near Beaver Lake dam to (a) measured water temperature, (B) date, and (C) water depth, January through December 1995.

Simulated dissolved-oxygen concentrations near the Beaver Lake dam exhibited the same general patterns and magnitudes as measured values (fig. 12). All simulated dissolved-oxygen concentrations (553) for January through December 1994 were compared to corresponding measured values (Evans and others, 1995). Measured dissolved-oxygen concentrations ranged from 0.1 to 11.0 mg/L, whereas simulated dissolved-oxygen concentrations ranged from 0.0 to 12.4 mg/L. Simulated dissolved-oxygen concentrations in the vertical profile generally (73 percent) were within 1 mg/L of measured values. The AME and RMSE between measured and simulated dissolved-oxygen concentrations were 0.80 and 1.24 mg/L, respectively. The difference between measured and simulated values ranged from -8.8 to 2.1 mg/L, and the average and median absolute differences were -0.1 and 0.6 mg/L, respectively.

Differences between measured and simulated dissolved-oxygen concentrations were compared to corresponding measured dissolved-oxygen concentrations, sampling date, and the measurement depth (fig. 13). Simulated dissolved-oxygen concentrations typically were less than measured values when measured dissolved-oxygen concentrations were below 2 mg/L. Errors in simulated dissolved-oxygen concentration were greater during the stratification season. The December 7, 1994 results produced the greatest differences between measured and simulated dissolved-oxygen concentrations. Thermal destratification was occurring during this time and the model simulation lagged a little in time to what actually occurred.

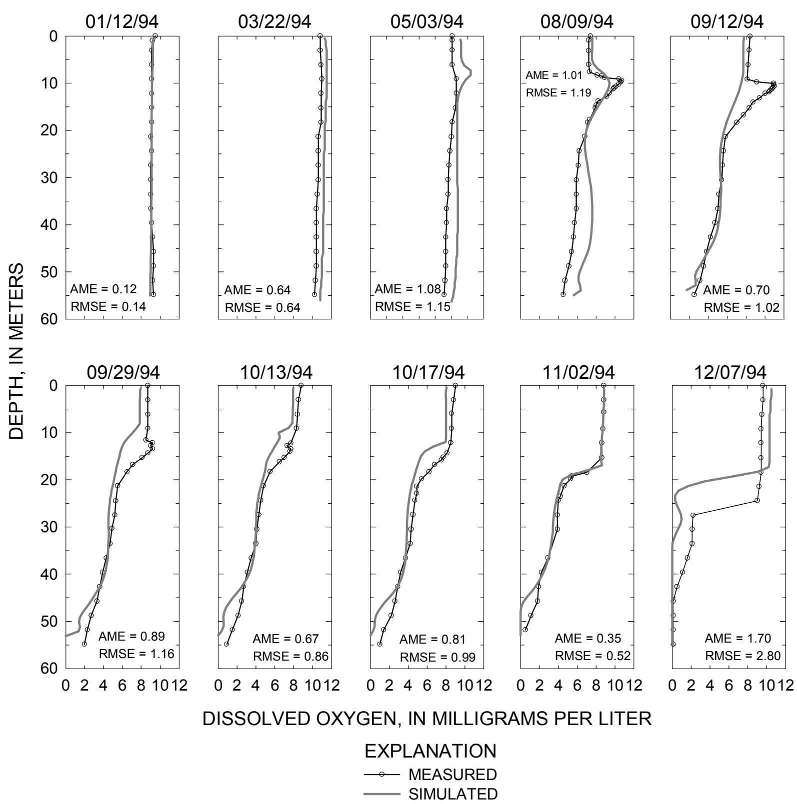


**Figure 12.** Relation between measured and simulated dissolved-oxygen concentrations in the water column near the Beaver Lake dam, January through December 1994.

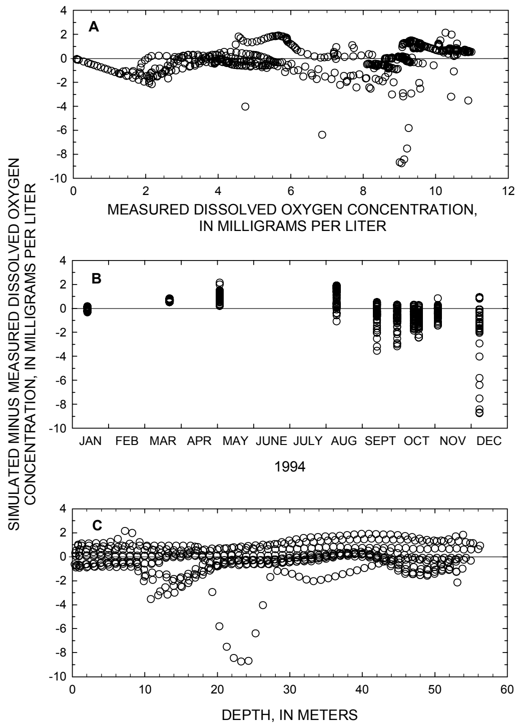


**Figure 13.** Relation of difference between measured and simulated dissolved-oxygen concentrations near Beaver Lake dam to (A) measured dissolved-oxygen concentrations, (B) date, and (C) water depth, January through December 1994

Simulated dissolved-oxygen concentrations in 1995 were similar to 1995 measured dissolved-oxygen concentrations (fig. 14), but differences were somewhat greater in 1995 than in 1994. Seasonal variations in simulated dissolved-oxygen concentration were reproduced despite pronounced differences in the vertical distribution. All simulated dissolved-oxygen concentrations (560) were compared with corresponding measured values near the Beaver Lake dam. Measured dissolved-oxygen concentrations ranged from 0.1 to 10.4 mg/L whereas simulated values ranged from 0.0 to 13.2 mg/L. Simulated dissolved-oxygen concentrations in the vertical profile were generally (61 percent) within 1.0 mg/L of measured values. The AME and RMSE between measured and simulated dissolved-oxygen concentrations were 1.15 and 1.70, respectively. The difference between measured and simulated dissolved-oxygen concentrations ranged from -2.3 to 7.0 mg/L, and the average and median differences were 0.28 and 0.7 mg/L, respectively.

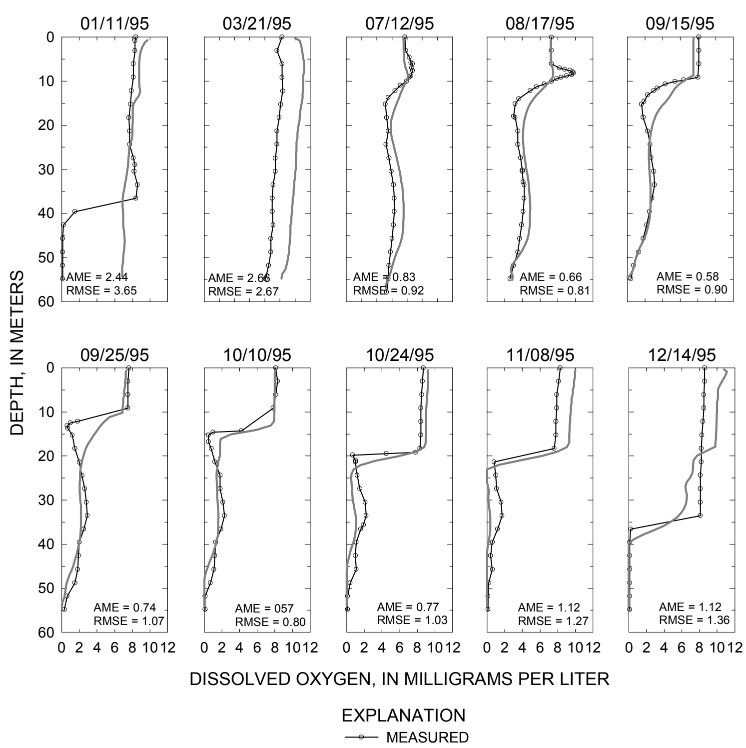


**Figure 14.** Relation between measured and simulated dissolved-oxygen concentrations in the water column near the Beaver Lake dam, January through December 1995.

Simulated dissolved-oxygen concentrations were generally over-predicted when compared to measured values (fig. 15); however, greater than half of the measured dissolved-oxygen concentrations were within 1 mg/L of the simulated values. Simulated dissolved-oxygen concentrations consistently were greater than measured values when measured dissolved-oxygen concentration was between 3 and 7 mg/L. The greatest error occurred during the end of the stratification period and during turnover (November-January). Simulated dissolved-oxygen concentrations often were greater than measured regardless of depth. Despite these tendencies, simulation of dissolved-oxygen concentration in the vertical profile near the Beaver Lake dam followed the same general patterns as measured values.

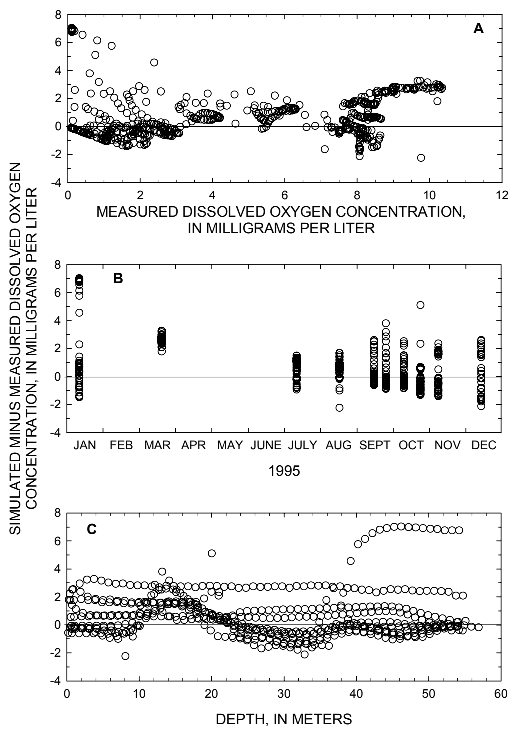


**Figure 15.** Relation of difference between measured and simulated dissolved-oxygen concentrations near Beaver Lake dam to (A) measured dissolved-oxygen concentrations, (B) date, and (C) water depth, January through December 1995.

## 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 Beaver Lake model was not conducted because the Beaver 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) in other reservoirs form the basis for the sensitivity analysis. The sensitivity of water temperature and dissolved-oxygen concentrations near the dam to changes in the wind-sheltering coefficient (WSC), coefficient of bottom heat exchange (CBHE), light extinction ($\alpha$), sediment-oxygen demand (SOD), and changes in inflow temperature and dissolved-oxygen concentrations was assessed.

Of the hydraulic parameters (tables 1 and 2), water temperature in the Beaver Lake model was most sensitive to changes in the WSC and $\alpha$ (fig 16). Wind speed in the calibrated and verified Beaver Lake model was adjusted (WSC = 0.7) from the meteorological data recorded at Harrison, Arkansas; that is, the effective wind speed was 70 percent of the recorded wind speed at Harrison. Surface-water temperatures were not impacted as much by changes in WSC as was the position of the thermocline and hypolimnetic temperatures. During stratification, vertical mixing was over-predicted when WSC was increased (>0.7) and under-predicted when WSC was decreased (<0.7). Changes in the $\alpha$ affected vertical water temperature profiles during stratification. Increasing $\alpha$ elevated the thermocline and decreasing $\alpha$ lowered the thermocline. Changes in inflow water temperature had little affect on vertical water temperature profiles near the dam. The combination of WSC and $\alpha$ appear to be the driving factors in the model responsible for the development, duration, and vertical location of the thermocline in Beaver Lake near the dam.

In the Beaver Lake model, dissolved-oxygen concentrations appeared to be most affected by changes in the WSC, $\alpha$, and FSOD (fig. 17). FSOD is the fraction of the zero-order SOD rate and is applied to adjust SOD equally among all segments. Near the air-water interface, dissolved-oxygen concentrations were not impacted by changes in these coefficients. Changes in the WSC tended to affect dissolved-oxygen concentrations near the thermocline and throughout the hypolimnion. Both increases and decreases in FSOD affected dissolved-oxygen concentrations deeper than about 8 m. The $\alpha$ regulates the amount of light penetrating the water, indirectly affecting dissolved-oxygen concentrations by influencing algal production. Inflow dissolved-oxygen concentrations had little effect on the vertical distribution of dissolved oxygen near the dam.

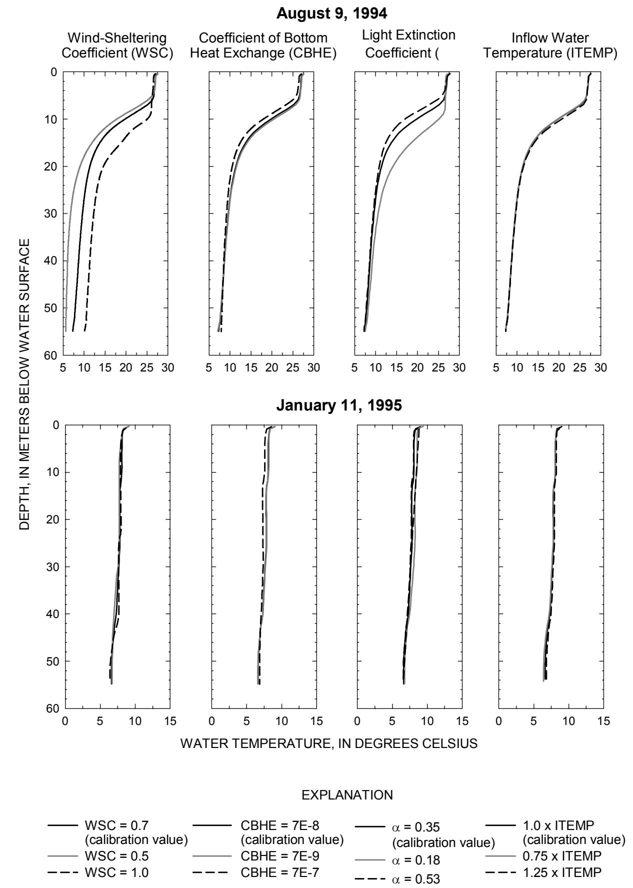


**Figure 16.** Vertical temperature distributions near the Beaver Lake dam on August 9, 1994 (top) and January 11, 1995 (bottom), showing calibrated model profiles and profiles as a result of differing model parameters.

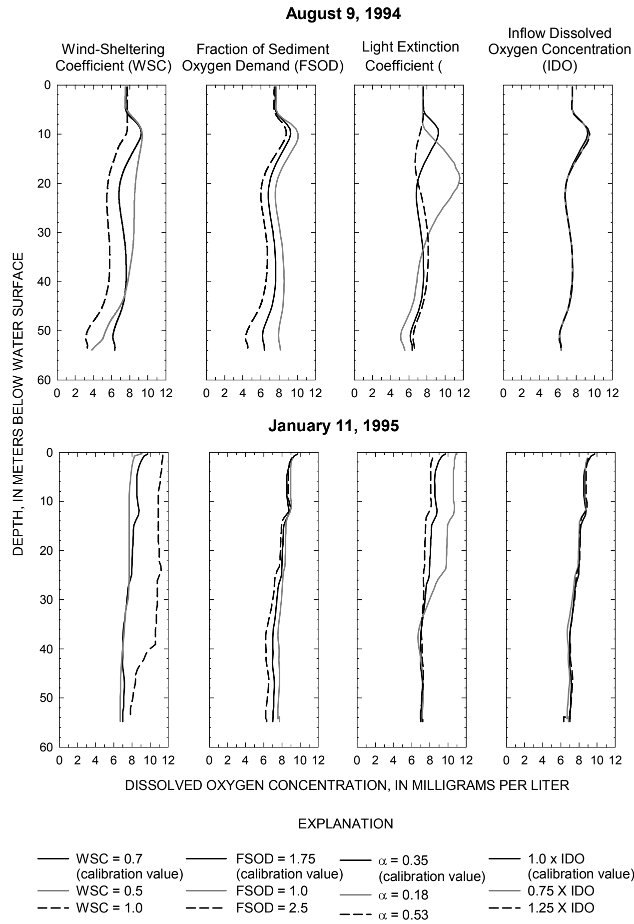


**Figure 17.** Vertical dissolved-oxygen concentration distributions near the Beaver Lake dam on August 9, 1994 (top) and January 11, 1995 (bottom), showing calibrated model profiles and profiles as a result of differing model parameters.

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

## Model Applications

The calibrated Beaver Lake model was used to assess the impacts of minimum flow scenarios on reservoir stage and on temperature and dissolved-oxygen concentrations in the dam release waters. Increased minimum flow simulations were developed by increasing the discharges that originally were less than 3.85 $m^3/s$ (1.76 to 3.84 $m^3/s$) to 3.85 $m^3/s$ in the outflow discharge file. Changes in reservoir stage were evaluated and a second scenario was applied correcting for the volume displaced by additional minimum flow.

When 3.85 $m^3/s$ was applied as the minimum amount of discharge (minimum flow scenario), average annual outflow increased from 42.60 to 43.57 $m^3/s$, about a 2.3 percent increase. Approximately 47 percent of the hourly outflow data required an increase to 3.85 $m^3/s$. Average annual outflow increased from 1,344 to 1,374 million $m^3$, which is equivalent to about 30 million $m^3$ per year increase, about 1.5 percent of reservoir volume at conservation pool elevation. The difference in reservoir elevation by the end of 1994 was reduced 0.25 m and by the end of 1995, about 0.5 m (figs. 18 and 19). The initial elevation on January 1, 1994 was 342.75 m. When 0.5 m of water was applied to the initial elevation (minimum flow plus increased pool elevation scenario), the difference in elevation after 1 year was 0.27 m greater than the calibrated model and ended up after 2 years about the same elevation (340.40 m) as the calibrated model without the additional minimum flow.

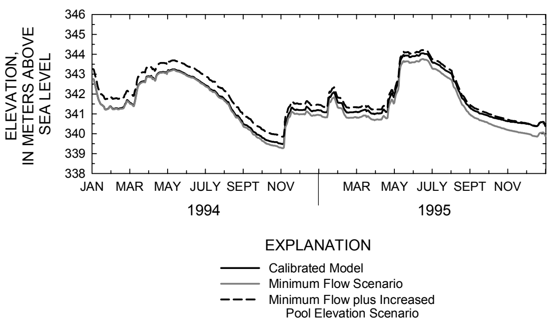


**Figure 18.** Simulated surface elevations resulting from additional minimum flow with and without increasing pool elevation.

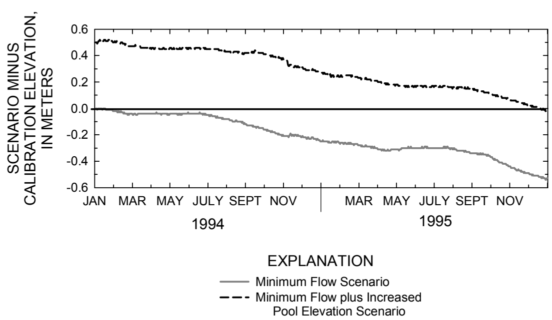


**Figure 19.** Relation of difference between calibrated model pool elevation and pool elevations predicted from minimum flow scenarios.

Temperature in the discharged water differed little between results from the calibrated model and the minimum flow scenarios (figs. 20 and 21). Absolute maximum difference in outflow water temperature between the minimum flow scenario and the calibrated model was 0.9 °C and between the minimum flow plus increased pool elevation and the calibrated model was 0.5 °C. Temperature differences for both scenarios were within the AME and RMSE between observed and simulated water-column profile temperature differences reported earlier in this report. Modeled outflow temperatures were similar to estimated outlet values from water-column profiles above the dam and measured downstream (3.5 km) tailwater temperature (fig. 20). It appears that water temperature in the dam outflow increased slightly through time with the addition of increased minimum flow. Conversely, with the increase in pool elevation plus the addition of minimum flow, it appears that water temperature in the dam outflow decreased slightly through time.

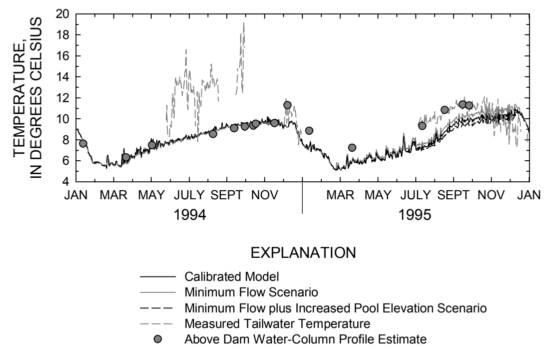


**Figure 20.** Simulated water temperatures in Beaver Lake outflows and measured in the tailwater.

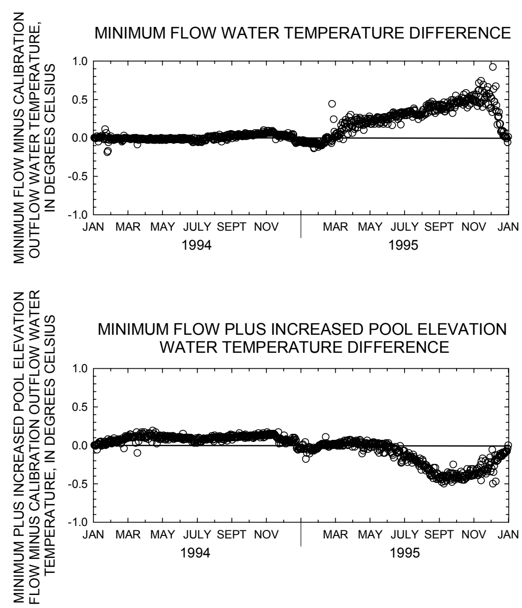


**Figure 21.** Simulated water temperature difference between calibrated base condition and additional minimum flow scenarios.

Dissolved-oxygen concentrations in the discharged water also differed little between results from the calibrated model and the two minimum flow scenarios (figs. 22 and 23). Absolute maximum difference in outflow dissolved oxygen between the minimum flow scenario and the calibrated model was 2.2 mg/L and between the minimum flow plus increased pool elevation and the calibrated model was 1.9 mg/L. Dissolved-oxygen concentration differences for both scenarios were about the same as the AME and RMSE between observed and simulated water-column profile dissolved-oxygen differences reported earlier in this report. Modeled outflow dissolved-oxygen concentrations were similar to estimated outlet values from water-column profiles above the dam and measured downstream (3.5 km) tailwater temperature (fig. 22). It appears the dissolved-oxygen concentrations in the dam outflow decreased slightly through time with the addition of increased minimum flow. Conversely, with the increase in pool elevation plus the increase minimum flow, it appears that dissolved-oxygen concentrations in the dam outflow increased slightly through time.

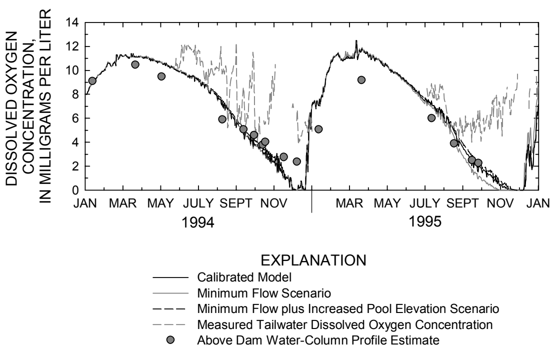


**Figure 22.** Simulated dissolved-oxygen concentrations in Beaver Lake outflows and measured in the tailwater.

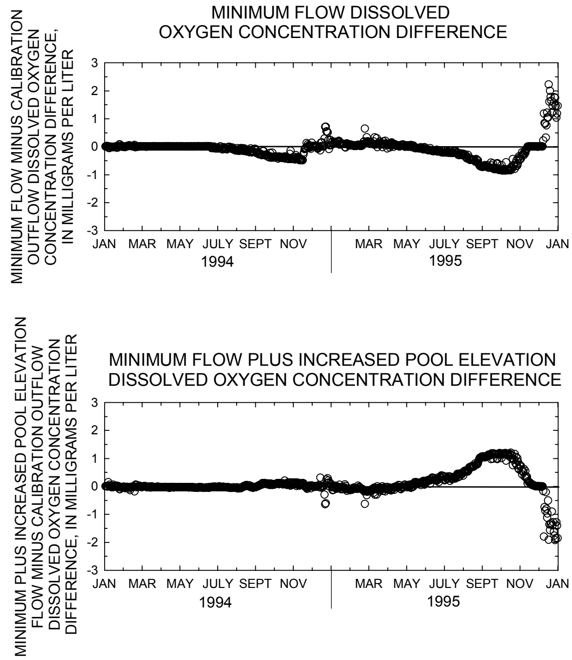


**Figure 23.** Simulated dissolved-oxygen concentration differences between calibrated base condition and additional minimum flow scenarios.

## SUMMARY

The tailwaters of Beaver Lake and other White River reservoirs support a cold-water trout fishery of significant economic yield in northwestern Arkansas. Proposed increases in minimum flows released from the dam have produced concerns about the sustainability of cold-water temperature and dissolved oxygen in the bottom water above the Beaver Lake Dam. There is concern that even slight warming of the release waters might decrease the length of the tailwaters thermally suitable for trout growth and sustainability, possibly adversely impacting the trout fishery. Thus, this study intended to assess the impact of additional minimum flows on the temperature and dissolved-oxygen qualities in Beaver Lake water above the dam and the released water.

A two-dimensional laterally averaged hydrodynamic, thermal, and dissolved-oxygen model was developed for Beaver Lake, Arkansas. The model was calibrated and verified using hydrologic, meteorological, physicochemical and other water-quality data measured in or near Beaver Lake from January 1994 through December 1995. The model simulates surface-water elevation, currents, heat transport, and dissolved-oxygen dynamics. The model was developed to assess the impacts of proposed increases in minimum flows from 1.76 $m^3/s$ (the existing minimum flow) to 3.85 $m^3/s$ (the additional minimum flow). Simulations included (1) the impact of additional minimum flows on tailwater temperature and dissolved-oxygen qualities and (2) increasing initial water-surface elevation 0.5 m and assessing the impact of additional minimum flow on tailwater temperatures and dissolved-oxygen concentrations. With the increase in minimum flow, water temperatures appeared to increase (<0.9 °C) and dissolved oxygen appeared to decrease (<2.2 mg/L) in the outflow discharge. Conversely, increasing minimum flow plus increasing initial pool elevation (0.5 m) apparently lowered the outflow water temperature (<0.5 °C) and increased dissolved-oxygen concentrations (<1.2 mg/L). However, these results were within the boundaries or similar to the error between measured and simulated water-column profile values.

This model provides the basis and framework for future water-quality modeling of Beaver Lake—as extensive data are collected in both the reservoirs and tributaries the existing model can be adjusted 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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