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Analysis of Ambient Conditions and Simulation of Hydrodynamics and Water-Quality Characteristics in Beaver Lake, Arkansas, 2001 through 2003

Prepared in cooperation with the
U.S. Army Corps of Engineers, the
Beaver Water District, and the
Arkansas Department of Environmental Quality

Scientific Investigations Report 2006-5003

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

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Front cover: Photograph of Beaver Lake by Chuck Haralson, Arkansas Department of Parks and Tourism.

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Contents

Figures

Tables

Conversion Factors, Vertical Datum, Abbreviations, and Acronyms

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)
square meter (m^2)	0.0002471	acre
square kilometer (km^2)	247.1	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)	264.2	gallon (gal)
cubic centimeter (cm^3)	0.06102	cubic inch (in^3)
liter (L)	61.02	cubic inch (in^3)
cubic meter (m^3)	35.31	cubic foot (ft^3)
cubic meter per second (m^3/s)	70.07	acre-foot per day (acre-ft/d)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
cubic meter per day (m^3/d)	35.31	cubic foot per day (ft^3/d)
cubic meter per second (m^3/s)	22.83	million gallons per day (Mgal/d)
kilogram per day (kg/d)	2.205	pound per day (lb/d)
kilogram per year (kg/yr)	2.205	pound per year (lb/yr)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C = (°F-32)/1.8$$

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)

Abbreviations and acronyms used in this report:

mg/L, milligrams per liter

µg/L, micrograms per liter

USACE, U.S. Army Corps of Engineers

USGS, U.S. Geological Survey

AMLE, adjusted maximum likelihood estimator

LAD, least absolute deviation

LOWESS, locally weighted smooth line

NTU, nephelometric turbidity unit

AME, absolute mean error

RMSE, root mean square error

Analysis of Ambient Conditions and Simulation of Hydrodynamics and Water-Quality Characteristics in Beaver Lake, Arkansas, 2001 through 2003

By Joel M. Galloway and W. Reed Green

Abstract

Beaver Lake is a large, deep-storage reservoir located in the upper White River Basin in northwestern Arkansas. The purpose of this report is to describe the ambient hydrologic and water-quality conditions in Beaver Lake and its inflows and describe a two-dimensional model developed to simulate the hydrodynamics and water quality of Beaver Lake from 2001 through 2003.

Water-quality samples were collected at the three main inflows to Beaver Lake; the White River near Fayetteville, Richland Creek at Goshen, and War Eagle Creek near Hindsville. Nutrient concentrations varied among the tributaries because of land use and contributions of nutrients from point sources. The median concentrations of total ammonia plus organic nitrogen were greater for the White River than Richland and War Eagle Creeks. The greatest concentrations of nitrite plus nitrate and total nitrogen, however, were observed at War Eagle Creek. Phosphorus concentrations were relatively low, with orthophosphorus and dissolved phosphorus concentrations mostly below the laboratory reporting limit at the three sites. War Eagle Creek had significantly greater median orthophosphorus and total phosphorus concentrations than the White River and Richland Creek. Dissolved organic-carbon concentrations were significantly greater at the White River than at War Eagle and Richland Creeks. The White River also had significantly greater turbidity than War Eagle Creek and Richland Creek.

The temperature distribution in Beaver Lake exhibits the typical seasonal cycle of lakes and reservoirs located within similar latitudes. Beaver Lake is a monomictic system, in which thermal stratification occurs annually during the summer and fall and complete mixing occurs in the winter. Isothermal conditions exist throughout the winter and early spring.

Nitrogen concentrations varied temporally, longitudinally, and vertically in Beaver Lake for 2001 through 2003. Nitrite plus nitrate concentrations generally decreased from the upstream portion of Beaver Lake to the downstream portion and generally were greater in the hypolimnion. Total ammonia plus organic nitrogen concentrations also decreased from the upstream end of Beaver Lake to the downstream end and were substantially greater in the hypolimnion of Beaver Lake. Phosphorus concentrations mostly were near or below laboratory detection limits in the epilimnion and metalimnion in Beaver Lake and were substantially greater in the hypolimnion in the upstream and middle parts of the reservoir. Measured total and dissolved organic carbon in Beaver Lake was relatively uniform spatially, longitudinally, and vertically in the reservoir from January 2001 through December 2003. Chlorophyll *a* concentrations measured at sites in the upstream portion of the lake were significantly greater than at the other sites in the downstream portion of Beaver Lake.

During the study period, water clarity in Beaver Lake was significantly greater at the downstream end of the reservoir than at the upstream end. The greatest Secchi depths at the downstream end of the reservoir generally were observed in 2001 compared to 2002 and 2003, but did not have a seasonal pattern as observed at sites in the middle and upstream portion of the reservoir. Similar to Secchi depth results, turbidity results indicated greater water clarity in the downstream portion of Beaver Lake compared to the upstream portion. Turbidity also was greater in the hypolimnion than in the epilimnion in the reservoir during the stratification season.

A two-dimensional, laterally averaged, hydrodynamic, and water-quality model using CE-QUAL-W2 Version 3.1 was developed for Beaver Lake and calibrated based on vertical profiles of temperature and dissolved oxygen, and water-quality constituent concentrations collected at various depths at four sites in the reservoir from April 2001 to April 2003. Simulated temperatures and dissolved-oxygen concentrations compared reasonably well with measured temperatures and dissolved-oxygen concentrations and differences varied spatially in Beaver Lake for April 2001 to April 2003. The greatest differences between measured and simulated temperature data occurred in the upstream portion of the reservoir, which is the most dynamic part of the reservoir. In general, the differences between measured and simulated temperature were the least in 2001 at the two upstream sites and in 2002 at the two downstream sites, and greatest in 2003 for all four sites. Similar to temperature, differences between simulated and measured values of dissolved-oxygen concentrations were greater in the upstream portion of the reservoir compared to differences in the downstream portion. At the upstream portion of the reservoir, the greatest differences between simulated and measured dissolved oxygen generally occurred in 2002 and the least differences occurred in 2003. Simulated ammonia and total nitrogen

concentrations in Beaver Lake compared relatively well with the measured concentrations and simulated nitrite plus nitrate concentrations generally were less then the measured concentrations. Simulated values for orthophosphorus were comparable to measured concentrations and simulated total phosphorus concentrations generally were greater than the measured concentrations in Beaver Lake. Simulated chlorophyll *a* values were comparable to measured chlorophyll *a* values both spatially and temporally in Beaver Lake.

Introduction

Beaver Lake is a large, deep-storage reservoir located in the upper White River Basin in northwestern Arkansas. The reservoir was completed in 1963 for the purposes of flood control, hydroelectric power, and water supply. In addition, the reservoir is used for fish and wildlife habitat, recreation, and waste assimilation.

Beaver Lake is affected by both 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 the backwater of the reservoir. The city of West Fork discharges its sewage effluent into the West Fork of the White River and the city of Huntsville discharges its effluent into a tributary of War Eagle Creek. Nutrients, sediment, pathogenic bacteria, and other constituents can enter Beaver Lake through its tributaries and around its shoreline.

The water quality of Beaver Lake recently has become a focus of environmental concern because of the rapid population growth in northwestern Arkansas and because of agricultural activities in the basin. The greatest increase in population in the State of Arkansas from 1990 to 2000 occurred in Benton County (57 percent), Washington County (39 percent), and Carroll County (39 percent) (Arkansas Institute for Economic Advancement, 2004). The principal agricultural activity in the area is poultry production. As a result of the potential effects from population growth and activities in the watershed, there is concern about the current and future water-quality in Beaver Lake. Information is needed to assess current conditions and future reservoir water quality so water-resource managers can better manage the hydrologic system. From 2001 through 2003, a study was conducted by the U.S. Geological Survey (USGS) in cooperation with the U.S. Army Corps of Engineers (USACE), Beaver Water District, and the Arkansas Department of Environmental Quality (ADEQ) to assess the ambient water quality in Beaver Lake and its inflows and to develop a model that simulated current water-quality conditions.

The calibrated Beaver Lake model can be used in the future for the evaluation of different nutrient and sediment loading scenarios and conservative tracer simulations. Results of the nutrient and sediment loading scenarios for Beaver Lake can be used to assist the ADEQ in the development of water-quality criteria for its designated uses. Historically, Arkansas' water-quality standards for lakes have been adapted from the surface-water quality standards for streams. The standards, criteria, and assessment methodology for streams may not be well adapted to assess lake water quality where only a few data points exist. Another application of the model is the use of conservative tracer simulations to evaluate the time of travel of a conservative constituent from different locations on Beaver Lake to the four public water-supply intakes for response to possible spills that may occur on the reservoir.

Purpose and Scope

The purpose of this report is to describe the ambient hydrologic and water-quality conditions in Beaver Lake and its inflows and to describe a two-dimensional model developed to simulate the hydrodynamics and water quality of Beaver Lake from 2001 through 2003. Hydrologic and water-quality data are summarized for the period of January 2001 through December 2003 for streamflow, reservoir water-surface elevation, outflow, and selected water-quality characteristics including temperature, dissolved-oxygen concentrations, nutrient concentrations, organic-carbon concentrations, and chlorophyll *a* concentrations. Estimated loads of nutrients and organic carbon for the three main inflows to Beaver Lake are presented.

Hydrodynamics and water-quality characteristics in Beaver Lake were simulated using the USACE CE-QUAL-W2 Version 3.1 model. The laterally averaged, two-dimensional model was calibrated by using data collected from April 2001 to April 2003. The model was used to simulate the ambient conditions in Beaver Lake from April 2001 to April 2003.

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 capacity (Haggard and Green, 2002). The conservation capacity of the reservoir is the storage capacity used for hydroelectric power, water supply, fish and wildlife, recreation, and water quality (U.S. Corps of Engineers, 1997). The main inflows into Beaver Lake are the White River, Richland Creek, and War Eagle Creek (fig. 1). Several smaller tributaries also flow into the reservoir. The basin 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 NGVD of 1929) and the surface area is 114 km^2 (Haggard and Green, 2002). 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 60 m, and the average depth through the reservoir is 18 m (Haggard and Green, 2002).

Beaver Lake has three distinct zones with unique and dynamic physical, chemical, and biological characteristics that are typical for large reservoirs; a riverine, transitional, and a lacustrine zone (Wetzel, 2001). The riverine zone is relatively narrow, the water is well-mixed, and velocities are high enough to move fine suspended particles (silts, clays, and particulate

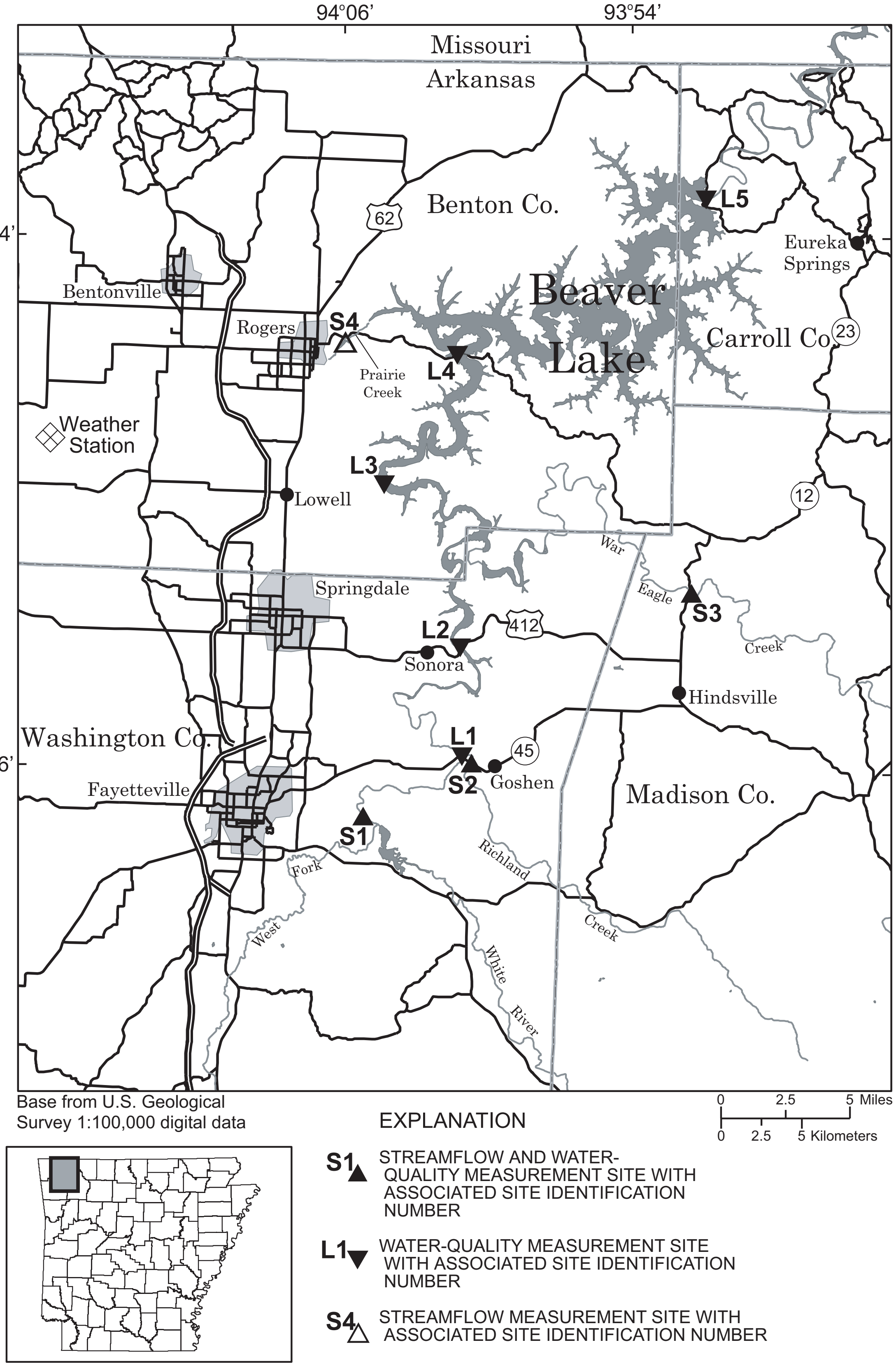

Figure 1. Beaver Lake study area, Arkansas, with locations of data-collection sites.

matter) through advective transport. High particulate turbidity reduces light penetration and limits algal production in this zone (Wetzel, 2001). Decomposition of organic matter usually is high, which consumes a substantial amount of dissolved oxygen in the water column. In the transitional zone, water velocities decrease as energy is dispersed over a larger area. A large portion of the suspended load settles out of the water column, enhancing the depth of light penetration, which increases the rates of photosynthetic productivity of algae in this zone. Anoxic conditions in the hypolimnion in the transitional zone usually occur early in the stratification season of the reservoir from sediment and biochemical demand from deposited material. The lacustrine zone (or lake-like zone) is characterized by having distinct stratification with small nutrient concentrations resulting in reduced algal production. Sedimentation of organic matter and decomposition in the lacustrine zone is less than in the riverine and transition zones, generally resulting in lower concentrations of nutrients and higher dissolved oxygen in the hypolimnion. The extent of the three zones can be spatially and temporally dynamic with changing inflow and outflow conditions in the reservoir.

Methods

This section describes the methods of data collection and analysis used to describe the ambient conditions in Beaver Lake, Arkansas. Streamflow and water-quality data were collected at four tributaries to Beaver Lake from January 2001 through December 2003. Annual constituent loads were estimated from streamflow and water-quality data at three of the tributary sites for the period. Water-quality data also were collected at five sites in Beaver Lake for the same period.

Streamflow

Stream stage was measured continuously at the White River near Fayetteville (site S1), Richland Creek at Goshen (site S2), War Eagle Creek near Hindsville (site S3), and Prairie Creek northeast of Rogers (site S4) (fig. 1 and table 1). Stage and instantaneous discharge were measured to compute the continuous streamflow from stage-discharge rating curves using methods described in Rantz and others (1982). Outflow data from Beaver Lake were produced by the USACE using stage-discharge relations and hourly power generation records for the period of January 2001 through December 2003 (John Kielczewski, U.S. Army Corps of Engineers, written commun., 2003).

Water-Quality Sampling

Water-quality samples were collected from April 2001 through December 2003 at five fixed sites established along the downstream gradient of Beaver Lake. Sample sites in the lake were located along the original stream channel, the deepest location within the lake cross section. Samples were collected on the White River near Goshen (site L1), at Highway 412 Bridge near Sonora (site L2), near Lowell (site L3), at Highway

Table 1. Water-quality and streamflow sites for Beaver Lake, Arkansas.

[Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD83)]

Site identification number (figure 1)	Station number	Station name	Station type	Latitude	Longitude
S1	07048600	White River near Fayetteville	Streamflow, water quality	36°04’23”	94°04’52”
S2	07048800	Richland Creek at Goshen	Streamflow, water quality	36°06’15”	94°00’28”
S3	07049000	War Eagle Creek near Hindsville	Streamflow, water quality	36°12’00”	93°51’18”
S4	07049563	Prairie Creek northeast of Rogers	Streamflow	36°20’25”	95°05’51”
L1	07048700	White River near Goshen	Water quality	36°06’21”	94°00’41”
L2	07048910	Beaver Lake at Highway 412 Bridge near Sonora	Water quality	36°10’00”	94°00’26”
L3	07049200	Beaver Lake near Lowell	Water quality	36°15’33”	94°04’08”
L4	07049500	Beaver Lake at Highway 12 Bridge near Rogers	Water quality	36°19’56”	94°01’08”
L5	07049690	Beaver Lake near Eureka Springs	Water quality	36°25’15”	93°50’50”

12 Bridge near Rogers (site L4), and near Eureka Springs (site L5) (fig. 1 and table 1). Samples were collected using a peristaltic pump and hose to collect samples at 2 m below the water surface once a month when isothermal and well-mixed conditions were present. During thermal stratification, samples were collected twice a month at 2 m below the water surface to represent the epilimnion (near surface), at variable depths in the metalimnion depending on the depth of the thermocline (middle depth), and at 2 m above the reservoir bottom to represent the hypolimnion (near bottom). Water-quality samples were analyzed for concentrations of nutrients (dissolved nitrite plus nitrate, total ammonia plus organic nitrogen, dissolved orthophosphorus, dissolved phosphorus, total phosphorus), total and dissolved organic carbon, iron, manganese, and turbidity. Samples collected in the epilimnion also were analyzed for chlorophyll *a* and phytoplankton composition. All sample analyses were conducted at USGS laboratories following USGS procedures (Fishman, 1993). Field measurements (water temperature, dissolved-oxygen concentration, pH, and specific conductance) also were measured at various depths at the time of sample collection. When thermal stratification was present, field measurements were made at depth intervals where the change in water temperature was approximately 1 °C or at 0.3-m intervals, whichever was greater. Secchi depth also was measured at each site as an indicator of water clarity.

Water-quality samples also were collected from three fixed inflow sites including the White River near Fayetteville (site S1), Richland Creek at Goshen (site S2), and War Eagle Creek near Hindsville (site S3), from April 2001 through December 2003 (fig. 1 and table 1). Water-quality samples were collected following equal-width increment methods using depth-integrated samplers and processed using protocols described in Wilde and Radke (1998), Wilde and others (1998a, 1998b, 1998c, 1999a, and 1999b), and Meyers and Wilde (1999). Samples were analyzed for nutrients, dissolved organic carbon, turbidity, suspended sediment, and fecal indicator bacteria (fecal coliform and fecal streptococci). Field measurements, including water temperature, dissolved-oxygen concentration, pH, and specific conductance, also were collected with each sample. Water-quality samples were collected monthly and during selected surface-runoff events.

Constituent Loads

Nutrient and organic carbon loads were estimated for three main inflows to Beaver Lake; the White River near Fayetteville (site S1), Richland Creek at Goshen (site S2), and War Eagle Creek near Hindsville (site S3) (fig. 1). Constituent load (L) is a function of the volumetric rate of water passing a point in the stream (Q) and the constituent concentration within the water (C). Regression methods used to estimate constituent loads use the natural logarithm (ln) transformed relation between Q and C to estimate daily C (or L) of the constituent. The regression method can account for non-normal data distributions, seasonal and long-term cycles, censored data, biases associated with using logarithmic transformations, and serial correlations of the residuals (Cohn, 1995). The regression method uses discrete water-quality samples often collected over several years and a daily streamflow hydrograph. Seasonality and time were not included in the regression analysis described in this report because the period of data collection was too short (3 years) to describe or identify seasonal or temporal trends in the data for the regression model. Therefore, only the relations between natural logarithmic-transformed L and Q were used:

$$\ln(L) = \beta_o + \beta_1 \ln(Q) \qquad (1)$$

Transforming the results of the model from logarithmic space to real space was accomplished using two methods; an adjusted maximum likelihood estimator (AMLE) and a least absolute deviation (LAD) (Cohn and others, 1992). The AMLE method was used if the constituent had censored values and the LAD method was used to transform the results if no censored values were included in the data or if outliers in the residuals were present. The S-LOADEST computer program (Runkel and others, 2004) was used to estimate daily loads for calendar years 2001 through 2003.

Data Analysis

The resulting streamflow and water-quality data (inflow and lake samples) were analyzed or summarized using several statistical and graphical techniques. Boxplots and time-series plots were used to compare concentrations of selected water-quality constituents between sites for data collected from April 2001 through December 2003. Concentrations reported as less than a laboratory reporting limit were converted to one-half the reporting limit for preparation of boxplots, calculation of total nitrogen concentrations (the sum of nitrite plus nitrate and ammonia plus organic nitrogen), and statistical analyses. The Wilcoxon rank sum test (Helsel and Hirsch, 1992) was used to test for differences in selected water-quality constituents between sites. The Wilcoxon rank sum test is a nonparametric test that determines the probability (p) that the mean of a dataset is similar to the mean of another dataset. A locally weighted smooth (LOWESS) line was included in some of the scatter plots of constituent concentrations with time. The LOWESS line is a locally weighted polynomial regression, where at each point along the line, a low-degree polynomial is fit to a subset of the data. The polynomial is fit using weighted least squares, giving more weight to points near the point whose response is being estimated and less weight to points further away.

Ambient Conditions

This section describes the ambient hydrologic and water-quality conditions for Beaver Lake from January 2001 through December 2003. Streamflow in the three major tributaries, outflow at Beaver Lake dam, and water-surface elevation for Beaver Lake are described for the period. In addition, water-quality conditions for the three major tributaries and for five sites on Beaver Lake are described for January 2001 through December 2003.

Hydrologic Conditions

Streamflow varied substantially during the period of January 2001 through December 2003 for the three major tributaries that provide inflow to Beaver Lake (fig. 2). The White River is the main inflow into Beaver Lake and approximately 34 percent of the drainage area at Beaver Lake dam is above the gaging station near Fayetteville (site S1; fig. 1). The daily mean streamflow for the White River ranged from 0.05 to 792 m^3/s for the period of January 2001 through December 2003. The streamflow was greatest in calendar year 2002 with an annual mean of 16.1 m^3/s and 2003 had the least streamflow with an annual mean of 10.3 m^3/s. The mean daily streamflow for the period was 13.6 m^3/s, which was less than the mean daily streamflow for the period of record (1963-1994, 1998-2003; 15.7 m^3/s) (Brossett and others, 2005). The drainage area of Richland Creek at the gaging station at Goshen (site S2; fig. 1) comprises 12 percent of the drainage area at Beaver Lake dam. The daily mean streamflow for Richland Creek ranged from 0.012 to 225 m^3/s for the period of January 2001 through December 2003, with a mean daily streamflow of 3.47 m^3/s for the period. Similar to the White River, the annual mean streamflow was greatest in 2002 (4.73 m^3/s) and least in 2003 (2.49 m^3/s). War Eagle Creek at the gaging station near Hindsville (site S3; fig. 1) has a drainage area that comprises 22 percent of the drainage area at Beaver Lake dam. The daily mean streamflow for War Eagle Creek ranged from 0.26 to 479 m^3/s for the period of January 2001 through December 2003, with a mean daily streamflow of 7.30 m^3/s for the period. All three tributaries had the greatest streamflow in March 2001 and from January 2002 to May of 2002 (fig. 2). The least streamflow occurred from September through December during all 3 years (2001 through 2003).

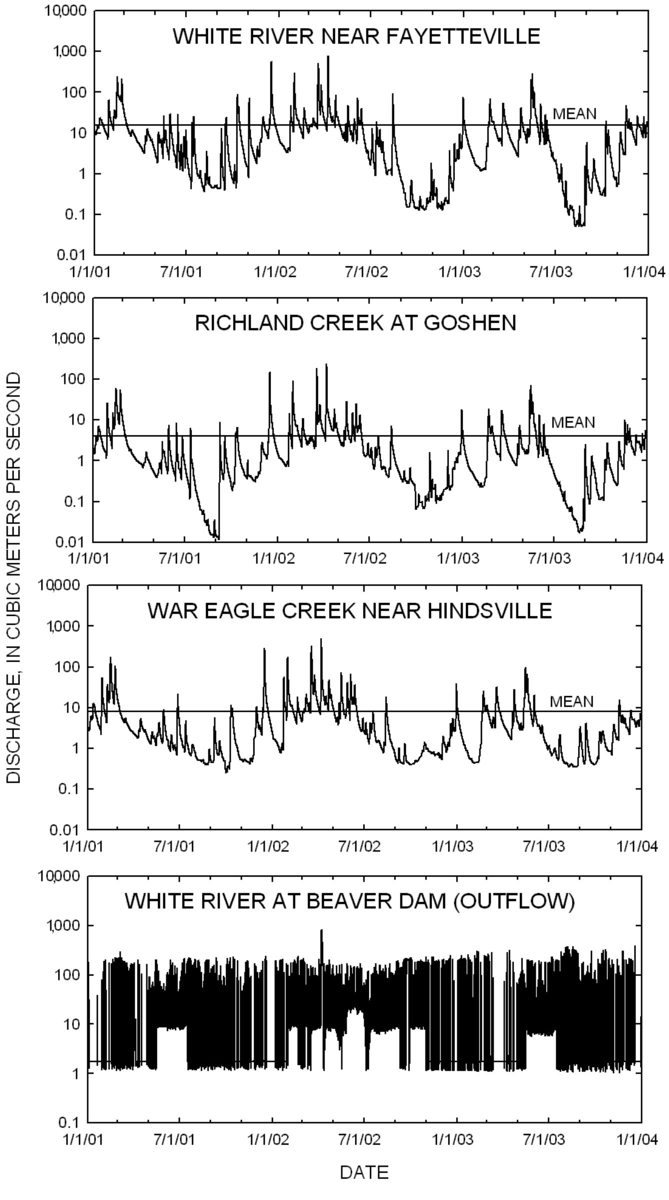

Figure 2. Daily inflow and hourly outflow for Beaver Lake, Arkansas, January 2001 through December 2003.

The outflow from Beaver Lake also varied substantially for the period of January 2001 through December 2003 (fig. 2). Outflow discharge at Beaver Dam ranged from 1.76 m^3/s to 828 m^3/s with a mean outflow discharge of 29.3 m^3/s for the period. Four public water-supply withdrawals also are located on Beaver Lake. Total annual mean withdrawal from all four public water supplies was approximately 2.41 m^3/s for the period (Terrance W. Holland, U.S. Geological Survey, oral commun., 2004).

The pool elevation (water-surface elevation) for Beaver Lake varied according to changes in the inflow and outflow for the reservoir (fig. 3). The pool elevation remained below the top

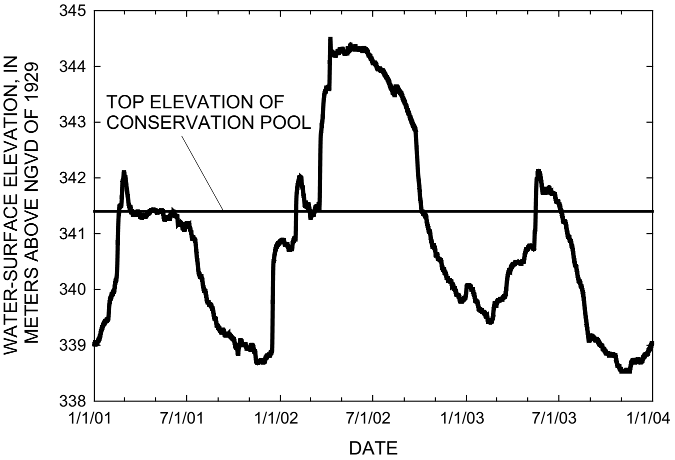

Figure 3. Daily reservoir water-surface elevation near Beaver Lake dam, January 2001 through December 2003.

of conservation pool (341.4 m above NGVD of 1929) for most of 2001 and reached a minimum elevation of 338.7 m above NGVD of 1929 on November 15, 2003. The pool elevation rose above the top of the conservation pool into the flood pool in February 2002 and reached a maximum elevation of 344.5 m above NGVD of 1929 on April 9, 2002.

Water-Quality Conditions

Inflow Water Quality

Water-quality samples were collected at the three main inflows to Beaver Lake; the White River near Fayetteville (site S1), Richland Creek at Goshen (site S2), and War Eagle Creek near Hindsville (site S3) (fig. 1). The inflows were sampled for nutrients, dissolved organic carbon, turbidity, and suspended sediment. Annual loads were estimated for nutrients and organic carbon using the constituent concentrations and daily streamflow at each station.

Nutrient concentrations varied among the tributaries because of differences in land use and contributions of nutrients from point sources. The White River had significantly (p-value <0.05) greater concentrations of total ammonia plus organic nitrogen among the three tributaries (figs. 4 and 5), probably because of a wastewater discharge upstream from the site on the West Fork of the White River. The median concentration of total ammonia plus organic nitrogen for the White River was 0.30 mg/L as nitrogen, Richland Creek had a median concentration of 0.20 mg/L as nitrogen, and War Eagle Creek had a median concentration of 0.10 mg/L as nitrogen. The White River (site S1) and Richland Creek (site S2) had median nitrite plus nitrate concentrations of 0.36 and 0.85 mg/L as nitrogen, respectively, and median concentrations of total nitrogen of 0.74 and 1.1 mg/L as nitrogen, respectively. The greatest concentrations of nitrite plus nitrate and total nitrogen, however, were observed at War Eagle Creek (site S3). The median concentrations of nitrite plus nitrate and total nitrogen for War Eagle Creek were 1.2 and 1.4 mg/L as nitrogen, respectively. War Eagle Creek has the greatest percentage of agricultural land use in the basin (36 percent) compared to the White River near Fayetteville drainage (23 percent) and Richland Creek drainage (34 percent) (U.S. Geological Survey, 2002), which may explain the greater nitrogen concentrations. Phosphorus concentrations were relatively low, with orthophosphorus and dissolved phosphorus concentrations mostly below the laboratory reporting limits (0.01 mg/L for orthophosphorus and 0.02 mg/L for dissolved phosphorus) at the three sites. War Eagle Creek had significantly greater median orthophosphorus, dissolved phosphorus, and total phosphorus concentrations (0.03, 0.03, and 0.04 mg/L as phosphorus, respectively) than the White River (0.01, 0.02, and 0.03 mg/L as phosphorus, respectively) and Richland Creek (0.01, 0.02, and 0.02 mg/L as phosphorus, respectively) (fig. 4).

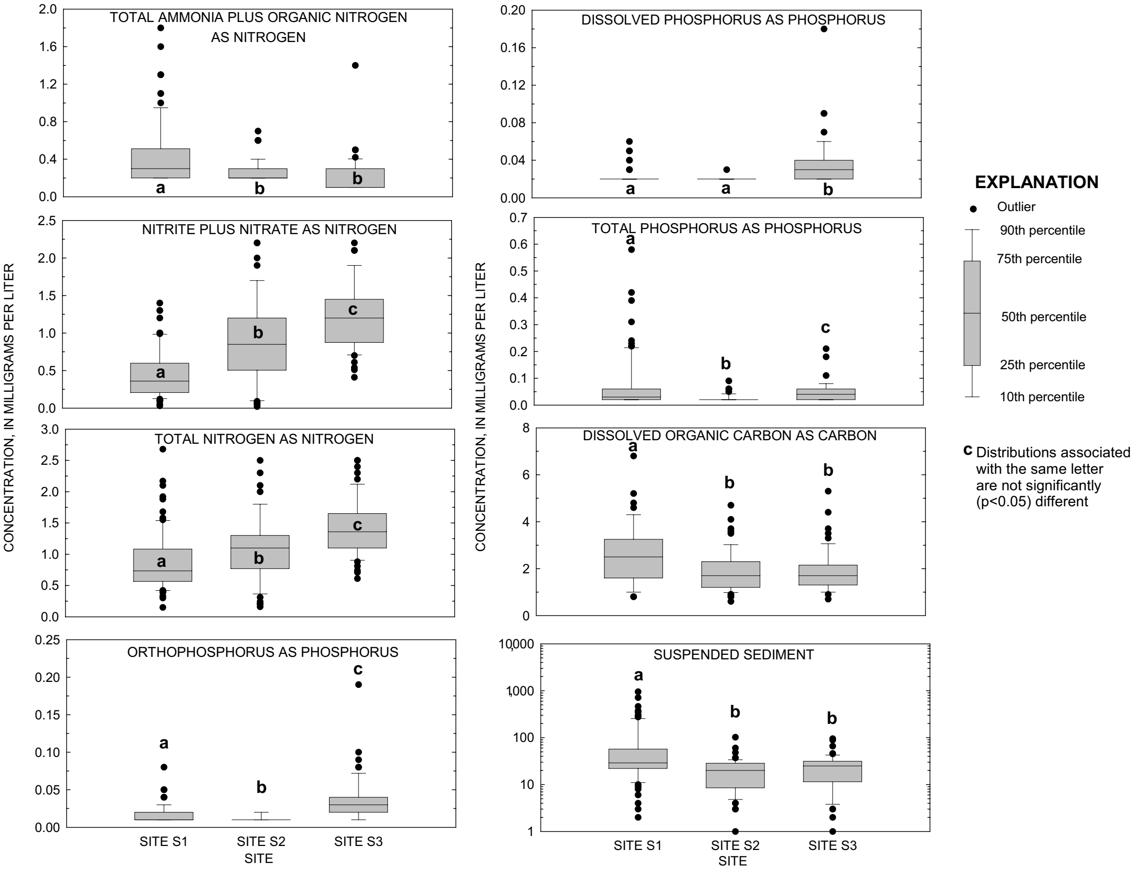

Figure 4. Distribution of nutrients, dissolved organic carbon, and suspended-sediment concentrations for the White River near Fayetteville (site S1), Richland Creek at Goshen (site S2), and War Eagle Creek near Hindsville (site S3), 2001-2003.

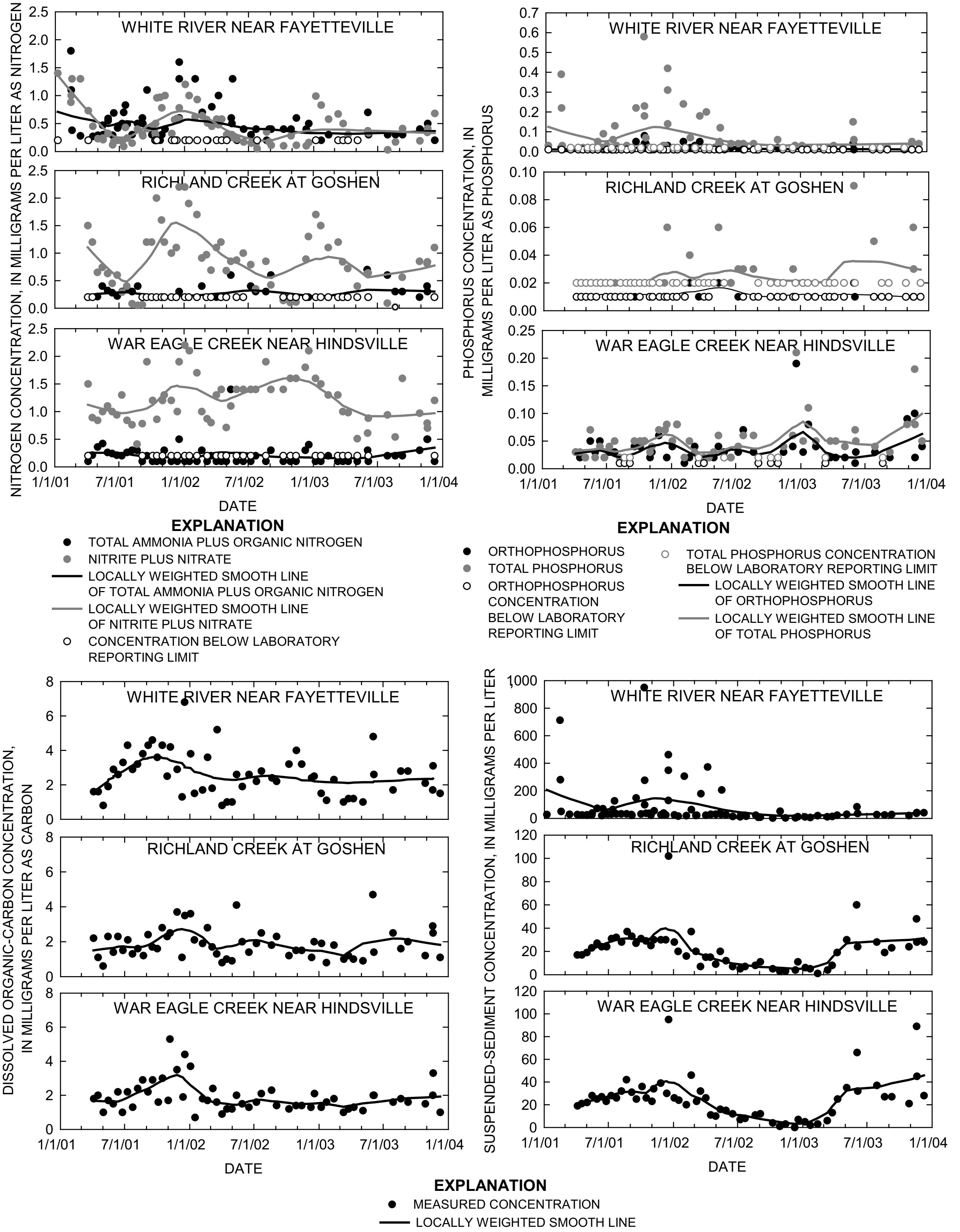

Figure 5. Time series of nutrients, dissolved organic-carbon, and suspended-sediment concentrations for the White River near Fayetteville (site S1), Richland Creek at Goshen (site S2), and War Eagle Creek near Hindsville (site S3), 2001-2003.

Dissolved organic-carbon concentrations were significantly greater for the White River than for War Eagle and Richland Creeks (figs. 4 and 5). The median dissolved organic-carbon concentration for the White River was 2.5 mg/L as carbon, which was approximately 1.5 percent greater than the median concentrations at War Eagle and Richland Creeks (1.7 mg/L as carbon).

Suspended-sediment concentrations also were significantly greater for the White River compared to War Eagle Creek and Richland Creek (figs. 4 and 5). The White River had suspended-sediment concentrations ranging from 2 to 950 mg/L and a median concentration of 29 mg/L. War Eagle Creek had concentrations ranging from less than 1 to 95 mg/L with a median concentration of 25 mg/L. Richland Creek had a median concentration of 20 mg/L with concentrations ranging from 1 to 102 mg/L.

Estimated annual nutrient and organic-carbon loads generally were greater for the White River than for Richland and War Eagle Creeks in 2001 through 2003 (fig. 6). Greater loads would be expected for the White River because of the greater volume of streamflow that occurs at the site. The greatest annual loads occurred in 2002 for all three tributaries and the least occurred in 2003 (fig. 6). Annual total ammonia plus organic nitrogen loads for the White River ranged from 220,000 to 401,000 kg/yr as nitrogen. Nitrite plus nitrate loads ranged from 182,000 to 333,000 kg/yr as nitrogen. Richland Creek had substantially less total ammonia plus organic nitrogen loads and similar nitrite plus nitrate loads compared to the loads estimated for the White River. Total ammonia plus organic nitrogen loads for Richland Creek ranged from 28,000 to 54,400 kg/yr as nitrogen and nitrite plus nitrate loads ranged from 166,000 to 484,000 kg/yr as nitrogen. Total ammonia plus organic nitrogen loads for War Eagle Creek ranged from 46,600 to 114,000 kg/yr as nitrogen and nitrite plus nitrate loads ranged from 171,000 to 419,000 kg/yr as nitrogen. Total phosphorus loads for the White River (32,700 to 68,600 kg/yr as phosphorus) were approximately nine times greater than the loads for Richland Creek (3,560 to 7,640 kg/yr as phosphorus) and approximately three to four times greater than the loads for War Eagle Creek (8,580 to 24,000 kg/yr as phosphorus). Similarly, dissolved organic-carbon loads for the White River (901,000 to 1,610,000 kg/yr as carbon) were approximately five to six times greater than the loads for Richland Creek (160,000 to 323,000 kg/yr as carbon) and approximately two to three times greater than the loads for War Eagle Creek (270,000 to 676,000 kg/yr as carbon).

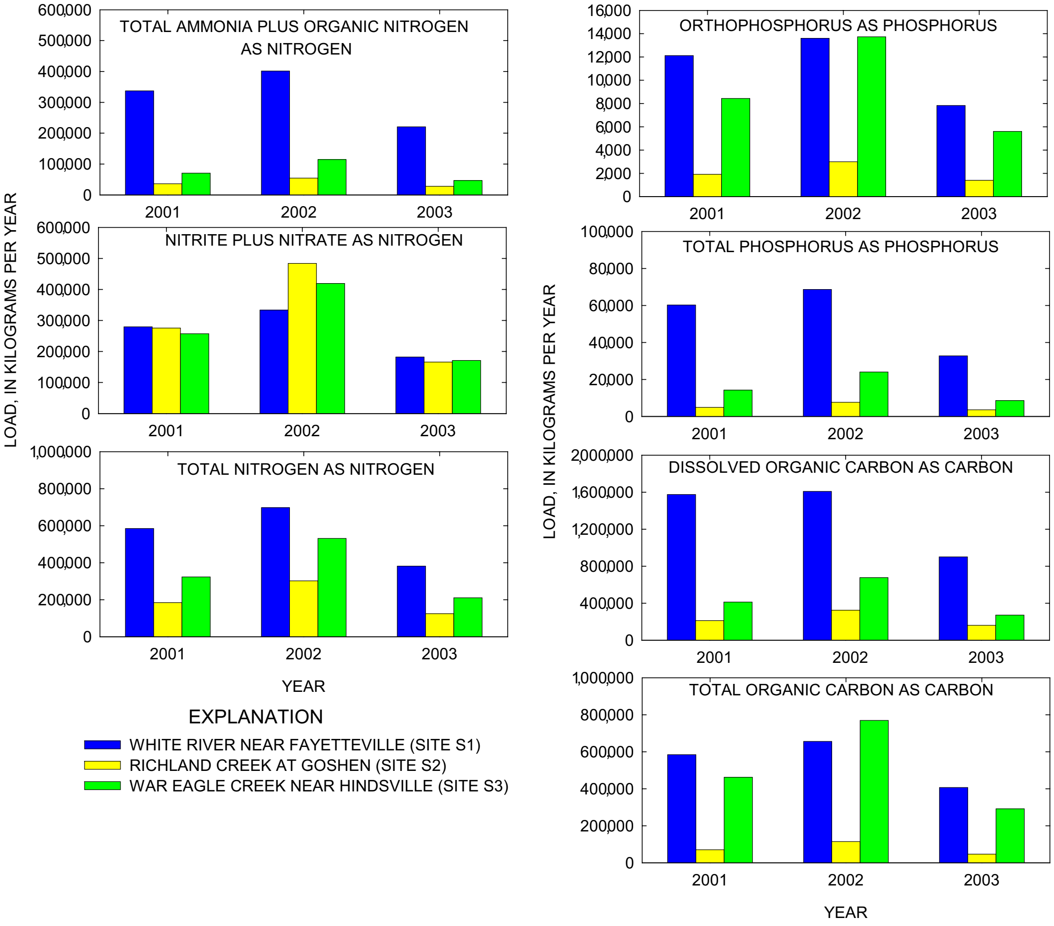

Figure 6. Annual nutrient and organic-carbon loads computed for the White River near Fayetteville, Richland Creek at Goshen, and War Eagle Creek near Hindsville, 2001-2003.

Turbidity measured at the White River was significantly greater than Richland and War Eagle Creeks from 2001 through 2003 (fig. 7). Turbidity is an expression of the optical properties of a sample that causes light rays to be scattered and absorbed rather than transmitted in straight lines through the sample (Gray and Glysson, 2003). Turbidity of water is caused by the presence of suspended and dissolved matter such as clay, silt, small organic matter, plankton, other microscopic organisms, and organic acids. The median turbidity for the White River was 8.6 nephlometric turbidity units (NTUs), and the median turbidities for Richland Creek and War Eagle Creek were 3.8 and 3.4 NTUs, respectively. The greatest values of turbidity generally occurred from October 2001 through April 2002 at all three sites (fig. 7). This period of time also had a substantial number of high-flow events resulting in increased runoff of organic and inorganic material into the streams, which would increase the turbidity. The suspended-sediment concentrations followed a similar pattern with significantly greater median concentrations occurring at the White River (29 mg/L) compared to War Eagle Creek (25 mg/L) and Richland Creek (20 mg/L) (fig. 4), and generally greater concentrations occurring from October 2001 through April 2002.

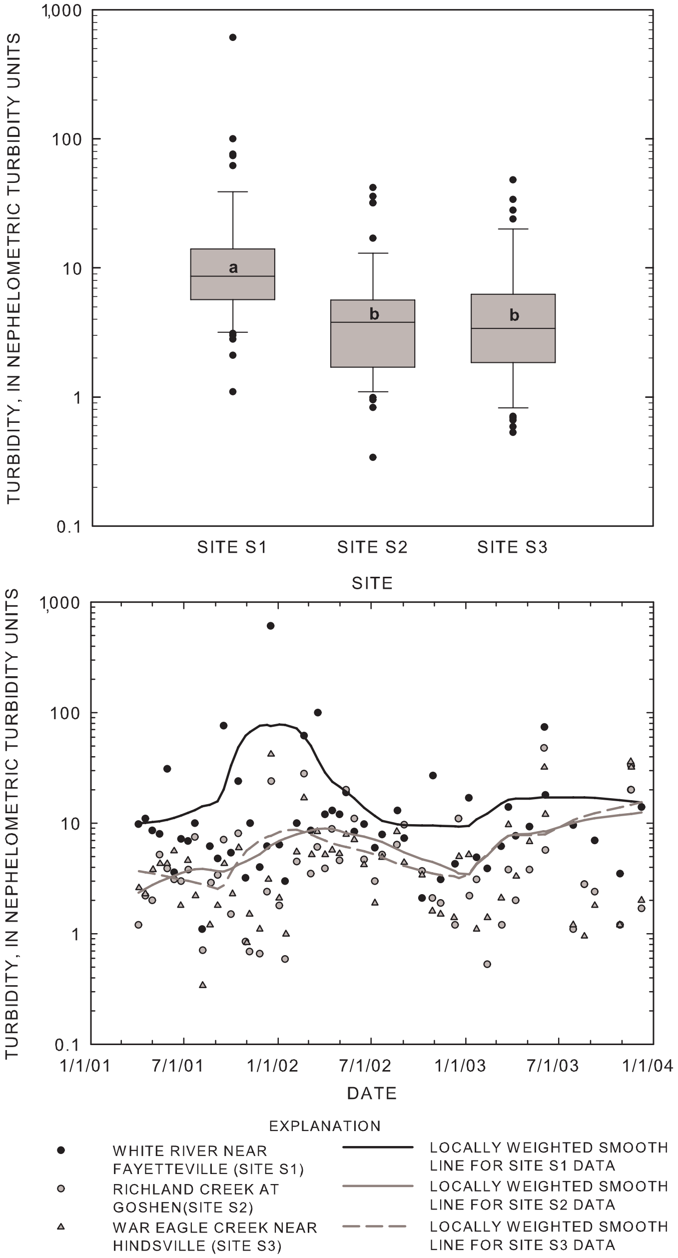

Figure 7. Distribution and time series of turbidity for the White River near Fayetteville (site S1), Richland Creek at Goshen (site S2), and War Eagle Creek near Hindsville (site S3), 2001-2003.

Reservoir Water Quality

Temperature

The temperature distribution in Beaver Lake exhibits the typical seasonal cycle of lakes and reservoirs located within similar latitudes (Wetzel, 2001) (figs. 8 and 9). Beaver Lake is a monomictic system, in which thermal stratification occurs annually during the summer (June through August) and fall (September through November) and complete mixing occurs in the winter (December through February). Isothermal conditions exist throughout the winter and early spring (March through May). Thermal stratification begins in Beaver Lake during May and June and generally becomes established by July (figs. 8 and 9). Thermal stratification is fully developed by late summer. Stratification occurs as the layer of water near the surface heats up during the spring, more rapidly than the heat is distributed throughout the water column, causing temperature or density gradients to develop. The warmer, less dense water remains near the surface and the cooler, more dense water remains near the bottom. As a result of the density gradients, thermal resistance to mixing becomes established, physically isolating the epilimnion or mixing layer from the hypolimnion.

The distribution of dissolved oxygen in Beaver Lake is affected by several factors including thermodynamics in the hypolimnion, algal photosynthesis and respiration, ammonia nitrification, decomposition of organic matter in the sediments and water column, and exchange with the atmosphere (Cole and Hannan, 1990). The solubility of oxygen increases with colder water, while warmer water holds less amounts of dissolved oxygen. Algal photosynthesis produces dissolved oxygen, while respiration consumes dissolved oxygen. Ammonia nitrification also can consume oxygen in the water column as ammonia (NH_3) is converted to nitrate (NO_3). The decomposition of dead algae as well as other organic matter in lake sediments can consume a substantial amount of oxygen in the overlying hypolimnion (Sullivan and Rounds, 2005). Exchange of the water in the epilimnion with the atmosphere can add oxygen to the water column through reaeration. Because the hypolimnion in Beaver Lake is isolated from the surface during periods of thermal stratification, reaeration from atmospheric exchange is eliminated and very little, if any, oxygen input from algal photosynthesis occurs below the thermocline (figs. 8 and 9). Dissolved-oxygen

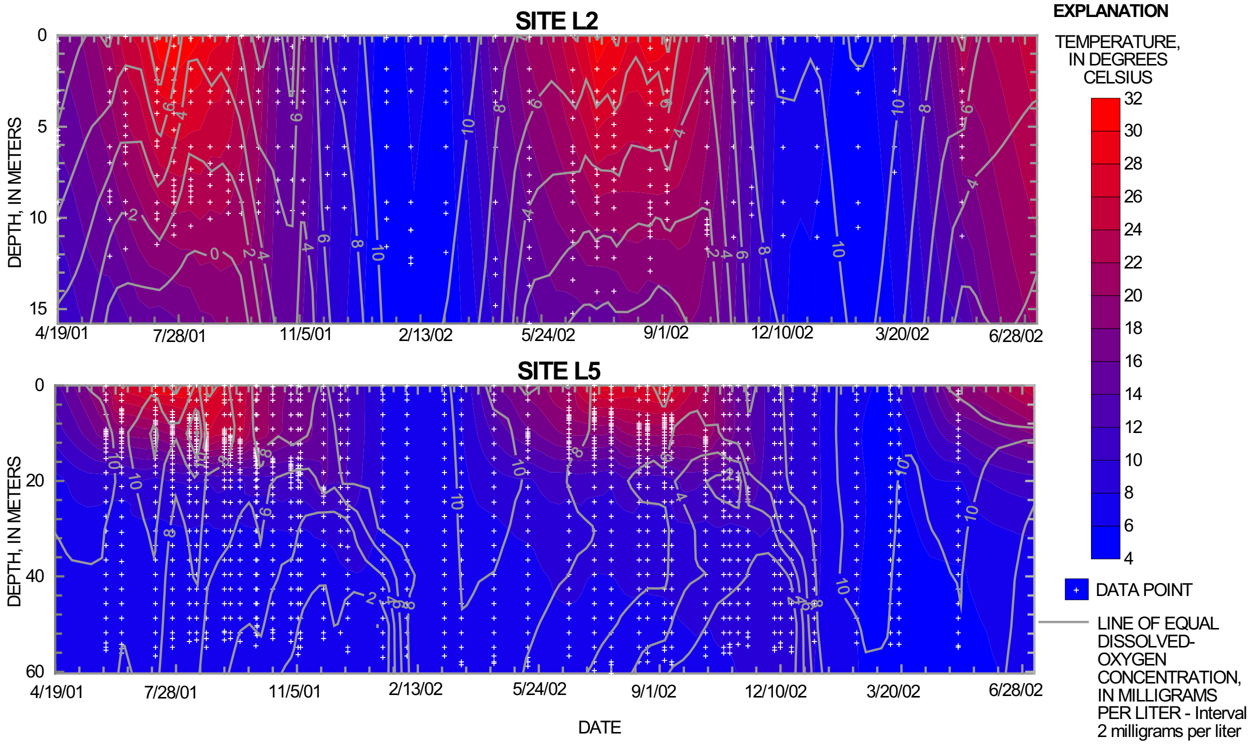

Figure 8. Distribution of temperature and dissolved-oxygen concentration at sites L2 and L5 in Beaver Lake, 2001-2002.

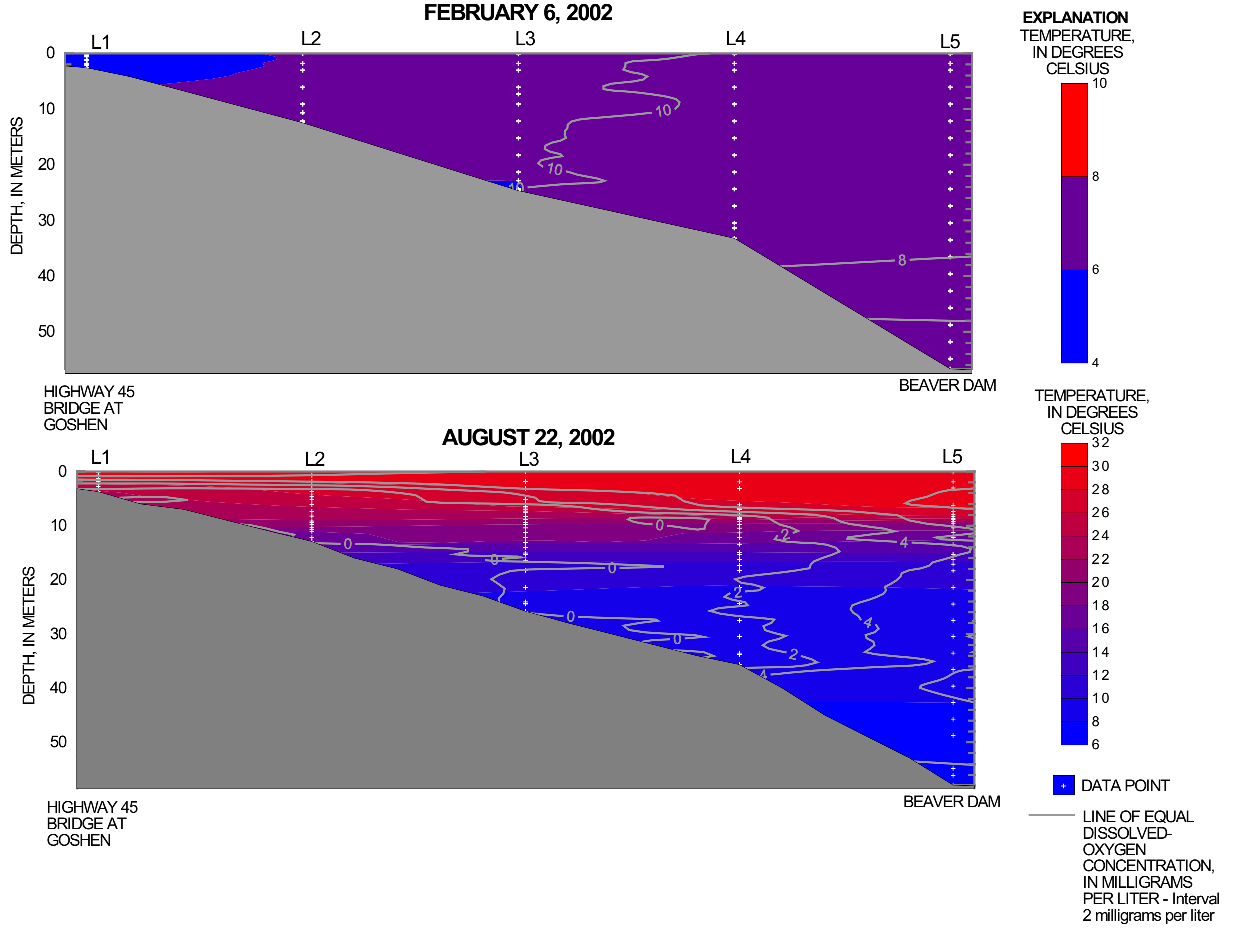

Figure 9. Distribution of temperature and dissolved-oxygen concentration in Beaver Lake on February 6, 2002 and August 22, 2002.

concentrations during the winter remain fairly uniform and near saturation levels because of complete water column mixing and isothermal conditions. As stratification becomes established, dissolved-oxygen concentrations in the hypolimnion decrease because of sediment and biochemical demand, and by summer, conditions in the hypolimnion are nearly anoxic (devoid of oxygen) (figs. 8 and 9).

Nutrients

Nitrogen concentrations varied temporally, longitudinally, and vertically in Beaver Lake for 2001 through 2003. Nitrite (NO_2) plus nitrate (NO_3) concentrations generally decreased from the upstream portion of Beaver Lake (site L1) to the downstream portion (site L5) and generally were greater in the hypolimnion (fig. 10). The median epilimnetic concentration of nitrite plus nitrate ranged from 0.15 mg/L as nitrogen at site L5 to 0.71 mg/L as nitrogen at site L1 and the median hypolimnetic concentration ranged from 0.36 mg/L as nitrogen at site L5 to 0.69 mg/L as nitrogen at site L4. Nitrite plus nitrate concentrations were greatest when the reservoir was isothermal and well oxygenated in the winter and spring probably because of the conversion of ammonia (NH_3) to nitrate (nitritification) (Wetzel, 2001) (fig. 11). Higher inflows also occur in the winter and spring (fig. 2) and may have caused higher nitrite plus nitrate concentrations. In this report, “ammonia” is used to refer to both NH_4^+ (ammonium) and NH_3. Concentrations were least in the summer and fall during stratification probably because of greater algal uptake in the epilimnion and the reduction of nitrate production in the anoxic hypolimnion because oxygen was not present to support nitrification.

Total ammonia plus organic nitrogen concentrations also decreased from the upstream end of Beaver Lake to the downstream end and were substantially greater in the hypolimnion of Beaver Lake (fig. 10). The median epilimnetic concentration of total ammonia plus organic nitrogen ranged from 0.15 mg/L as nitrogen at site L5 to 0.40 mg/L as nitrogen at site L1 and the median hypolimnetic concentration ranged from 0.10 mg/L as nitrogen at site L5 to 0.70 mg/L as nitrogen at site L2. Concentrations were greater in the hypolimnion probably because during stratification, when the hypolimnion becomes anoxic, ammonia can accumulate because oxygen is not present to support nitrification (fig. 11). Ammonia also can be released from organic matter in the sediments under anoxic conditions. When

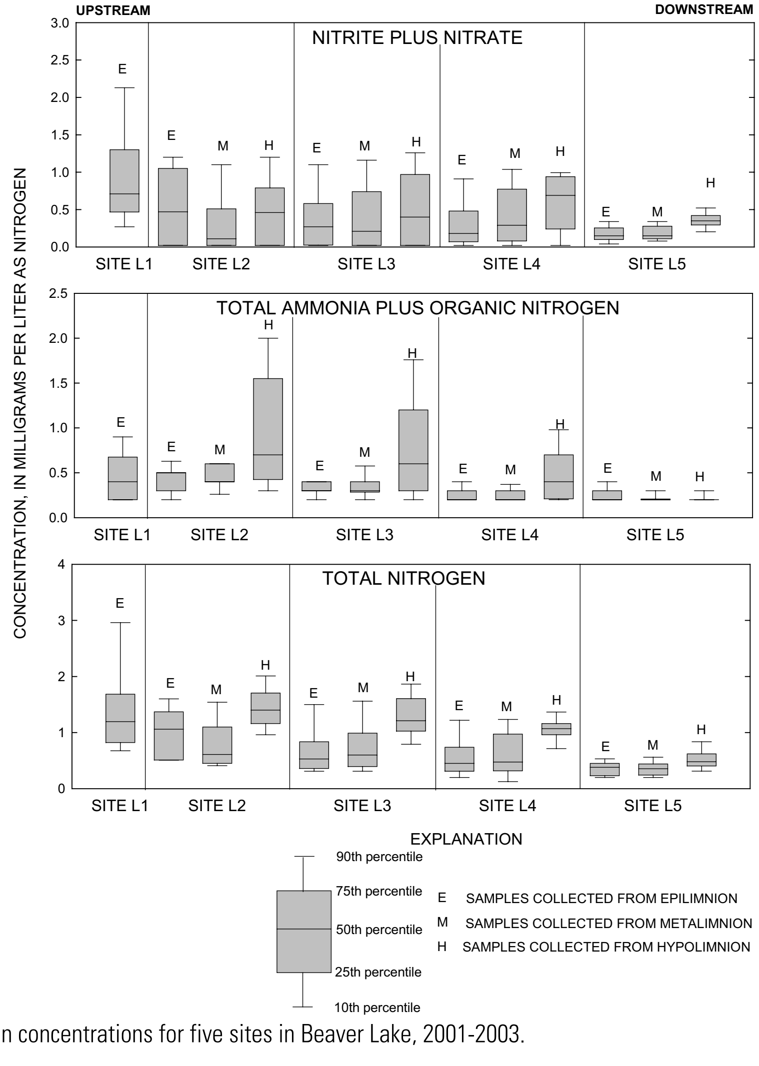

Figure 10. Distribution of nitrogen concentrations for five sites in Beaver Lake, 2001-2003.

the reservoir turns over in early winter and is oxygenated throughout the reservoir, the ammonia is mixed into the entire volume of the reservoir and production is diminished. Total nitrogen concentrations followed similar patterns as the nitrite plus nitrate and total ammonia plus organic carbon with greater concentrations at the upstream sites compared to the downstream sites and with the greatest concentrations in the hypolimnion.

Phosphorus concentrations mostly were near or below laboratory detection limits in the epilimnion and metalimnion in Beaver Lake and were substantially greater in the hypolimnion in the upstream and middle portions of the reservoir (fig. 12). Sources of phosphorus other than inputs from tributaries include algal respiration, decay of organic matter (dissolved, suspended, and sedimentary), and anaerobic release from the lake sediments. Sinks of phosphorus include algal uptake and settling of particles containing or adsorbing phosphorus. High concentrations of phosphorus in the hypolimnion of Beaver Lake occur during stratification in the summer and fall at the upstream (riverine zone) and middle portions (transitional zone) of the reservoir where anoxic conditions occur and most of the particles and suspended material from the inflows are deposited (fig. 13). The anoxic conditions in the hypolimnion allow for the release of phosphorus from the deposited sediments and decaying organic matter. Phosphorus that is adsorbed or coprecipitated to iron oxide solids in oxygenated conditions also can be released from sediments under anoxic conditions when the iron oxide solids can dissolve. Most of the phosphorus is consumed by algal uptake in the epilimnion and metalimnion through the transitional zone of the reservoir leaving low concentrations in the downstream portion (lacustrine zone) of the reservoir (figs. 12 and 13).

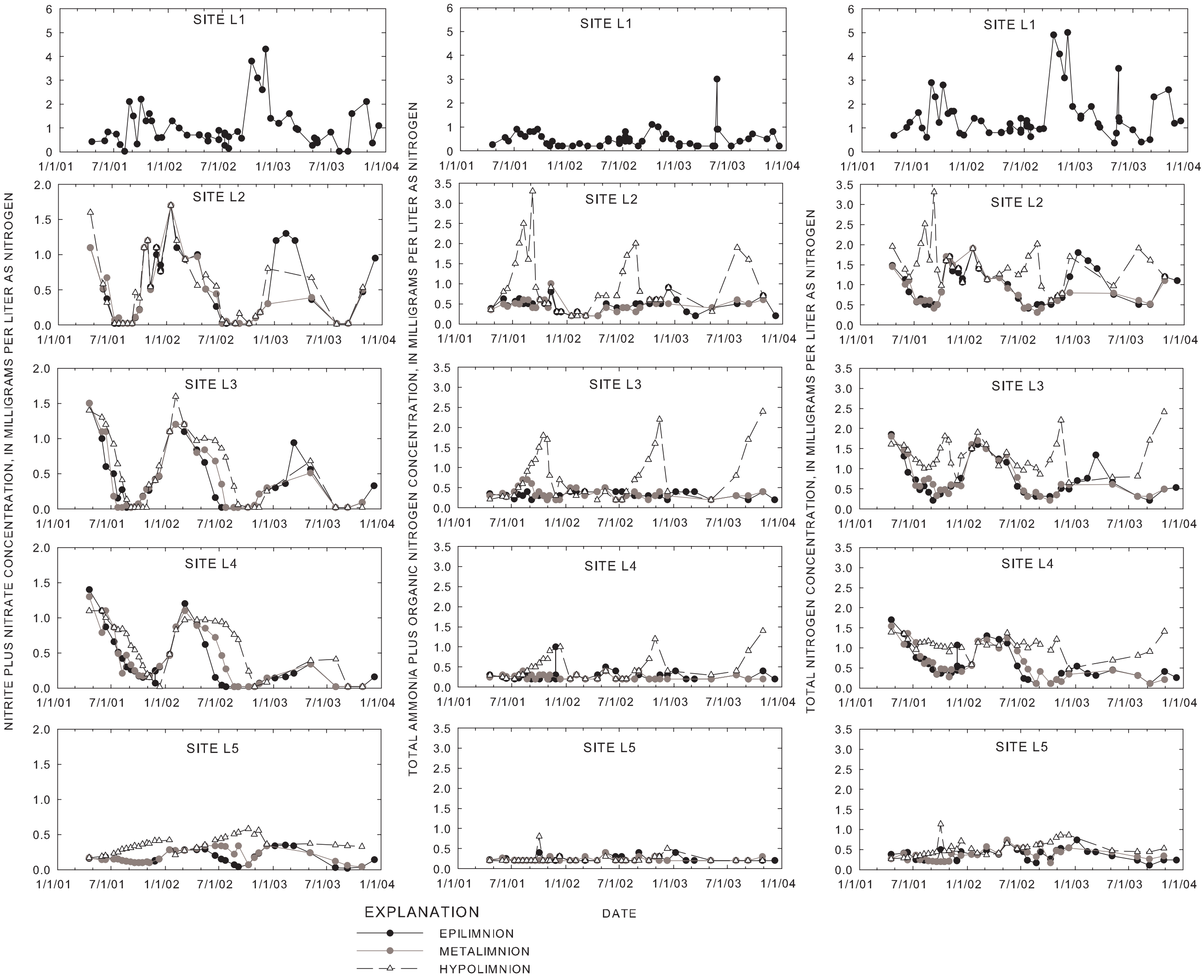

Figure 11. Time series of nitrogen concentrations for five sites in Beaver Lake, 2001-2003.

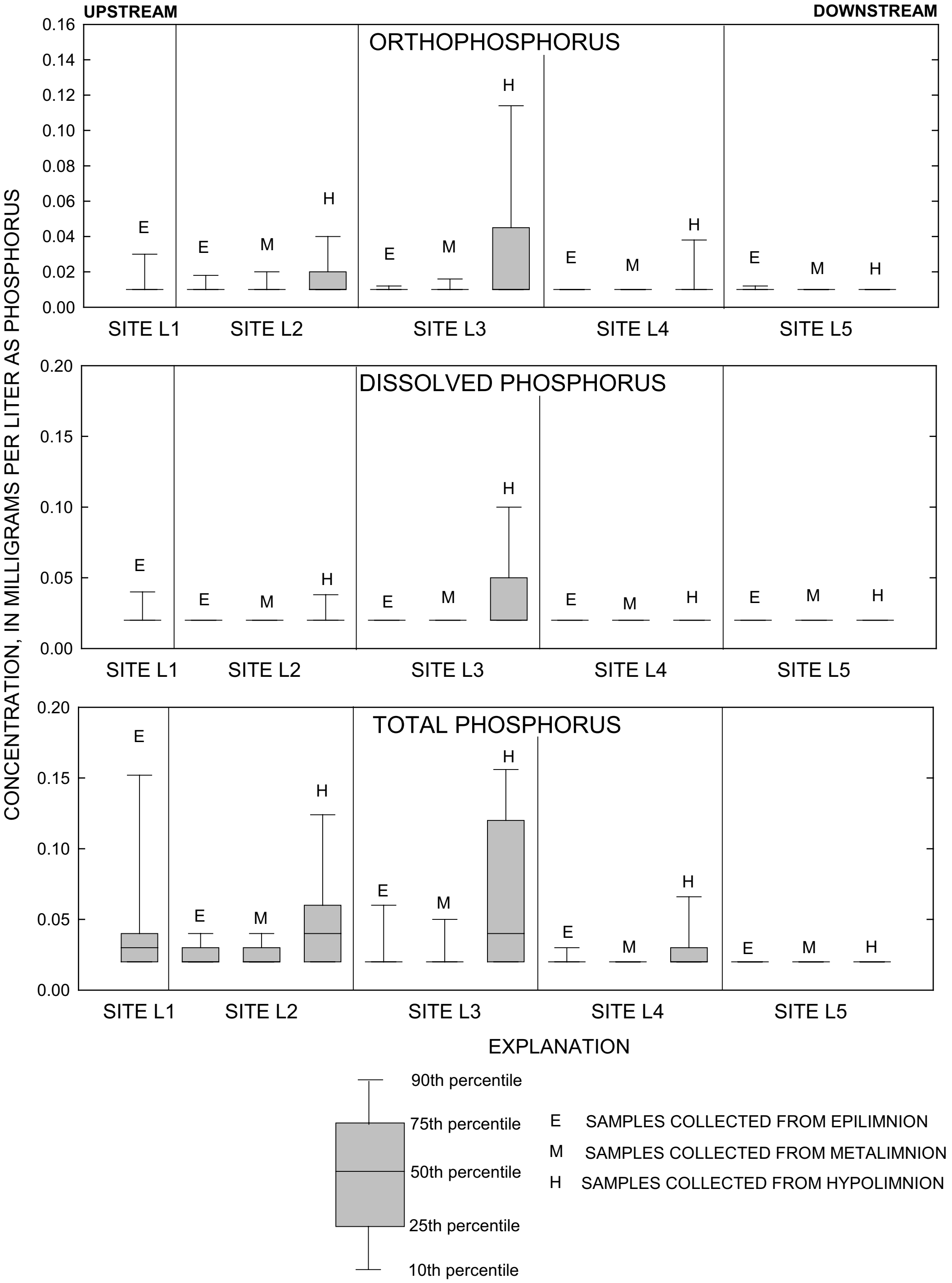

Figure 12. Distribution of phosphorus concentrations for five sites in Beaver Lake, 2001-2003.

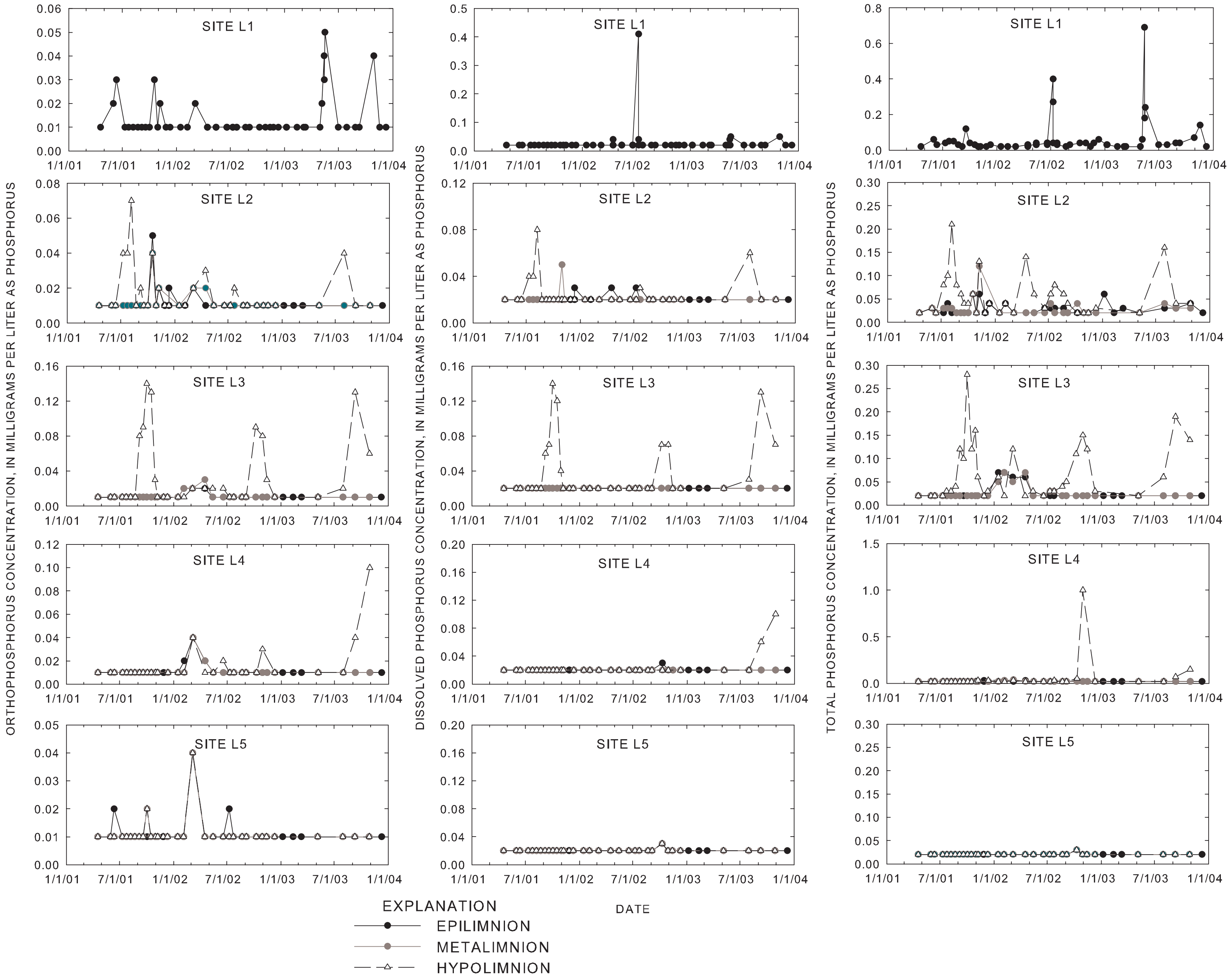

Figure 13. Time series of phosphorus concentrations for five sites in Beaver Lake, 2001-2003.

Organic Carbon

Measured dissolved and total organic carbon in Beaver Lake was relatively uniform spatially, longitudinally, and vertically in the reservoir from January 2001 through December 2003. The main source of dissolved organic carbon is from the inflows and surface runoff into Beaver Lake, which is noticeable by the fluctuations in concentration at the most upstream lake sampling site (L1) (figs. 14 and 15). Another smaller source of organic carbon is from photosynthesis in algae. The median dissolved organic-carbon concentrations ranged from 2.4 (site L4) to 2.9 mg/L as carbon (site L1) in the epilimnion and from 2.1 (site L5) to 3.2 mg/L as carbon (site L2) in the hypolimnion. The median total organic-carbon concentration in Beaver Lake ranged from 2.4 (site L4) to 2.9 mg/L as carbon (sites L1 and L2) in the epilimnion and from 2.2 (site L5) to 3.2 mg/L as carbon (site L3) in the hypolimnion.

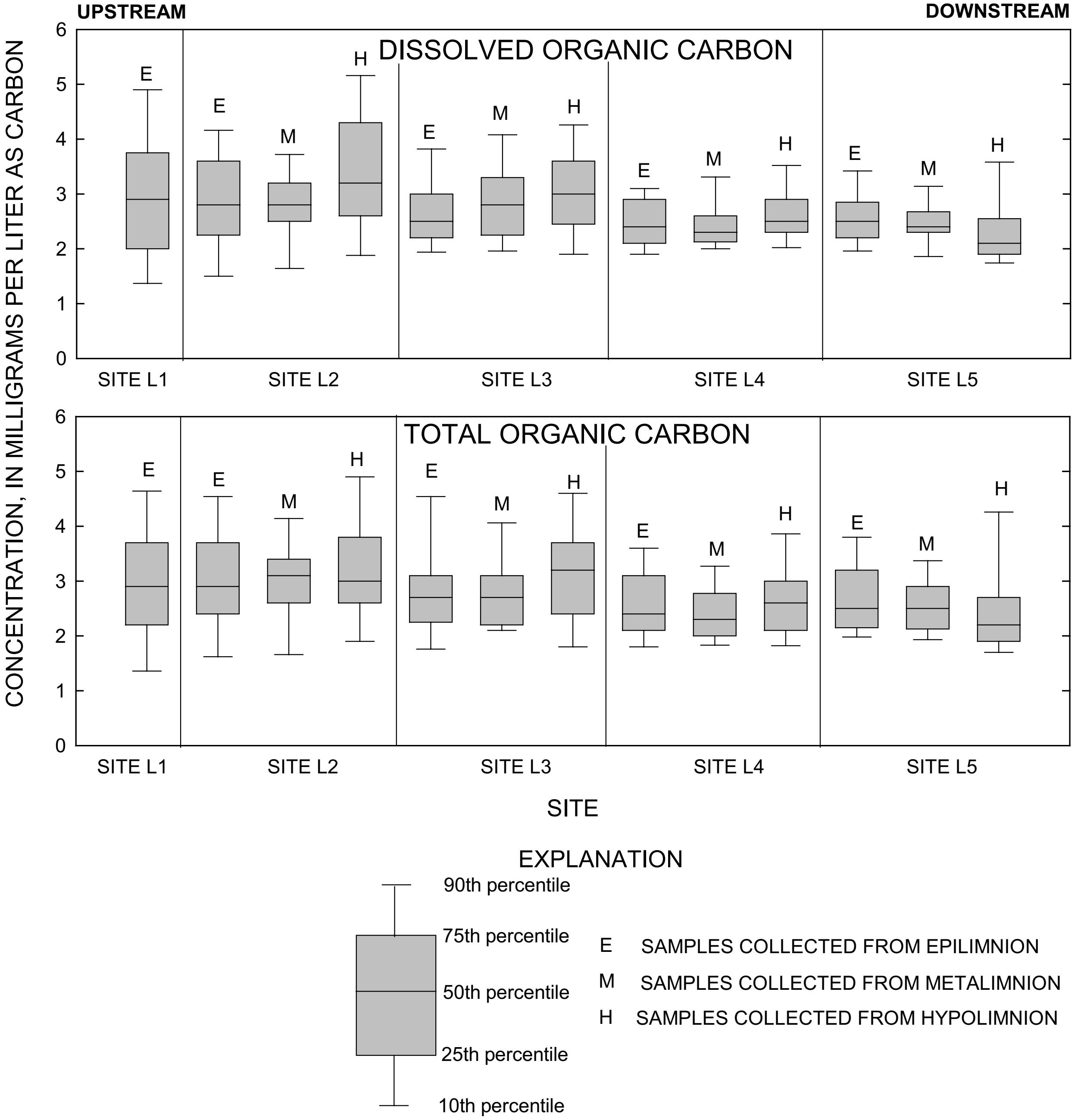

Figure 14. Distribution of organic-carbon concentrations for five sites in Beaver Lake, 2001-2003.

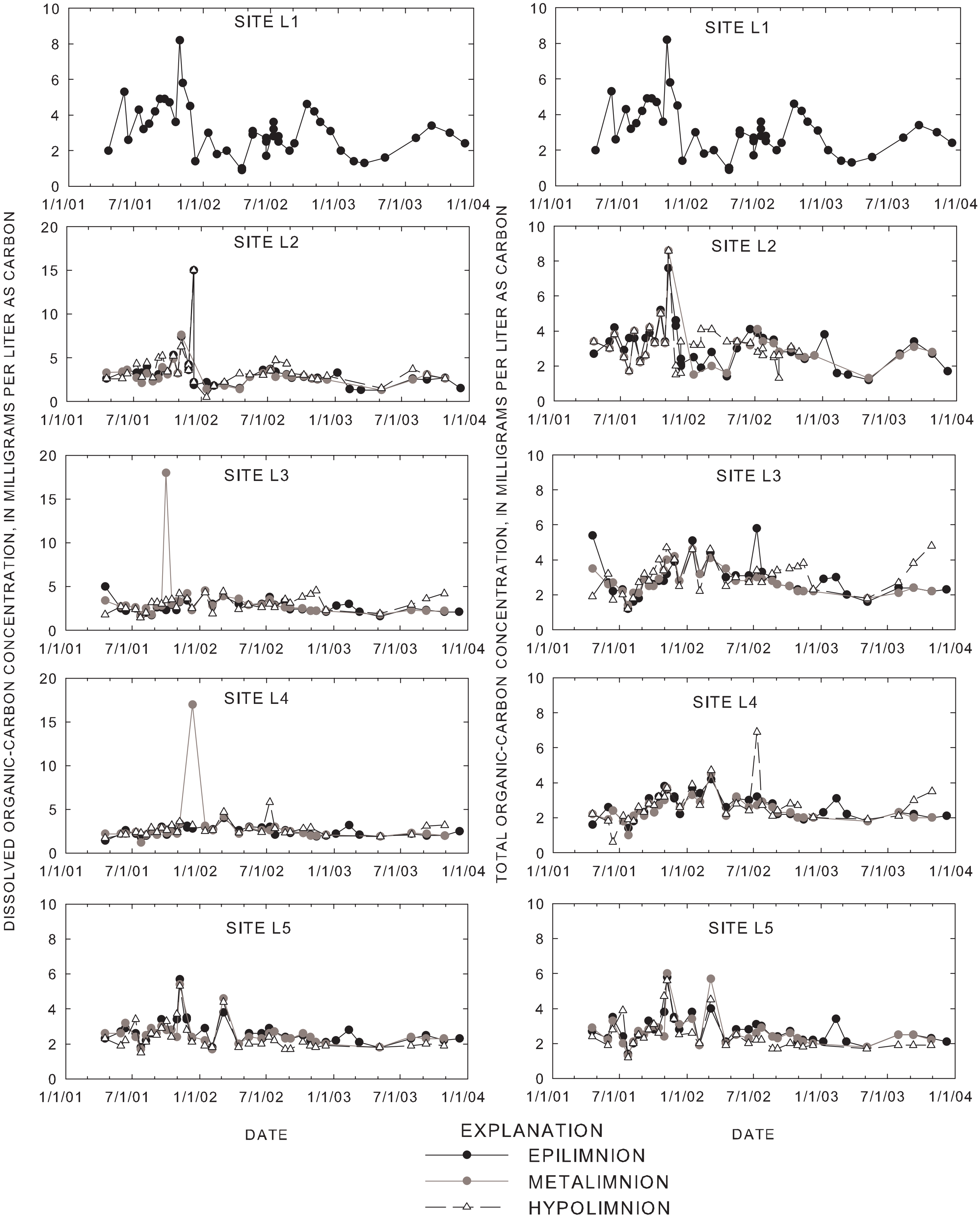

Figure 15. Time series of organic-carbon concentrations for five sites on Beaver Lake, 2001-2003.

Chlorophyll *a* and Phytoplankton

Chlorophyll *a* concentrations varied spatially and temporally in Beaver Lake. Chlorophyll *a* is a photosynthetic pigment found in algae and other green plants. The concentration of chlorophyll *a*, from samples collected in open water, commonly is used as a measure of the density of the algal (phytoplankton) population of a lake (Ruttner, 1963). Chlorophyll *a* concentrations measured at sites L1 and L2 were significantly greater than at the other sites on Beaver Lake with median concentrations of 7.2 micrograms per liter (µg/L) and 12.5 µg/L, respectively (fig. 16). Sites L3, L4, and L5 had median concentrations of 5.5, 3.4, and 1.8 µg/L, respectively. The increased depth of light penetration as suspended particles settle out of the water column in the transition zone (near site L2), and the availability of nutrients from the three main inflows probably allow for greater phytoplankton productivity in the upstream end and transitional zone of the reservoir. As nutrients are assimilated through the transitional zone, phytoplankton populations become more limited by nutrients in the downstream portion of Beaver Lake. Chlorophyll *a* concentrations were greater in the months of July through October probably because phytoplankton productivity generally is greater in the warmer months (fig. 17).

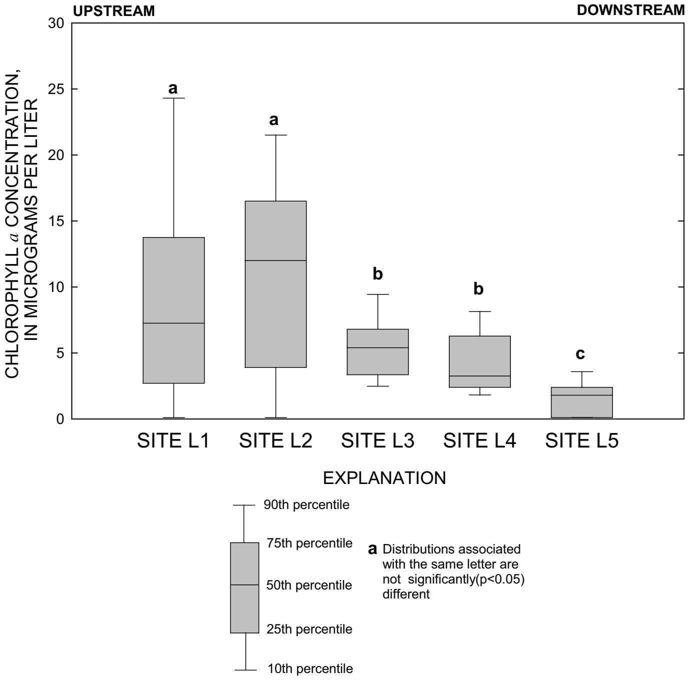

Figure 16. Distribution of chlorophyll *a* concentrations for five sites in Beaver Lake, 2001-2003.

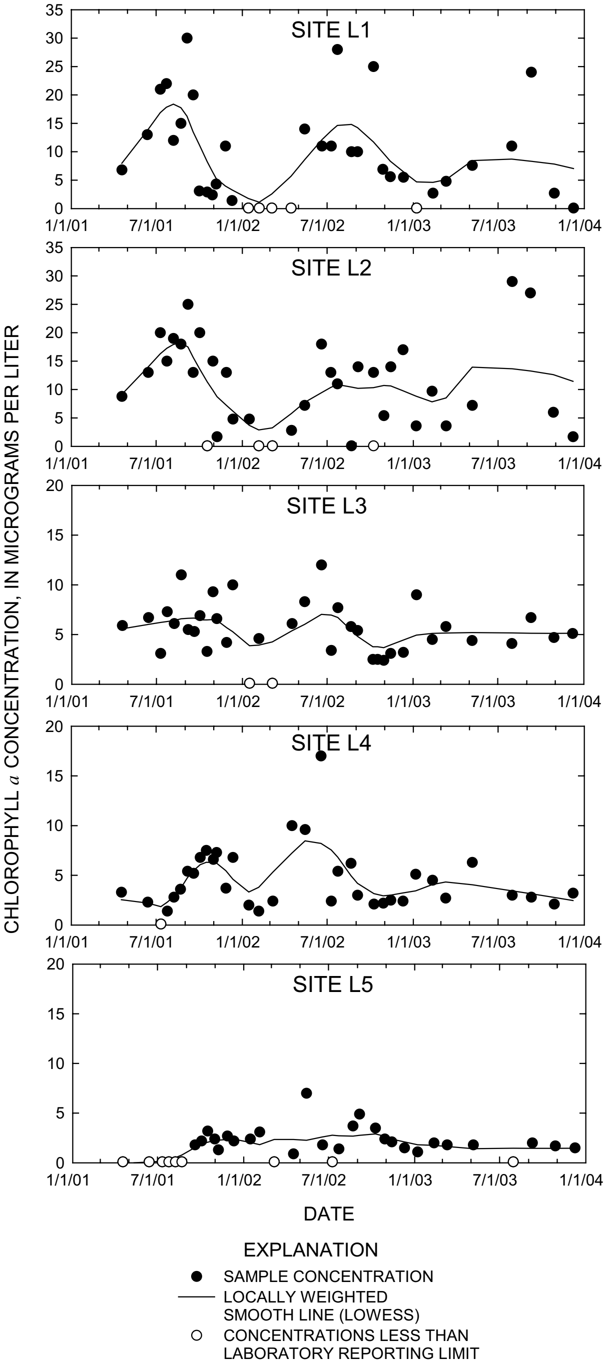

Figure 17. Time series of chlorophyll *a* concentrations for five sites in Beaver Lake, 2001-2003.

Phytoplankton populations are highly dynamic in lakes and reservoirs and are controlled by the availability of light and nutrients, and the effects of temperature and zooplankton grazing (Wetzel, 2001). Different populations of phytoplankton grow depending on the tolerance of each species to these factors. Blue-green algae, diatoms, flagellates, and green algae generally are the most common phytoplankton taxa in Beaver Lake.

Phytoplankton population dynamics varied over time among the five reservoir sites (fig. 18). Blue-green algae tended to be more abundant at the upstream sites, while diatoms tended to be more abundant at the downstream sites. The exception would be the abundance of flagellates at site L1 and L2 during 2002. Inflows at these upstream sites (L1 and L2) were greater in 2002, compared to 2001 with more frequent high-flow events (fig. 2) possibly shifting the phytoplankton population from blue-green algae to flagellates. Green algae were present at all sites, but did not dominate the assemblage with the exception of a couple of instances during the late summer in 2002 at sites L3 and L5. Chlorophyll *a* concentrations followed similar patterns as total phytoplankton cell numbers (concentrations), with the greatest concentrations at the upstream sites and decreasing concentrations downstream. At each site, chlorophyll *a* concentrations were greatest during the summer and early fall when water temperature was highest; concentrations were least during the winter and early spring when the water temperature was lowest.

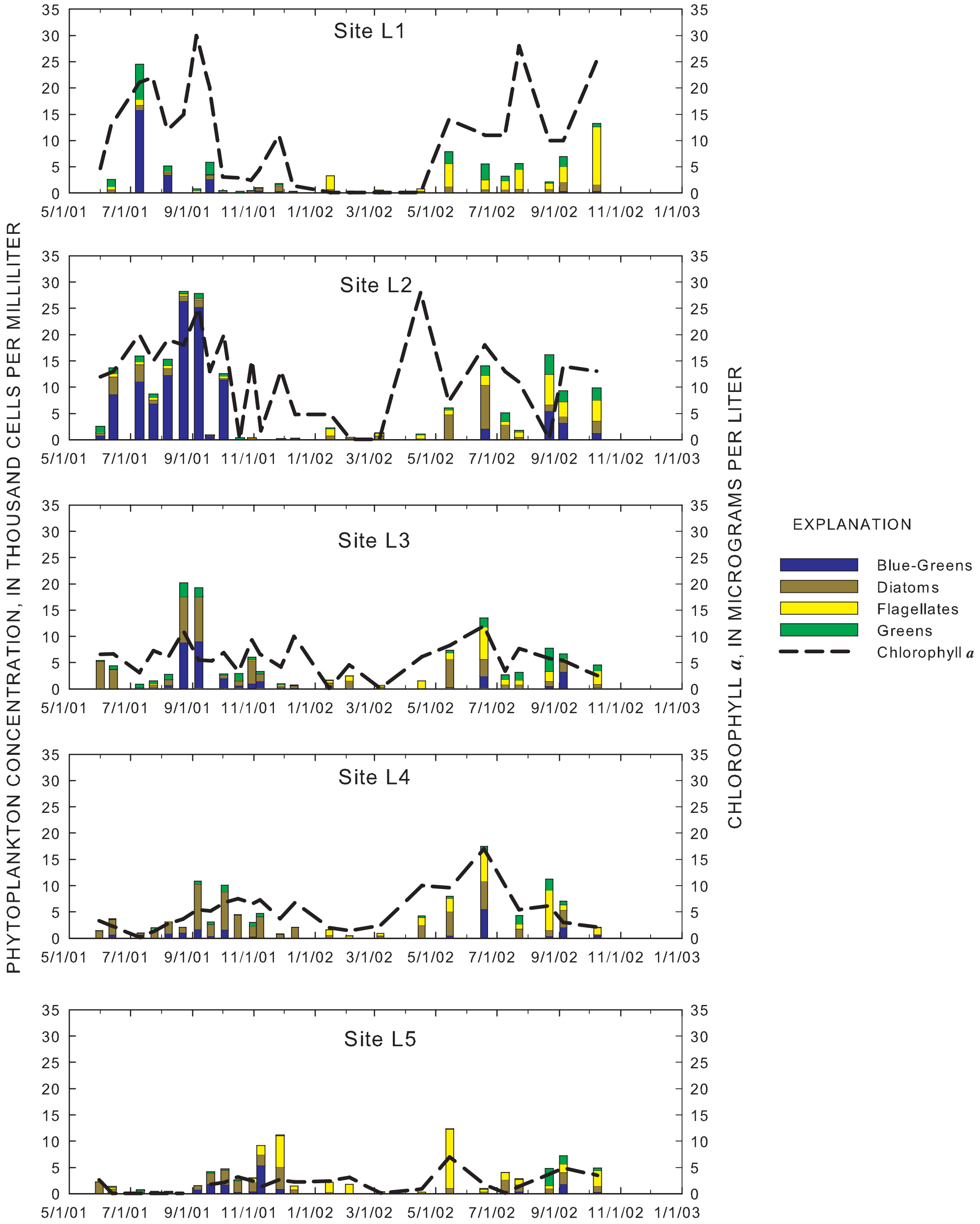

Figure 18. Distribution of phytoplankton and time series of chlorophyll *a* concentrations for five sites in Beaver Lake, 2001-2002.

Water Clarity

During the study period, water clarity in Beaver Lake was significantly greater at the downstream end of the reservoir (site L5) than at the upstream end (site L1) (fig. 19). The median Secchi depth ranged from 0.6 m at site L1 to 5.4 m at site L5 from 2001 through 2003. The lower values for Secchi depth, and, therefore, less water clarity, in the upstream portion of the reservoir is probably because of the input of organic and inorganic particulates from the main inflows. As water velocities decrease through the transitional zone, the particulates settle out of the water column and increase the water clarity in the downstream portion of the reservoir.

Secchi depth was more variable during the study period at the downstream sites (L3 through L5) compared to the upstream sites (L1 and L2) (fig. 20). At sites L3 and L4, greater Secchi depth values (greater water clarity) were observed from June through September in 2001 and 2002. The greatest values for Secchi depth at site L5 generally were observed in 2001 compared to 2002 and 2003, but did not have a seasonal pattern observed at sites L3 and L4.

Similar to Secchi depth results, turbidity results indicated greater water clarity in the downstream portion of Beaver Lake compared to the upstream portion (figs. 21 and 22). Turbidity also was greater in the hypolimnion than in the epilimnion in the reservoir during the stratification season. The median turbidity measured in the epilimnion ranged from 0.5 (site L5) to 8.3 NTUs (site L1). The median turbidity measured in the hypolimnion ranged from 1 (site L5) to 20 NTUs (site L2). The hypolimnetic turbidity was 5 times greater than the epilimnetic turbidity at sites L2 and L4 and nearly 10 times greater than the epilimnetic turbidity at site L3.

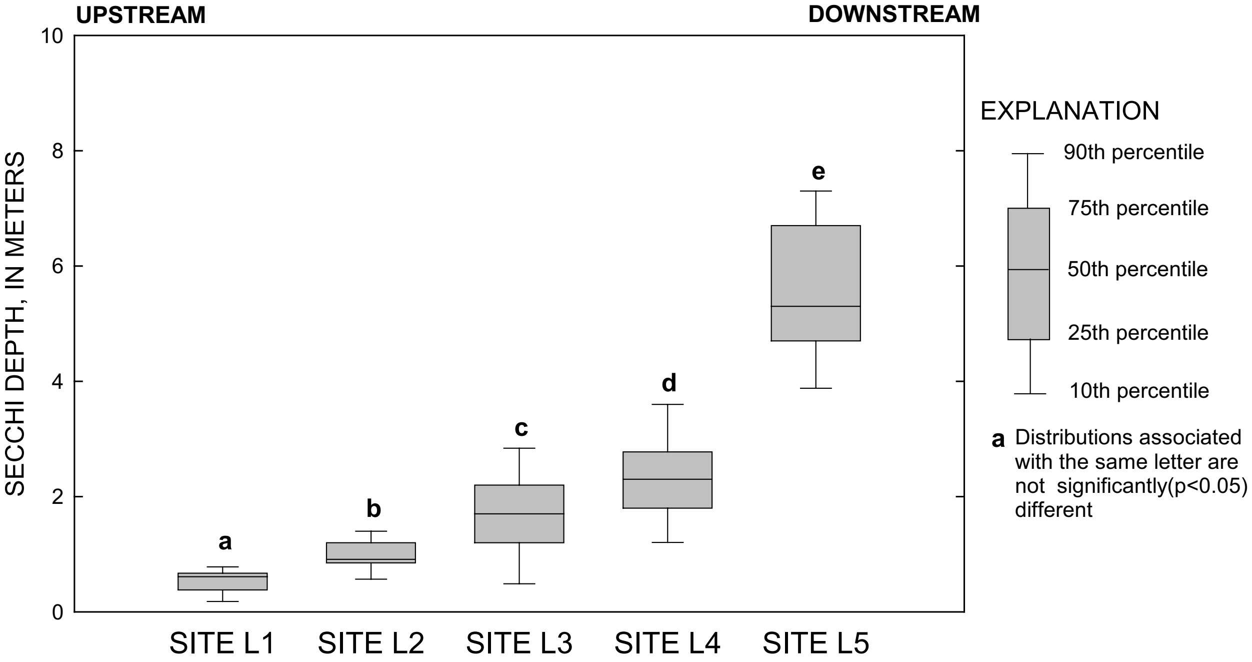

Figure 19. Distribution of Secchi depth for five sites in Beaver Lake, 2001-2003.

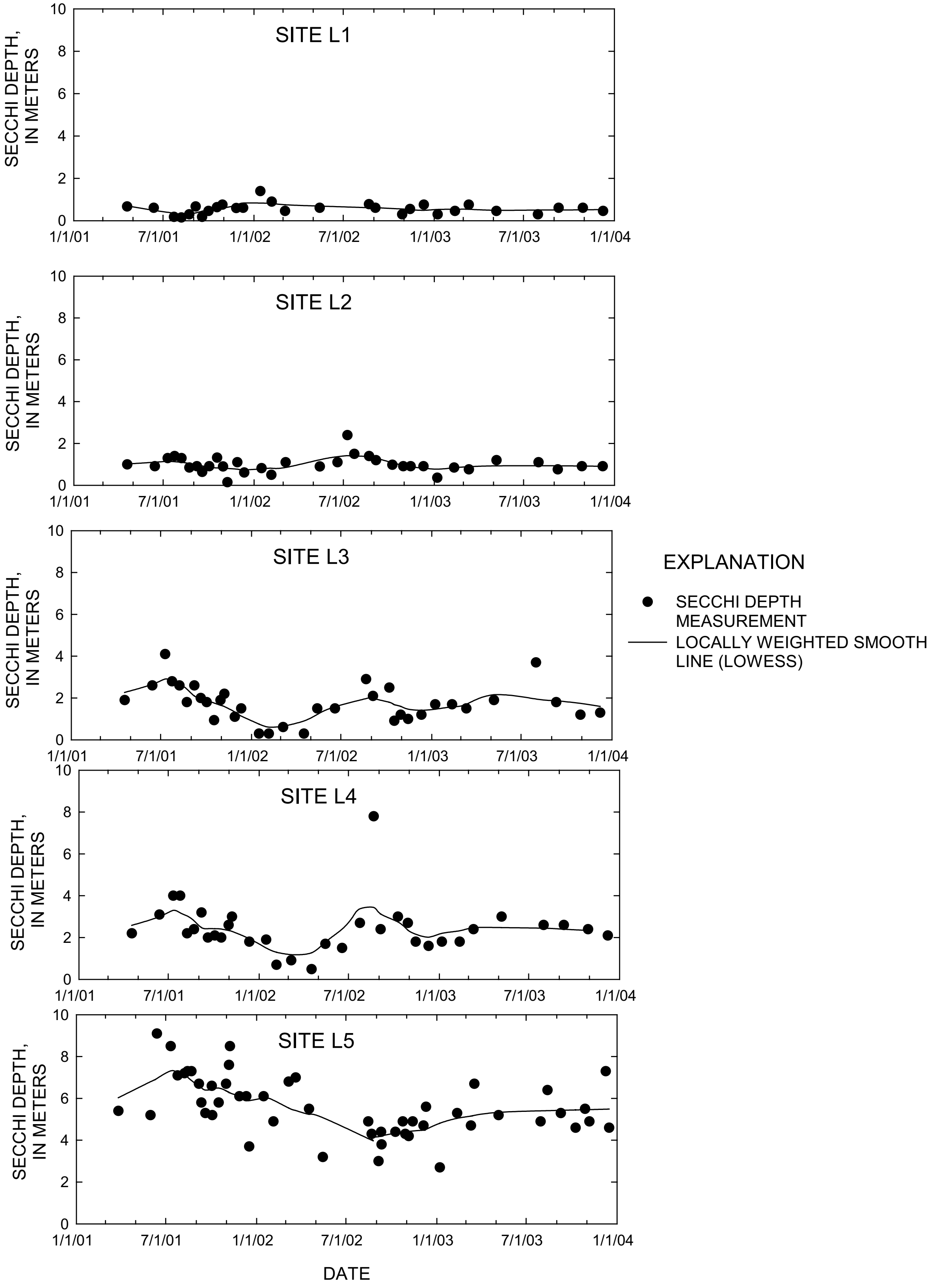

Figure 20. Time series of Secchi depth for five sites in Beaver Lake, 2001-2003.

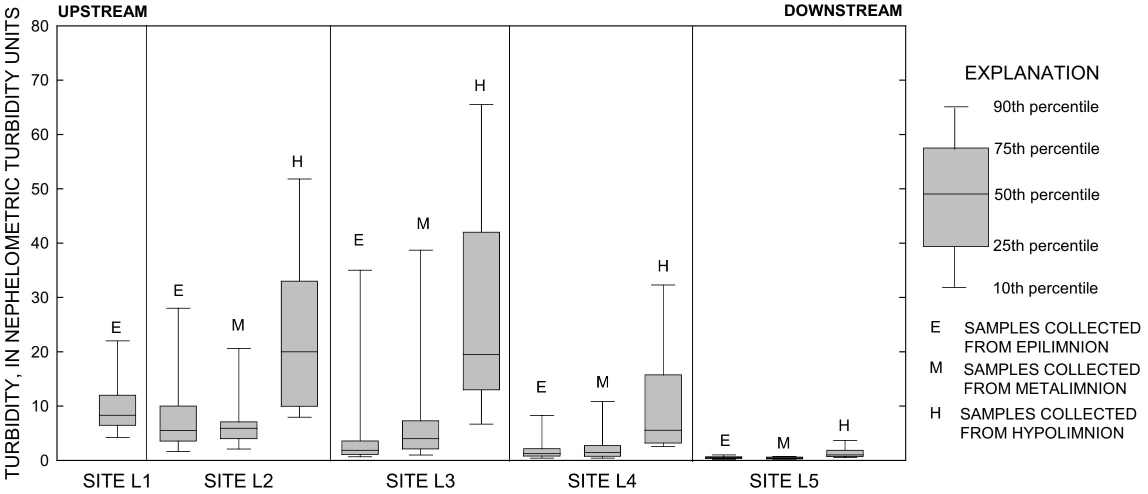

Figure 21. Distribution of turbidity for five sites in Beaver Lake, 2001-2003.

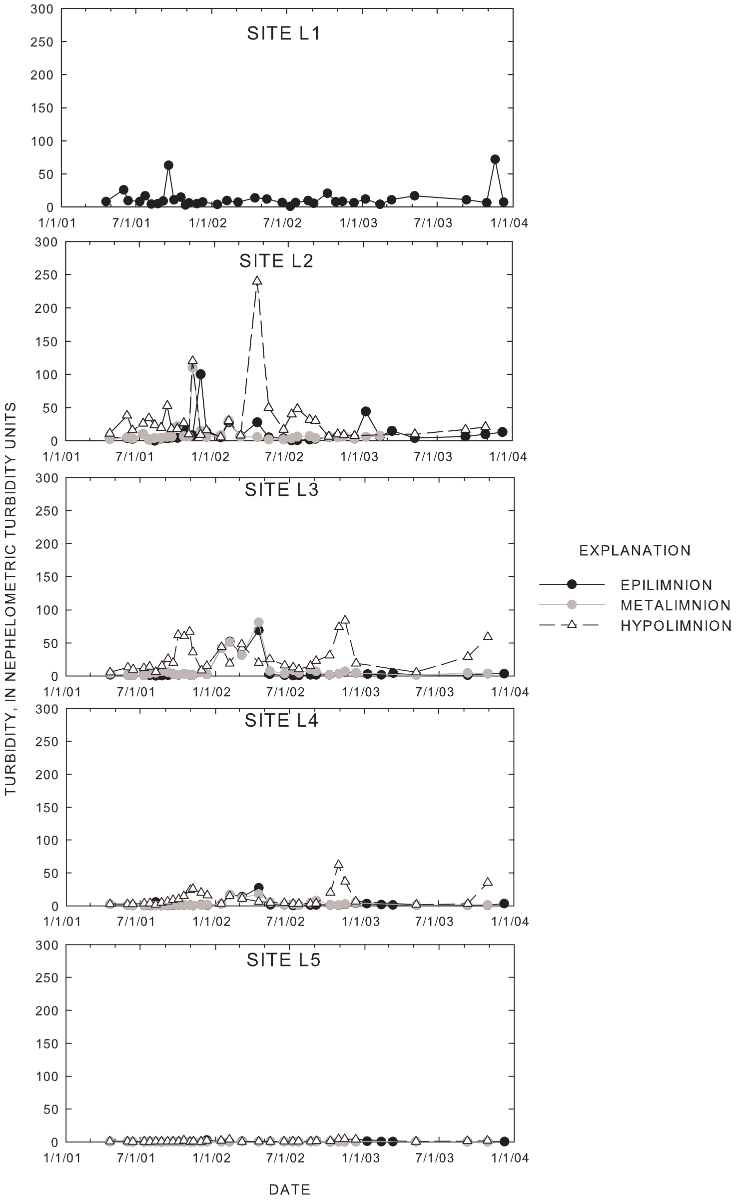

Figure 22. Time series of turbidity for five sites in Beaver Lake, 2001-2003.

Simulation of Hydrodynamics and Water Quality

A two-dimensional, laterally averaged, hydrodynamic and water-quality model using CE-QUAL-W2 Version 3.1 (Cole and Wells, 2003) was developed for Beaver Lake and calibrated based on vertical profiles of temperature and dissolved oxygen, and water-quality constituent concentrations collected at various depths at four sites in the reservoir from April 2001 to April 2003. The Beaver Lake CE-QUAL-W2 model simulates water-surface elevation and vertical and longitudinal gradients in water-quality constituents. The model includes routines for 18 state variables in addition to temperature, including any number of inorganic suspended solids groups, phytoplankton groups, nitrogen and phosphorus species, dissolved and particulate organic matter, total inorganic carbon, dissolved oxygen, and organic sediments. Additionally, over 60 derived variables can be computed from the state variables (Cole and Wells, 2003).

Model Implementation

Implementation of the CE-QUAL-W2 model for Beaver 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 model parameters are listed in this section.

Computational Grid

The computational grid is the geometric scheme that numerically represents the space and volume of the reservoir. The model extends 80 km from the upstream boundary (White River at the Highway 45 bridge) to the Beaver Lake dam (figs. 1 and 23). The grid originally was developed by Haggard and Green (2002) to simulate the hydrodynamics and distribution of temperature and dissolved oxygen in Beaver Lake for calendar years 1994 and 1995. Thirty-five computational segments exist along the mainstem of the White River in Beaver Lake and 12 computational segments are in War Eagle Creek. In addition, four other downstream branches 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. Each segment was divided vertically into 1-m layers. Two tributaries also were included in the model at the most upstream segment. Tributaries allow for the application of boundary conditions to the grid without affecting the geometry. One tributary was used to simulate the input from the Fayetteville wastewater-treatment plant discharge at the upstream segment and another to simulate the inflow from Richland Creek. A third tributary was used to simulate the inflow from Prairie Creek (fig. 1).

Boundary and Initial Conditions

Hydraulic and Thermal Boundary Conditions

Daily reservoir inflows used in the model were obtained from streamflow-gaging station data on the three main inflows (White River, Richland Creek, and War Eagle Creek) and were estimated for the three smaller branches. The mean daily streamflow recorded for War Eagle Creek (site S3) was used to estimate the streamflow for the other three other branches based on their respective drainage areas. Streamflow gaging station data were used to simulate inflow from the Prairie Creek tributary from April 2001 to October 2001. Because the gaging station was discontinued, streamflow was estimated from October 2001 to April 2003.

The downstream boundary for the Beaver Lake model consists of the outflow from Beaver Lake dam. Hourly outflow data was produced by the USACE using stage-discharge relations and hourly power generation records for the period of April 2001 to April 2003 (John Kielczewski, U.S. Army Corps of Engineers, written commun., 2003). The release structure (penstock) was simulated as a point release, and the middle of the structure was at an elevation of 302.2 m above NGVD of 1929, model layer 45 (fig. 23).

Other hydraulic boundary conditions included water withdrawal by four public water-supply districts (Beaver Water District, Carroll-Boone County Water District, Madison County Water District, and Benton-Washington County Water District). Withdrawal rates for each water-supply district were variable by month and based on reported 2001 through 2003 monthly intakes (Terrance W. Holland, U.S. Geological Survey, written commun., 2004).

Hydraulic boundary conditions at the water surface included evaporation, wind stress, and surface heat exchange. Meteorological data required for these computations were measured at the Northwest Arkansas Regional Airport (fig. 1) (National Climatic Data Center, Asheville, North Carolina, written commun., 2004) and generally were recorded at hourly intervals.

Hourly inflow water temperatures were estimated from the meteorological data and from periodic measurements at the three main inflow sites (White River, Richland Creek, and War Eagle Creek). Water temperatures for the smaller tributaries were estimated only from the meteorological data.

Chemical Boundary Conditions

Daily nutrient and dissolved organic-carbon concentrations were derived from daily loads calculated from sample concentrations and streamflow measured at sites S1, S2, and S3. Daily loads (kg/d) were divided by the daily mean streamflow (m^3/s) and multiplied by a conversion factor for a daily mean concentration (mg/L) for each of the main inflow sites. Daily streamflow is used to calculate daily concentrations from daily loads because it probably more accurately reflects the variation in constituent concentrations compared to using discrete concentrations as input, where the model linearly interpolates daily concentrations between sample collection dates. Daily

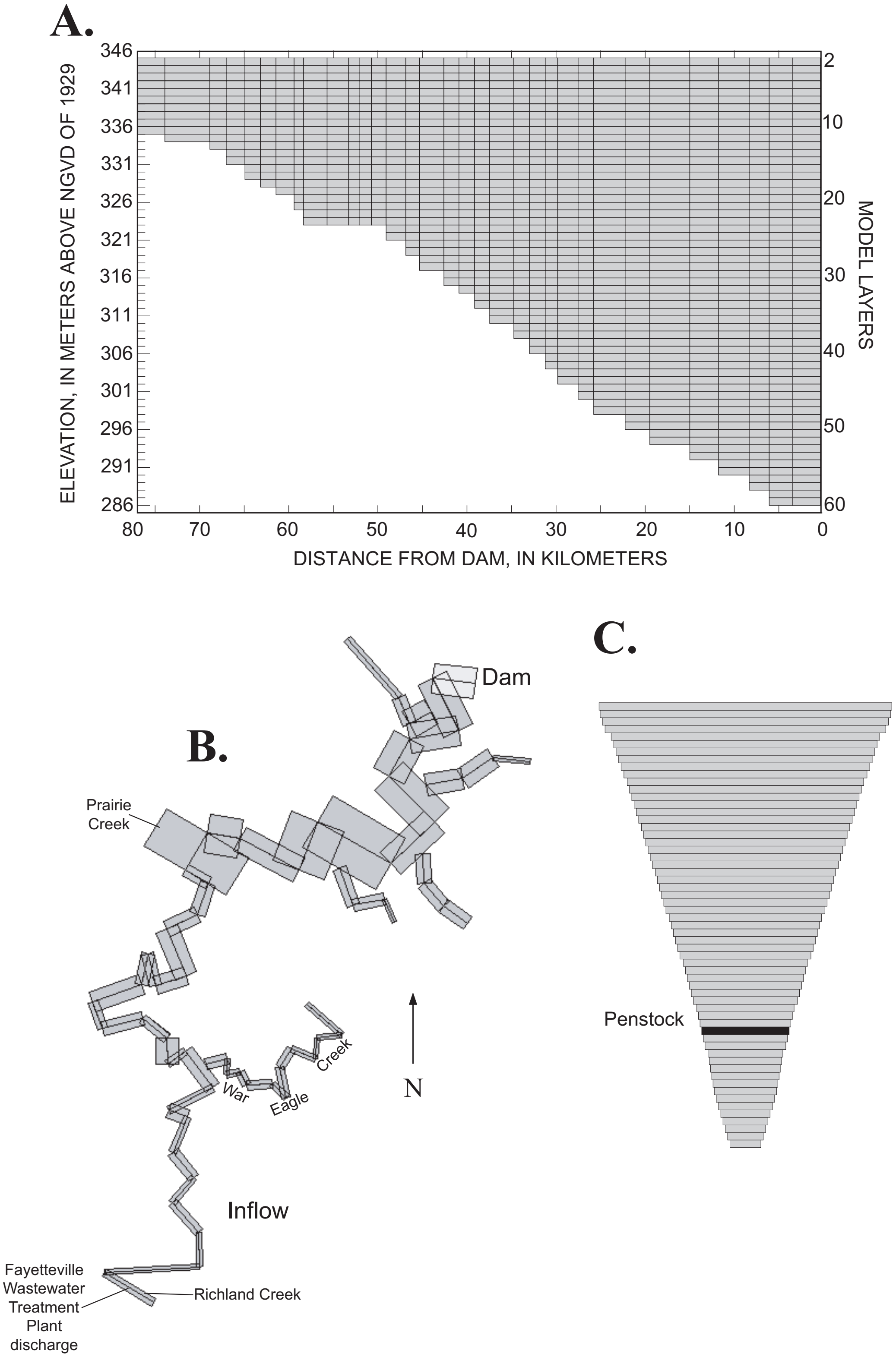

Figure 23. Side view (A), top view (B), and face view from the dam (C) of the computational grid of Beaver Lake used in the CE-QUAL-W2 model.

concentration data for the Fayetteville wastewater treatment plant discharge were obtained from daily outflow sample data (Paul R. Noland, city of Fayetteville Wastewater-Treatment Plant, written commun., 2003).

Hourly inflow dissolved-oxygen concentrations were estimated from measured data and from the meteorological data. Estimated values were computed as 80 percent dissolved-oxygen saturation from the temperature and barometric pressure when measured values for dissolved-oxygen concentration were missing. Daily dissolved-oxygen concentrations for the smaller tributaries were estimated only from the meteorological data.

Initial Conditions

Initial water-surface elevation, water temperature, and constituent concentrations for each model segment are required at the start of a model simulation. Initial water-surface elevations were set to the measured value on April 1, 2001. Beaver Lake was assumed to be in isothermal conditions throughout the entire reservoir and equal to 6 °C. Initial constituent concentrations also were assumed to be uniform, and concentrations measured at the five sampling sites on March 30, 2001, were used as the initial values.

Model Parameters

Parameters are used to describe the physical and chemical processes that are not explicitly modeled and to provide the chemical kinetic rate information. 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 hydrodynamic and thermal processes are modeled in CE-QUAL-W2, which results in very few adjustable hydraulic and thermal parameters. There are many chemical and biological rate coefficients required for the application of CE-QUAL-W2, which are all temporally constant (table 2). Many of the coefficients were based on suggested values given as default values for CE-QUAL-W2 and others were based on other model applications (Haggard and Green, 2002; Galloway and Green, 2002 and 2003; Green and others, 2003; Bales and others, 2001; Sullivan and Rounds, 2005).

Table 2. Parameters and values used for the Beaver Lake model, April 2001 to April 2003.

Parameter	Value
Hydraulic and thermal input parameters	
Coefficient of bottom heat exchange, watts/square meter/ second	7×10^{-7}
Sediment temperature, degrees Celsius	16
Wind-sheltering coefficient, dimensionless	0.70
Horizontal eddy viscosity, square meters /second	1
Horizontal eddy diffusivity, square meters/second	1
Rate coefficients for water-chemistry and biological simulations	
Light extinction coefficient for pure water, 1/meter	0.4
Light extinction coefficient for organic solids, 1/meter	0.01
Light extinction coefficient for inorganic solids, 1/meter	0.01
Light extinction coefficient because of algae (blue-green), 1/meter	0.1
Light extinction coefficient because of algae (diatoms), 1/meter	0.1
Light extinction coefficient because of algae (flagellates), 1/meter	0.1
Light extinction coefficient because of algae (green), 1/meter	0.1
Fraction of incident solar radiation absorbed at water surface, dimensionless	0.32
Suspended solids settling rate, meters/day	2
Algal growth rate (blue-green), 1/day	2
Algal growth rate (diatoms), 1/day	2
Algal growth rate (flagellates), 1/day	2
Algal growth rate (green), 1/day	2

Table 2. Parameters and values used for the Beaver Lake model, April 2001 to April 2003.—Continued

Parameter	Value
Algal mortality rate (blue-green), 1/day	0.08
Algal mortality rate (diatoms), 1/day	0.08
Algal mortality rate (flagellates), 1/day	0.08
Algal mortality rate (green), 1/day	0.08
Algal excretion rate (blue-green), 1/day	0.04
Algal excretion rate (diatoms), 1/day	0.04
Algal excretion rate (flagellates), 1/day	0.04
Algal excretion rate (green), 1/day	0.04
Algal dark respiration rate (blue-green), 1/day	0.04
Algal dark respiration rate (diatoms), 1/day	0.04
Algal dark respiration rate (flagellates), 1/day	0.04
Algal dark respiration rate (green), 1/day	0.04
Algal settling rate (blue-green), meters/day	0.08
Algal settling rate (diatoms), meters/day	0.08
Algal settling rate (flagellates), meters/day	0.08
Algal settling rate (green), meters/day	0.08
Saturation light intensity (blue-green), watts/square meter	75
Saturation light intensity (diatoms), watts/square meter	75
Saturation light intensity (flagellates), watts/square meter	75
Saturation light intensity (green), watts/square meter	75
Fraction of algal biomass lost by mortality to particulate organic matter (blue-green), dimensionless	0.8
Fraction of algal biomass lost by mortality to particulate organic matter (diatoms), dimensionless	0.8
Fraction of algal biomass lost by mortality to particulate organic matter (flagellates), dimensionless	0.8
Fraction of algal biomass lost by mortality to particulate organic matter (green), dimensionless	0.8
Lower temperature for algal growth (blue-green), degrees Celsius	15
Lower temperature for algal growth (diatoms), degrees Celsius	10
Lower temperature for algal growth (flagellates), degrees Celsius	10
Lower temperature for algal growth (green algae), degrees Celsius	10
Fraction of algal growth at lower temperature (blue-green), dimensionless	0.1
Fraction of algal growth at lower temperature (diatoms), dimensionless	0.2
Fraction of algal growth at lower temperature (flagellates), dimensionless	0.1
Fraction of algal growth at lower temperature (green), dimensionless	0.1

Table 2. Parameters and values used for the Beaver Lake model, April 2001 to April 2003.—Continued

Parameter	Value
Lower temperature for maximum algal growth (blue-green), degrees Celsius	20
Lower temperature for maximum algal growth (diatoms), degrees Celsius	15
Lower temperature for maximum algal growth flagellates), degrees Celsius	15
Lower temperature for maximum algal growth (green), degrees Celsius	20
Fraction of maximum algal growth at lower temperature (blue-green), dimensionless	0.99
Fraction of maximum algal growth at lower temperature (diatoms) dimensionless	0.99
Fraction of maximum algal growth at lower temperature (flagellates), dimensionless	0.99
Fraction of maximum algal growth at lower temperature (green), dimensionless	0.99
Upper temperature for algal growth (blue-green), degrees Celsius	35
Upper temperature for algal growth (diatoms), degrees Celsius	20
Upper temperature for algal growth (flagellates), degrees Celsius	25
Upper temperature for algal growth (green), degrees Celsius	30
Fraction of algal growth at upper temperature (blue-green), dimensionless	0.99
Fraction of algal growth at upper temperature (diatoms), dimensionless	0.99
Fraction of algal growth at upper temperature (flagellates), dimensionless	0.99
Fraction of algal growth at upper temperature (green), dimensionless	0.99
Upper temperature for maximum algal growth (blue-green), degrees Celsius	40
Upper temperature for maximum algal growth (diatoms), degrees Celsius	35
Upper temperature for maximum algal growth (flagellates), degrees Celsius	35
Upper temperature for maximum algal growth (green), degrees Celsius	35
Fraction of maximum algal growth at upper temperature (blue-green), dimensionless	0.1
Fraction of maximum algal growth at upper temperature (diatoms), dimensionless	0.1
Fraction of maximum algal growth at upper temperature (flagellates), dimensionless	0.1
Fraction of maximum algal growth at upper temperature (green), dimensionless	0.1
Algal half-saturation constant for phosphorus (blue-green), grams/cubic meter	0.003
Algal half-saturation constant for phosphorus (diatoms), grams/cubic meter	0.003
Algal half-saturation constant for phosphorus (flagellates), grams/cubic meter	0.003
Algal half-saturation constant for phosphorus (greens), grams/cubic meter	0.003
Algal half-saturation constant for nitrogen (blue-green), grams/cubic meter	0.014
Algal half-saturation constant for nitrogen (diatoms), grams/cubic meter	0.014
Algal half-saturation constant for nitrogen (flagellates), grams/cubic meter	0.014

Table 2. Parameters and values used for the Beaver Lake model, April 2001 to April 2003.—Continued

Parameter	Value
Algal half-saturation constant for nitrogen (greens), grams/cubic meter	0.014
Algal half-saturation constant for silica (blue-green), grams/cubic meter	0
Algal half-saturation constant for silica (diatoms), grams/cubic meter	0
Algal half-saturation constant for silica (flagellates), grams/cubic meter	0
Algal half-saturation constant for silica (greens), grams/cubic meter	0
Chlorophyll-algae ratio, dimensionless	0.4
Labile dissolved organic matter decay rate, 1/day	0.1
Refractory dissolved organic matter decay rate, 1/day	0.015
Labile to refractory dissolved organic matter decay rate, 1/day	0.01
Labile particulate organic matter decay rate, 1/day	0.1
Refractory particulate organic matter decay rate, 1/day	0.01
Labile to refractory particulate organic matter decay rate, 1/day	0.001
Particular organic matter settling rate, meters/day	0.1
Lower temperature for organic matter decay, degrees Celsius	5
Upper temperature for organic matter decay, degrees Celsius	30
Fraction of organic matter decay at lower temperature, dimensionless	0.1
Fraction of organic matter decay at upper temperature, dimensionless	0.99
Sediment decay rate, 1/day	0.1
Zero-order sediment oxygen demand, grams/square meter/day	1
Fraction of sediment oxygen demand, dimensionless	1.4
5-day biological oxygen demand decay rate, 1/day	0.25
Biological oxygen demand temperature rate coefficient, dimensionless	1.0147
Ratio of 5-day biological oxygen demand to ultimate biological oxygen demand, dimensionless	1.85
Release rate of phosphorus from bottom sediment, fraction of sediment oxygen demand	0.001
Phosphorus partitioning coefficient, dimensionless	0
Release rate of ammonia from bottom sediment, fraction of sediment oxygen demand	0.2
Ammonia decay rate, 1/day	0.12
Lower temperature for ammonia decay, degrees Celsius	5
Fraction of nitrification at lower temperature, dimensionless	0.1
Upper temperature for ammonia decay, degrees Celsius	20
Fraction of maximum nitrification at lower temperature, dimensionless	0.99
Nitrate decay rate, 1/day	0.03
Lower temperature for nitrate decay, degrees Celsius	5
Fraction of denitrification at lower temperature, dimensionless	0.1
Upper temperature for nitrate decay, degrees Celsius	20
Fraction of maximum denitrification at lower temperature, dimensionless	0.99
Iron release from bottom sediment, fraction of sediment oxygen demand	0.5

Table 2. Parameters and values used for the Beaver Lake model, April 2001 to April 2003.—Continued

Parameter	Value
Iron settling velocity, meters/day	2
Oxygen stoichiometric equivalent for ammonia decay, dimensionless	4.57
Oxygen stoichiometric equivalent for organic matter decay, dimensionless	1.4
Oxygen stoichiometric equivalent for algal dark respiration (blue-green), dimensionless	1.8
Oxygen stoichiometric equivalent for algal dark respiration (diatoms), dimensionless	1.8
Oxygen stoichiometric equivalent for algal dark respiration (flagellates), dimensionless	1.8
Oxygen stoichiometric equivalent for algal dark respiration (greens), dimensionless	1.8
Oxygen stoichiometric equivalent for algal growth (blue-green), dimensionless	1.1
Oxygen stoichiometric equivalent for algal growth (diatoms), dimensionless	1.1
Oxygen stoichiometric equivalent for algal growth (flagellates), dimensionless	1.1
Oxygen stoichiometric equivalent for algal growth (green), dimensionless	1.1

Model Calibration and Testing

Successful model application requires model calibration that includes comparing simulated results with measured reservoir conditions. The Beaver Lake model calibration was completed by adjusting parameters for the 2-year period from April 2001 to April 2003. Calibration was achieved generally by first calibrating the water balance and thermodynamics, then calibrating the water-quality conditions (dissolved oxygen, nutrients, and algae).

Two statistics were used to compare simulated and measured water-surface elevation, water temperature, dissolved-oxygen, and nutrient concentrations. The absolute mean error (AME) indicates the average difference between simulated and measured values and is computed by equation 2.

$$AME = \frac{\Sigma|\text{simulated value - measured value}|}{\text{number of observations}} \qquad (2)$$

An AME of 0.5 °C means that the average difference between simulated temperatures and measured temperature is 0.5 °C.

The root mean square error (RMSE) indicates the spread of how far simulated values deviate from the measured values and is computed by equation 3:

$$RMSE = \sqrt{\frac{\Sigma(\text{simulated value - measured value})^2}{\text{number of observations}}} \qquad (3)$$

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.

Water Balance

Simulated water-surface elevations in Beaver Lake were adjusted to the measured water surface for the model period of April 2001 to April 2003 (fig. 24). 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 added or subtracted so that the simulated water-surface elevation reflected the measured water-surface elevation, therefore, accounting for unmeasured inflow and ground-water interaction in Beaver Lake. By correcting the distributed inflow, the temperature and water quality could be calibrated without the uncertainty incurred with having differences between simulated and measured water-surface elevations.

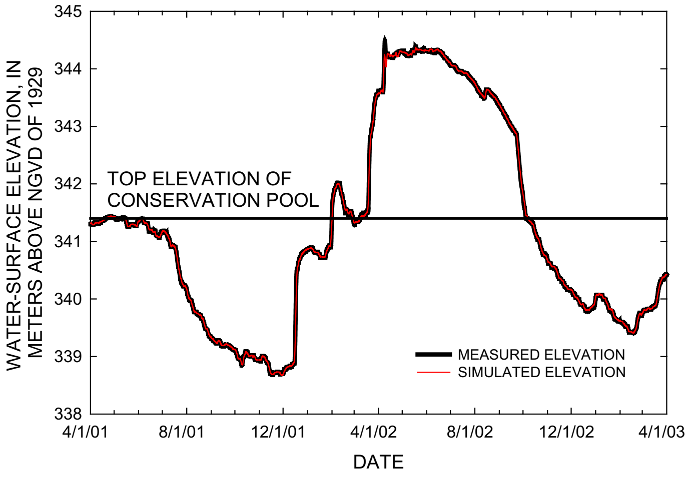

Figure 24. Simulated and measured water-surface elevations near Beaver Lake dam, April 2001 to April 2003.

Temperature

Simulated water temperatures in Beaver Lake were compared to 144 depth profiles of temperature measured at four sites on Beaver Lake (fig. 1). Temperatures were adjusted to the measured values for the model period of April 2001 to April 2003.

Simulated temperatures compared reasonably well with measured temperatures and differences varied spatially in Beaver Lake for April 2001 to April 2003. Differences in temperature between simulated and measured values decreased from site L2 to site L5. The AME ranged from 0.8 °C at site L5 to 3.1 °C at L2 and the RMSE ranged from 0.9 °C at site L5 to 3.2 °C at site L2 from April 2001 to April 2003 (figs. 25-28; table 3). The greatest differences between measured and simulated data occurred in the upstream portion of the reservoir, which is the most dynamic part of the reservoir. The upstream portion of the reservoir is the shallowest section of Beaver Lake and has more riverine characteristics than the deep lacustrine-type characteristics of the downstream portion of the reservoir. The upstream portion also receives most of the inflow to the reservoir, which creates more dynamic conditions. The greatest differences between simulated and measured temperatures generally occurred in simulating the location of the thermocline (figs. 25-28).

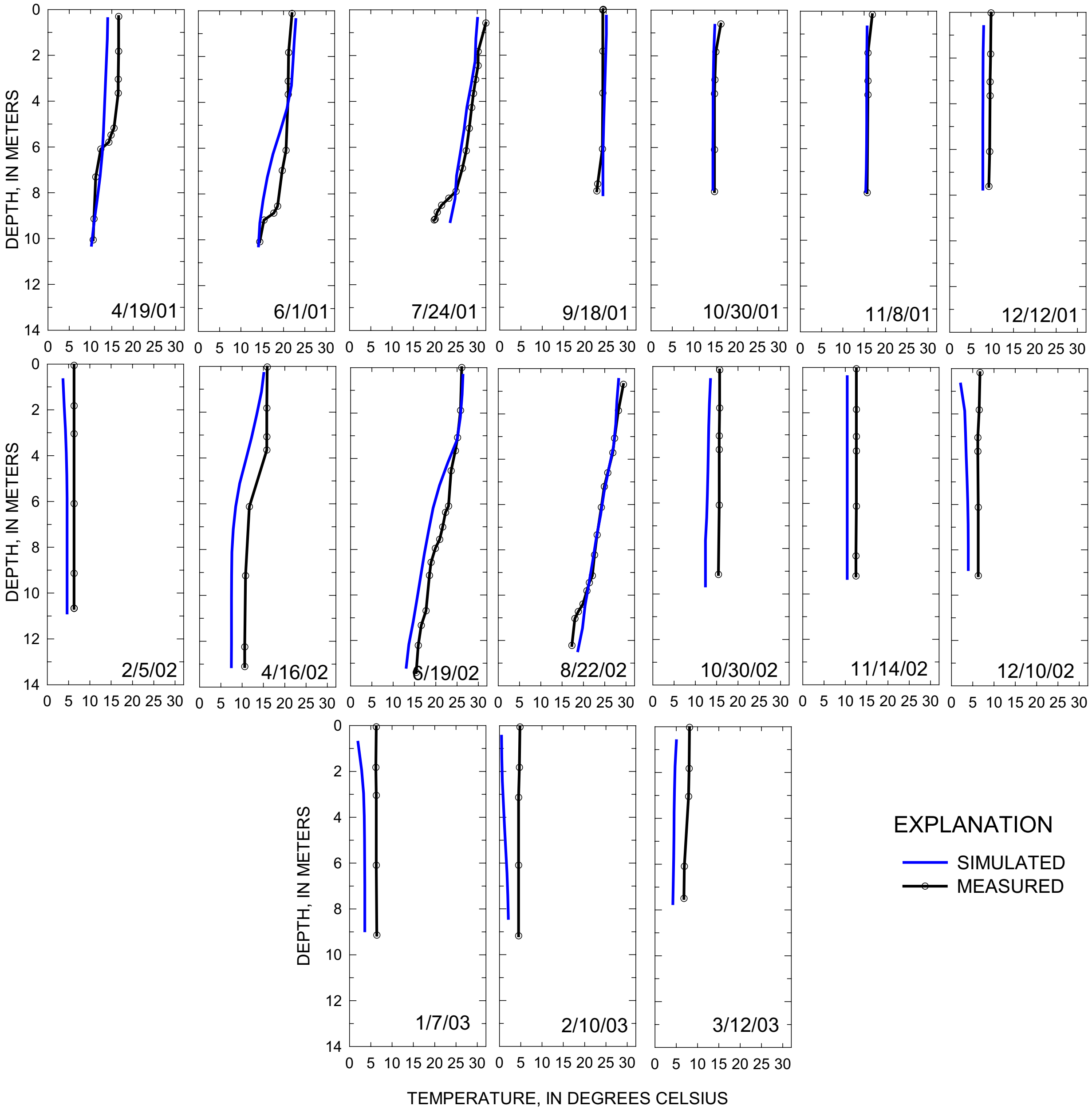

Figure 25. Selected simulated and measured water-temperature profiles for Beaver Lake at Highway 412 bridge near Sonora, Arkansas (site L2), April 2001 to April 2003.

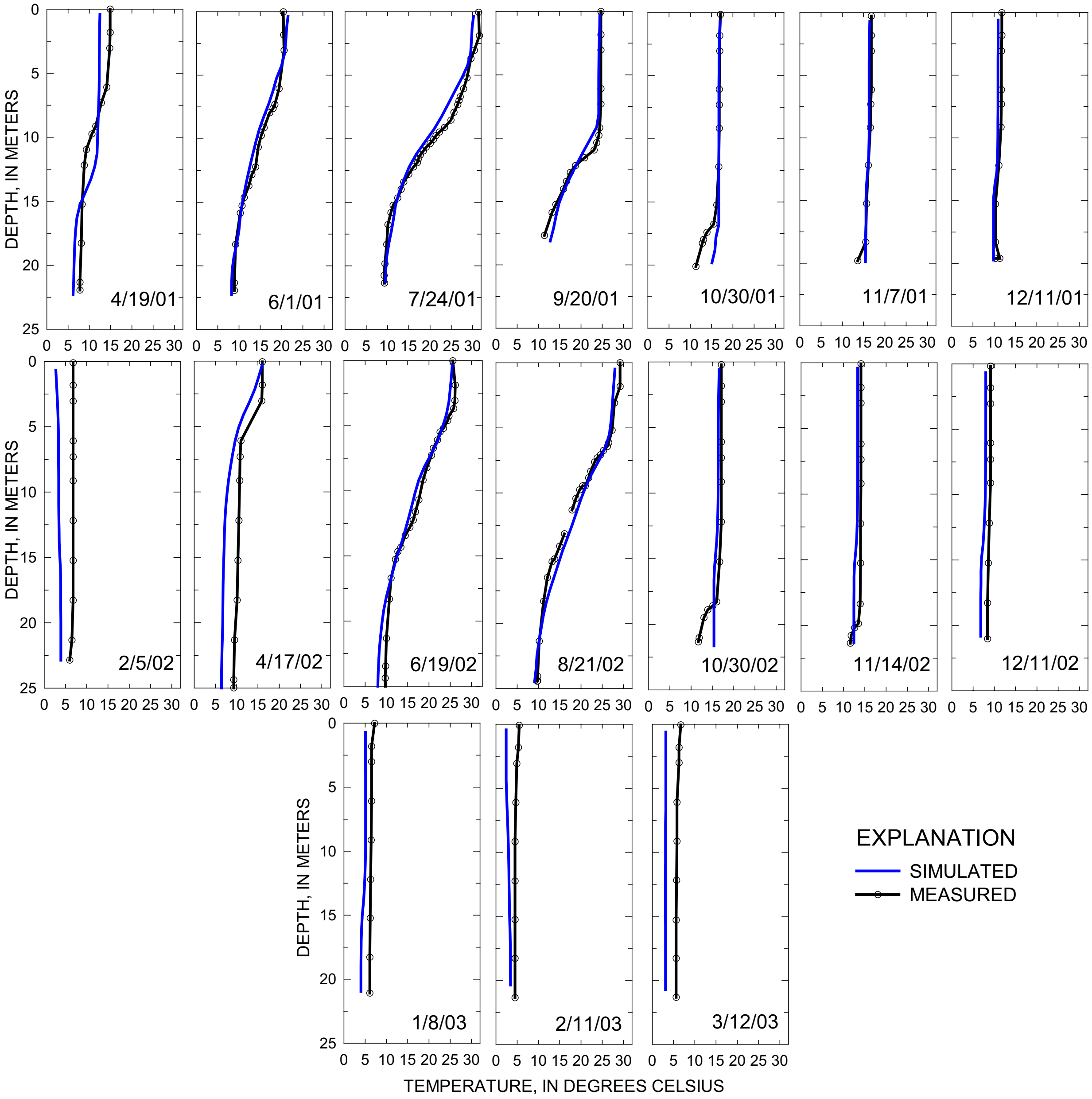

Figure 26. Selected simulated and measured water-temperature profiles for Beaver Lake near Lowell, Arkansas (site L3), April 2001 to April 2003.

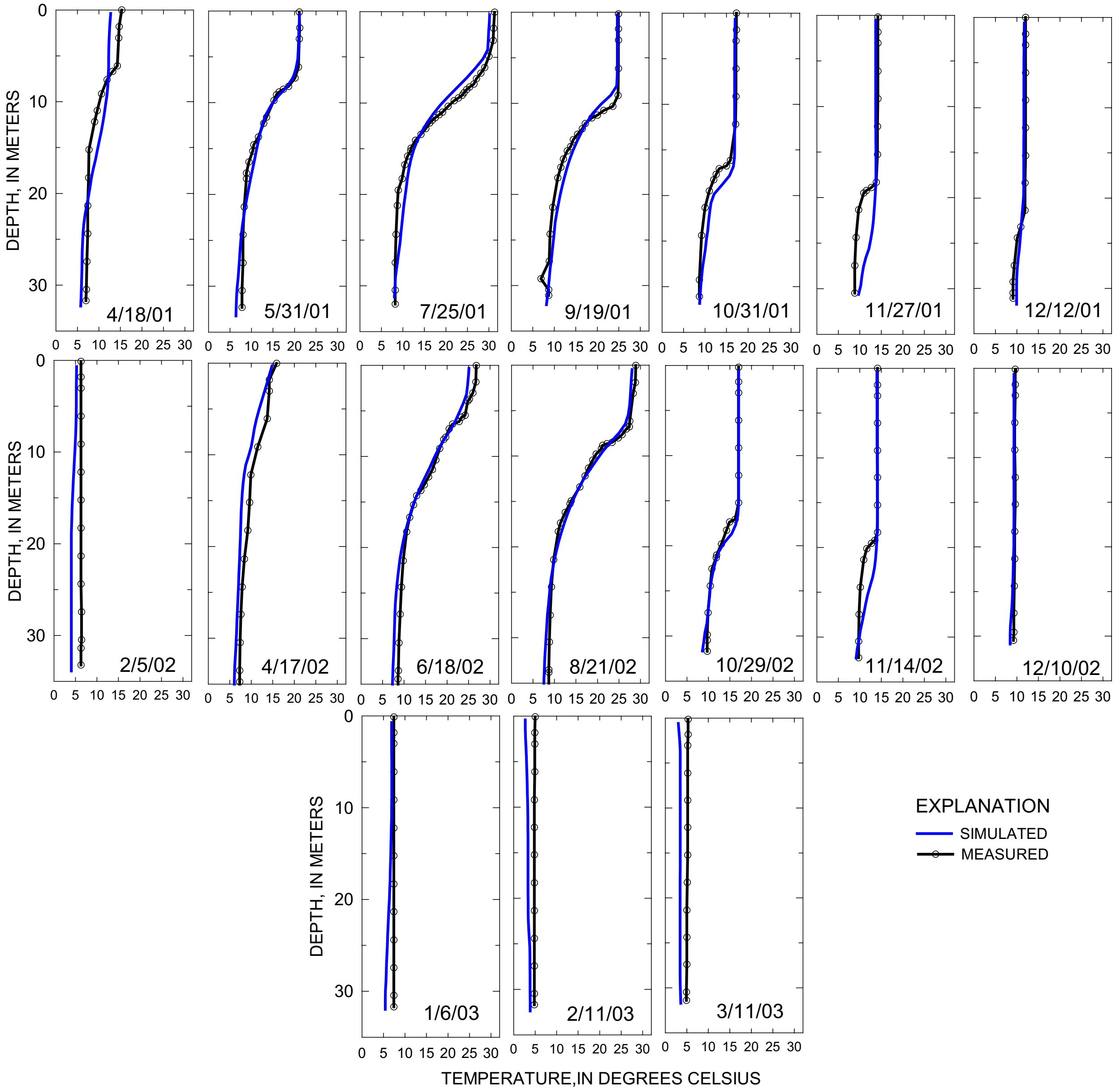

Figure 27. Selected simulated and measured water-temperature profiles for Beaver Lake at Highway 12 bridge near Rogers, Arkansas (site L4), April 2001 to April 2003.

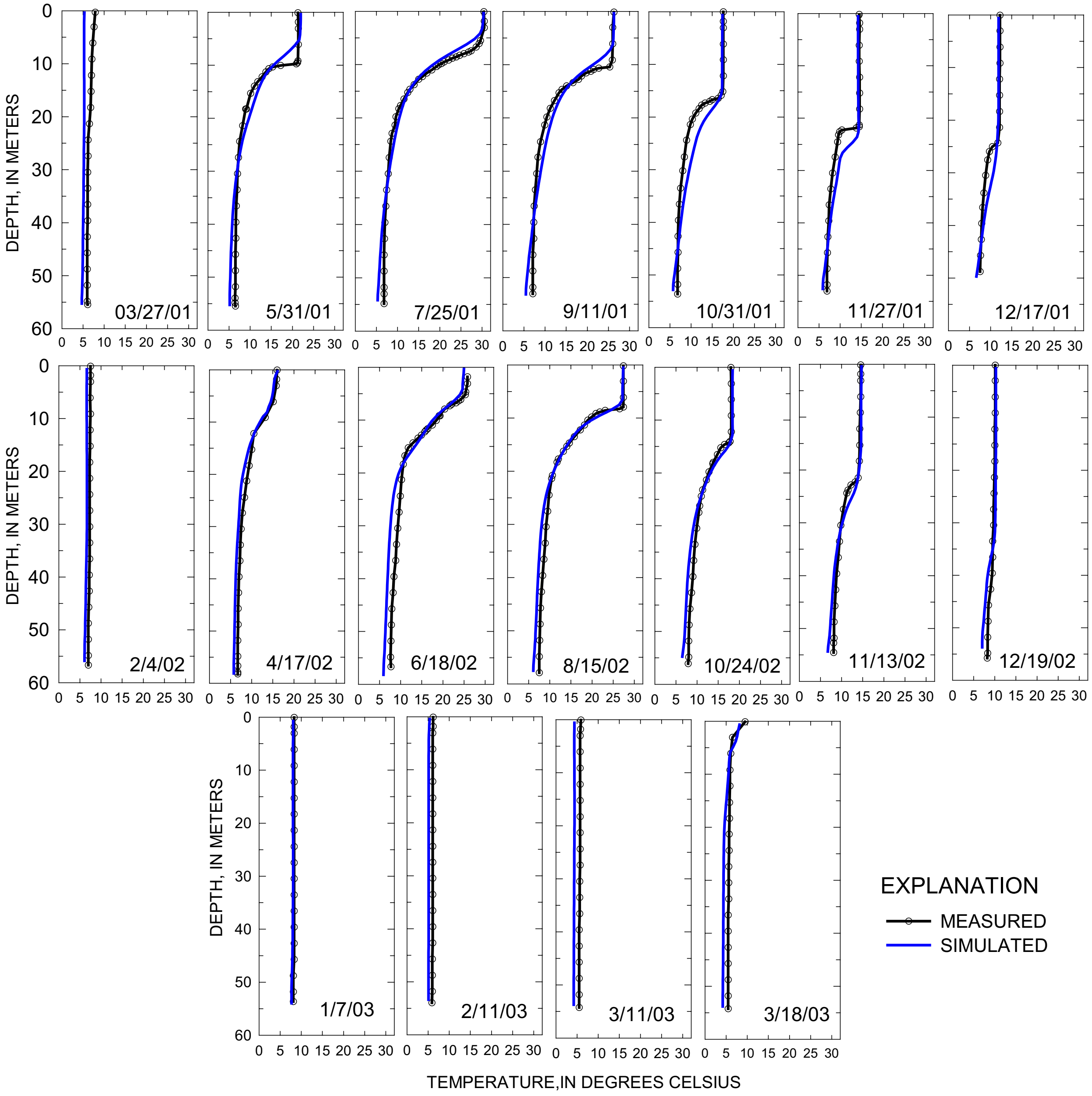

Figure 28. Selected simulated and measured water-temperature profiles for Beaver Lake near Eureka Springs, Arkansas (site L5), April 2001 to April 2003.

Table 3. Comparative statistics of simulated and measured temperature and dissolved-oxygen concentration for Beaver Lake, April 2001 to April 2003.

[Difference is simulated minus measured]

Site identi-fication number (figure 1)	Year	Statistic						
		Number of compared data points	**Maximum difference**	**Minimum difference**	**Median difference**	**Mean difference**	**Absolute mean error**	**Root mean square error**
Temperature, in degrees Celsius								
L2	2001	153	4.7	-3.9	1.0	1.0	1.4	1.8
	2002	161	4.5	-2.1	1.6	1.6	1.7	2.0
	2003	28	4.3	2.4	3.0	3.1	3.1	3.2
	All	342	4.7	-3.9	1.4	1.4	1.7	2.0
L3	2001	296	5.2	-3.5	0.5	0.5	0.9	1.2
	2002	302	4.1	-4.0	0.8	0.7	1.3	1.6
	2003	48	3.4	1.1	2.1	2.1	2.1	2.2
	All	646	5.2	-4.0	0.7	0.7	1.2	1.5
L4	2001	334	4.2	-3.8	0.1	0.0	1.0	1.3
	2002	289	2.4	-2.7	0.7	0.6	0.9	1.1
	2003	57	2.3	0.5	1.5	1.4	1.4	1.5
	All	680	4.2	-3.8	0.4	0.4	1.0	1.2
L5	2001	628	6.2	-5.9	0.2	0.1	0.9	1.2
	2002	576	2.1	-2.4	0.8	0.5	0.8	0.9
	2003	103	1.5	-0.9	1.0	0.9	0.9	1.0
	All	1,307	6.2	-5.9	0.5	0.4	0.8	1.0
Dissolved-oxygen concentration, in milligrams per liter								
L2	2001	153	3.4	-6.8	-1.8	-1.7	2.0	2.6
	2002	161	3.9	-8.5	-1.1	-1.2	2.1	2.8
	2003	28	1.6	-1.4	0.7	0.4	0.8	0.9
	All	342	3.9	-8.5	-1.2	-1.3	2.0	2.6
L3	2001	296	3.2	-8.7	-2.1	-1.6	1.9	2.4
	2002	302	1.5	-9.1	-1.9	-1.9	2.0	2.7
	2003	48	-0.3	-2.2	-1.5	-1.3	1.3	1.3
	All	646	3.2	-9.1	-1.8	-1.7	1.9	2.5
L4	2001	334	6.0	-8.8	-0.6	-1.1	1.5	2.2
	2002	289	5.3	-8.0	-1.3	-1.3	1.5	1.9
	2003	57	0.5	-1.2	-0.3	-0.3	0.5	0.6
	All	680	6.0	-8.8	-0.8	-1.1	1.4	2.0
L5	2001	628	10.3	-6.2	-0.3	0.3	1.7	2.4
	2002	576	6.3	-5.9	-1.1	-0.7	1.5	1.9
	2003	103	4.8	-2.4	-1.2	-0.8	1.2	1.5
	All	1,307	10.3	-6.2	-0.8	-0.3	1.6	2.1

Differences between simulated and measured temperatures also varied temporally in Beaver Lake for April 2001 to April 2003. In general, the AME and RMSE were the least in 2001 at the two upstream sites (L2 and L3) and in 2002 at the two downstream sites (L4 and L5) and greatest in 2003 for all four sites (table 3). At site L5, near the dam (fig. 1), the AMEs for 2001 (April through December) and 2003 (January through March) were both 0.9 °C and RMSEs were 1.2 °C for 2001 and 1.0 °C for 2003. The AME for 2002 was 0.8 °C and RMSE was 0.9 °C. In comparison, at site L2, in the upstream portion of the reservoir (fig. 1), the AME ranged from 1.4 °C in 2001 to 3.1 °C in 2003 and the RMSE ranged from 1.8 °C in 2001 to 3.2 °C in 2003. Variations in the spatial differences between simulated and measured temperature generally were because of the wide variation of hydrologic conditions that occurred during the simulation.

Water Quality

Simulated data were compared to measured depth profile data (144 depth profiles) for dissolved-oxygen concentration at four sites in Beaver Lake. Simulated nutrient data were compared to samples collected in the epilimnion, metalimnion, and hypolimnion.

Dissolved Oxygen

In general, simulated dissolved-oxygen concentrations were spatially similar to measured values in Beaver Lake from April 2001 to April 2003 (figs. 29-32). Similar to temperature, differences between simulated and measured values of dissolved-oxygen concentrations were greater in the upstream portion of the reservoir compared to differences in the downstream portion. The AME for the entire simulated period for site L2 was 2.0 mg/L and the RMSE was 2.6 mg/L (table 3). The AME and RMSE for site L4 was 1.4 mg/L and 2.0 mg/L, respectively. Again, greater differences between simulated and measured values in the upstream portion of the reservoir compared to the downstream portion may be because of the more dynamic, riverine-type conditions in the upstream portion. The model generally overestimated the dissolved-oxygen concentration with the median difference (measured minus simulated) between simulated and measured values ranging from -2.1 mg/L (site L3 in 2001) to 0.7 mg/L (site L2 in 2003) (table 3).

Simulated dissolved-oxygen concentrations also compared well to measured values temporally in Beaver Lake. At the upstream portion of the reservoir at sites L2 and L3, the greatest differences between simulated and measured dissolved oxygen generally occurred in 2002 and the least differences occurred in 2003 (table 3). At sites L4 and L5 the greatest differences occurred in 2001 and the least differences occurred in 2003. A possible explanation for the greater differences in 2002 at the upstream portion of the reservoir may be that during that time there was an increase in the number of high flow events from the tributaries, which may have changed the dynamics of dissolved oxygen because of loading and distribution of nutrients and organic matter, which was not simulated as well as in 2001 and 2003.

Nitrogen and Phosphorus

Simulated ammonia and total nitrogen concentrations in Beaver Lake compared relatively well with the measured concentrations, and simulated nitrite plus nitrate concentrations generally were less then the measured concentrations (figs. 33-35). The greatest differences between simulated and measured nitrogen concentrations generally occurred in the upstream portion of the reservoir and generally were greatest in the hypolimnion. The AME for ammonia ranged from 0.03 (site L5) to 0.14 mg/L (site L3) and the RMSE ranged from 0.05 to 0.27 mg/L for all of the compared data at each site (table 4). The measured concentrations of ammonia were greater in samples collected in the hypolimnion and similarly, the differences in simulated and measured concentrations also were greater in the hypolimnion (fig. 33). Simulated nitrite plus nitrate had AMEs ranging from 0.19 to 0.37 mg/L and RMSEs ranging from 0.26 to 0.52 mg/L when compared to all of the measured data at each site. The AME for total nitrogen ranged from 0.21 (site L5) to 0.45 mg/L (site L2) and the RMSE ranged from 0.29 to 0.57 mg/L for all of the compared data at each site. Similar to ammonia concentrations, measured nitrite plus nitrate and total nitrogen concentrations were greater in the hypolimnion, and likewise, the differences between simulated and measured concentrations also were greater (figs. 34 and 35). Because the simulated total nitrogen was comparable to the measured data and the nitrite plus nitrate was less, the model may be simulating greater concentrations of nitrogen in the form of organic nitrogen, instead of in the form of nitrite plus nitrate as is shown in the measured data. However, the temporal changes in the concentrations of nitrogen in the reservoir in the Beaver Lake model were adequately simulated (figs. 33-35).

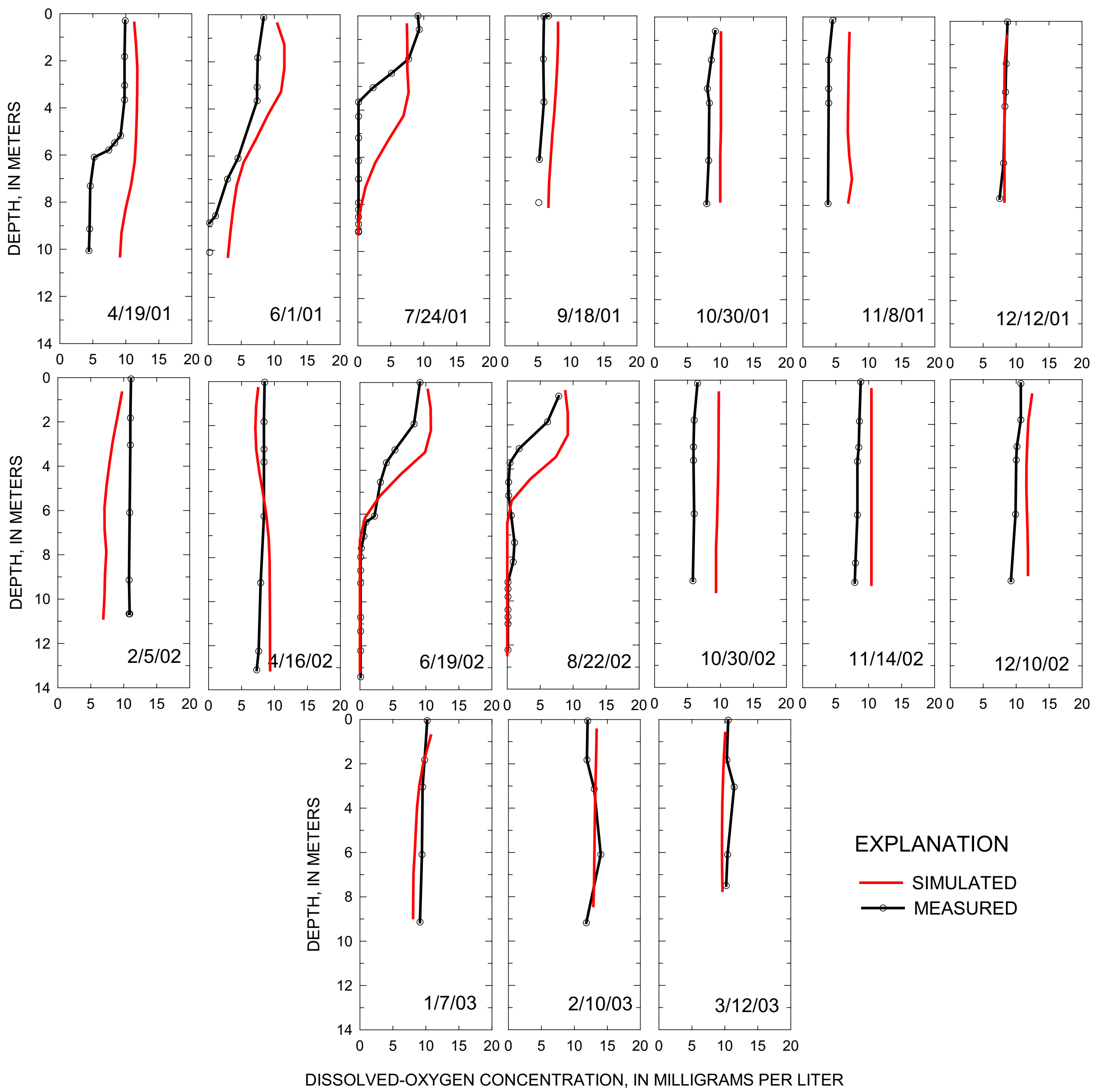

Figure 29. Selected simulated and measured dissolved-oxygen concentration profiles for Beaver Lake at Highway 412 bridge near Sonora, Arkansas (site L2), April 2001 to April 2003.

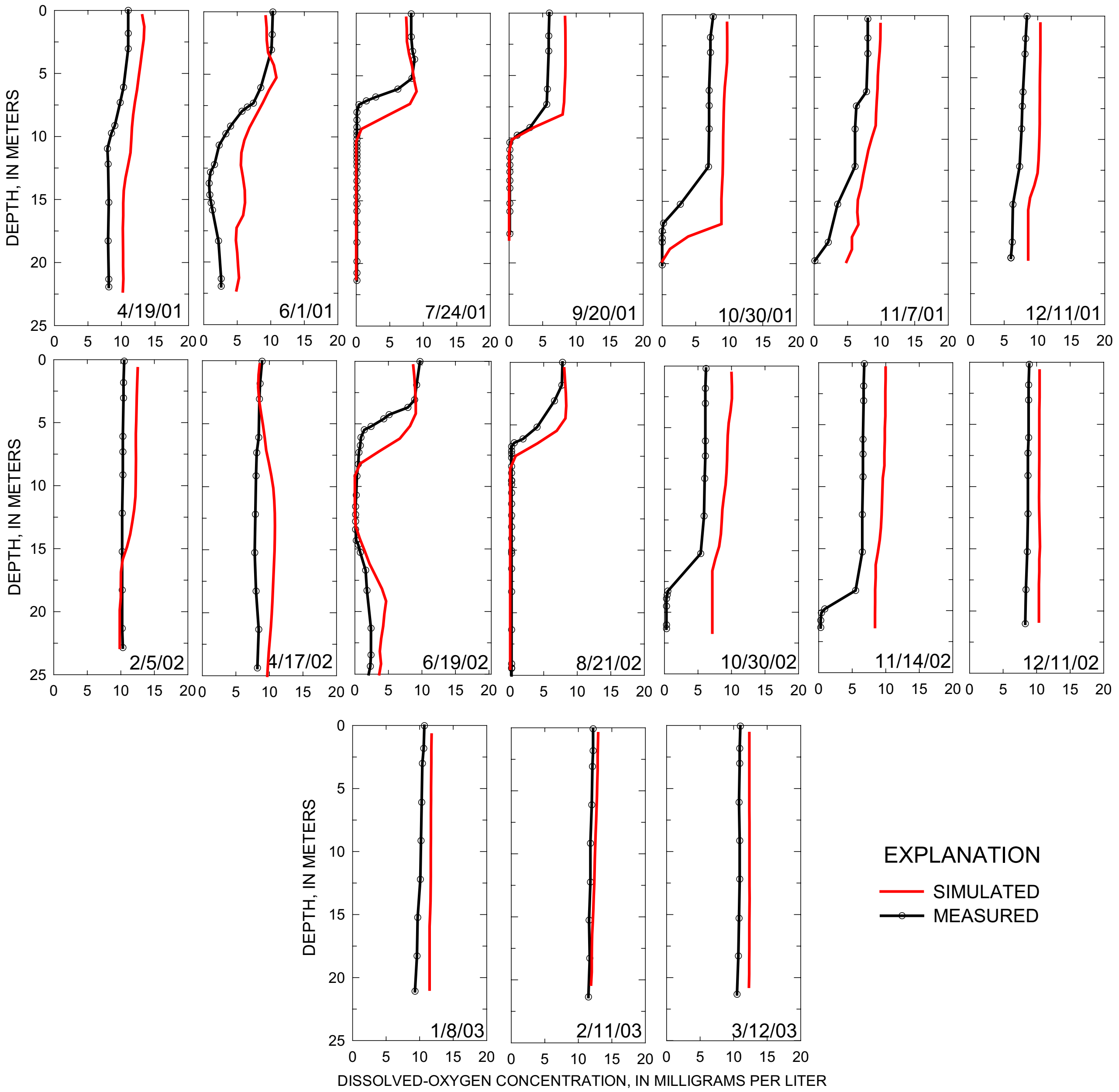

Figure 30. Selected simulated and measured dissolved-oxygen concentration profiles for Beaver Lake near Lowell, Arkansas (site L3), April 2001 to April 2003.

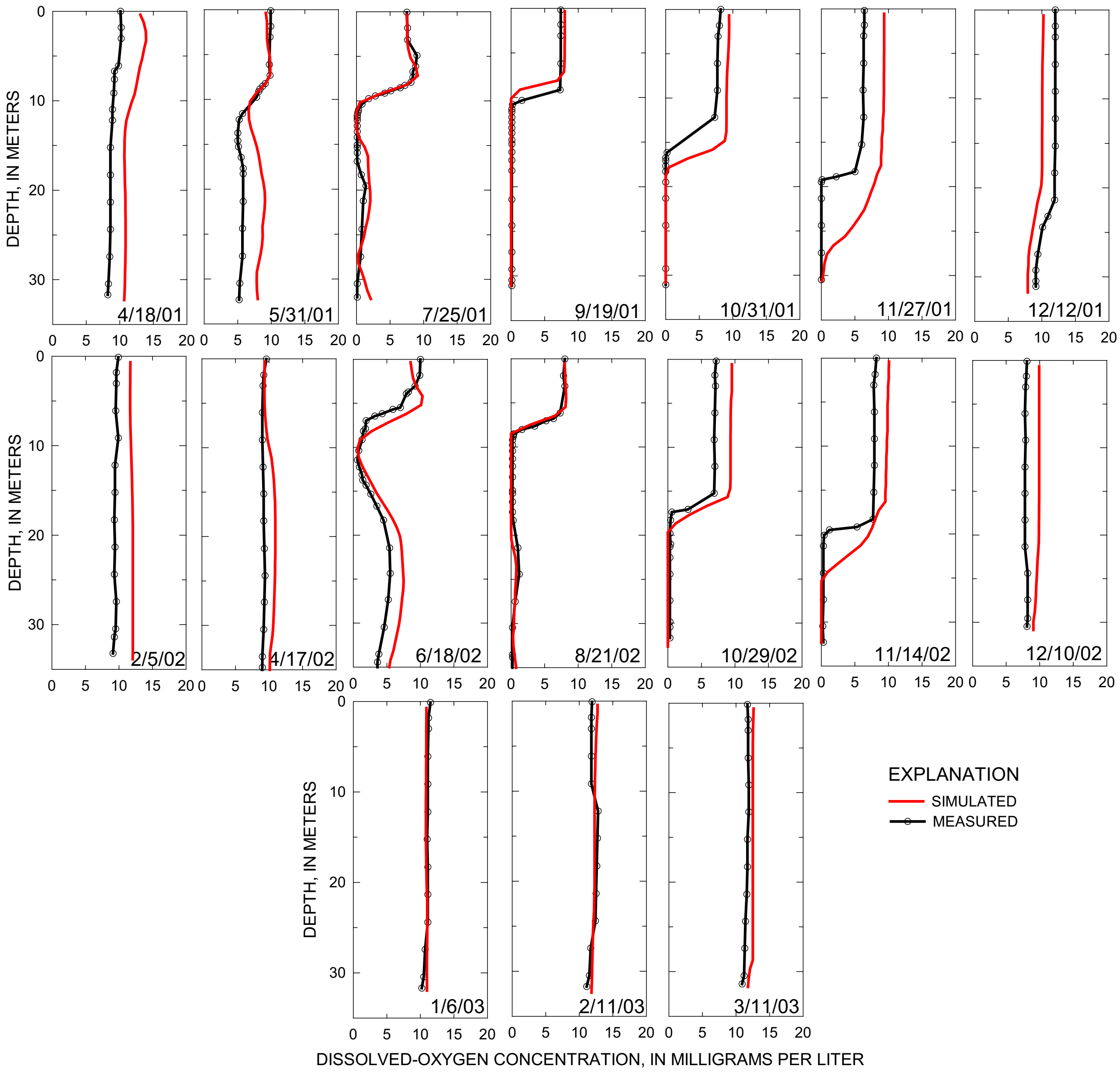

Figure 31. Selected simulated and measured dissolved-oxygen concentration profiles for Beaver Lake at Highway 12 bridge near Rogers, Arkansas (site L4), April 2001 to April 2003.

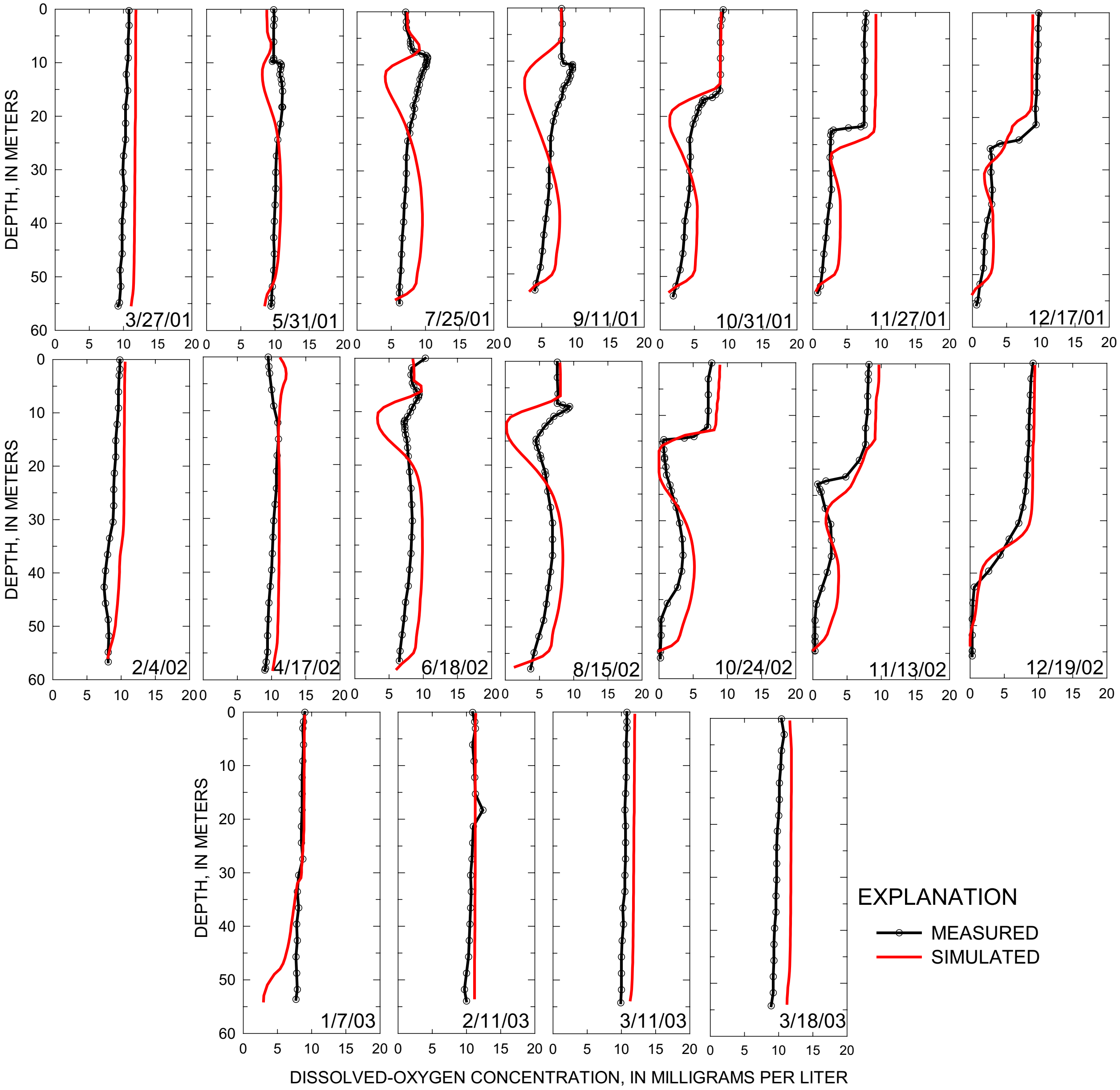

Figure 32. Selected simulated and measured dissolved-oxygen concentration profiles for Beaver Lake near Eureka Springs, Arkansas (site L5), April 2001 to April 2003.

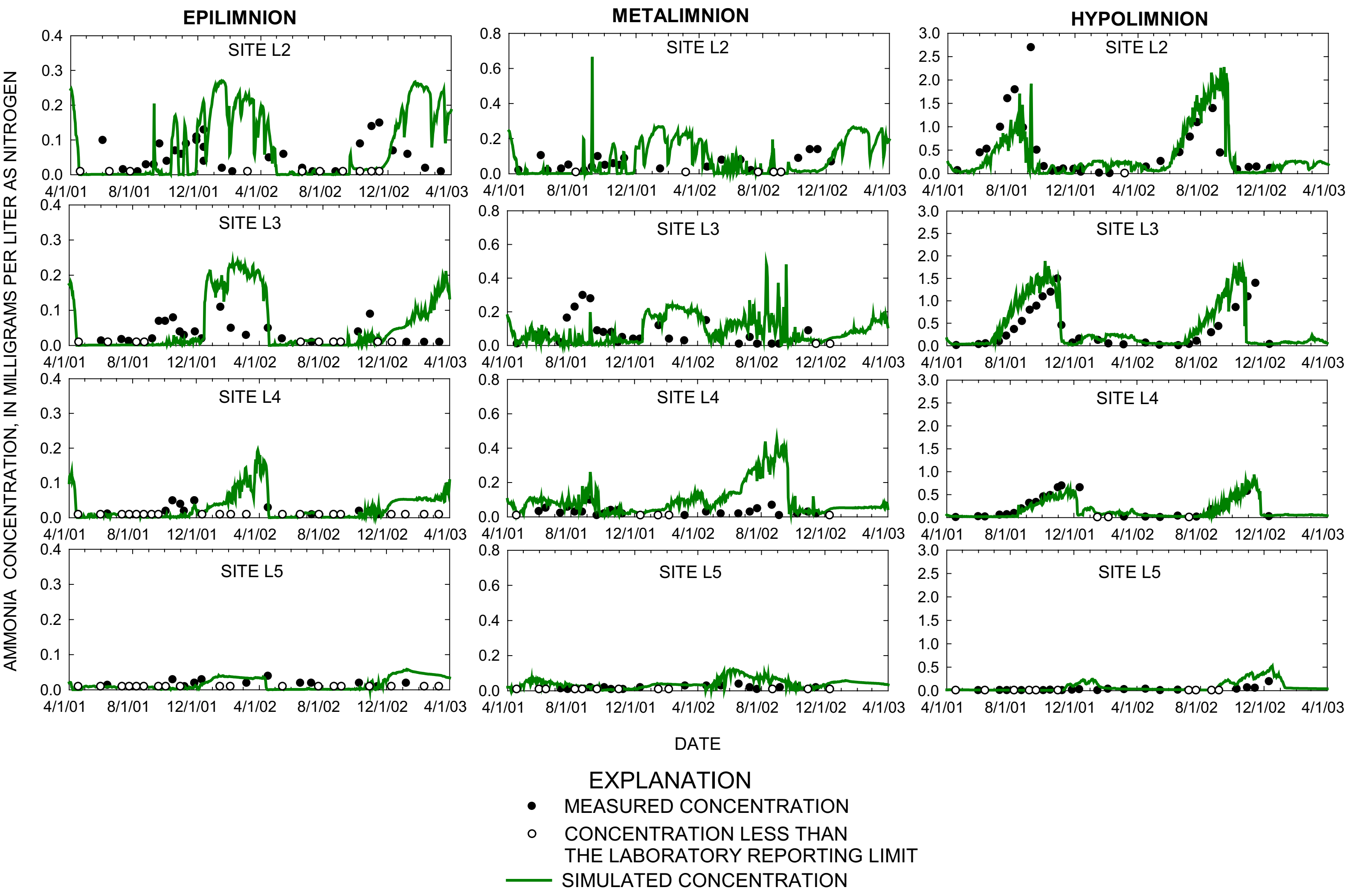

Figure 33. Simulated and measured ammonia concentrations for Beaver Lake, Arkansas, April 2001 to April 2003.

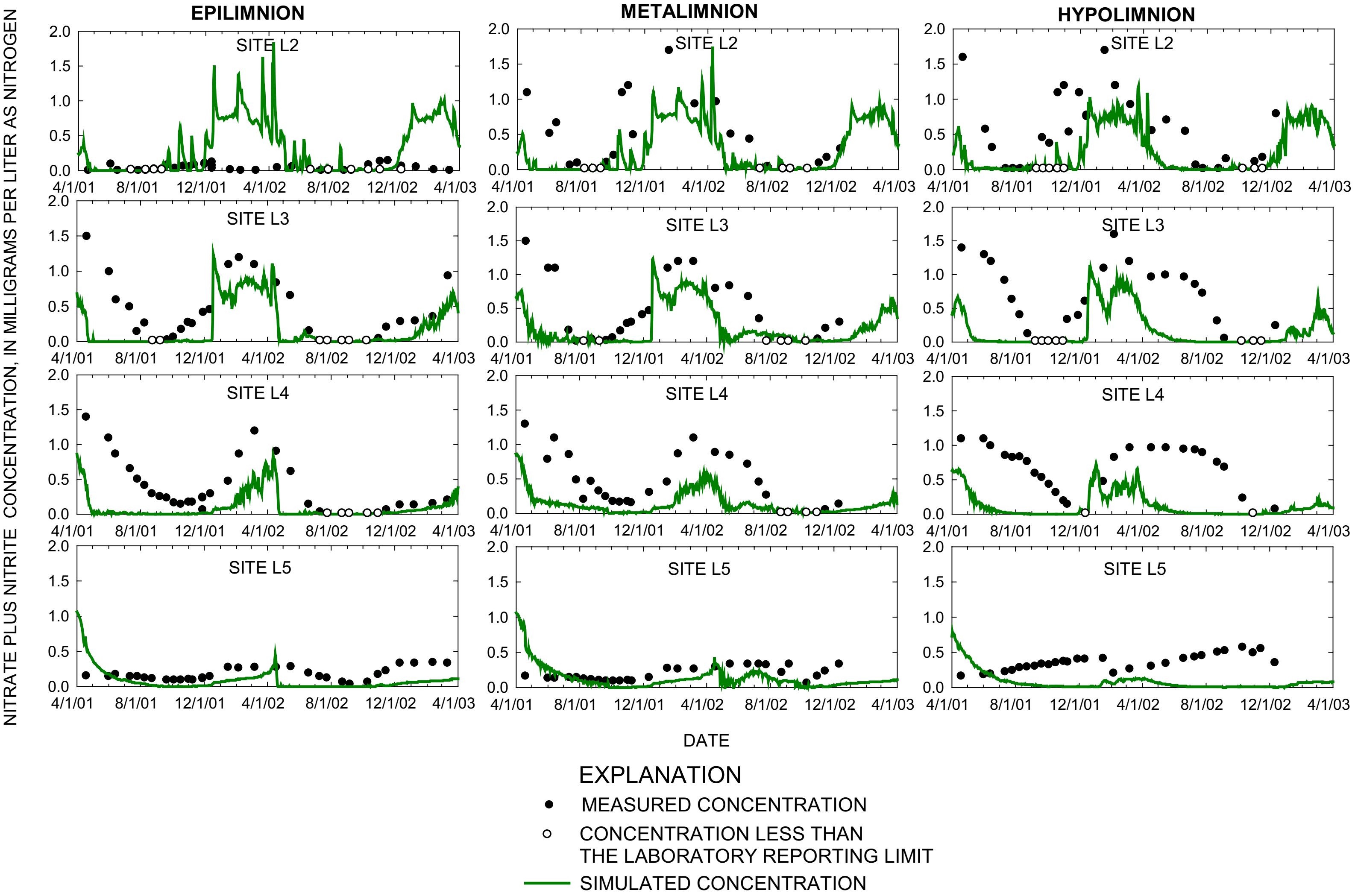

Figure 34. Simulated and measured nitrite plus nitrate concentrations for Beaver Lake, Arkansas, April 2001 to April 2003.

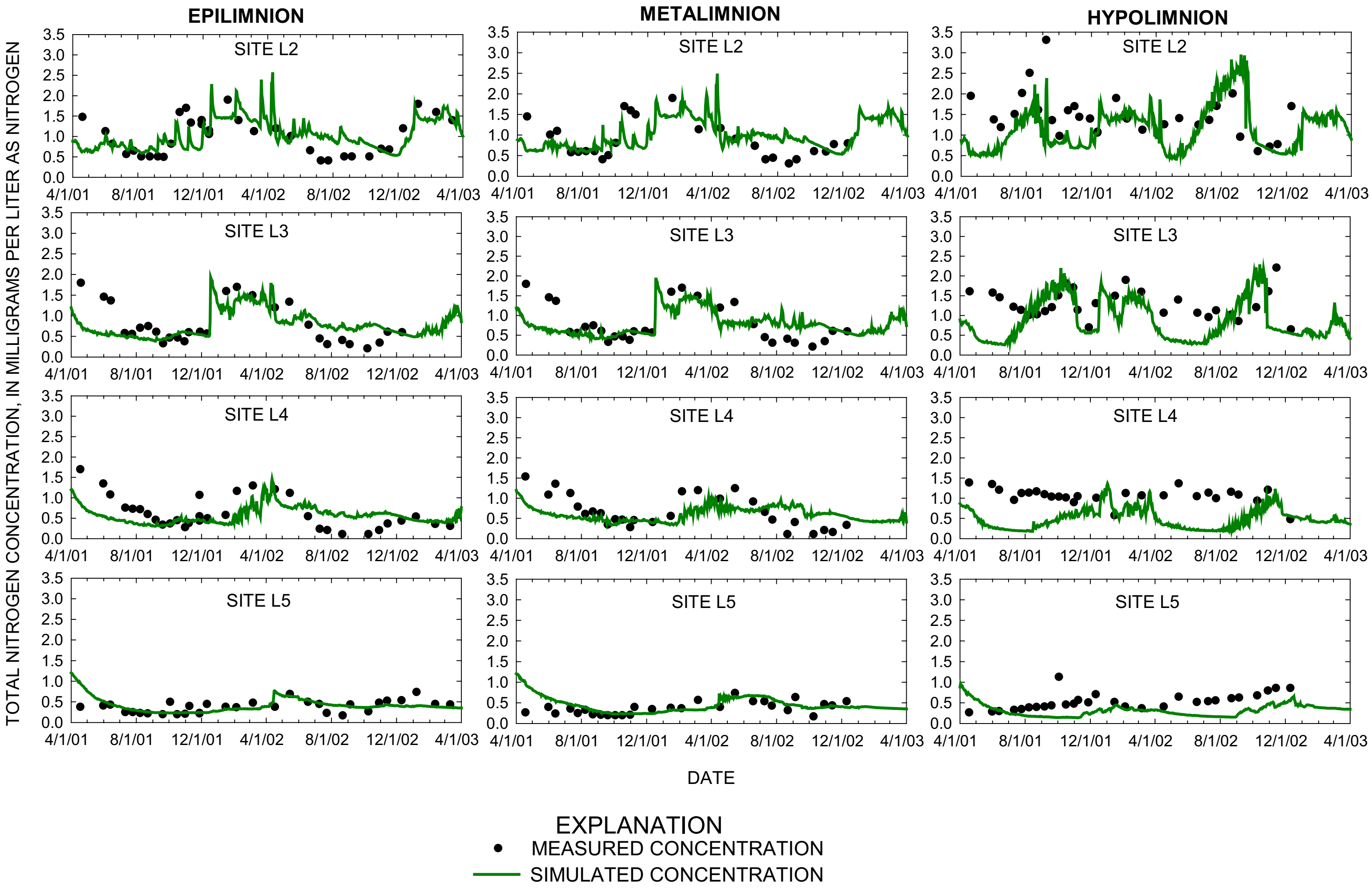

Figure 35. Simulated and measured total nitrogen concentrations for Beaver Lake, Arkansas, April 2001 to April 2003.

Table 4. Comparative statistics of simulated and measured nutrient concentrations for Beaver Lake, April 2001 to April 2003.

[Difference is simulated minus measured]

Site identification number	Year	Number of compared data	Mean difference	Maximum difference	Minimum difference	Absolute mean error	Root mean square error
Ammonia, in milligrams per liter as nitrogen							
L2	2001	45	-0.09	0.22	-1.08	0.15	0.28
	2002	47	0.07	1.31	-0.20	0.13	0.24
	2003	3	0.04	0.09	-0.01	0.04	0.06
	All	95	-0.01	1.31	-1.08	0.13	0.26
L3	2001	45	0.02	0.65	-0.55	0.12	0.20
	2002	43	0.04	0.92	-1.35	0.17	0.33
	2003	3	0.09	0.14	0.05	0.09	0.10
	All	91	0.03	0.92	-1.35	0.14	0.27
L4	2001	45	-0.05	0.15	-0.67	0.07	0.15
	2002	41	0.05	0.34	-0.10	0.05	0.09
	2003	3	0.04	0.05	0.04	0.04	0.04
	All	89	0.00	0.34	-0.67	0.06	0.12
L5	2001	53	0.01	0.14	-0.03	0.01	0.03
	2002	49	0.03	0.26	-0.04	0.04	0.07
	2003	4	0.04	0.04	0.03	0.04	0.04
	All	106	0.02	0.26	-0.04	0.03	0.05
Nitrite plus nitrate, in milligrams per liter as nitrogen							
L2	2001	45	-0.35	0.60	-1.44	0.39	0.55
	2002	47	-0.11	1.31	-0.99	0.32	0.46
	2003	3	-0.74	-0.38	-1.26	0.74	0.83
	All	95	-0.24	1.31	-1.44	0.37	0.52
L3	2001	45	-0.38	0.06	-1.28	0.38	0.54
	2002	43	-0.30	0.09	-0.95	0.31	0.42
	2003	3	-0.27	-0.11	-0.46	0.27	0.30
	All	91	-0.34	0.09	-1.28	0.34	0.48
L4	2001	45	-0.45	0.00	-1.08	0.45	0.54
	2002	41	-0.36	0.03	-0.93	0.36	0.49
	2003	3	-0.07	-0.05	-0.09	0.07	0.08
	All	89	-0.39	0.03	-1.08	0.40	0.51

Table 4. Comparative statistics of simulated and measured nutrient concentrations for Beaver Lake, April 2001 to April 2003.—Continued

[Difference is simulated minus measured]

Site identification number	Year	Number of compared data	Mean difference	Maximum difference	Minimum difference	Absolute mean error	Root mean square error
L5	2001	53	-0.06	1.07	-0.40	0.17	0.25
	2002	49	-0.20	0.15	-0.57	0.21	0.26
	2003	4	-0.18	0.10	-0.28	0.23	0.24
	All	106	-0.13	1.07	-0.57	0.19	0.26
Total nitrogen, in milligrams per liter as nitrogen							
L2	2001	45	-0.26	1.00	-1.43	0.44	0.57
	2002	47	0.24	1.47	-1.14	0.46	0.57
	2003	3	-0.31	-0.07	-0.45	0.31	0.36
	All	95	-0.02	1.47	-1.43	0.45	0.57
L3	2001	45	-0.21	0.62	-1.29	0.33	0.48
	2002	43	-0.04	1.01	-1.57	0.44	0.53
	2003	3	-0.24	-0.12	-0.41	0.24	0.27
	All	91	-0.13	1.01	-1.57	0.38	0.50
L4	2001	45	-0.38	0.16	-1.06	0.40	0.51
	2002	41	-0.13	0.66	-1.10	0.45	0.51
	2003	3	0.03	0.12	-0.10	0.10	0.10
	All	89	-0.25	0.66	-1.10	0.41	0.50
L5	2001	53	0.02	1.22	-0.99	0.21	0.31
	2002	49	-0.02	0.42	-0.47	0.21	0.26
	2003	4	-0.03	0.35	-0.34	0.21	0.25
	All	106	0.00	1.22	-0.99	0.21	0.29
Orthophosphorus, in milligrams per liter as phosphorus							
L2	2001	45	0.01	0.03	-0.04	0.01	0.02
	2002	47	0.01	0.05	-0.01	0.02	0.02
	2003	3	0.02	0.03	0.00	0.02	0.02
	All	95	0.01	0.05	-0.04	0.02	0.02
L3	2001	45	0.00	0.03	-0.09	0.01	0.02
	2002	43	0.01	0.04	-0.07	0.02	0.02
	2003	3	0.01	0.02	0.00	0.01	0.02
	All	91	0.00	0.04	-0.09	0.02	0.02

Table 4. Comparative statistics of simulated and measured nutrient concentrations for Beaver Lake, April 2001 to April 2003.—Continued

[Difference is simulated minus measured]

Site identification number	Year	Number of compared data	Mean difference	Maximum difference	Minimum difference	Absolute mean error	Root mean square error
L4	2001	45	0.00	0.02	-0.01	0.01	0.01
	2002	41	0.01	0.03	-0.02	0.01	0.01
	2003	3	0.01	0.01	0.01	0.01	0.01
	All	89	0.01	0.03	-0.02	0.01	0.01
L5	2001	53	0.00	0.01	-0.02	0.01	0.01
	2002	49	0.01	0.02	-0.02	0.01	0.01
	2003	4	0.02	0.02	0.01	0.02	0.02
	All	106	0.00	0.02	-0.02	0.01	0.01
Total phosphorus, in milligrams per liter as phosphorus							
L2	2001	45	0.02	0.07	-0.14	0.03	0.04
	2002	47	0.03	0.08	-0.09	0.04	0.04
	2003	3	0.03	0.06	0.01	0.03	0.04
	All	95	0.03	0.08	-0.14	0.04	0.04
L3	2001	45	0.01	0.03	-0.22	0.03	0.04
	2002	43	0.01	0.05	-0.10	0.03	0.03
	2003	3	0.02	0.03	0.02	0.02	0.02
	All	91	0.01	0.05	-0.22	0.03	0.04
L4	2001	45	0.01	0.03	0.00	0.01	0.01
	2002	41	0.00	0.05	-0.95	0.04	0.15
	2003	3	0.02	0.02	0.02	0.02	0.02
	All	89	0.01	0.05	-0.95	0.03	0.10
L5	2001	53	0.00	0.03	-0.01	0.01	0.01
	2002	49	0.02	0.04	0.00	0.02	0.02
	2003	4	0.02	0.04	0.02	0.02	0.03
	All	106	0.01	0.04	-0.01	0.01	0.02

Simulated values for orthophosphorus were comparable to measured concentrations and simulated total phosphorus concentrations generally were greater than the measured concentrations in Beaver Lake for April 2001 to April 2003 (figs. 36-37). Measured orthophosphorus concentrations mostly were below laboratory reporting limits and simulated concentrations were very low, resulting in AMEs and RMSEs ranging from 0.01 to 0.02 mg/L for all the compared data at each site (table 4). The AME for total phosphorus ranged from 0.01 to 0.04 mg/L and the RMSE ranged from 0.02 to 0.10 mg/L for all the compared data at each site. Because simulated total phosphorus was greater than the measured total phosphorus although the simulated orthophosphorus was consistent with the measured data suggested that the model simulated more organic phosphorus (stored in the algal biomass) than evident from the measured data.

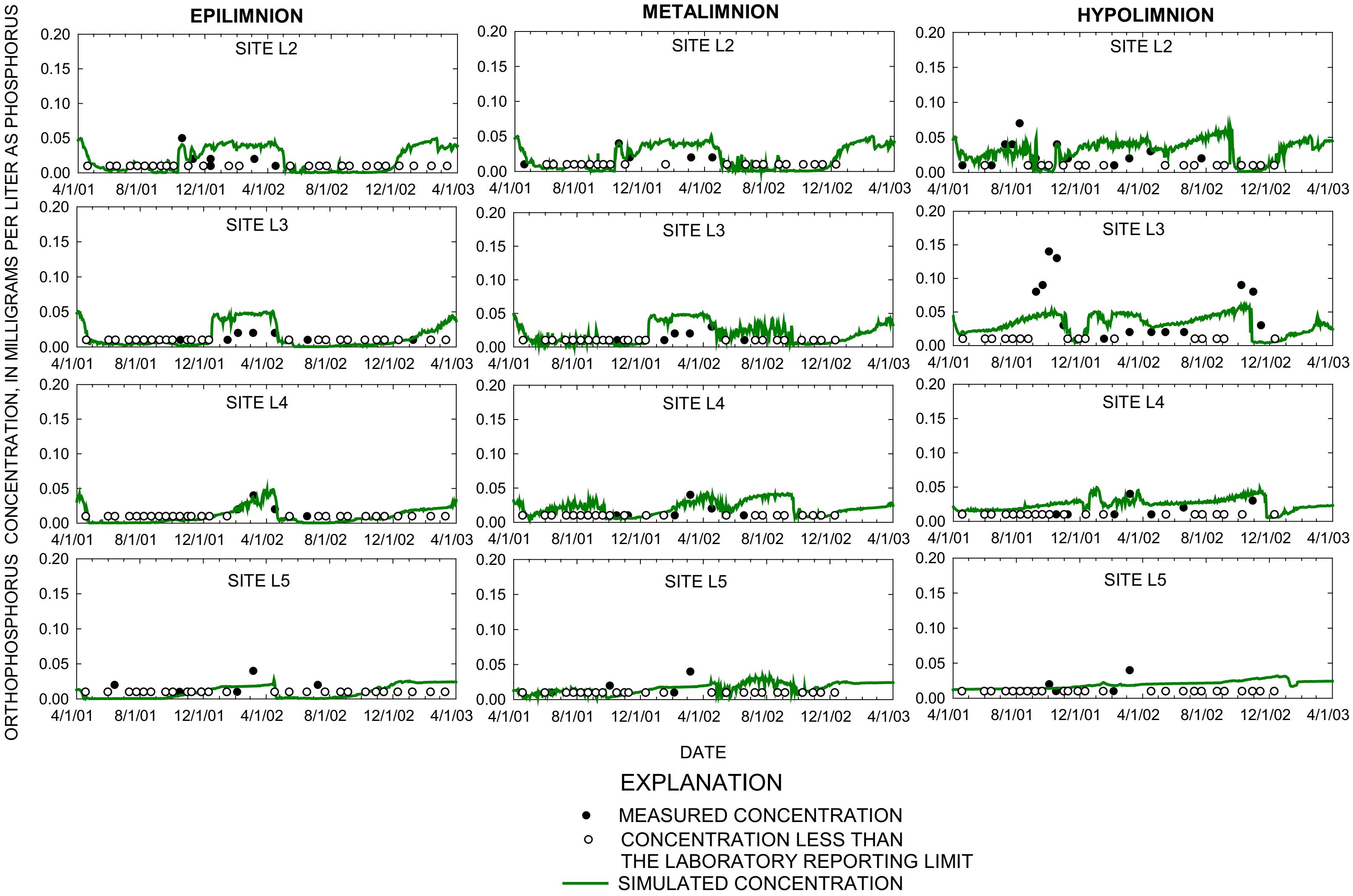

Figure 36. Simulated and measured orthophosphorus concentrations for Beaver Lake, Arkansas, April 2001 to April 2003.

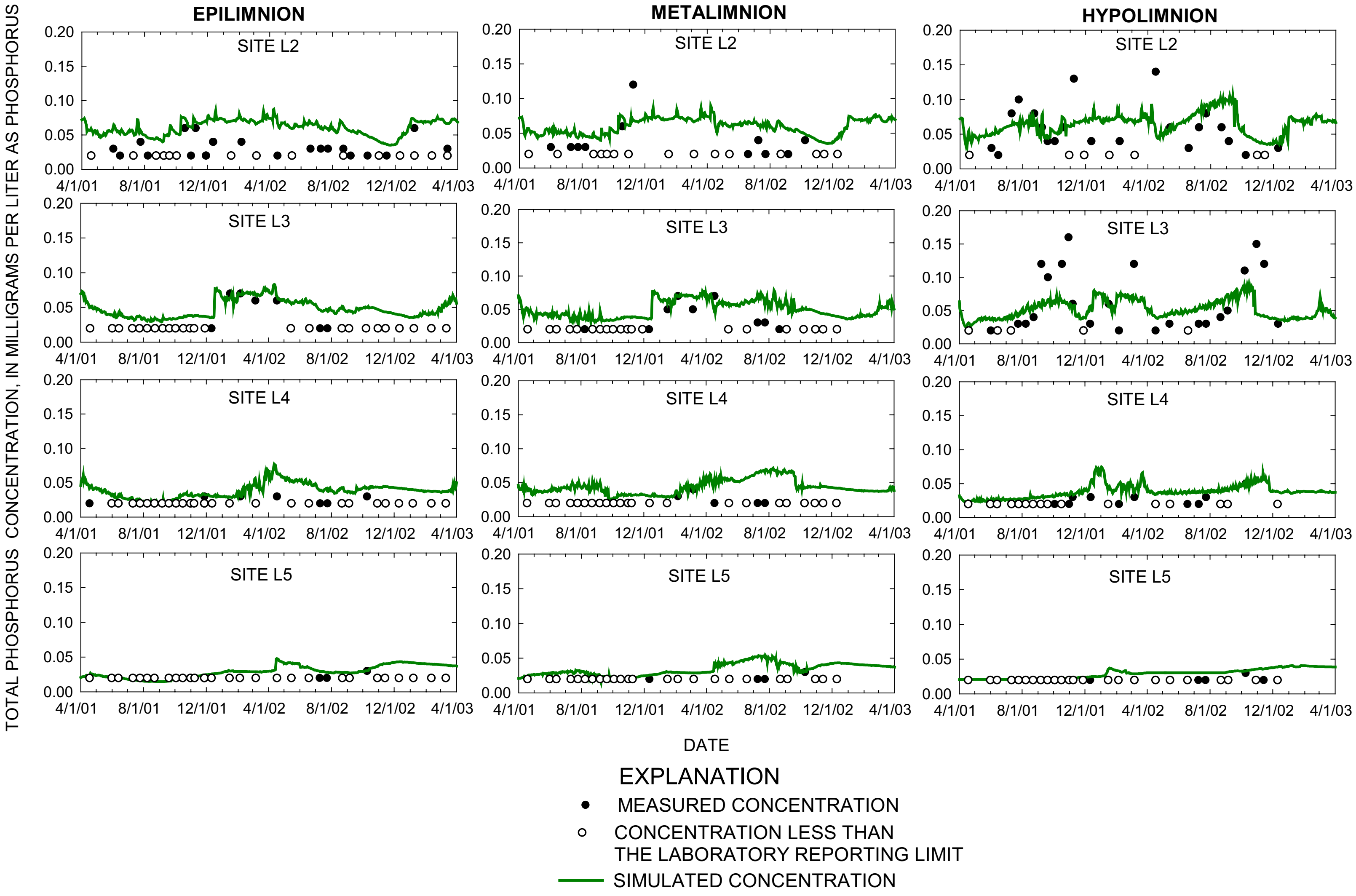

Figure 37. Simulated and measured total phosphorus concentrations for Beaver Lake, Arkansas, April 2001 to April 2003.

Algae

Simulated algal biomass was compared to measured chlorophyll *a* at the four sites in Beaver Lake from April 2001 to April 2003. The concentration of chlorophyll *a* commonly is used as a measure of the density of the algal population of a lake. Algal biomass in the CEQUAL-W2 model is converted to chlorophyll *a* using a ratio (table 2) for comparison with measured data. Limited phytoplankton data were used to adjust the distribution of the four phytoplankton groups in the model (green, blue-green, diatoms, and flagellates) to reflect the ambient conditions in Beaver Lake.

Simulated chlorophyll *a* values were comparable to measured chlorophyll *a* values in Beaver Lake (fig. 38). The greatest differences between simulated and measured chlorophyll *a* occurred at site L2 with an AME of 5.6 µg/L and an RMSE of 7.3 µg/L (table 5). The AME and RMSE for simulated chlorophyll *a* concentrations at site L5 were 1.8 and 2.3 µg/L, respectively. Some of the differences between simulated and measured data can be explained by the variability in the measured concentrations because of the uneven vertical distribution of phytoplankton in the water column. However the simulated chlorophyll *a* followed the measured pattern of occurrence in the measured data with greater concentrations in May through November and lower concentrations in December through April (fig. 38).

The composition and dynamics of the algal community in a reservoir can be complex. Modeling of the algal dynamics and composition is a large simplification of what actually occurs in a reservoir. In Beaver Lake, at least 114 different species have been identified from samples collected from 2001 through 2003 (Russell Rhodes, Missouri State University, written commun., 2003). To reduce the complexity and uncertainty in the Beaver Lake model because of limited information, the diverse species composition was generalized into four main groups; blue-green algae, green algae, diatoms, and flagellates.

The occurrence and distribution of the four simulated phytoplankton groups generally reflected the measured distribution in Beaver Lake (fig. 39). Blue-green and green algae tended to be more abundant at the upstream sites, while diatoms and flagellates tended to be more abundant at the downstream sites as was reflected in the measured data (fig. 18). The Beaver Lake model simulated the occurrence and distribution better at the downstream sites (L3, L4, and L5) than at the upstream sites (L1 and L2). The model generally simulated higher concentrations of blue-green and green algae in the upstream sites than were observed in the measured data (fig. 18). Diatoms and flagellates also were more abundant when water temperatures were lower and blue-green and green algae were more abundant when water temperatures were higher.

Table 5. Comparative statistics of simulated and measured chlorophyll *a* concentrations for Beaver Lake, April 2001 to April 2003.

[Values in micrograms per liter. Difference is simulated minus measured]

Site identification number (figure 1)	Year	Number of compared data	Mean difference	Maximum difference	Minimum difference	Absolute mean error	Root mean square error
L2	2001	15	-6.4	1.8	-17.3	6.7	8.3
	2002	14	-1.2	15.1	-14.2	4.4	6.4
	2003	3	-5.5	-3.5	-9.5	5.5	6.2
	All	32	-4.0	15.1	-17.3	5.6	7.3
L3	2001	15	-0.9	3.4	-6.5	1.9	2.5
	2002	15	1.9	7.0	-4.5	3.2	3.9
	2003	3	-3.6	-1.9	-4.6	3.6	3.9
	All	33	0.1	7.0	-6.5	2.6	3.3
L4	2001	15	0.2	4.5	-2.4	2.1	2.5
	2002	14	0.5	4.7	-8.3	3.2	4.1
	2003	3	-0.9	-0.2	-1.5	0.9	1.0
	All	32	0.2	4.7	-8.3	2.5	3.2
L5	2001	15	1.5	7.0	-0.7	1.6	2.4
	2002	14	1.5	5.0	-1.2	1.9	2.4
	2003	4	1.5	2.6	0.8	1.5	1.7
	All	32	1.5	7.0	-1.2	1.8	2.3

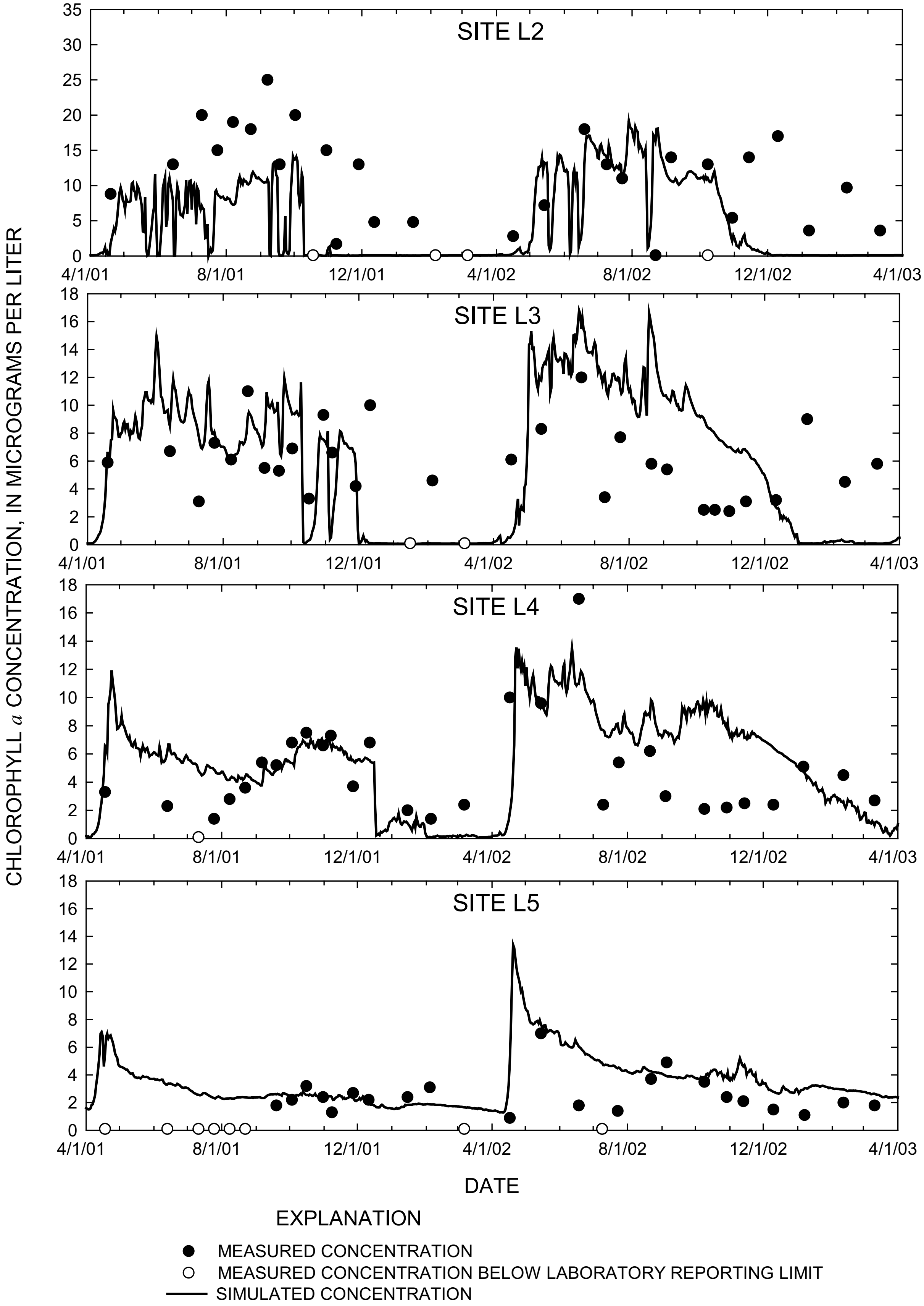

Figure 38. Simulated and measured chlorophyll *a* concentrations in the epilimnion for Beaver Lake, Arkansas, April 2001 to April 2003.

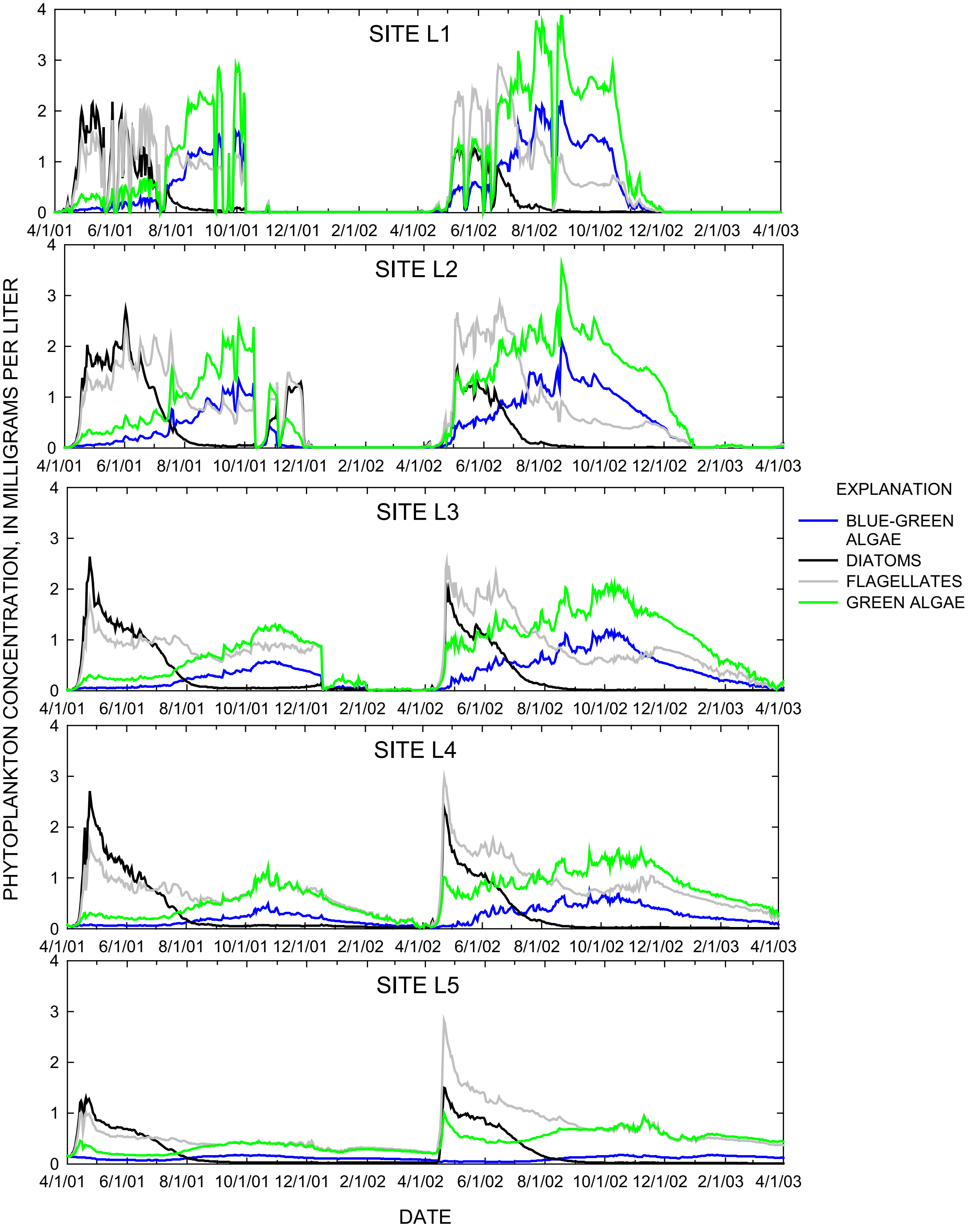

Figure 39. Simulated phytoplankton distribution for Beaver Lake, Arkansas, April 2001 to April 2003.

Eddy coefficients are used to model turbulence in a reservoir in which vertical turbulence equations are written in the conservative form using the Boussinesq and hydrostatic approximations (Cole and Wells, 2003). Since vertical momentum is not included, the model may give inaccurate results where there is substantial vertical acceleration.

Some other limitations of the water-quality interactions in the model are that zooplankton or macrophytes are not included and the model uses simplistic sediment-oxygen demand computations. The zooplankton and macrophyte communities not represented in the model may have an effect on how the phytoplankton community or recycling of nutrients are simulated. The model does not have a sediment compartment that models kinetics in the sediment and at the sediment-water interface. The simplistic sediment computation in the model places a limitation on long-term predictive capabilities of the water-quality portion of the model.

Sensitivity

Sensitivity analysis is the determination of the effects of small changes in calibrated model parameters and input on model results. A complete sensitivity analysis for the Beaver Lake model was not conducted because the model includes a large number of parameters (table 2). However, testing of how changes in different parameters affect the hydrodynamics, temperature, and water quality was conducted as part of the model development and calibration. Results from these simulations and information from previous model studies (Haggard and Green, 2002; Galloway and Green, 2002; 2003; Green and others, 2003; Bales and others, 2001; Sullivan and Rounds, 2005) were used to identify several parameters for evaluation in the sensitivity analysis. The sensitivity of simulated water temperature and water quality were assessed with changes in the wind-sheltering coefficient, light extinction coefficient for pure water, fraction of sediment-oxygen demand, algal growth rate, algal half-saturation constant for phosphorus, algal half-saturation constant for nitrogen, saturation of light intensity, inflow phosphorus, inflow nitrogen, and inflow organic matter. Each selected parameter was increased and decreased by 40 percent with all other parameters held constant. Vertical profiles, at 1 m depth intervals, of water temperature and concentrations of dissolved oxygen, ammonia, nitrite plus nitrate, total nitrogen, orthophosphorus, total algae, and chlorophyll *a* between the calibrated model and the sensitivity test were compared at sites L2 through L5.

Water temperature in the Beaver Lake model was the most sensitive to wind speed (wind-sheltering coefficient) and light extinction in the water column (table 6). The wind speed, adjusted using the wind-sheltering coefficient, affects the amount of mixing in the reservoir, which can change the depth of the thermocline and increase or decrease the evaporative cooling. Higher wind speeds result in more mixing, thus a deeper thermocline and lower surface temperatures, while lower wind speeds result in a shallower thermocline and higher surface temperatures. The changes in the thermocline depth resulted in the greatest differences at the thermocline between the calibrated model and the sensitivity test because of the rapid change in water temperature with depth that occurs at the thermocline.

Dissolved-oxygen concentrations were most affected by changes in light extinction, wind speed, and sediment-oxygen demand (fraction of sediment oxygen demand) (table 6). Dissolved-oxygen dynamics are controlled mainly by changes in temperature, which were most sensitive to changes in wind speed and light extinction. Wind speed also can affect dissolved-oxygen dynamics by aeration in the epilimnion. Sediment-oxygen demand is a substantial sink for dissolved oxygen in the Beaver Lake model and had the greatest affect on the concentrations.

Nitrogen concentrations were affected by changes in several parameters in the Beaver Lake model (table 6). Ammonia was sensitive to changes in the sediment-oxygen demand and wind speed. Increases in sediment-oxygen demand decreases the amount of dissolved oxygen in the hypolimnion, and, therefore, limits the amount of nitrification (conversion of ammonia to nitrate) and increases the amount of release of ammonia from the sediments resulting in higher ammonia concentrations. Nitrite plus nitrate concentrations were sensitive to changes in the two sources of nitrate in the model, inflow nitrogen, and nitrification from ammonia as a result of changes in wind speed. Total nitrogen was most sensitive to sediment-oxygen demand, mainly because of changes in ammonia, and sensitive to parameters affecting algal concentrations such as algal growth rate, inflow nitrogen, inflow phosphorus, and inflow organic matter, which affected the organic nitrogen concentrations in the model.

Phosphorus was relatively insensitive to changes in the selected model parameters for the Beaver Lake model (table 6). Orthophosphorus concentrations were slightly decreased by a 40 percent decrease in algal growth and slightly increased with a 40 percent increase in the inflow phosphorus concentrations. Total phosphorus was slightly increased by a 40 percent increase in inflow organic matter and phosphorus.

Total algae and chlorophyll *a* in the Beaver Lake model were most sensitive to changes in the algal growth rate, light extinction, and inflow of phosphorus and organic matter (table 6). Because Beaver Lake generally is phosphorus limited, changes in inflow phosphorus had the greatest effect on the chlorophyll *a* and algal concentrations in the reservoir, while changes in inflow nitrogen concentrations had little effect. Because algae are dependent on light in the water column for photosynthesis, changes in light penetration (light extinction) have a substantial effect on algal growth.

Model Limitations

An understanding of model limitations is essential for effective use of reservoir models. The accuracy of the Beaver Lake model is limited by the simplification of complexities of

Table 6. Results of sensitivity analysis for the Beaver Lake model, April 2001 to April 2003, showing the mean difference of all computed values at five sites in Beaver Lake compared to calibrated values.

[°C, degrees Celsius; mg/L, milligrams per liter]; N, nitrogen; P, phosphorus; µg/L, micrograms per liter

Constituent	Input, in percent change from calibrated value	Mean differences (sensitivity test value minus calibrated value)								
		Temperature, °C	Dissolved oxygen, mg/L	Ammonia, mg/L as N	Nitrite plus nitrate, mg/L as N	Total nitrogen, mg/L as N	Orthophosphorus, mg/L as P	Total phosphorus, mg/L as P	Total algae, mg/L	Chlorophyll *a*, µg/L
Algal growth rate	+40	0.01	0.09	0.00	-0.01	0.01	0.00	0.00	0.15	0.37
	-40	0.01	-0.03	-0.01	0.01	-0.05	0.01	0.00	-0.31	-0.77
Saturation of light intensity	+40	-0.01	-0.07	0.00	0.00	0.00	0.00	0.00	-0.05	-0.13
	-40	-0.01	0.13	-0.01	0.00	0.00	0.00	0.00	0.02	0.05
Algal half-saturation constant for nitrogen	+40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.02	-0.04
	-40	-0.01	-0.07	0.00	0.00	0.00	0.00	0.00	-0.05	-0.13
Algal half-saturation constant for phosphorus	+40	-0.01	0.01	0.00	0.00	0.00	0.00	0.00	-0.01	-0.03
	-40	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02
Light extinction coefficient for pure water	+40	-0.12	-0.17	0.00	0.00	-0.01	0.00	0.00	-0.10	-0.25
	-40	0.19	0.36	-0.01	0.00	0.00	0.00	0.00	0.08	0.20
Fraction of sediment oxygen demand	+40	0.00	-0.52	0.06	0.01	0.08	0.00	0.00	0.05	0.13
	-40	0.00	0.66	-0.05	0.00	-0.07	0.00	0.00	-0.09	-0.23
Wind-sheltering coefficient	+40	2.24	-0.19	0.04	-0.02	0.03	0.00	0.00	0.00	0.01
	-40	-1.98	0.60	-0.02	0.06	0.04	0.00	0.00	-0.01	-0.03
Inflow nitrogen	+40	-0.02	-0.16	0.01	0.05	0.10	0.00	0.00	0.07	0.17
	-40	0.00	-0.11	0.00	-0.03	-0.02	0.00	0.00	-0.04	-0.09
Inflow organic matter	+40	-0.03	-0.26	0.02	0.01	0.13	0.00	0.01	0.13	0.33
	-40	0.00	-0.04	0.00	0.01	-0.03	0.00	0.00	-0.04	-0.09
Inflow phosphorus	+40	-0.03	-0.19	0.01	0.01	0.07	0.01	0.01	0.13	0.31
	-40	0.01	-0.09	0.00	0.01	0.01	0.00	0.00	-0.09	-0.22

the water quality and hydrodynamics within the reservoir, by spatial and temporal discretization effects, and by assumptions made in the formulation of the governing equations. Model accuracy also is limited by segment size, boundary conditions, accuracy of calibration, and parameter sensitivity. Model accuracy also is limited by the availability of data and by the interpolations and extrapolations that are inherent in using data in a model. Although a model might be calibrated, calibration parameter values are not necessarily unique in yielding acceptable values for the selected water-quality constituents, algal biomass, and reservoir water-surface elevation.

Another limitation of the Beaver Lake model is that it is a two dimensional representation of a three dimensional waterbody. The governing equations are laterally and vertically averaged within layers. Although the model may accurately represent vertical and longitudinal processes within the reservoir, processes that occur laterally, or from shoreline to shoreline perpendicular to the downstream axis, may not be properly represented.

Summary

Beaver Lake is a large, deep-storage reservoir located in the upper White River Basin in northwestern Arkansas. The water quality of Beaver Lake recently has become a focus of environmental concern because of the rapid population growth in northwestern Arkansas and because of agricultural activities in the basin. The purpose of this report is to describe the ambient hydrologic and water-quality conditions in Beaver Lake and its inflows and describe a two-dimensional model developed to simulate the hydrodynamics and water quality of Beaver Lake from 2001 through 2003.

Water-quality samples were collected at the three main inflows to Beaver Lake; the White River near Fayetteville, Richland Creek at Goshen, and War Eagle Creek near Hindsville. Nutrient concentrations varied among the tributaries because of land use and contributions of nutrients from point sources. The median concentration of total ammonia plus organic nitrogen for the White River was 0.30 mg/L as nitrogen, Richland Creek had a median concentration of 0.20 mg/L as nitrogen, and War Eagle Creek had a median concentration of 0.10 mg/L as nitrogen. The greatest concentrations of nitrite plus nitrate and total nitrogen, however, were observed at War Eagle Creek. The median concentrations of nitrite plus nitrate and total nitrogen for War Eagle Creek were 1.2 and 1.4 mg/L as nitrogen, respectively. The White River and Richland Creek had median nitrite plus nitrate concentrations of 0.36 and 0.85 mg/L as nitrogen, respectively, and median concentrations of total nitrogen of 0.74 and 1.1 mg/L as nitrogen, respectively. Phosphorus concentrations were relatively low, with orthophosphorus and dissolved phosphorus concentrations mostly below the laboratory reporting limit at the three sites. War Eagle Creek had significantly greater median orthophosphorus and total phosphorus concentrations (0.03 and 0.04 mg/L as phosphorus, respectively) than the White River (0.01 and 0.03 mg/L as phosphorus, respectively) and Richland Creek (0.01 and 0.02 mg/L as phosphorus, respectively). Dissolved organic-carbon concentrations were significantly greater at the White River than at War Eagle and Richland Creeks. Estimated annual nutrient and dissolved organic-carbon loads generally were greater for the White River than for Richland and War Eagle Creeks in 2001 through 2003. Greater loads would be expected for the White River because of the greater volume of streamflow that occurs at the site. The greatest annual loads occurred in 2002 for all three tributaries and the least occurred in 2003. The White River had significantly greater turbidity than Richland Creek and War Eagle Creek. The median turbidity for the White River was 8.6 NTUs, and the median turbidities for Richland Creek and War Eagle Creek were 3.8 and 3.4 NTUs, respectively.

The temperature distribution in Beaver Lake exhibits the typical seasonal cycle of lakes and reservoirs located within similar latitudes. Beaver Lake is a monomictic system, in which thermal stratification occurs annually during the summer and fall and complete mixing occurs in the winter. Isothermal conditions exist throughout the winter and early spring.

Nitrogen concentrations varied temporally, longitudinally, and vertically in Beaver Lake for 2001 through 2003. Nitrite plus nitrate concentrations generally decreased from the upstream portion of Beaver Lake to the downstream portion and generally were greater in the hypolimnion. Total ammonia plus organic nitrogen concentrations also decreased from the upstream end of Beaver Lake to the downstream end and were substantially greater in the hypolimnion of Beaver Lake. Phosphorus concentrations mostly were near or below laboratory detection limits in the epilimnion and metalimnion in Beaver Lake and were substantially greater in the hypolimnion in the upstream and middle parts of the reservoir. Measured total and dissolved-organic carbon in Beaver Lake was relatively uniform spatially, longitudinally, and vertically in the reservoir from January 2001 through December 2003. Chlorophyll *a* concentrations measured at sites L1 and L2 (upper lake) were significantly greater than at the other sites on Beaver Lake with median concentrations of 7.2 μg/L and 12.5 μg/L, respectively. Sites L3, L4, and L5 had median concentrations of 5.5, 3.4, and 1.8 μg/L, respectively.

During the study period, water clarity in Beaver Lake was significantly greater at the downstream end of the reservoir than at the upstream end. The median Secchi depth ranged from 0.6 m at site L1 to 5.4 m at site L5 from January 2001 through December 2003. The greatest values for Secchi depth at site L5 generally were observed in 2001 compared to 2002 and 2003, but did not have a seasonal pattern observed at sites L3 and L4. Similar to Secchi depth results, turbidity results indicated greater water clarity in the downstream portion of Beaver Lake compared to the upstream portion. Turbidity was also greater in the hypolimnion than in the epilimnion in the reservoir during the stratification season.

A two-dimensional, laterally averaged, hydrodynamic, and water-quality model using CE-QUAL-W2 Version 3.1 was developed for Beaver Lake and calibrated based on vertical profiles of temperature and dissolved oxygen, and water-quality constituent concentrations collected at various depths at five sites in the reservoir from April 2001 to April 2003. Simulated temperatures compared reasonably well with measured temperatures and differences varied spatially in Beaver Lake for April 2001 to April 2003. The greatest differences between measured and simulated data occurred in the upstream portion of the reservoir, which is the most dynamic part of the reservoir. In general, the AME and RMSE were the least in 2001 at the two upstream sites (L2 and L3) and in 2002 at the two downstream sites (L4 and L5) and greatest in 2003 for all four sites. In general, simulated dissolved-oxygen concentrations were spatially similar to measured values in Beaver Lake from April 2001 to April 2003. Similar to temperature, differences between simulated and measured values of dissolved-oxygen concentrations were greater in the upstream portion of the reservoir compared to differences in the downstream portion. At the upstream portion of the reservoir at sites L2 and L3, the greatest differences between simulated and measured dissolved oxygen generally occurred in 2002 and the least differences occurred in 2003. Simulated ammonia and total nitrogen concentrations in Beaver Lake compared relatively well with the measured concentrations and simulated nitrite plus nitrate concentrations generally were less than the measured concentrations. Simulated values for orthophosphorus were comparable to measured concentrations and simulated total phosphorus concentrations generally were greater than the measured concentrations in Beaver Lake. Simulated chlorophyll *a* values were comparable to measured chlorophyll *a* values both spatially and temporally in Beaver Lake. The greatest differences between simulated and measured chlorophyll *a* occurred at site L2.

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