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ANALYSIS OF AMBIENT CONDITIONS AND SIMULATION OF HYDRODYNAMICS, CONSTITUENT TRANSPORT, AND WATER-QUALITY CHARACTERISTICS IN LAKE MAUMELLE, ARKANSAS, 1991-92

Water-Resources Investigations Report 01-4045

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

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By W. Reed Green

U.S. GEOLOGICAL SURVEY
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Little Rock, Arkansas
2001

U.S. DEPARTMENT OF THE INTERIOR
GALE A. NORTON, Secretary

U.S. GEOLOGICAL SURVEY
Charles G. Groat, Director

For additional information
write to:

District Chief
U.S. Geological Survey, WRD
401 Hardin Road
Little Rock, Arkansas 72211

Copies of this report can be
purchased from:

U.S. Geological Survey
Branch of Information Services
Box 25286
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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
centimeter (cm)	0.3937	inch
meter (m)	3.281	foot
kilometer (km)	0.6214	mile (mi)
hectare (ha)	2.471	acre
square meter (m^2)	10.76	square foot
square kilometer (km^2)	0.3861	square mile
cubic meter (m^3)	35.31	cubic foot
gram (g)	0.03527	ounce
kilogram (k)	2.205	pound
degree Celsius (°C)	1.8 x °C + 32	degree Fahrenheit

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

Water year: October 1 through September 30.

Analysis of Ambient Conditions and Simulation of Hydrodynamics, Constituent Transport, and Water-Quality Characteristics in Lake Maumelle, Arkansas, 1991-92

by W. Reed Green

ABSTRACT

Lake Maumelle is the major drinking-water source for the Little Rock metropolitan area in central Arkansas. Urban and agricultural development has increased in the Lake Maumelle Basin and information is needed related to constituent transport and water-quality response to changes in constituent loading or hydrologic regime. This report characterizes ambient conditions in Lake Maumelle and its major tributary, Maumelle River; describes the calibration and verification of a numerical model of hydrodynamics and water quality; and provides several simulations that describe constituent transport and water quality response to changes in constituent loading and hydrologic regime.

Ambient hydrologic and water-quality conditions demonstrate the relatively undisturbed nature of Lake Maumelle and the Maumelle River. Nitrogen and phosphorus concentrations were low, one to two orders of magnitude lower than estimates of national background nutrient concentrations. Phosphorus and chlorophyll *a* concentrations in Lake Maumelle demonstrate its oligotrophic/mesotrophic condition. However, concentrations of chlorophyll *a* appeared to increase since 1990 within the upper and middle reaches of the reservoir.

A two-dimensional, laterally averaged hydrodynamic and water-quality model developed and calibrated for Lake Maumelle simulates water level, currents, heat transport and temperature distribution, conservative material transport, and the transport and transformation of 11 chemical constituents. Simulations included the movement and dispersion of spills or releases in the reservoir during stratified and unstratified conditions, release of the fish nursery pond off the southern shore of Lake Maumelle, and algal responses to changes in external loading.

The model was calibrated using 1991 data and verified using 1992 data. Simulated temperature and dissolved oxygen concentrations related well when compared to measured values. Simulated nutrient and algal biomass also related reasonably well when compared to measured values. A simulated spill of conservative material at the upper end of Lake Maumelle during a major storm event took less than 102 hours to disperse the entire length of the reservoir. Simulation of a nursery pond release into a tributary to Lake Maumelle demonstrated how the released water plunges within the receiving embayment and enters the main stem of the reservoir at mid depths. Simulations of algal response to increases of nitrogen and phosphorus loads demonstrate the phosphorus limiting condition in Lake Maumelle.

Results from this study will provide water-resource management with information to better understand how changes in hydrology and water quality in the basin affects water quality in the reservoir. With this information, managers will be able to more effectively manage their drinking-water source supply.

INTRODUCTION

Lake Maumelle (fig. 1) was constructed in 1956 for drinking-water supply for the Little Rock, Arkansas, metropolitan area. In addition to water supply, Lake Maumelle is used for recreation and provides habitat for fish and wildlife. Concerns about the sustainability of the quality of the drinking-water source have grown as urban and agricultural (grass farming, silviculture, cattle grazing) development have increased in the Lake Maumelle Basin during the past 20 years.

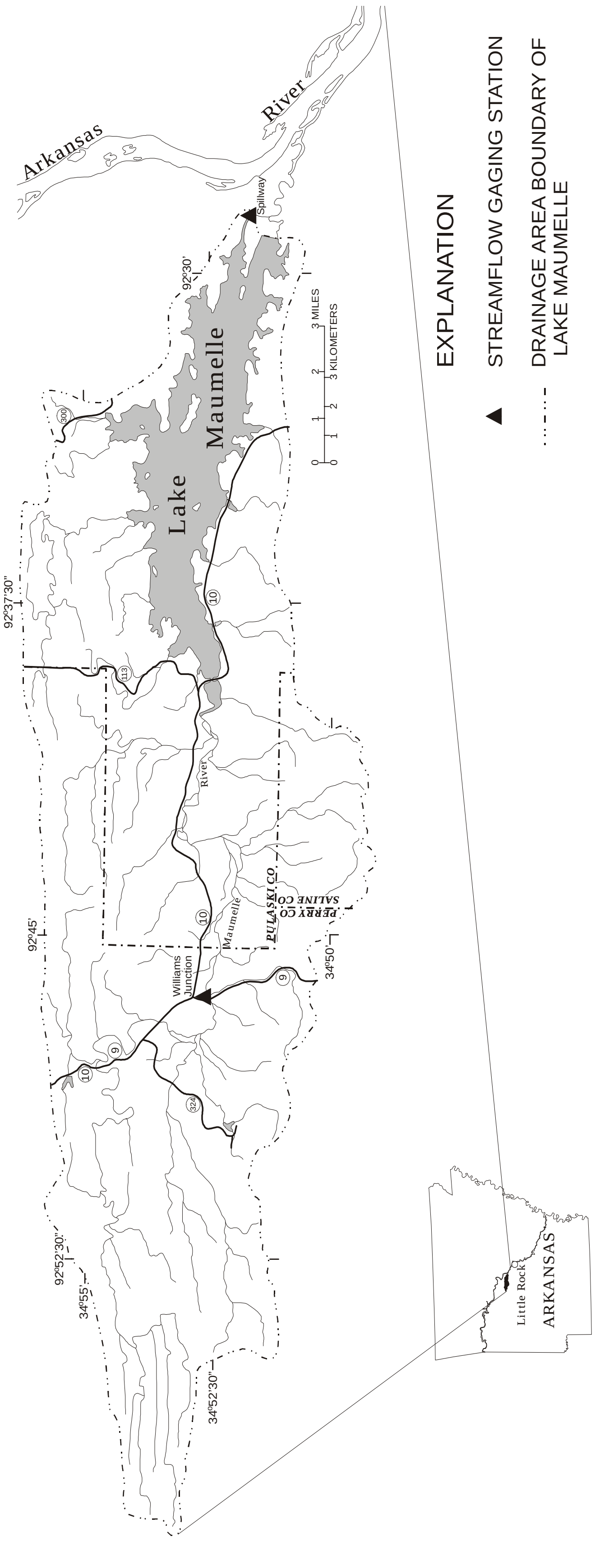


Figure 1. Lake Maumelle Basin.

Information regarding circulation and constituent transport in Lake Maumelle is lacking. This information is needed to more effectively manage the reservoir and its watershed and to predict water-quality responses to changes in constituent loading or hydrologic regime. Such changes may result from increased agricultural activity and urban expansion within the watershed. Runoff volume and loads of nonpoint-source nutrients, pesticides, and other contaminants could change in response to conversion of forested areas to pasture, conversion of grass farms to pasture, and the associated increase in cattle, and conversion of non-urban areas to urban areas.

During 1991, a study was undertaken to characterize ambient conditions and hydrodynamics in Lake Maumelle by calibrating a model and using it to simulate the effects of changes in external loads to the reservoir. This study was part of a larger study conducted by the U.S. Geological Survey (USGS) in cooperation with Little Rock Municipal Water Works (LRMWW) to monitor water levels, streamflow, and water quality in the drinking-water-supply reservoir, Lake Maumelle.

Purpose and Scope

Purposes of this report were to (1) describe ambient hydrologic and water-quality conditions in Lake Maumelle and its major tributary, the Maumelle River; (2) describe calibration and verification of a model developed by the U.S. Army Corps of Engineers (CE-QUAL-W2) to simulate ambient water-quality conditions and hydrodynamics in Lake Maumelle; and (3) describe several model simulations of movement and dispersion of spills or releases in the reservoir during thermally stratified and unstratified conditions, of an adjacent fish nursery pond release, and the response of water quality (nutrient, algal, and dissolved-oxygen concentrations) to possible changes in external loads. This report describes ambient conditions and presents the results of model calibration, verification, and simulations.

Hydrologic and water-quality data are summarized for the period October 1990 through September 1998 for precipitation, streamflow, and selected water-quality characteristics including temperature, dissolved oxygen (DO), nitrogen and phosphorus species, and chlorophyll *a*. Estimated loads of nitrogen and phosphorus to Lake Maumelle from the Maumelle River are presented.

Hydraulic circulation and water-quality characteristics in Lake Maumelle were simulated by using the U.S. Army Corps of Engineers CE-QUAL-W2 model. This laterally averaged, two-dimensional model was calibrated by using data collected from January through December 1991 and verified using data collected from January through December 1992. The calibrated model was used to simulate the effects of nutrient loads from the Maumelle River and the nursery pond release on reservoir water quality.

Description of Study Area

Lake Maumelle is a surface-water-supply reservoir completed in 1956 on the Maumelle River, west of the city of Little Rock (fig. 1). The Maumelle River Basin has a drainage area of 355 km^2 at the Lake Maumelle dam, and is part of the Arkansas River Basin. The average annual precipitation within the Maumelle River Basin is about 137 cm (Freiwald, 1984). Lake Maumelle contains 2.70×10^8 m^3 of water at spillway elevation (88.39 m above sea level) and has 2.31×10^8 m^3 of usable water. The surface area of Lake Maumelle at spillway elevation is 36 km^2. The maximum length of the reservoir is 19.3 km, with a maximum depth of 13.7 m, and an average depth of 7.5 m (Green, 1993).

The general land use classification for the Maumelle basin is “forest and woodland grazed” (U.S. Geological Survey, 1970, p. 159). The upper one-third of the watershed primarily is forest land owned and managed by the Ouachita National Forest. The forest land is classified by the U.S. Forest Service, U.S. Department of Agriculture (USDA) as moderate to low productive land with a full range of site conditions that have been determined to be suitable for timber production (U.S. Department of Agriculture, 1989). The general soil type, defined by the USDA soil surveys of Pulaski and Perry Counties (Haley and others, 1975; Townsend and Williams, 1982), is Carnasaw-Pirum Clebit: well drained gently sloping to very steep, deep, moderately deep, and shallow, loamy, gravelly and stony soils; on uplands. The remainder of the watershed primarily is forest with some agriculture existing in the lowland area of the Maumelle River above the lake. Turf (sod) farming is the most common agricultural practice in the flood plain of the basin.

Adjacent to the reservoir is a fish nursery pond formed by a dam on Twin Creek, a small lateral tributary entering Lake Maumelle on the southern shore (fig. 2). At its spillway elevation (108.2 m above sea level), the nursery pond contains about 1.38×10^6 m^3 of water, about 0.5 percent of the volume of Lake Maumelle, and covers about 0.28 km^2. The drainage area of the nursery pond is about 5.1 km^2, about 1.4 percent of the area of the Lake Maumelle Basin. The maximum depth of the nursery pond is about the same as Lake Maumelle (13.7 m) and the average depth is about 5.0 m.

Previous Studies

USGS and LRMWW have collected reservoir elevation, streamflow, and water-quality data for the Maumelle River and Lake Maumelle since 1989 as part of an ongoing monitoring program. Data are stored in the USGS National Water Information System database and published annually (Moore and others, 1990; Porter and others, 1991; Morris and others, 1992; Porter and others, 1993; Westerfield and others, 1994; Evans and others, 1995; Porter and others, 1996; 1997; 1998; 1999; 2000). Hydrologic data collected in Lake Maumelle from May 1989 through October 1992 (Green and Louthian, 1993) were used to assess water quality (Green, 1993). Green (1993) concluded that the water quality of the Maumelle River and Lake Maumelle when compared to other streams and reservoirs in the region is more pristine (oligotrophic). From these comparisons, it can be considered that the water quality of the Maumelle Basin represents relatively undisturbed water-quality conditions within the region. The trophic condition of Lake Maumelle can be considered oligo-mesotrophic (Green, 1993) based on nutrient concentrations, chlorophyll *a*, and secchi disk transparency. If nutrient inputs are maintained at 1993 levels, the water quality of Lake Maumelle should remain relatively stable. However, increases in nutrient loads may alter trophic conditions from oligo-mesotrophic to more eutrophic.

Nursery pond releases into Lake Maumelle are a major water-quality issue. A report assessing the impact of nursery pond releases into the lake determined that the water-quality impact of the nursery pond release was variable and appeared to be related to the volume of the nursery pond at the time of release and the amount of fertilizer applied to the nursery pond earlier in the year (Green, 1998). Much of the material released from the nursery pond originated in the cooler, anoxic, hypolimnetic water of the pond. Because the initial water released from the nursery pond was cooler (and denser) than the receiving surface water, it plunged into the hypolimnion of Lake Maumelle.

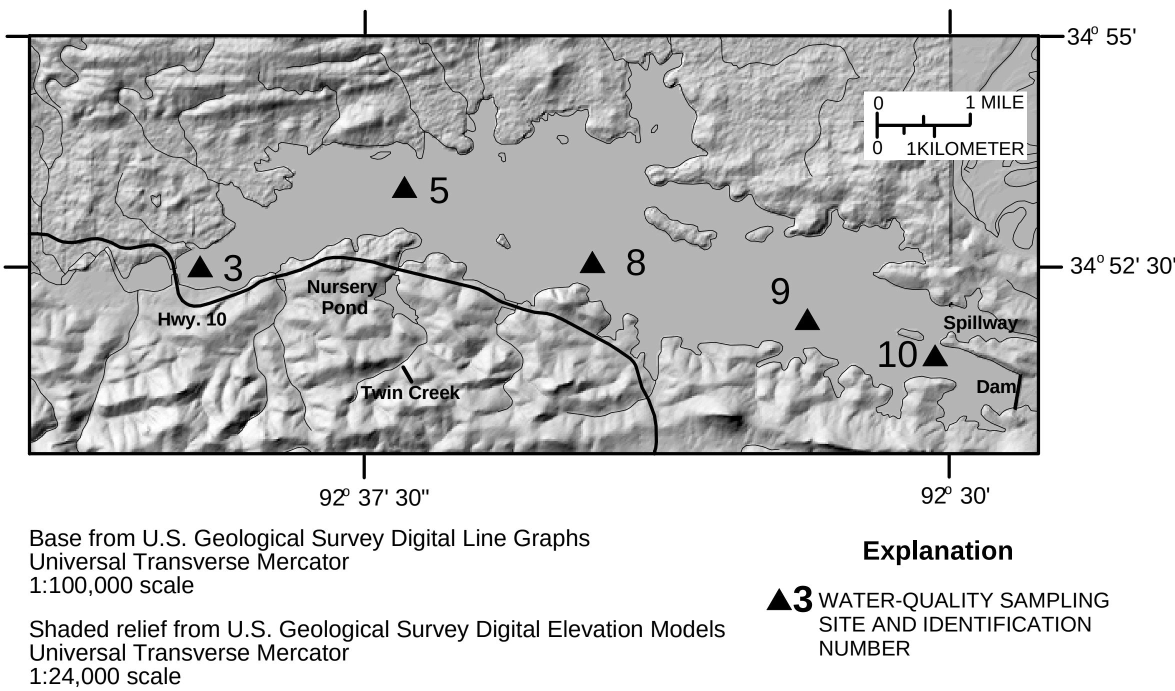


Figure 2. Lake Maumelle and the nursery pond on Twin Creek.

Acknowledgments

Tom Cole of the U.S. Army Corps of Engineers provided valuable guidance on the CE-QUAL-W2 model. Jerad Bales of the USGS provided valuable model calibration and report preparation support.

METHODS OF DATA COLLECTION

Continuous 1-hour interval reservoir elevation and 15-minute interval streamflow gaging sites were installed on Lake Maumelle and the Maumelle River in August 1989. The drainage basin above the discharge site (fig. 1) on the Maumelle River accounts for about 34 percent of the Lake Maumelle drainage. The rating curve established for the Maumelle River was based on instantaneous discharge measurements following methods described by Rantz and others (1982) and continues to be updated. The reservoir-elevation site measures water-surface elevation at the spillway and accounts for reservoir volume based on established elevation-volume curves provided by LRMWW. A theoretical rating curve for discharge flowing over the spillway was established and verified with periodic discharge measurements immediately downstream.

Fixed water-quality sampling sites were established at the streamflow-gaging site (fig. 1) and along the downstream gradient within the reservoir (fig. 2). Sample sites in the reservoir were located along the original stream channel, the deepest location within the reservoir cross section. Samples were collected in Lake Maumelle at sites 3, 8, and 10 from 1991 through 1998 using a 1-m by 5-cm bailer to collect depth-integrated composite samples representing the entire water column when isothermal conditions were present. During thermal stratification, depth-integrated samples were collected representing the epilimnion (surface) and hypolimnion (bottom). Samples were collected monthly during the winter and twice monthly during the summer during 1991 through 1992. Field parameters (water temperature, DO concentration, pH, and specific conductance) were measured at various depths within the water column at sites 3, 5, 8, 9, and 10 during 1991 through 1992 and 3, 8, and 10 the rest of the period. When thermal stratification was present, measurements were taken at depth intervals where the change in temperature was 1 °C or at 0.3-m intervals, whichever was greater. Water-quality samples were analyzed for nutrients (dissolved orthophosphorus, total phosphorus, total ammonia plus organic nitrogen, dissolved ammonia, and dissolved nitrite plus nitrate nitrogen), total and dissolved organic carbon, and chlorophyll *a*. All sample analyses were conducted at USGS laboratories following USGS methods.

Water-quality samples were collected at the Maumelle River gaging site following equal width increment methods using depth-integrated samplers described by Wilde and others (1999). Field parameters (water temperature, DO concentration, pH, and specific conductance) were measured using a multiparameter-metering unit. Water-quality samples were collected from October 1990 through September 1998 using depth-integrated techniques covering various depth ranges.

AMBIENT CONDITIONS

Hydrologic and water-quality conditions for the period 1990 through 1998 describe the nature of Lake Maumelle and its major tributary, the Maumelle River. In its present condition, Lake Maumelle appears to have little stress from anthropogenic sources. However, changes in land use and urban migration into the basin can be expected to affect the water quality of this drinking-water source.

Hydrologic Conditions

Over the period October 1990 through August 1998, precipitation at Little Rock Adams Field (National Oceanographic Atmospheric Administration (NOAA) station 13963) (fig. 3) averaged 121.8 cm/yr. Little Rock Adams Field is located about 26 km southeast of Lake Maumelle dam. Streamflow at the Maumelle River gaging station from January 1991 through December 1998 (fig. 4) averaged 1.74 m^3/sec. Hydraulic residence time based on reservoir volume, discharge over the spillway, and water-supply withdrawal, varied during the period water year 1990 through 1997 (fig. 5). The mean annual residence time during this period was 1.51 years. The average spillway outflow was 4.82 m^3/s and the average withdrawal rate was 1.56 m^3/s.

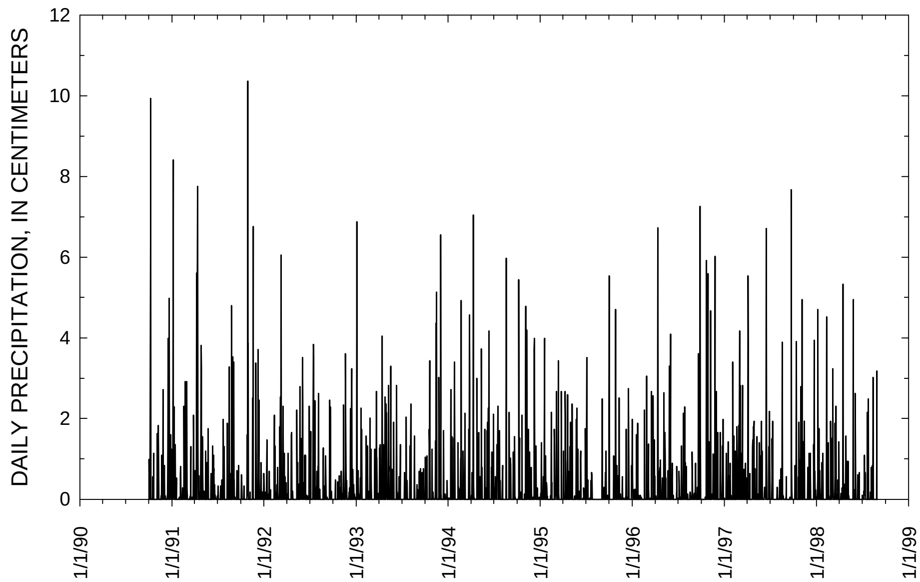


Figure 3. Daily precipitation at Little Rock Adams Field between October 1, 1990 and August 31, 1998.

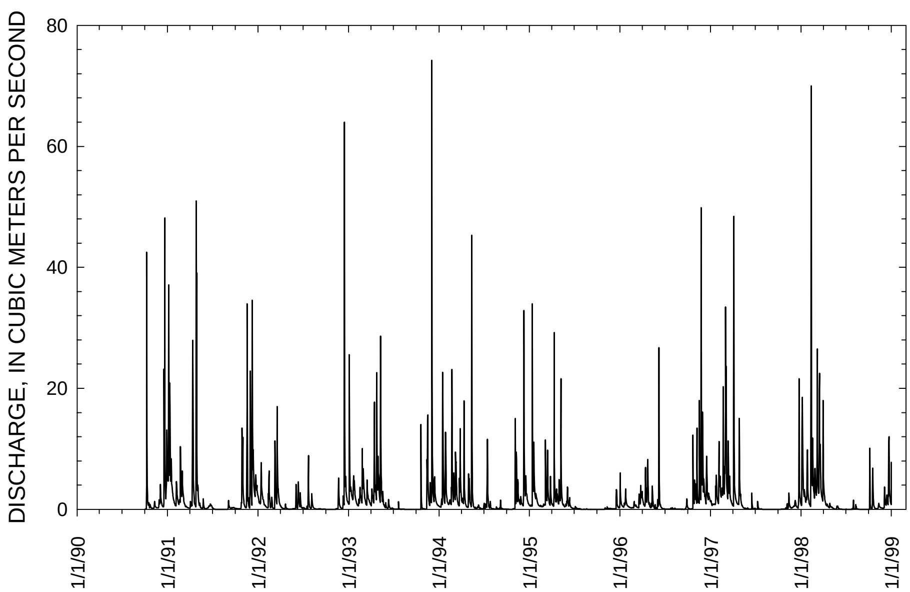


Figure 4. Daily discharge at Maumelle River gaging station.

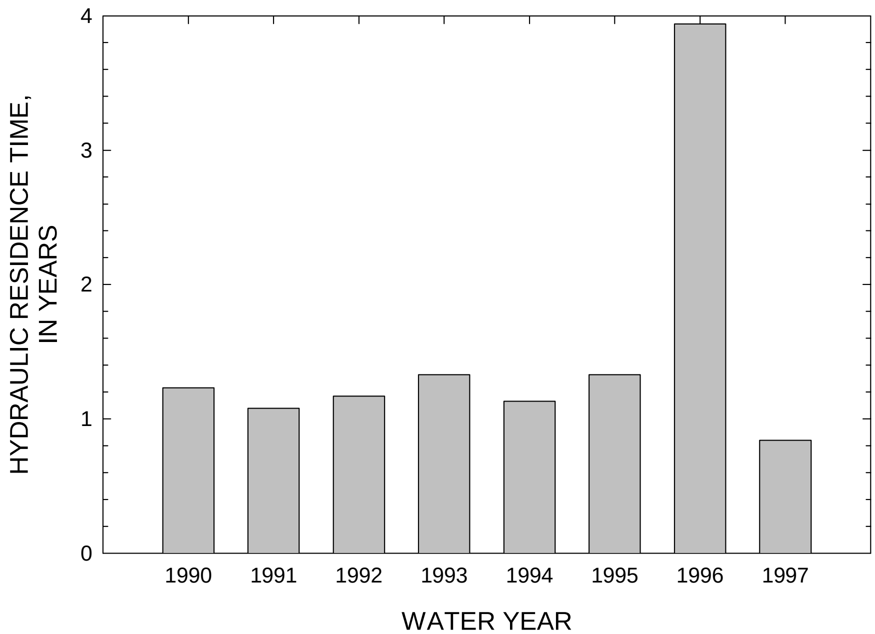


Figure 5. Annual hydraulic residence time for Lake Maumelle based on outflow and water-supply withdrawal.

Water-Quality Conditions

In order to develop a model that simulates hydrodynamics, constituent transport, and water-quality characteristics, ambient conditions need to be defined and understood. Water-quality conditions most important in this study include temperature, DO, nitrogen phosphorus, and chlorophyll *a*. Water temperature and DO concentration were measured at five sites and nitrogen, phosphorus, and chlorophyll *a* at three sites in Lake Maumelle (fig. 2) and at the Maumelle River streamflow gaging site (fig. 1). Temperature and DO data collected during 1991 and 1992 from the five reservoir sites are presented graphically as depth-distance diagrams (figs. 6 and 7). Each diagram shows conditions for one date and represents a longitudinal cross section of the reservoir along the thalweg from the upper end of the reservoir to the dam. Lines of equal temperature or concentration delineate regions with similar values. Results for eight selected sampling dates over the 2-year period illustrate seasonal patterns in temperature and DO.

Temperature

Temperature varied annually, seasonally, and spatially in Lake Maumelle (fig. 6). Water temperature was generally cooler in 1992 than at similar dates in 1991, with the exception of February. In early February 1991, temperature varied somewhat between the surface and bottom. However, in early February 1992, temperature of the entire water body was within 1.0 °C of 8.0 °C. Thermal stratification was well established in June 1991 with temperatures ranging from 18.5 °C near the bottom to nearly 30.0 °C at the surface. In June 1992, the temperature ranged from about 17.0 °C near the bottom to 22.0 °C at the surface. By the end of August 1991, temperature ranged from about 19.0 °C near the bottom to almost 29.0 °C near the surface. By the end of August 1992, temperature ranged from 19.5 °C near the bottom to almost 28.0 °C near the surface.

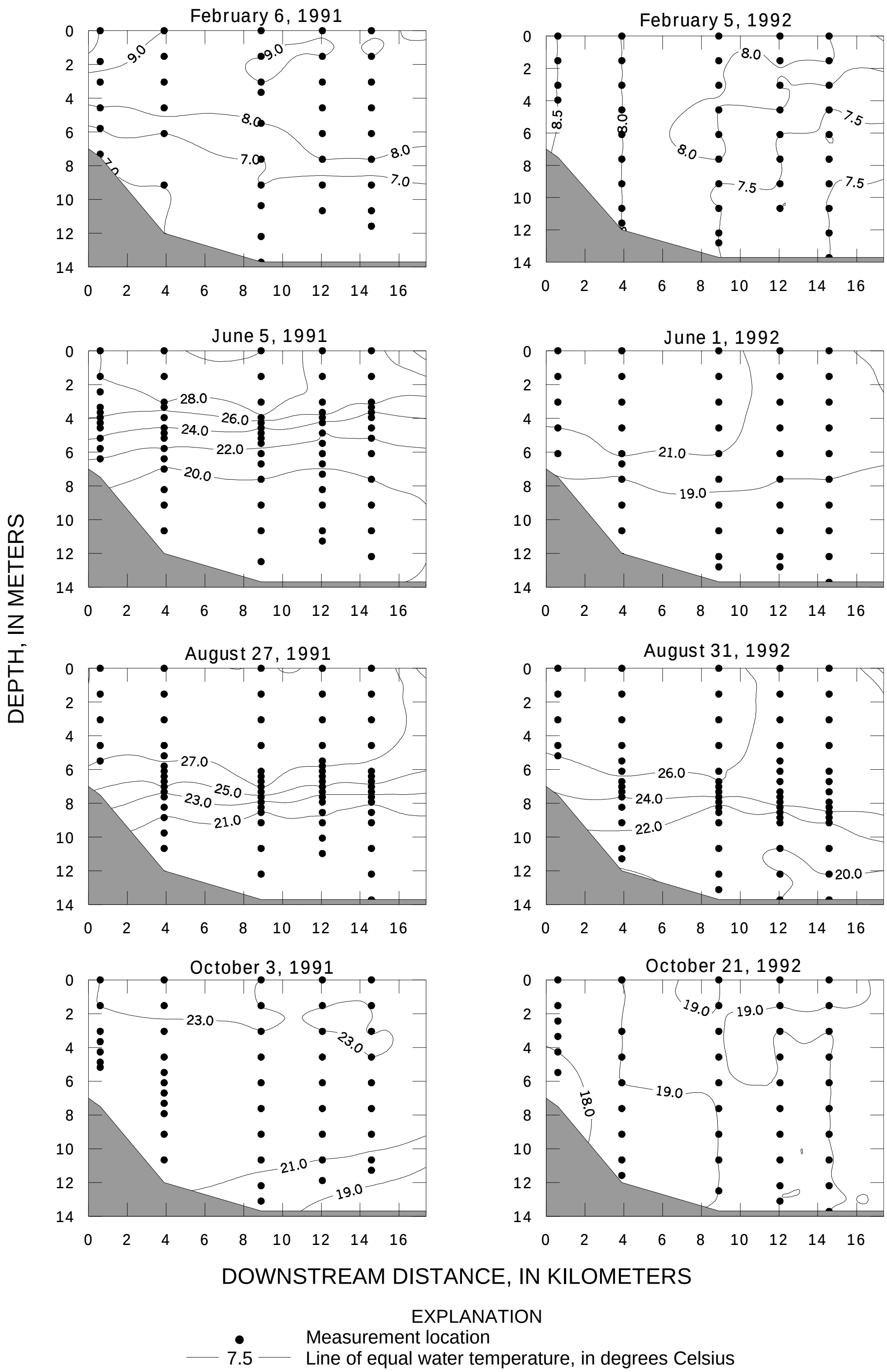


Figure 6. Water temperature in Lake Maumelle for selected days during the study.

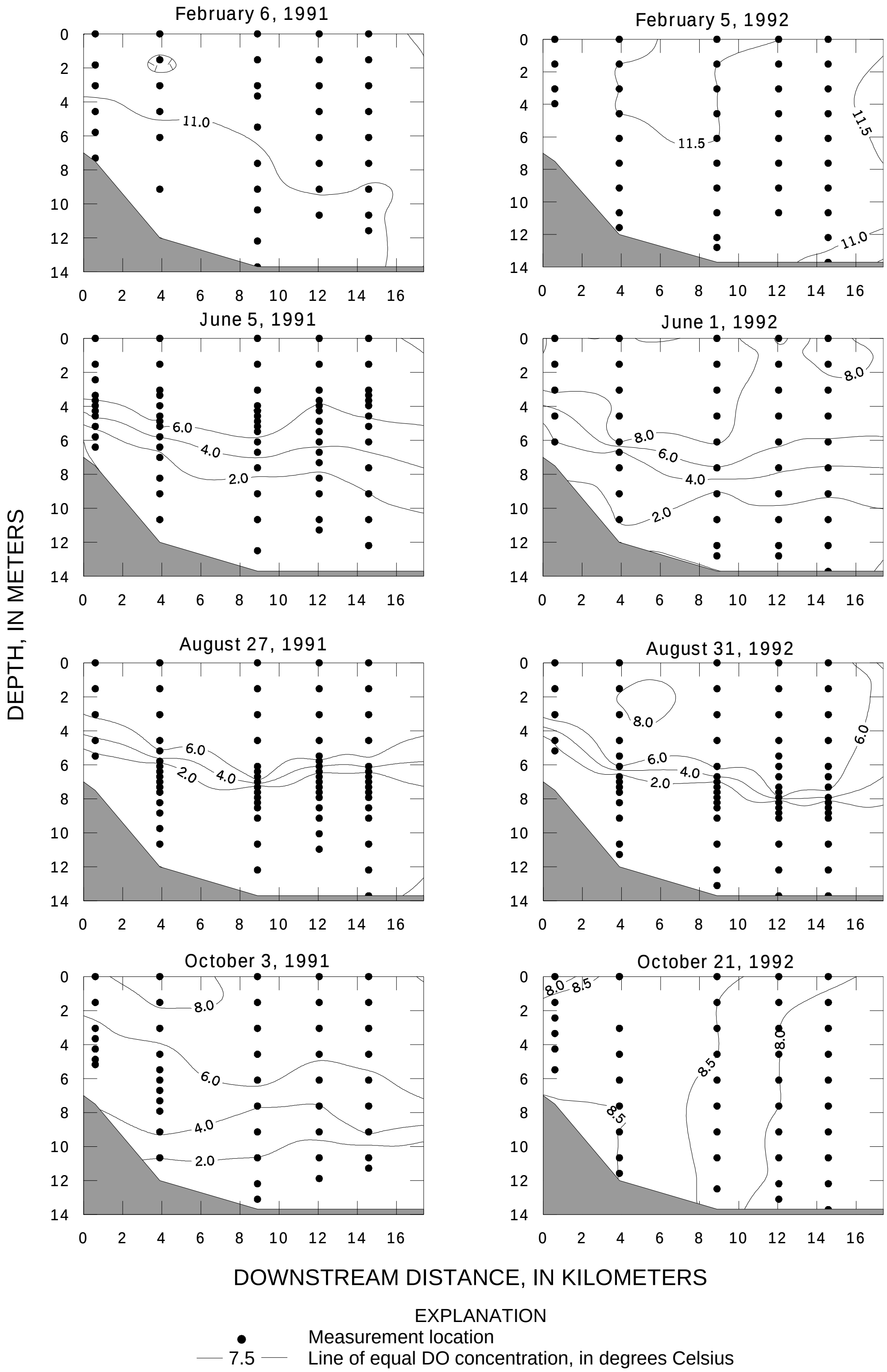


Figure 7. Dissolved oxygen concentrations in Lake Maumelle for selected days during the study.

Breakdown of the thermocline had occurred by early October 1991. Temperature ranged from 19.0 °C near the bottom to 23.5 °C near the surface. Likewise, in 1992, the thermocline had disintegrated by late October.

Dissolved Oxygen

DO concentrations in Lake Maumelle are strongly related to vertical temperature distributions. In general, DO in Lake Maumelle remains near saturation and well mixed in the water column from late October through mid-April. By early June 1991 and 1992, DO concentrations approached zero (0.7 and 0.6 mg/L, respectively) near the bottom and were less than 2.0 mg/L within much of the hypolimnion (fig. 7). Anoxic conditions (DO <2.0 mg/L) remained in the hypolimnion during both years until turnover and by late October, DO concentrations were more uniformly distributed throughout the water column.

Nitrogen

Nitrogen (N) and phosphorus (P) are primary nutrients that usually regulate algal productivity in lakes and reservoirs (Wetzel, 1983). Three nitrogen species—dissolved nitrite plus nitrate (NO_2+NO_3), dissolved ammonia (NH_4), and total ammonia plus organic nitrogen— were measured during this study.

At the Maumelle River streamflow-gaging site, NO_2+NO_3 and NH_4 were present at similar concentrations (fig. 8). Concentrations of NO_2+NO_3 ranged from less than 0.002 to 0.203 mg/L as N with a median value of 0.0135 mg/L as N. Concentrations of NH_4 ranged from less than 0.002 to 0.087 mg/L as N with a median value of 0.011 mg/L as N. Concentrations of total ammonia plus organic nitrogen ranged from less than 0.20 to 0.90 mg/L as N with a median value of less than 0.2 mg/L as N.

Concentrations of nitrite plus nitrate varied little between reservoir sites and depth (table 1, fig. 9). Nitrite plus nitrate nitrogen concentrations ranged from less than 0.002 to 0.075 mg/L as N, considering all samples at all sites with the exception of one sample collected in the bottom water at site 10 (0.25 mg/L as N). No site-to-site or surface (top) and bottom sample groups were statistically different ($p < 0.05$) based on the Kruskal-Wallis one-way analysis of variance on ranks (Helsel and Hirsch, 1992). Ammonia concentrations in surface samples varied somewhat among reservoir sites and depth (fig. 9). Concentrations ranged from less than 0.002 to 0.170 mg/L as N. Concentrations in surface water did not differ among sites. Ammonia concentrations in bottom water at site 8 were statistically different ($p < 0.05$) than surface water at all sites and bottom water at site 3. Median concentrations in bottom water at sites 8 and 10 were greater than twice the median concentrations in surface water as a result of sediment release during stratified anoxic periods. Total ammonia plus organic nitrogen concentrations varied little between sites and depth (fig. 9). Concentrations ranged from less than 0.2 to 0.7 mg/L as N. More than one-half of all concentrations were less than 0.2 mg/L.

Considering estimates of national background nutrient concentrations (U.S. Geological Survey, 1999), nitrogen concentrations in Lake Maumelle were considerably lower relative to undeveloped areas across the Nation minimally affected by agriculture, urbanization, and associated land uses. Nitrite plus nitrate concentrations in Lake Maumelle were one to two orders of magnitude lower than estimates of national background concentrations (0.6 mg/L as N). Likewise, ammonia concentrations were one to two orders of magnitude lower than estimates of national background concentrations (0.1 mg/L as N). Total nitrogen (sum of nitrite, nitrate, ammonia, and organic nitrogen) concentrations in Lake Maumelle were at least an order of magnitude lower than estimates of national background concentrations (1.0 mg/L as N).

Phosphorus

At the Maumelle River streamflow-gaging site, total phosphorus and dissolved orthophosphorus concentrations were low and varied little through time (fig. 10). Concentrations of total phosphorus ranged from less than 0.001 to 0.100 mg/L with a median value of 0.011 mg/L. Concentrations of dissolved orthophosphorus ranged from less than 0.001 to 0.060 mg/L with a median of 0.001 mg/L.

Concentrations of total phosphorus varied between sites and with depth (table 1, fig. 11). Total phosphorus concentrations ranged from 0.001 to 0.035 mg/L in both surface and bottom samples at all sites. The median concentration at site 10 near the surface was 0.011 mg/L and was lower than both surface and bottom water at site 3, and bottom water at sites 8 and 10. Dissolved orthophosphorus concentrations did not vary much between sites and depth (fig. 11). More than one-half of all dissolved orthophosphorus concentrations were less than 0.001 mg/L.

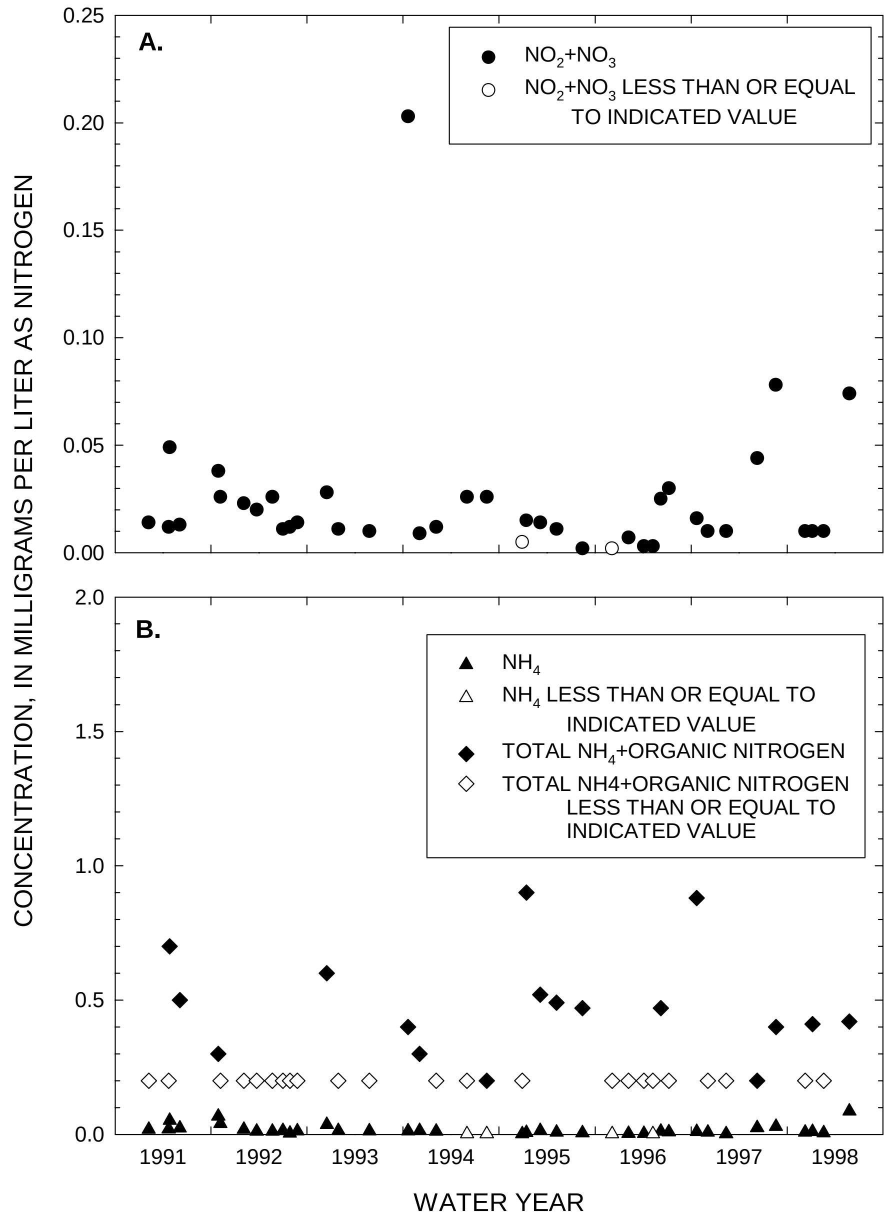


Figure 8. Concentrations of nitrite plus nitrate (A), ammonia, and total ammonia plus organic nitrogen (B) at Maumelle River streamflow gaging site, water year 1991 through 1998.

Table 1. Statistical summary of selected water-quality parameters at Lake Maumelle sites 3, 8, and 10, water years 1991 through 1998

[m, meter; mg/L, milligrams per liter; µg/L, microgram per liter; <, less than; --, no data]

Constituent of property	Site 3, surface			Site 3, bottom		
	Minimum	Median	Maximum	Minimum	Median	Maximum
Secchi disk transparency (meters)	0.20	1.40	3.70	--	--	--
Nitrogen, nitrite plus nitrate dissolved (mg/L as N)	<0.002	0.005	0.058	<0.002	0.006	0.039
Nitrogen, ammonia dissolved (mg/L as N)	<0.002	0.008	0.071	<0.002	0.010	0.049
Nitrogen, ammonia plus organic total (mg/L as N)	<0.2	<0.2	0.7	<0.2	<0.2	0.5
Phosphorus, total (mg/L as P)	0.004	0.011	0.030	0.001	0.014	0.035
Phosphorus, orthophosphate dissolved (mg/L as P)	<0.001	<0.001	0.010	<0.001	<0.001	0.010
Carbon, total organic (mg/L)	1.1	3.7	7.2	1.1	3.7	7.2
Carbon, dissolved (mg/L)	1.5	3.0	6.7	1.5	3.0	6.7
Chlorophyll *a* (µg/L)	0.4	2.4	7.0	--	--	--

Constituent of property	Site 8, surface			Site 8, bottom		
	Minimum	Median	Maximum	Minimum	Median	Maximum
Secchi disk transparency (meters)	1.20	1.40	3.70	--	--	--
Nitrogen, nitrite plus nitrate dissolved (mg/L as N)	<0.002	0.008	0.053	<0.002	0.010	0.075
Nitrogen, ammonia dissolved (mg/L as N)	<0.002	0.009	0.058	<0.002	0.025	0.170
Nitrogen, ammonia plus organic total (mg/L as N)	<0.2	<0.2	0.5	<0.2	<0.2	0.7
Phosphorus, total (mg/L as P)	0.005	0.010	0.020	0.005	0.013	0.029
Phosphorus, orthophosphate dissolved (mg/L as P)	<0.001	<0.001	0.010	<0.001	<0.001	0.010
Carbon, total organic (mg/L)	2.2	3.3	6.7	2.1	3.3	6.9
Carbon, dissolved (mg/L)	2.0	3.0	6.2	2.0	3.1	6.3
Chlorophyll *a* (µg/L)	0.6	2.3	6.9	--	--	--

Constituent of property	Site 10, surface			Site 10, bottom		
	Minimum	Median	Maximum	Minimum	Median	Maximum
Secchi disk transparency (meters)	1.50	2.35	4.60	--	--	--
Nitrogen, nitrite plus nitrate dissolved (mg/L as N)	<0.002	0.005	0.062	<0.002	0.008	0.25
Nitrogen, ammonia dissolved (mg/L as N)	<0.002	0.008	0.065	<0.002	0.019	0.17
Nitrogen, ammonia plus organic total (mg/L as N)	<0.2	<0.2	0.32	<0.2	<0.2	0.5
Phosphorus, total (mg/L as P)	0.003	0.009	0.020	0.005	0.011	0.033
Phosphorus, orthophosphate dissolved (mg/L as P)	<0.001	<0.001	0.005	<0.001	<0.001	0.023
Carbon, total organic (mg/L)	1.7	3.4	6.6	1.7	3.4	7.5
Carbon, dissolved (mg/L)	1.7	3.0	6.5	1.7	2.9	7.3
Chlorophyll *a* (µg/L)	0.5	1.6	7.0	--	--	--

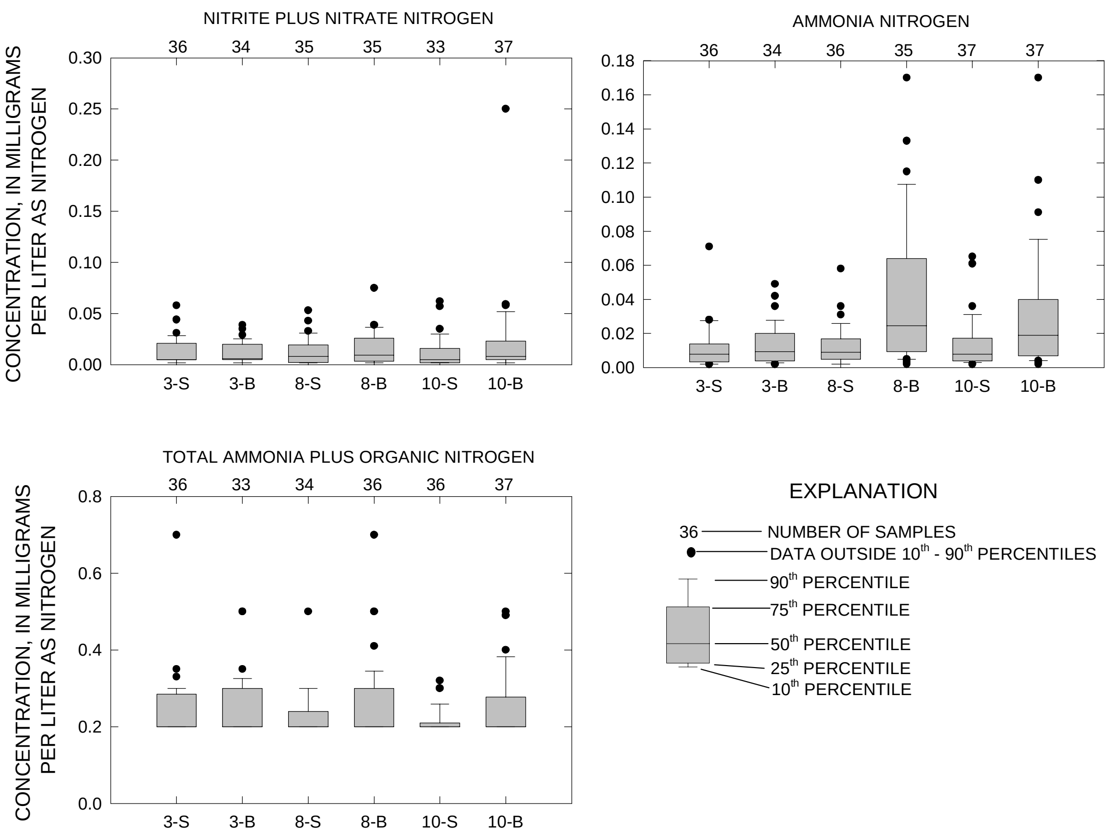


Figure 9. Concentrations of nitrite plus nitrate, ammonia, and total ammonia plus organic nitrogen at the three reservoir sites, water year 1991 through 1998 (3, site number; S, surface samples; B, bottom samples).

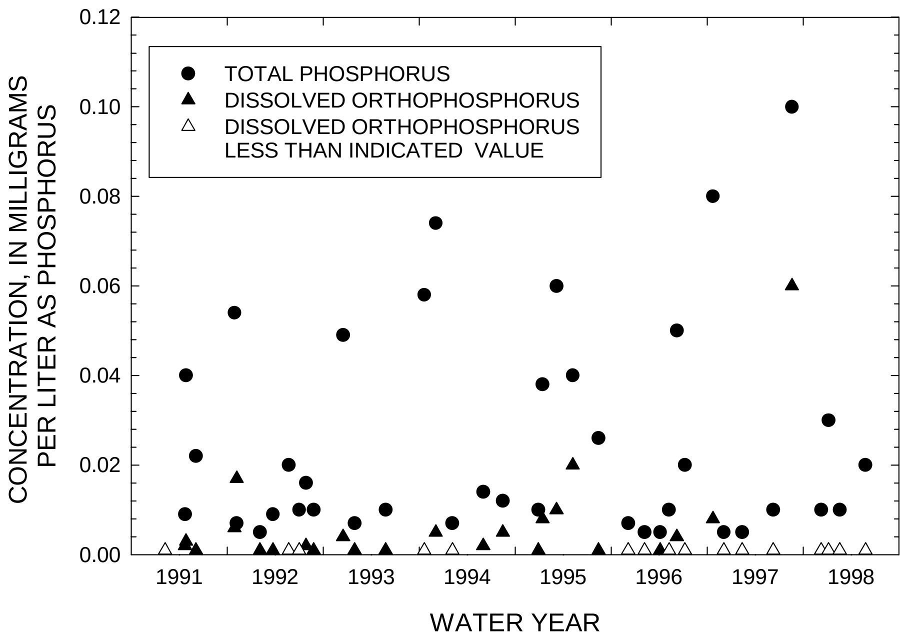


Figure 10. Concentrations of total phosphorus and dissolved orthophosphorus at Maumelle River streamflow gaging site, water year 1991 through 1998.

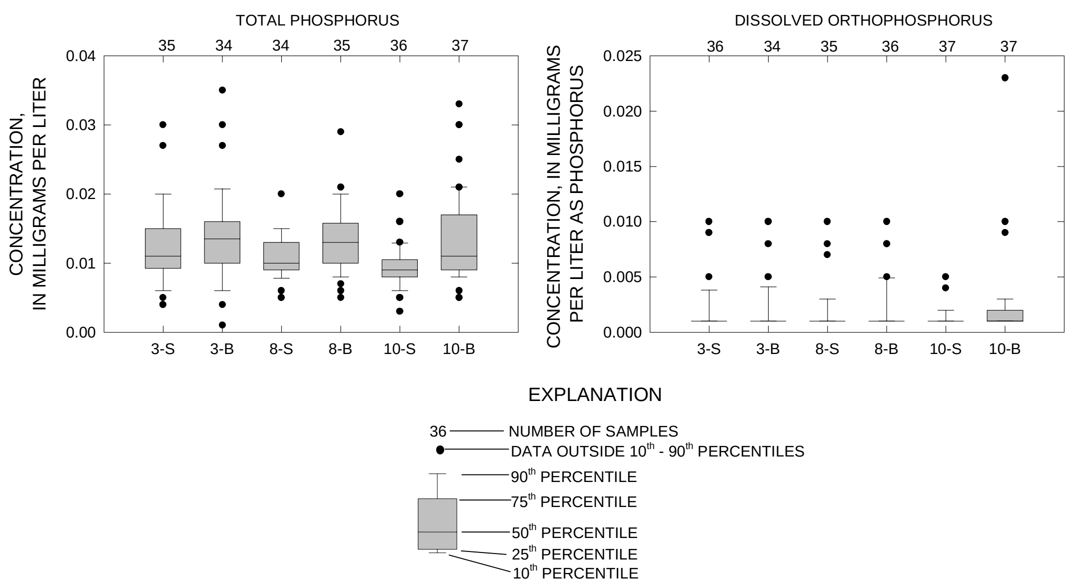


Figure 11. Concentrations of total phosphorus and dissolved orthophosphorus at three reservoir sites, water year 1991 through 1998 (3, site number; S, surface samples; B, bottom samples).

Considering estimates of national background nutrient concentrations (U.S. Geological Survey, 1999), total phosphorus concentrations were considerably lower relative to undeveloped areas across the Nation minimally affected by agriculture, urbanization, and associated land uses. Total phosphorus concentrations in Lake Maumelle were one to two orders of magnitude lower than estimates of national background concentrations (0.1 mg/L).

Chlorophyll *a*

Concentrations of chlorophyll *a* varied little among reservoir sites. Concentrations ranged from 0.4 to 7.0 µg/L. The median concentrations at sites 3, 8, and 10 were 2.4, 2.3, and 1.6 µg/L, respectively. Concentrations of chlorophyll *a* at each site were not statistically different from one another. However, concentrations tended to increase over time at sites 3 and 8 (fig. 12). Positive trends in chlorophyll *a* concentrations were identified using Kendall's rank correlation coefficient (tau) (Helsel and Hirsch, 1992) at site 3 (tau = 0.218, p = 0.044) and site 8 (tau = 0.271, p = 0.015). No trend was identified for chlorophyll *a* concentrations at site 10 (tau = 0.143, p = 0.199).

The increasing trend in chlorophyll *a* concentration at sites 3 and 8 (the more upstream sites) suggests that eutrophication may be increasing within the reservoir, although no trends were identified for nutrient concentrations. However, changes in residence time (fig. 5) and/or air temperature also could influence changes in concentration. Chlorophyll *a* concentrations of 2 µg/L or less indicate oligotrophic conditions (Carlson, 1977; Olem and Flock, 1990). Concentrations between 2 and 10 µg/L indicate mesotrophic conditions. Likewise, total phosphorus concentrations less than 0.010 mg/L indicate oligotrophic conditions and between 0.010 and 0.030 mg/L indicate mesotrophic conditions. Both chlorophyll *a* and total phosphorus concentrations in Lake Maumelle generally occur within the range of oligotrophic to mesotrophic conditions. The positive trends in chlorophyll *a* concentrations at site 3 and 8 might suggest that the system is progressing from a more oligotrophic condition to a more mesotrophic condition. The lack of trend in chlorophyll *a* concentration at site 10 might suggest a lag in trophic response within the farthest downstream water in the reservoir.

Loads of Sediment and Nutrients in the Maumelle River

Loads of suspended sediment and nutrients were estimated for the Maumelle River streamflow-gaging site. Loads were estimated for water years 1990 through 1997.

Simultaneous measurements of streamflow and constituent concentrations collected by USGS were used to develop regression relations (Cohn and others, 1989) for the Maumelle River site. Continuous records of streamflow were used to compute monthly and annual loads. Annual loads were divided by drainage area to provide annual yield. Annual loads and yields are summarized in table 2.

Constituent loads and yields were consistently lower in 1996 than other years (table 2). Precipitation (fig. 3) and streamflow (fig. 4) were considerably lower during 1996 than other years, accounting for the lower loads and yields. Loads and yield during years other than 1996 (1990 - 1995, 1997) were consistently low, representative of relatively undeveloped areas, minimally affected by agriculture, urbanization, and associated land uses (U.S. Geological Survey, 1999). Background concentrations and yields in undeveloped areas are controlled primarily by naturally occurring minerals and biological activity in soil and streambed sediment. Chemical properties of the atmosphere and rainwater, which can reflect human-related fuel combustion and other activities both within and external to the Maumelle River watershed, could lead to an increase in concentrations and yields.

SIMULATION OF HYDRODYNAMICS, CONSTITUENT TRANSPORT, AND WATER QUALITY

A two-dimensional, laterally averaged, hydrodynamic and water-quality model (CE-QUAL-W2) was constructed for Lake Maumelle, calibrated using data collected during January 1991 through December 1991, and verified using data collected during January 1992 through December 1992. The model simulates water level, currents, heat transport and temperature distribution, conservative material transport, and the transport and transformation of 11 chemical constituents. Complete details of model theory and structure, and extensive bibliography for theoretical development and application, are given by Cole and Buchak (1995).

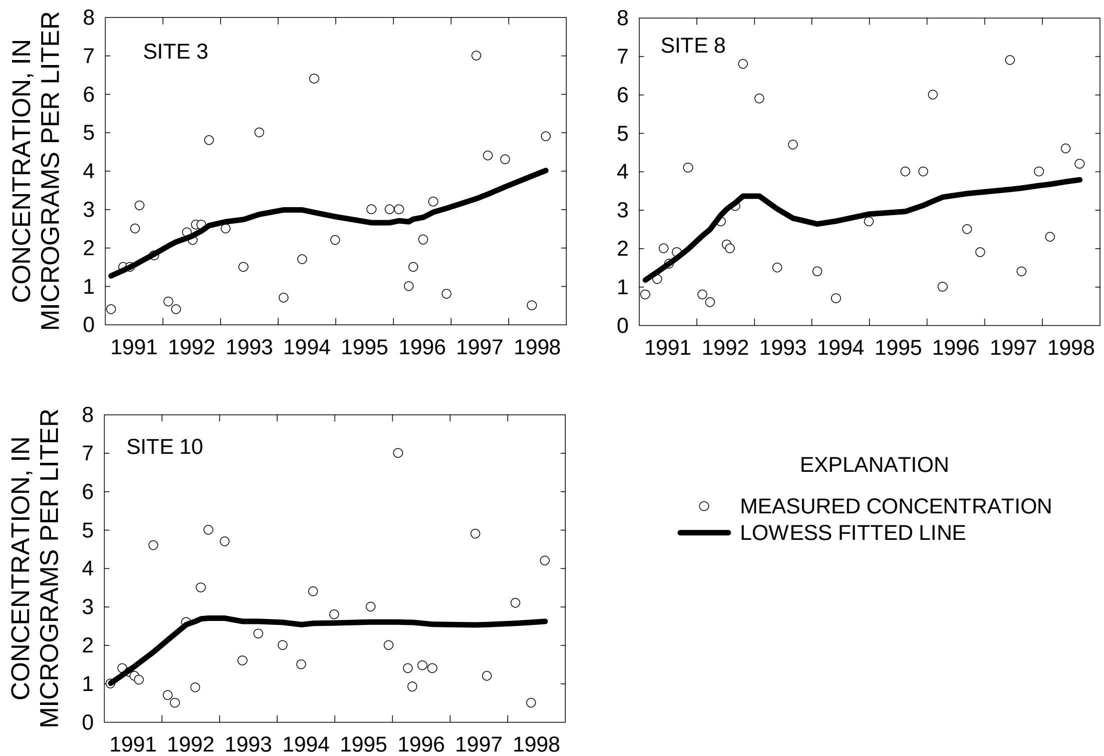


Figure 12. Concentrations of chlorophyll *a* at reservoir sites, 1991 through 1998. LOWESS is locally weighted scatter plot smooth line (Helsel and Hirsch, 1992).

Table 2. Annual sediment and nutrient loads and yields at the Maumelle River streamflow gaging site

[kg, kilogram; yr, year; ha, hectare]

Constituent	Water year							
	1990	1991	1992	1993	1994	1995	1996	1997
Sediment load (kg/yr)	2.08×10^{6}	2.11×10^{6}	1.66×10^{6}	1.53×10^{6}	1.99×10^{6}	1.49×10^{6}	5.35×10^{5}	2.21×10^{6}
Sediment yield (kg/ha/yr)	175	177	139	128	167	125	44.8	185
Nitrite plus nitrate nitrogen load (kg/yr)	2,030	1,860	1,370	1,090	1,340	928	318	1,080
Nitrite plus nitrate nitrogen yield (kg/ha/yr)	0.170	0.156	0.115	0.092	0.112	0.078	0.027	0.090
Ammonia nitrogen load (kg/yr)	2,760	2,310	1,450	992	986	586	152	511
Ammonia nitrogen yield (kg/ha/yr)	0.231	0.194	0.122	0.083	0.083	0.049	0.013	0.043
Total ammonia plus organic nitrogen load (kg/yr)	24,300	23,600	17,900	15,300	18,700	13,500	4,700	17,700
Total ammonia plus organic nitrogen yield (kg/ha/yr)	2.04	1.97	1.50	1.28	1.57	1.13	0.393	1.48
Total phosphorus load (kg/yr)	1,340	1,470	1,290	1,110	1,600	1,210	502	1,910
Total phosphorus yield (kg/ha/yr)	0.113	0.123	0.108	0.093	0.134	0.101	0.042	0.160
Dissolved orthophosphorus load (kg/yr)	561	488	332	243	262	164	49.3	157
Dissolved orthophosphorus yield (kg/ha/yr)	0.047	0.041	0.028	0.020	0.022	0.014	0.004	0.013

Model Implementation

Implementation of the CE-QUAL-W2 model for Lake Maumelle included (1) development of the computational grid, (2) specification of boundary and initial conditions, and (3) preliminary selection of model parameter values.

Computational Grid

The model domain extends from west of the Highway 10 bridge to the Lake Maumelle dam and spillway, a distance of 17.4 km along the longitudinal axis of the reservoir. There are 11 computational segments along the mainstem of the reservoir (fig. 13). Segments 1 and 11 are inactive boundary segments. Segments 2 and 10 are the farthest upstream and downstream active segments. The mathematical formulation of the model suggests that segment lengths generally should exceed the maximum reservoir width in that segment. Segments ranged in length from 294 to 3,667 m. Each segment was divided vertically into 1-m layers. Depth from the elevation of the spillway crest to the bottom of the reservoir ranged from about 5 m at the upstream end to 14 m at the dam. The orientation of the longitudinal axis of each segment relative to north was determined for each segment. This information is used in the computation of surface wind stress in each segment.

Original grid geometry was developed using pre-impoundment elevation contours of the reservoir bottom. In April 1999, reservoir bathymetry was determined from surveys made by the USGS using a recording fathometer and global positioning system. The bathymetry data were used to revise the computational grid. Reservoir surface area and volume of the pre-impoundment engineering data compared to that of the final model grid were similar (fig. 14). The estimated full-pool volume in the model is about 276 million m^3, which is a little greater than the original engineering design volume of 270 million m^3.

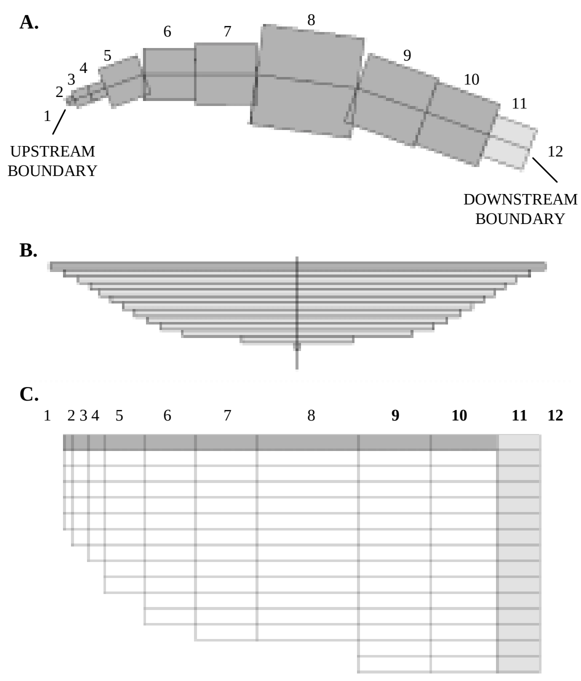


Figure 13. Plan view of (A) cross section (B) and downstream view (C) of model grid. Segments 1 and 12 are inactive boundary cells.

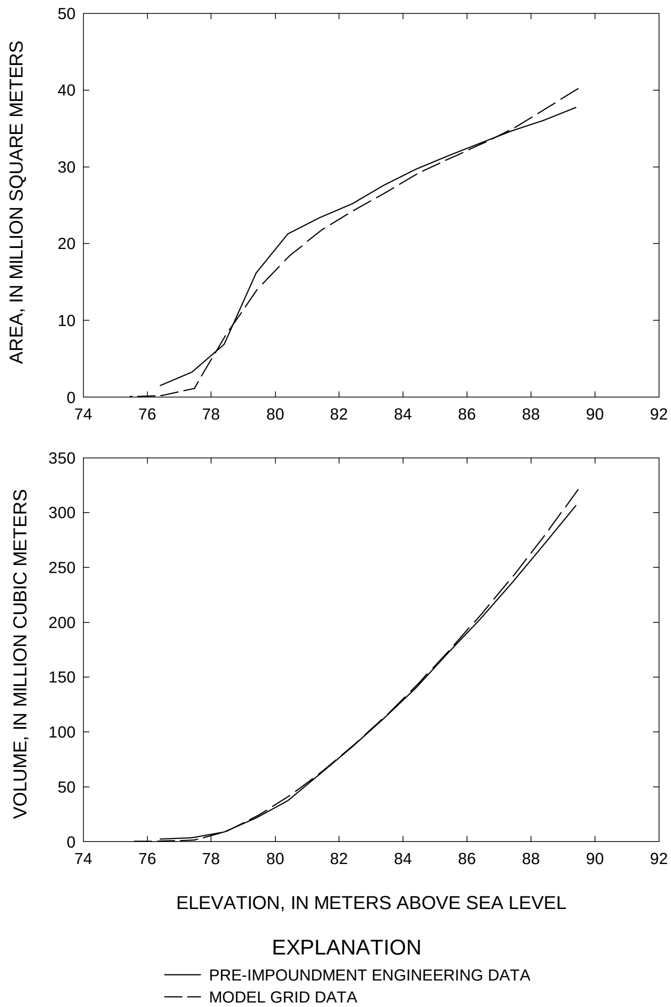


Figure 14. Surface area and volume curves for Lake Maumelle from pre-impoundment engineering data and model grid.

Boundary and Initial Conditions

Boundaries of the Lake Maumelle model include the reservoir bottom, the shoreline, the upstream boundary, the downstream boundary, and the water surface. Both hydraulic (which includes temperature) and chemical boundary conditions are required.

Hydraulic Boundary Conditions

The reservoir bottom is assumed to be an impermeable boundary with no discharge of ground water to the reservoir within the model domain or loss of water from the reservoir to the ground-water system. The magnitude of ground-water recharge or discharge from Lake Maumelle is unknown and not considered in the model. The reservoir bottom also is assumed to be immobile; that is, sediments are not resuspended by flow. The reservoir bottom causes resistance to the flow and thereby extracts energy from mean flow. The Chezy formulation is used in CE-QUAL-W2 to describe this phenomenon and varies with the magnitude of the flow. A single resistance coefficient, which is an empirical value and cannot be measured directly, is applied to all of the bottom computational gridcells (table 3).

Heat exchange between the reservoir bottom and overlying water is computed from (1) the reservoir bottom temperature, (2) the simulated water temperature, and (3) a coefficient of bottom heat exchange (table 3). The reservoir bottom temperature and coefficient of heat exchange are assumed to be constant in space and time. Heat exchange at the reservoir bottom is typically quite small (about two orders of magnitude less than surface heat exchange).

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

The drainage area of the Maumelle River Basin almost doubles between the Maumelle River streamflow-gaging site and the upstream end of the reservoir (119.4 km^2 to 231.5 km^2). The drainage area increases by 38 percent between the point where the Maumelle River enters the reservoir and the dam (231.5 km^2 to 318.8 km^2) not counting the reservoir pool area.

For the purposes of this model, daily streamflow measured at the Maumelle River gaging site was multiplied by a drainage-area ratio of 1.94 to account for all flow entering the reservoir from the Maumelle River. Drainage entering the reservoir from around the perimeter, between the upper end and the dam, was considered to be distributed equally among segments. To account for flow entering the reservoir from around the perimeter of the reservoir, daily streamflow measured at the Maumelle River gaging site was multiplied by a drainage-area ratio of 1.5. This flow was accounted for in the model as distributed tributary inflow.

Table 3. Hydraulic and thermal parameters specified as Lake Maumelle model input

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

Parameter	Purpose	Value in Lake Maumelle model	Constant or temporally variable
Chezy resistance coefficient	Represents turbulent exchange of energy at reservoir bottom	70 m$^{0.5}$/s	Constant
Coefficient of sediment-water heat exchange	Computes heat exchange between reservoir bottom and overlying water	2.0×10^{-7} (watts/m^2)/°C	Constant
Wind-sheltering coefficient	Reduces measured wind speed to effective wind speed at water surface	1.0 (dimensionless)	Temporally variable
Longitudinal eddy viscosity	Represents laterally averaged longitudinal turbulent transport of momentum	1 m^2/s	Constant
Longitudinal eddy diffusivity	Represents laterally averaged longitudinal turbulent transport of mass and heat	1 m^2/s	Constant

Discharge over the spillway (88.39 m above sea level) was monitored by a stage recorder. Outflow over the spillway was positioned in the farthest downstream active segment. Daily drinking-water-supply withdrawal was monitored by LRMWW. The withdrawal structure was positioned at an elevation of 87 m, in the farthest downstream active segment.

Hydraulic boundary conditions at the water surface included (1) precipitation, (2) evaporation, (3) wind stress, and (4) surface heat exchange. All meteorological data, with the exception of precipitation, required for these computations were measured at Little Rock (Adams Field) airport, about 29 km southeast of the Lake Maumelle dam, and generally were recorded at hourly intervals.

Precipitation on the reservoir pool was based on data collected near the Lake Maumelle dam. Evaporation was computed from a time series of water surface temperature, dewpoint temperature, wind speed, width of the surface layer, and length of the segment. Wind stress was computed from a time series of wind speed and direction, the orientation of the computational segment, and a wind-sheltering coefficient (table 3). The temporally variable wind-sheltering coefficient reduces the effects of wind on the reservoir because of topographic sheltering of the water surface.

Surface heat exchanges were computed from reservoir latitude and longitude, and from a time series of measured air temperature, dewpoint temperature, cloud cover, and wind speed and direction. Simulated surface-water temperature also is required for the computation of surface heat exchange. Surface heat exchange can be computed from the heat exchange equation as the sum of seven separate terms, or by using a more simple linearization of the heat exchange equation and an estimated equilibrium temperature (the temperature at which incoming radiation heat rates are balanced by outgoing water-surface temperature-dependent processes). The estimation of equilibrium temperature was the method used in this application. The loss of heat from the reservoir resulting from evaporation was included in the heat budget.

Chemical Boundary Conditions

In addition to temperature, concentrations of the following constituents were simulated for Lake Maumelle: labile dissolved organic matter, refractory dissolved organic matter, algae, particulate organic matter, nitrite plus nitrate nitrogen, ammonia nitrogen, phosphate, and dissolved oxygen. A time series of concentrations of selected constituents at all inflow boundaries is required for model operation. However, boundary conditions need not be supplied for all constituents that are included in model simulations.

Inflow chemical boundary conditions for the Maumelle River at the upstream end of the reservoir and distributed tributary inflow were based on monthly or semimonthly measurements at the Maumelle River streamflow gaging site (Green and Louthian, 1993). Daily loads of constituents at the Maumelle River streamflow-gaging site were divided by daily discharge to estimate daily concentrations. Atmospheric inputs of nitrate and ammonia nitrogen were supplied from data obtained at the National Atmospheric Deposition Program site at Caddo Valley located about 90 km southwest of Lake Maumelle. No phosphorus deposition data were available. Constituent inputs from the reservoir bottom boundary generally were computed within the model and were based on the value of selected parameters (table 4) and the concentration of the constituent in the overlying waters.

Initial Conditions

Initial water level, velocity, temperature, and constituent concentrations for each computational cell are required prior to beginning a simulation. Initial water level was set to the measured value at the Lake Maumelle spillway for the day simulations were to begin. Velocities were assumed to be zero. Initial water temperature and constituent concentrations were defined at appropriate spatial locations based on measurements obtained at the various sites at the time simulations were to begin.

Model Parameters

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

Most of the relevant hydrodynamic and thermal processes are simulated in CE-QUAL-W2, so that there are relatively few adjustable hydraulic and thermal parameters (table 3). The resistance, bottom heat exchange, and wind-sheltering coefficients were previously described. The longitudinal eddy viscosity and the eddy diffusivity describe horizontal turbulent mixing of mass and heat. Simulation results are relatively

Table 4. Rate coefficients used in water-chemistry simulations and specified as model input

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

Parameter	Computational purpose	Value in Lake Maumelle model
Light extinction coefficient for water	Amount of solar radiation absorbed in the surface layer	0.66/m
Light extinction coefficient for organic solids	Amount of solar radiation absorbed in the surface layer	0.10/m
Light extinction coefficient for inorganic solids	Amount of solar radiation absorbed in the surface layer	0.01/m
Fraction of incident solar radiation absorbed at water surface	Amount of solar radiation absorbed in the surface layer	0.49*
Suspended solids settling rate	Settling rates and sediment accumulation on reservoir bottom	2.0 m/d
Algal growth rate	Maximum gross algal production rate, uncorrected for respiration, mortality, excretion or settling; temperature dependent	2.0/d
Algal mortality rate	Maximum algal mortality rate; temperature dependent	0.08/d
Algal excretion rate	Maximum algal photorespiration rate, which becomes labile dissolved organic matter	0.005/d
Algal dark respiration rate	Maximum algal dark respiration rate	0.005/d
Algal settling rate	Representative settling velocity for algal assemblages	0.1 m/d
Saturation light intensity	Saturation light intensity at maximum algal photosynthesis rate	100 watts/m^2
Fraction of algal biomass lost by mortality to detritus	Detritus and dissolved organic matter concentrations; remaining biomass becomes labile dissolved organic matter	0.8*
Lower temperature for algal growth	Algal growth rate as a function of water temperature	5.0 °C
Fraction of algal growth at lower temperature	Algal growth rate as a function of water temperature	0.01*
Lower temperature for maximum algal growth	Algal growth rate as a function of water temperature	10.0 °C
Fraction of maximum growth at lower temperature	Algal growth rate as a function of water temperature	0.99*
Upper temperature for maximum algal growth	Algal growth rate as a function of water temperature	35 °C
Fraction of maximum growth at upper temperature	Algal growth rate as a function of water temperature	0.99*
Upper temperature for algal growth	Algal growth rate as a function of water temperature	40 °C
Fraction of algal growth at upper temperature	Algal growth rate as a function of water temperature	0.01*
Labile dissolved organic matter decay rate	Dissolved oxygen loss and production of inorganic carbon, ammonia, and phosphate from algal decay; temperature dependent	0.01/d
Labile to refractory decay rate	Transfer of labile to refractory dissolved organic matter	0.001/d
Maximum refractory dissolved organic matter decay rate	Dissolved oxygen loss and production of inorganic carbon, ammonia, and phosphate from decay of refractory dissolved organic matter; temperature dependent	0.001/d

Table 4. Rate coefficients used in water-chemistry simulations and specified as model input--Continued

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

Parameter	Computational purpose	Value in Lake Maumelle model
Detritus decay rate	Dissolved oxygen loss and production of inorganic carbon, ammonia, and phosphate from decay of particulate organic matter, temperature dependent	0.001/d
Detritus settling velocity	Loss of particulate organic matter to bottom sediment	1.0 m/d
Lower temperature for organic matter decay	Organic matter decay as a function of temperature	5.0 °C
Fraction of organic matter decay at lower temperature	Organic matter decay as a function of temperature	0.10*
Lower temperature for maximum organic matter decay	Organic matter decay as a function of temperature	30.0 °C
Fraction of maximum organic matter decay at lower temperature	Organic matter decay as a function of temperature	0.99*
Sediment decay rate	Decay rate of organic matter in bed sediments	0.1/d
Sediment oxygen demand	Zero-order sediment oxygen demand for each computational segment	0.1-0.2 $(g/m^2)/d$
5-day BOD decay rate	Effects of BOD loading on dissolved oxygen	0.15/d
BOD temperature rate coefficient	Adjusts 5-day BOD decay rate at 20°C to ambient temperature	1.047*
Ratio of 5-day BOD to ultimate BOD	Effects of BOD loading on dissolved oxygen	1.2*
Release rate of phosphorus from bottom sediments	Phosphorus balance; computed as a fraction of sediment oxygen demand	0.001*
Phosphorus partitioning coefficient	Describes sorption of phosphorus on suspended solids	2.0*
Algal half-saturation constant for phosphorus	The phosphorus concentration at which the uptake rate is one-half the maximum uptake rate; upper concentration at which algal growth is proportional to phosphorus concentration	0.005 mg/L
Release rate of ammonia from bottom sediments	Nitrogen balance; computed as a fraction of the sediment oxygen demand	0.001*
Ammonia decay rate	Rate at which ammonia is oxidized to nitrate	0.1/d
Algal half-saturation constant for ammonia	Nitrogen concentration at which the algal uptake rate is one-half the maximum uptake rate; upper concentration at which algal growth is proportional to ammonia concentration	0.1 mg/L
Lower temperature for ammonia decay	Ammonia nitrification as a function of temperature	5.0 °C
Fraction of nitrification at lower temperature	Ammonia nitrification as a function of temperature	0.1*
Lower temperature for maximum ammonia decay	Ammonia nitrification as a function of temperature	20.0 °C
Fraction of maximum nitrification at lower temperature	Ammonia nitrification as a function of temperature	0.99*
Nitrate decay rate	Rate at which nitrate is denitrified; temperature dependent	100.0/d
Lower temperature for nitrate decay	Denitrification as a function of temperature	5.0 °C
Fraction of denitrification at lower temperature	Denitrification as a function of temperature	0.1*
Lower temperature for maximum nitrate decay	Denitrification as a function of temperature	20.0 °C
Fraction of maximum denitrification at lower temperature	Denitrification as a function of temperature	0.99*

Table 4. Rate coefficients used in water-chemistry simulations and specified as model input--Continued

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

Parameter	Computational purpose	Value in Lake Maumelle model
Iron release from bottom sediments	Iron balance; computed as a fraction of sediment oxygen demand	0.5*
Iron settling velocity	Particulate iron settling velocity under oxic conditions	2.0 m/d
Oxygen stoichiometric equivalent for ammonia decay	Relates oxygen consumption to ammonia decay	4.57*
Oxygen stoichiometric equivalent for organic matter decay	Relates oxygen consumption to decay of organic matter	1.4*
Oxygen stoichiometric equivalent for dark respiration	Relates oxygen consumption to algal dark respiration	0.005*
Oxygen stoichiometric equivalent for algal growth	Relates oxygen production to algal growth	1.4*
Stoichiometric equivalent between organic matter and phosphorus	Relates phosphorus release to decay of organic matter	0.008*
Stoichiometric equivalent between organic matter and nitrogen	Relates nitrogen release to decay of organic matter	0.10*
Dissolved oxygen limit	Dissolved oxygen concentration below which anaerobic processes such as nitrification and sediment nutrient releases occur	0.1 mg/L

insensitive to changes in all five of these parameters, with the exception of the wind-sheltering coefficient.

There are 57 chemical kinetic rate coefficients required for application of CE-QUAL-W2 (table 4). The values specified for most of the coefficients were based on suggestions given by Cole and Buchak (1995), and all of the coefficients are temporally and spatially invariant.

Other Model Options

The maximum computational time step was limited to 1 hour, so that the computational time step would not exceed the interval at which boundary data were supplied to the model; the model-selected computational interval generally was about 5 minutes. The "QUICKEST" numerical scheme (Leonard, 1979) was used for solving the transport equations. A Crank-Nicholson scheme (Roache, 1982) was used to solve the vertical advection equation.

Model calculations occurred at time steps smaller than the time increments at which boundary data were provided. Boundary data can be assumed to vary linearly between measured values or remain constant between measured values. For this application, all boundary data were assumed to vary linearly between measured values.

Model Calibration and Testing

Model calibration was achieved by adjusting model parameters, within reasonable ranges, for the period February 7 through December 31, 1991. Verification of model parameters was achieved for the period January 21 through December 31, 1992.

Hydrodynamics

There was good agreement between measured and simulated water levels at Lake Maumelle spillway (fig. 15) between February 6 and December 31, 1991. The root mean square difference between measured and simulated water levels was 0.17 m. The difference between measured and simulated water levels ranged from -0.57 to 0.11 m, and the mean difference was -0.06 m. The total range in measured and modeled water level during the simulation period was 1.38 and 1.49 m, respectively. Measured water level was about 0.5 m higher than the model elevation during the November-December period after large rainfall events occurred. It is possible that a considerable amount of rainfall and runoff occurred downstream of the Maumelle River streamflow gage and was not accounted for in the model input data. The 0.5 m error represents about 10 percent of reservoir volume at spillway elevation. Water-budget adjustments in the model could have been made to better represent measured elevations, but these adjustments would be specific for the period of error and could not be applied to other periods.

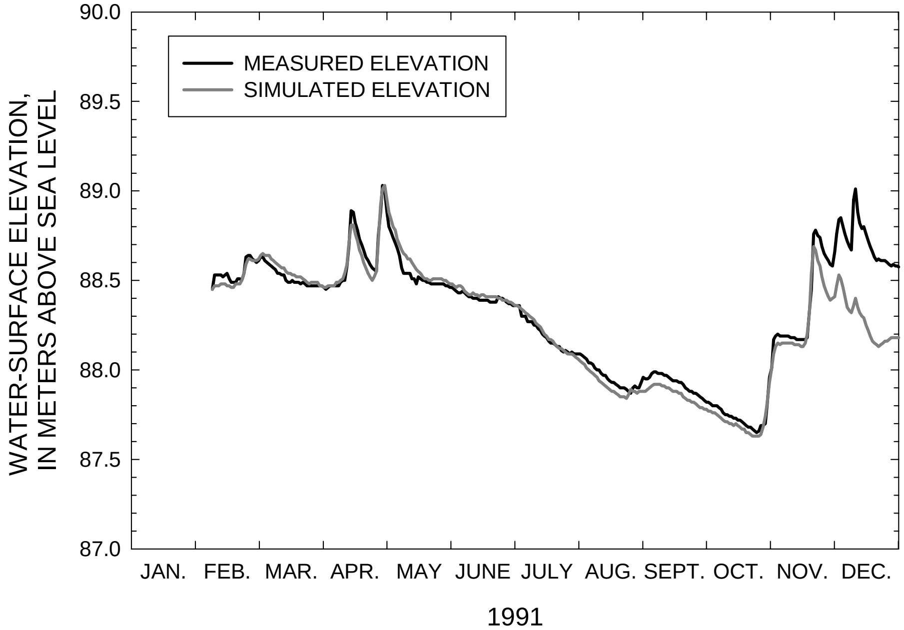


Figure 15. Measured and simulated water-surface elevation at Lake Maumelle spillway, February 6 through December 31, 1991.

Agreement between measured and simulated water levels at Lake Maumelle spillway during 1992 (fig. 16), using the same distributed tributary correction factor as in 1991 (1.5 times discharge at the Maumelle River gaging station) was not as good as in 1991. The root mean square difference between measured and simulated water levels was 0.31 m. The difference between measured and simulated water levels ranged from -0.57 to 0.08 m, and the mean difference was -0.25 m. The total range in measured and simulated water level during the 1992 simulation period was 1.09 and 1.27 m, respectively. A divergence between measured and simulated water level occurred during March 1992, and after about April, the two levels paralleled each other until mid December, at which time simulated levels approached measured levels again. Considering that all inflow data are estimated using gage data that represents only 42 percent of the basin, (not including the reservoir pool), these results are within reason. Precipitation events that occur downstream of the gage would not be included in the inflow data, resulting in error in the simulation.

Simulated water temperatures agreed well with seasonal variations in near-surface and near-bottom ambient water temperature measured in Lake Maumelle (fig. 17). Simulated near-surface and near-bottom water temperatures were generally within 2 °C of the corresponding measured values. Differences between simulated and measured values ranged from -2.4 to 2.8 °C and the average difference was 0.3 °C.

The vertical distribution of water temperature affects vertical mixing of dissolved and suspended materials and can be used to define the general location of the epilimnion and hypolimnion of the reservoir. The epilimnion and hypolimnion are typically separated by a thermocline, in which there is a relatively large change in temperature over a small change in depth. A strong thermocline existed in Lake Maumelle during June through August 1991 (fig. 18). Simulated vertical distributions agreed quite closely with measured distributions, even for complex temperature profiles.

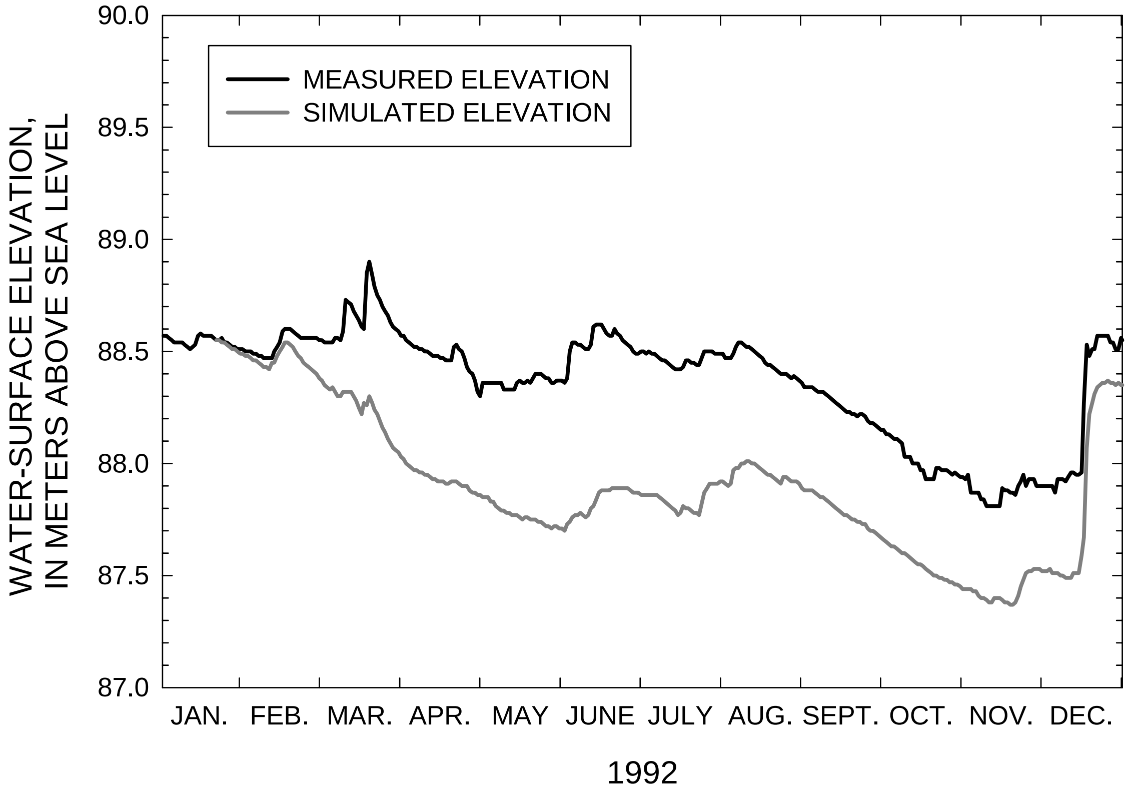


Figure 16. Measured and simulated water-surface elevation at Lake Maumelle spillway, January 1 through December 31, 1992.

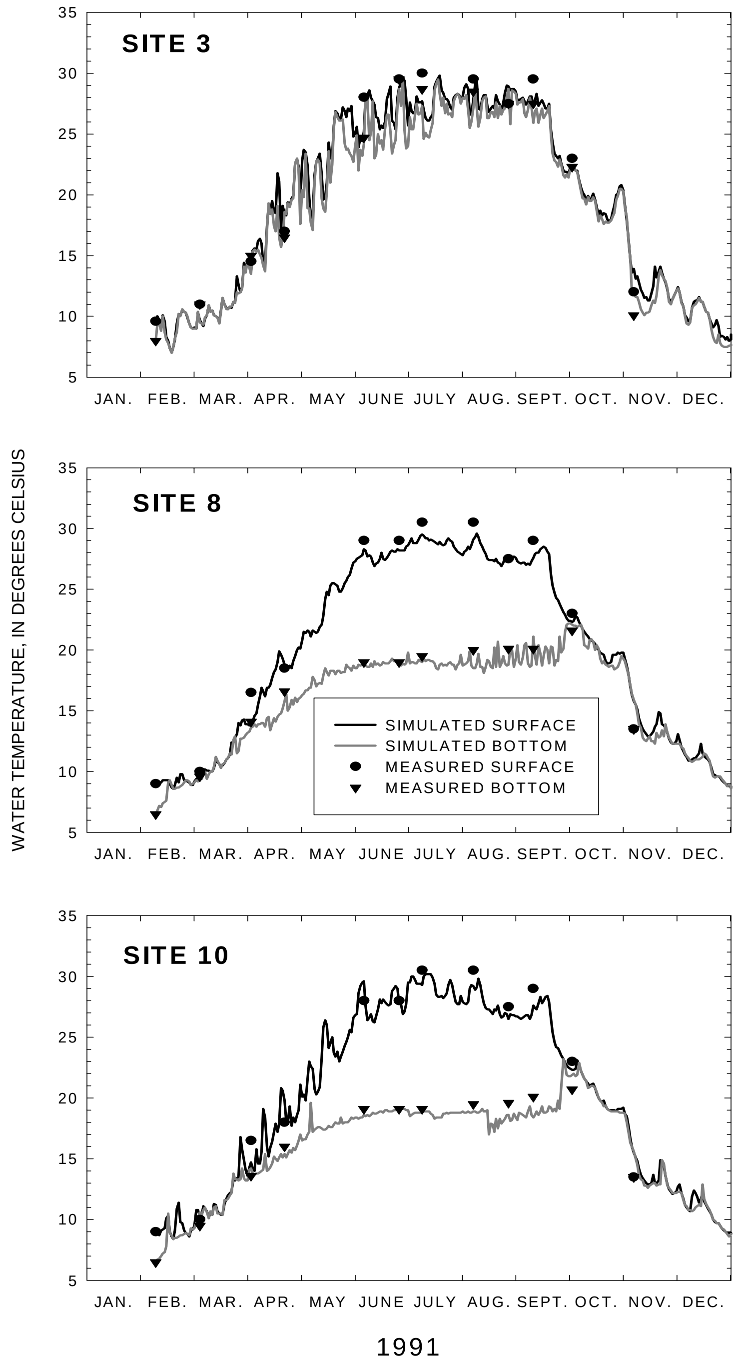


Figure 17. Measured and simulated near-surface and near-bottom water temperatures for February 8 through December 31, 1991, at Lake Maumelle sites 3, 8, and 10.

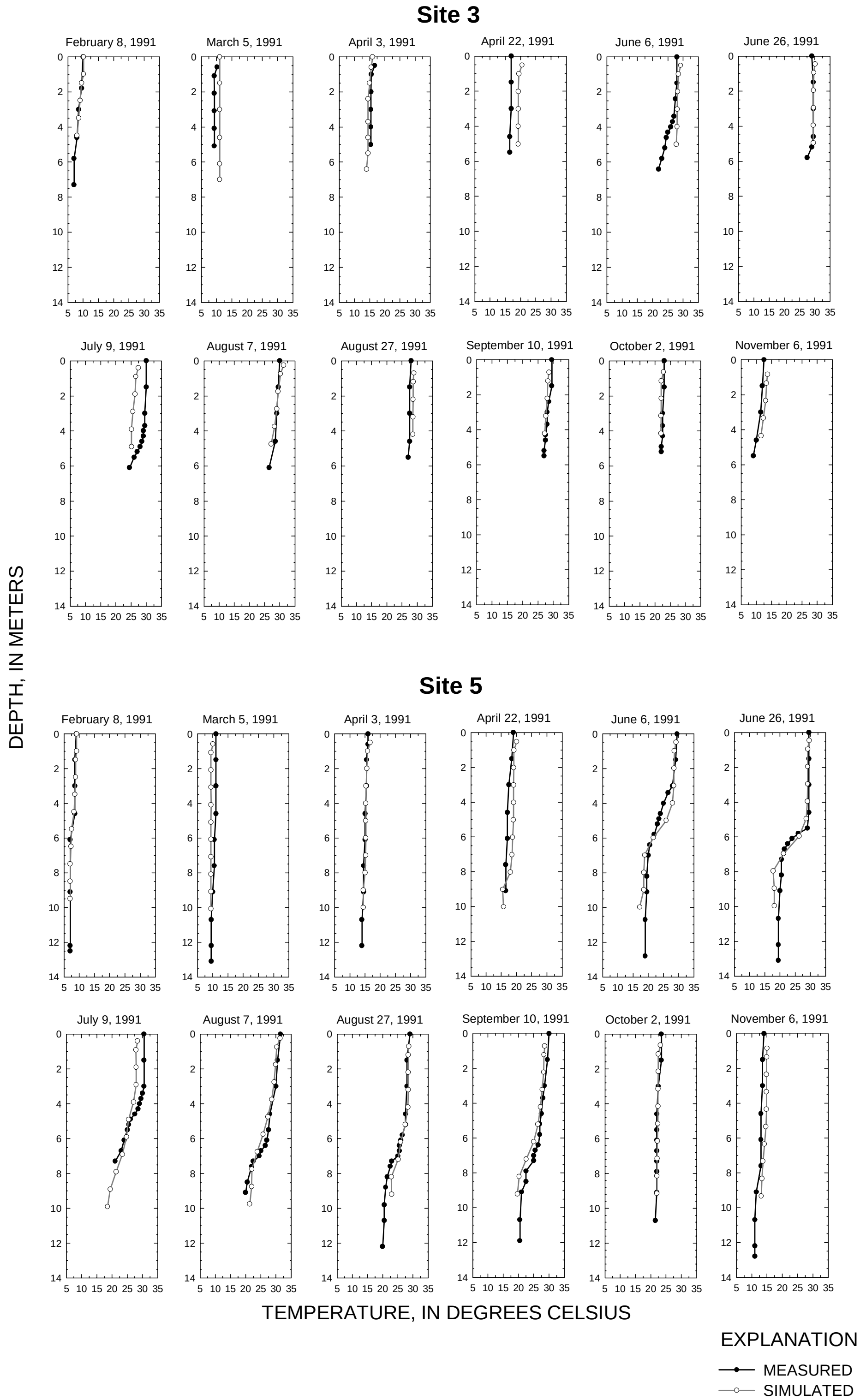


Figure 18. Measured and simulated vertical profiles of water temperature at Lake Maumelle sites 3, 5, 8, 9, and 10, February 8 through November 6, 1991 (page 1 of 3).

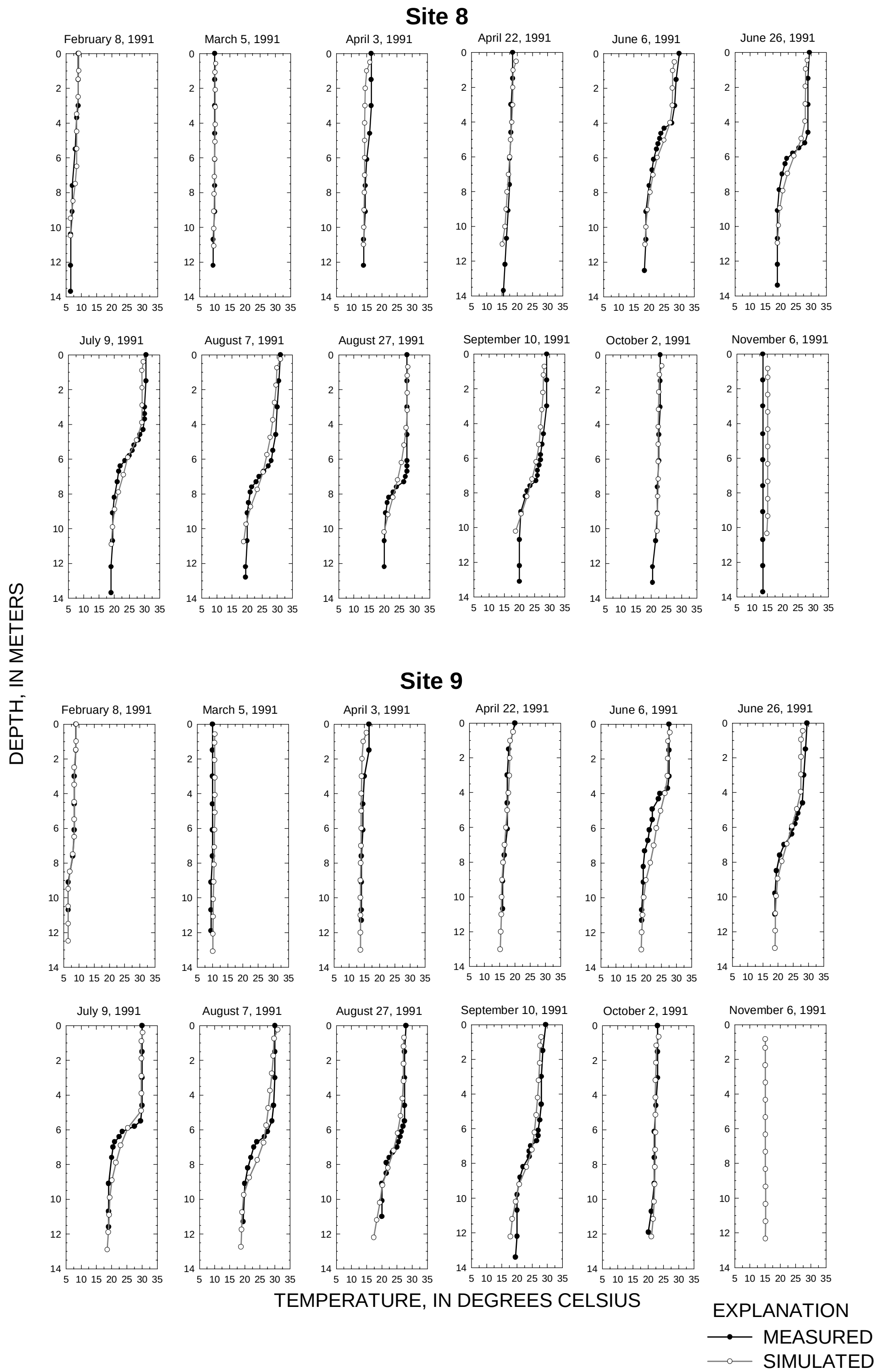


Figure 18. Measured and simulated vertical profiles of water temperature at Lake Maumelle sites 3, 5, 8, 9, and 10, February 8 through November 6, 1991 (page 2 of 3).

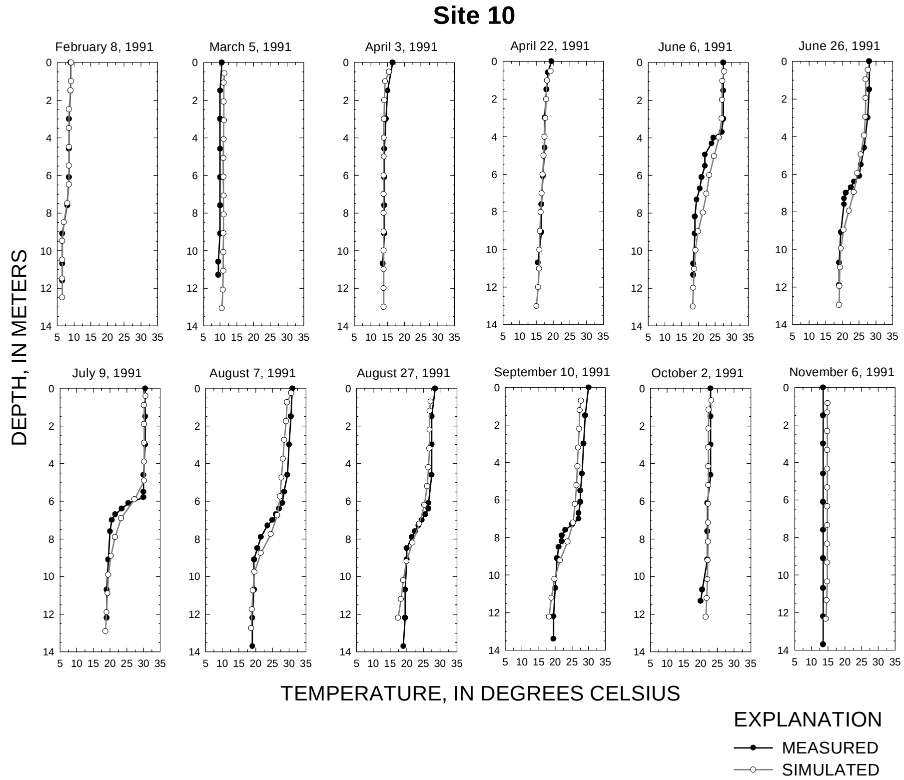


Figure 18. Measured and simulated vertical profiles of water temperature at Lake Maumelle sites 3, 5, 8, 9, and 10, February 8 through November 6, 1991 (page 3 of 3).

All measured water temperatures (611 observations) for February through November 1991 were compared with corresponding simulated values for all five sites (fig. 18). Measured water temperatures ranged from 6.5 to 31.4 °C. Differences between measured and simulated temperatures ranged from -3.6 to 4.3 °C with a root mean square difference of 1.11. The mean and median difference between measured and simulated water temperatures was 0.1 °C, indicating little bias toward overprediction or underprediction of temperatures during the calibration period. Sixty-five percent of the simulated temperatures were within 1 °C of the measured temperature.

Although the calibrated model generally provided an excellent simulation of water temperature in Lake Maumelle, the accuracy of simulated temperatures varied with temperature, season, and depth (fig. 19). Simulated water temperatures during the 1991 calibration period were lower than measured temperatures more often when measured temperatures were greater than 25 °C. Error in simulated water temperatures tended to be greater during the stratification season and at depths near the surface through the thermocline.

Results from the water temperature simulations provide information on physical characteristics and processes in the reservoir—information that might not be obtained from monthly or semimonthly measurements. For example, the measurements of water temperature indicate only that the reservoir became thermally mixed between early September and early October. The simulations, however, indicate that the reservoir was mixed in late September, a few days before the early October measurements (fig. 17). Had the October measurements occurred later in the month, the turnover date would have been more difficult to estimate without the simulation.

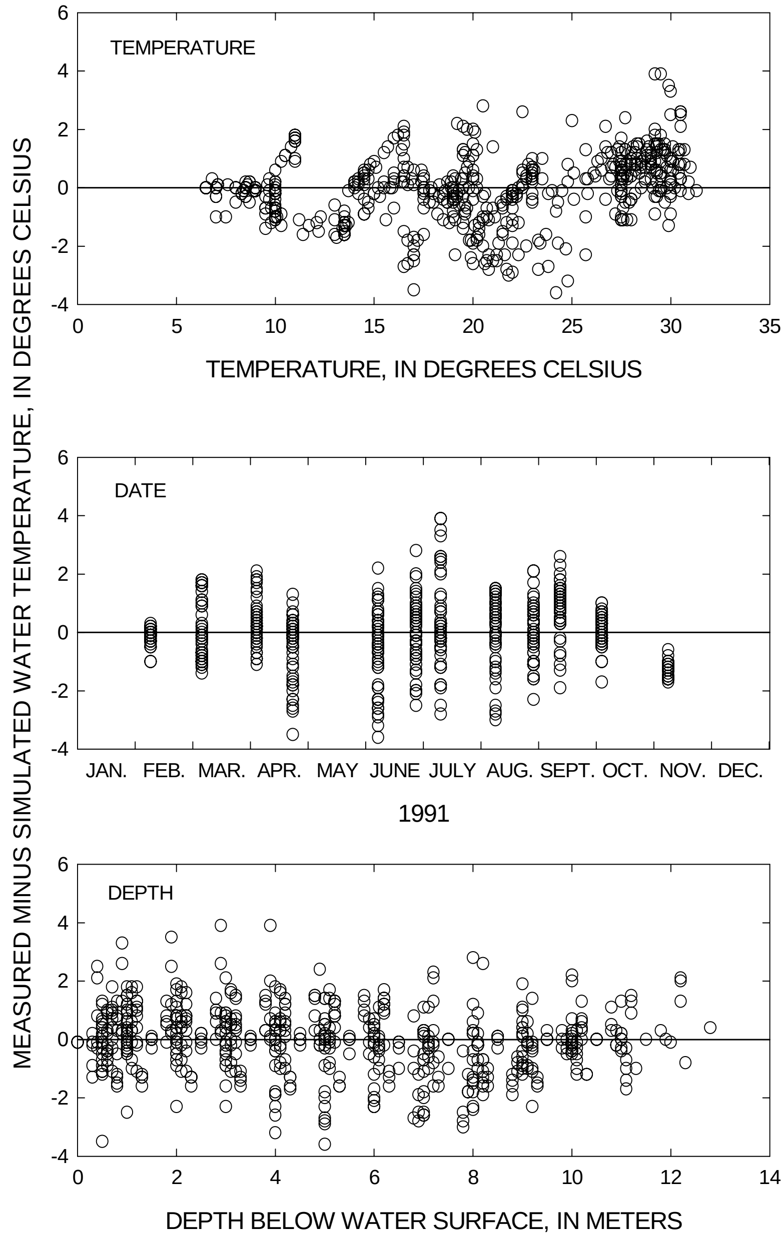


Figure 19. Relation of difference between measured and simulated water temperatures at Lake Maumelle for all sites to measured water temperature, date, and depth below water surface, February 8 through November 6, 1991.

Simulated water temperatures in 1992, using the same parameter values as in the 1991 calibration, were very similar to measured temperatures (fig. 20). All measured water temperatures (574 observations) for February through October 1992 were compared with corresponding simulated values for all five sites. Measured water temperatures in 1992 ranged from 7.4 to 29.9 °C. Differences between measured and simulated temperatures ranged from -2.5 to 6.1 °C with a root mean square difference of 1.03. The mean and median difference between measured and simulated water temperature was 0.2 and 0.0 °C, respectively, indicating little bias toward overprediction or underprediction of temperatures during the verification period. Seventy-six percent of the simulated temperatures were within 1 °C of the measured temperature.

Simulated water temperatures during the 1992 verification period, like the 1991 calibration period, were generally underpredicted more often when measured temperatures were greater than 25 °C (fig. 21). Error in simulated water temperatures tended to be greater during the stratification season and at depths near the surface through the thermocline (fig. 21). In general, the verification (1992) provided an excellent simulation of water temperature in Lake Maumelle, with most simulated values within plus or minus 1 °C of the actual value.

Water Chemistry

Complex biochemical reactions affecting the 11 simulated water-chemistry constituents in the Lake Maumelle model are expressed in part within the simulated dissolved oxygen results. Algal biomass (chlorophyll *a*) is used as an indicator of the trophic state of a reservoir and additional information on simulated algal biomass is presented. Algal growth in Lake Maumelle appears to be limited by orthophosphate concentrations and light availability. Nitrate and ammonia concentrations appear to have only a limited effect on DO and algal concentrations in Lake Maumelle. Oxygen is used during the decay of labile and refractory dissolved organic matter, BOD, organic sediments, and detritus. Decay processes consume DO and release phosphate and ammonia to the system. Particulate matter affects light penetration and heat distribution affecting algal growth and DO production. Results of DO simulations provide an indicator of how well other processes are simulated.

Dissolved Oxygen

Simulated DO concentrations for Lake Maumelle exhibited the same general patterns and magnitudes as measured values (fig. 22). The onset of low DO levels and the recovery to higher DO levels were well simulated throughout the reservoir.

Near-bottom DO concentrations at site 3 were overpredicted by as much as 3.7 mg/L on August 8, 1991, and throughout the stratification season. DO profiles were measured at site 3 above the thalweg, which was about 3 to 4 m deep and only about 6 to 8 m wide. Near-bottom measurements were collected within the thalweg. The resolution of the model grid at site 3, as well as throughout the reservoir, did not represent the spatial geometry of the thalweg and did not accurately simulate the DO dynamics occurring within. Farther downstream (sites 8 and 10, fig. 22), near-bottom dissolved oxygen concentrations were better simulated.

All measured DO concentrations (611 observations) for February through November 1991 were compared with corresponding simulated concentrations for all five sites (fig. 23). Measured DO concentrations in Lake Maumelle ranged from 0.6 to 11.8 mg/L. Differences between simulated and measured concentrations ranged from -4.2 to 5.3 mg/L with a root mean square difference of 1.04. The mean and median differences were -0.3 and -0.1 mg/L, respectively. Seventy-four percent of the simulated concentrations were within 1.0 mg/L of the measured concentration.

Simulated vertical profiles of DO concentrations generally agreed with measurements (fig. 23). Agreement was better at sites 5, 8, 9, and 10, than at site 3. Simulated values had the greatest departures from measured values within the thermocline during the stratification season. In many cases, measured DO changed from near saturation to anoxic conditions within a vertical distance of 1.0 m or less (for example, June 26, July 9, August 7, and August 27, 1991 at sites 8, 9, and 10). Such abrupt changes in measured DO concentrations could not be simulated within 1-m-thick layers represented in the model grid. Generally, within 2 meters below the measured oxycline, simulated concentrations again agreed with measured concentrations.

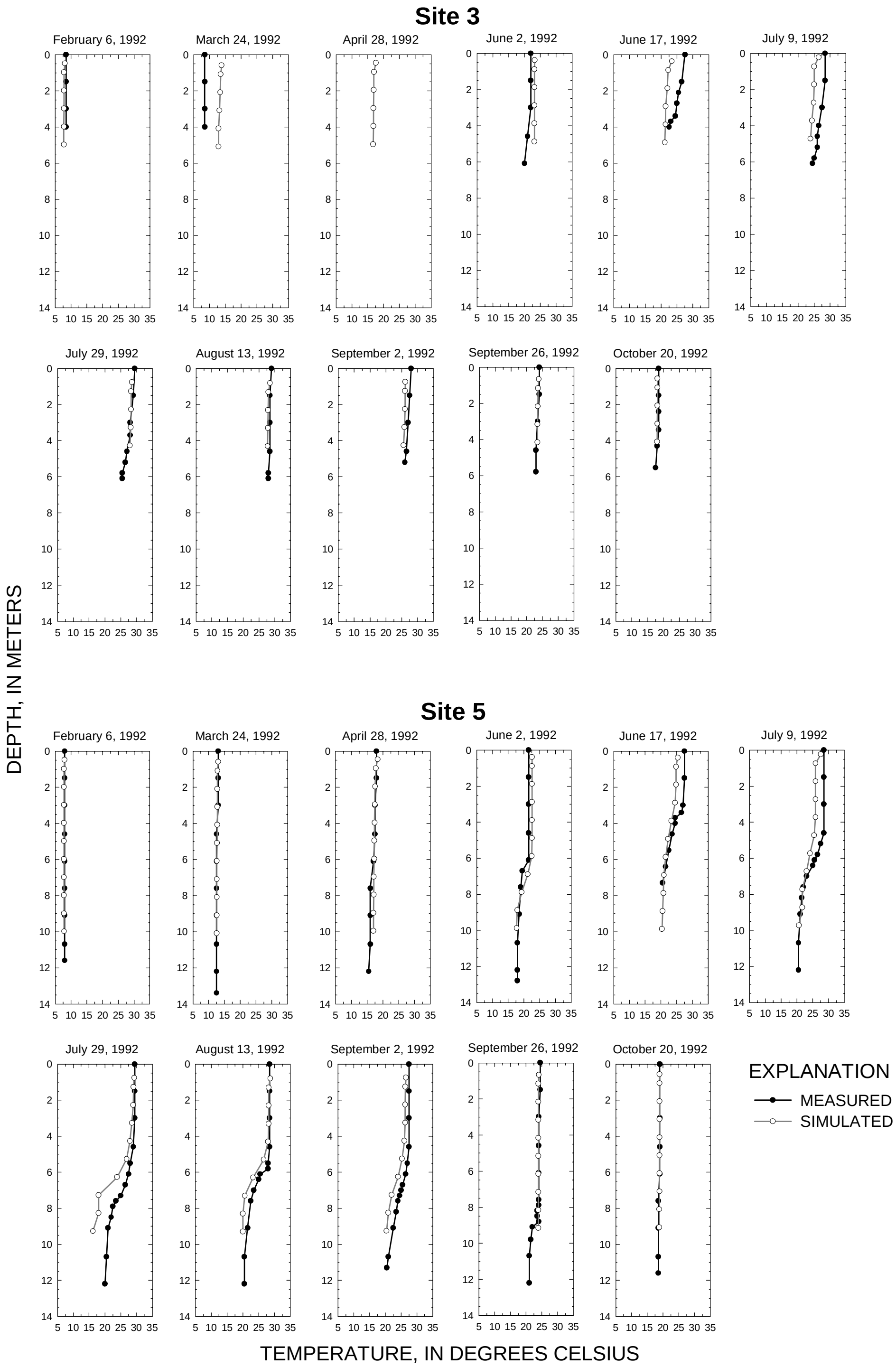


Figure 20. Measured and simulated vertical profiles of water temperature at Lake Maumelle sites 3, 5, 8, 9, and 10, February 6 through October 20, 1992 (page 1 of 3).

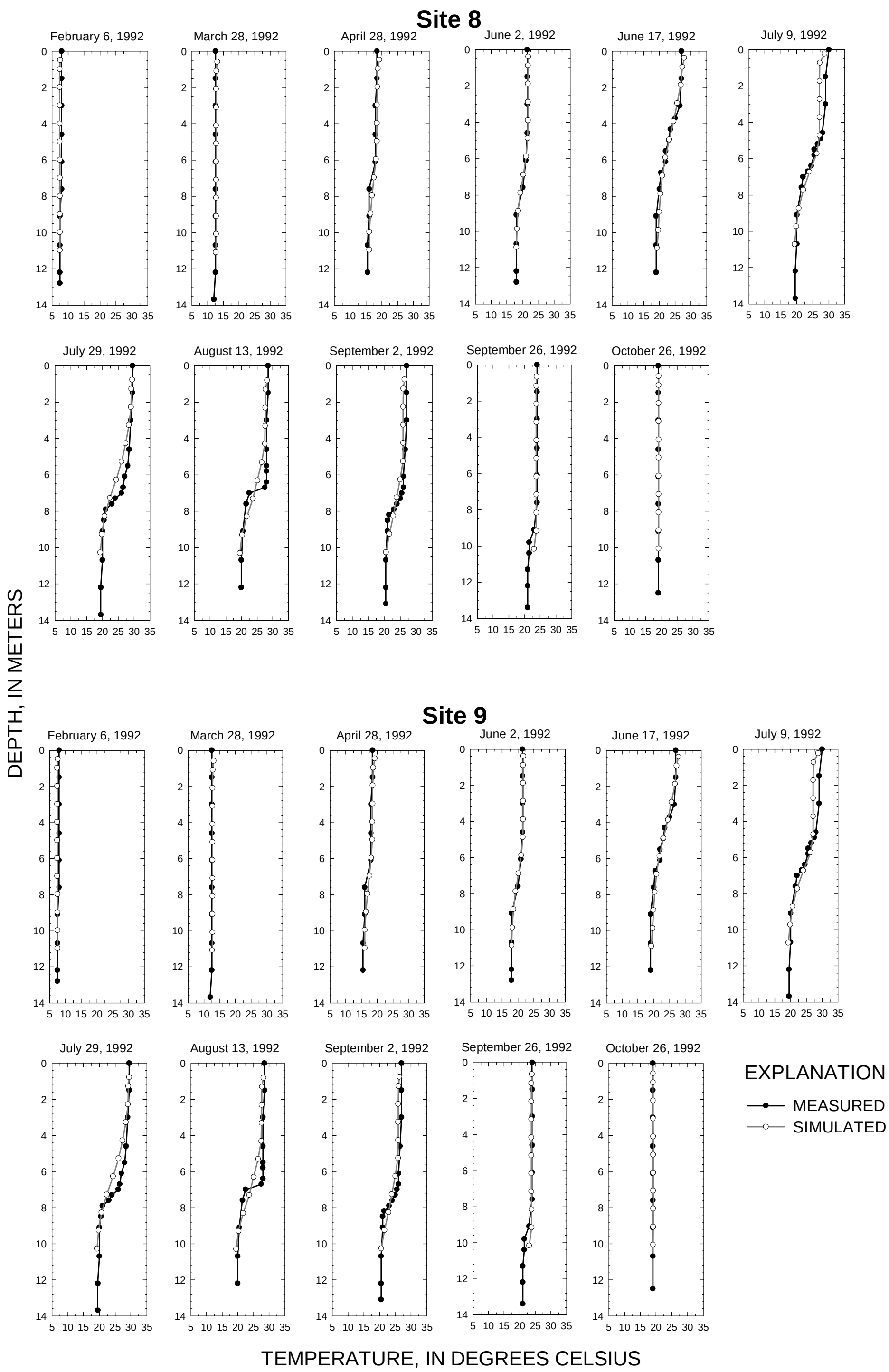


Figure 20. Measured and simulated vertical profiles of water temperature at Lake Maumelle sites 3, 5, 8, 9, and 10, February 6 through October 20, 1992 (page 2 of 3).

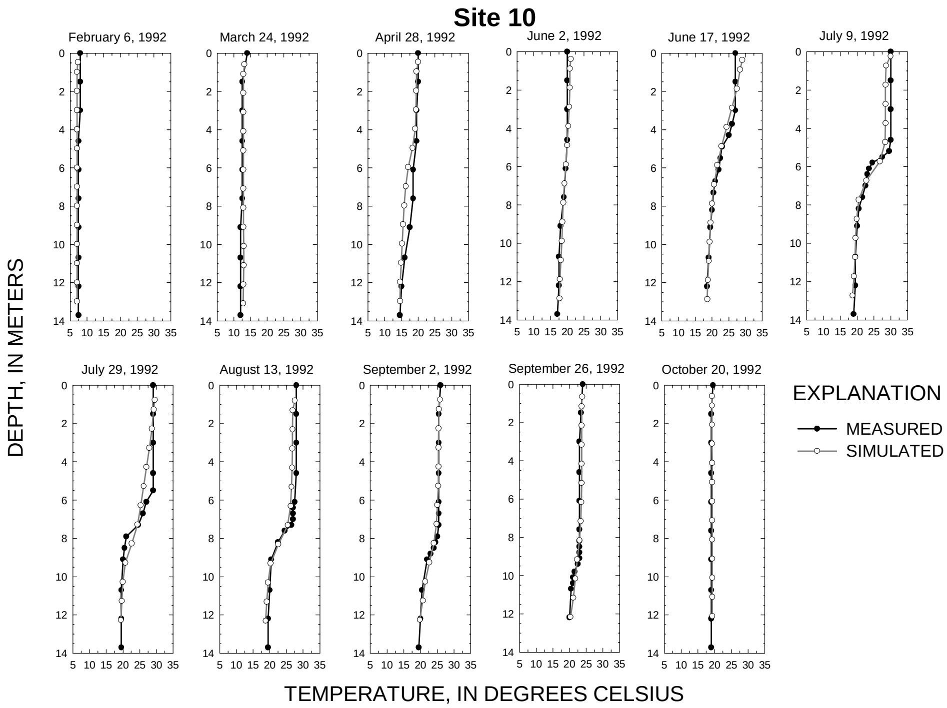


Figure 20. Measured and simulated vertical profiles of water temperature at Lake Maumelle sites 3, 5, 8, 9, and 10, February 6 through October 20, 1992 (page 3 of 3).

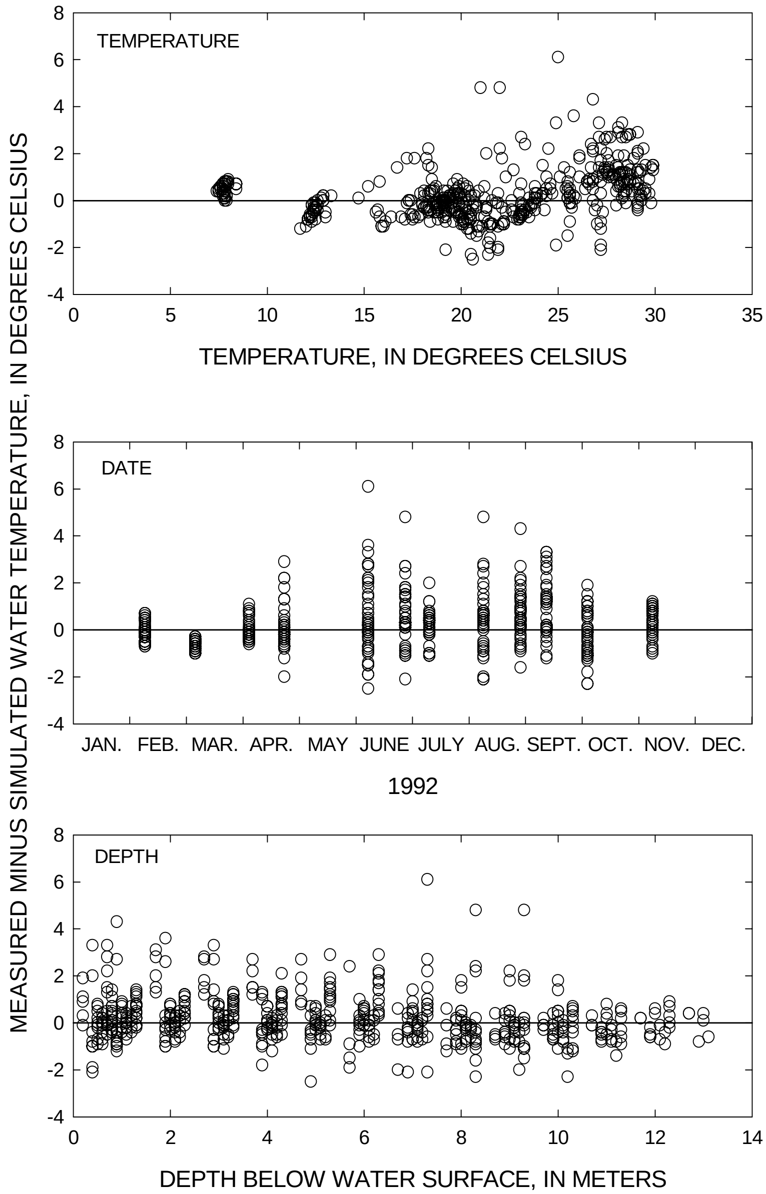


Figure 21. Relation of difference between measured and simulated water temperatures at Lake Maumelle for all sites to measured water temperature, date, and depth below water surface, February 8 through October 20, 1992.

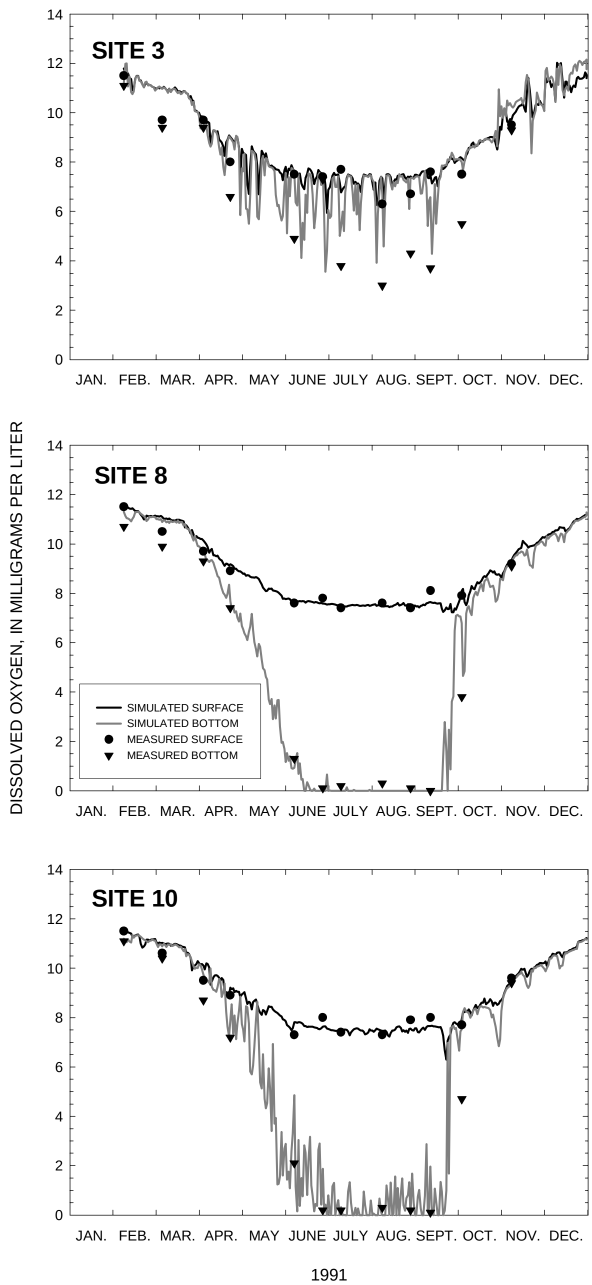


Figure 22. Measured and simulated dissolved oxygen concentrations, February through December 1991, at Lake Maumelle sites 3, 8, and 10.

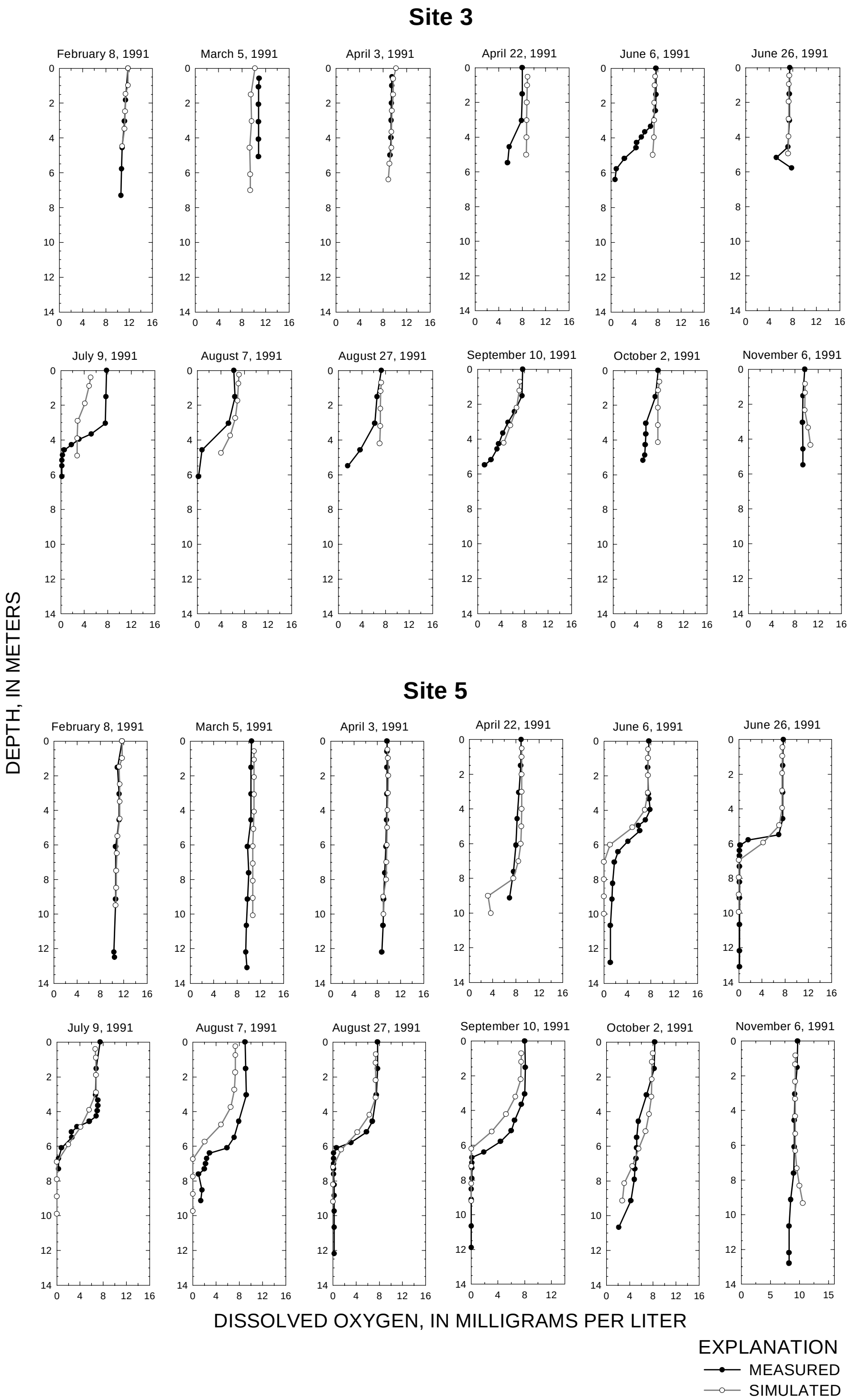


Figure 23. Measured and simulated vertical profiles of dissolved oxygen concentrations at Lake Maumelle sites 3, 5, 8, 9, and 10, February 8 through November 6, 1991 (page 1 of 3).

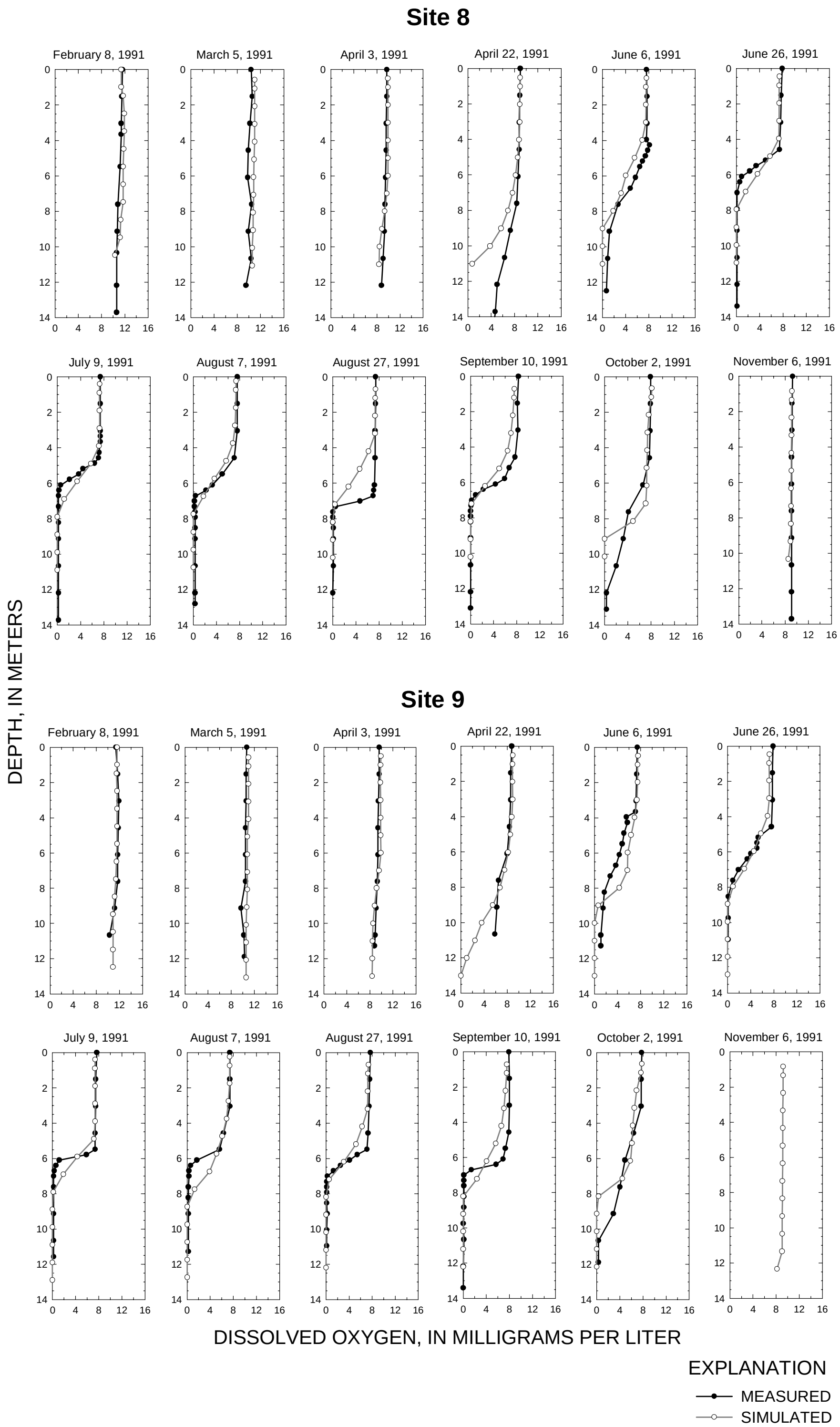


Figure 23. Measured and simulated vertical profiles of dissolved oxygen concentrations at Lake Maumelle sites 3, 5, 8, 9, and 10, February 8 through November 6, 1991 (page 2 of 3).

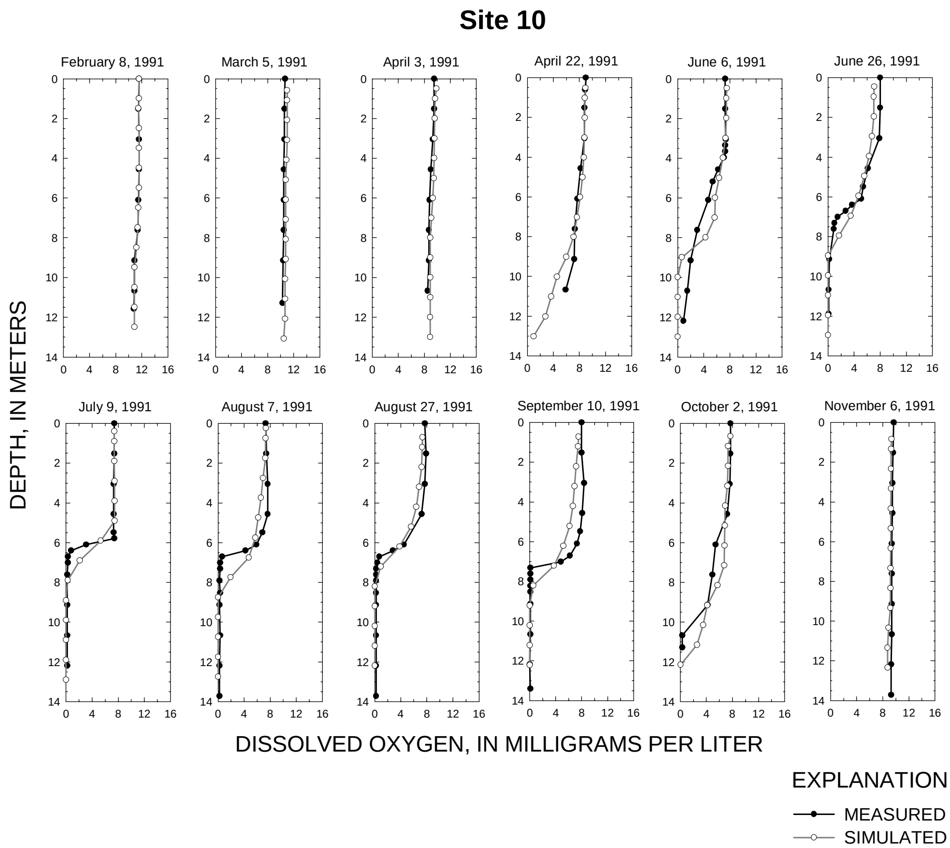


Figure 23. Measured and simulated vertical profiles of dissolved oxygen concentrations at Lake Maumelle sites 3, 5, 8, 9, and 10, February 8 through November 6, 1991 (page 3 of 3).

Differences between measured and simulated DO concentrations at all sites were compared to the corresponding measured DO concentrations, to the date, and to the depth below water surface (fig. 24). There appeared to be a greater tendency to overestimate DO concentrations, during periods of thermal stratification, and at depths within the thermocline than at other depths. At the upper depths within the epilimnion and lower depths within the hypolimnion and during periods of isothermal conditions, simulated DO concentrations generally were within plus or minus 1 mg/L of measured values.

Simulated dissolved oxygen concentrations during the 1992 verification period provided results similar to the 1991 calibration period (fig. 25). Measured dissolved oxygen concentrations (574 observations) for February through October 1992 ranged from 0.1 to 11.6 mg/L. Simulated dissolved oxygen concentrations ranged from 0.0 to 11.8 mg/L. Differences between simulated and measured concentrations ranged from -4.2 to 5.6 mg/L with a root mean square difference of 1.06 mg/L. The mean and median differences were -0.2 mg/L. Seventy-nine percent of the simulated concentrations were within 1.0 mg/L of the measured concentration.

The 1992 verification period provided an excellent simulation of dissolved oxygen concentrations in Lake Maumelle, with most simulated values within 1 mg/L of the actual value. Simulated dissolved oxygen concentrations during the 1992 verification period, like the 1991 calibration period, tended to overpredict DO concentrations during periods of thermal stratification at depths within the thermocline (fig. 26). Error in simulated DO concentrations tended to be greater during the stratification season and at depths near the surface through the thermocline (fig. 26).

Phosphorus, Ammonia, and Algae

Considering the oligo-mesotrophic condition of Lake Maumelle, simulated algae, phosphorus, and ammonia concentrations compared well with measured values. As discussed earlier, phosphorus and ammonia concentrations in Lake Maumelle were low— one to two orders of magnitude lower than estimates of national background concentrations. Chlorophyll *a* concentrations in Lake Maumelle reflect the nutrient stressed condition. The CE-QUAL-W2 model uses algal biomass (mg/L) as carbon as the algal response variable. To convert chlorophyll *a* into algal biomass, measured chlorophyll *a* concentrations (μg/L) were multiplied by a factor of 0.067 (Cole and Buchak, 1995) to provide an estimate of algal biomass (mg/L).

Simulated phosphorus concentrations in the near-surface water (top three meters) in segments 3, 8, and 10 tracked measured concentrations rather well (fig. 27). Simulated concentrations at segment 3, the upper end of the reservoir, were more variable because of variable inflow concentrations. This variability was reduced farther downstream in the reservoir (segments 8 and 10). Phosphorus concentrations tended to be lowest at the downstream sites during the summer stratification period and increased slightly following turnover, during the winter nonstratification period.

Simulated ammonia concentrations in the near-surface water (top three meters) at segments 3, 8, and 10 also tracked measured concentrations rather well (fig. 28). As with phosphorus concentrations, simulated ammonia concentrations were slightly more variable at segment 3 than farther downstream. Ammonia concentrations, like phosphorus, tended to be lowest during the summer stratification period and increased following turnover, during the winter nonstratification period.

Simulated algal biomass concentrations in the near-surface water (top three meters) at segments 3, 8, and 10 did not relate as well to chlorophyll *a* converted biomass concentrations (fig. 29), as did simulated to measured phosphorus and ammonia concentrations. Many factors are involved in the production of algae. However, it appears that if a multiplication factor other than 0.067 was used to convert chlorophyll *a* to algal biomass, differences between simulated and measured concentrations could be less. A different multiplication factor might require changes in algal growth parameters that also may affect nutrient dynamics. Again, concentrations at the upper end of the reservoir, at segment 3, were more variable than farther downstream. Algal biomass also was lower during the summer stratification period when nutrient concentrations were lowest. Algal biomass peaked following turnover when nutrient concentrations were greatest.

Sensitivity Analysis

Sensitivity analysis is the determination of the effects of small changes in calibrated model parameters on model results. A complete sensitivity analysis for all model parameters in the Lake Maumelle model was not conducted. The Lake Maumelle model includes more than 50 parameters (tables 3 and 4), and a complete sensitivity analysis would be a very lengthy process.

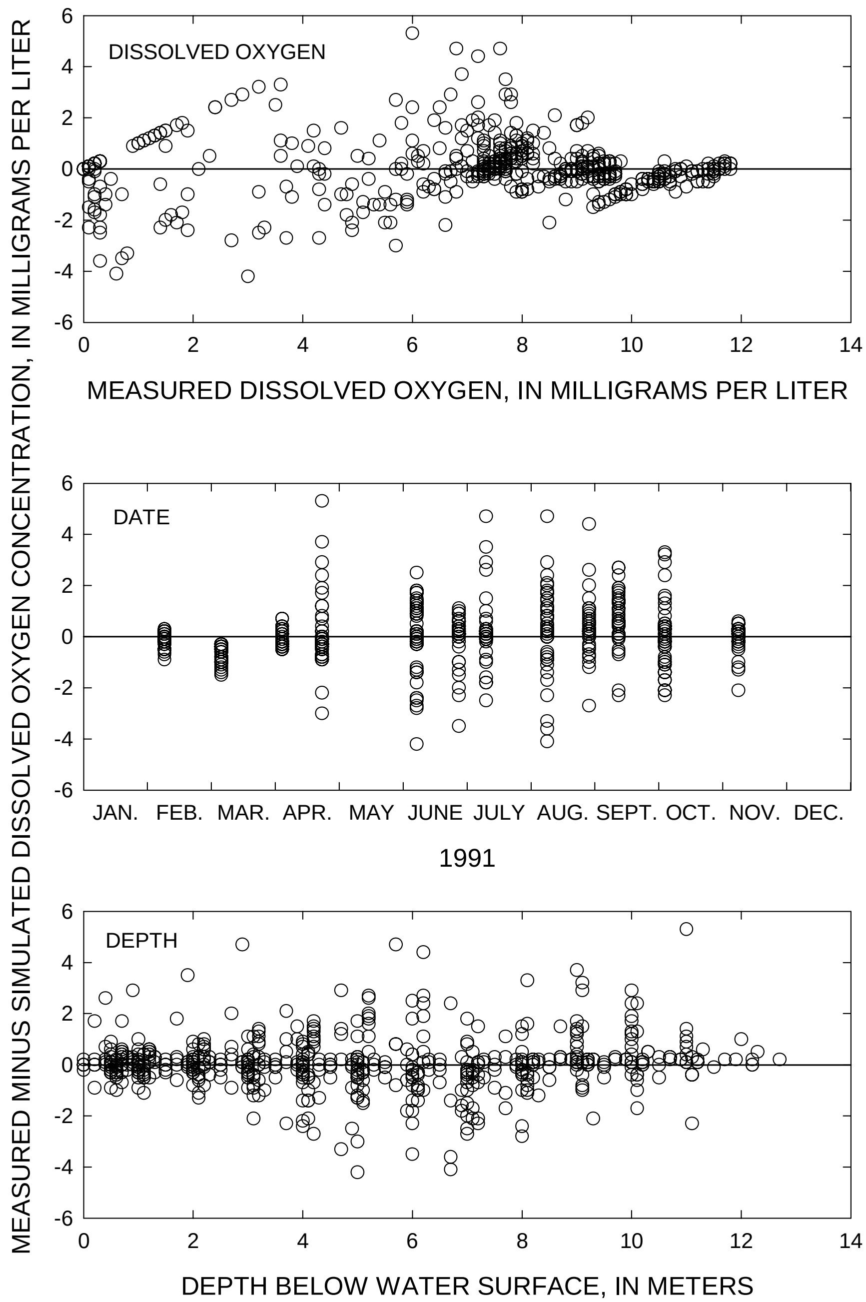


Figure 24. Relation of difference between measured and simulated dissolved oxygen concentrations at Lake Maumelle for all sites to measured dissolved oxygen concentration, date, and depth below water surface, February 8 through November 6, 1991.

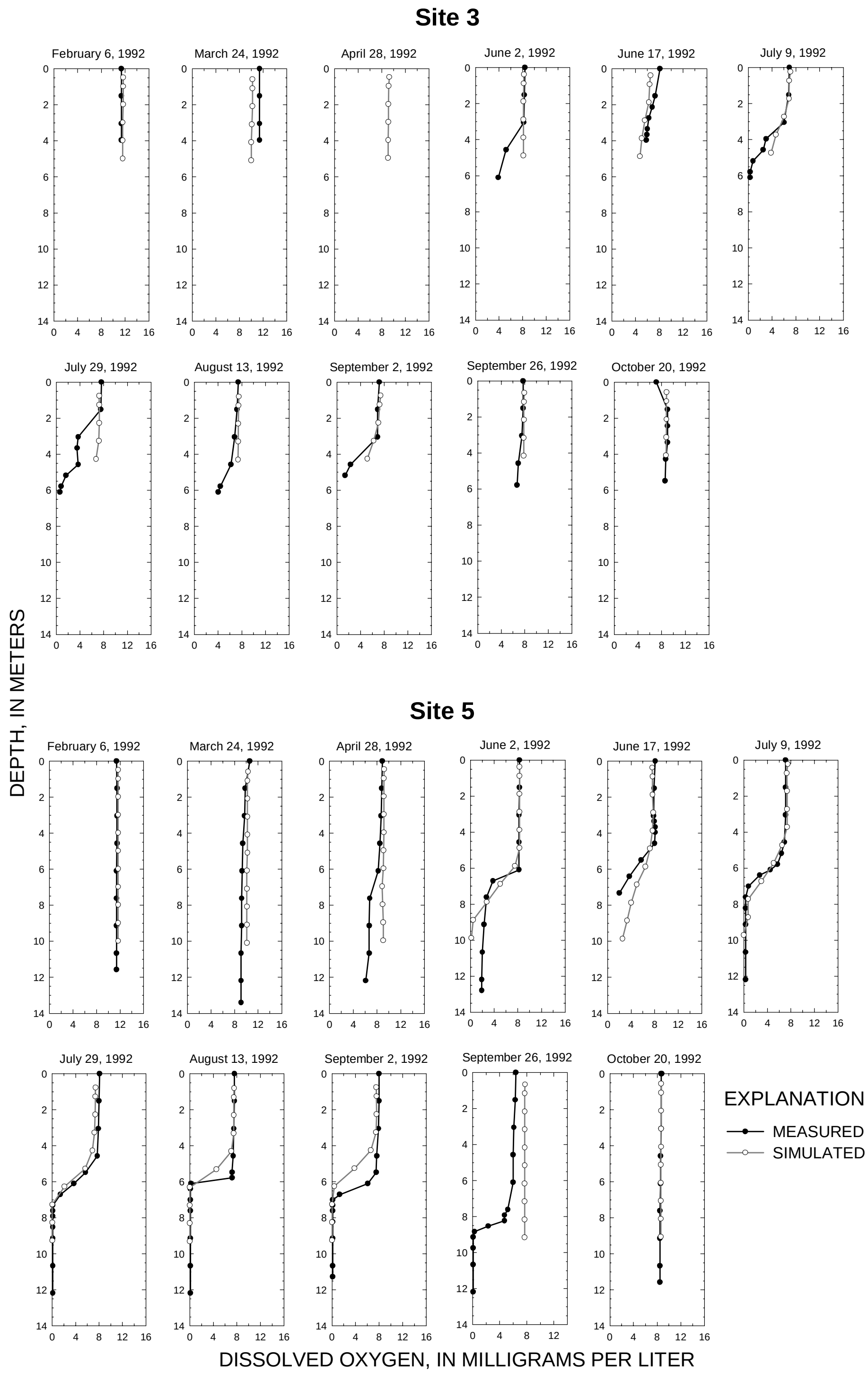


Figure 25. Measured and simulated vertical profiles of dissolved oxygen concentrations at Lake Maumelle sites 3, 5, 8, 9, and 10, February 6 through October 20, 1992 (page 1 of 3).

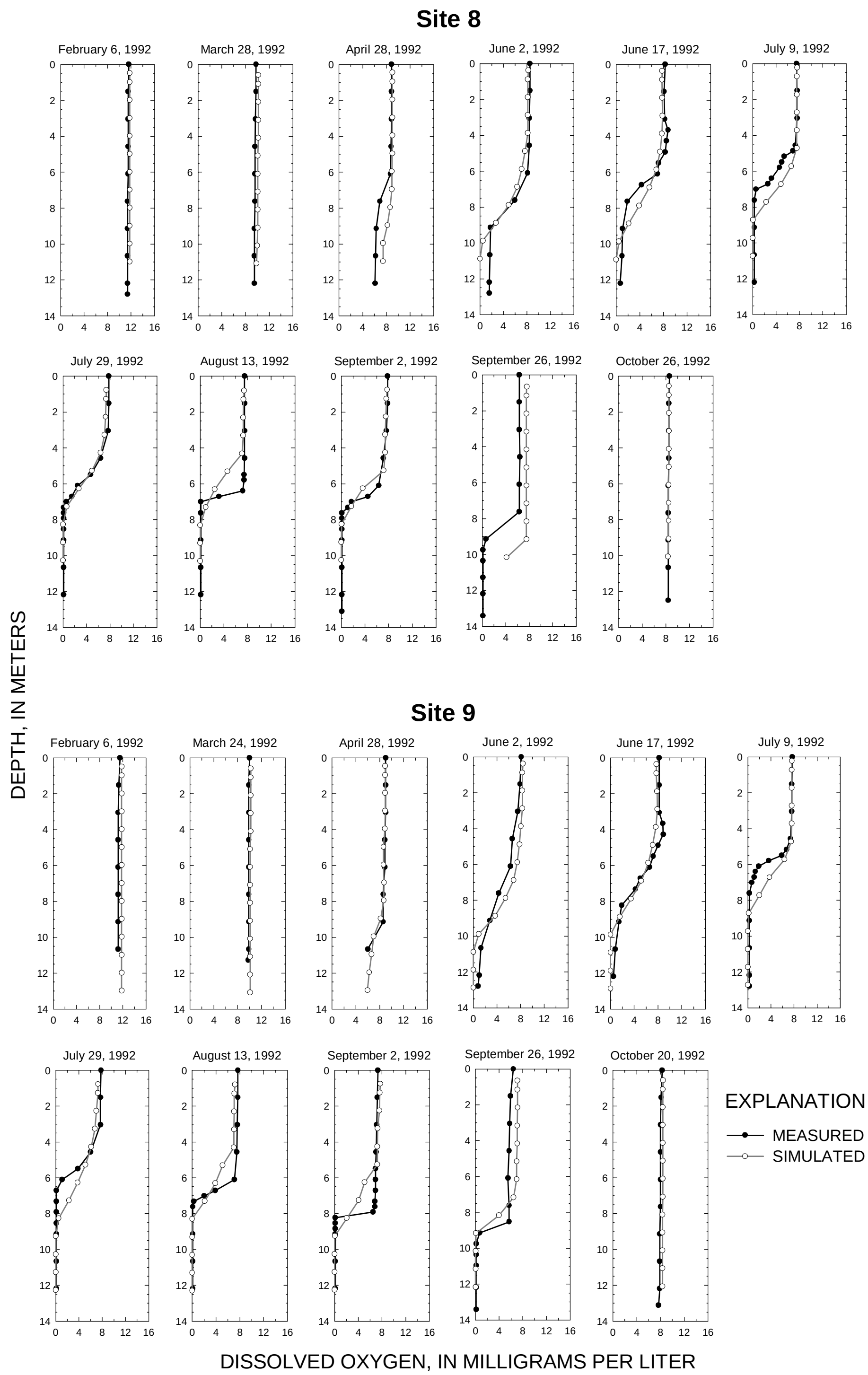


Figure 25. Measured and simulated vertical profiles of dissolved oxygen concentrations at Lake Maumelle sites 3, 5, 8, 9, and 10, February 6 through October 20, 1992 (page 2 of 3).

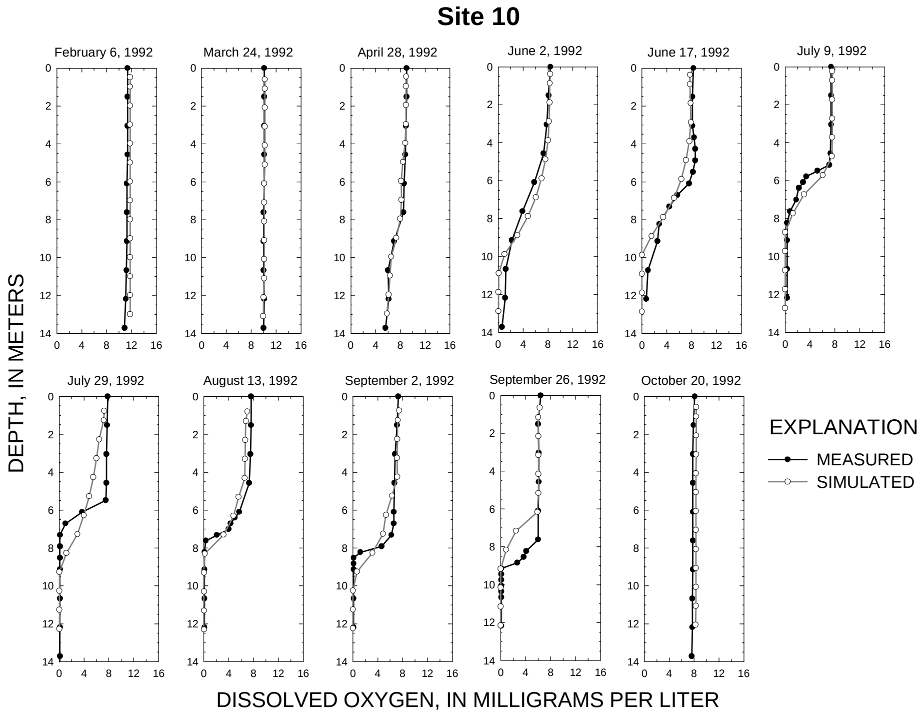


Figure 25. Measured and simulated vertical profiles of dissolved oxygen concentrations at Lake Maumelle sites 3, 5, 8, 9, and 10, February 6 through October 20, 1992 (page 3 of 3).

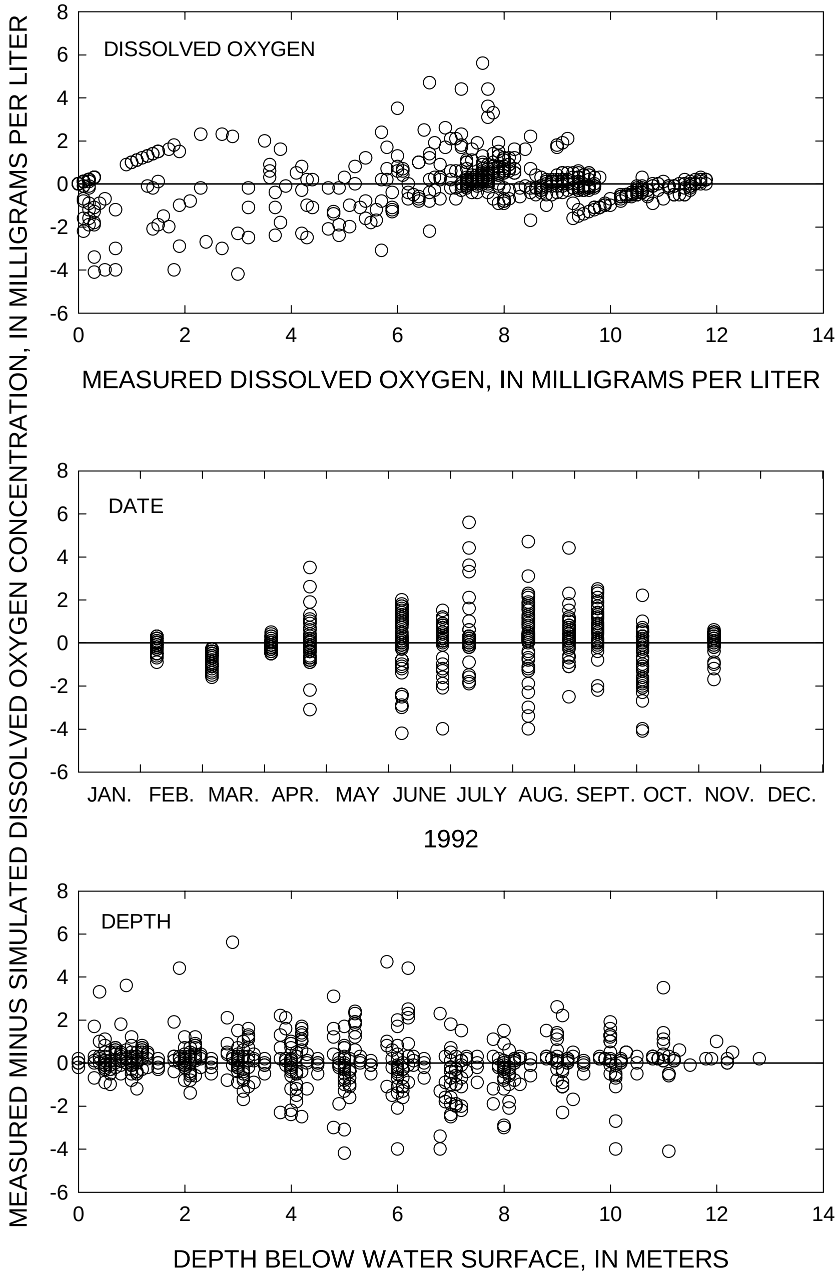


Figure 26. Relation of difference between measured and simulated dissolved oxygen concentrations at Lake Maumelle for all sites to measured dissolved oxygen concentrations, date, and depth below water surface, February 6 through October 20, 1992.

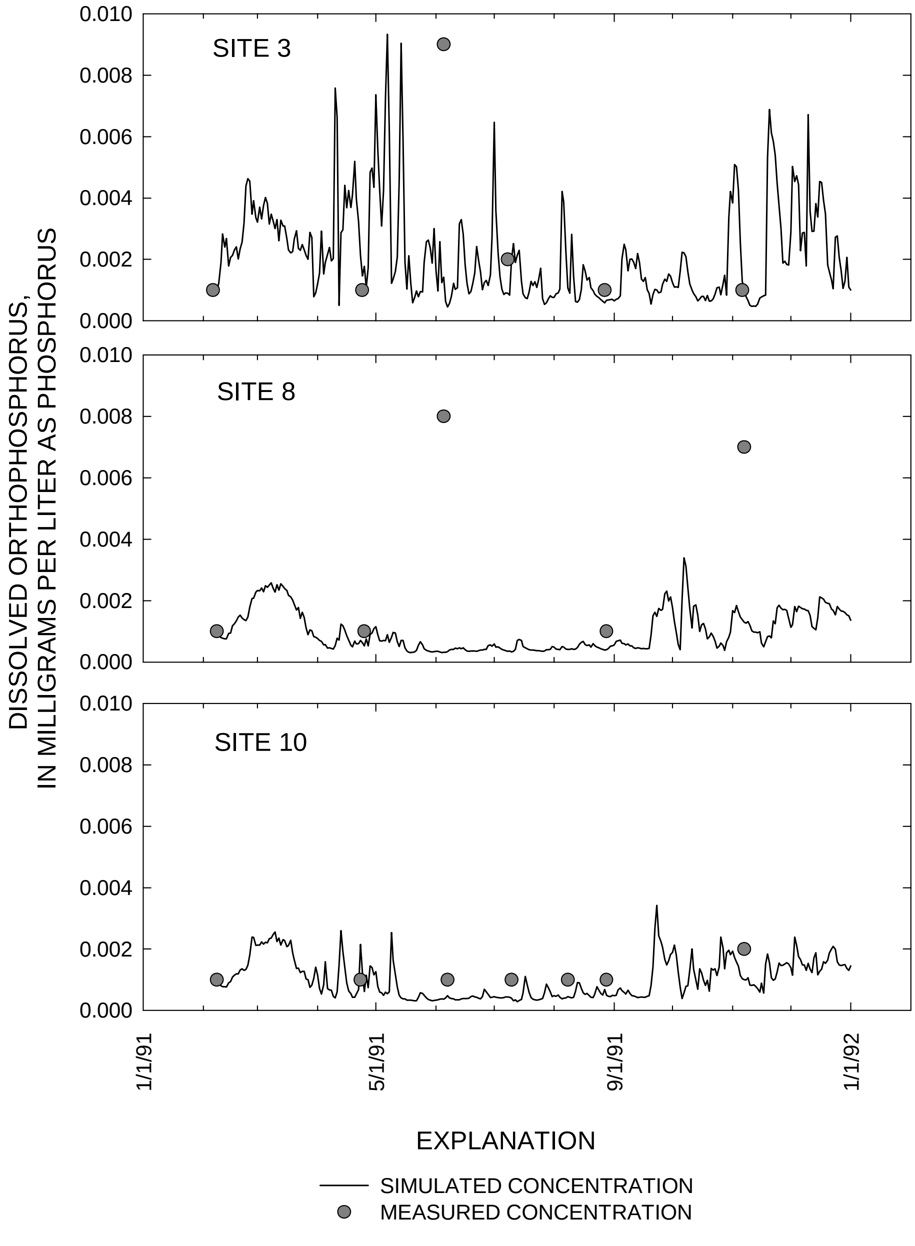


Figure 27. Measured and simulated phosphorus concentrations (PO_4 as P) at Lake Maumelle sites 3, 8, and 10, February through December 1991. Simulated values are the mean of top 3 meters in the model grid.

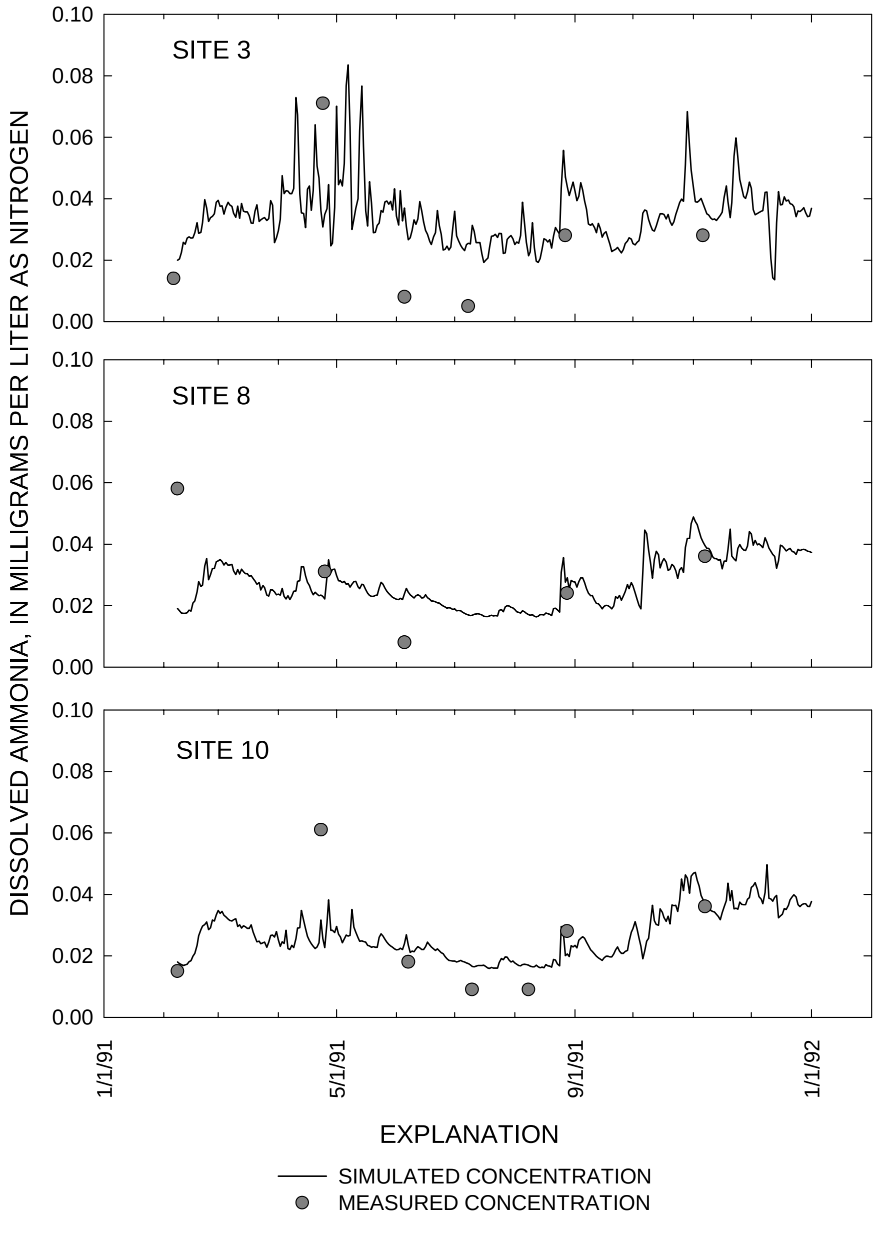


Figure 28. Measured and simulated ammonia concentrations (NH_4 as N) at Lake Maumelle sites 3, 8, and 10, February through December 1991. Simulated values are the mean of top 3 meters in the model grid.

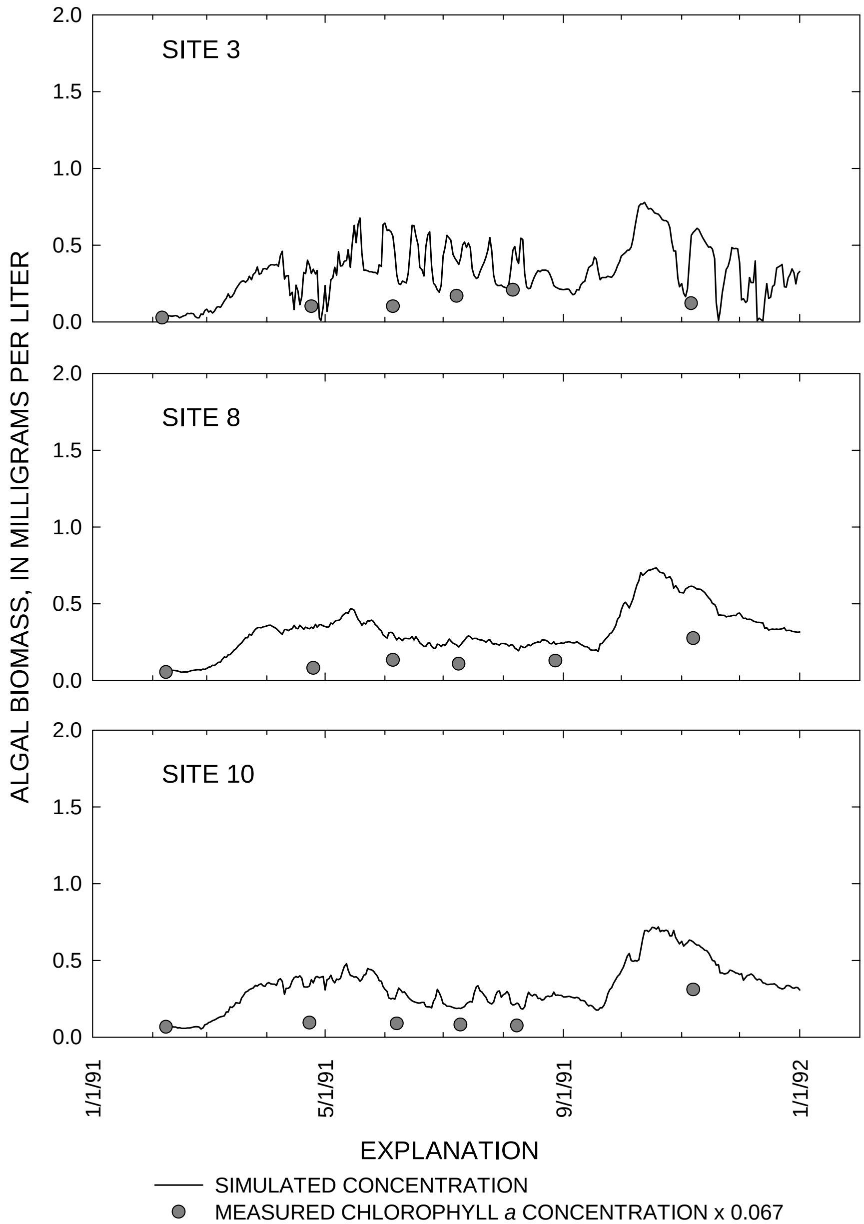
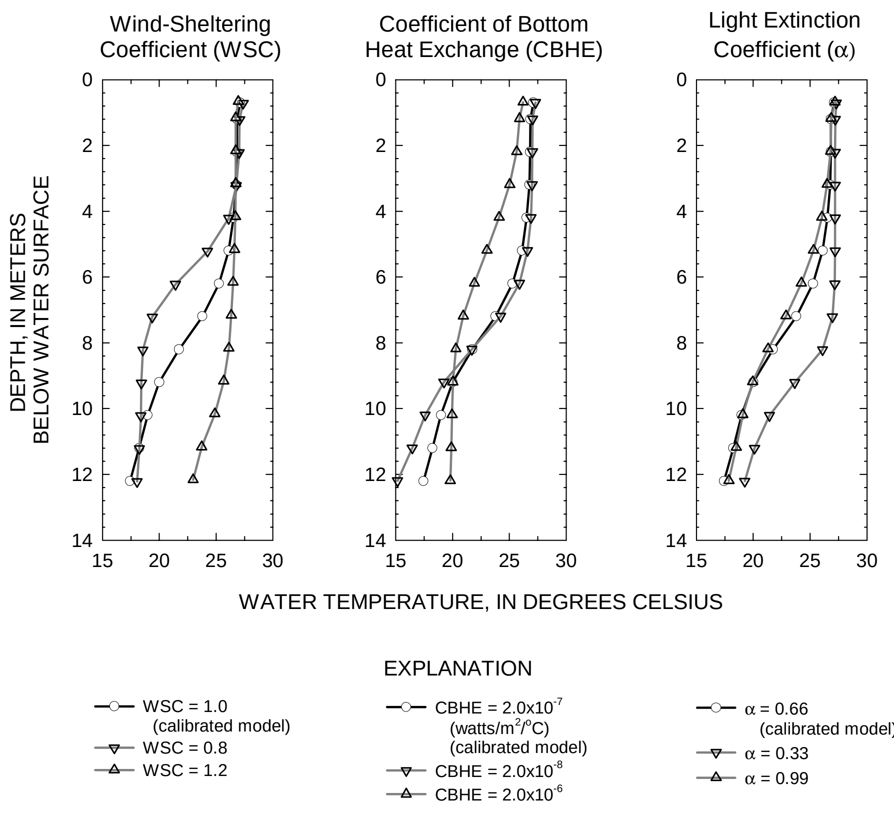


Figure 29. Measured and simulated algal biomass at Lake Maumelle sites 3, 8, and 10, February through December 1991. Simulated values are the mean of top 3 meters in the model grid.

However, many hydrodynamic and water-quality simulations were conducted as a component of model calibration. Results from these simulations form the basis for the sensitivity analysis.

Of the hydraulic parameters (table 3), simulated temperatures were most sensitive to changes in the wind-sheltering coefficient (WSC), and the coefficient of bottom heat exchange (CBHE) (fig. 30). Wind speed was not adjusted (WSC = 1.0) in the calibrated Lake Maumelle model. Vertical mixing was overpredicted when WSC was increased (>1.0) and underpredicted when WSC was decreased (<1.0). Wind speed appears to be a major factor affecting the development, duration, and vertical location of the thermocline in Lake Maumelle. The CBHE was the primary determinant of thermal condition in the lower depths of the reservoir (fig. 30). Water in lower depths did not heat as rapidly, from winter to summer, in model simulations when CBHE values were less than the calibrated value (2.0×10^{-7} watts/m^2/°C). In addition, temperatures in lower depths did not reach measured temperatures when CBHE values were lower than the calibrated values. When CBHE values were greater than the calibrated value, temperatures in lower depths tended to mimic measured values, but temperatures through and above the thermocline were reduced.



igure 30. Vertical temperature distributions at site 10 on August 27, 1991, showing calibrated model profiles and profiles s a result of differing wind sheltering, bottom heat exchange, and light extinction coefficients.

The light extinction coefficient (α) also affected position of the thermocline and temperatures above and below the thermocline (fig. 30). When α was less than the calibrated value (α = 0.66), the thermocline was lowered, extending the depth of the epilimnion. When α was greater than the calibrated value, temperatures in the epilimnion were reduced, reducing the depth of the epilimnion.

Simulated DO appeared to be most sensitive to changes in sediment oxygen demand and thermal patterns (fig. 31). Sediment oxygen demand (SOD) in the Lake Maumelle model was set at 0.7 $g/m^2/d$ for all segments. SOD above 0.7 $g/m^2/d$ tended to underpredict DO concentrations in the lower depths during early stages of stratification. SOD lower than 0.7 $g/m^2/d$ overpredicted DO concentrations in the hypolimnion during the peak of the stratification season. Changes in the wind-sheltering coefficient, which affected thermal patterns, also affected DO concentration. Lower and higher WSC values than the 1.0 calibration value tended to affect DO concentrations in the thermocline and immediately above and below the thermocline. DO concentrations were underpredicted when WSC values were reduced (increased wind sheltering) in the thermocline. DO concentrations were overpredicted in the thermocline and upper levels of the hypolimnion when WSC values were increased.

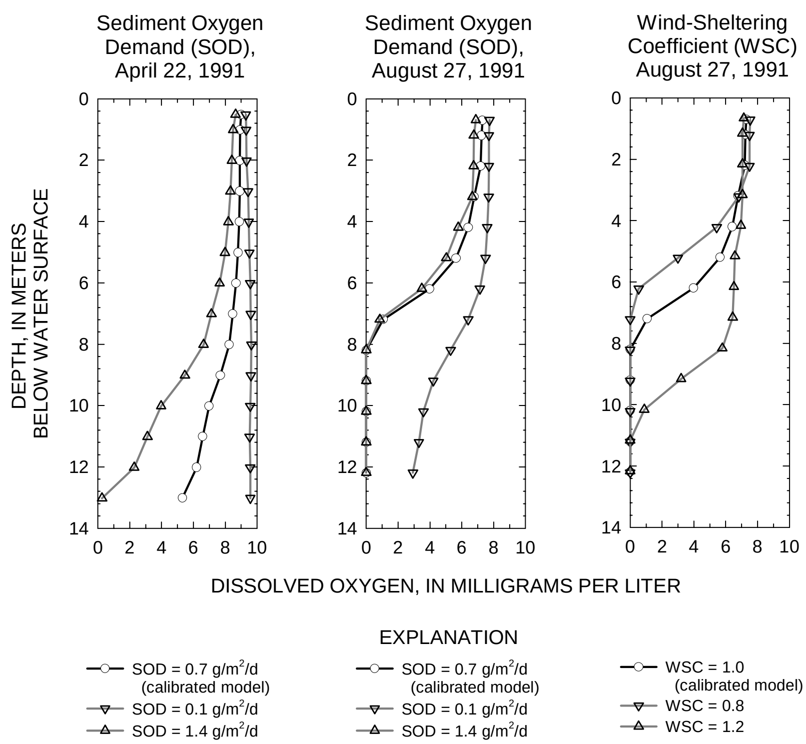


Figure 31. Vertical dissolved oxygen distributions at site 10 on April 22 and August 27, 1991, showing calibrated model profiles and profiles as a result of differing sediment oxygen demand and wind-sheltering coefficients.

Model parameters affecting chemical and algal kinetics are summarized in table 4. Cole and Buchak (1995) suggested reasonable values, and in some cases a range of values, for each parameter. Initial Lake Maumelle model simulations were made using the values suggested by Cole and Buchak (1995).

Algal concentrations were most sensitive to the algal growth rate and were sensitive to mortality and settling rates. Algal growth during the cooler seasons also was sensitive to light saturation, light intensity, and algal temperature-rate multipliers. Algal growth also was affected by algal half saturation constants for phosphorus and ammonia. The algal half saturation constants affected nutrient uptake, and therefore, nutrient concentrations. Also, phosphorus and nitrogen concentrations were sensitive to release rates from bottom sediments. According to model simulations, algal growth in Lake Maumelle was limited by phosphorus concentrations and light at lower depths.

Model Applications

The calibrated Lake Maumelle model was used to run various water-resource management scenarios. Simulations were developed to evaluate the movement of water, conservative material (a hypothetical spill), nitrogen, and phosphorus; algal response from a nursery pond release on a lateral tributary of Lake Maumelle; and simulations also were developed to assess the effects of increasing nitrogen and phosphorus load on algal production in Lake Maumelle.

Simulation of Conservative Material Transport

To assess material transport from a hypothetical spill at the western end of Lake Maumelle, where Highway 10 crosses the reservoir, the following simulation was applied. Initial concentration of conservative material (no decay or production) in the reservoir was set at 0.1 mg/L. On April 26, 1991, a major storm event occurred (fig. 32). At 6:30 a.m. on this day, 19 m^3 of liquid (equivalent to a 5,000-gallon tanker truck) containing 1,000 kg of conservative material was introduced into the upper boundary of the reservoir model over a 14.4-minute (0.01 day) period. Figure 33 shows the simulated transport of this material in terms of

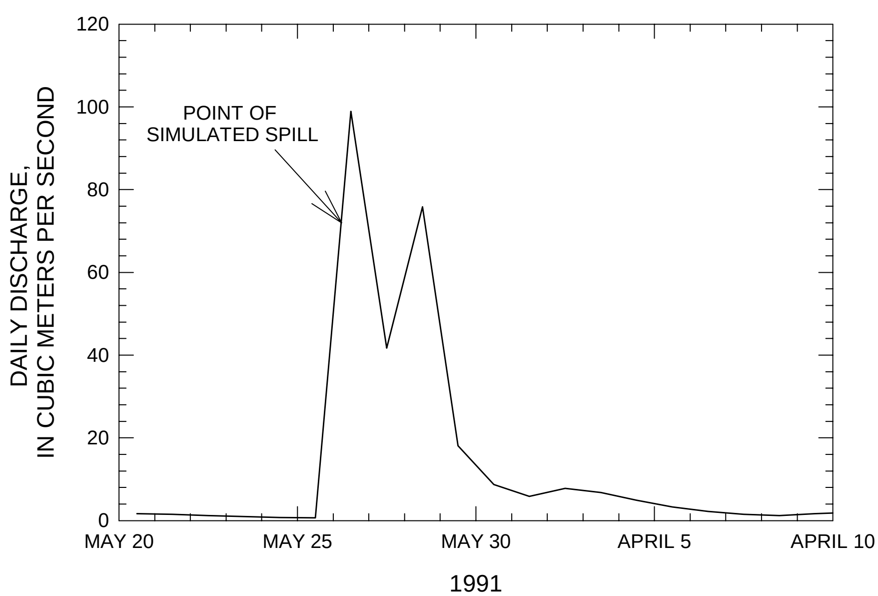


Figure 32. Daily discharges into Lake Maumelle from April 20 through May 10, 1991, showing location on the hydrograph where spill was simulated.

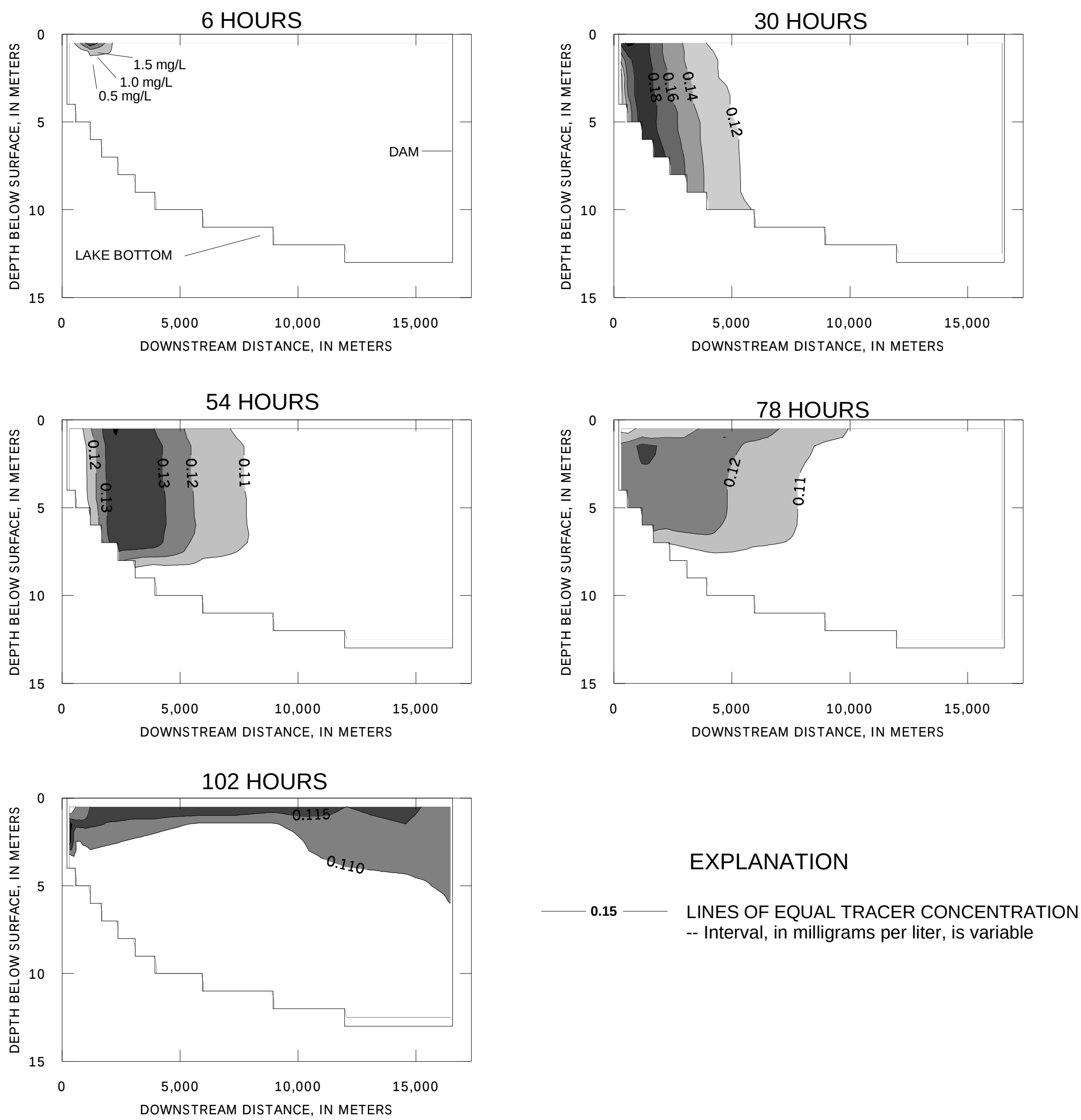


Figure 33. Simulated concentrations of a conservative material introduced at the upstream boundary at 6:00 a.m. on April 26, 1991.

downstream distance and depth through time. Six hours after the simulated spill, a small plume of concentrated material had been displaced downstream from the upstream boundary. By noon on April 27 (30 hours), the front of conservative material had reached 5,000 to 6,000 m downstream. There was very little variability in concentration with depth at this time but some difference in concentration with distance was indicated. By noon on April 28 (54 hours), the front of conservative material had reached 8,000 m downstream. Concentrations varied with depth below about 7 m; concentrations were higher in water less than 7 m deep. By noon on April 29 (78 hours), the front of conservative material had reached about 10,000 m at the surface. Downstream movement of material appeared to be limited to water less than 7 m deep. By noon on April 30, (102 hours after loading), conservative material at concentrations above pre-spill concentrations (0.10 mg/L) had reached the downstream boundary.

Simulation of Nursery Pond Release

The Arkansas Game and Fish Commission manages a fish nursery pond on a lateral tributary that enters Lake Maumelle (fig. 2). The entire contents of this pond are discharged into Lake Maumelle every summer or fall. Nursery pond releases were not simulated in the calibration of the Lake Maumelle model. Green (1998) assessed the water-quality impacts of the nursery pond release from 1991 through 1996. A modeling application was prepared to simulate a typical nursery pond release to further assess impacts in Lake Maumelle.

The nursery pond, in general, took about 3 days to drain its entire contents into Lake Maumelle (Green, 1998) depending on volume (stage) of the pond at the time of release and size of the gate opening (fig. 34). The location of the release structure in the pond was at the bottom, about 14 meters below the normal surface elevation. The cold, anoxic, bottom water is the first to be released from the nursery pond. This cold water enters the receiving embayment and plunges under the less dense embayment water (fig. 35). After the cold water is removed from the pond, warmer water is released and mixes with the embayment water before entering the main part of Lake Maumelle.

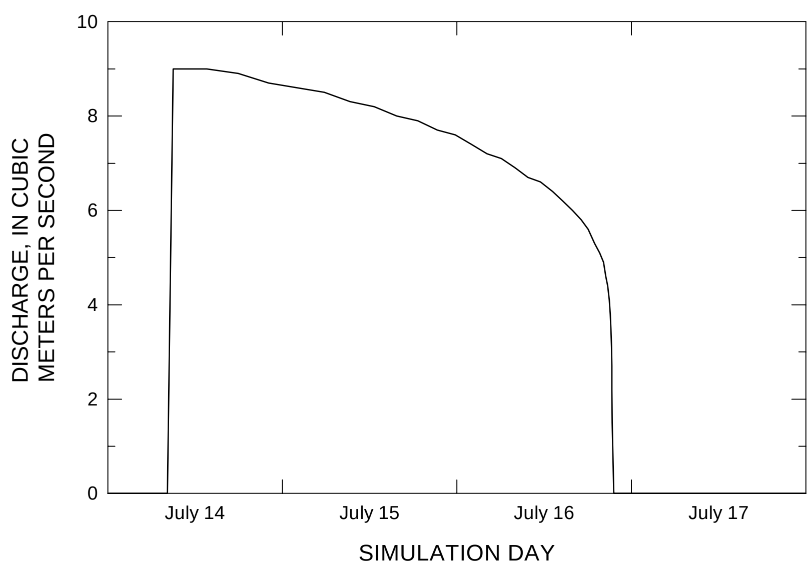


Figure 34. Discharge from the nursery pond into Lake Maumelle.

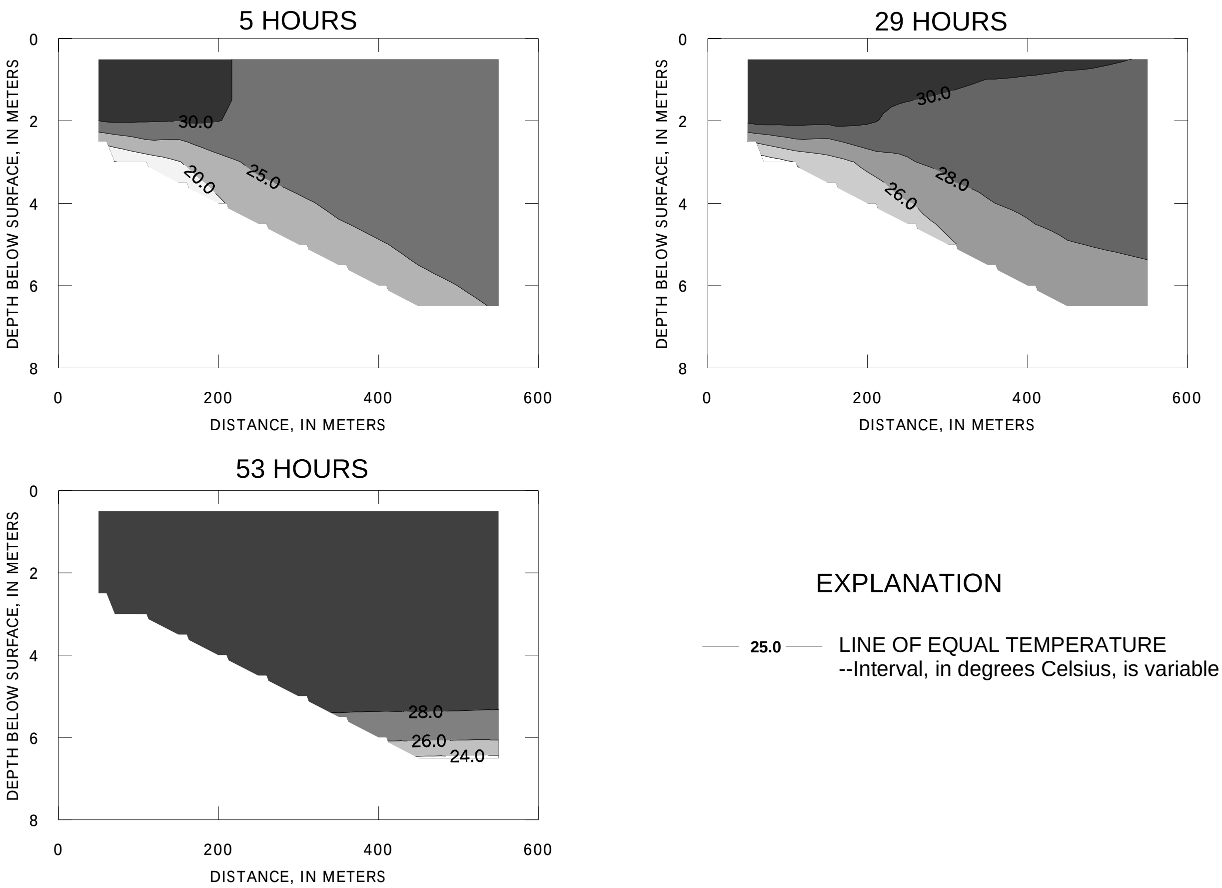


Figure 35. Simulated temperatures in the receiving embayment of the nursery pond release.

To understand transport of the release water from the nursery pond, a simulation was developed by adding a branch to the calibrated model to represent the receiving embayment. A conservative tracer (100 mg/L) was added to the nursery pond water and released into the receiving embayment branch. This tracer material was tracked through the embayment and into the main part of Lake Maumelle (fig. 36). The tracer entered the main part of Lake Maumelle at the level of the bottom of the embayment (7 m) (fig. 37). After the first day, the tracer plume in Lake Maumelle moved both upstream and downstream from the point of entry, but stayed in the middle depth layers. The tracer continued to dissipate and 2 weeks later concentrations of tracer were present in about one-half the water contained in Lake Maumelle.

Simulated nutrient concentrations tended to mimic the tracer results, although nutrient persistence was reduced because of uptake and transformation. Algal growth did not appear to differ as a result of the simulated nursery pond release 2 weeks following the release. This is presumably because of the plunging of the initial plume that contained the greatest concentrations of nutrients. This nutrient load was not delivered into the upper layers of the lake where algal production is greatest.

Simulation of Nutrient Enrichment

To obtain a general understanding of the relation between algal growth and nutrient enrichment, an application was developed wherein nitrogen as ammonia and phosphorus as phosphate loads in the main tributary were increased by a factor of 10, separately and together. Algal production was only sensitive to increases in phosphorus load (fig. 38). Increase in ammonia load did not increase algal production. Increasing both phosphorus and ammonia by a factor of 10 provided almost the same algal response as 10 times phosphorus alone. Results indicate that increases in phosphorus load will allow increasing algal production.

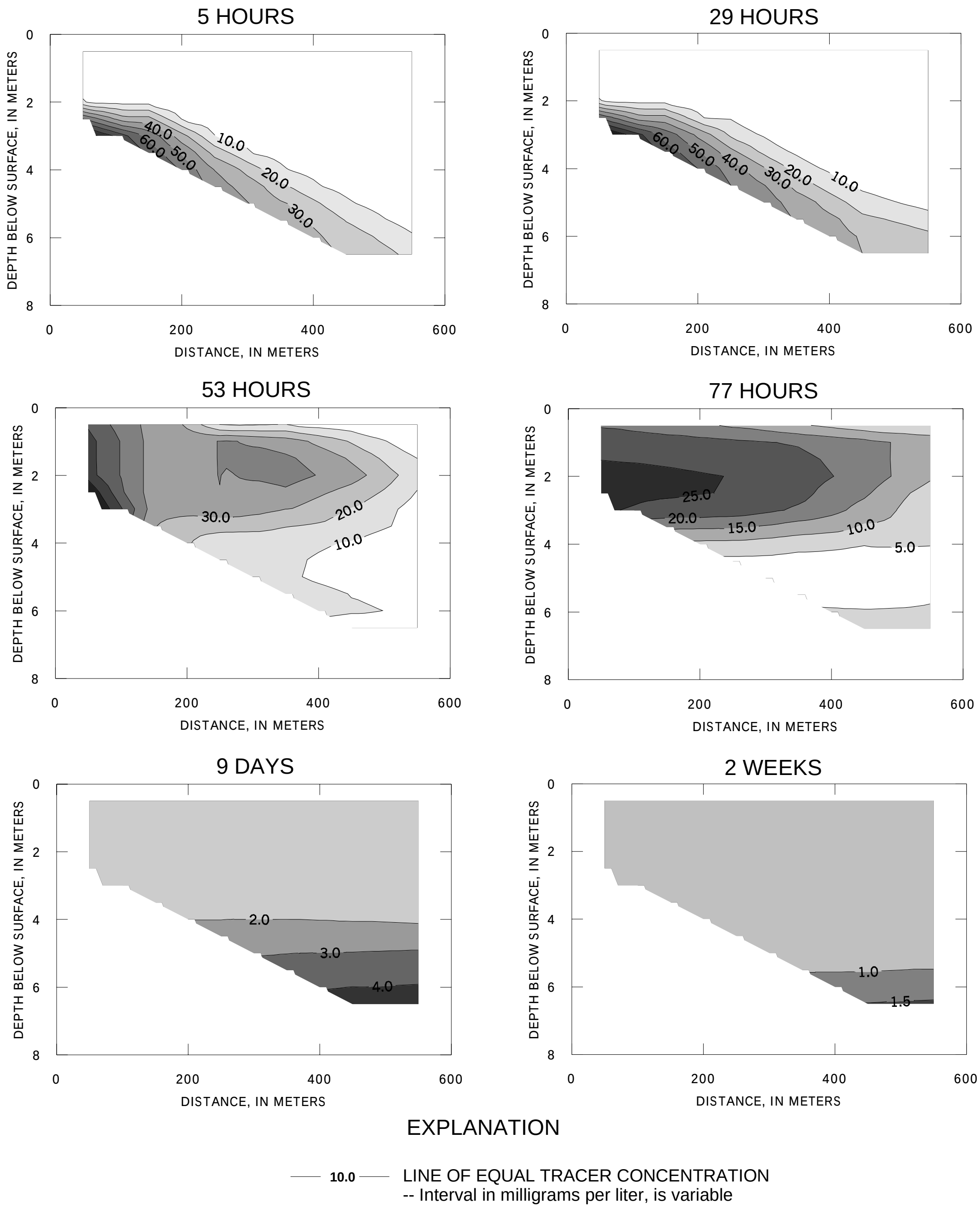


Figure 36. Distance and depth plots of simulated tracer concentrations in the receiving embayment after release of the nursery pond.

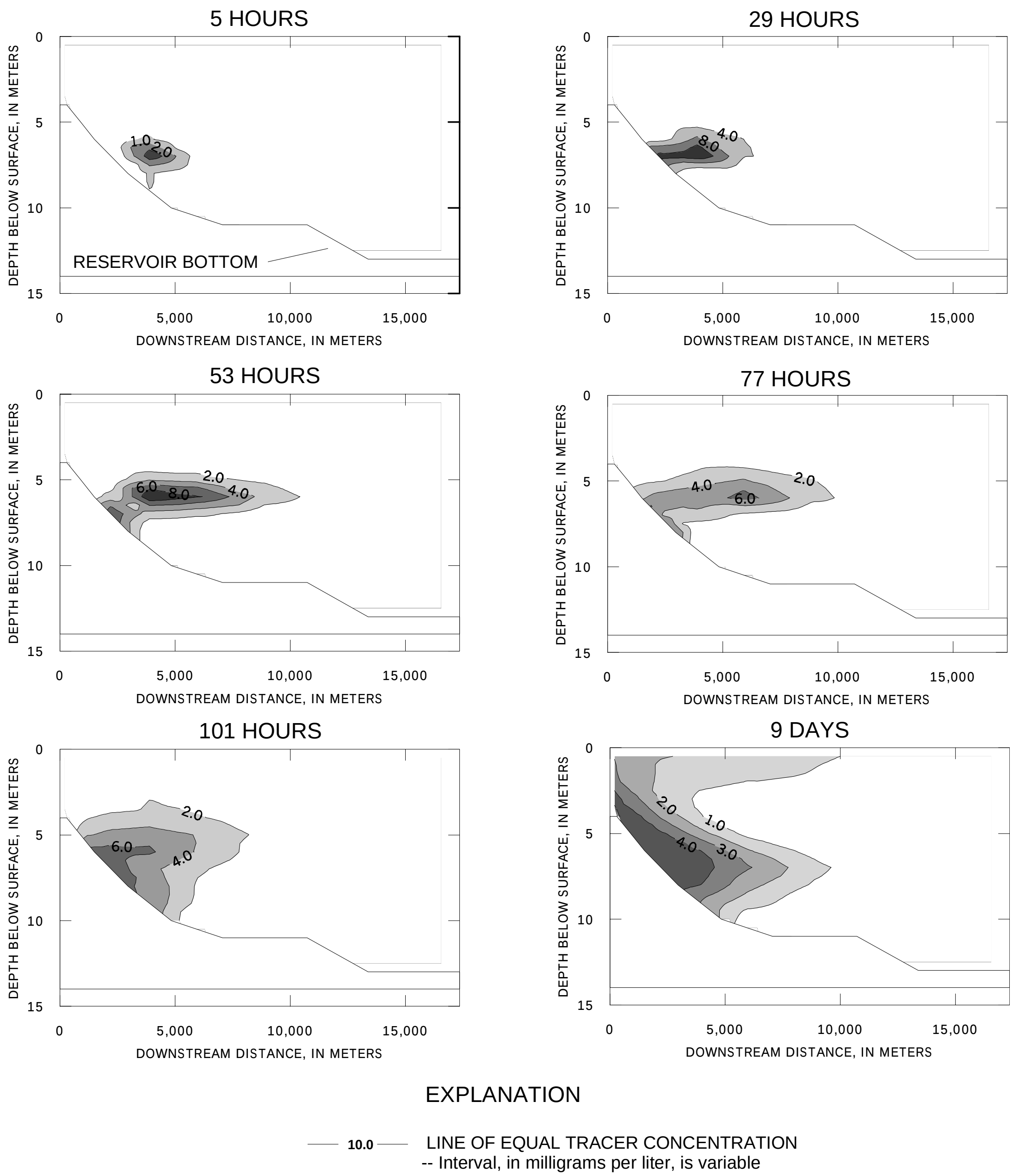


Figure 37. Distance and depth plots of simulated conservative tracer released from the nursery pond into Lake Maumelle.

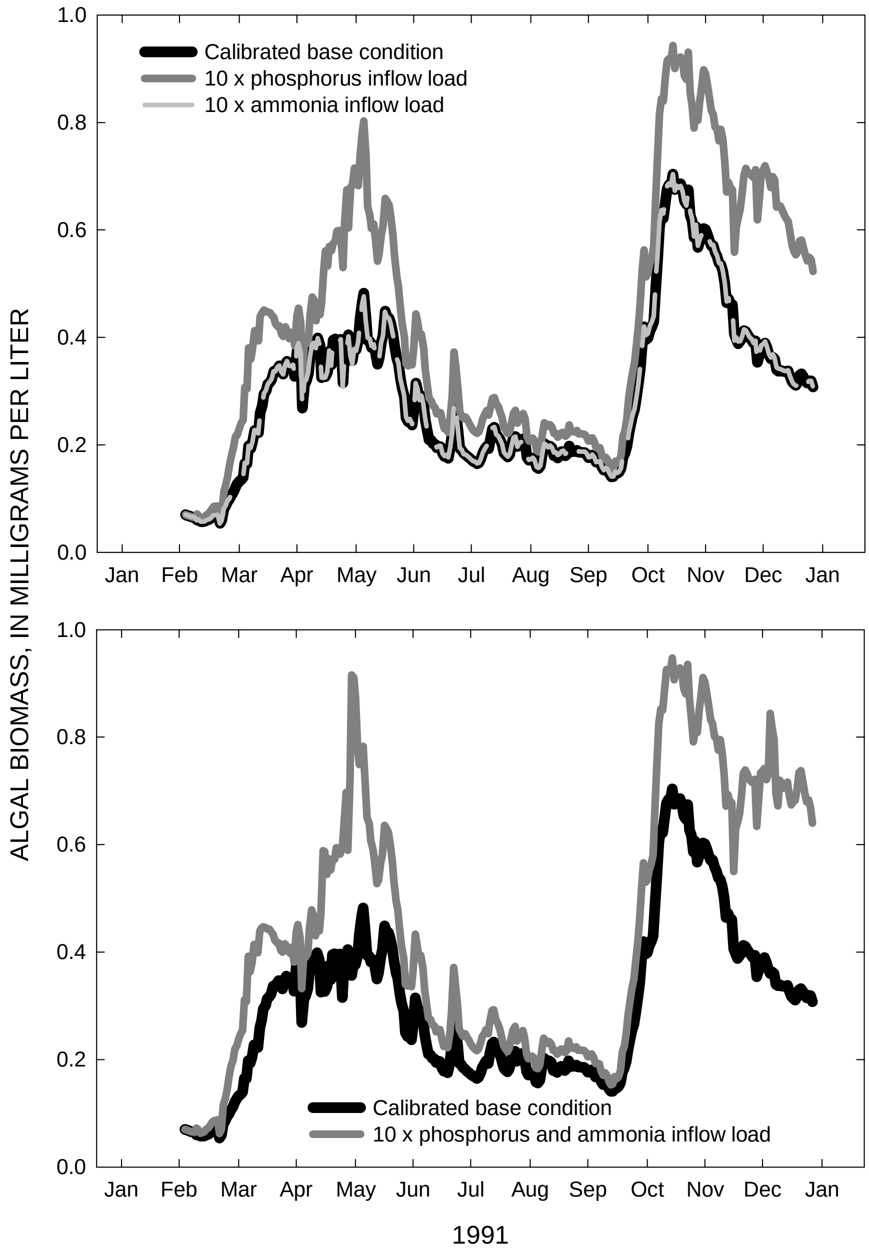


Figure 38. Time series of algal biomass resulting from various nutrient enrichment scenarios at segment 10, layer 4, at the downstream end of Lake Maumelle.

SUMMARY

Lake Maumelle is the major drinking-water source for the Little Rock metropolitan area in central Arkansas. Urban and agricultural development has increased in the Lake Maumelle Basin and so have concerns about the sustainability and quality of this resource. Information is needed concerning constituent transport and water-quality response to changes in constituent loading or hydrologic regime. The purpose of this report was to (1) characterize ambient conditions in Lake Maumelle and its major tributary, Maumelle River; (2) calibrate a numerical model of hydrodynamics and water quality; and (3) run several model simulations to describe constituent transport and water-quality response to changes in constituent loading and hydrologic regime.

Ambient hydrologic and water-quality conditions demonstrate the relatively undisturbed nature of Lake Maumelle and the Maumelle River. Nitrogen and phosphorus concentrations are low, one to two orders of magnitude lower than estimates of national background nutrient concentrations. Phosphorus and chlorophyll *a* concentrations in Lake Maumelle demonstrate its oligotrophic/mesotrophic condition. However, concentrations of chlorophyll *a* appear to be increasing since 1990 within the upper and middle reaches of the reservoir.

A two-dimensional, laterally averaged hydrodynamic and water-quality model (CE-QUAL-W2) was constructed, calibrated, and verified for Lake Maumelle. The model simulates water level, currents, heat transport and temperature distribution, conservative material transport, and the transport and transformation of 11 chemical constituents. Objectives were to develop the capability to simulate the movement and dispersion of spills or releases in the reservoir during stratified and unstratified conditions, simulate and track the release of the fish nursery pond off the southern shore of Lake Maumelle, and simulate water-quality response to possible changes in external loads. The model was calibrated using 1991 data and verified using 1992 data. Simulated temperature and DO concentrations related well when compared to measured values. Simulated nutrient and algal biomass also related reasonably well when compared to measured values. Although, it would be recommended that chlorophyll *a* to biomass ratios be determined in the modeled system to get a better calibration.

A simulated spill of conservative material at the upper end of Lake Maumelle during a major storm event took less than 102 hours (4.25 days) to disperse the entire length of the reservoir. Simulation of the nursery pond release demonstrated how the released water plunges within the receiving embayment and enters the mainstem of the reservoir at mid depths. Simulations of algal response to increases of nitrogen and phosphorus loads by a factor of 10, demonstrate the phosphorus limiting condition in Lake Maumelle. Increasing nitrogen load without increasing phosphorus resulted in no change in algal biomass from the calibrated or base condition. Increasing phosphorus load resulted in an increase in algal biomass. The algal biomass resulting from the increases in both phosphorus and nitrogen was very similar to the biomass resulting from an increase of phosphorus only.

Results from this study will aid in the protection and management of the Lake Maumelle drinking-water resource. Management can use the existing simulations and others to evaluate how changes in hydrology and water quality in the basin may affect water quality in the reservoir. With this information, water resources management can more effectively manage their source supply.

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