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Simulation of Hydrodynamics and Water Quality in Pueblo Reservoir, Southeastern Colorado, for 1985 through 1987 and 1999 through 2002

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U.S. Department of the Interior
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By Joel M. Galloway, Roderick F. Ortiz, Jerad D. Bales, and David P. Mau

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Conversion Factors

Multiply	By	To obtain
Length		
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Area		
acre	4,047	square meter (m^2)
acre	0.004047	square kilometer (km^2)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
Volume		
cubic foot (ft^3)	0.02832	cubic meter (m^3)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
Flow rate		
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
Mass		
pound, avoirdupois (lb)	0.4536	kilogram (kg)
ounce, avoirdupois (oz)	28.35	gram (g)

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

$$°F=(1.8×°C)+32$$

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Water year is defined as beginning October 1 and ending September 30.

Abbreviations and acronyms used in this report:

ADAPS	Automated Data Processing System
AME	absolute mean error
AMLE	adjusted maximum likelihood estimator
BOR	Bureau of Reclamation
EIS	Environmental Impact Statement
GIS	Geographic Information System
LAD	least absolute deviation
NEPA	National Environmental Policy Act of 1969
SDS	Southern Delivery System
SC	specific conductance
TDS	total-dissolved solids
USACE	U.S. Army Corps of Engineers
RMSE	root mean square error
USGS	U.S. Geological Survey
WY	water year

Simulation of Hydrodynamics and Water Quality in Pueblo Reservoir, Southeastern Colorado, for 1985 through 1987 and 1999 through 2002

By Joel M. Galloway, Roderick F. Ortiz, Jerad D. Bales, and David P. Mau

Abstract

Pueblo Reservoir is west of Pueblo, Colorado, and is an important water resource for southeastern Colorado. The reservoir provides irrigation, municipal, and industrial water to various entities throughout the region. In anticipation of increased population growth, the cities of Colorado Springs, Fountain, Security, and Pueblo West have proposed building a pipeline that would be capable of conveying 78 million gallons of raw water per day (240 acre-feet) from Pueblo Reservoir. The U.S. Geological Survey, in cooperation with Colorado Springs Utilities and the Bureau of Reclamation, developed, calibrated, and verified a hydrodynamic and water-quality model of Pueblo Reservoir to describe the hydrologic, chemical, and biological processes in Pueblo Reservoir that can be used to assess environmental effects in the reservoir.

Hydrodynamics and water-quality characteristics in Pueblo Reservoir were simulated using a laterally averaged, two-dimensional model that was calibrated using data collected from October 1985 through September 1987. The Pueblo Reservoir model was calibrated based on vertical profiles of water temperature and dissolved-oxygen concentration, and water-quality constituent concentrations collected in the epilimnion and hypolimnion at four sites in the reservoir. The calibrated model was verified with data from October 1999 through September 2002, which included a relatively wet year (water year 2000), an average year (water year 2001), and a dry year (water year 2002).

Simulated water temperatures compared well to measured water temperatures in Pueblo Reservoir from October 1985 through September 1987. Spatially, simulated water temperatures compared better to measured water temperatures in the downstream part of the reservoir than in the upstream part of the reservoir. Differences between simulated and measured water temperatures also varied through time. Simulated water temperatures were slightly less than measured water temperatures from March to May 1986 and 1987, and slightly greater than measured data in August and September 1987. Relative to the calibration period, simulated water temperatures during the verification period did not compare as well to measured water temperatures.

In general, simulated dissolved-oxygen concentrations for the calibration period compared well to measured concentrations in Pueblo Reservoir. Spatially, simulated concentrations deviated more from the measured values at the downstream part of the reservoir than at other locations in the reservoir. Overall, the absolute mean error ranged from 1.05 (site 1B) to 1.42 milligrams per liter (site 7B), and the root mean square error ranged from 1.12 (site 1B) to 1.67 milligrams per liter (site 7B). Simulated dissolved oxygen in the verification period compared better to the measured concentrations than in the calibration period. The absolute mean error ranged from 0.91 (site 5C) to 1.28 milligrams per liter (site 7B), and the root mean square error ranged from 1.03 (site 5C) to 1.46 milligrams per liter (site 7B).

Simulated total dissolved solids generally were less than measured total dissolved-solids concentrations in Pueblo Reservoir from October 1985 through September 1987. The largest differences between simulated and measured total dissolved solids were observed at the most downstream sites in Pueblo Reservoir during the second year of the calibration period. Total dissolved-solids data were not available from reservoir sites during the verification period, so in-reservoir specific-conductance data were compared to simulated total dissolved solids. Simulated total dissolved solids followed the same patterns through time as the measured specific conductance data during the verification period.

Simulated total nitrogen concentrations compared relatively well to measured concentrations in the Pueblo Reservoir model. The absolute mean error ranged from 0.21 (site 1B) to 0.27 milligram per liter as nitrogen (sites 3B and 7B) and the root mean square error ranged from 0.21 (site 1B) to 0.29 milligram per liter as nitrogen (sites 3B and 7B). The Pueblo Reservoir model generally simulated lower concentrations of nitrate and ammonia compared to measured concentrations from October 1985 through September 1987. Simulated ammonia compared better to measured concentrations during the verification period than during the calibration period, and simulated nitrate did not compare as well to measured concentrations as in the calibration period.

Simulated orthophosphorus concentrations in the Pueblo Reservoir model were similar to the measured concentrations

for the calibration period. The absolute mean error for orthophosphorus ranged from 0.01 (sites 3B and 5C) to 0.02 milligram per liter (sites 1B and 7B) as phosphorus, and the root mean square error ranged from 0.01 (sites 3B and 5C) to 0.02 milligram per liter (sites 1B and 7B) as phosphorus. The absolute mean error for total phosphorus ranged from 0.02 (sites 5C and 7B) to 0.05 milligram per liter (site 1B) as phosphorus, and the root mean square error ranged from 0.02 (sites 5C and 7B) to 0.05 milligram per liter (sites 1B and 3B) as phosphorus. The greatest difference between simulated and measured values occurred in the hypolimnion at sites 1B and 3B in May through July 1987, where simulated concentrations were considerably less than the measured concentrations. Simulated orthophosphorus and total phosphorus compared better to measured concentrations during the verification period than in the calibration period.

The simulated distribution of algal populations was highly variable in Pueblo Reservoir during the calibration period. The highest algal biomass in Pueblo Reservoir generally occurred from May through September when blue-green and green algae were the dominant algal groups in the reservoir. The lowest algal biomass generally occurred from November through March when diatoms and flagellates were the dominant groups. The distribution of algae in Pueblo Reservoir during the verification period differed slightly from what was observed during the calibration period where diatoms and flagellates were the dominant algal groups in the upstream part of Pueblo Reservoir, and green and blue-green algae were the dominant groups in the downstream part of the reservoir.

Simulated chlorophyll *a* concentrations were similar to measured concentrations in Pueblo Reservoir during the calibration period. The highest chlorophyll *a* concentrations occurred at the two upstream reservoir sites, where the absolute mean error ranged from 3.0 (site 1B) to 3.7 micrograms per liter (site 3B), and the root mean square error ranged from 5.3 (site 1B) to 6.8 micrograms per liter (site 3B). Chlorophyll *a* concentrations generally were lower in the downstream part of the reservoir (sites 5C and 7B) where nutrients were less available for algal growth. The absolute mean error ranged from 1.6 (site 7B) to 2.2 micrograms per liter (site 5C), and the root mean square error ranged from 2.5 (site 7B) to 3.7 micrograms per liter (site 5C). Simulated chlorophyll *a* concentrations generally were less than the measured concentrations during the verification period.

Introduction

Pueblo Reservoir, located west of the city of Pueblo, Colorado, is an important resource to southeastern Colorado (fig. 1). The reservoir is a municipal and industrial water supply for the cities of Pueblo, Pueblo West, and St. Charles Mesa and is a supplemental water supply for Colorado Springs, Stratmoor Hills, Security, Widefield, and Fountain,

located north of the reservoir (Lewis and Edelmann, 1994). In addition, Pueblo Reservoir is used extensively for boating, fishing, and other recreational activities. Pueblo Reservoir also provides water to a warm-water and cold-water fish hatchery located immediately downstream from the dam.

Population growth in the area, particularly in the cities of Colorado Springs, Fountain, Security, and Pueblo West has prompted the need to develop a regional water-delivery project to meet all or most of the future (through 2046) water needs of these cities (fig. 1). The population of these cities has increased rapidly in the past 10 years and is expected to nearly double by the year 2040 (GEI Consultants Inc., 2000); more than 85 percent of the 430,000 residents live in Colorado Springs (U.S. Census Bureau, 2000). In anticipation of this growth, the cities of Colorado Springs, Fountain, Security, and Pueblo West (hereafter referred to as "Participants") have proposed building a pipeline that would be capable of conveying 78 million gallons of raw water per day (240 acre-ft) from Pueblo Reservoir to the Participants. The project, known as the Southern Delivery System (SDS), would divert untreated water from the municipal outlet at the Pueblo Reservoir dam and deliver it to the Participants (Bureau of Reclamation, 2007). The main purpose of the SDS is to provide a sustainable water supply to meet projected future demands through 2046 and to provide additional water storage, delivery, and treatment capacity for the existing water-delivery system. The most substantial aspect of the project would be the delivery of water 43 mi north to Colorado Springs through a 66-inch diameter pipeline. Return flows would be stored in a new reservoir on Williams Creek prior to exchange down Fountain Creek to the Arkansas River downstream from Pueblo Reservoir (fig. 1).

The Bureau of Reclamation (BOR) owns and operates Pueblo Reservoir as part of the Fryingpan-Arkansas Project and, as such, is required by the National Environmental Policy Act of 1969 (NEPA) to integrate environmental values into their decision-making processes by considering the environmental effects of the proposed actions and reasonable alternatives to those actions. The USGS, in cooperation with Colorado Springs Utilities and the BOR, developed, calibrated, and verified a hydrodynamic and water-quality model of Pueblo Reservoir to describe the hydrologic, chemical, and biological processes in Pueblo Reservoir. Ortiz and others (2008) describe the application of the calibrated and verified model to evaluate the environmental effects of the proposed SDS and to assess various water-delivery alternatives to assess their effects on the hydrodynamics and water quality in Pueblo Reservoir.

Purpose and Scope

The purpose of this report is to describe the simulation of hydrodynamics and water-quality in Pueblo Reservoir that can provide a better understanding of processes affecting the hydrology and water quality in Pueblo Reservoir. Hydrodynamics and water-quality characteristics in Pueblo Reservoir were simulated using the U.S. Army Corps of Engineers
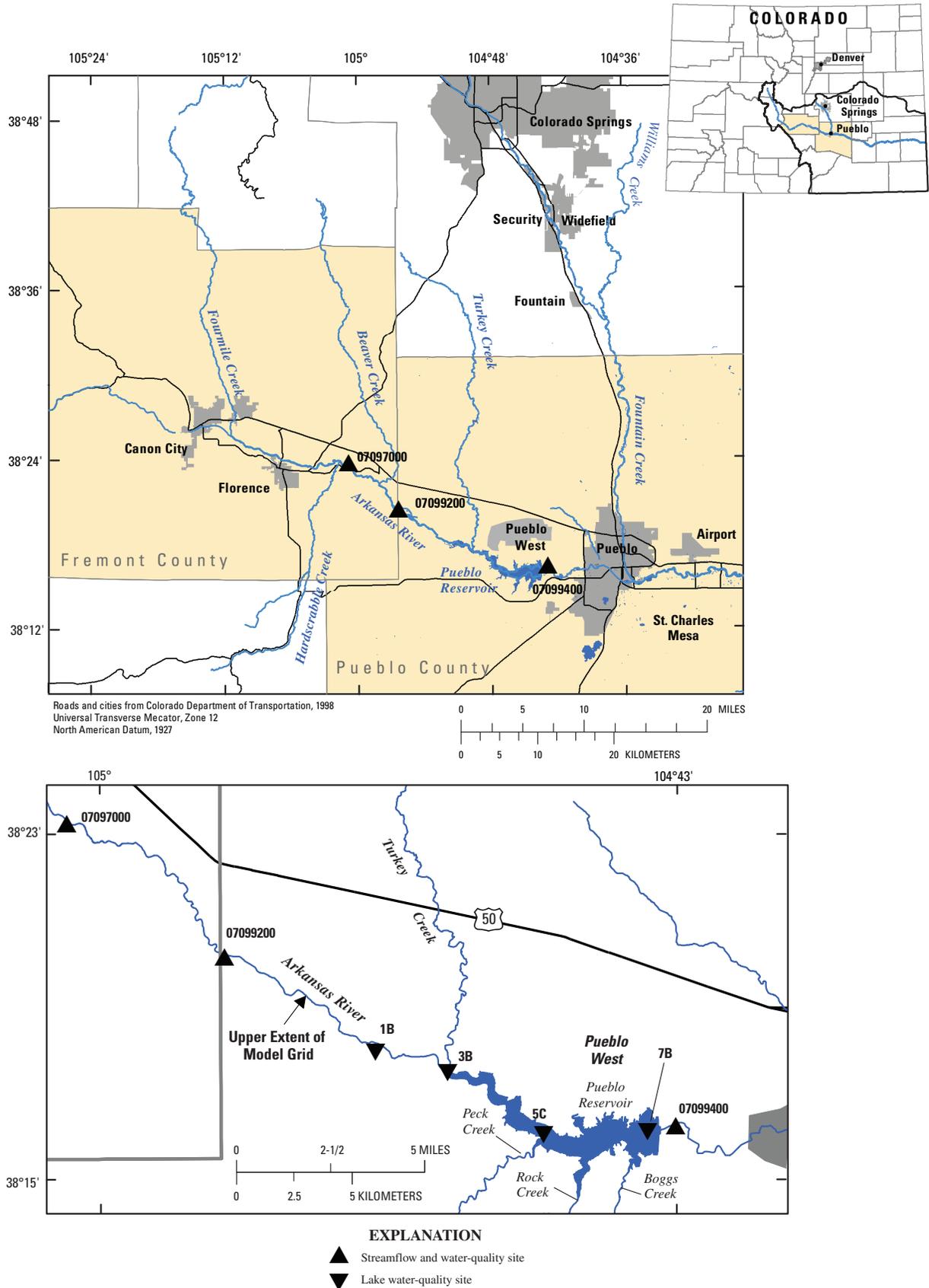
Figure 1.   Location of Pueblo Reservoir study area, Colorado, and associated data-collection sites.

(USACE) CE-QUAL-W2 modeling software, version 3.2 (Cole and Wells, 2003). The laterally averaged, two-dimensional model was calibrated using data collected from October 1985 through September 1987 (water years 1986 and 1987) when measured water-quality data were available in the reservoir. The calibrated model was verified with data from October 1999 through September 2002 (WY 2000, 2001, and 2002). This 3-year contiguous period included various hydrologic conditions that allowed for verification of the model during a relatively wet year (WY 2000), an average year (WY 2001), and a dry year (WY 2002).

Description of the Study Area

The study area for this report encompasses the body of Pueblo Reservoir and the Arkansas River upstream from the reservoir to Florence, Colorado (fig. 1). Climate in the Arkansas River drainage basin is affected greatly by differences in elevation. Mean annual precipitation ranges from more than 40 inches along the Continental Divide to less than 12 inches in the plains near Pueblo Reservoir (Crouch and others, 1984). Precipitation in the mountains results in the formation of a deep snowpack that accumulates during the winter months and melts and runs off during the spring and early summer. Storm runoff and snowmelt result in a large percentage of annual streamflow that occurs during a relatively short time (Abbott, 1985). From 1976 to 2005, the mean annual precipitation at Pueblo Reservoir (measured at Pueblo Memorial Airport) was 12.7 inches, where 75 percent of the precipitation occurred from March through August (Western Regional Climate Center, 2007). Much of the precipitation in the summer is from intense localized thunderstorms.

Pueblo Reservoir is approximately 6 mi west of Pueblo, Colorado, and is an important water resource for southeastern Colorado (fig. 1). The reservoir is the terminal storage feature for the Fryingpan-Arkansas Project and provides irrigation, municipal, and industrial water to various entities throughout the region. Specifically, water is released from Pueblo Reservoir to the Arkansas River for downstream irrigation and municipal use, to the Fountain Valley Conduit for municipal use by various entities, and to the Bessemer Ditch for irrigation use (Southeastern Colorado Water Conservancy District, 2006). Nonproject water is conveyed to Pueblo and Pueblo West through the municipal outlet works in Pueblo Dam. A fish hatchery immediately downstream from the reservoir relies on water from the reservoir to raise several cold- and warm-water species. The reservoir also provides flood control, recreational activities, sport fishing, and wildlife enhancement to the region.

The reservoir has a total storage capacity of 357,678 acre-ft (U.S. Bureau of Reclamation, 1977). The recreation pool consists of 30,355 acre-ft of dead and inactive capacity (the reservoir pool that would be left if all water was released from the lowest elevation outlet). The conservation pool is consists of 234,347 acre-ft of capacity used to regulate transmountain and native water for municipal, industrial, and irrigation uses. The joint-use pool (volume of water in the reservoir greater than the conservation pool) consists of 65,952 acre-ft of capacity that must be vacated from April 15 to November 1 of each year for flood control. An additional 27,024 acre-ft of capacity is reserved exclusively for flood-control and extends to the crest of the spillway at an altitude of 4,898.7 ft above NGVD 29. The crest of the dam is 26 ft above the crest of the spillway and would temporarily hold an additional 131,500 acre-ft of flood flows, if needed.

Pueblo Reservoir is dendritic at all pool altitudes and the shoreline is very irregular. At the minimum pool altitude of 4,797 ft above NGVD 29, the reservoir is about 3.5 mi long and ranges in width from a few hundred feet to about 1.3 mi (U.S. Bureau of Reclamation, 1972). During water years 1986 and 1987 (model calibration period), the reservoir was near the top of the conservation pool at an altitude of 4,880 ft above NGVD 29 and it had a length of more than 9 mi and a width that ranged from less than 0.3 to about 2.2 mi. At this pool altitude, reservoir depth was about 155 ft at the dam, and the reservoir shoreline extended for about 60 mi.

Inflow and outflow for Pueblo Reservoir varies annually and seasonally (fig. 2). Pueblo Reservoir derives almost all of its contents from streamflow in the Arkansas River which consisted of about 80 percent native flow and 20 percent transmountain flow (Edelmann, 1989). From water years 1986 through 2002 the mean annual streamflow at the Arkansas River at Portland (USGS station number 07097000) ranged from 264 to 1,387 cubic feet per second (ft^3/s), with a mean of 771 ft^3/s for the entire period. Most of the annual inflow to Pueblo Reservoir enters during May through July (fig. 2). In general, a volume of water comparable to the amount of annual inflow is released annually from the reservoir outlet (fig. 2). Water is released from the reservoir through the river outlets, the Bessemer Ditch outlet, the south outlets, and the fish hatchery outlet. The mean annual streamflow at the Arkansas River above Pueblo (USGS station number 07099400), downstream from Pueblo Reservoir, ranged from 174 to 1,131 ft^3/s, with a mean of 702 ft^3/s for water years 1986 through 2002. From 1985 through 1989, outflow from the river outlets represented 88.2 percent of the total outflow from the reservoir whereas the Bessemer Ditch and south outlets accounted for 11.3 and 0.5 percent, respectively (Lewis and Edelmann, 1994). Reservoir storage decreases substantially by the end of the growing season because of decreased inflow and large downstream demands for irrigation water. Water is stored in the reservoir from November 15 to March 15 of each year as part of the Winter-Water Storage Program. The program allows downstream irrigation-canal companies to store their direct-flow water in the reservoir for release in the spring or late summer when streamflow in the river may not be sufficient for irrigation needs (Lewis and Brendle, 1998).

The reservoir inundates four large canyons and several small canyons. The canyon walls are composed of sedimentary rocks. The Fort Hays Limestone Member of the Niobrara Formation of Cretaceous age lies at the top of the canyon
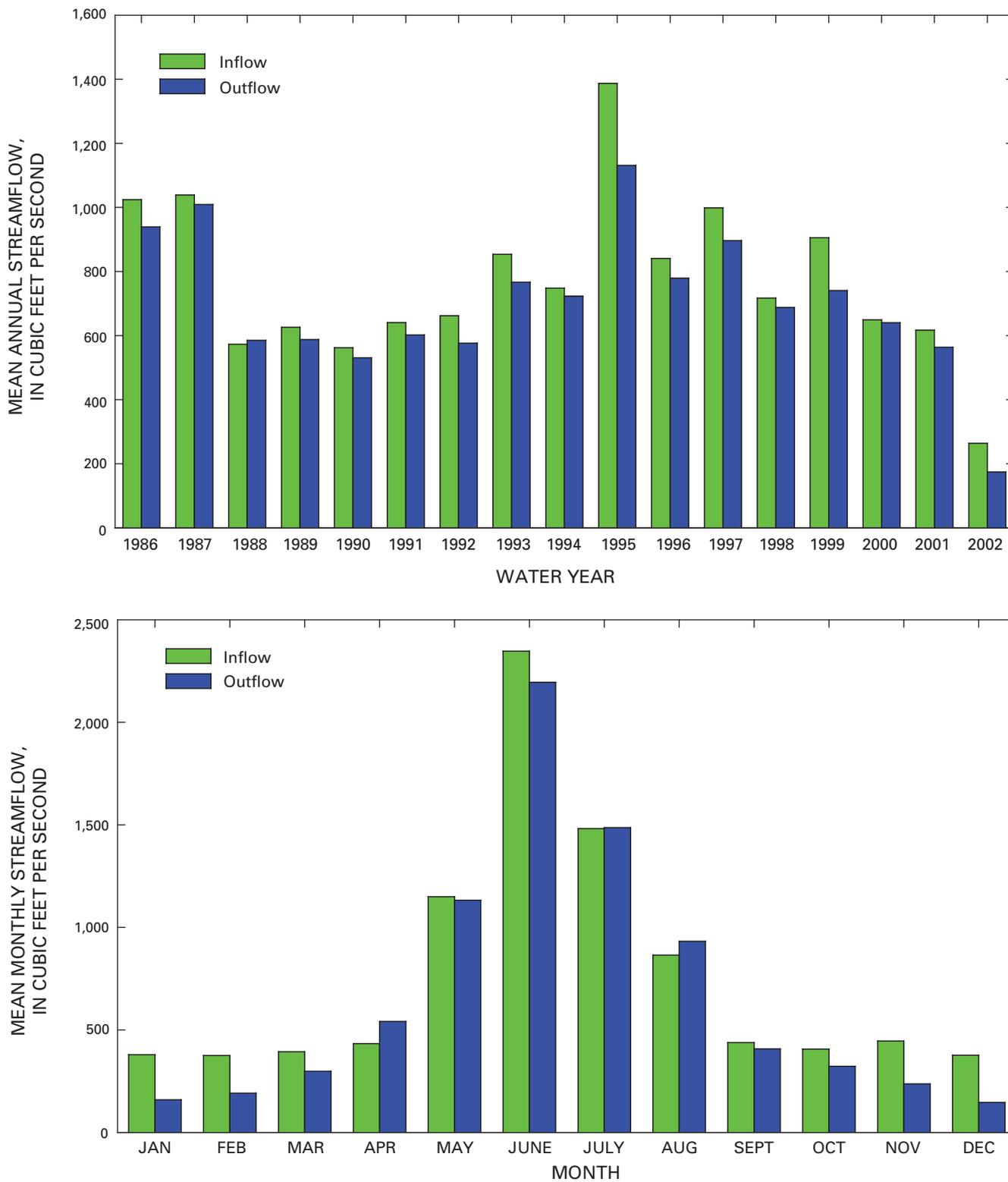
Figure 2. Mean annual and monthly streamflow for the Arkansas River at Portland, Colorado (07097000; inflow to Pueblo Reservoir), and for the Arkansas River above Pueblo, Colorado (07099400; outflow from Pueblo Reservoir), water years 1986 through 2002.

walls surrounding the reservoir and is about 40 ft thick (Scott, 1972a). Underlying the Fort Hays Limestone Member is the Carlile Shale that contains, from top to bottom, the Juana Lopez Member (2.5 ft thick), the Codell Sandstone Member (30 ft thick), the Blue Hill Member (100 ft thick), and the Fairport Member (100 ft thick) (Scott, 1964, 1969, 1972a, 1972b). At most stages, the reservoir is in contact with the insoluble and relatively impermeable Blue Hill Member (Scott, 1969), and lateral or vertical movement of water from the reservoir is inhibited. The Codell Sandstone Member is permeable and, if inundated, could transmit water to and from the reservoir. The Fort Hays Limestone Member is not very permeable; however, water may flow at the contact between the shale and the limestone beds. The Fort Hays Limestone Member could transmit water to and from the reservoir if inundated.

Previous Work

Numerous studies have been completed that have quantified, described, and analyzed the hydrologic and water-quality data collected in Pueblo Reservoir and in the Arkansas River upstream from Pueblo Reservoir. Abbott (1985) described the water-systems operations in the Arkansas River. Ugland and others (1987 and 1988), Edelmann (1989), and Lewis and Edelmann (1994) described data-collection activities, sampling protocols, and analyses of hydrologic and water-quality data collected from October 1985 through September 1987 at several sites on Pueblo Reservoir and in the Arkansas River upstream from Pueblo Reservoir. Results of additional water-quality sampling in the Arkansas River from 1990 through 1993 were documented by Dash and Ortiz (1996) and Ortiz and others (1998). Streamflow and water-quality-data collected from October 1999 to October 2003 at several sites on Pueblo Reservoir and in the Arkansas River upstream from Pueblo Reservoir are documented in Crowfoot and others (2001, 2002, and 2003).

Acknowledgments

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Simulation of Hydrodynamics and Water Quality in Pueblo Reservoir

A two-dimensional, laterally averaged, hydrodynamic and water-quality model using CE-QUAL-W2 Version 3.2 (Cole and Wells, 2003) was developed for Pueblo Reservoir. The model was calibrated using vertical profiles of temperature and dissolved oxygen, and selected water-quality constituent concentrations collected at various depths at four sites in the reservoir (table 1 and fig. 1). The calibration period spanned water years 1986 and 1987 (October 1985 through September 1987) and the model was verified at three different hydrologic conditions observed for water years 2000, 2001, and 2002 (October 1999 through September 2002). The CE-QUAL-W2 model simulates water-surface altitude and vertical and longitudinal gradients in water-quality constituents. In addition to temperature, the model includes routines for 18 state variables including dissolved oxygen, any number of inorganic suspended-solids groups, nitrogen and phosphorus species, phytoplankton groups, dissolved and particulate organic matter, total inorganic carbon, and organic sediments. Additionally, any number of generic constituents can be included, which can be affected by a designated settling and first-order decay rate, and over 60 derived variables can be computed from the state variables (Cole and Wells, 2003).

Model Implementation

Implementation of the CE-QUAL-W2 model for Pueblo Reservoir included development of the computational grid, specification of boundary and initial conditions, and preliminary selection of model parameter values. Model development and associated assumptions in the selection of boundary and initial conditions are described, and model parameters are given in this section.

Bathymetric Data and Computational Grid

The computational grid is the geometric scheme that numerically represents the space and volume of the reservoir. Bathymetric data and a GIS analysis were used in the development of the computational grid.

Thirty-three cross sections were measured in 1975 and 1993 in intervals along the main stem of the Arkansas River in Pueblo Reservoir (Ron Ferrari, Bureau of Reclamation, written commun., 2006). Cross sections were measured across the main reservoir and across embayments that contribute to the main reservoir. Most of the cross sections were collected below an elevation of 4,940 ft above NGVD 29. The cross-section data were superimposed upon digital USGS 7.5-minute topographic contour data and extended so that the end-points of each cross section reached an elevation of 4,940 ft above NGVD 29, which is 15 feet above the current dam elevation of 4,925 ft above NGVD 29. Additional contour data were

Table 1. Water-quality and streamflow sites for Pueblo Reservoir, Colorado.

Site number	Site name	Site type
07097000	Arkansas River at Portland	Inflow streamflow, water quality
381754104515100	1B	Lake water quality
381725104494400	3B	Lake water quality
381559104465500	5C	Lake water quality
381602104435200	7B	Lake water quality
07099400	Arkansas River above Pueblo	Outflow streamflow, water quality

added to the extended cross sections only where the extended parts of the cross sections crossed elevation contours. Using the original cross-section data and the extended cross-section contour data, elevations for CE-QUAL-W2 model input were derived along the extended cross sections at an interval of one horizontal meter. To further refine the bathymetry where cross-section data were unavailable, digital USGS 7.5-minute topographic contour data were interpolated by GIS analysis into a digital elevation surface model. In addition, a digital version of the main stem of the Arkansas River and selected tributaries was extracted from the 1:24,000-scale National Hydrography Dataset to determine the lengths and orientation of the model segments. Lengths of the main-stem computational segments were calculated by superimposing the main stem of the Arkansas River on the cross sections, and the orientation of the main-stem computational segments were calculated by estimating the angle where the cross sections and the main stem intersect.

The resulting model grid extended about 13 mi from the upstream boundary of the computational grid to the Pueblo Reservoir dam (fig. 3). Twenty-three computational segments exist along the main stem of the Arkansas River in Pueblo Reservoir. Volumes of the embayments were added to adjacent main-stem segments to preserve reservoir volume. Each segment was divided vertically into 2.5-ft layers. Relations between water-surface elevation and volume and surface area in the Pueblo Reservoir model were similar to BOR pre-impoundment data (U.S. Bureau of Reclamation, 1977) (fig. 4).

Boundary and Initial Conditions

Boundary conditions generally can be described as a time series of data that define the inflows of momentum, mass, and heat to the model domain, and the outflows of water from the model domain. The initial conditions of the model included the water-surface elevation, water temperatures, and constituent concentrations that are used to initialize the start of the model run. The boundary and initial conditions for the Pueblo Reservoir water-quality model are described in the following sections.

Hydraulic and Thermal Boundary Conditions

Reservoir inflow data used in the model were obtained from a Colorado Division of Water Resources streamflow-gaging station at the Arkansas River at Portland (USGS station number 07097000) located approximately 6 mi upstream from the computational grid boundary of the model (fig. 1). Mean-daily streamflow data for the calibration and verification periods were published in Ugland and others (1987 and 1988) and Crowfoot and others (2001, 2002, and 2003). It was determined, however, that the results of the model could be enhanced by providing hourly streamflow data as input to the model. Because electronic unit values were unavailable for water years 1986, 1987, and 2000, original streamflow strip charts were provided by the Colorado Department of Natural Resources (Monique Morey, Colorado Department of Natural Resources, written commun., 2006) and recomputed to provide hourly streamflow data for this site.

Similarly, streamflow data from the Colorado Division of Water Resources streamflow station Arkansas River above Pueblo (USGS station number 07099400) were recomputed to provide hourly streamflow for the downstream boundary for the Pueblo Reservoir model. This site is located just down-stream from Pueblo Dam and represents the outflow from Pueblo Reservoir (figs. 1 and 2). For the model, the outflow structure was simulated as a point release located in the middle of the dam structure at an altitude of 4,766 ft above NGVD 29 at model layer 73 (fig. 3). Mean-daily streamflow data for the calibration and verification periods were published in Ugland and others (1987 and 1988) and Crowfoot and others (2001, 2002, and 2003).

Results from available quality-assurance data associated with input streamflow data to the model were reviewed prior to the modeling efforts. Daily streamflow data met acceptable protocols for publication (Ugland and others, 1987 and 1988; Crowfoot and others, 2001, 2002, and 2003). As such, published streamflow data used to calibrate and verify hydrodynamics in the CE-QUAL-W2 model were deemed reasonable for the application

Other hydraulic boundary conditions in the model included withdrawal points at the Pueblo Dam (model segment 23) by several municipal water suppliers, an irrigation ditch company, and a fish hatchery. The primary municipal outlet
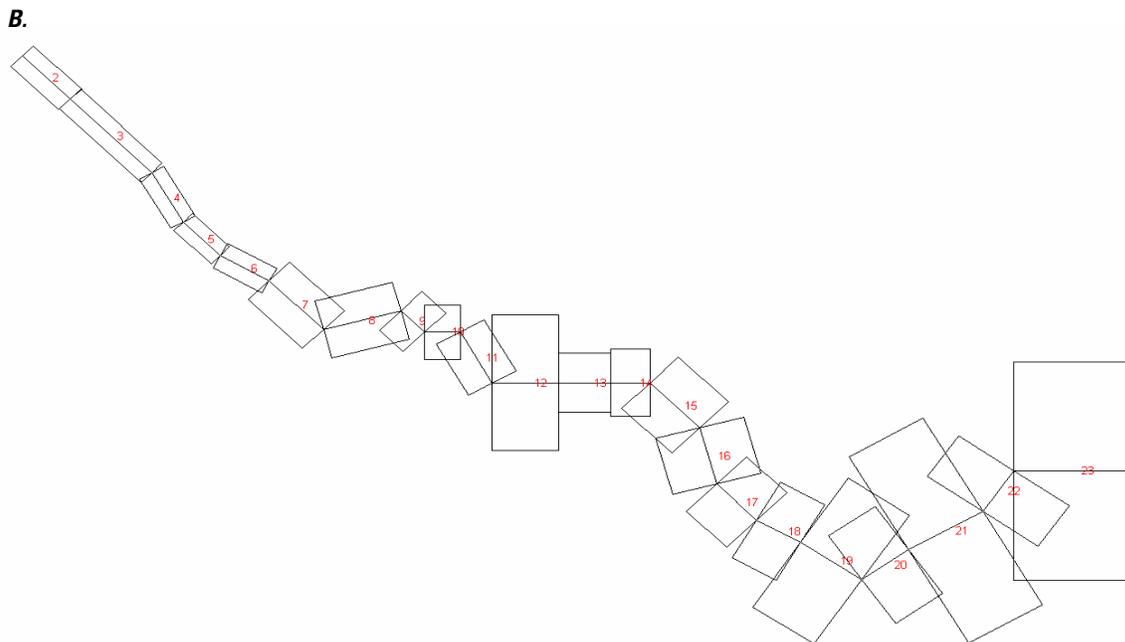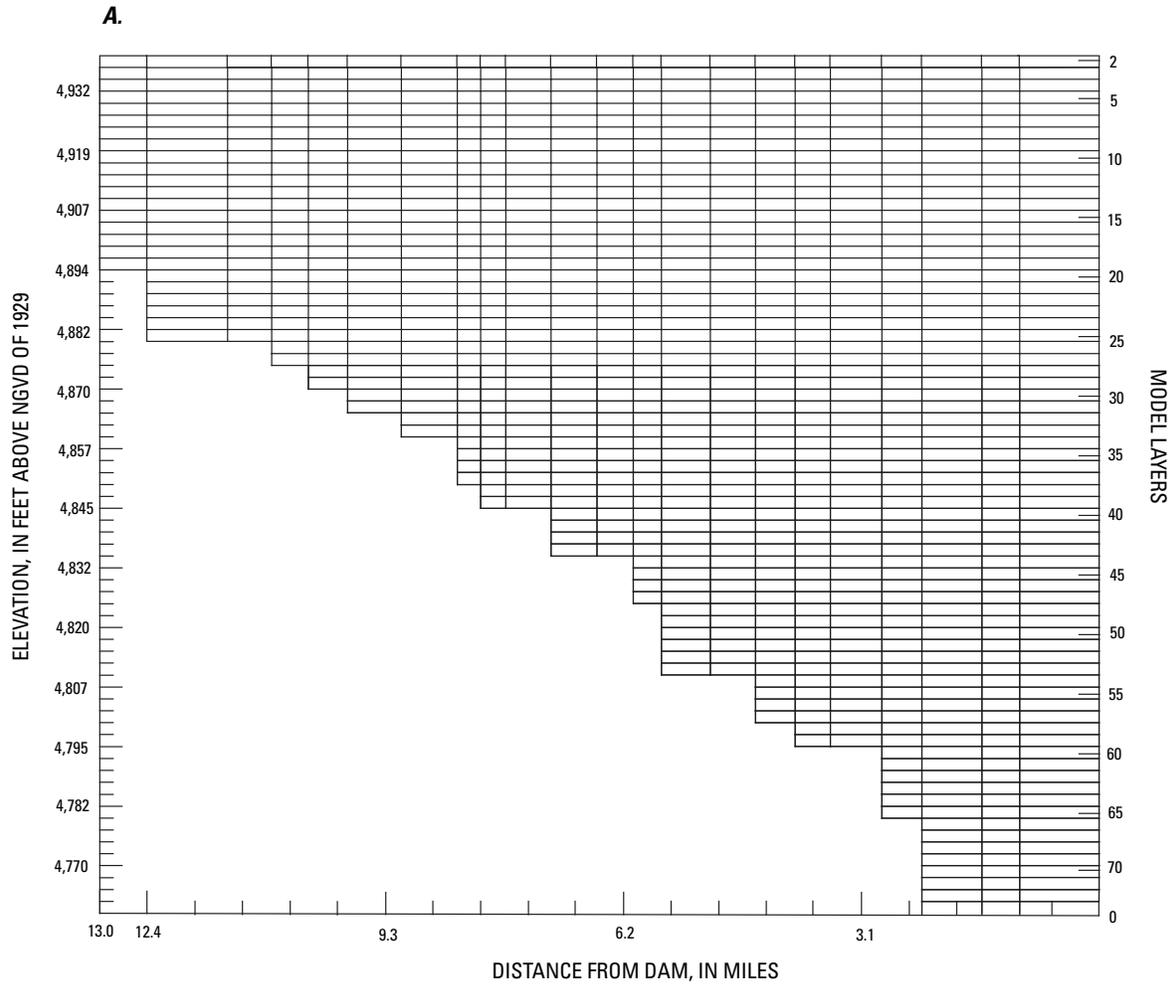
A.

B.

Figure 3.   Side view and top view of the computational grid of Pueblo Reservoir used in the CE-QUAL-W2 model.
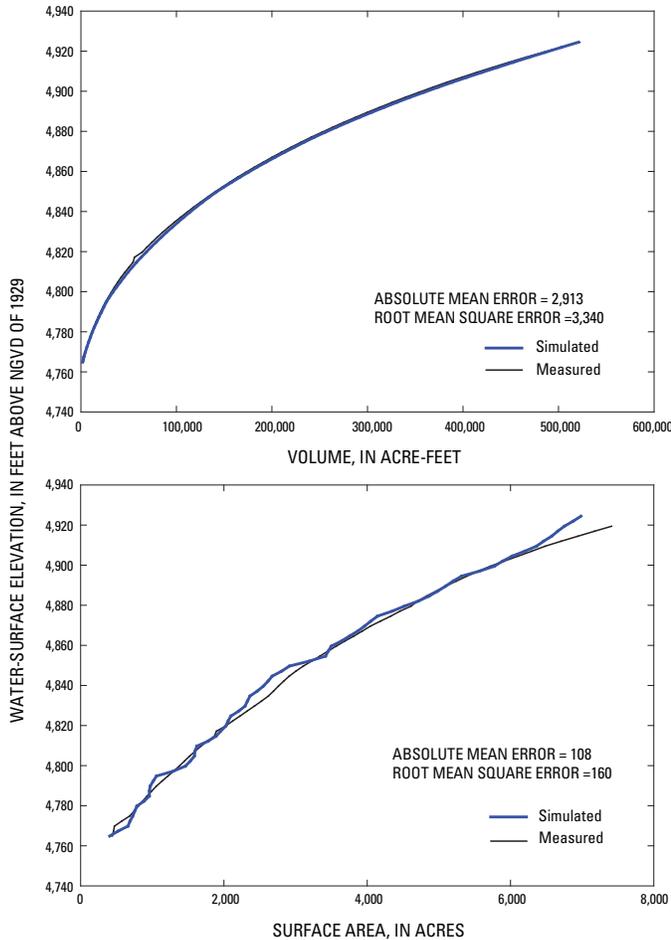
Figure 4.   Relation between simulated and measured water-surface elevation and volume and water-surface elevation and surface area for Pueblo Reservoir, Colorado.

was located at an altitude of 4,776 ft above NGVD 29 and was used to simulate municipal withdrawals for the Fountain Valley Authority and Pueblo West during the calibration and verification period. The Bessemer Ditch withdrawal was located at an altitude of 4,781 ft above NGVD 29, and the fish hatchery withdrawal was located at an altitude of 4,786 ft above NGVD 29 (Linda Hopkins, Bureau of Reclamation, written commun., 2006). Withdrawal rates for the municipal and fish hatchery outlets for water years 1986, 1987, and 2000 through 2002 were provided as daily values (Linda Hopkins, Bureau of Reclamation, written commun., 2006). Withdrawal rates for the Bessemer ditch outlet for water years 1986, 1987, and 2000 through 2002 also were provided to the USGS as daily values (Joe Florey, Colorado Department of Natural Resources, written commun., 2006).

Hydraulic boundary conditions at the water surface included evaporation, wind stress, and surface heat exchange. Meteorological data required for these computations were measured at Pueblo Memorial Airport (National Climatic Data Center, 2006) and generally were recorded at hourly intervals.

Periods of missing meteorological data were estimated by using linear interpolation between existing data points.

Water temperature is an important input parameter for modeling reservoir hydrodynamics in the CE-QUAL-W2 model. Mean-daily values from a continuous water-quality monitor (water temperature and specific conductance) at the Arkansas River at Portland for the calibration and verification periods were published in Ugland and others (1987 and 1988) and Crowfoot and others (2001, 2002, and 2003). The operation of the water-quality monitor and data computations were conducted according to methods described in Wagner and others (2006). Because water temperature in the Arkansas River can have large diurnal fluctuations, hourly water temperatures were used for input into the model. Hourly water temperatures were available for water years 1987 (calibration) and 2000, 2001, and 2002 (verification) from the USGS National Water Information System (NWIS). Prior to water year 1987, however, no continuous (instantaneous) water-temperature data were available. Estimations of hourly water temperatures for that period were made by using linear regression techniques from instantaneous data collected in 1987. The developed regression equation estimated water temperature from measured streamflow and air temperature (Kenneth Watts, U.S. Geological Survey, written commun., 2006). Additionally, the regression equation included daily and seasonal components (time) in the analysis:

$$T_{water} = 21.831 + (0.194 \times T_{air}) - (2.029 \times \ln Q) - (1.540 \times cosDay) - (0.804 \times sinDay) + (1.809 \times cos Year) - (7.612 \times sinYear) \tag{1}$$

where

T_{water} is the estimated water temperature, in degrees Celsius,

T_{air} is the measured air temperature, in degrees Celsius,

$\ln Q$ is the natural logarithm of the measured streamflow, in cubic feet per second,

$cosDay$ is the $cos(2\pi \times T_{hour} / 24)$,

$sinDay$ is the $sin(2 \pi \times T_{hour} / 24)$,

$cosYear$ is the $cos(2 \pi \times T_{year} / 1)$,

$sinYear$ is the $sin(2 \pi \times T_{year} / 1)$,

cos is the cosine function,

sin is the sine function,

T_{hour} is the hour of the day, in military time, and

T_{year} is the elapsed time, in years since midnight September 30, as a fraction of a year.

The coefficient of determination of the regression was 0.951, and the standard error of estimate was 1.52, which showed good correlation between the measured and estimated results.

Chemical Boundary Conditions

Constituent concentrations and streamflow data collected at the Arkansas River at Portland (USGS station number 07097000) were used to estimate iron, nutrient, and organic carbon loads into Pueblo Reservoir. Constituent load

is a function of the volumetric rate of water passing a point in the stream and the constituent concentration in the water. Regression methods used the natural logarithmic-transformed relation between streamflow and concentration to estimate daily constituent loads. The regression method can account for non-normal data distributions, seasonal and long-term cycles, censored data, biases associated with using logarithmic transformations, and serial correlations of the residuals (Cohn, 1995). The regression method used discrete water-quality samples collected over several years and a daily stream-flow hydrograph for the calibration and verification periods. Seasonality and time were included in the regression analysis for several of the constituents such as total iron, nitrite plus nitrate, and suspended sediment. Other constituents such as ammonia, orthophosphorus, and total organic carbon only included a relation with streamflow. The general equation that includes streamflow, time, and seasonality used in the analysis was:

$$\ln(L) = \beta_o + \beta_1 \ln(Q) + \beta_2 \ln(Q^2) + \beta_3 \ln(T) + \beta_4 \ln(T^2) + \beta_5 \ln(\sin T) + \beta_6 \ln(\cos T) \qquad (2)$$

where

   L is the constituent load, in kilograms per day;
   β_o is the regression constant;
   β_1, β_2, β_3, β_4, β_5, and β_6 are regression coefficients;
   $\ln$ is the natural logarithmic function;
   Q is daily streamflow, in cubic feet per second; and
   T is decimal time.

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

Total-dissolved solids (TDS) concentrations were significantly correlated with specific conductance (SC) at the Arkansas River at Portland site (Ortiz, 2004). Furthermore, continuous SC data were collected from the water-quality monitor at this site and mean-daily SC data were available (Ugland and others, 1987 and 1988; Crowfoot and others, 2001, 2002, and 2003). As such, the published mean-daily SC data were used to estimate daily TDS concentrations for input into the model using relations described in Ortiz (2004). This method was preferred over the S-LOADEST approach because the results were more similar to the measured data for the calibration and verification periods.

Results from available quality-assurance data associated with water-quality data used for input to the model and for calibration and verification of the model were reviewed

prior to the modeling efforts. Eight replicate water-quality samples were submitted to the USGS National Water Quality Laboratory in Arvada, Colorado. Additionally, these 8 samples were split and submitted for analysis to the Pueblo Board of Waterworks Laboratory for independent confirmation of the results. Analyses of the results indicated that water-quality data-collection procedures resulted in acceptable reproducibility for replicate samples. Additionally, two sample blanks collected at the Arkansas River at Portland site (0709700) upstream from Pueblo Reservoir indicated that contamination was not a concern for applicable sampling procedures. As such, published water-quality data used as input to the model and to verify and calibrate the water quality in the model were deemed reasonable for the application. Overall, the streamflow and water-quality data sets for the calibration and verification periods were considered appropriate for the range of environmental conditions simulated for this report.

Initial Conditions

Initial water-surface elevation, water temperature, and constituent concentrations for each model segment are required at the start of a model simulation. The initial water-surface elevation was set to the measured value on October 1, 1985, for the calibration period and to the measured value on October 1, 1999, for the verification period. Pueblo Reservoir was assumed to be in isothermal conditions throughout the entire reservoir and equal to 18.2°C on October 1 for the calibration and verification periods. Initial constituent concentrations also were assumed to be uniform. Concentrations measured on September 30, 1985, were used as the initial values for the calibration period, and constituent concentrations measured on September 30, 1999, were used for initial values for the verification period.

Model Parameters

Parameters are used to describe the physical and chemical processes that are not explicitly modeled and to provide the chemical kinetic rate information. Many parameters cannot be measured directly and often are adjusted during the model calibration process until simulated values agree with measured observations. Most of the hydrodynamic and thermal processes are modeled in CE-QUAL-W2, which results in relatively few adjustable hydraulic and thermal parameters. There are many chemical and biological rate coefficients required for the application of CE-QUAL-W2, which are all temporally constant (table 2). Many of the coefficients were based on suggested values given as default values for CE-QUAL-W2, and others were based on other model applications (Haggard and Green, 2002; Galloway and Green, 2002 and 2003; Green and others, 2003; Bales and others, 2001; Sullivan and Rounds, 2005; Galloway and Green, 2006).

Table 2. Parameters and values used for the Pueblo Reservoir model, October 1985 through September 1987 and October 1999 through September 2002.

Parameter	Value
Hydraulic and thermal input parameters	
Coefficent of bottom heat exchange, watts/square meter/second	0.7
Sediment temperature, degrees Celsius	10.5
Wind-sheltering coefficient, dimensionless	0.90
Horizontal eddy viscosity, square meters/second	1
Horizontal eddy diffusivity, square meters/second	1
Rate coefficients for water-chemistry and biological simulations	
Light extinction coefficient for pure water, 1/meter	0.3
Light extinction coefficient for organic solids, 1/meter	0.01
Light extinction coefficient for inorganic solids, 1/meter	0.01
Light extinction coefficient due to algae (blue-green), 1/meter	0.01
Light extinction coefficient due to algae (diatoms), 1/meter	0.01
Light extinction coefficient due to algae (flagellates),1/meter	0.01
Light extinction coefficient due to algae (green), 1/meter	0.01
Fraction of incident solar radiation absorbed at water surface, dimensionless	0.28
Suspended solids settling rate, meters/day	1.5
Algal growth rate (blue-green), 1/day	1.8
Algal growth rate (diatoms), 1/day	2.6
Algal growth rate (flagellates), 1/day	2.6
Algal growth rate (green), 1/day	1.8
Algal mortality rate (blue-green), 1/day	0.22
Algal mortality rate (diatoms), 1/day	0.10
Algal mortality rate (flagellates), 1/day	0.10
Algal mortality rate (green), 1/day	0.15
Algal excretion rate (blue-green), 1/day	0.04
Algal excretion rate (diatoms), 1/day	0.04
Algal excretion rate (flagellates), 1/day	0.04
Algal excretion rate (green), 1/day	0.04
Algal dark respiration rate (blue-green), 1/day	0.03
Algal dark respiration rate (diatoms), 1/day	0.03
Algal dark respiration rate (flagellates), 1/day	0.03
Algal dark respiration rate (green), 1/day	0.03
Algal settling rate (blue-green), 1/day	0.02
Algal settling rate (diatoms), meters/day	0.08
Algal settling rate (flagellates), meters/day	0.08
Algal settling rate (green), meters/day	0.08
Saturation light intensity (blue-green), watts/square meter	300
Saturation light intensity (diatoms), watts/square meter	300
Saturation light intensity (flagellates), watts/square meter	300
Saturation light intensity (green), watts/square meter	300
Fraction of algal biomass lost by mortality to particulate organic matter (blue-green), dimensionless	0.8

Table 2. Parameters and values used for the Pueblo Reservoir model, October 1985 through September 1987 and October 1999 through September 2002. —Continued

Parameter	Value
Rate coefficients for water-chemistry and biological simulations	
Fraction of algal biomas lost by mortality to particulate organic matter (diatoms), dimensionless	0.8
Fraction of algal biomas lost by mortality to particulate organic matter (flagellates), dimensionless	0.8
Fraction of algal biomas lost by mortality to particulate organic matter (green), dimensionless	0.8
Lower temperature for algal growth (blue-green), degrees Celsius	10
Lower temperature for algal growth (diatoms), degrees Celsius	2
Lower temperature for algal growth (flagellates), degrees Celsius	2
Lower temperature for algal growth (green algae), degrees Celsius	5
Fraction of algal growth at lower temperature (blue-green), dimensionless	0.1
Fraction of algal growth at lower temperature (diatoms), dimensionless	0.1
Fraction of algal growth at lower temperature (flagellates), dimensionless	0.1
Fraction of algal growth at lower temperature (green), dimensionless	0.1
Lower temperature for maximum algal growth (blue-green), degrees Celsius	17
Lower temperature for maximum algal growth (diatoms), degrees Celsius	7
Lower temperature for maximum algal growth (flagellates), degrees Celsius	5
Lower temperature for maximum algal growth (green), degrees Celsius	15
Fraction of maximum algal growth at lower temperature (blue-green), dimensionless	0.99
Fraction of maximum algal growth at lower temperature (diatoms), dimensionless	0.99
Fraction of maximum algal growth at lower temperature (flagellates), dimensionless	0.99
Fraction of maximum algal growth at lower temperature (green), dimensionless	0.99
Upper temperature for algal growth (blue-green), degrees Celsius	35
Upper temperature for algal growth (diatoms), degrees Celsius	25
Upper temperature for algal growth (flagellates), degrees Celsius	20
Upper temperature for algal growth (green), degrees Celsius	35
Fraction of algal growth at upper temperature (blue-green), dimensionless	0.99
Fraction of algal growth at upper temperature (diatoms), dimensionless	0.99
Fraction of algal growth at upper temperature (flagellates), dimensionless	0.99
Fraction of algal growth at upper temperature (green), dimensionless	0.99
Upper temperature for maximum algal growth (blue-green), degrees Celsius	32
Upper temperature for maximum algal growth (diatoms), degrees Celsius	10
Upper temperature for maximum algal growth (flagellates), degrees Celsius	15
Upper temperature for maximum algal growth (green), degrees Celsius	30
Fraction of maximum algal growth at upper temperature (blue-green), dimensionless	0.1
Fraction of maximum algal growth at upper temperature (diatoms), dimensionless	0.1
Fraction of maximum algal growth at upper temperature (flagellates), dimensionless	0.1
Fraction of maximum algal growth at upper temperature (green), dimensionless	0.1
Algal half-saturation constant for phosphorus (blue-green), grams/cubic meter	0.004
Algal half-saturation constant for phosphorus (diatoms), grams/cubic meter	0.002
Algal half-saturation constant for phosphorus (flagellates), grams/cubic meter	0.004
Algal half-saturation constant for phosphorus (greens), grams/cubic meter	0.004
Algal half-saturation constant for nitrogen (blue-green), grams/cubic meter	0

Table 2.   Parameters and values used for the Pueblo Reservoir model, October 1985 through September 1987 and October 1999 through September 2002. —Continued

Parameter	Value
Rate coefficients for water-chemistry and biological simulations	
Algal half-saturation constant for nitrogen (diatoms), grams/cubic meter	0.014
Algal half-saturation constant for nitrogen (flagellates), grams/cubic meter	0.014
Algal half-saturation constant for nitrogen (greens), grams/cubic meter	0.014
Algal half-saturation constant for silica (blue-green), grams/cubic meter	0
Algal half-saturation constant for silica (diatoms), grams/cubic meter	0
Algal half-saturation constant for silica (flagellates), grams/cubic meter	0
Algal half-saturation constant for silica (greens), grams/cubic meter	0
Oxygen stoichiometric equivalent for algal dark respiration (blue-green), dimensionless	1.4
Oxygen stoichiometric equivalent for algal dark respiration (diatoms), dimensionless	1.4
Oxygen stoichiometric equivalent for algal dark respiration (flagellates), dimensionless	1.4
Oxygen stoichiometric equivalent for algal dark respiration (greens), dimensionless	1.4
Oxygen stoichiometric equivalent for algal growth (blue-green), dimensionless	1.1
Oxygen stoichiometric equivalent for algal growth (diatoms), dimensionless	1.1
Oxygen stoichiometric equivalent for algal growth (flagellates), dimensionless	1.1
Oxygen stoichiometric equivalent for algal growth (greens), dimensionless	1.1
Chlorophyll-algae ratio, dimensionless	0.28
Labile dissolved organic matter decay rate, 1/day	0.03
Refractory dissolved organic matter decay rate, 1/day	0.003
Labile to refractory dissolved organic matter decay rate, 1/day	0.005
Labile particulate organic matter decay rate, 1/day	0.01
Refractory particulate organic matter decay rate, 1/day	0.002
Labile to refractory particulate organic matter decay rate, 1/day	0.003
Particular organic matter settling rate, meters/day	0.08
Lower temperature for organic matter decay, degrees Celsius	4
Upper temperature for organic matter decay, degrees Celsius	30
Fraction of organic matter decay at lower temperature, dimensionless	0.1
Fraction of organic matter decay at upper temperature, dimensionless	0.99
Oxygen stoichiometric equivalent for organic matter decay, dimensionless	1.4
Stoichiometric equivalent between organic matter and phosphorus, dimensionless	0.005
Stoichiometric equivalent between organic matter and nitrogen, dimensionless	0.08
Stoichiometric equivalent between organic matter and carbon, dimensionless	0.45
Sediment decay rate, 1/day	0.01
Zero-order sediment oxygen demand, grams/square meter/day	0.2-1
Fraction of sediment oxygen demand, dimensionless	3.5
5-day biological oxygen demand decay rate, 1/day	0.0418
Biological oxygen demand temperature rate coefficient, dimensionless	1.0147
Ratio of 5-day biological oxygen demand to ultimate biological oxygen demand, dimensionless	1
Release rate of phosphorus from bottom sediment, fraction of sediment oxygen demand	0.001
Phosphorus partitioning coefficient, dimensionless	0
Release rate of ammonia from bottom sediment, fraction of sediment oxygen demand	0.001

Table 2.   Parameters and values used for the Pueblo Reservoir model, October 1985 through September 1987 and October 1999 through September 2002. —Continued

Parameter	Value
Rate coefficients for water-chemistry and biological simulations	
Ammonia decay rate, 1/day	0.12
Lower temperature for ammonia decay, degrees Celsius	4
Fraction of nitrification at lower temperature, dimensionless	0.1
Upper temperature for ammonia decay, degrees Celsius	25
Fraction of maximum nitrification at lower temperature, dimensionless	0.99
Nitrate decay rate, 1/day	0.05
Lower temperature for nitrate decay, degrees Celsius	5
Fraction of denitrification at lower temperature, dimensionless	0.1
Upper temperature for nitrate decay, degrees Celsius	25
Fraction of maximum denitrification at lower temperature, dimensionless	0.99
Iron release from bottom sediment, fraction of sediment oxygen demand	0.5
Iron settling velocity, meters/day	2
Oxygen stoichiometric equivalent for ammonia decay, dimensionless	4.57

Statistical Methods

Two statistics were used to compare simulated and measured water-surface elevations, water temperatures, dissolved-oxygen concentrations, and nutrient concentrations for calibration and verification of the Pueblo Reservoir model. The absolute mean error (AME) indicates the average difference between simulated and measured values and is computed by equation 3:

$$AME = \frac{\Sigma \, |\text{simulated value} - \text{measured value}|}{\text{number of observations}} \qquad (3)$$

An AME of $0.5^{\circ}C$ means that the simulated temperatures are, on average, within +/- $0.5^{\circ}C$ of the measured temperatures. The root mean square error (RMSE) indicates the spread of how far simulated values deviate from the measured values and is computed by equation 4:

$$RMSE = \sqrt{\frac{\Sigma \, (\text{simulated value} - \text{measured value})^2}{\text{number of observations}}} \qquad (4)$$

An RMSE of $0.5^{\circ}C$ means that the simulated temperatures are within +/- $0.5^{\circ}C$ of the measured temperatures about 67 percent of the time.

Model Calibration and Verification

The Pueblo Reservoir model was calibrated using vertical profiles of water temperature and dissolved-oxygen concentration and water-quality constituent concentrations collected in the epilimnion (near the water surface) and hypolimnion (near the reservoir bottom) at four sites in the reservoir (fig. 1 and table 1) from October 1985 through September 1987. The model was verified at different hydrologic conditions from October 1999 through September 2002.

Calibration

Successful model application requires model calibration that includes comparing simulated results with measured reservoir conditions. The Pueblo Reservoir model calibration was completed by adjusting parameters for the 2-year period from October 1985 through September 1987. Generally, calibration was achieved by calibrating the water balance and thermodynamics before calibrating the water-quality conditions (dissolved oxygen, nutrients, and algae).

Water Balance

Simulated water-surface elevations for Pueblo Reservoir were adjusted to the measured water-surface elevations for the calibration period (October 1985 through September 1987) and for the verification period (October 1999 through September 2002) (fig. 5). The water-surface elevations were corrected to the measured values by adjusting the unmeasured inflow into the reservoir that was distributed to all the segments within a branch. Inflow was either added or subtracted so that the simulated water-surface elevation reflected the measured water-surface elevation. By correcting the distributed inflow, the temperature and water quality could be calibrated and verified without the uncertainty incurred with having differences between simulated and measured water-surface elevations.
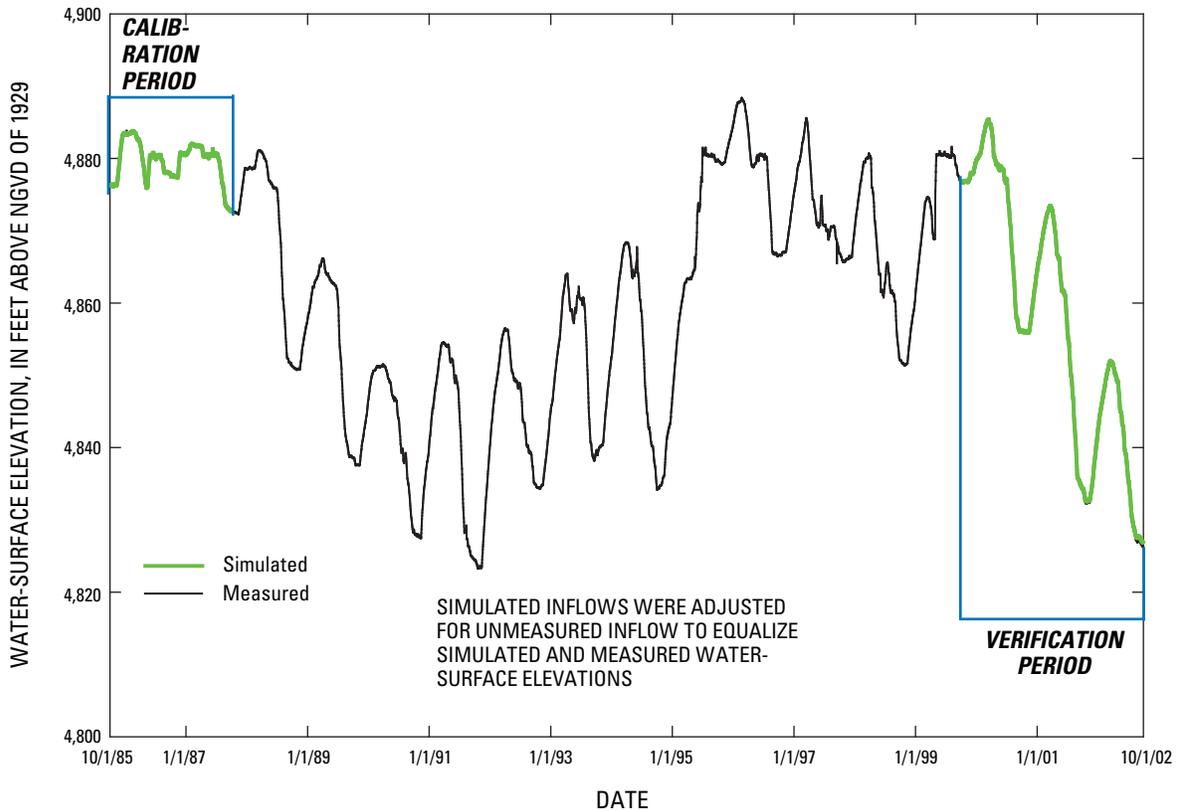
Figure 5. Simulated and measured water-surface elevations for Pueblo Reservoir, Colorado, October 1985 to October 2002.

Temperature

Water temperature in Pueblo Reservoir is affected by inflows and outflows, exchange of heat at the air-water interface (short- and long-wavelength radiative inputs, long-wavelength radiative emissions, evaporation, conduction, and convection), depth penetration by solar radiation, and mixing by wind (Sullivan and Rounds, 2005). The hydrodynamics are largely influenced by water temperature because of its effect on water density. Generally, inflows from the Arkansas River have colder, more dense water than in the upper part of water column in the reservoir (epilimnion), resulting in the inflows to be placed near the bottom part of the water column in the reservoir (hypolimnion) called underflow, or placed in the middle part of the water column in the reservoir (metalimnion), called interflow (Lewis and Edelmann, 1994). Water temperature in the reservoir stays relatively uniform, except when the inflow from the Arkansas River has enough energy to place the colder water further downstream into the reservoir.

Simulated temperatures in Pueblo Reservoir were compared to 106 vertical profiles collected at four sites (fig. 1) in the reservoir. Temperatures were calibrated to the measured values for October 1985 through September 1987.

Simulated water temperatures compared well to measured water temperatures in Pueblo Reservoir from October 1985 through September 1987 (figs. 6-9). Spatially, simulated water temperatures compared better to measured water temperatures in the downstream part of the reservoir (sites 5C and 7B) (figs. 8-9) than in the upstream part of the reservoir (sites 1B and 3B) (figs. 6-7). The AME and RMSE at site 1B were 1.68 and 1.83°C, respectively. In comparison, the AME and RMSE for site 7B were 0.70 and 0.85°C, respectively (table 3).

Differences between simulated and measured water temperatures varied through time from October 1985 through September 1987. Generally, simulated water temperatures were slightly less than measured water temperatures from March to May 1986 and 1987, and slightly greater than measured data in August and September 1987 (figs. 6-9). At site 1B, simulated water temperatures were less than measured water temperatures for most of the model period except for April to June 1987, when simulated water temperatures were greater than the measured data.

Water Quality

The Pueblo Reservoir model was calibrated for dissolved oxygen, TDS, total iron, dissolved ammonia, dissolved nitrate

Figure 6. Simulated and measured water-temperature profiles for Pueblo Reservoir, Colorado, at site 1B, October 1985 through September 1987.

Figure 7.   Simulated and measured water-temperature profiles for Pueblo Reservoir, Colorado, at site 3B, October 1985 through September 1987.
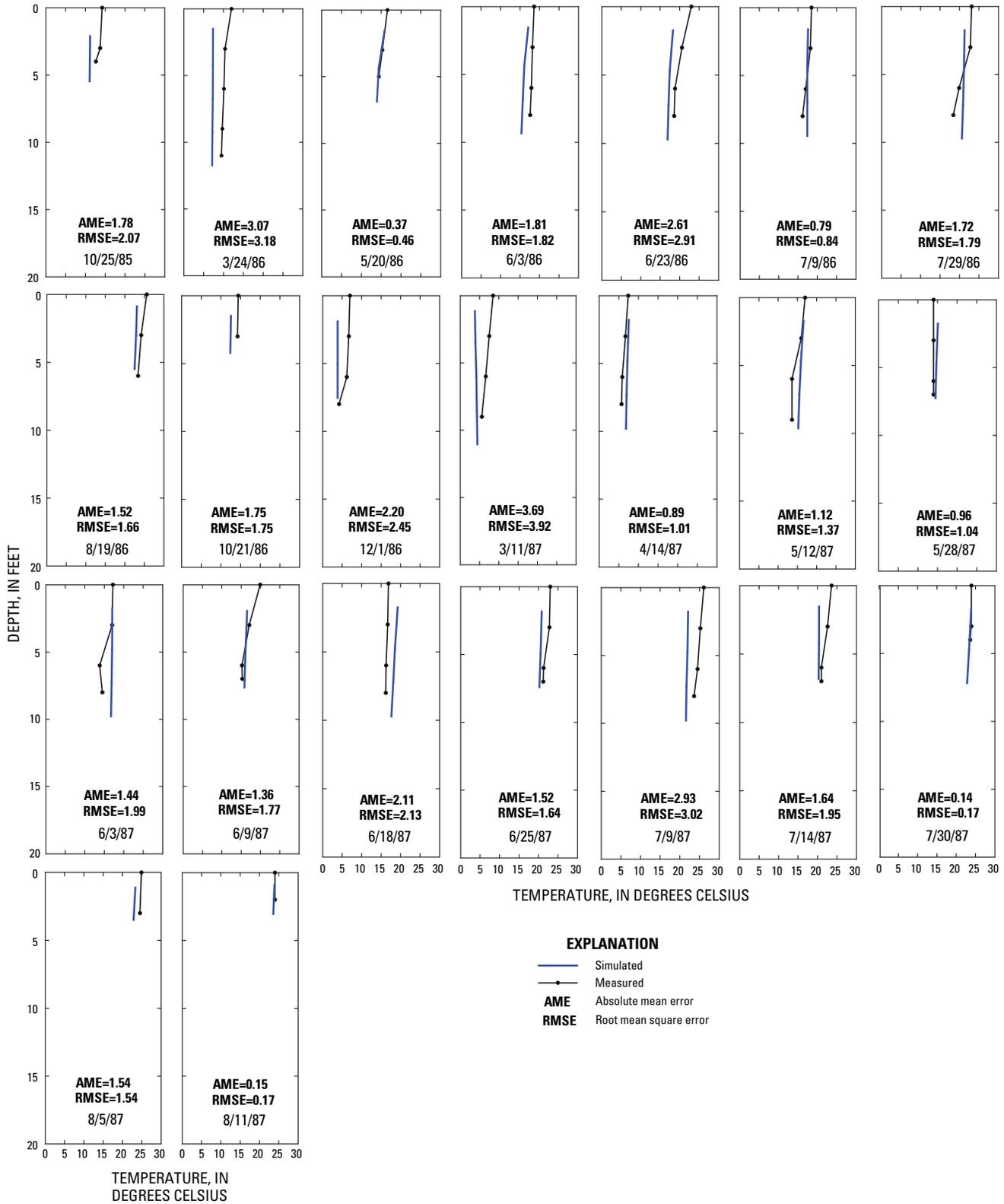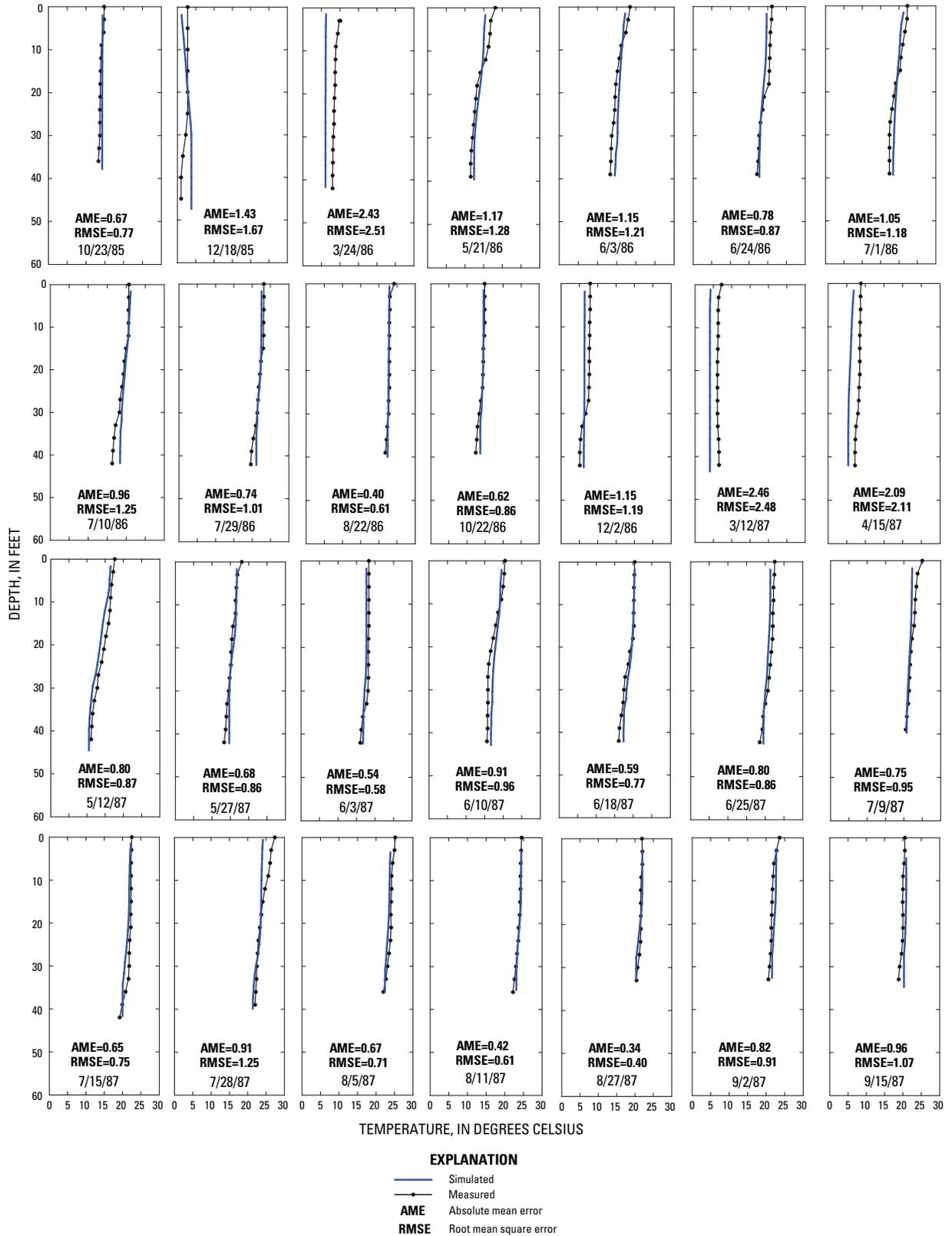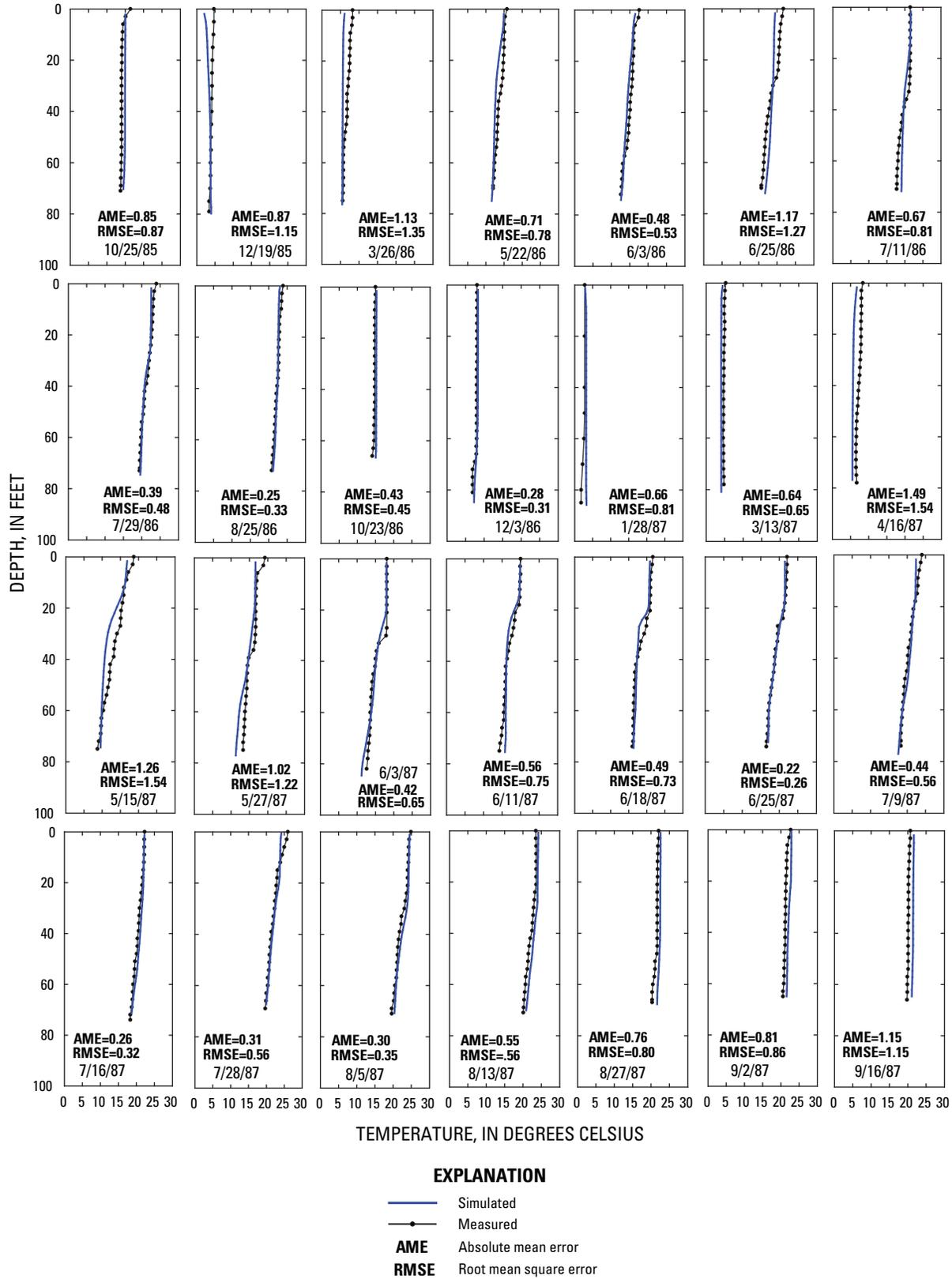
Figure 8.   Simulated and measured water-temperature profiles for Pueblo Reservoir, Colorado, at site 5C, October 1985 through September 1987.
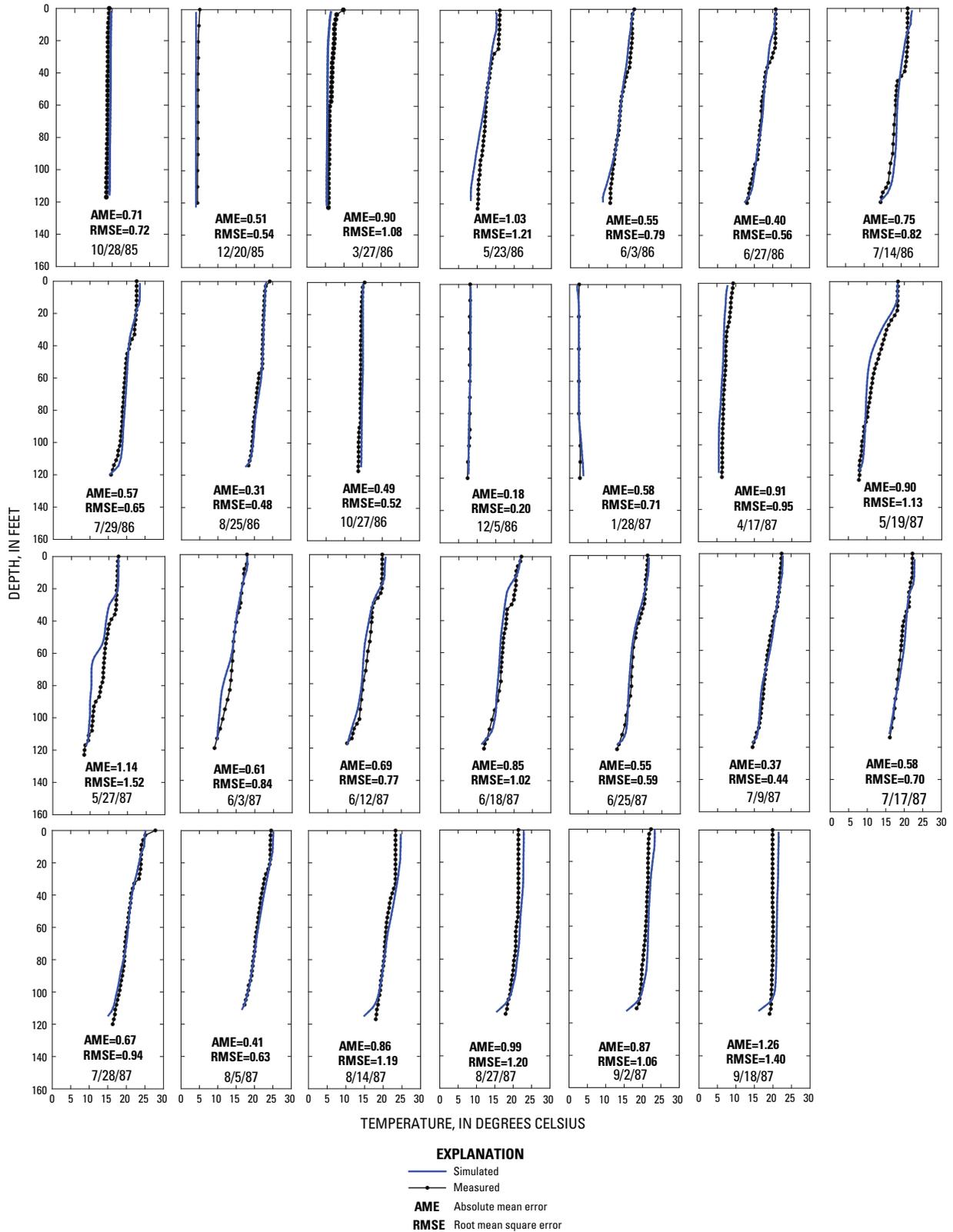
Figure 9. Simulated and measured water-temperature profiles for Pueblo Reservoir , Colorado, at site 7B, October 1985 through September 1987.

Table 3. Comparative statistics of simulated and measured water temperature and constituent concentrations at four sites in Pueblo Reservoir, Colorado, October 1985 through September 1987.

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

Constituent	Site number	Number of compared data points	Mean difference (simulated minus measured)	Absolute mean error	Root mean square error
Temperature, in deg. C	1B	114	-0.90	1.68	1.83
	3B	659	-0.06	0.92	1.05
	5C	685	-0.13	0.66	0.77
	7B	1024	-0.18	0.70	0.85
Dissolved oxygen, in mg/L	1B	112	-0.43	1.05	1.12
	3B	662	0.48	1.18	1.39
	5C	660	0.80	1.14	1.30
	7B	981	0.71	1.42	1.67
Total dissolved solids, in mg/L	1B	25	-34	33	33
	3B	28	-44	46	47
	5C	29	-42	42	43
	7B	27	-44	45	47
Total iron, in mg/L	1B	25	0.33	1.67	1.72
	3B	27	-0.27	0.84	1.09
	5C	29	0.25	0.41	0.55
	7B	27	1.42	1.48	2.06
Nitrite plus nitrate, in mg/L as N	1B	9	-0.01	0.11	0.11
	3B	12	-0.04	0.09	0.10
	5C	11	-0.04	0.05	0.07
	7B	11	-0.09	0.15	0.18
Ammonia, in mg/L as N	1B	9	-0.04	0.05	0.05
	3B	12	-0.05	0.05	0.05
	5C	15	-0.02	0.05	0.06
	7B	11	-0.04	0.04	0.04
Total nitrogen, in mg/L as N	1B	24	0.02	0.21	0.21
	3B	28	0.12	0.27	0.29
	5C	24	0.14	0.23	0.26
	7B	24	0.10	0.27	0.29
Orthophosphorus, in mg/L as P	1B	7	0.00	0.02	0.02
	3B	8	0.00	0.01	0.01
	5C	10	0.01	0.01	0.01
	7B	10	0.01	0.02	0.02
Total phosphorus, in mg/L as P	1B	19	-0.04	0.05	0.05
	3B	22	-0.02	0.04	0.05
	5C	24	0.02	0.02	0.02
	7B	23	0.02	0.02	0.02
Chorophyll *a*, in μg/L	1B	24	-2.1	3.0	5.3
	3B	31	-1.9	3.7	6.8
	5C	32	-1.4	2.2	3.7
	7B	30	-0.4	1.6	2.5

(measured as nitrite plus nitrate), total nitrogen, dissolved orthophosphorus, total phosphorus, and algal biomass (measured as chlorophyll *a*). Dissolved oxygen was calibrated by comparison of simulated values to 105 measured vertical profiles collected at 4 sites in the reservoir. Simulated TDS, total iron, nutrient (dissolved ammonia, dissolved nitrate, total nitrogen, dissolved orthophosphorus, total phosphorus), and chlorophyll *a* data were compared to discrete samples collected in the epilimnion and hypolimnion at four sites in Pueblo Reservoir. Model calibration was limited by the small number of measured data for several of the dissolved constituents including ammonia, nitrate, and orthophosphorus. Measured concentrations of these dissolved constituents were available only from April 1987 to October 1987.

Dissolved Oxygen

Dissolved-oxygen concentrations in the Pueblo Reservoir model were affected by algal photosynthesis and respiration, nitrification, decay of organic matter, aeration from interaction with the atmosphere, inflow and outflow dissolved-oxygen concentrations, and water temperature (Cole and Wells, 2003). Simulated dissolved-oxygen concentrations in Pueblo Reservoir were compared to vertical profiles collected at four sites in the reservoir (figs. 10-13). Concentrations were calibrated to the measured values for October 1985 through September 1987.

In general, simulated dissolved-oxygen concentrations for the calibration period compared well to measured concentrations in Pueblo Reservoir. Spatially, simulated concentrations deviated more from the measured values at the downstream part of the reservoir than at other locations in the reservoir. Overall, the AME ranged from 1.05 (site 1B) to 1.42 mg/L (site 7B) and the RMSE ranged from 1.12 (site 1B) to 1.67 mg/L (site 7B) (table 3). Simulated dissolved-oxygen concentrations were slightly overpredicted in the downstream part of the reservoir because of the simplified algal dynamics defined in the model. Simplification of a complex algal community can affect the timing of algal growth and the distribution of algae resulting in slightly different simulated dissolved-oxygen concentrations. Vertically, simulated dissolved-oxygen concentrations in the hypolimnion compared better to measured concentrations than did simulated concentrations in the epilimnion (figs. 10-13). The dissolved-oxygen concentrations in the epilimnion had the highest variability because algal dynamics and aeration from wind have substantial effects on dissolved oxygen near the water surface. The main process that affects dissolved oxygen in the hypolimnion is organic matter decay (Cole and Wells, 2003), which was fairly well simulated in the Pueblo Reservoir model.

Seasonally, simulated dissolved-oxygen concentrations in Pueblo Reservoir compared well to measured concentrations (figs. 10-13). Simulated concentrations compared well to measured concentrations during the fall and winter when the reservoir was isothermal and algal growth generally was

limited. In late spring and early summer, simulated dissolved-oxygen concentrations were higher than the measured concentrations. Generally, the highest simulated algal growth occurred during this period which contributed to the higher simulated dissolved-oxygen concentrations through photosynthesis. As mentioned earlier, some of the complexities of the algal community may not have been completely simulated, and the timing of the algal growth and mortality may not have been fully captured by the model.

Total-dissolved solids

TDS can affect water density and ionic strength, thereby affecting water movements, pH, and the distribution of carbonate species (not simulated in the Pueblo Reservoir model) (Cole and Wells, 2003). Simulated TDS were compared to 109 measured concentrations in the epilimnion and hypolimnion at four sites in Pueblo Reservoir (fig. 14). There are no adjustable rate parameters for TDS in the CE-QUAL-W2 model because the constituent is assumed to be conservative.

Simulated TDS generally were less than measured TDS concentrations in Pueblo Reservoir from October 1985 through September 1987. The mean difference between simulated and measured data at sites 1B, 3B, 5C and 7B was -34, -44, -42, and -44 mg/L, respectively (table 3). The AME at site 1B and 7B was 33 and 45 mg/L, respectively, whereas the RMSE was 33 and 47 mg/L, respectively. Throughout the model period, simulated TDS followed the same temporal patterns as the measured TDS concentrations in Pueblo Reservoir in the epilimnion and the hypolimnion (fig. 14). The largest differences between simulated and measured TDS were observed at the most downstream sites in Pueblo Reservoir (sites 5C and 7B) during the second year of the calibration period (October 1986 to June 1987).

Total Iron

Iron commonly is released from anoxic sediments and may influence nutrient dynamics in reservoirs (Cole and Wells, 2003). In the Pueblo Reservoir model, total iron is affected by anaerobic release from the sediment, adsorption to sediment, and settling. Anaerobic release is modeled as a zero-order process in the model (Cole and Wells, 2003).

Changes in simulated total iron concentrations through time followed similar patterns as the measured concentrations in the Pueblo Reservoir model (fig. 15). The greatest variation in total iron concentrations occurred in the hypolimnion because of the release of iron from the bottom sediments during anoxic conditions. The greatest difference between simulated and measured total iron concentrations occurred in the hypolimnion at sites 1B and 7B (table 3 and fig. 15). The AME at sites 1B and 7B were 1.67 and 1.48 mg/L, respectively, and the RMSE for sites 1B and 7B were 1.72 and 2.06 mg/L, respectively. The differences at the upstream part of the reservoir (site 1B) may be because the estimated daily inflow of total iron may not accurately reflect the ambient conditions or the simulated dissolved oxygen in the hypolimnion

Figure 10.   Simulated and measured dissolved-oxygen concentration profiles for Pueblo Reservoir, Colorado, at site 1B, October 1985 through September 1987.
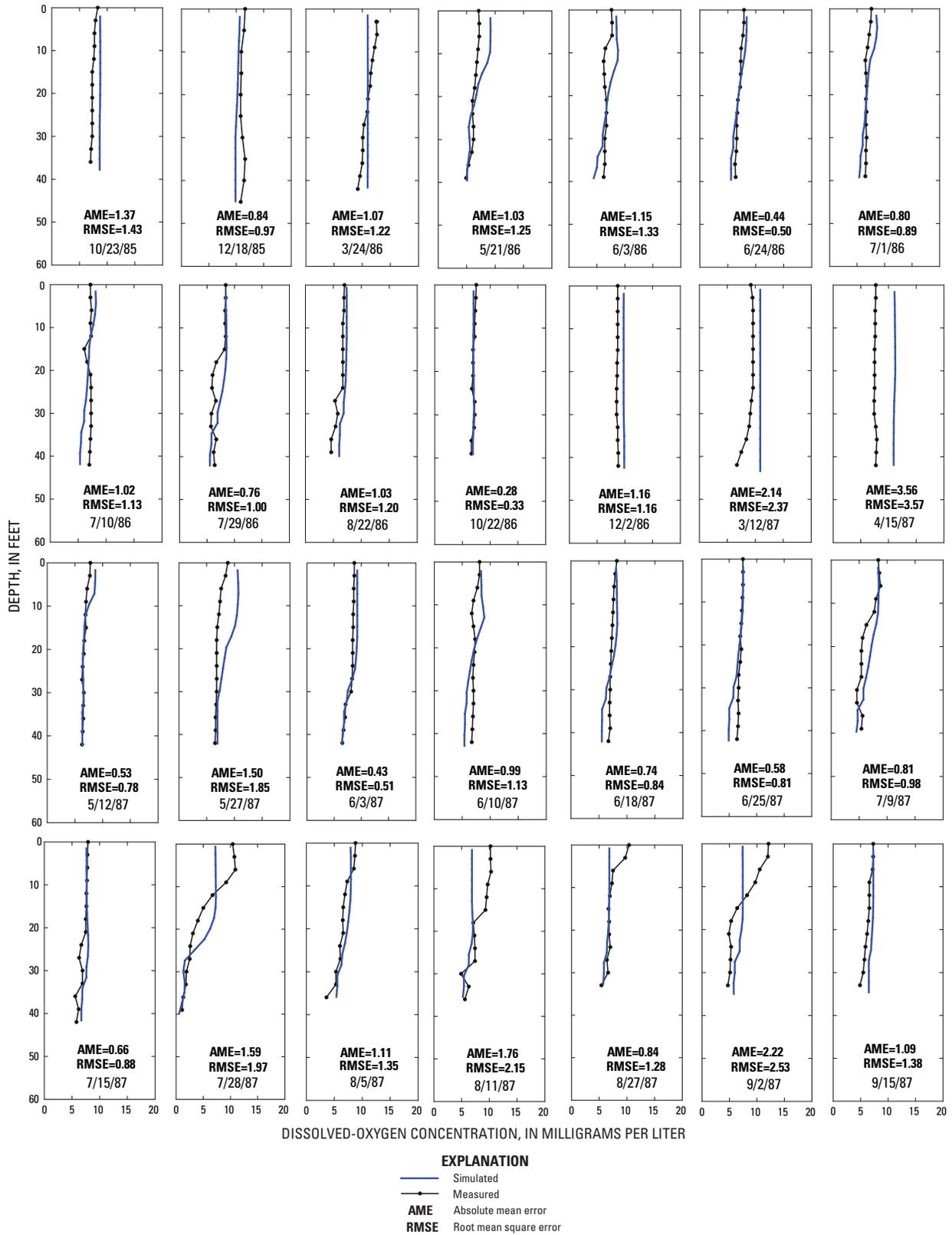
Figure 11.   Simulated and measured dissolved-oxygen concentration profiles for Pueblo Reservoir, Colorado, at site 3B, October 1985 through September 1987.
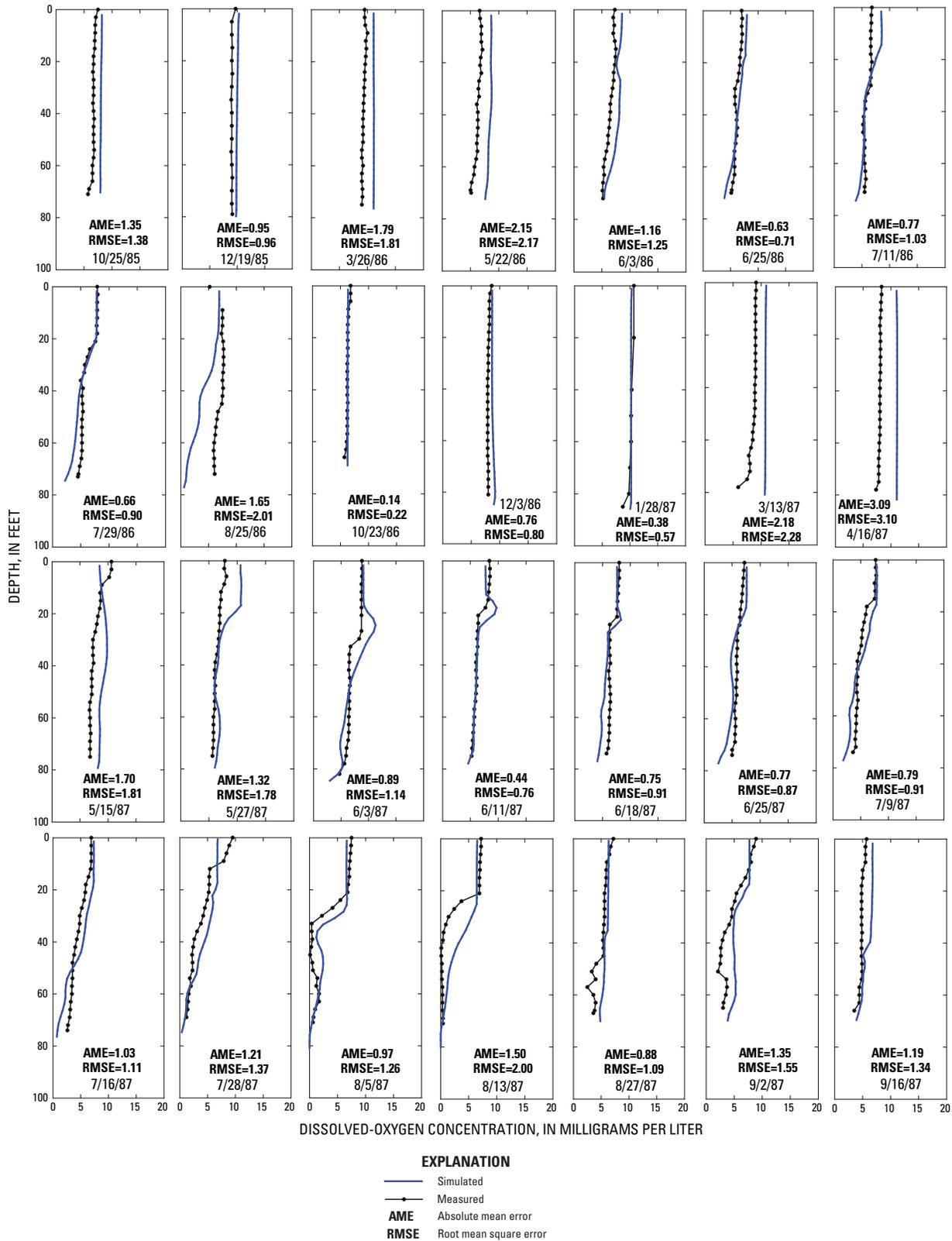
Figure 12.   Simulated and measured dissolved-oxygen concentration profiles for Pueblo Reservoir, Colorado, at site 5C, October 1985 through September 1987.
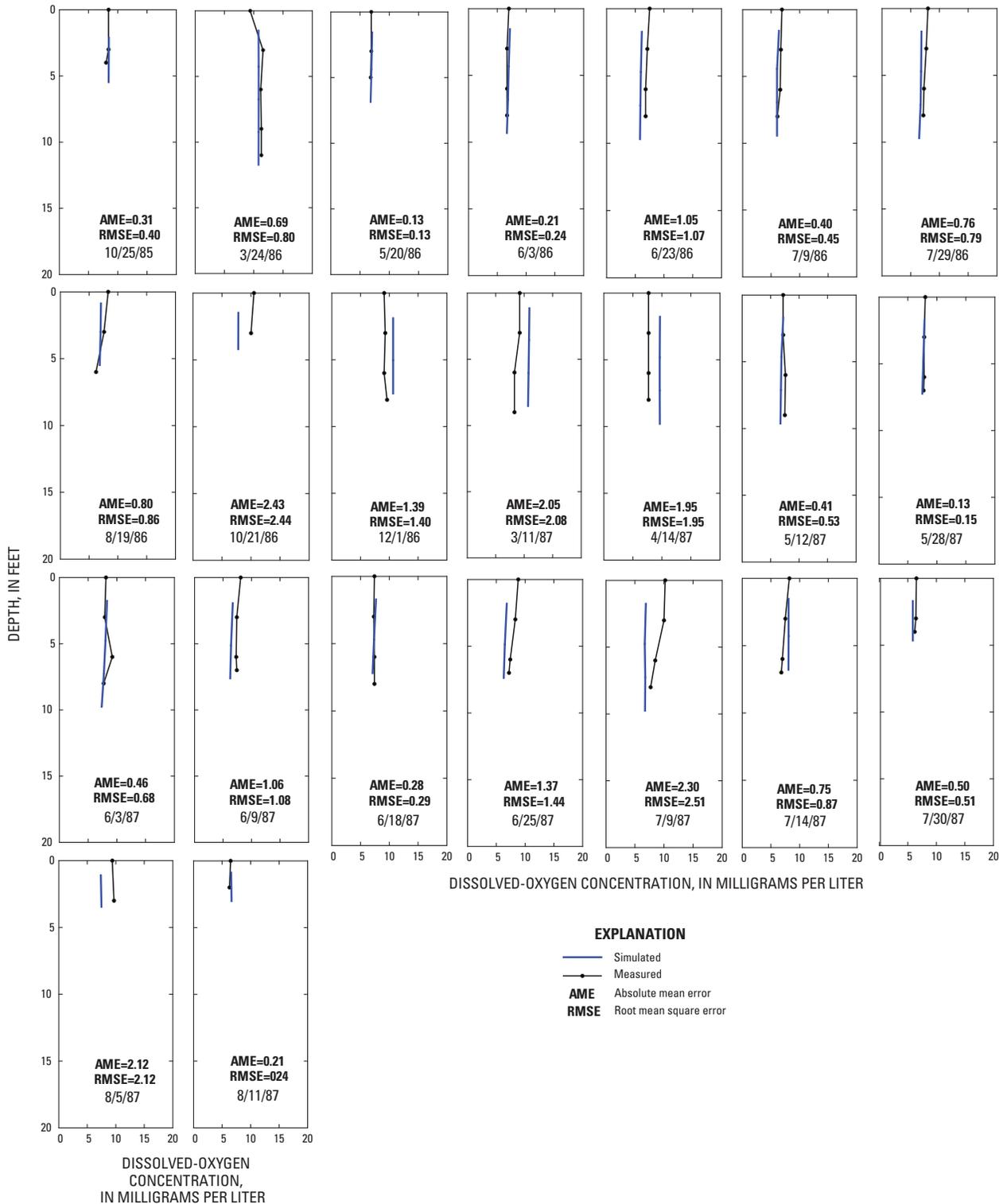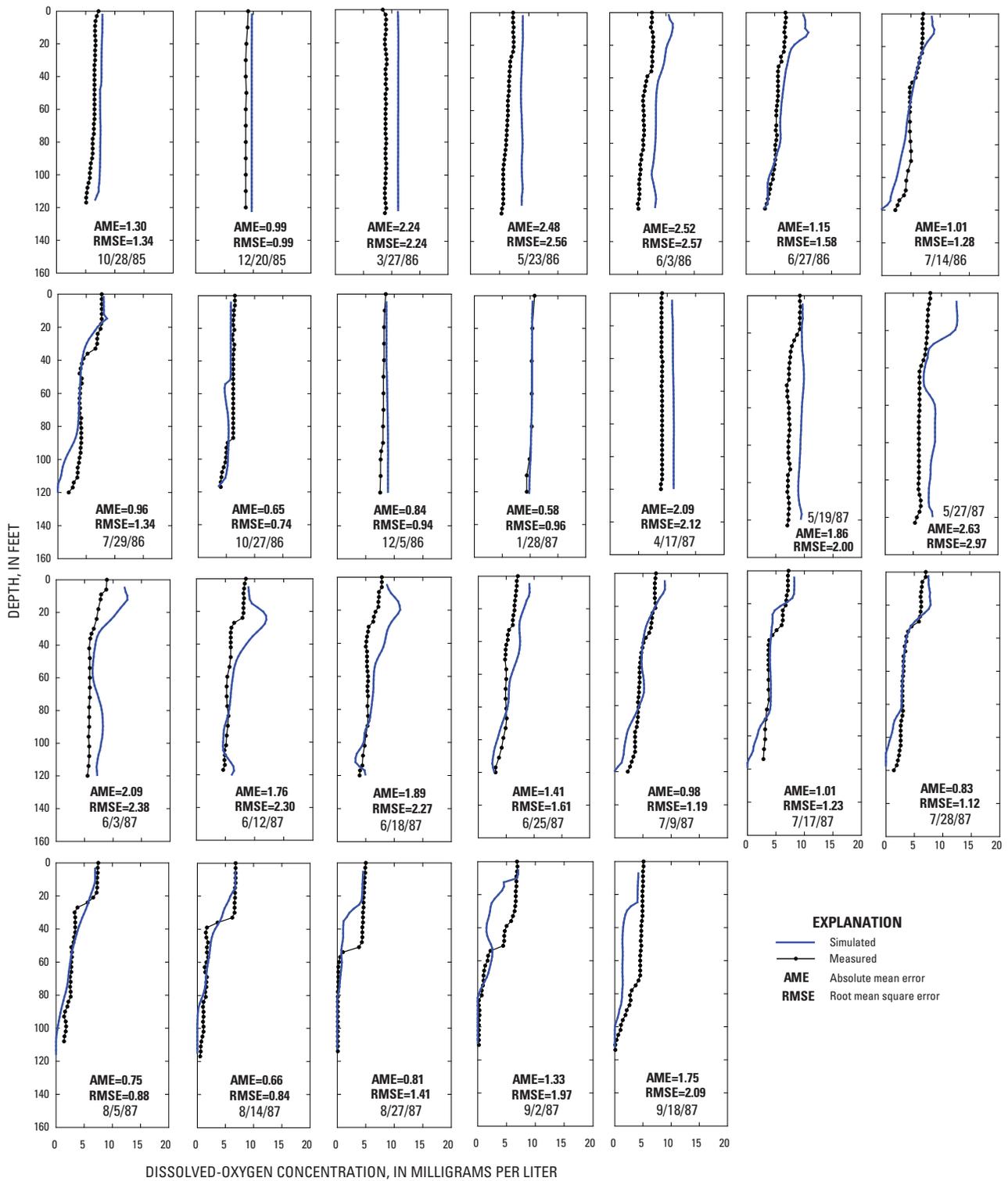
Figure 13.   Simulated and measured dissolved-oxygen concentration profiles for Pueblo Reservoir, Colorado, at site 7B, October 1985 through September 1987.

Figure 14.   Simulated daily and measured total-dissolved solids concentrations at four sites in Pueblo Reservoir, Colorado, October 1985 through September 1987.
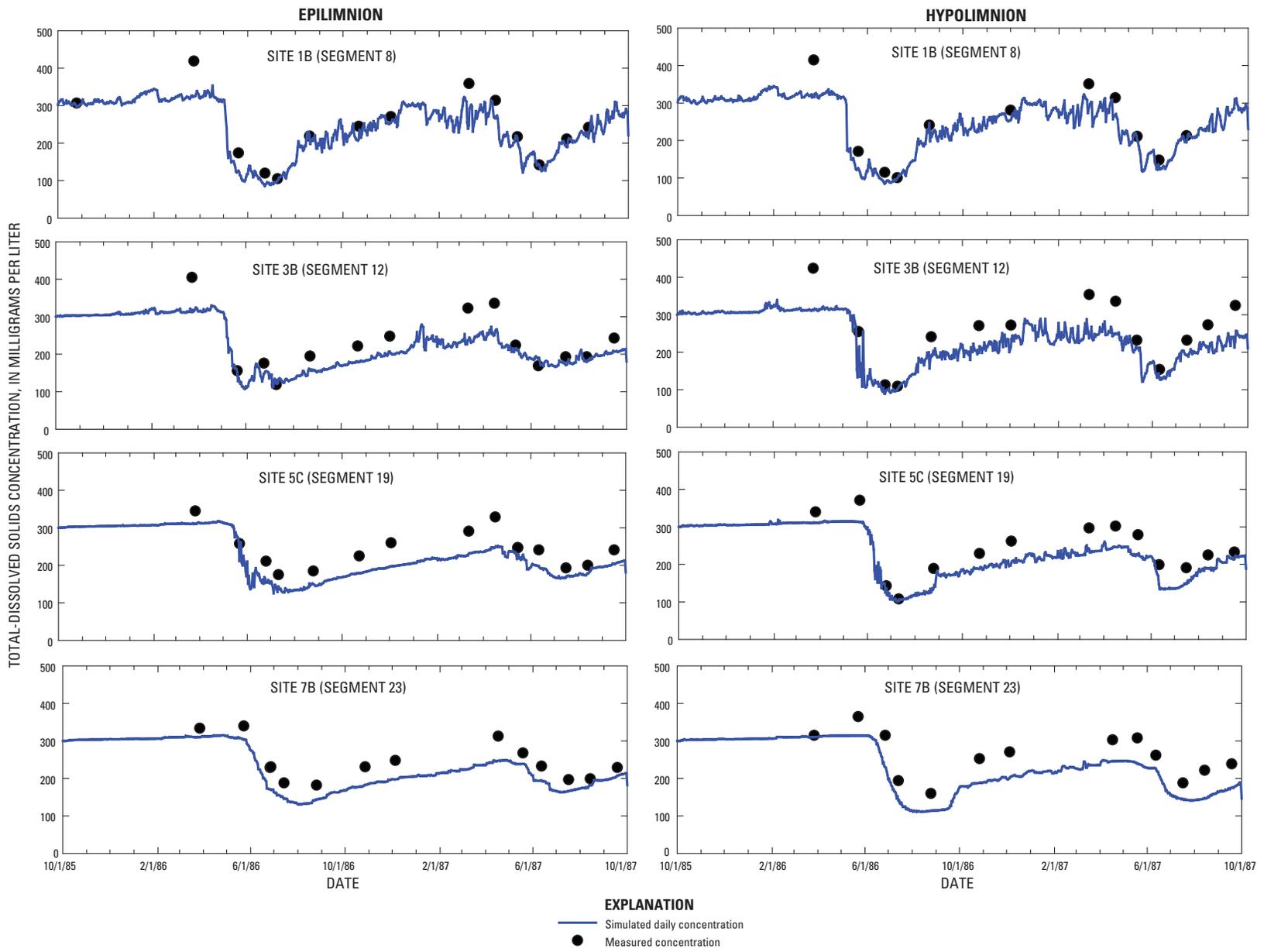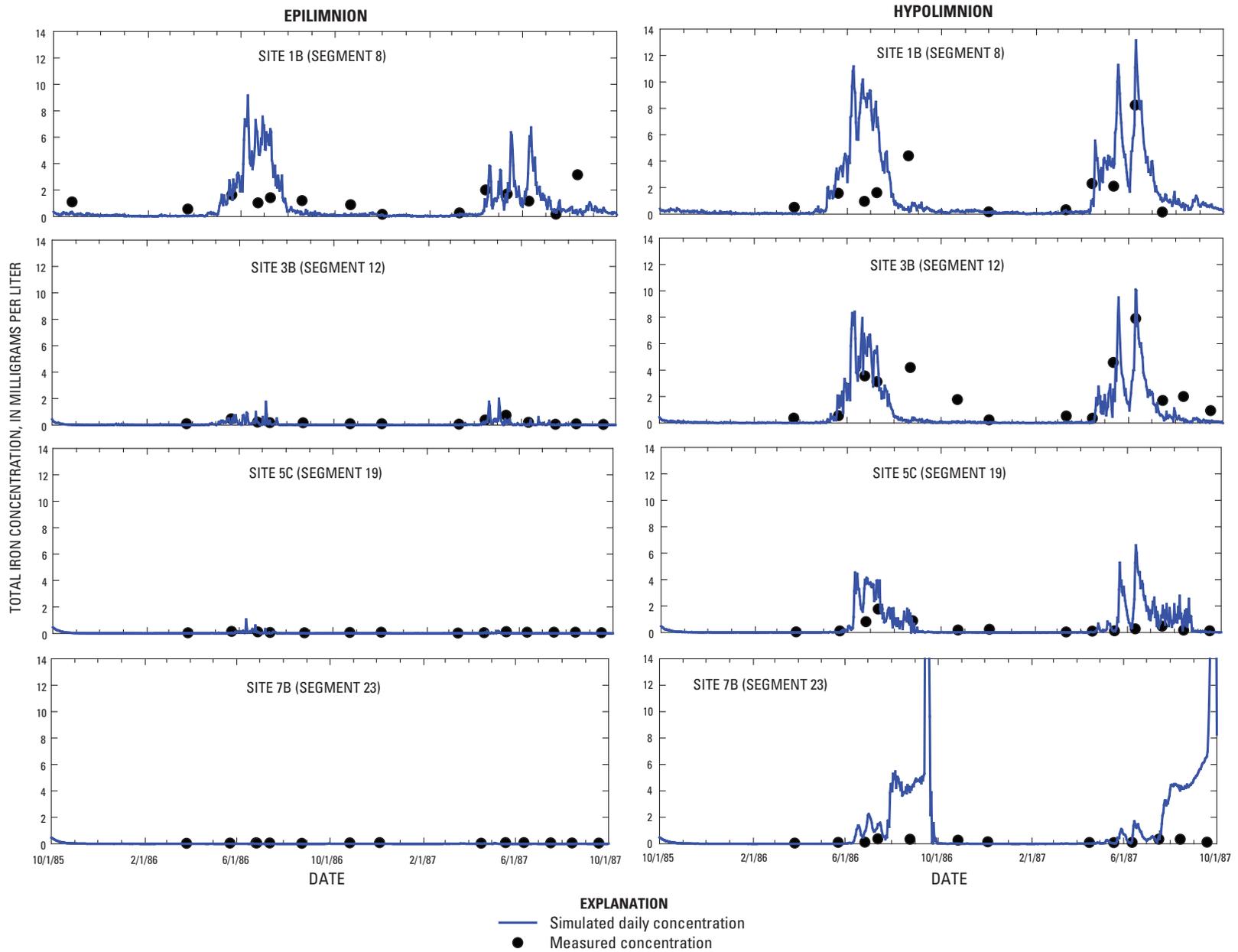
Figure 15. Simulated daily and measured total iron concentrations at four sites in Pueblo Reservoir, Colorado, October 1985 through September 1987.

may be slightly underpredicted, resulting in more release of iron from the bottom sediment. The differences at the downstream end (site 7B) probably also are caused by lower simulated dissolved oxygen than the ambient conditions, resulting in more iron released from the sediment. The difference between simulated and measured concentrations at sites 3B and 5C were comparatively less than observed at sites 1B and 7B. The AME at sites 3B and 5C were 0.84 and 0.41 mg/L, respectively and the RMSE for sites 3B and 5C were 1.09 and 0.55 mg/L, respectively (table 3).

Nutrients

Nutrient concentrations in the Pueblo Reservoir model were affected by a number of processes. Nitrate in the Pueblo Reservoir model is contributed by tributary inflows and nitrification of ammonia, and is consumed by algal uptake during growth and denitrification in anaerobic conditions. Sources of ammonia (NH_3) and ammonium (NH_4^+), referred to as "ammonia" in this report, include tributary inflows, algal respiration, decay of organic matter, and anaerobic release from bottom sediments. Sinks include nitrification (conversion to nitrate) algal uptake during growth, and reservoir outflow (Cole and Wells, 2003). Sources of orthophosphorus in the Pueblo Reservoir model included tributary inflow, algal respiration, decay of organic matter in the sediment and water column, and anaerobic release from bottom sediments. Sinks included algal uptake during growth, settling of particles containing or absorbing phosphorus, and reservoir outflow (Cole and Wells, 2003).

The distribution of nitrate and ammonia in Pueblo Reservoir was affected mainly by the hydrodynamics and the algal dynamics in the reservoir. Nitrate and ammonia concentrations at site 1B were higher in the epilimnion compared to the hypolimnion, and concentrations at site 1B were higher when compared to sites farther downstream in the reservoir (figs. 16 and 17). The concentrations at 1B were higher than farther downstream possibly because the site is in a more riverine section of the reservoir, where the reservoir cross section is relatively narrow, the water is well mixed, and velocities are high enough to move fine suspended particles, reducing light penetration and limiting algal production in the epilimnion. Farther downstream, the reservoir transitions into a zone where velocities decrease, resulting in a large portion of the suspended material to settle out of the water column, allowing more light penetration into the water column, which increases the rates of photosynthetic productivity in this zone. Nitrate and ammonia are readily utilized by algae during growth, and are consumed relatively quickly in the transitional zone, when the suspended material in the reservoir settles out, and light penetration into the water column allows for greater photosynthetic productivity of algae. Most of the ammonia and nitrate are consumed in the transitional zone, resulting in relatively low concentrations in the epilimnion of the more lacustrine, downstream part of the reservoir.

Higher nitrate and ammonia concentrations in the hypolimnion also can be attributed to the placement of inflow because of density gradients. In the spring, when most of the high-flow events occur, the inflow water is colder (more dense) than in the epilimnion of the reservoir, and the constituent load is distributed near the bottom of the reservoir in the hypolimnion where the nitrate and ammonia is unavailable for algal uptake.

The Pueblo Reservoir model generally simulated lower concentrations of nitrate and ammonia compared to measured concentrations (figs. 16 and 17). The mean difference between simulated and measured nitrate was -0.01 (site 1B), -0.04 (sites 3B and 5C), and -0.09 mg/L as nitrogen (site 7B) (table 3). The AME ranged from 0.05 (site 5C) to 0.15 mg/L as nitrogen (site 7B), and the RMSE ranged from 0.07 (site 5C) to 0.18 mg/L as nitrogen (site 7B). For ammonia, the mean difference between simulated and measured concentrations were -0.04 (site 1B), -0.05 (site 3B), -0.02 (site 5C), and -0.04 mg/L as nitrogen (site 7B) (table 3). The AME ranged from 0.04 (site 7B) to 0.05 mg/L as nitrogen (sites 1B, 3B, and 5C), and the RMSE ranged from 0.04 (site 7B) to 0.06 mg/L as nitrogen (site 5C). The temporal dynamics of nitrate and ammonia is somewhat uncertain because simulated values were compared to only a small number of measured values from April through September.

Simulated total nitrogen concentrations compared relatively well to measured concentrations in the Pueblo Reservoir model (fig. 18). Although measured nitrite plus nitrate and ammonia data were sparse during the calibration period, a total of 100 total nitrogen samples were collected from April 1986 through September 1987. The AME ranged from 0.21 (site 1B) to 0.27 mg/L as nitrogen (sites 3B and 7B), and the RMSE ranged from 0.21 (site 1B) to 0.29 mg/L as nitrogen (sites 3B and 7B) (table 3). The total nitrogen concentrations generally were overpredicted in the model with mean differences ranging from 0.02 to 0.14 mg/L as nitrogen.

The distribution of phosphorus in Pueblo Reservoir also was mainly affected by the hydrodynamics and the algal dynamics in the reservoir. Similar to nitrate and ammonia, higher concentrations were measured in the epilimnion compared to the hypolimnion at site 1B (figs. 19 and 20). Farther downstream at sites 3B, 5C, and 7B, the measured concentrations were higher in the hypolimnion than in the epilimnion, and concentrations at both depths were lower than observed at site 1B. The orthophosphorus probably is consumed quickly in the transitional zone because of the greater photosynthetic productivity of algae, resulting in lower concentrations in the epilimnion. Even farther downstream, where the reservoir has more lacustrine characteristics, most of the orthophosphorus has been consumed and generally is no longer available for uptake by algae, therefore limiting algal growth in this zone. Higher concentrations in the hypolimnion also could be attributed to the cold, dense inflow that transports constituents into the reservoir at greater depths (underflow).

Simulated orthophosphorus concentrations in the Pueblo Reservoir model were similar to the measured concentrations

Figure 16. Simulated daily and measured nitrite plus nitrate concentrations at four sites in Pueblo Reservoir, Colorado, October 1985 through September 1987.

Figure 17.   Simulated daily and measured ammonia concentrations at four sites in Pueblo Reservoir, Colorado, October 1985 through September 1987.

Figure 18. Simulated daily and measured total nitrogen concentrations at four sites in Pueblo Reservoir, Colorado, October 1985 through September 1987.

Figure 19. Simulated daily and measured orthophosphorus concentrations at four sites in Pueblo Reservoir, Colorado, October 1985 through September 1987.
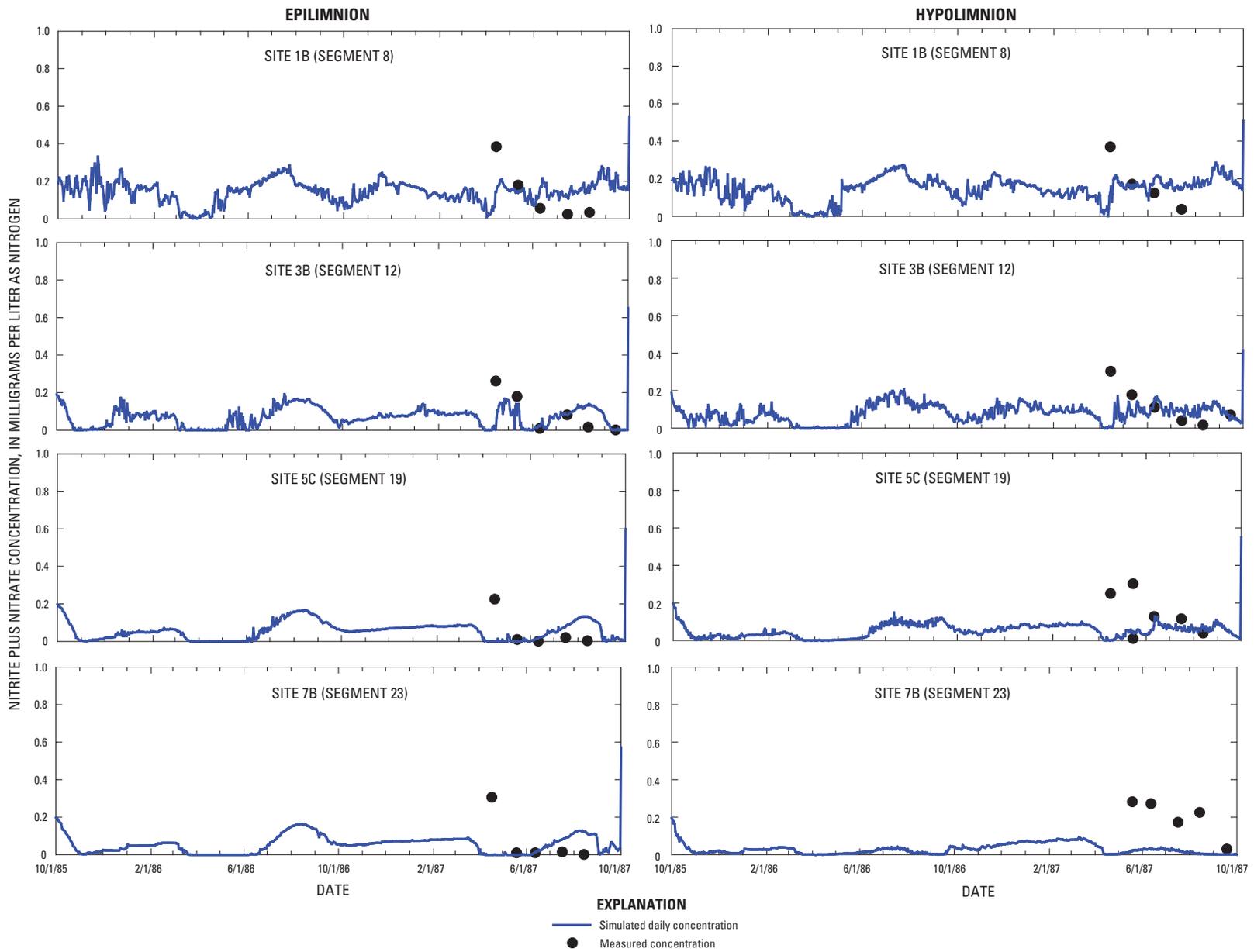
Figure 20. Simulated daily and measured total phosphorus concentrations at four sites in Pueblo Reservoir, Colorado, October 1985 through September 1987.

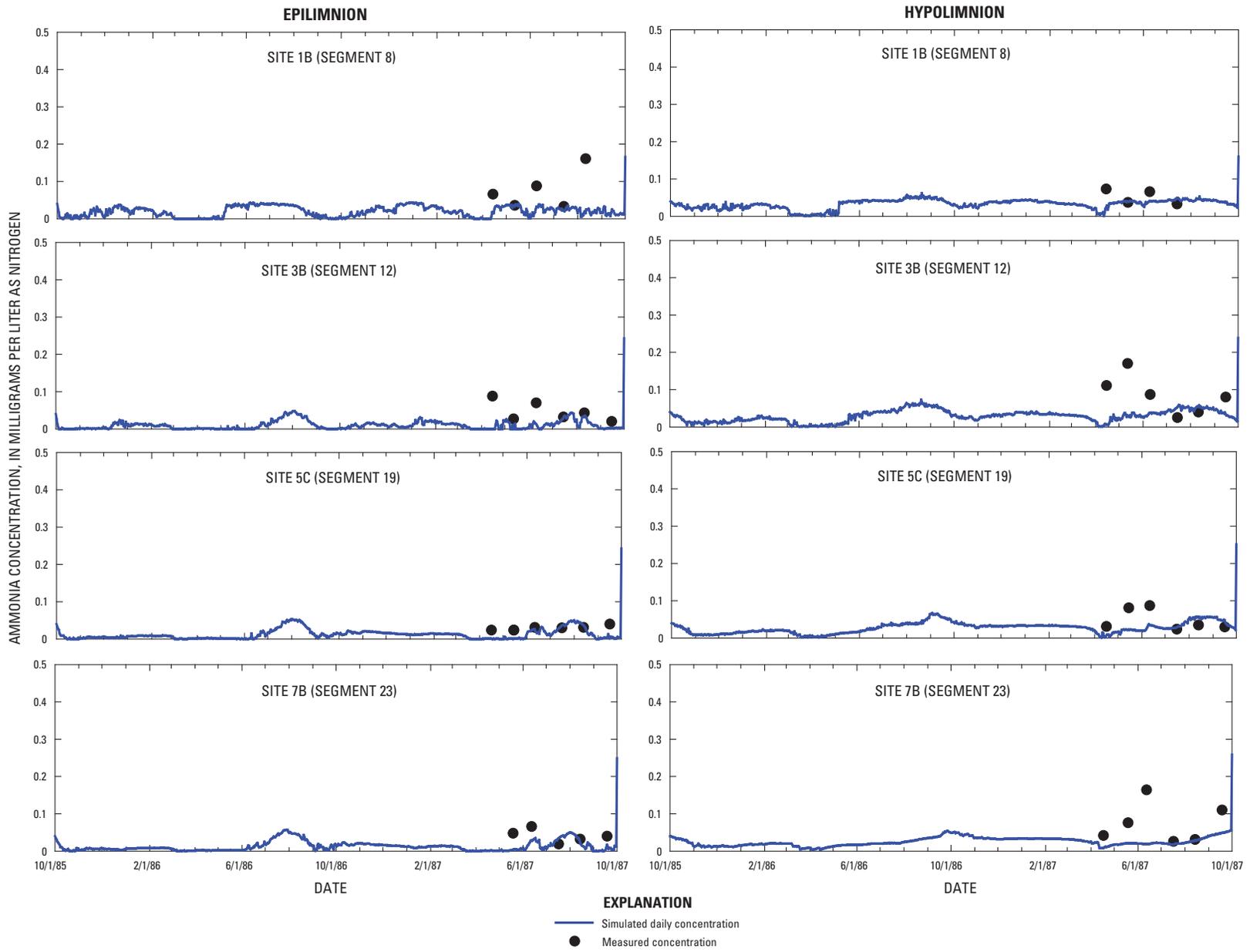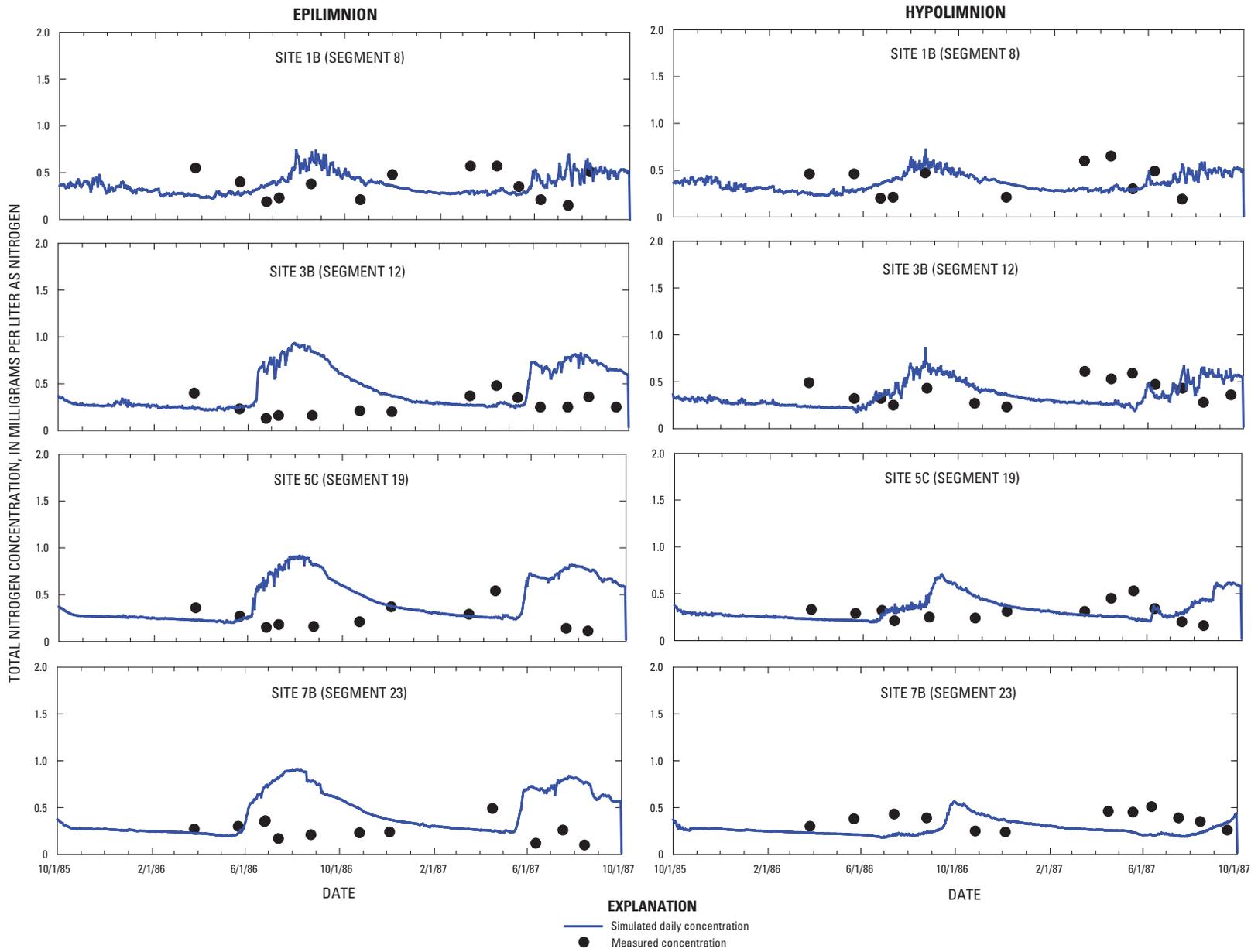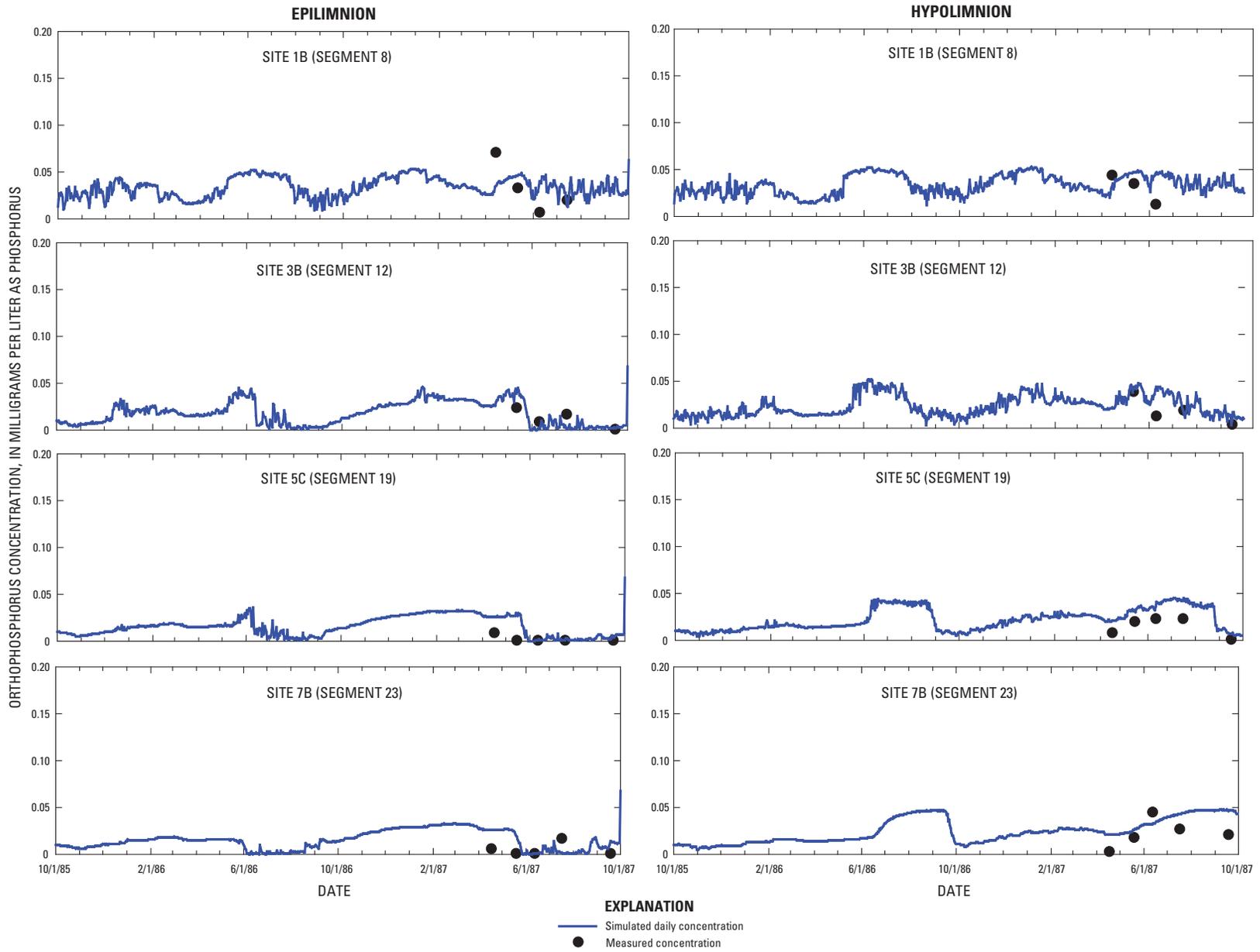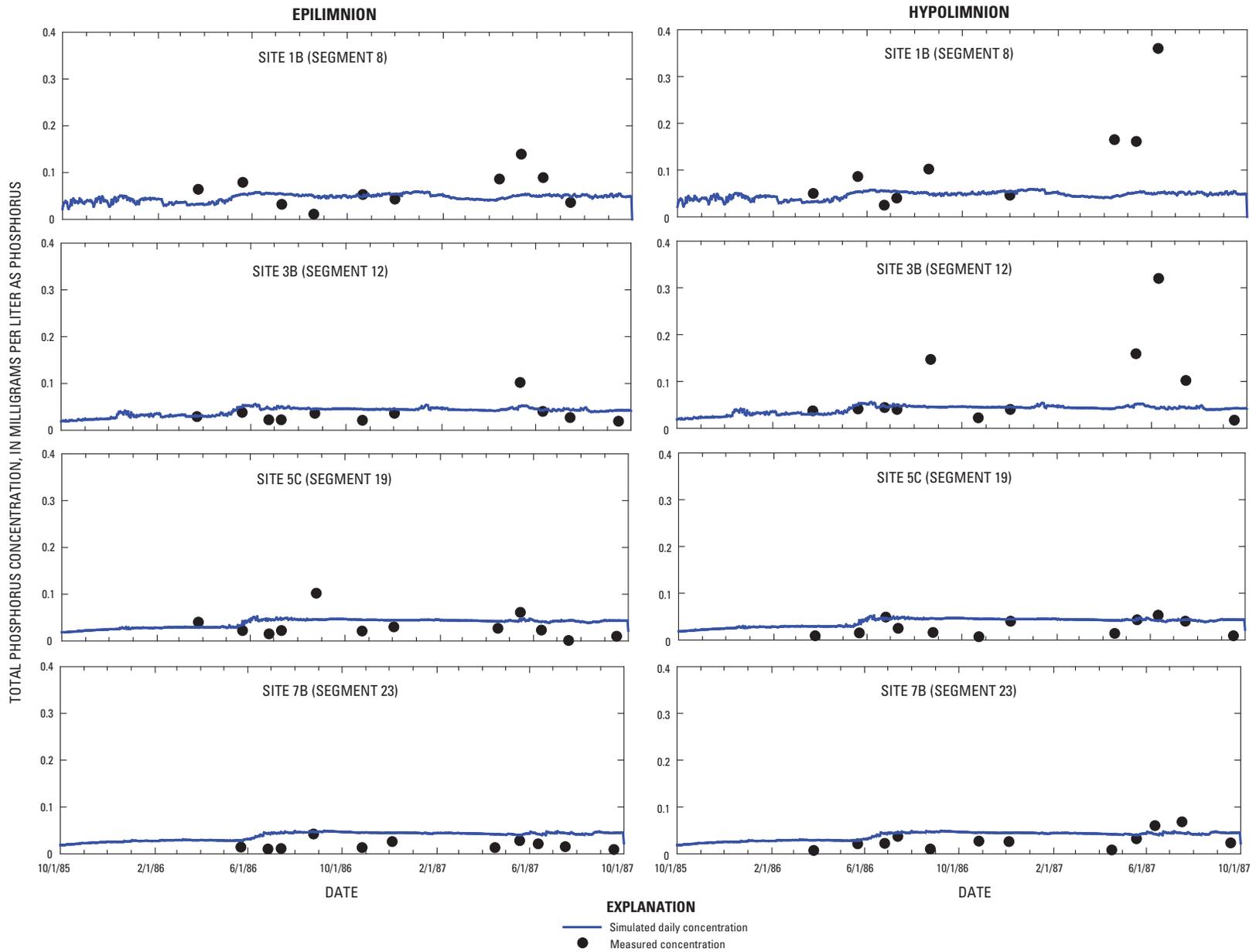for October 1985 through September 1987 (fig. 19). The AME for orthophosphorus ranged from 0.01 (sites 3B and 5C) to 0.02 mg/L as phosphorus (sites 1B and 7C), and the RMSE ranged from 0.01 (sites 3B and 5C) to 0.02 mg/L as phosphorus (sites 1B and 7C) (table 3). The temporal dynamics of orthophosphorus is somewhat uncertain because simulated values were compared to only 35 measured values from April through September 1987.

Although measured orthophosphorus data were sparse during the calibration period, a total of 88 total phosphorus samples were collected from April 1986 through September 1987 to compare with simulated values (fig. 20). The AME for total phosphorus ranged from 0.02 (sites 5C and 7B) to 0.05 mg/L as phosphorus (site 1B), and the RMSE ranged from 0.02 (sites 5C and 7B) to 0.05 mg/L as phosphorus (sites 1B and 3B) (table 3). The greatest difference between simulated and measured values occurred in the hypolimnion at sites 1B and 3B in May through July 1987, where simulated concentrations were considerably less than the measured concentrations (fig. 20). A possible explanation for the lower simulated concentrations during that period may be that daily inflow concentrations from the Arkansas River may have been underestimated, or phosphorus associated with settling organic matter may not have been completely simulated during that period.

Algae

The composition and dynamics of the algal community in a reservoir can be highly complex. Modeling of the algal dynamics and composition is a simplification of what actually occurs in a reservoir. In the Pueblo Reservoir model, the diverse species composition was generalized into four main groups to reduce the complexity of the modeling effort and to limit the uncertainty due to limited data availability. The four algal groups modeled as part of this report include blue-green algae, green algae, diatoms, and flagellates. The four groups generally reflect the dominant algal communities measured in Pueblo Reservoir (Edelmann, 1989 and Lewis and Edelmann, 1994). Algal growth in the Pueblo Reservoir model was affected by temperature, light, and the availability of nutrients. Decreases in algal population in the model were due to mortality, respiration, excretion, and settling to the bottom sediments (Cole and Wells, 2003).

The simulated distribution of algal populations was highly variable in Pueblo Reservoir from October 1985 through September 1987 (fig. 21). The highest algal biomass in Pueblo Reservoir generally occurred from May through September when blue-green and green algae were the dominant algal groups in the reservoir. The lowest algal biomass generally occurred from November through March when diatoms and flagellates were the dominant groups. Lewis and Edelmann (1994) showed similar results with measured phytoplankton data. Seasonal differences in algal communities were the result of nutrient availability and differences in water temperature. Blue-green and green algae generally favor

relatively higher water temperatures, whereas diatoms and flagellates generally favor colder temperatures (Wetzel, 2001). Blue-green algae had the highest overall concentrations of the four algal groups mainly because some species are able to fix nitrogen, which was accounted for in the Pueblo Reservoir model by designating the half-saturation constant for nitrogen limited growth as 0 grams per cubic meter (table 2).

Generally, simulated chlorophyll *a* concentrations were similar to measured concentrations in Pueblo Reservoir from October 1985 through September 1987 (fig. 22). The highest chlorophyll *a* concentrations occurred at the two upstream reservoir sites, where the AME ranged from 3.0 (site 1B) to 3.7 µg/L (site 3B), and the RMSE ranged from 5.3 (site 1B) to 6.8 µg/L (site 3B) (table 3). Chlorophyll *a* concentrations were generally lower in the downstream part of the reservoir (sites 5C and 7B) where nutrients were less available for algal growth. The AME ranged from 1.6 (site 7B) to 2.2 µg/L (site 5C), and the RMSE ranged from 2.5 (site 7B) to 3.7 µg/L (site 5C) (table 3). Overall, the CE-QUAL-W2 model slightly under predicted chlorophyll *a* concentrations although the temporal fluctuations generally were similar to the measured concentrations. The mean differences between simulated and measured chlorophyll *a* concentrations were -2.1 (site 1B), -1.9 (site 3B), -1.4 (site 5C), and -0.4 µg/L (site 7B).

Verification

In order to assess the applicability of the model, the calibrated model was applied over a range of hydrologic conditions in Pueblo Reservoir from October 1999 through September 2002. This 3-year period represented a relatively wet year (WY 2000), an average year (WY 2001), and a dry year (WY 2002). Water-surface elevations in Pueblo Reservoir during the calibration period (WY 1986 and WY 1987) were similar to those observed during the first year of the verification period (fig. 5).

Relative to the calibration period, simulated water temperatures during the verification period did not compare as well to measured water temperatures. For the verification period, the AME ranged from 1.15 (site 3B) to 1.54°C (site 5C), and the RMSE ranged from 1.35 (site 3B) to 1.70°C (site 5C) (figs. 23–25, table 4). In general, simulated water temperatures during the verification period were higher than measured water temperatures. The mean differences between simulated and measured water temperatures were 0.28 (site 3B), 0.81 (site 5C), and 1.15°C (site 7B). Water levels in Pueblo Reservoir were lower than site 1B during most of the verification period, so no comparisons were made between simulated and measured values for this site. Water levels also were lower than site 3B in the model during certain periods from October 1999 through September 2002.

From October 1999 through September 2002, simulated dissolved oxygen compared better to the measured concentrations than in October 1985 through September 1987 (calibration period). The AME ranged from 0.91 (site 5C) to 1.28 mg/L (site 7B), and the RMSE ranged from 1.03 (site 5C)
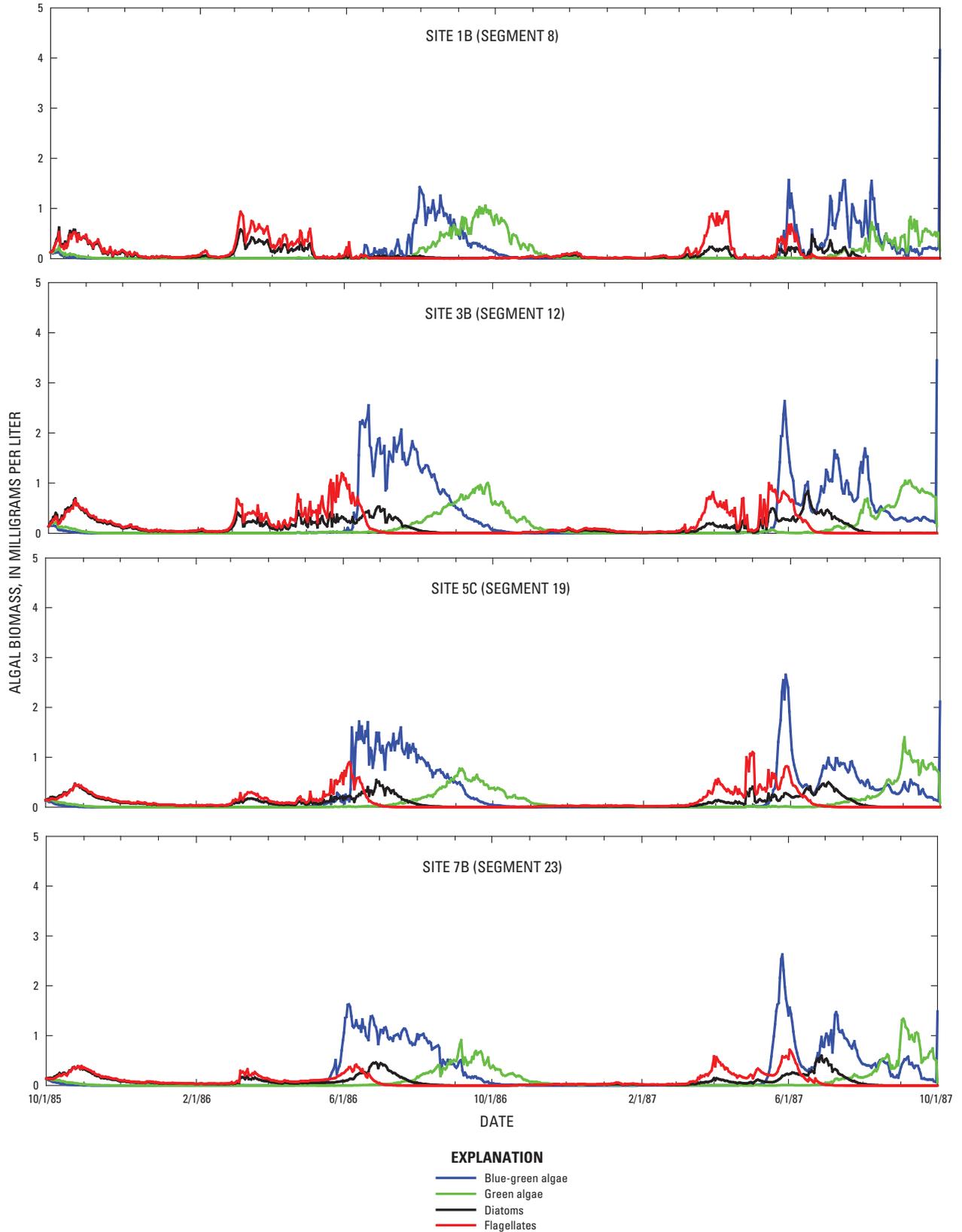
Figure 21.   Simulated algal distribution at four sites in Pueblo Reservoir, Colorado, October 1985 through September 1987.
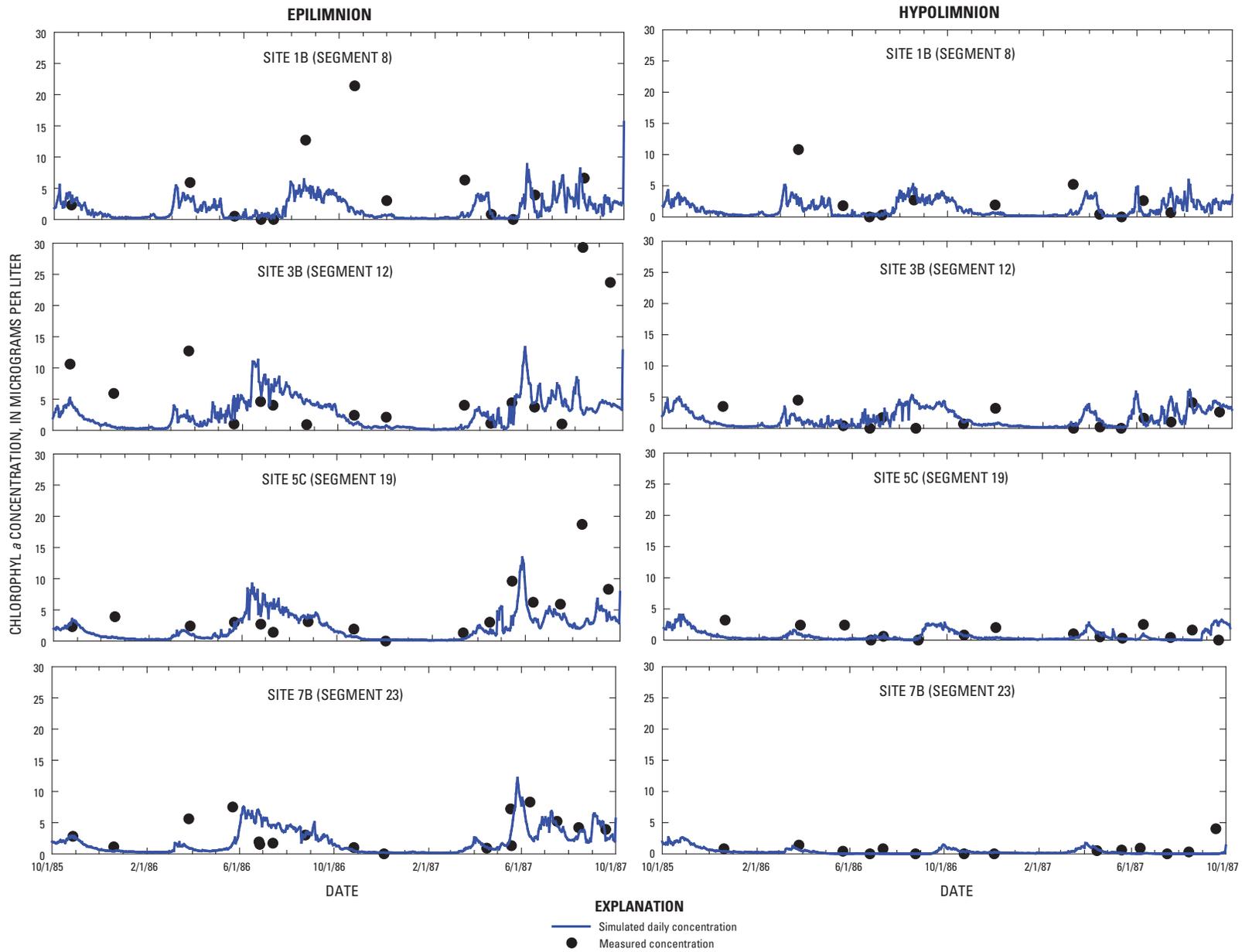
Figure 22.   Simulated daily and measured chlorophyll *a* concentrations at four sites in Pueblo Reservoir, Colorado, October 1985 through September 1987.
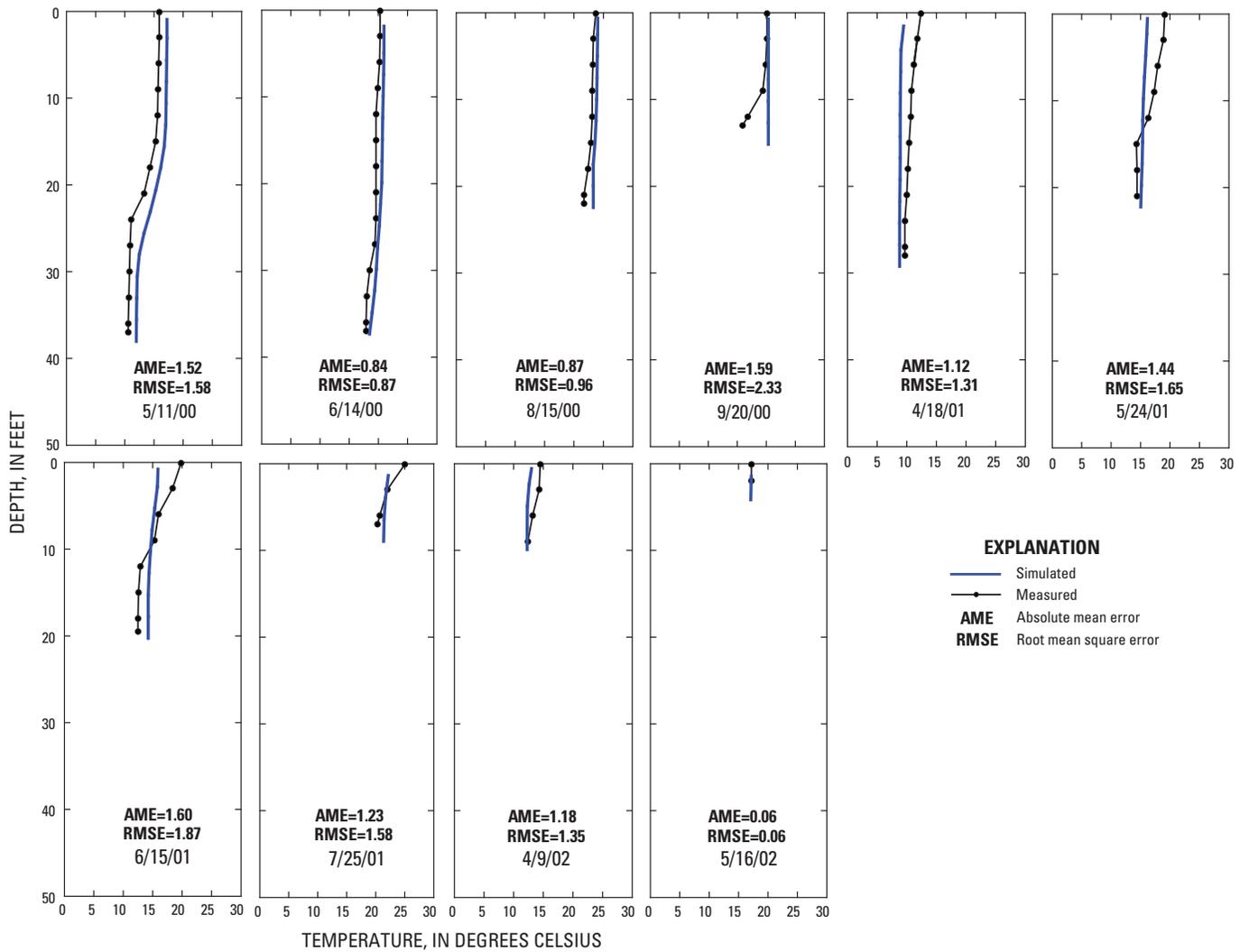
Figure 23. Simulated and measured water-temperature profiles for Pueblo Reservoir, Colorado, at site 3B, October 1999 through September 2002.
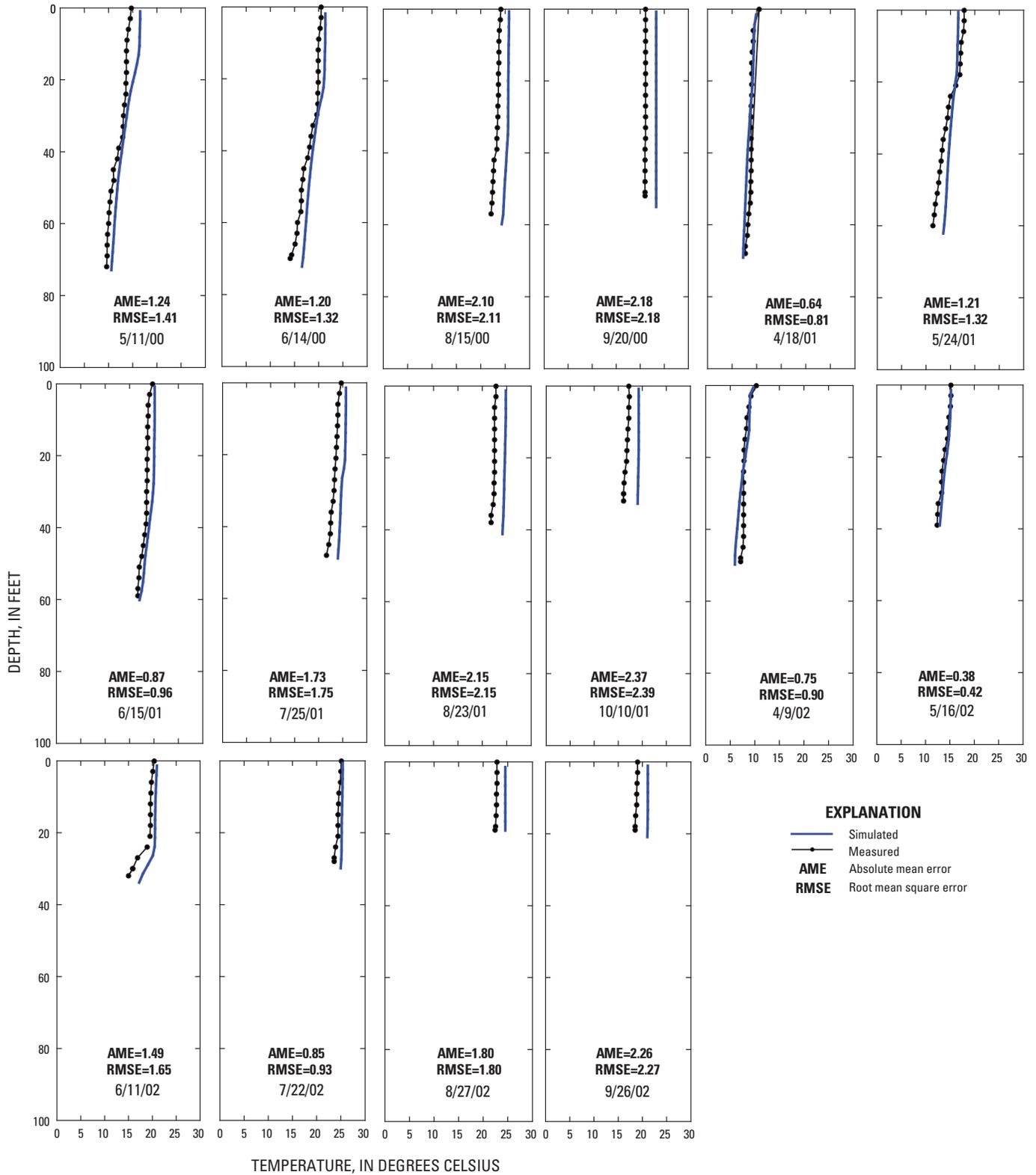
Figure 24.   Simulated and measured water-temperature profiles for Pueblo Reservoir, Colorado, at site 5C, October 1999 through September 2002.

Figure 25. Simulated and measured water-temperature profiles for Pueblo Reservoir, Colorado, at site 7B, October 1999 through September 2002.

Table 4.   Comparative statistics of simulated and measured water temperature and constituent concentrations at three sites in Pueblo Reservoir, Colorado, October 1999 through September 2002.

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

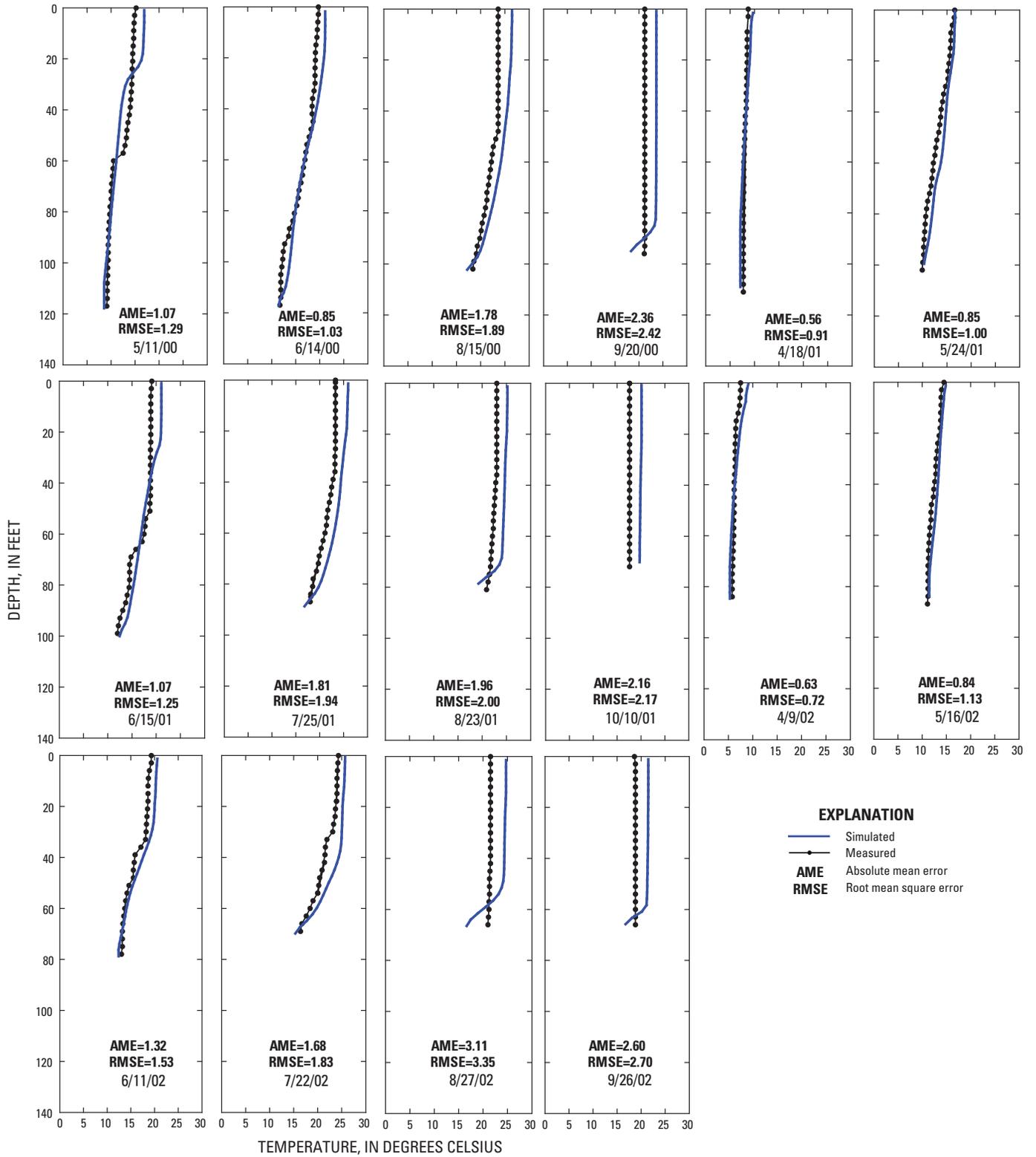| Constituent	Site number	Number of compared data points	Mean difference (simulated minus measured)	Absolute mean error	Root mean square error
Temperature, in deg. C	1B[1]	--	--	--	--
	3B	81	0.28	1.15	1.35
	5C	529	0.81	1.54	1.70
	7B	270	1.15	1.45	1.52
Dissolved oxygen, in mg/L	1B[1]	--	--	--	--
	3B	81	-0.19	0.92	1.08
	5C	272	0.12	0.91	1.03
	7B	529	-0.05	1.28	1.46
Nitrite plus nitrate, in mg/L as N	1B[1]	--	--	--	--
	3B	8	-0.12	0.13	0.15
	5C	23	-0.13	0.14	0.14
	7B	26	-0.20	0.21	0.21
Ammonia, in mg/L as N	1B[1]	--	--	--	--
	3B	8	-0.06	0.06	0.07
	5C	23	-0.02	0.03	0.03
	7B	26	-0.01	0.02	0.02
Orthophosphorus, in mg/L as P	1B[1]	--	--	--	--
	3B	8	0.01	0.01	0.01
	5C	23	0.00	0.01	0.01
	7B	26	0.01	0.01	0.01
Total phosphorus, in mg/L as P	1B[1]	--	--	--	--
	3B	8	-0.05	0.05	0.06
	5C	23	0.00	0.01	0.01
	7B	25	0.01	0.02	0.02
Chorophyll *a*, in μg/L	1B[1]	--	--	--	--
	3B	4	-7.4	7.4	8.9
	5C	7	-6.5	6.5	7.5
	7B	10	-2.5	2.5	3.1

[1]Water levels in Pueblo Reservoir were lower than site 1B during most of the verification period, so no comparisons were made between simulated and measured values for this site

to 1.46 mg/L (site 7B) for the verification period (table 4 and figs. 26-28). The mean differences between simulated and measured dissolved-oxygen concentrations were -0.19 mg/L at site 3B, 0.12 mg/L at site 5C, and -0.05 mg/L at site 7B. Unlike the calibration period, where simulated concentrations deviated more from the measured concentrations in the epilimnion compared to the hypolimnion, the verification period showed the greatest differences in the hypolimnion.

During the verification period, no samples were collected in Pueblo Reservoir for the analysis of TDS and, as such, direct comparisons to simulated TDS could not be done. However, numerous SC profiles were collected in the reservoir at sites 3B, 5C, and 7B. No profile data were available at site 1B during this period. Because TDS data were not available from reservoir sites during the verification period, in-reservoir SC data were used to compare to simulated TDS. Specific conductance generally will reflect the dissolved-solids data, although a statistical evaluation of the simulated data was not conducted. Simulated TDS followed the same patterns through time as the measured SC data during the verification period (fig. 29).

Simulated nitrate did not compare as well to measured concentrations as in the calibration period. The AME ranged from 0.13 (site 3B) to 0.21 mg/L (site 7B) as nitrogen, and the RMSE ranged from 0.15 (site 3B) to 0.21 mg/L (site 7B) as nitrogen (table 4 and fig. 30). Simulated nitrate generally was less than the measured concentrations during the verification period with mean differences of -0.12 (site 3B), -0.13 (site 5C), and -0.20 mg/L (site 7B) as nitrogen (table 4). Total nitrogen data were not available for the verification period for comparison between simulated and measured values.

Simulated ammonia, orthophosphorus, and total phosphorus compared better to measured concentrations during the verification period than during the calibration period. The AME for ammonia ranged from 0.02 (site 7B) to 0.06 mg/L (site 3B) as nitrogen, and the RMSE ranged from 0.02 (site 7B) to 0.07 mg/L as nitrogen (site 3B) (table 4 and fig. 31). The AME and RMSE for orthophosphorus were both 0.01 mg/L as phosphorus for all of the sites (table 4 and fig. 32). The AME for total phosphorus ranged from 0.01 (site 5C) to 0.05 mg/L (site 3B) as phosphorus, and the RMSE ranged from 0.01 (site 5C) to 0.06 mg/L (site 3B) as phosphorus (fig. 33; table 4).

The distribution of algae in Pueblo Reservoir during the verification period differed slightly from what was observed during the calibration period. Diatoms and flagellates were the dominant algal groups in the upstream part of Pueblo Reservoir, and green and blue-green algae were the dominant groups in the downstream part of the reservoir (fig. 34). In comparison, the green and blue-green algae were the dominant algal groups throughout the reservoir during the calibration period. A possible explanation could be that decreased light penetration due to reduced water clarity limited green and blue-green algal growth in the more riverine (upstream) part of the reservoir. During much of the verification period, the volume of water in the reservoir was considerably less than what was

observed during the calibration period. Farther downstream, suspended material settled out of the water column and water clarity increased. In response to more light, more green and blue-green algal growth occurred.

Simulated chlorophyll *a* concentrations generally were less than the measured concentrations during the verification period (fig. 35). However, evaluation of how well the model simulated algal dynamics was limited because there were few measured chlorophyll *a* data during the verification period (table 4). The greatest differences were observed in the upstream part of the reservoir (site 3B) with an AME of 7.4 µg/L and a RMSE of 8.9 µg/L (table 4). However, only four measured values were available for comparison. The AME and RMSE at site 5C were 6.5 and 7.5 µg/L, respectively. The AME and RMSE at site 7B were 2.5 and 3.1 µg/L, respectively.

Sensitivity

Sensitivity analysis is the determination of the effects of small changes in calibrated model parameters and input on model results. A complete sensitivity analysis for the Pueblo Reservoir model was not conducted because the model includes a large number of parameters (table 2). However, testing of how changes in different parameters affect the hydrodynamics, temperature, and water quality were conducted as part of the model development and calibration. Results from these simulations and information from previous model studies (Haggard and Green, 2002; Galloway and Green, 2003; Galloway and Green; 2002; Green and others, 2003; Bales and others, 2001; Sullivan and Rounds, 2005; Galloway and Green, 2006) were used to identify several parameters for evaluation in the sensitivity analysis. The sensitivity of simulated water temperature and water quality were assessed with changes in the wind-sheltering coefficient, light-extinction coefficient for pure water, fraction of sediment-oxygen demand, algal growth rate (for green, blue-green, diatoms, and flagellate algal groups), algal half-saturation constant for phosphorus (for green, blue-green, diatoms, and flagellate algal groups), algal half-saturation constant for nitrogen (for green, blue-green, diatoms, and flagellate algal groups), saturation of light intensity, inflow phosphorus, inflow nitrogen, and inflow organic matter. Each selected parameter was increased and decreased by 40 percent and all other parameters held constant (table 2). Vertical profiles (at 2.5-ft depth intervals) of water temperature and concentrations of dissolved oxygen, ammonia, nitrite plus nitrate, total nitrogen, orthophosphorus, total algae, and chlorophyll *a* between the calibrated model and the sensitivity test were compared at the four monitoring sites in Pueblo Reservoir for the calibration period (October 1985 through September 1987).

Water temperature in the Pueblo Reservoir model was the most sensitive to wind speed (wind-sheltering coefficient) and light extinction in the water column (table 5). The wind-sheltering coefficient is used to adjust the windspeed in the model, which affects the amount of mixing in the reservoir and can
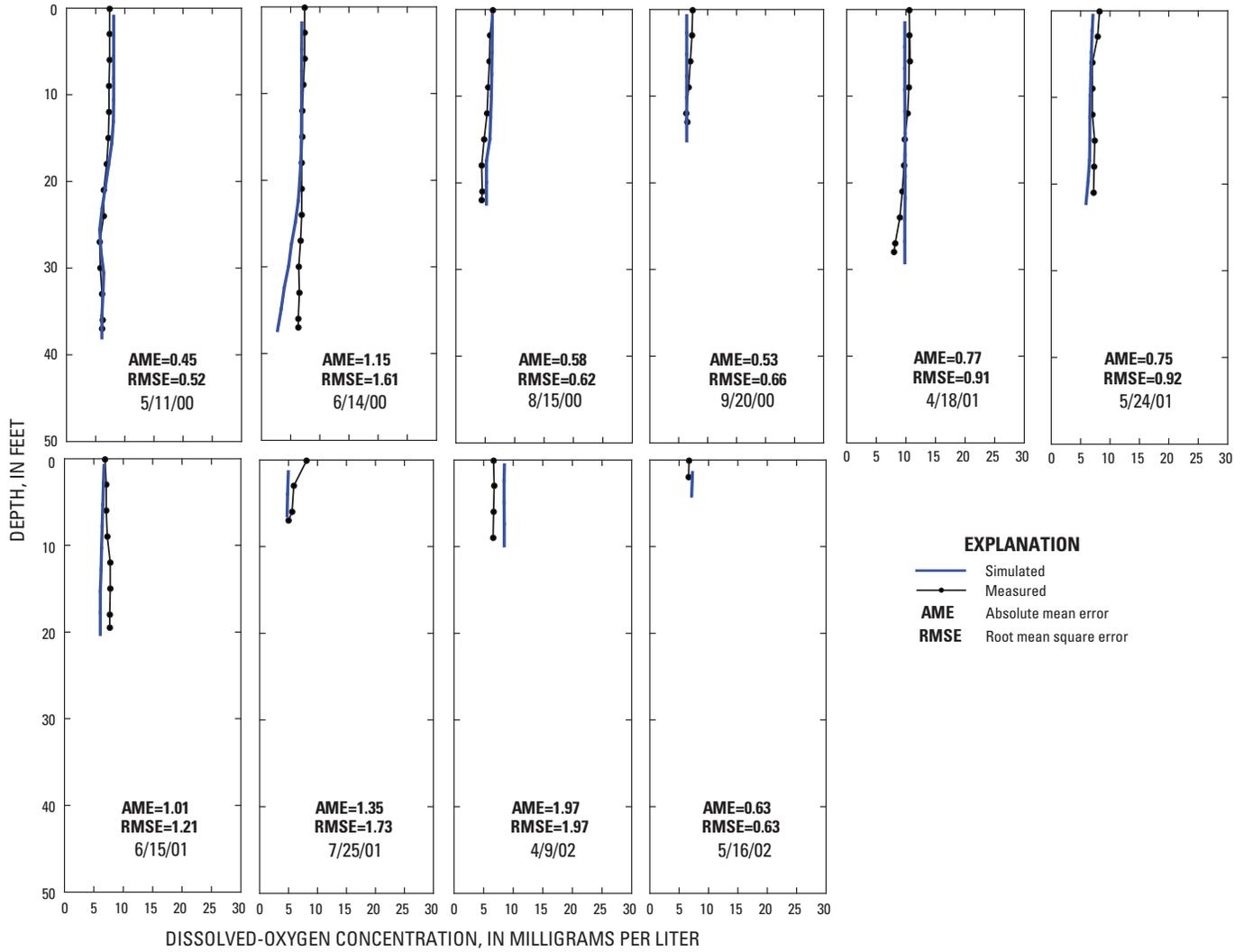
Figure 26.   Simulated and measured dissolved-oxygen concentration profiles for Pueblo Reservoir, Colorado, at site 3B, October 1999 through September 2002.
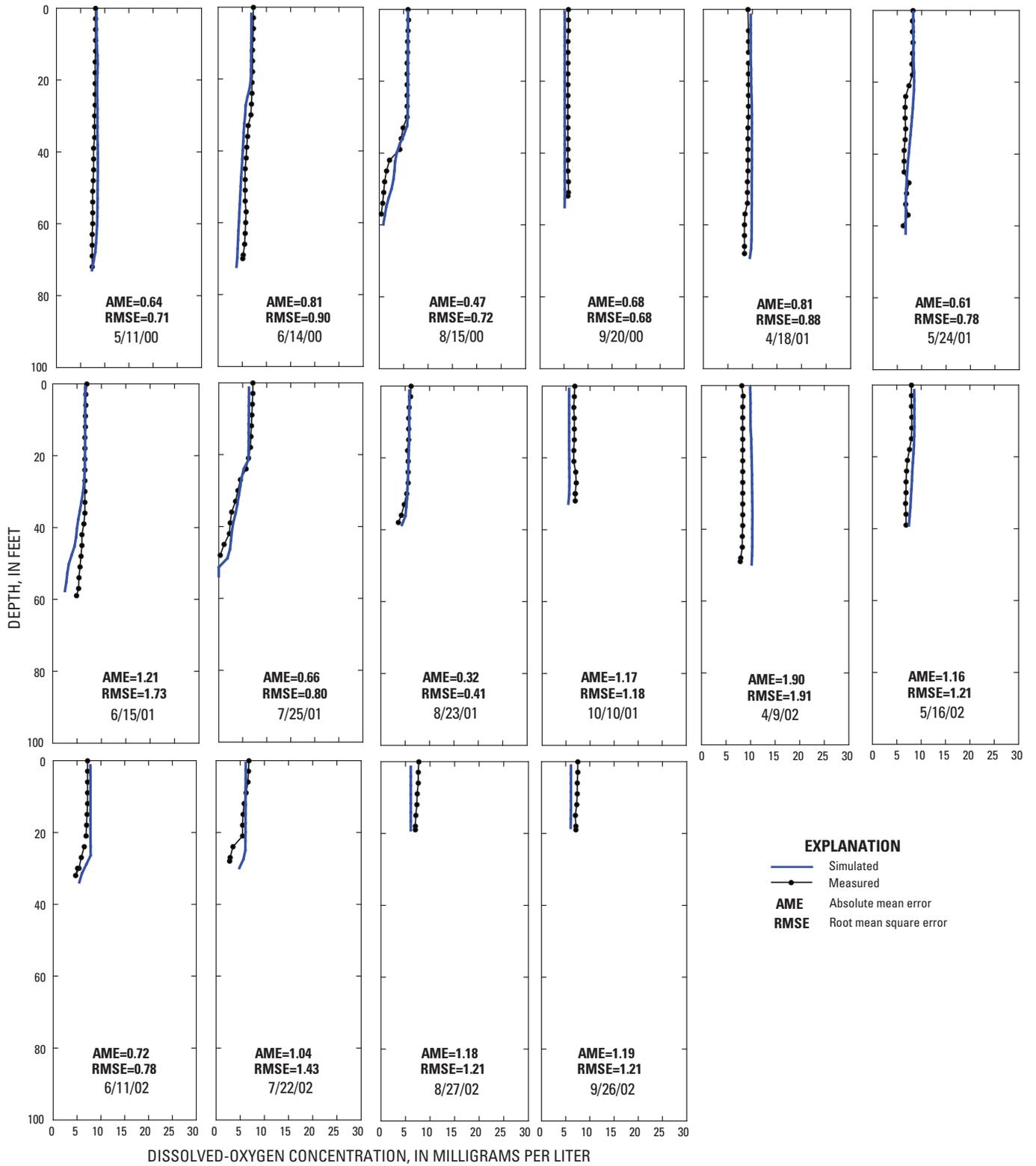
Figure 27.   Simulated and measured dissolved-oxygen concentration profiles for Pueblo Reservoir, Colorado, at site 5C, October 1999 through September 2002.
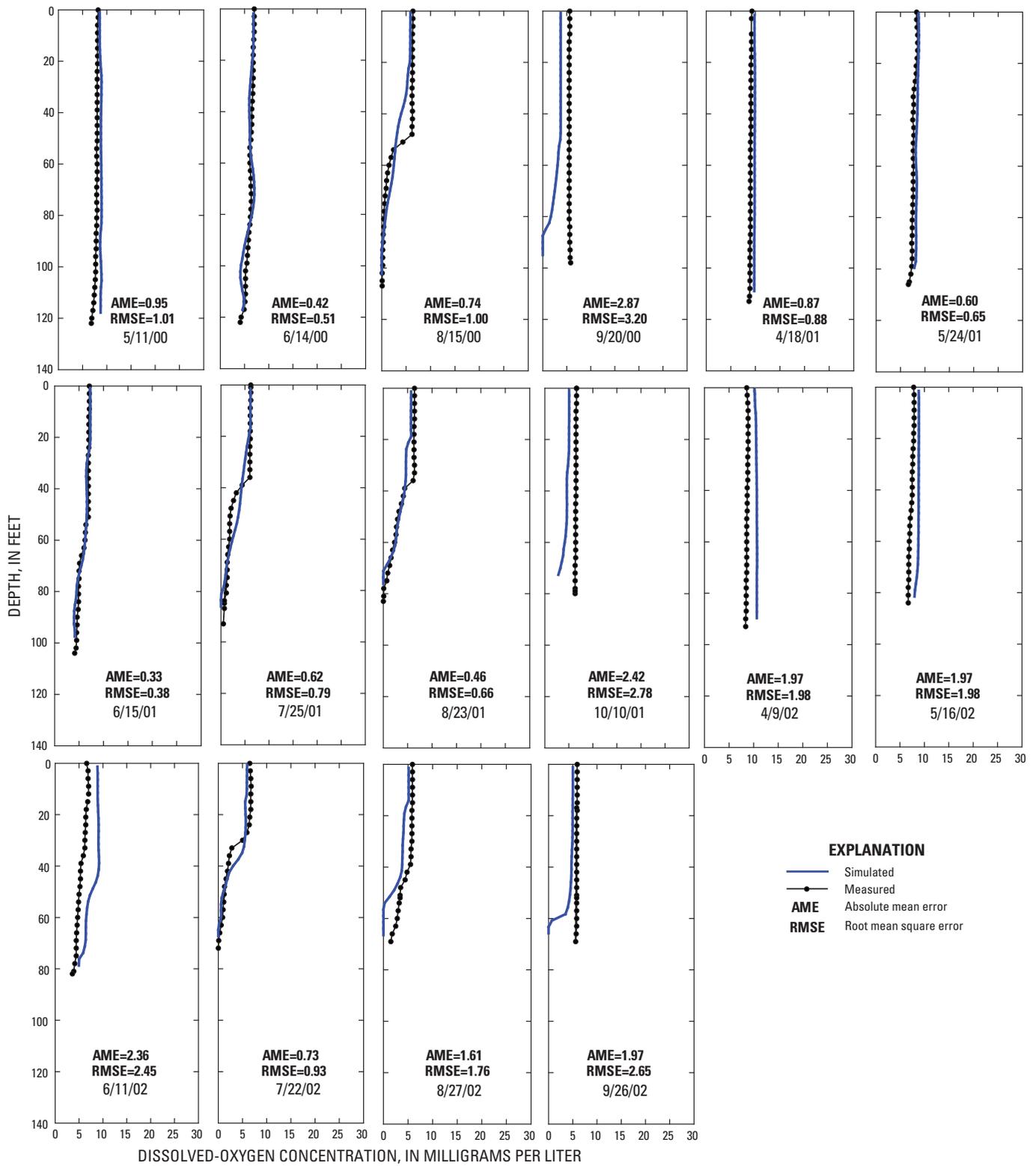
Figure 28.   Simulated and measured dissolved-oxygen concentration profiles for Pueblo Reservoir, Colorado, at site 7B, October 1999 through September 2002.
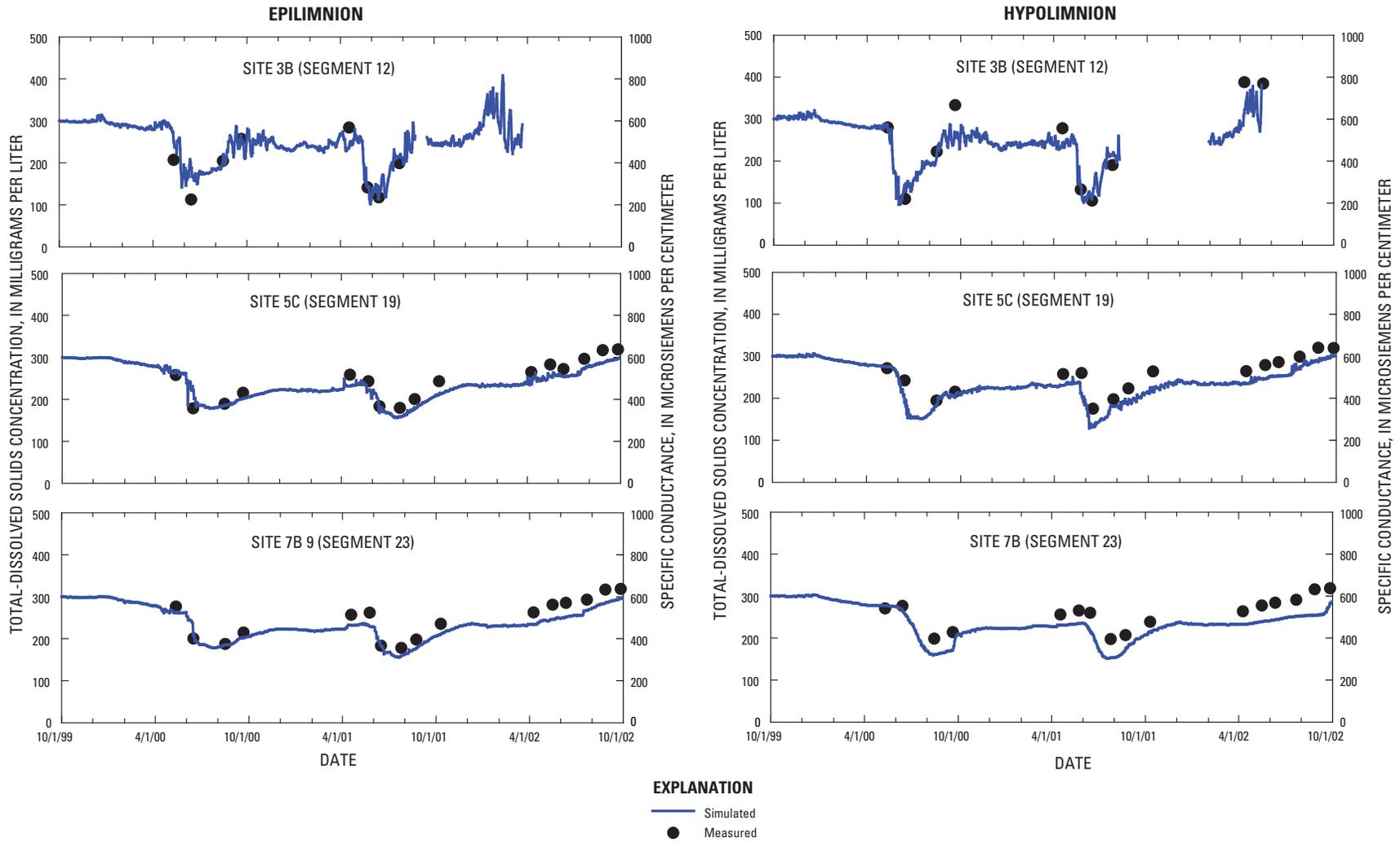
Figure 29. Simulated daily total-dissolved solids concentrations and measured specific conductance values at three sites in Pueblo Reservoir, Colorado, October 1999 through September 2002.
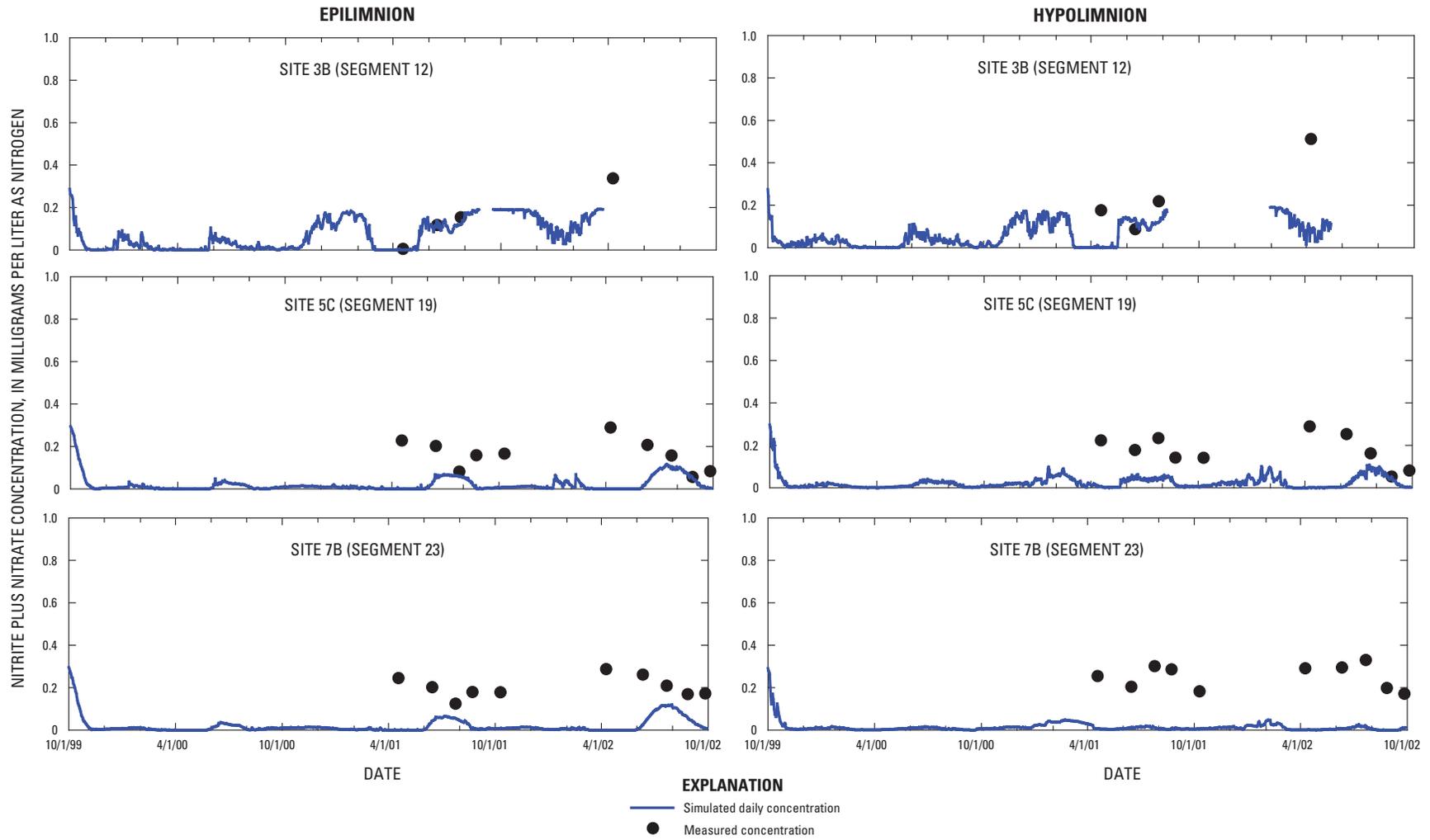
Figure 30. Simulated daily and measured nitrite plus nitrate concentrations at three sites in Pueblo Reservoir, Colorado, October 1999 through September 2002.
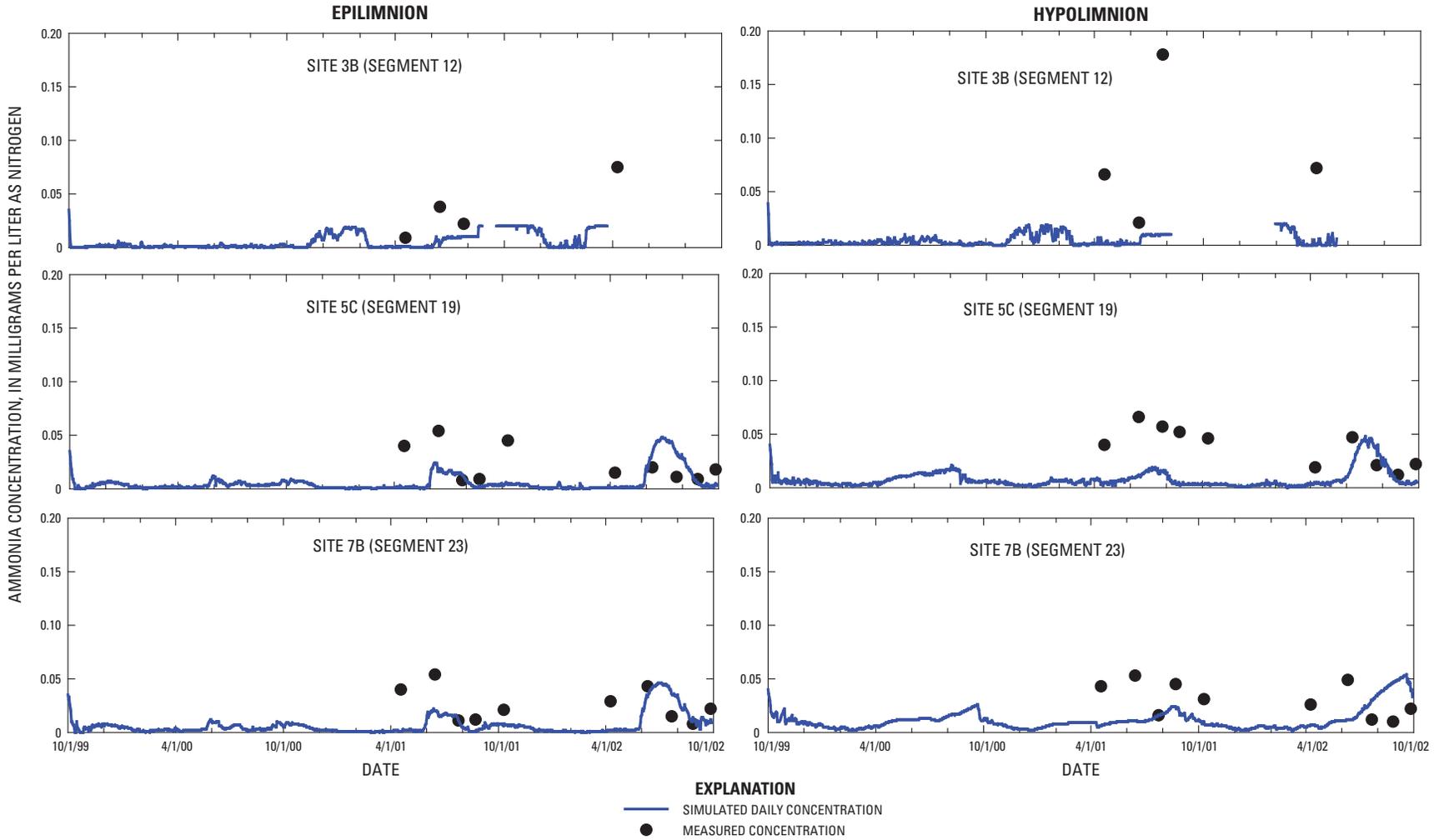
Figure 31. Simulated daily and measured ammonia concentrations at three sites in Pueblo Reservoir, October 1999 through September 2002.
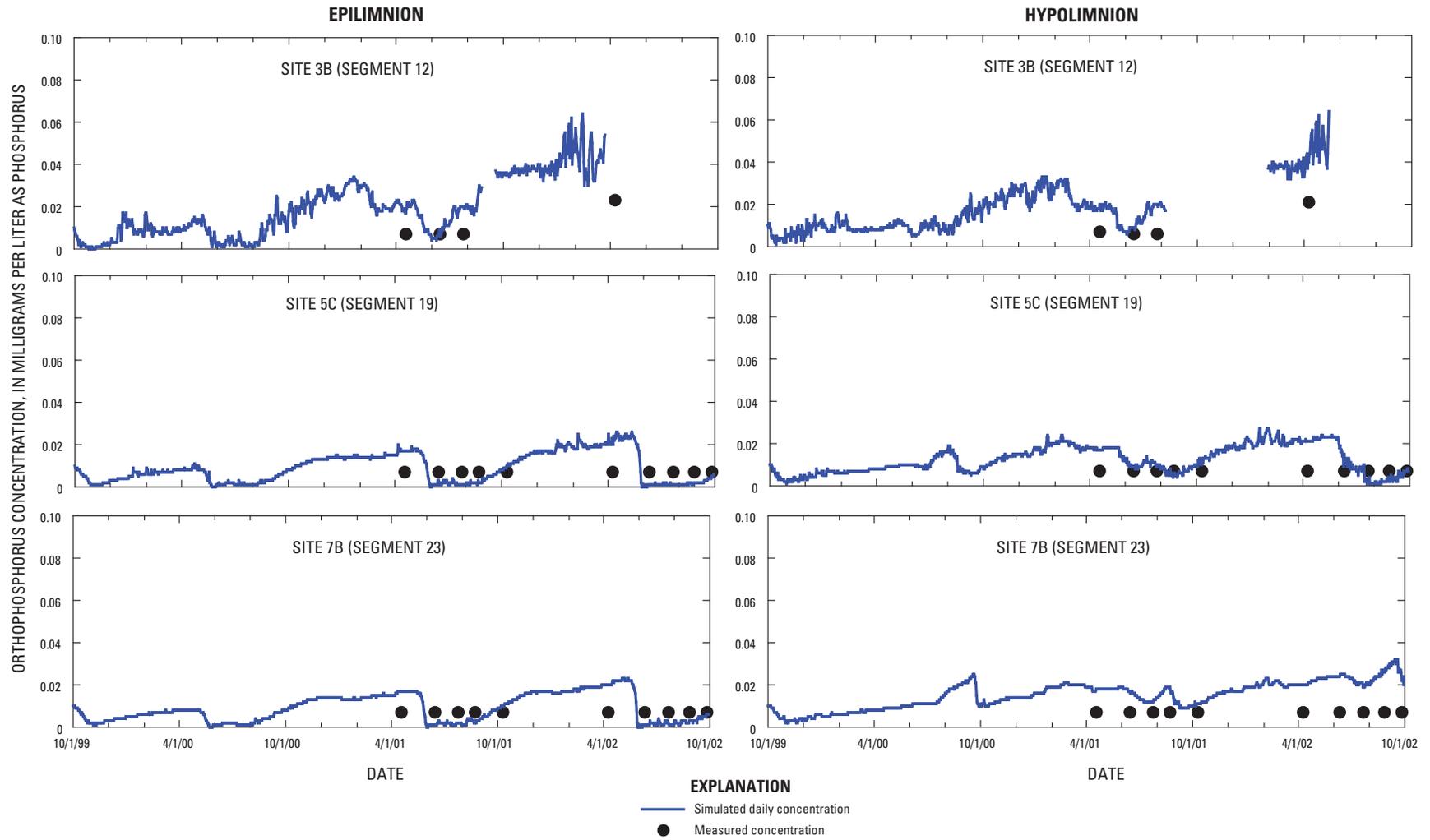
Figure 32. Simulated daily and measured orthophosphorus concentrations at three sites in Pueblo Reservoir, Colorado, October 1999 through September 2002.

Figure 33. Simulated daily and measured total phosphorus concentrations at three sites in Pueblo Reservoir, Colorado, October 1999 through September 2002.

Figure 34.   Simulated algal distribution at three sites in Pueblo Reservoir, Colorado, October 1999 through September 2002.

Figure 35. Simulated daily and measured chlorophyll *a* concentrations at three sites in Pueblo Reservoir, Colorado, October 1999 through September 2002.
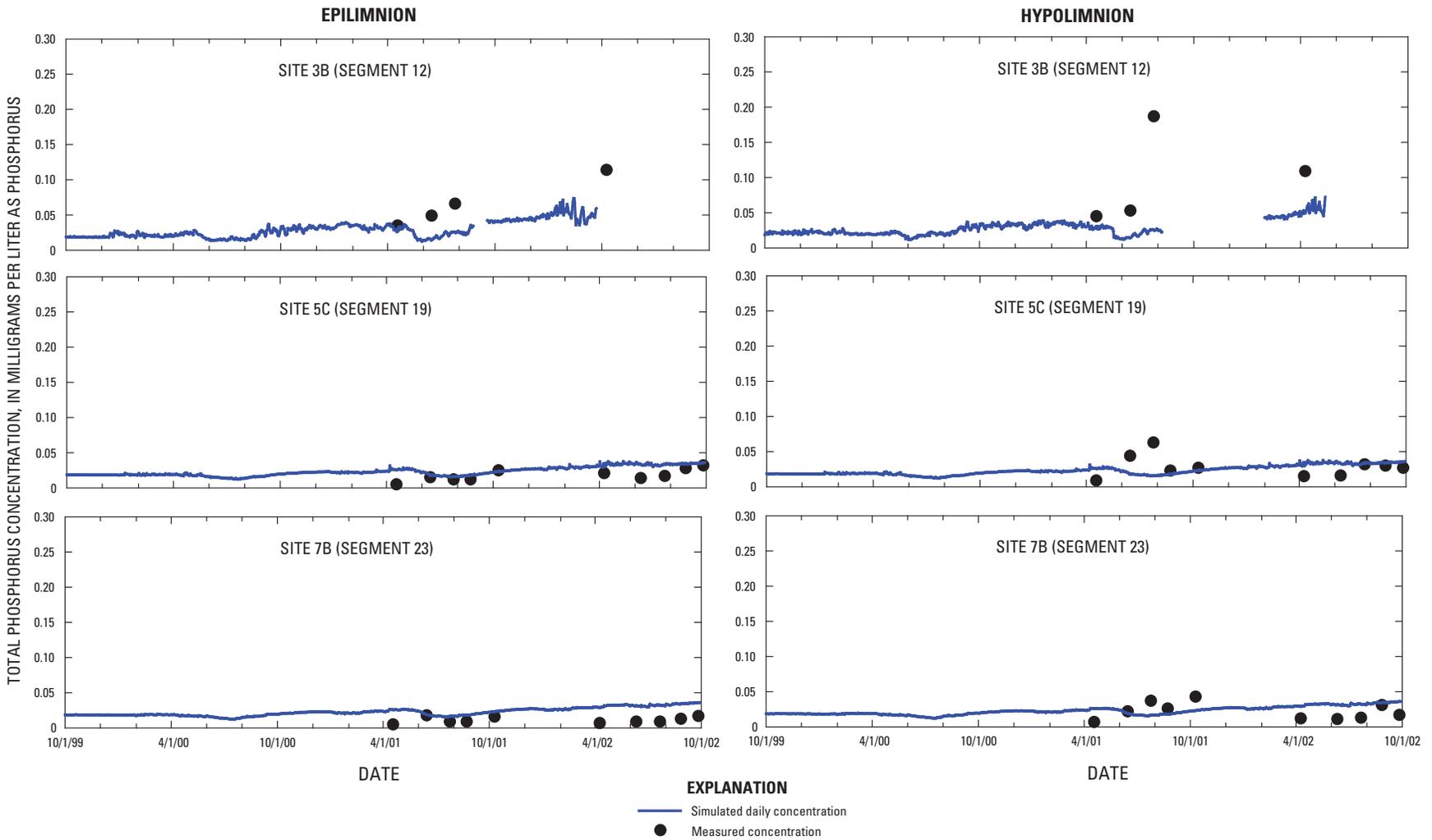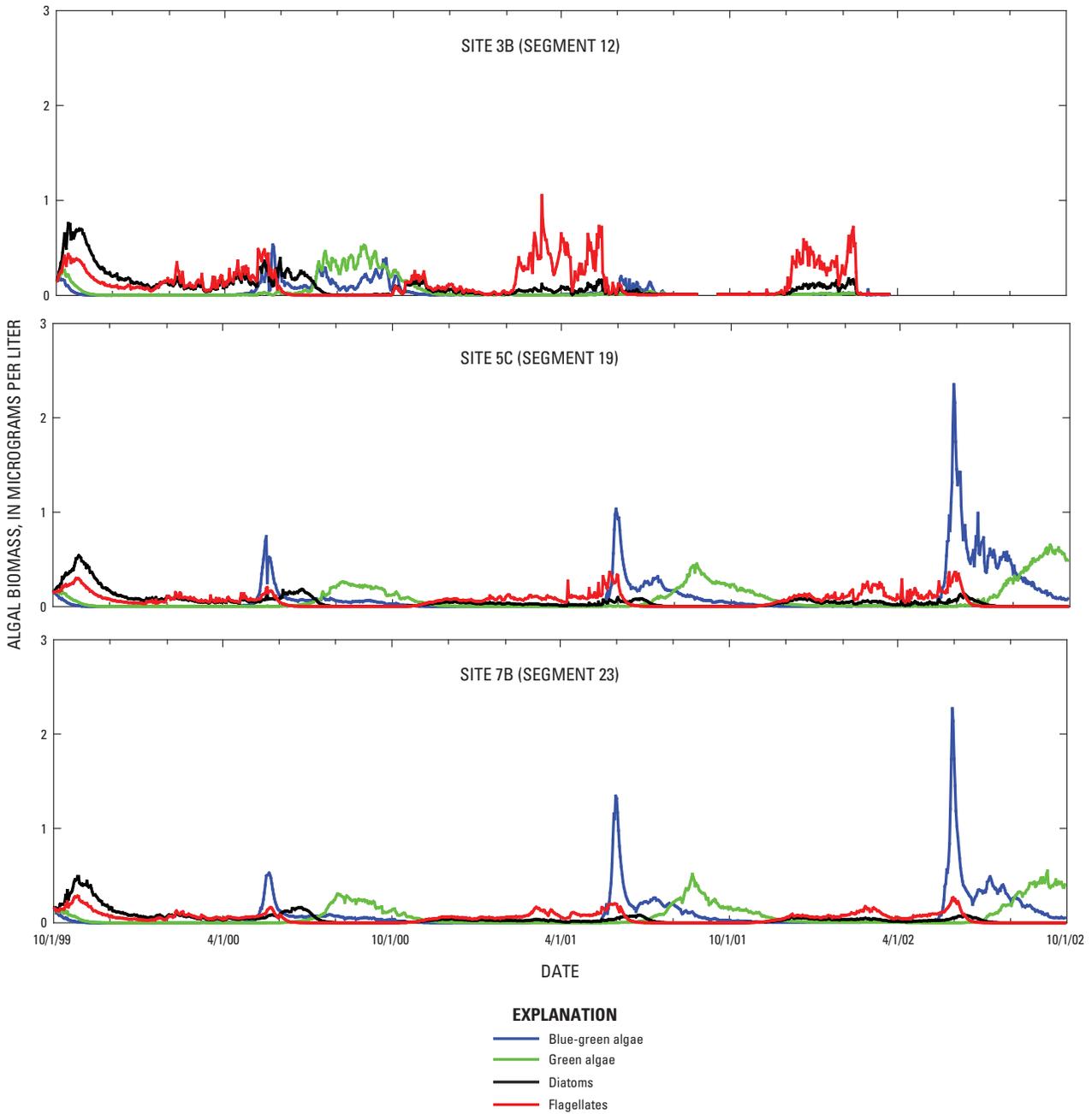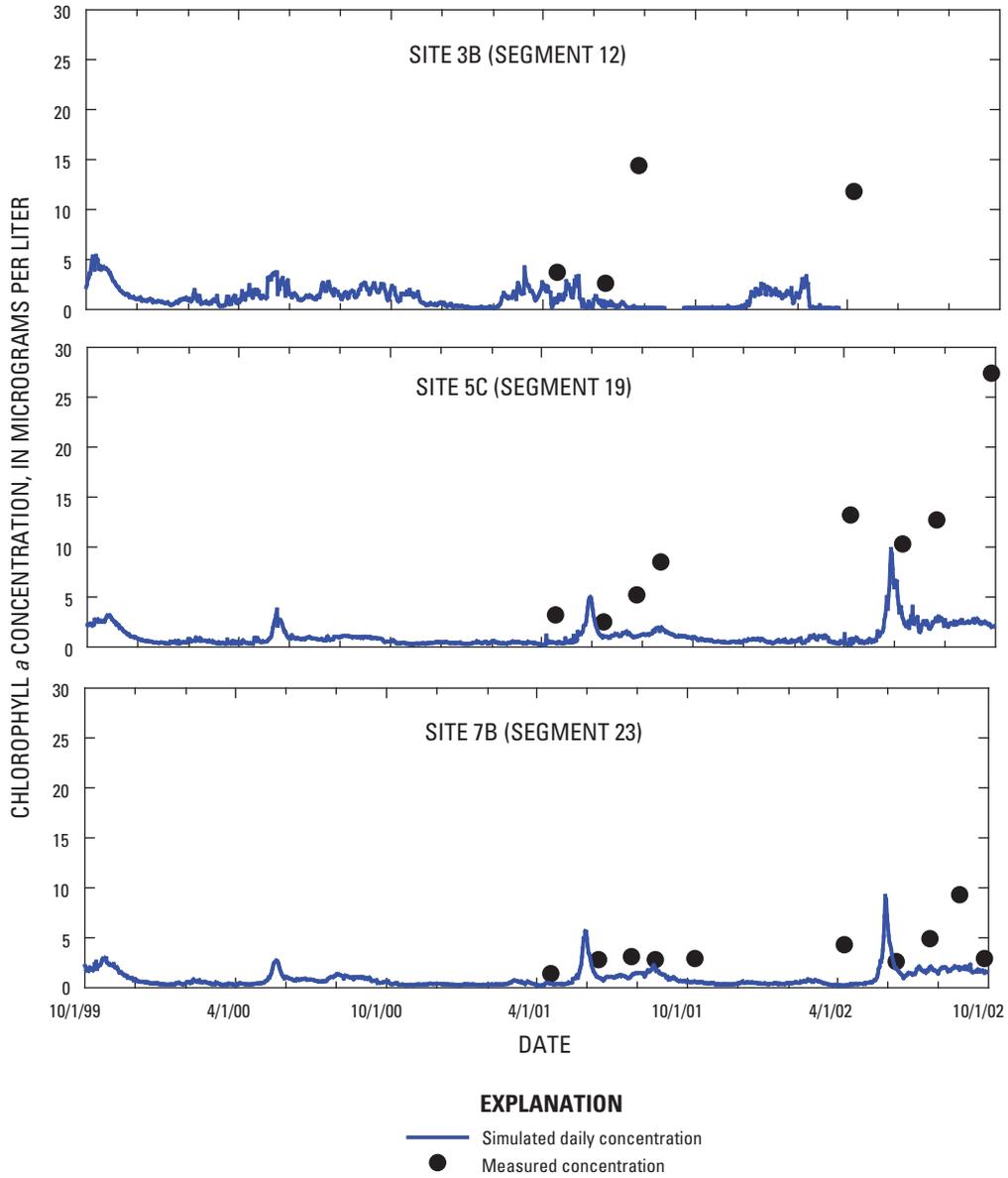
change the depth of the thermocline and increase or decrease the evaporative cooling. Higher windspeeds result in more mixing, thus a deeper thermocline and lower water-surface temperatures. Lower windspeeds result in a shallower thermocline and higher water-surface temperatures. The changes in the thermocline depth resulted in the greatest differences at the thermocline between the calibrated model and the sensitivity test because of the rapid change in water temperature with depth that occurs at the thermocline. The resulting changes in water temperature from changes in the wind-sheltering coefficient were less than 0.7°C from the calibrated model, and the resulting changes from changes in the light extinction coefficient were less than 0.2°C from the calibrated model (table 5).

Dissolved-oxygen concentrations were most affected by changes in light extinction, sediment oxygen demand (fraction of sediment oxygen demand), and windspeed (wind-sheltering coefficient) (table 5). Dissolved oxygen was controlled mainly by changes in water temperature, which was most sensitive to changes in light extinction and windspeed. Windspeed also can affect dissolved-oxygen dynamics by aeration in the epilimnion. Sediment-oxygen demand is a major sink for dissolved oxygen in the Pueblo Reservoir model and had a noticeable effect on the concentrations.

Nitrogen concentrations were affected by changes in several parameters in the Pueblo Reservoir model (table 5). Ammonia was most affected by changes in the light extinction and inflow phosphorus concentrations. Because algal dynamics affect ammonia concentrations through uptake during photosynthesis and release during respiration, changes in parameters that affect algal growth such as light extinction and inflow phosphorus, also resulted in the greatest changes in ammonia concentrations. Nitrite plus nitrate concentrations were most affected by algal growth rate, saturation of light intensity, and light extinction. Because the main sink for nitrate in the Pueblo Reservoir model is uptake by algae during photosynthesis, parameters that had the greatest affect on algae also had the greatest affect on nitrate concentrations. The nitrite plus nitrate concentrations also were most sensitive to changes in inflow nitrogen, which is one of the two sources of nitrate in the model.

Orthophosphorus was the most sensitive to changes in algal growth rate and inflow phosphorus (table 5). Phosphorus concentrations primarily are controlled by the algal dynamics in the Pueblo Reservoir model, and therefore were affected by parameters that had the greatest effect on the algal dynamics in the reservoir.

Total algae concentrations (represented as chlorophyll *a*) were most sensitive to changes in the algal growth rate, light-extinction coefficient, and inflow phosphorus concentrations (table 5). Because algae are dependent on light in the water column for photosynthesis, changes in the light penetration (light extinction) had a substantial affect on algal growth. The sensitivity of the chlorophyll *a* concentrations to the inflow phosphorus and relative insensitivity to changes in the inflow

nitrogen concentrations indicates that the simulated algae in the Pueblo Reservoir model were limited by phosphorus.

Model Limitations

Understanding the limitations of the CE-QUAL-W2 model is essential for effective application of the model. Model limitations that affect the accuracy of the Pueblo Reservoir model include simplification of naturally complex hydrodynamics and water-quality processes in the reservoir; spatial and temporal discretization effects; and assumptions made in the formulation of the governing equations. Model accuracy also is limited by segment size, boundary conditions, accuracy of calibration, and parameter sensitivity. Additionally, model accuracy is limited by the availability of data and by the interpolations and extrapolations that are inherent in using data in a model. Although a model might be calibrated, calibration parameter values are not necessarily unique in yielding acceptable values for the selected water-quality constituents, algal biomass, and reservoir water-surface elevation.

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

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

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

Specifically for the Pueblo Reservoir model, the absence of data during certain periods resulted in more uncertainty and limited ability to assess the accuracy of the calibration and verification of the model. For the calibration period (October 1985 through September 1987), measured dissolved orthophosphorus, nitrite plus nitrate, and ammonia only were available at the four sites from April 1987 through September 1987. During the verification period (October 1999 through September 2002), these constituents were only available April 2001 through September 2002. The model's ability to simulate

Table 5. Results of sensitivity analysis of the Pueblo Reservoir model, October 1985 to October 1987, showing the mean difference of all computed values at four sites in Pueblo Reservoir compared to calibrated values.

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

			Mean differences (sensitivity test value-calibrated value)				
Constituent	Input, in percent change from calibrated value	Water temperature, in °C	Dissolved oxygen, in mg/L	Ammonia, in mg/L as N	Nitrite plus nitrate, in mg/L as N	Orthophosphorus, in mg/L as P	Chlorophyll *a*, in µg/L
Algal growth rate[1]	+40	-0.01	0.3	-0.005	-0.027	-0.007	0.40
	-40	0.03	-0.3	-0.004	0.007	0.012	-0.88
Saturation of light intensity[1]	+40	0.00	-0.1	0.000	0.011	0.002	-0.19
	-40	0.00	0.3	-0.005	-0.023	-0.005	0.29
Algal half-saturation constant for nitrogen[1]	+40	0.00	0.1	-0.002	-0.007	-0.002	0.07
	-40	0.00	0.1	-0.003	-0.010	-0.002	0.07
Algal half-saturation constant for phosphorus[1]	+40	0.00	0.0	-0.003	-0.008	-0.001	0.00
	-40	0.00	0.1	-0.002	-0.008	-0.003	0.13
Light-extinction coefficient for pure water	+40	-0.13	-0.2	0.000	0.011	0.003	-0.24
	-40	0.17	0.4	-0.006	-0.027	-0.007	0.37
Fraction of sediment oxygen demand	+40	0.00	-0.3	-0.002	-0.009	-0.002	0.07
	-40	0.00	0.5	-0.003	-0.008	-0.002	0.07
Wind-sheltering coefficient	+40	-0.58	0.6	-0.004	-0.014	-0.001	0.13
	-40	0.71	-0.4	-0.003	-0.011	-0.001	-0.07
Inflow nitrogen	+40	0.00	0.1	-0.001	0.012	-0.003	0.15
	-40	0.00	0.0	-0.004	-0.029	-0.001	-0.02
Inflow organic matter	+40	0.00	0.0	-0.001	-0.007	-0.002	0.09
	-40	0.00	0.1	-0.004	-0.010	-0.002	0.04
Inflow phosphorus	+40	-0.02	0.2	0.004	0.004	0.009	0.48
	-40	0.02	0.0	-0.008	-0.020	-0.012	-0.36

[1]Parameters for green, blue green, diatom, and flagellate algal groups were all increased or decreased equally

seasonal changes in nutrients and their effects on the algal dynamics could not be completely evaluated because of the lack of data throughout the entire period. During the verification period, chlorophyll *a* data also were sparse, so the algal dynamics during the different hydrologic conditions could not be completely evaluated.

Summary

Pueblo Reservoir is approximately 6 miles west of Pueblo, Colorado, and is an important water resource for southeastern Colorado. The reservoir is the terminal storage feature for the Fryingpan-Arkansas Project and provides irrigation, municipal, and industrial water to various entities throughout the region. In anticipation of increased population growth, the cities of Colorado Springs, Fountain, Security, and Pueblo West have proposed building a pipeline that would be capable of conveying 78 million gallons of raw water per day (240 acre-feet). The U.S. Geological Survey, in cooperation with Colorado Springs Utilities and the Bureau of Reclamation, developed, calibrated, and verified a hydrodynamic and water-quality model of Pueblo Reservoir to describe the hydrologic, chemical, and biological processes in Pueblo Reservoir that can be used to assess environmental effects in the reservoir.

Hydrodynamics and water-quality characteristics in Pueblo Reservoir were simulated using a laterally averaged, two-dimensional model that was calibrated using data collected from October 1985 through September 1987. The Pueblo Reservoir model was calibrated based on vertical profiles of water temperature and dissolved-oxygen concentration, and water-quality constituent concentrations collected in

the epilimnion and hypolimnion at four sites in the reservoir. The calibrated model was verified with data from October 1999 through September 2002. This three-year contiguous period included various hydrologic conditions that allowed for verification of the model during a relatively wet year (water year 2000), an average year (water year 2001), and a dry year (water year 2002).

Simulated water-surface elevations for Pueblo Reservoir were adjusted to the measured water-surface elevations for the calibration period and the verification period. The water-surface elevations were corrected to the measured values by adjusting the unmeasured inflow into the reservoir that was distributed to all the segments within a branch.

Simulated water temperatures compared well to measured water temperatures in Pueblo Reservoir from October 1985 through September 1987. Spatially, simulated water temperatures compared better to measured water temperatures in the downstream part of the reservoir (sites 5C and 7B) than in the upstream part of the reservoir (sites 1B and 3B). The absolute mean error (AME) and root mean square error (RMSE) at site 1B were 1.68 and 1.83 degrees Celsius (°C), respectively. In comparison, the AME and RMSE for site 7B were 0.70 and 0.85°C, respectively. Differences between simulated and measured water temperatures also varied through time. Simulated water temperatures were slightly less than measured water temperatures from March to May 1986 and 1987, and slightly greater than measured data in August and September 1987. Relative to the calibration period, simulated water temperatures during the verification period did not compare as well to measured water temperatures. For the verification period, the AME ranged from 1.15 (site 3B) to 1.54°C (site 5C) and the RMSE ranged from 1.35 (site 3B) to 1.70°C (site 5C). On average, simulated water temperatures during the verification period were higher than measured water temperatures.

In general, simulated dissolved-oxygen concentrations for the calibration period compared well to measured concentrations in Pueblo Reservoir. Spatially, simulated concentrations deviated more from the measured values at the downstream part of the reservoir than at other locations in the reservoir. Overall, the AME ranged from 1.05 (site 1B) to 1.42 milligrams per liter (mg/L) (site 7B), and the RMSE ranged from 1.12 (site 1B) to 1.67 mg/L (site 7B). Simulated dissolved-oxygen concentrations were slightly overpredicted in the downstream part of reservoir because of the simplified algal dynamics defined in the model. From October 1999 through September 2002, simulated dissolved oxygen compared better to the measured concentrations than in October 1985 through September 1987. The AME ranged from 0.91 (site 5C) to 1.28 mg/L (site 7B) and the RMSE ranged from 1.03 (site 5C) to 1.46 mg/L (site 7B).

Simulated TDS generally were less than measured TDS concentrations in Pueblo Reservoir from October 1985 through September 1987. The mean differences between simulated and measured data at sites 1B, 3B, 5C and 7B were -34, -44, -42, and -44 mg/L, respectively. The largest

differences between simulated and measured TDS were observed at the most downstream sites in Pueblo Reservoir (sites 5C and 7B) during the second year of the calibration period. TDS data were not available from reservoir sites during the verification period, so in-reservoir specific conductance (SC) data were used to compare to simulated TDS. Simulated TDS followed the same patterns through time as the measured SC data during the verification period.

The Pueblo Reservoir model generally simulated lower concentrations of nitrate and ammonia compared to measured concentrations from October 1985 through September 1987. The AME for nitrate ranged from 0.05 (site 5C) to 0.15 mg/L as nitrogen (site 7B), and the RMSE ranged from 0.07 (site 5C) to 0.18 mg/L as nitrogen (site 7B). For ammonia, the AME ranged from 0.04 (site 7B) to 0.05 mg/L as nitrogen (sites 1B, 3B, and 5C), and the RMSE ranged from 0.04 (site 7B) to 0.06 mg/L as nitrogen (site 5C). Simulated total nitrogen concentrations compared relatively well to measured concentrations in the Pueblo Reservoir model. The AME ranged from 0.21 (site 1B) to 0.27 mg/L as nitrogen (sites 3B and 7B), and the RMSE ranged from 0.21 (site 1B) to 0.29 mg/L as nitrogen (sites 3B and 7B). Simulated nitrate in the verification period did not compare as well to measured concentrations as in the calibration period. The AME for nitrate ranged from 0.13 (site 3B) to 0.21 mg/L (site 7B) as nitrogen, and the RMSE ranged from 0.15 (site 3B) to 0.21 mg/L (site 7B) as nitrogen. Simulated ammonia compared better to measured concentrations during the verification period than during the calibration period. The AME for ammonia ranged from 0.02 (site 7B) to 0.06 mg/L (site 3B) as nitrogen, and the RMSE ranged from 0.02 (site 7B) to 0.07 mg/L as nitrogen (site 3B) for the verification period. Total nitrogen data were not available for the verification period for comparison between simulated and measured values.

Simulated orthophosphorus concentrations in the Pueblo Reservoir model were similar to the measured concentrations for the period of October 1985 through September 1987. The AME for orthophosphorus ranged from 0.01 (sites 3B and 5C) to 0.02 mg/L (sites 1B and 7B) as phosphorus, and the RMSE ranged from 0.01 (sites 3B and 5C) to 0.02 mg/L (sites 1B and 7B) as phosphorus. The AME for total phosphorus ranged from 0.02 (sites 5C and 7B) to 0.05 mg/L (site 1B) as phosphorus, and the RMSE ranged from 0.02 (sites 5C and 7B) to 0.05 mg/L (sites 1B and 3B) as phosphorus. The greatest difference between simulated and measured values occurred in the hypolimnion at sites 1B and 3B in May through July 1987, where simulated concentrations were considerably less than the measured concentrations. Simulated orthophosphorus and total phosphorus compared better to measured concentrations during the verification period than during the calibration period. The AME for orthophosphorus was 0.01 mg/L as phosphorus for all of the sites, and the AME for total phosphorus ranged from 0.01 (site 5C) to 0.05 mg/L (site 3B) as phosphorus.

The simulated distribution of algal populations was highly variable in Pueblo Reservoir from October 1985 through September 1987. The highest algal biomass in Pueblo Reservoir generally occurred from May through September when blue-green and green algae were the dominant algal groups in the reservoir. The lowest algal biomass generally occurred from November through March when diatoms and flagellates were the dominant groups. The distribution of algae in Pueblo Reservoir during the verification period differed slightly from what was observed during the calibration period where diatoms and flagellates were the dominant algal groups in the upstream part of Pueblo Reservoir, and green and blue-green algae were the dominant groups in the downstream part of the reservoir.

Simulated chlorophyll *a* concentrations were similar to measured concentrations in Pueblo Reservoir from October 1985 through September 1987. The highest chlorophyll *a* concentrations occurred at the two upstream reservoir sites, where the AME ranged from 3.0 (site 1B) to 3.7 micrograms per liter (µg/L) (site 3B), and the RMSE ranged from 5.3 (site 1B) to 6.8 µg/L (site 3B). Chlorophyll *a* concentrations were generally lower in the downstream part of the reservoir (sites 5C and 7B) where nutrients were less available for algal growth. The AME ranged from 1.6 (site 7B) to 2.2 µg/L (site 5C), and the RMSE ranged from 2.5 (site 7B) to 3.7 µg/L (site 5C). Simulated chlorophyll *a* concentrations generally were less than the measured concentrations during the verification period. Evaluation of how well the model simulated algal dynamics was limited because there were few measured chlorophyll *a* data during the verification period.

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