Prepared in cooperation with the
COLORADO RIVER WATER CONSERVATION DISTRICT

Hydrology and Water Quality of Elkhead Creek and Elkhead Reservoir near Craig, Colorado, July 1995–September 2001

Water-Resources Investigations Report 03–4220

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

Cover Photographs

Large photograph: Elkhead Creek about 4 miles upstream from Elkhead Reservoir.
Top right: Elkhead Creek at station 09246200.
Middle right: Elkhead Creek at station 09246400.
Bottom left: Inflow to Elkhead Reservoir showing deltaic sediment deposits.
Bottom right: Elkhead Dam and spillway.
All photographs taken by John G. Elliott, U.S. Geological Survey.

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Gale A. Norton, Secretary

U.S. Geological Survey
Charles G. Groat, Director

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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATIONS

Multiply	By	To obtain
acre	0.00156	square mile
acre-foot (acre-ft)	1,233	cubic meter
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot (ft)	0.3048	meter
inch	2.54	centimeter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer (km^2)

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 North American Vertical Datum of 1988 (NAVD88); horizontal coordinate information is referenced to the North American Datum of 1927 (NAD27)

Water year: A continuous 12-month period selected to present data relative to hydrologic or meteorological phenomena during which a complete annual hydrologic cycle normally occurs. The water year used by the U.S. Geological Survey runs from October 1 through September 30, and is designated by the year in which it ends.

ADDITIONAL ABBREVIATIONS

ASTM	American Society for Testing and Materials
MRL	Minimum Reporting Level
L	liter
mg	milligram
μg	microgram
mg/L	milligram per liter
mL	milliliter
mm	millimeter
NTU	nephelometric turbidity units
ton/d	ton per day
μg/L	microgram per liter
μS/cm	microsiemens per centimeter at 25 degrees Celsius

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Abstract

The U.S. Geological Survey, in cooperation with the Colorado River Water Conservation District, collected and analyzed baseline streamflow and water-quality information for Elkhead Creek and water-quality and trophic-state information for Elkhead Reservoir from July 1995 through September 2001.

In the study area, Elkhead Creek is a meandering, alluvial stream dominated by snowmelt in mountainous headwaters that produces most of the annual discharge volume and discharge peaks during late spring and early summer. During most of water year 1996 (a typical year), daily mean discharge at station 09246400 (downstream from the reservoir) was similar to daily mean discharge at station 09246200 (upstream from the reservoir). Flow-duration curves for stations 09246200 and 09246400 were nearly identical, except for discharges less than about 10 cubic feet per second.

Specific conductance generally had an inverse relation to discharge in Elkhead Creek. During late fall and winter when discharge was small and derived mostly from ground water, specific conductance was high, whereas during spring and early summer, when discharge was large and derived mostly from snowmelt, specific conductance was low. Water temperatures in Elkhead Creek were smallest during winter, about 0.0 degrees Celsius (°C), and largest during summer, about 20–25°C.

Concentrations of major ions, nutrients, trace elements, organic carbon, and suspended sediment in Elkhead Creek indicated no substantial within-year variability and no substantial differences in variability from one year to the next. A seasonal pattern in the concentration data was evident for most constituents. The seasonal concentration pattern for most of the dissolved constituents followed the seasonal pattern of specific conductance, whereas some nutrients, some trace elements, and suspended sediment followed the seasonal pattern of discharge.

Statistical differences between station 09246200 (upstream from the reservoir) and station 09246400 (downstream from the reservoir) were indicated for specific conductance, dissolved calcium, magnesium, sodium, and sulfate, acid-neutralizing capacity, and dissolved solids. Trend analysis indicated upward temporal trends for pH, dissolved ammonia plus organic nitrogen, total nitrogen, and total phosphorus at station 09246200; upward temporal trends for dissolved and total ammonia plus organic nitrogen, total nitrogen, and total phosphorus were indicated at station 09246400. No downward trends were indicated for any constituents.

Annual loads for dissolved constituents during water years 1996–2001 were consistently larger at station 09246400 than at station 09246200, except for silica and sulfate. Mean monthly loads for dissolved constituents followed the seasonal pattern of discharge, indicating that most of the annual loads were transported during March–June. Annual dissolved nutrient loads at stations 09246400 and 09246200 were not substantially different, except for total phosphorus and total nitrogen loads, which were smaller at the downstream station than at the upstream station, most likely due to biological uptake and settling in the reservoir. Mean annual suspended-sediment load during water years 1996–2001 was about 87-percent smaller at the downstream station than at the upstream station.

Temperature in Elkhead Reservoir varied seasonally, from about 0°C during winter when ice develops on the reservoir to about 20°C during summer. Specific conductance varied from minimums of 138 to 169 microsiemens per centimeter at 25°C (μS/cm) during snowmelt inflow to maximums of 424 to 610 μS/cm during early spring low flow (April). Median pH in the reservoir ranged from 7.2 to 8.0 at all sites near the surface. Median dissolved oxygen ranged from 7.1 to 7.2 milligrams per liter (mg/L) in near-surface samples and from 4.8 to 5.6 mg/L in near-bottom samples.

During reservoir stratification, specific conductance generally was largest in the epilimnion, resulting from warm and relatively concentrated water from Elkhead Creek that was routed through the reservoir in the relatively warm epilimnion. The pH in the epilimnion generally increased from May to September, probably a result of algal productivity. In the hypolimnion, pH decreased slightly with depth in the July and September, probably a result of biomass decay processes and a lack of circulation during stratification.

Concentrations of nutrients in both near-surface and near-bottom samples from Elkhead Reservoir were highest during snowmelt inflow (April–May). Total phosphorus concentra-

tions in near-surface samples generally were largest during runoff, whereas total phosphorus concentrations in near-bottom samples generally were largest during July or September. Concentrations of nitrite plus nitrate in near-surface samples were substantially depleted by biological uptake during July, September, and October, compared to near-bottom samples. Variations in concentration of chlorophyll-*a* in near-surface samples were large during the growing season with peak seasonal concentrations during runoff or late summer and fall. Trophic state for Elkhead reservoir ranged from oligotrophic to eutrophic.

Introduction

Elkhead Creek is in northwestern Colorado and flows into the Yampa River about 4 mi east of Craig; Elkhead Reservoir is about 9 river miles (RM) upstream from the confluence (fig. 1). The reservoir is an important water resource for aquatic habitat, industrial use, recreation, and water storage; the city of Craig also owns part of the stored water for emergency municipal use. Enlargement of Elkhead Reservoir has been considered for a variety of reasons, but no plans ever were finalized until October 2002, when the Colorado River Water Conservation District (CRWCD) approved a 13,000 acre-ft enlargement of Elkhead Reservoir. This decision resulted from two factors: first, establishment of the Upper Colorado River Endangered Fish Recovery Program (U.S. Fish and Wildlife Service, 2002a) in 1988 to implement and conduct a long-term recovery program for the Colorado pike minnow, razorback sucker, bonytail, and humpback chub, which are upper Colorado River basin fish species protected under the Endangered Species Act of 1973, and second, formulation of "A Management Plan for the Yampa River Basin" (U.S. Fish and Wildlife Service, 2002b).

The potential effects of enlarging Elkhead Reservoir on the downstream discharge and water quality and on water quality in the reservoir itself are of concern to many interest groups. Changes in reservoir capacity can affect the quantity and timing of downstream discharge and the quality of that discharge and can result in different hydrologic and physical conditions in the reservoir. To evaluate any potential effects of reservoir enlargement, the existing hydrology and water quality of Elkhead Creek and Elkhead Reservoir need to be characterized.

In anticipation of the possible enlargement of Elkhead Reservoir, the U.S. Geological Survey (USGS), in cooperation with the CRWCD, began a data-collection program in 1995 to obtain baseline streamflow and water-quality data for Elkhead Creek and water-quality and trophic-state data for Elkhead Reservoir. The data collection was expanded in 2001 to provide for the analysis and interpretation of data obtained to date and publication of the results in an interpretive report. Analysis of the existing hydrology and water quality in Elkhead Creek, the existing water quality and trophic state of Elkhead Reservoir, and the effects of the reservoir on downstream discharge and water quality in Elkhead Creek will provide a benchmark for comparisons to data obtained following reservoir enlargement.

Purpose and Scope

The purpose of this report is to describe the hydrology and water quality of Elkhead Creek and Elkhead Reservoir. Specifically, the purpose includes descriptions of the following:

1. Hydrology of Elkhead Creek upstream and downstream from Elkhead Reservoir, including development of selected streamflow statistics, trend analysis, and comparison to historical data;
2. Water quality in Elkhead Creek upstream and downstream from Elkhead Reservoir and the downstream differences resulting from the reservoir;
3. Water quality, including the existing trophic state, in Elkhead Reservoir and interpretation of the possible effects of the reservoir on downstream discharge and water quality; and
4. Comparison of the water-quality data to the 2002 Colorado water-quality standards and guidelines.

The scope of this report includes analysis of (1) discharge and water-quality data collected on Elkhead Creek at one streamflow-gaging and water-quality station (hereinafter, "station") upstream and one station downstream from Elkhead Reservoir and (2) water-quality and trophic-state data collected at three transects (eight sampling sites) on Elkhead Reservoir. Data for July 1995 through September 2001 were used in the analyses.

Description of Study Area

The Elkhead Creek and Elkhead Reservoir study area (fig. 1) primarily consists of rolling hills separated by small ephemeral stream valleys; elevation in the area ranges from about 6,200 ft at the confluence of Elkhead Creek with the Yampa River to about 6,900 ft at station 09245000. Elkhead Creek generally flows south from its headwaters in the Elkhead Mountains (not shown in fig. 1, but about 3–10 mi north of study area) where elevations range from about 7,500 to about 10,500 ft. Annual precipitation in the study area is about 16–20 inches, but increases to about 30 inches in the Elkhead Mountains (Driver and others, 1984, p. 20–21); most winter precipitation is in the form of snow that accumulates in mountain areas to form snowpacks with 10–20 inches of water equivalent. Snowmelt during late spring and early summer provides most of the streamflow in Elkhead Creek; summer thunderstorms usually are scattered and result in little runoff.

In 1974 Elkhead Dam was completed and Elkhead Reservoir was filled. The facility includes an earthen embankment 85 ft high and 1,160 ft long, a 36-inch concrete pipe outlet with hydraulically operated gates, and a 40-ft wide spillway with a chute and stilling basin. The reservoir is about 3 mi long and 0.2 to 0.5 mi wide and has a surface area of about 460 acres and a storage volume of about 13,700 acre-ft (Ayres Associates, 2002b; URS Corporation, 2001). Additional details regarding

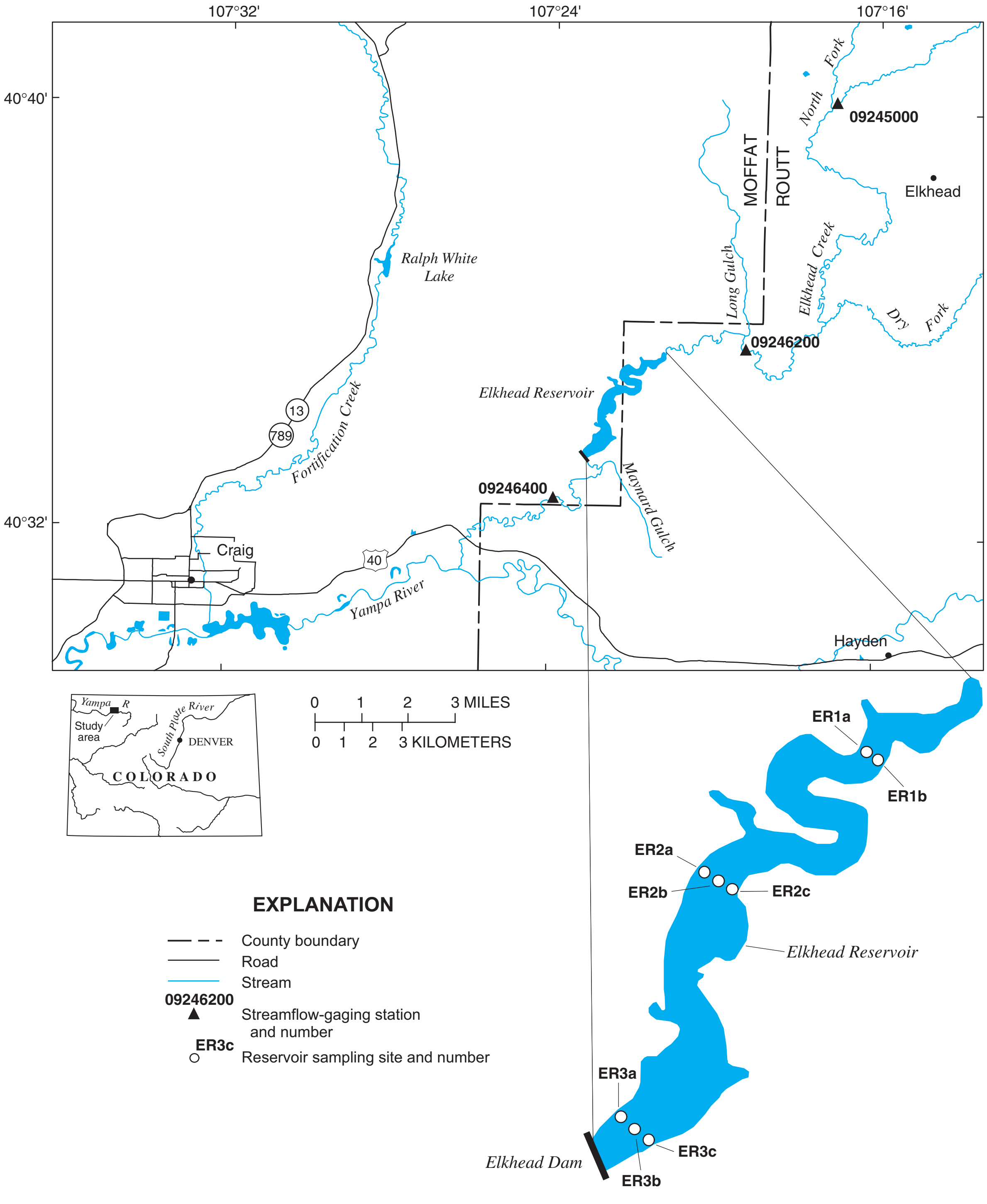

Figure 1. Location of study area, streamflow-gaging stations on Elkhead Creek, and sampling sites on Elkhead Reservoir.

Elkhead Reservoir and the proposed enlargement are available from the CRWCD Web pages (accessed November 22, 2002, at URL: http://www.crwcd.gov/index.html).

Geology of the headwater areas includes the sedimentary Iles Formation, the Williams Fork Formation, and the Lewis Shale of Cretaceous age; the sedimentary Fort Union and Wasatch Formations of Tertiary age; and isolated basaltic intrusives of Tertiary age. Downstream from the headwaters, Elkhead Creek and most of the principal tributaries flow over shales and sandstones of the Lance Formation (Upper Cretaceous age) and alluvium of Holocene age (Tweto, 1976).

The mountainous headwaters are heavily forested, whereas vegetation on the hillslopes and in the ephemeral stream valleys mostly is grasses, sagebrush, and scrub oak. The alluvial valley along Elkhead Creek also contains cottonwood trees and willows. Most of the headwaters area is in the Routt

National Forest and is largely undeveloped, but the valley floor and adjacent hillslopes in the lower valley are used for grazing, dry-land wheat production, and hay production (Ayres Associates, 2002a, p. 3.3; Elliott and Gyetvai, 1999, p. 4). In some areas, agriculture and ranching have modified the native ground cover, contributing to increased sediment loads in Elkhead Creek (Ayres Associates, 2002a, p. 3.2).

Previous Studies

Most of the previous studies that relate exclusively to Elkhead Creek and Elkhead Reservoir are engineering and hydraulic studies related to the proposed reservoir enlargement or to rehabilitation of the existing dam, and any description of these studies is beyond the scope of this report. One of these studies, however, investigated hydrologic aspects of Elkhead Creek that are related to reservoir construction; these aspects included analysis of precipitation and modeling of inflow volumes and probable maximum floods (Ayres Associates, 2002b). A paleoflood approach to assess extreme flood potential for Elkhead Creek also was completed by Jarrett and Tomlinson (2000); this study was completed for the hydrologic safety recertification for Elkhead Dam as part of a statewide program conducted by the Colorado State Engineer.

Elliott and Gyetvai (1999) completed a detailed geomorphic analysis of Elkhead Creek, especially in regard to channel stability and streambank erosion downstream from Elkhead Reservoir. To evaluate factors that could affect channel instability, their investigation used (1) analysis of seven sets of aerial photographs taken over the Elkhead Creek basin between 1937 and 1997; (2) analysis of discharge data, including flow duration and peak-flow frequency; (3) onsite measurements of channel morphology and particle-size analysis of streambed sediment; and (4) calculations of shear stress.

Elliott and Gyetvai (1999) determined that channel instability and meander migration rates in Elkhead Creek were partly a function of annual streamflow, flood magnitude, and other local factors such as land use and riparian vegetation. Elliott and Gyetvai (1999) found that meander migration rates in Elkhead Creek were smaller during 1938–53 than during 1954–93. By contrast, annual discharges in Elkhead Creek for the 1932–53 period were greater than the long-term mean, indicating that changes in land use or riparian vegetation may have contributed to increased meander migration rates during the later time periods (Elliott and Gyetvai, 1999).

The Yampa River basin was studied extensively during the 1970’s and 1980’s in conjunction with energy resources development. Although usually a minor component in these studies, Elkhead Creek and Elkhead Reservoir were considered in studies that evaluated (1) the effects of reservoir development on water quantity and quality (Adams and others, 1983; Veenhuis and Hillier, 1982); (2) aspects of energy-resource development on water quality in the Yampa River (Wentz and Steele, 1980) and on regional water resources (Steele and others, 1979); (3) existing sediment yields and potential yields during energy-resource development (Andrews, 1978); and (4) calibration of a dissolved-solids model for the Yampa River and its tributaries (Parker and Litke, 1987). A summary and overview of Yampa River basin hydrology, especially in relation to surface mining of coal, also is presented in Driver and others (1984).

Acknowledgments

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Methods

This section of the report describes (1) how data and samples were collected for Elkhead Creek and Elkhead Reservoir, (2) how the samples were processed, (3) what laboratory methods were used, and (4) how the data were analyzed for hydrologic interpretation.

Data Collection

With initiation of the data-collection program in 1995, two stations were established on Elkhead Creek and three water-quality transects were established on Elkhead Reservoir in July 1995. Each transect had two or three sampling sites (eight total) to provide water-quality information at multiple sites across each transect (fig. 1, table 1).

Daily Discharge, Specific Conductance, and Water Temperature

The stations established on Elkhead Creek were station 09246200 Elkhead Creek above Long Gulch near Hayden (about 3 RM upstream from the high-water elevation of Elkhead Reservoir) and station 09246400 Elkhead Creek below Maynard Gulch near Craig (about 3 RM downstream from Elkhead Dam) (fig. 1; table 1). Continuous records of discharge were collected at these stations beginning in August 1995 through September 2001. Stage data (water-surface elevation relative to some arbitrary datum) were measured, recorded, and converted to discharge data by using stage-discharge relations that were defined by making instantaneous discharge measurements on about a monthly basis. These methods are described in detail in Buchanan and Somers (1969), Kennedy (1983), and Rantz and others (1982a, 1982b).

Continuous records of specific conductance and water temperature (hereinafter, “temperature,” unless another specifi-

Table 1. Streamflow-gaging and water-quality stations on Elkhead Creek and water-quality sampling sites on Elkhead Reservoir.

[mi^2, square miles; --, does not apply or no data]

Map number (fig. 1)	U.S. Geological Survey station number	Station name	Drainage area (mi^2)	Period of record (month and year)		
				Discharge	Water quality	
					Continuous	Periodic
09245000	09245000	Elkhead Creek near Elkhead[1]	64.2	04/1953 to 09/1996	--	05/1958; 09/1975 to 08/1976; 12/1993 to 09/1996
09246200	09246200	Elkhead Creek above Long Gulch near Hayden[2]	171	08/1995 to 09/2001	08/1995 to 09/2001	07/1995 to 09/2001
09246400	09246400	Elkhead Creek below Maynard Gulch near Craig[2]	212	08/1995 to 09/2001	08/1995 to 09/2001	07/1995 to 09/2001
ER1a	403507107214900	Elkhead Reservoir site 1a	--	--	--	08/1995 to 09/2001
ER1b	403506107214500	Elkhead Reservoir site 1b	--	--	--	07/1995 to 09/2001
ER2a	403439107223800	Elkhead Reservoir site 2a	--	--	--	07/1995 to 09/2001
ER2b	403437107223300	Elkhead Reservoir site 2b	--	--	--	07/1995 to 09/2001
ER2c	403435107222900	Elkhead Reservoir site 2c	--	--	--	07/1995 to 09/2001
ER3a	403336107230700	Elkhead Reservoir site 3a	--	--	--	07/1995 to 09/2001
ER3b	403333107230100	Elkhead Reservoir site 3b	--	--	--	07/1995 to 09/2001
ER3c	403331107225500	Elkhead Reservoir site 3c	--	--	--	07/1995 to 09/2001
		Other discontinued stations on Elkhead Creek (not shown in figure 1)				
--	09244500	Elkhead Creek near Clark	45.4	10/1942 to 09/1944; 10/1958 to 09/1973	--	--
--	09245500	North Fork Elkhead Creek near Elkhead[1]	21.0	10/1958 to 09/1973	--	12/1975 to 09/1976
--	09246500	Elkhead Creek near Craig[1]	249	10/1910 to 02/1918	--	10/1957 to 08/1958; 09/1975 to 03/1978

[1] Water-quality data not analyzed for this report.

[2] Station was in operation at beginning of water year 2002.

cation is given, such as "air temperature"), using water-quality monitors, also were obtained at the two stations beginning in August 1995 through September 2001, but only during the open-water season (about April through October); the monitors also were operated during the winter of 1998–99 because of mild winter conditions. Specific conductance and temperature were checked during field visits by using ASTM thermometers and specific-conductance meters that were calibrated against standard solutions. Adjustments to the monitor data, if needed, were applied during computation of the daily record using the methods described in Wagner and others (2000).

Periodic Water-Quality Samples from Elkhead Creek

Periodic water-quality samples were collected from Elkhead Creek beginning in July 1995 through September 2001, at the two stations—one upstream and one downstream from Elkhead Reservoir. Samples were collected approximately monthly and included onsite field measurement of atmospheric pressure, discharge, dissolved oxygen, pH, specific conductance, temperature, and turbidity (field measurements, table 2). The monthly samples were analyzed for dissolved major ions, dissolved and total nutrients, and suspended sediment (table 2); however, some of the constituents in these categories were not analyzed in every monthly sample. Samples for analysis of coliform-bacteria, dissolved and total organic carbon, and dissolved and total-recoverable trace elements were collected 2–4 times per year.

Samples for laboratory analyses were collected with depth-integrated, isokinetic samplers, using the equal-width-increment (EWI) method and compositing the collected samples in a USGS churn splitter, from which separate aliquots were withdrawn for each required analytical bottle (U.S. Geological Survey, 1998). Suspended-sediment samples also were collected by using the EWI method, except during high flow when the equal-discharge-increment method was used (Edwards and Glysson, 1988; Guy and Norman, 1970). Samples for dissolved and total organic-carbon analysis were

Table 2. Field and analytical methods and minimum reporting limits for water-quality field measurements and constituent concentrations in samples collected from Elkhead Creek and Elkhead Reservoir.

[mm, millimeters; Hg, mercury; ft^3/s, cubic feet per second; mg/L, milligrams per liter; mL, milliliter; mm, millimeters; µg/L, micrograms per liter; µS/cm, microsiemens per centimeter at 25°C; Hg, mercury; EWI, equal-width increment; °C, degrees Celsius; NTU, nephelometric turbidity units; total, total recoverable; ICP, inductively coupled plasma; IC, ion chromatography; POIS, persulfate oxidation and infrared spectrometry; HPLC, high-performance liquid chromatography; Col, colonies; MF, membrane filtration; ICPMS, inductively coupled plasma mass spectrometry; GFAA, graphite furnace atomic absorption; AA, atomic absorption; CVAF, cold vapor atomic fluorescence; --, not applicable]

Measurement or constituent	Units	Field method[1]	Analytical method	Minimum reporting limit
Field measurements				
Atmospheric pressure	mm of Hg	Barometer	Observation	1
Discharge, instantaneous	ft^3/s	Current meter	Mid-interval	Variable
Oxygen, dissolved	mg/L	Point	Electrode	0.1
pH	units	EWI	Electrode	.1
Secchi-disk depth	inches	Disk	Observation	1
Specific conductance	mS/cm	Point	Electrode	1
Temperature	°C	Point	Observation	.1
Turbidity	NTU	EWI	Nephelometry	.1
Major Ions				
Acid-neutralizing capacity, lab, as $CaCO_3$	mg/L	EWI	Titration	1
Calcium, dissolved, as Ca	mg/L	EWI	ICP	.1
Chloride, dissolved, as Cl	mg/L	EWI	IC	.1
Fluoride, dissolved, as F	mg/L	EWI	Ion selective electrode	.1
Hardness, total, as $CaCO_3$	mg/L	--	Calculated	1
Magnesium, dissolved, as Mg	mg/L	EWI	ICP	.1
Potassium, dissolved, as K	mg/L	EWI	ICP	.1
Silica, dissolved, as Si	mg/L	EWI	ICP	.1
Sodium, dissolved, as Na	mg/L	EWI	ICP	.1
Solids, dissolved, sum of constituents	mg/L	--	Calculated	1
Sulfate, dissolved, as SO_4	mg/L	EWI	IC	.1
Nutrients				
Nitrite, dissolved, as N	mg/L	EWI	Colorimetry	.001
Nitrite plus nitrate, dissolved, as N	mg/L	EWI	Colorimetry	.005
Nitrogen, ammonia, dissolved, as N	mg/L	EWI	Colorimetry	.002
Nitrogen, ammonia plus organic, dissolved, as N	mg/L	EWI	Colorimetry	.2
Nitrogen, ammonia plus organic, total, as N	mg/L	EWI	Colorimetry	.2
Nitrogen, total, as N	mg/L	--	Calculated	.2
Phosphorus, dissolved, as P	mg/L	EWI	Colorimetry	.001
Phosphorus, orthophosphate, dissolved as P	mg/L	EWI	Colorimetry	.001
Phosphorus, total, as P	mg/L	EWI	Colorimetry	.001; .05
Biological indicators				
Carbon, organic, dissolved	mg/L	Point	POIS	.1
Carbon, organic, total	mg/L	Point	POIS	.1
Chlorophyll-*a* and *b*	µg/L	Point	HPLC	.1
Coliform, *e. coli*	Col/100 mL	EWI, point	MF	1
Coliform, fecal	Col/100 mL	EWI, point	MF	1
Trace elements				
Aluminum, total, as Al	µg/L	EWI	ICPMS	1
Antimony, dissolved, as Sb	µg/L	EWI	ICPMS	1

Table 2. Field and analytical methods and minimum reporting limits for water-quality field measurements and constituent concentrations in samples collected from Elkhead Creek and Elkhead Reservoir.—Continued

[mm, millimeters; Hg, mercury; ft^3/s, cubic feet per second; mg/L, milligrams per liter; mL, milliliter; mm, millimeters; µg/L, micrograms per liter; µS/cm, microsiemens per centimeter at 25°C; Hg, mercury; EWI, equal-width increment; °C, degrees Celsius; NTU, nephelometric turbidity units; total, total recoverable; ICP, inductively coupled plasma; IC, ion chromatography; POIS, persulfate oxidation and infrared spectrometry; HPLC, high-performance liquid chromatography; Col, colonies; MF, membrane filtration; ICPMS, inductively coupled plasma mass spectrometry; GFAA, graphite furnace atomic absorption; AA, atomic absorption; CVAF, cold vapor atomic fluorescence; --, not applicable]

Measurement or constituent	Units	Field method[1]	Analytical method	Minimum reporting limit
Arsenic, dissolved, as As	µg/L	EWI	ICPMS; GFAA	1; 4
Arsenic, total, as As	µg/L	EWI	ICPMS; GFAA	1; 4
Barium, dissolved, as Ba	µg/L	EWI	ICPMS	1
Barium, total, as Ba	µg/L	EWI	ICPMS	1
Beryllium, total, as Be	µg/L	EWI	ICPMS	1
Boron, dissolved, as B	µg/L	EWI	ICPMS	1
Boron, total, as B	µg/L	EWI	ICPMS	1
Cadmium, dissolved, as Cd	µg/L	EWI	ICPMS; GFAA	1
Cadmium, total, as Cd	µg/L	EWI	GFAA	1
Chromium, dissolved, as Cr	µg/L	EWI	ICPMS	1
Chromium, total, as Cr	µg/L	EWI	ICPMS	1
Cobalt, total, as Co	µg/L	EWI	ICPMS	1
Copper, dissolved, as Cu	µg/L	EWI	ICP; ICPMS; GFAA	10; 1; 1
Copper, total, as Cu	µg/L	EWI	ICP; GFAA	10; 1
Iron, dissolved, as Fe	µg/L	EWI	ICP; AA	3; 10
Iron, total, as Fe	µg/L	EWI	AA; ICP	10
Lead, dissolved, as Pb	µg/L	EWI	ICP; ICPMS; GFAA	10; 1; 1
Lead, total, as Pb	µg/L	EWI	GFAA	1
Lithium, total, as Li	µg/L	EWI	GFAA	1
Manganese, dissolved, as Mn	µg/L	EWI	ICP; ICPMS	10; 4; 1
Manganese, total, as Mn	µg/L	EWI	AA; ICP	10
Mercury, dissolved, as Hg	µg/L	EWI	CVAF	0.01; .1
Mercury, total, as Hg	µg/L	EWI	CVAF	.01; .1
Molybdenum, total, as Mo	µg/L	EWI	ICPMS	1
Nickel, dissolved, as Ni	µg/L	EWI	ICPMS	1
Nickel, total, as Ni	µg/L	EWI	ICPMS	1
Selenium, dissolved, as Se	µg/L	EWI	ICPMS	1
Selenium, total, as Se	µg/L	EWI	ICPMS	1
Silver, dissolved, as Ag	µg/L	EWI	ICPMS	1
Silver, total, as Ag	µg/L	EWI	ICPMS	1
Strontium, dissolved, as Sr	µg/L	EWI	ICPMS	1
Zinc, dissolved, as Zn	µg/L	EWI	ICP; ICPMS	20; 3
Zinc, total, as Zn	µg/L	EWI	ICP, AA	10; 31; 40
Suspended sediment				
Sediment, bedload, size fractions	Percent	EWI	Dry sieve	1.
Sediment, suspended, concentration	mg/L	EWI	Gravimetric	1.

[1] The listed field methods generally apply to sample collection on Elkhead Creek. For Elkhead Reservoir, field methods for dissolved oxygen, pH, specific conductance, and temperature were multipoint, and for dissolved constituents field methods were point.

collected in a baked glass bottle by dip (point) method at the centroid of flow.

Water samples collected for analysis of dissolved constituents were filtered through a disposable 0.45-µm capsule filter in an enclosed filter chamber using a peristaltic pump. Dissolved organic-carbon samples were filtered through a 0.45-µm silver filter using compressed nitrogen. Nutrient and organic-carbon samples were chilled to approximately 4°C for transportation to the laboratory. Trace-element samples were preserved with trace-element grade nitric acid. Detailed descriptions of all the field methods used in this investigation are presented in U.S. Geological Survey (1998).

Periodic Water-Quality Samples at Elkhead Reservoir

Water-quality samples were collected from Elkhead Reservoir about 2–4 times per year beginning July 1995 through August 2001, at three horizontal transects—one near the Elkhead Creek inflow (inlet), one at midlake, and one near the dam (fig. 1; table 1). No samples were collected during water year 2000. During each sampling, temperature, dissolved oxygen, specific conductance, and pH depth-profiles were measured at two sites at the inlet transect and at three sites at each of the other two transects. Depth-profiles were measured at 1- to 3-ft increments, depending on the total depth at the site, with a multiparameter water-quality instrument. Transparency of the water also was measured at each of the depth-profile sites by using a Secchi disk and cloth tape or folding rule (U.S. Geological Survey, 1998).

Water-quality samples for analysis of nutrients, chlorophyll-*a,* and chlorophyll-*b* were collected at only one of the depth-profile sites (sites ER1b, ER2b, and ER3b; fig. 1) in each transect. Nutrient samples were collected from just below the water surface and near the bottom of the reservoir by using a Van Dorn point sampler (a horizontal PVC cylinder with end seals that are triggered by a surface messenger) lowered on a cable (U.S. Geological Survey, 1998). Sample water was transferred from the sampler to clean, acid-rinsed, deionized-water rinsed, and native-water rinsed polyethylene containers in the boat. Once onshore, the raw sample was transferred to a clean, acid-rinsed, deionized-water rinsed, and native-water rinsed USGS churn splitter and then processed and preserved as described in the previous section of this report (U.S. Geological Survey, 1998). Chlorophyll-*a* and chlorophyll-*b* samples were collected at the surface by grab method with a clean 1-L amber polyethylene bottle and processed onshore according to methods described in Britton and Greeson (1987). Depth-profile measurements and water-quality samples were collected four times during 1995 (July, August, September, and October); four times during 1996 and 1997 (April–May, July–August, September, and October); three times during 1998 (April, August, and October); twice during 1999 (May and August); none during 2000; and twice during 2001 (April and August).

Laboratory Analysis

Major ion, nutrient, and trace-element concentrations were analyzed at the USGS National Water Quality Laboratory (NWQL) in Lakewood, Colo., using standard analytical techniques described in Fishman and Friedman (1989), Fishman (1993), and Fishman and others (1994). Samples collected for concentrations of organic constituents were analyzed at the NWQL using standard analytical techniques described in Wershaw and others (1987) and Fishman (1993). Suspended-sediment and bed-material samples were analyzed at the USGS Sediment Laboratory in Iowa City, Iowa, using the techniques described in Guy (1969). USGS quality-assurance procedures used in collection and analysis of samples are described in Friedman and Erdmann (1982). All data have been published in the annual USGS data reports for Colorado and are stored in the USGS National Water Information System (NWIS) database. Analytical methods and minimum reporting limits for the analyzed properties and constituents are listed in table 2.

Data Analysis

Daily discharge, specific conductance, and temperature data were analyzed by using time-series plots, flow-duration curves, frequency analysis, and trend analysis. Periodic water-quality data for Elkhead Creek (field measurements, major ions, nutrients, trace elements, suspended sediment, and biological indicators) were analyzed (1) graphically for annual and seasonal (temporal) comparisons and upstream to downstream (spatial) comparisons; and (2) statistically to determine if there was a significant difference in the data characteristics upstream and downstream from Elkhead Reservoir or if the data changed over time.

Water-quality data for Elkhead Reservoir (field measurements, nutrients, and chlorophyll) were analyzed by evaluation of general characteristics, spatial variability, and near-surface and near-bottom variability; seasonality was evaluated by use of time-series plots, statistics, and boxplots. Stratification patterns were evaluated by analysis of depth profiles to understand vertical variability in temperature, specific conductance, pH, and dissolved oxygen.

Statistical Testing and Load Computation

Differences in annual discharge for two time periods at station 09245000 Elkhead Creek near Elkhead (fig. 1; table 1) were evaluated by statistical analysis. Differences in the mean annual discharge for the two periods were analyzed by using a two-sample t-test for small sample sizes ($n < 30$) (Iman and Conover, 1983, p. 272–274), and differences in the variances of the mean annual discharge for the two periods were analyzed using an F-test for small sample sizes ($n < 30$) (Iman and Conover, 1983, p. 274–278).

The Wilcoxson-Mann-Whitney rank-sum test (Iman and Conover, 1983, p. 280) (hereinafter, “rank-sum test”), was used to test for statistical differences between the field-measurement values for stations 09246200 and 09246400. The rank-sum test is a nonparametric procedure in which data for the two population samples (data for both stations) are ranked; a two-sample t-test then is performed on the ranks of the data. The advantages of the rank-sum test over a simple two-sample t-test (Iman and Conover, 1983, p. 280) are that (1) the data do not need to be normally distributed, which often is the case with hydrologic data, and (2) the rank-sum test is less sensitive to the assumption of equal variances, which may be likely when comparing data upstream and downstream from a reservoir. The rank-sum tests used in this report were two-sided tests and were made at a 0.05 significance level.

Trend analysis for periodic water-quality data was performed using the seasonal Kendall procedure (Hirsch and others, 1982) and the Tobit procedure (Cohn, 1988). The seasonal Kendall procedure is a nonparametric trend test that reduces the adverse effects that seasonal differences in concentrations may have on trend detection by making comparisons of data only from similar seasons (Schertz and others, 1991). The seasonal Kendall procedure can be used to analyze uncensored data or data censored with only one reporting limit, and the data also can be analyzed using flow-adjusted values; however, if more than about 5 percent of the data are censored, flow-adjusted values should not be used for the seasonal Kendall test (Schertz and others, 1991). The Tobit procedure is a parametric trend test that uses regression and adjusted maximum likelihood estimates (Cohen, 1976; Cohn, 1988) to relate water-quality values to time; the procedure is used when more than 5 percent of the data are censored at one or more reporting limits.

Both of these trend analysis procedures have been incorporated into the EStimate TREND (ESTREND) computer program (Schertz and others, 1991). The ESTREND program also has been adapted as a special USGS application (David Lorenz, U.S. Geological Survey, written commun., 2002) in the S-Plus 2000 statistical analysis package (Insightful Corp., 2000), which was used for the analyses described in this report. When using the Tobit procedure within the S-Plus package, data also can be flow adjusted, which is an option not available in the original ESTREND program (David Lorenz, U.S. Geological Survey, written commun., 2002).

The seasonal Kendall procedure was used to evaluate trends in field measurements, major ion, and suspended-sediment data, using both unadjusted and flow-adjusted values as appropriate. The Tobit procedure was used to analyze the nutrient data because of many censored values, also using both unadjusted and flow-adjusted values. Trends in trace-element data were not evaluated because the number of samples was insufficient. Trend tests were made at a 0.05 significance level.

Because concentration data for water-quality constituents from instantaneous samples sometimes do not clearly show the temporal and spatial differences between two stations, especially if the differences are not very pronounced, annual and monthly loads were computed for selected constituents. Loads at stations 09246200 and 09246400 were computed using the load estimator program (LOADEST) (R.L. Runkel, U.S. Geological Survey, written commun., 2002) that incorporates several previously developed methods (Cohn and others, 1989; Crawford, 1991 and 1996; and Gilroy and others, 1990). The LOADEST program uses regression techniques to estimate constituent loads in streams and rivers for a given time series of discharge data, additional independent variables, and constituent concentration. The calibration and estimation procedures within LOADEST are based on four statistical estimation methods that include the Adjusted Maximum Likelihood Estimation (AMLE); the AMLE method was used for the analyses described herein. AMLE is the preferred method when the calibration data set (time-series of flow, additional independent variables, and concentration) contains censored data (R.L Runkel, U.S. Geological Survey, written commun., 2002).

Reservoir Trophic State and Nutrient Limitation

Trophic state for Elkhead Reservoir was estimated using three methods developed by Carlson (1977). The derived equations to compute trophic-state index (TSI) values on the basis of chlorophyll-*a* concentration, Secchi-disk depth, or total phosphorus concentration are as follows:

$$\mathrm{TSI(CHLA)} = 9.81(\ln \mathrm{CHLA}) + 30.6 \tag{1}$$

$$\mathrm{TSI(SD)} = 60 - 14.41(\ln \mathrm{SD}) \tag{2}$$

$$\mathrm{TSI(TP)} = 14.42(\ln \mathrm{TP}) + 4.15 \tag{3}$$

where

CHLA = chlorophyll-*a* concentration, in micrograms per liter;
SD = Secchi-disk depth, in meters;
TP = total phosphorus concentration, in micrograms per liter; and
ln = the natural logarithm function.

The TSI equations presented in Carlson (1977) are different from equations 1–3, which are algebraically simplified versions of the equations in Carlson.

The equations provide a normalized value for TSI; therefore, each of the three TSI’s can be used independently to describe the trophic state of a water body. For Elkhead Reservoir, TSI values were computed using all three TSI estimating equations. The TSI values were averaged for each set of reservoir samples, and the mean sample values then were used to compute a mean annual TSI for the reservoir.

Nitrogen (N) to phosphorus (P) mass ratios have been used to characterize the limiting nutrient for algal growth present in water (Britton and Gaggiani, 1987; Woods, 1992) and were computed for Elkhead Reservoir. The ratio (N:P) is computed by dividing concentration of dissolved inorganic nitrogen by concentration of dissolved orthophosphorus (Redfield, 1958).

Nutrient limitation information is important because it indicates the nutrient that controls algal growth. If a nutrient is limiting, the hypothesis is that the addition of that nutrient then would cause an increase in algal production (in the absence of other limiting factors) (Britton and Gaggiani, 1987; Woods, 1992). A mass ratio of about 7N:1P is the theoretical boundary between N and P limitation (Redfield, 1958). In practice, N:P ratios smaller than 5 are thought to represent nitrogen-limiting situations, whereas N:P ratios larger than 10 represent phosphorus-limiting conditions. Nitrogen to phosphorus ratios between 5 and 10 could indicate nitrogen or phosphorus limitation (Britton and Gaggiani, 1987; Woods, 1992).

Water-Quality Standards

The designated use classifications for Elkhead Creek and Elkhead Reservoir are Aquatic life cold 1, Recreation 1, Water supply, and Agriculture (Colorado Department of Public Health and Environment, Water Quality Control Commission, 2002). In addition to the use classifications, the State of Colorado has established detailed water-quality standards for individual constituents that are based on numeric fixed standards or on equations, referred to as “Table of Value Standards (TVS)” (Colorado Department of Public Health and Environment, Water Quality Control Commission, 2002). The State methodology uses hardness concentrations to calculate the chronic trace-element standards, specifying that the trace-element standards be computed by using the lower 95-percent confidence limit of the mean hardness at the periodic low-flow criteria determined from regression analysis of site-specific or regional data. The 85th percentile of available data for a given trace element at a specific site then is compared to the standard. Calculation of trace-element standards using this rigorous method was beyond the scope of this report; therefore, the hardness concentration for each trace-element sample was used to compute trace-element standard values, and the computed standard value was compared to the trace-element concentration in the sample. In this report, the comparison of trace-element concentrations to the computed (estimated) trace-element standards, therefore, should be regarded as a general indicator rather than a rigorous statistical comparison to State standards.

Laboratory minimum reporting limits (MRLs) for trace elements such as cadmium, mercury, silver, and lead commonly were too high to determine concentrations at the level of the standards. These constituents might be present in the sample at concentrations lower than the MRL but higher than the standard. Certain constituents listed in the Colorado water-quality standards were not analyzed in the samples (for example, chlorine, cyanide, and sulfide).

Hydrology of Elkhead Creek

In addition to the two daily discharge stations established in 1995 for the monitoring program (see “Daily Discharge, Specific Conductance, and Water Temperature” section), the USGS has operated four other stations at various times in the Elkhead Creek basin (table 1); station 09245000 Elkhead Creek near Elkhead (fig. 1) has the longest period of record, 1953–96 (table 1) and is used as the reference station for the hydrologic analysis. Station 09245000 was discontinued at the end of water year 1996 after 1 year of concurrent operation with stations 09246200 and 09246400. Station 09245000 recorded runoff from about 27 percent of the basin area, measured at the confluence with the Yampa River; station 09246200 recorded runoff from about 68 percent of the basin, including most of the inflow to Elkhead Reservoir; and station 09246400 recorded runoff from about 85 percent of the basin and includes outflow from Elkhead Reservoir. Most of the following hydrologic analyses are based on the streamflow data recorded for stations 09245000, 09246200, and 09246400 on Elkhead Creek.

Daily Mean Discharge

Elkhead Creek is a meandering, alluvial stream dominated by snowmelt that produces most of the annual discharge volume and discharge peaks during late spring and early summer. Hydrographs for daily mean discharge 12(fig. 2) during water year 1996 at stations 09245000, 09246200, and 09246400 are generally similar in shape and show the snowmelt-dominated discharge pattern. Discharge at the most upstream station, 09245000, usually is less than at the two downstream stations owing to the much smaller drainage area (table 1); however, discharge at station 09245000 is larger during late summer and fall than it is at stations 09246200 and 09246400 (fig. 2). The smaller discharges at the two downstream stations probably results from streamflow diversion for irrigated agriculture downstream from station 09245000, and, in the case of station 09246400, storage effects of Elkhead Reservoir.

During most of water year 1996, daily mean discharge downstream from the reservoir (station 09246400) was similar to daily mean discharge upstream from the reservoir (station 09246200) (fig. 2). This primarily resulted from two factors: (1) The reservoir outlet works only has a capacity of about 180 ft^3/s (Ayres Associates, 2002b), resulting in frequent outflow discharge at the spillway, especially during snowmelt, and (2) downstream demand on water stored in the reservoir is minimal, resulting in little drawdown during low-flow periods. Together, these factors resulted in reservoir outflow that was about equal to reservoir inflow and a reservoir that was full or nearly full at all times (“flow-through” operation). [Note: No daily contents data are available for Elkhead Reservoir.] The noticeable increase in discharge between stations 09246200 and 09246400 during August and September (fig. 2) likely was the result of reservoir release to augment the irrigation-depleted inflow; the increase also could have resulted from irrigation return flows downstream from the reservoir or from unmeasured tributary inflow.

Instantaneous diurnal discharge peaks at station 09246400 lagged the peaks at station 09246200 by about 7 hours. The diurnal range in discharge and the instantaneous daily discharge

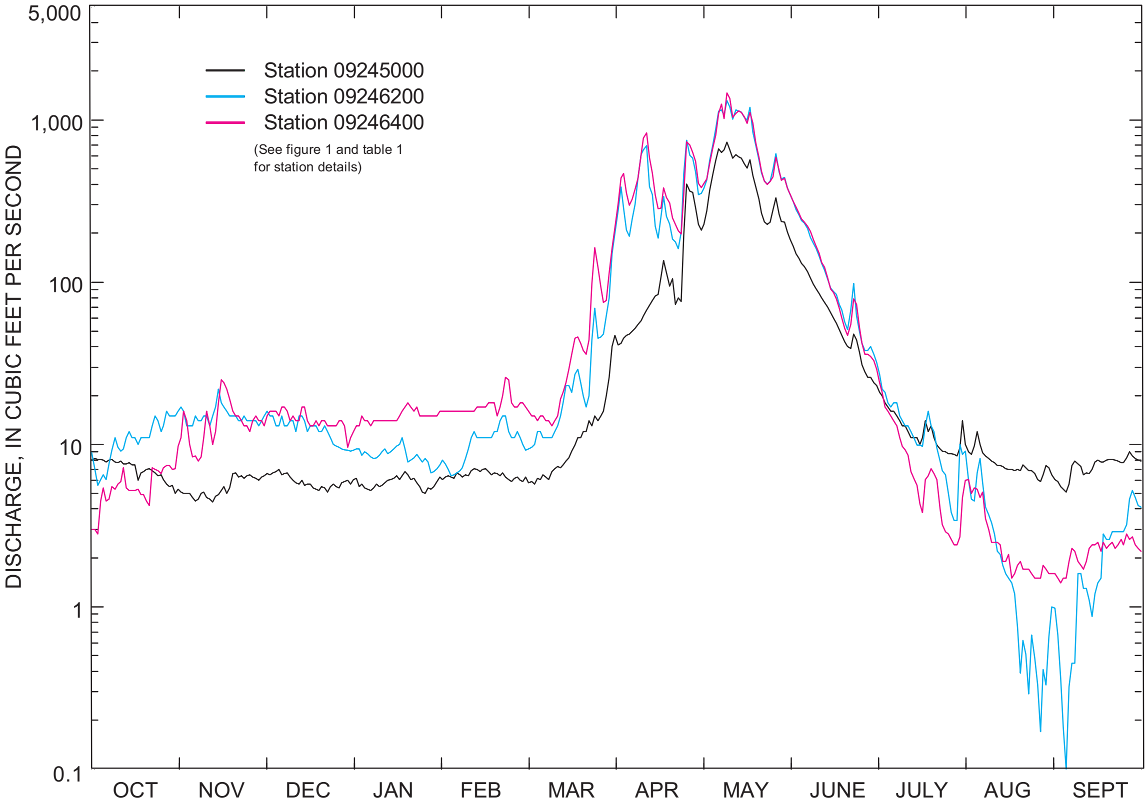


Figure 2. Daily mean discharge for Elkhead Creek at selected stations, water year 1996.

peaks tended to be less at the downstream station than at the upstream station; however, the daily mean discharge, adjusted for traveltime, tended to be greater at the downstream station, 09246400, than at the upstream station, 09246200. The attenuation of diurnal peaks at station 09246400 probably resulted from the storage effects of Elkhead Reservoir, whereas the larger daily mean discharges at station 09246400 probably resulted from additional runoff contributed by tributaries entering between the two stations. The drainage area of Elkhead Creek is 24 percent larger at station 09246400 than at station 09246200; the additional area represents 17 percent of the total Elkhead Creek basin area measured at the mouth.

Flow Duration

Flow-duration curves of daily mean discharge for stations 09245000, 09246200, and 09246400 (fig. 3a) provide a graphical representation of streamflow characteristics throughout the range of discharge without considering the timing of the discharges (Searcy, 1959, p. 1). Flow durations for stations 09246200 and 09246400 were nearly identical for discharges larger than about 10 ft^3/s, but there was some divergence in the curves for discharges less than 10 ft^3/s, primarily because of the effects of upstream diversion on low-flow discharge at station 09246200 and the effects of reservoir regulation on low-flow discharge at station 09246400. The range in discharge for station 09245000 was less than that for the two downstream stations, again owing to the differences in drainage area; however, the shape of the flow-duration curve for station 09245000 is similar to the shape of the curves for the other two stations, indicating that hydrologic characteristics were similar at all three stations. When drainage area is considered (fig. 3b), the position of the flow-duration curve for station 09245000 is closer to the position of the curves for the two downstream stations.

The periods of record for the two current downstream stations are much shorter than the period of record for the historic upstream station, 09245000. Flow duration for shorter time periods can be representative of flow duration for longer time periods if the hydrologic variability in the shorter period is about equal to the variability in the longer period. Because it is not known if hydrologic conditions during water years 1996–2001 are representative of long-term hydrologic conditions, some caution should be used in comparing and using the flow-duration curves for the three stations.

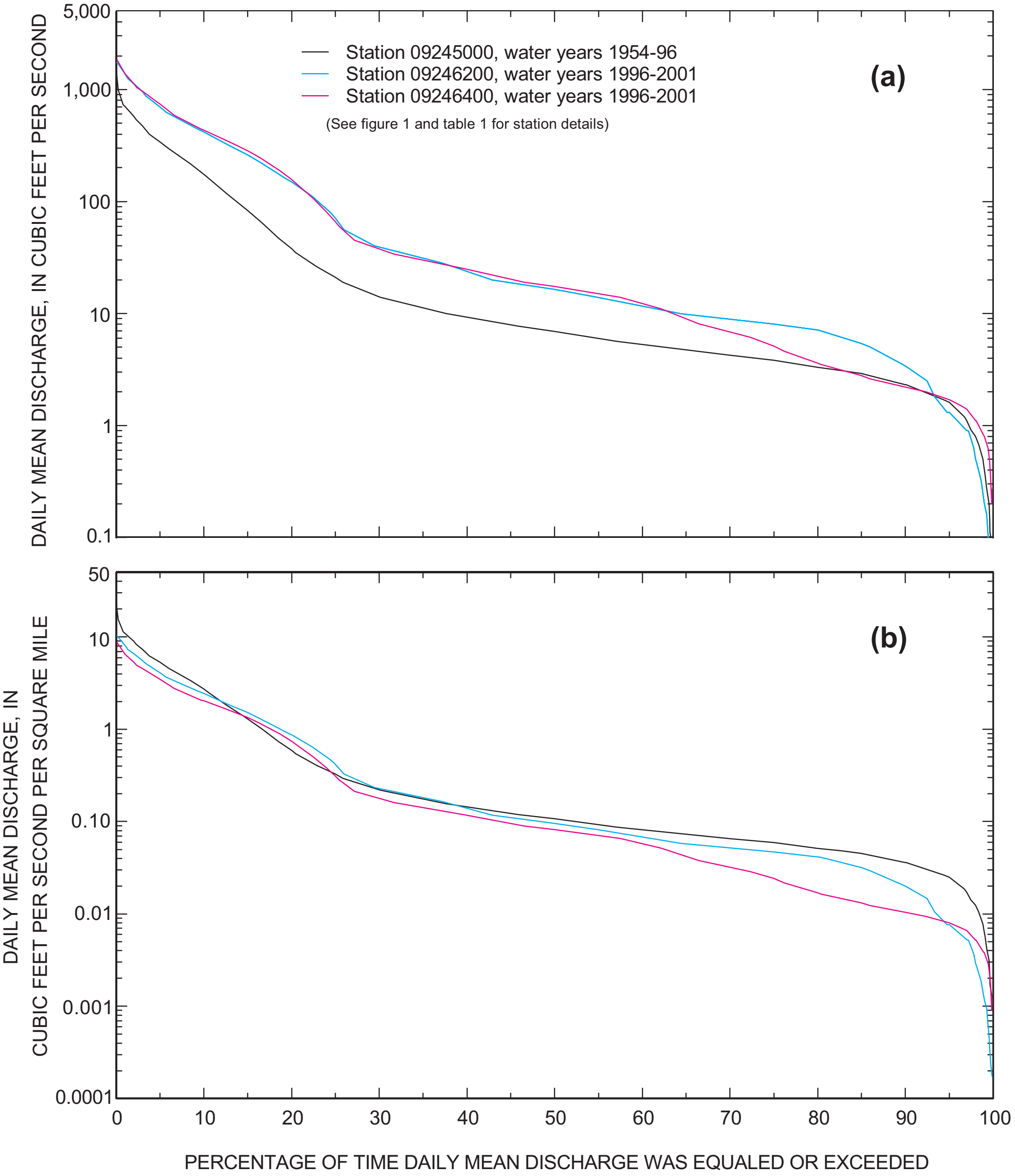


Figure 3. Flow duration of daily mean discharge for Elkhead Creek at selected stations.

Instantaneous Peak Discharge and Bankfull Discharge

Annual instantaneous peak discharges vary widely in magnitude and reflect the water content of snowpack from the preceding winter and the spring weather patterns. Annual peak discharges recorded at station 09245000 varied from 224 ft^3/s during 1992 to 2,850 ft^3/s during 1984; annual peak discharges recorded at station 09246200 varied from 1,420 ft^3/s during 2001 to 2,760 ft^3/s during 1997; and annual peak discharges recorded at station 09246400 varied from 1,120 ft^3/s during 1999 to 2,430 ft^3/s during 1997 (fig. 4). Although data for water year 2002 were provisional at the time this report was prepared, peak discharges during 2002 were substantially less than previous years because of a low snowpack the preceding winter; the provisional instantaneous peak discharges for 2002 were 337 ft^3/s at station 09246200 and 269 ft^3/s at station 09246400 (R.G. Carver, U.S. Geological Survey, oral commun., 2002).

Peak-flow frequency was computed for station 09245000 by standard USGS procedures (U.S. Interagency Advisory Committee on Water Data, 1982) for the 44 years of record. The estimated 10-year peak discharge for the station is 1,700 ft^3/s, and the estimated 100-year peak discharge is 2,580 ft^3/s (table 3). Peak-flow frequency cannot be computed for stations 09246200 and 09246400 because the period of record is only

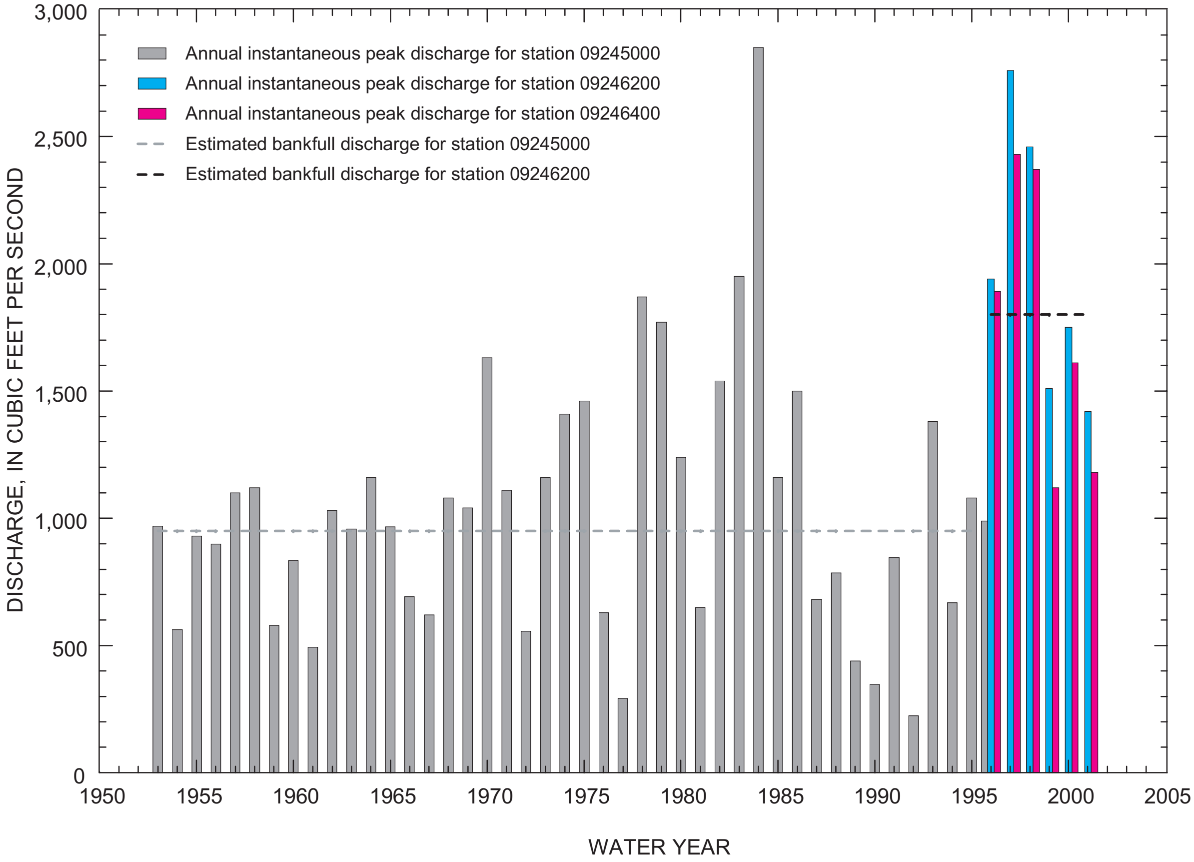


Figure 4. Annual instantaneous peak discharge and estimated bankfull discharge for Elkhead Creek at selected stations.

7 years. Peak discharges at stations 09246200 and 09246400 during 1996 (fig. 4) were about two times larger than the peak discharge at station 09245000, but it is not known if this is representative of the long-term ratio. Additionally, although larger daily mean discharges at station 09246400 are not affected substantially by Elkhead Reservoir (figs. 2–3), the instantaneous peak discharges at station 09246400 are attenuated in comparison to the instantaneous peak discharges at station 09246200 (fig. 4). The attenuation likely results from the storage effects of Elkhead Reservoir; however, there could be some natural attenuation of peak discharges between stations 09246200 and 09246400. Any natural attenuation cannot be determined because concurrent upstream and downstream discharge data are not available prior to 1975 when Elkhead Dam was completed.

By using commonly accepted statistical methods for bankfull discharge, discharge record analysis, and onsite high-streamflow observations during 1998, the bankfull discharge (the discharge having a 0.50 annual exceedance probability or a 2-year recurrence interval) for station 09245000 was estimated to be about 950 ft^3/s (Elliott and Gyetvai, 1999). This discharge, as an instantaneous annual flood peak, was equaled or exceeded in 25 of the 44 years of record, or in 57 percent of years (fig. 4). A daily mean discharge of 950 ft^3/s was equaled or exceeded approximately 0.7 percent of the time (fig. 3), or an average of about 2–3 days per year.

Bankfull discharge for station 09246200 was estimated to be about 1,800 ft^3/s, based on surveyed channel characteristics in 1997, the 1997 high water marks (peak discharge 2,760 ft^3/s), and observations of water-surface elevations in the

Table 3. Estimated peak-flow frequency discharges for station 09245000 Elkhead Creek near Elkhead, water years 1954–96.

Annual exceedance probability	Recurrence interval (years)	Estimated peak discharge (cubic feet per second)
0.95	1.05	403
.90	1.11	493
.80	1.25	623
.50	2	950
.20	5	1,400
.10	10	1,700
.04	25	2,060
.02	50	2,320
.01	100	2,580
.005	200	2,830
.002	500	3,160

spring of 1998 (Elliott and Gyetvai, 1999). Bankfull discharge for station 09246400 could not be determined precisely; however, based on the strong correlation between discharge at stations 09246200 and 09246400 and channel surveys, the estimated bankfull discharge is from 1,800 to 2,200 ft^3/s in the reach downstream from Elkhead Reservoir (Elliott and Gyetvai, 1999, p. 6 and p. 15).

Trend Analysis of Annual Discharge

Annual discharge (total runoff from a basin in a year) at station 09245000 varied from 12,010 acre-ft in 1977 to 82,380 acre-ft in 1984; mean annual discharge for 1954–96 was 40,200 acre-ft (fig. 5). Annual discharge at station 09246200 varied from 54,230 acre-ft in 2001 to 135,000 acre-ft in 1997; mean annual discharge for 1996–2001 was 90,010 acre-ft. Annual discharge at station 09246400 varied from 54,670 acre-ft in 2001 to 139,100 acre-ft in 1997; mean annual discharge for 1996–2001 was 91,790 acre-ft. Provisional annual discharges for water year 2002 for stations 09246200 and 09246400 are 8,760 and 9,100 acre-ft, respectively (R.G. Carver, U.S. Geological Survey, oral commun., 2002).

Variation in annual discharges at station 09245000 (fig. 5) was larger after the mid-1970's compared to years before the mid-1970's. Annual discharges were evaluated for two time periods of nearly equal length, water years 1954–74 (21 years) and water years 1975–96 (22 years). The subdivision before and after 1975 corresponds to the year that Elkhead Reservoir was first filled. The mean annual discharge was 37,970 acre-ft for 1954–74 and 42,320 acre-ft for 1975–96 (fig. 5; table 4). Mean annual discharges for the two time periods are, respectively, about 5.6 percent smaller and 5.3 percent larger than the mean annual discharge for the entire record (table 4). Standard deviation of the mean annual discharge was 11,960 acre-ft for 1954–74 and was 19,980 acre-ft for 1975–96, compared to 16,510 acre-ft for the entire record (table 4). Standard deviations of the mean annual discharge, however, are about 28 percent smaller and 21 percent larger than the standard deviation of mean annual discharge for the entire record (table 4). A t-test (see p. 8) did not indicate a statistical difference (*p*-value = 0.39) in the mean annual discharges for the two time periods; however, an F-test (see p. 8) did indicate a statistical difference (*p*-value = 0.025) between the variances (standard deviation squared) of the mean annual discharges for the two time periods.

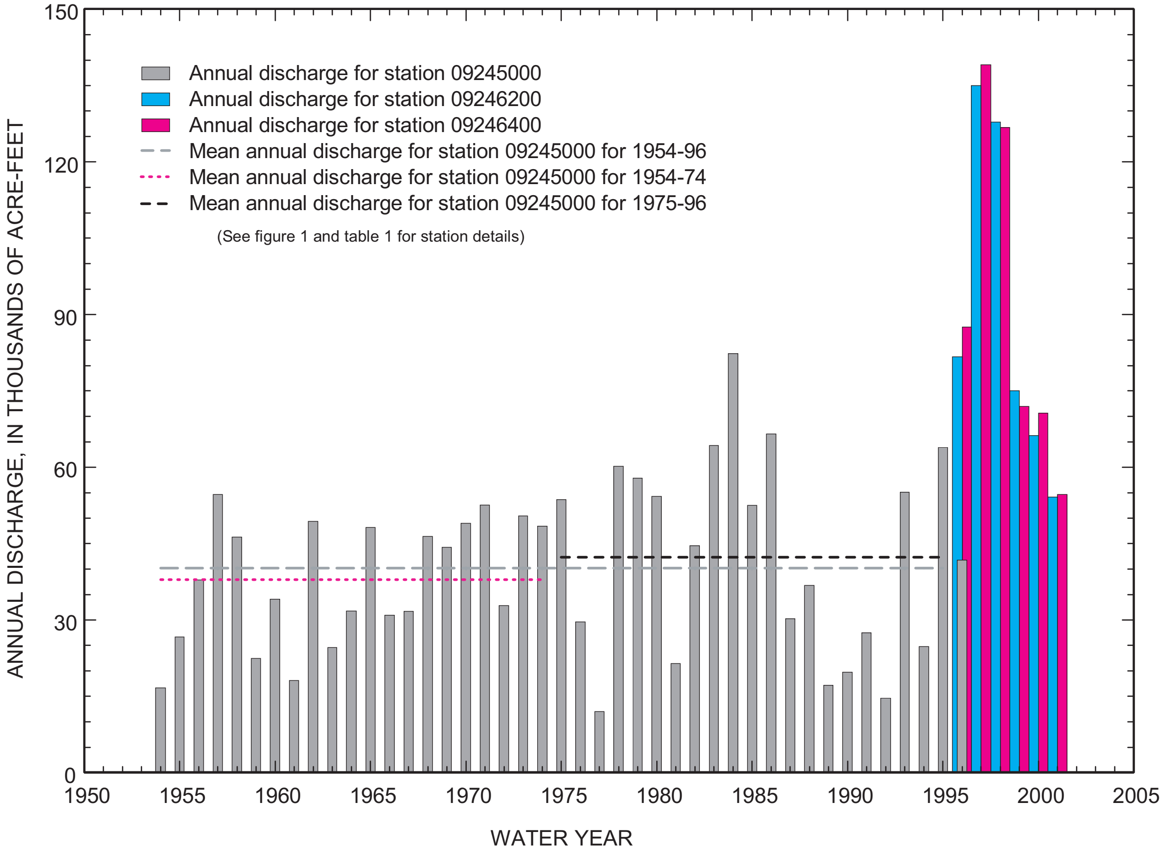


Figure 5. Annual discharge for Elkhead Creek at selected stations.

Table 4. Mean annual discharge and standard deviation for selected time periods for stations 09241000 Elk River at Clark and 09245000 Elkhead Creek near Elkhead.

[--, does not apply]

Time period (water years)	Mean annual discharge (acre-feet)	Change in mean annual discharge compared to long-term mean		Standard deviation (acre-feet)	Change in standard deviation compared to long-term standard deviation	
		In acre-feet	In percent		In acre-feet	In percent
Station 09241000 Elk River at Clark						
1932-91 (long term)	231,700	--	--	60,600	--	--
1932-53	239,700	8,000	3.5	48,130	-12,470	-21
1954-74	223,000	-8,700	-3.8	51,130	-9,470	-16
1975-91	231,400	-300	-.13	83,970	23,370	39
Station 09245000 Elkhead Creek near Elkhead						
1954-96 (long term)	40,200	--	--	16,510	--	--
1954-74	37,970	-2,230	-5.6	11,960	-4,550	-28
[1]1975-96	42,320	2,120	5.3	19,980	3,470	21

[1] Elkhead Reservoir was filled during water year 1975.

To further evaluate the variability of annual discharge in Elkhead Creek and to extrapolate to a period before records were collected at station 09245000, annual discharge data from a nearby basin, station 09241000 Elk River at Clark (not shown in fig. 1, about 10 mi east of study area), were examined. The Elk River station records discharge from a 216-mi^2 area that is geographically similar to the Elkhead Creek basin. Annual discharge data for station 09241000 are available for 1932–91.

Annual discharge at station 09241000 was highly variable during the period of record (fig. 6). The long-term (1932–91) mean annual discharge was 231,500 acre-ft, and the standard deviation was 60,600 acre-ft (table 4). The annual discharges

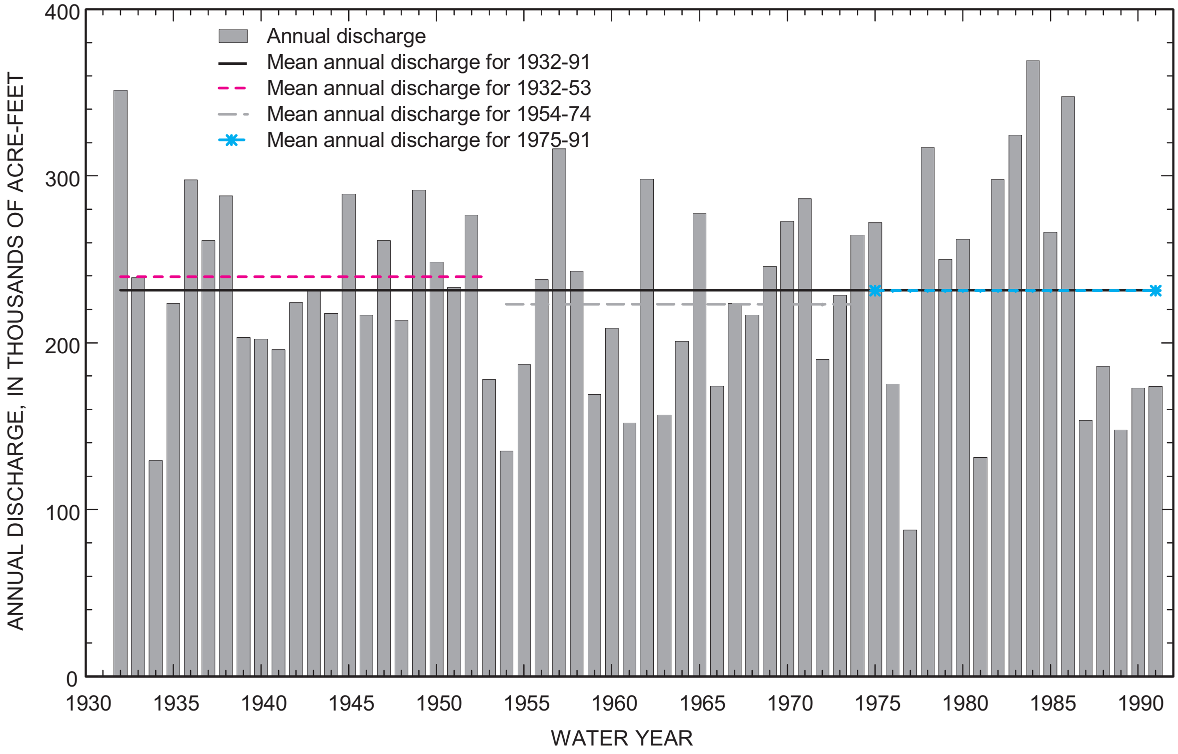


Figure 6. Annual discharge for station 09241000 Elk River at Clark.

were subdivided into three periods: (1) 1932–53, an interval for which there are no data at station 09254000 (Elkhead Creek); (2) 1954–74, an interval identical to the pre-reservoir period at station 09245000; and (3) 1975–91, an interval nearly comparable to the post-reservoir period at station 09245000. Mean annual discharges and the standard deviations at the Elk River station (fig. 6; table 4) were similar to those at the Elkhead Creek station (fig. 5; table 4) for the two comparable periods; the 1975–96 period was one of slightly larger than average annual discharge and greater variability, and the 1954–74 period was one of slightly smaller than average discharge and lesser variability.

At station 09241000, mean annual discharge (239,700 acre-ft) for 1932–53 is about 3.5 percent larger, and mean annual discharge (223,000 acre-ft) for 1954–74 is about 3.8 percent smaller than the long-term mean annual discharge; mean annual discharge (231,400 acre-ft) for 1975–91 is nearly identical to the long-term mean (fig. 6; table 4). Results of t-tests, at a 0.05 significance level, indicated that mean annual discharges at station 09241000 (Elk River) in each of the three periods were not statistically different from one period or another, nor from the long-term mean. F-tests, however, indicated that variance for 1975–91 was statistically greater than the variance for 1932–53 ($p = 0.018$) and for 1954–74 ($p = 0.038$).

Annual discharge at station 09241000 (Elk River) for 1932–53 (fig. 6) is of interest because it may be representative of annual discharge at station 09245000 (Elkhead Creek) during a period for which no discharge data are available at station 09245000 (fig. 5). Mean annual discharge in the Elk River for 1932–53, 239,700 acre-ft, was about 4 percent greater than the long-term mean, whereas the standard deviation, 48,130 acre-ft, was about 20 percent less than the long-term standard deviation (fig. 6; table 4). During 1932–53, characteristics of annual discharge at station 09245000 (Elkhead Creek) may have been similar to those at station 09241000 (Elk River) in that annual discharge was larger than average with relatively little year to year variability.

Annual discharges for stations 09245000 (Elkhead Creek) and 09241000 (Elk River) also were compared for the concurrent period (1954–91) using regression analysis. The relation between annual discharges at the two stations is expressed as:

$$Y = 0.0025\ X^{1.342} \tag{4}$$

where

Y = annual streamflow at station 09245000 Elkhead Creek near Elkhead, and
X = annual streamflow at station 09241000 Elk River at Clark.

The coefficient of determination (R^2) for the regression is 0.891, indicating a substantial degree of correlation between annual discharges at the two stations.

The strong relation between annual discharges in Elkhead Creek and the Elk River was used to evaluate the possible cause of the greater mean and standard deviation in annual discharge of Elkhead Creek after 1975. A double-mass curve of cumulative annual discharges for Elkhead Creek and the Elk River shows a consistent, uniform relation between the two stations for the concurrent period and little departure from a straight regression line (fig. 7) that had an R^2 of 0.999. If the slightly greater mean and standard deviation of annual discharge in Elkhead Creek after 1975 (fig. 5) was a result of a local (within the basin) change in land use or vegetation cover, the double-mass curve segment after 1975 would have had some change in slope or linearity (fig. 7). Because the double-mass curve is consistent and uniform, it is concluded that the cause of the slightly greater magnitude and variability in annual discharge for Elkhead Creek after 1975 was regional and affected discharge in the Elk River similarly during the period of concurrent discharge record.

One additional conclusion can be made from the strong correlation between the cumulative annual discharges at stations 09241000 and 09245000 (fig. 7) and the annual discharge trend at station 09241000 (fig. 6). For station 09241000 (Elk River), mean annual discharge during 1975–91 is similar to the long-term mean; however, the variability is greater during 1975–91 than during the long term (fig. 6; table 4). Therefore, it can be hypothesized that mean annual discharge for station 09245000 (Elkhead Creek) during 1975–96 could be more representative of a 1932–96 long-term mean annual discharge than the mean annual discharge for the 1954–96 period of record (table 4). This hypothesis does not apply to the long-term standard deviation, which for both streams is greater in the post 1975 interval than for the respective periods of record.

Water Quality of Elkhead Creek

Water quality of Elkhead Creek can be affected by a number of different basin factors, such as quantity and source of baseflow contribution, quantity and distribution of precipitation, quantity and timing of snowmelt, diversion for irrigation, irrigation return flow, and bedrock geology. Human activities, such as agriculture, mining, reservoir development, and urban development also can affect variation in streamwater quality.

The following sections of the report describe (1) continuous measurements of specific conductance and temperature; (2) annual and seasonal distribution of field measurements, major ions, nutrients, trace elements, and other constituents measured or analyzed during the periodic water-quality sampling; (3) water-quality seasonal trends; and (4) annual and monthly loads for selected water-quality constituents. Differences between the data at the stations upstream from Elkhead Reservoir (09246200) and downstream from Elkhead Reservoir (09246400) also will be described.

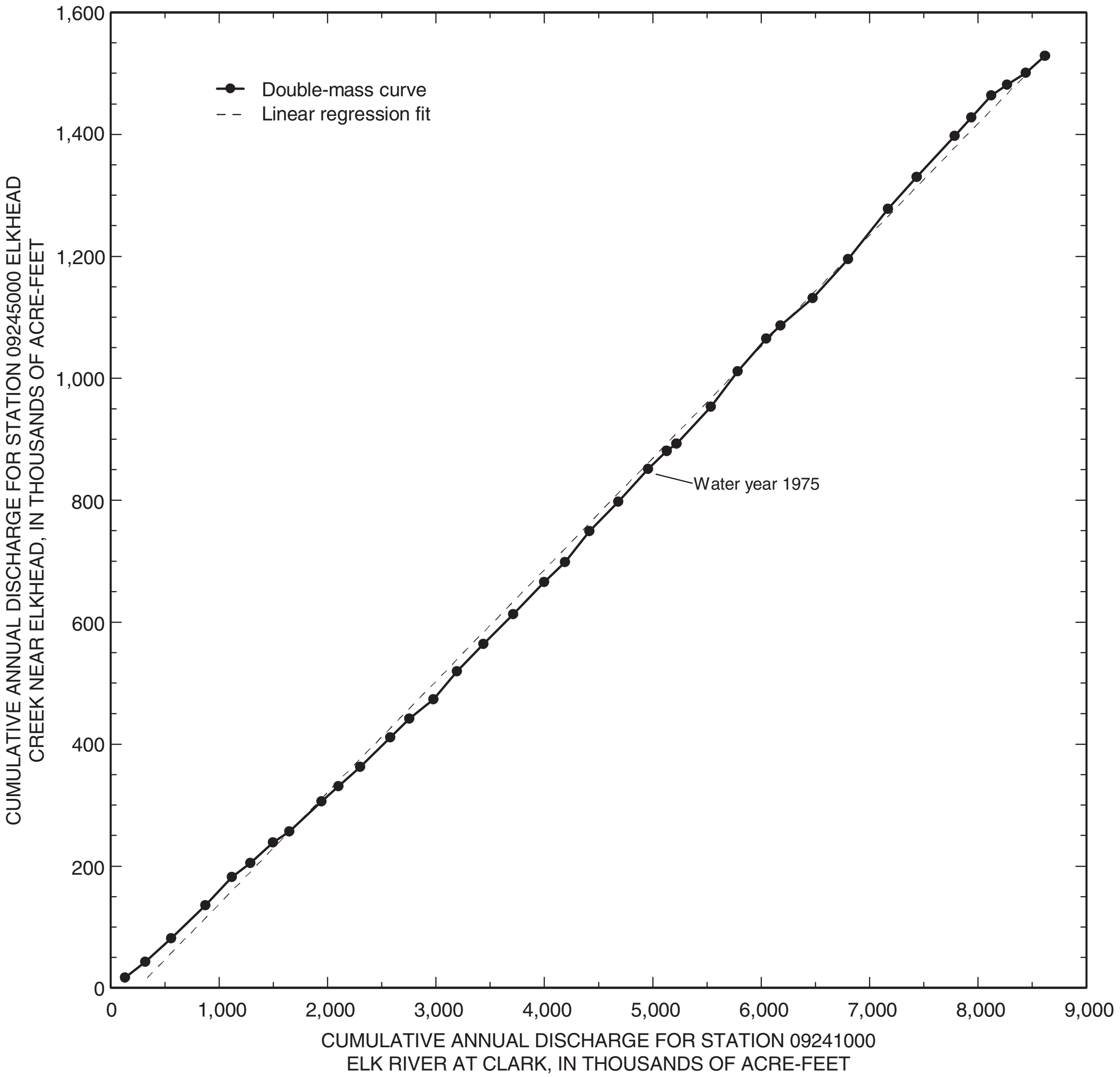


Figure 7. Double-mass curve of cumulative annual discharge for stations 09241000 Elk River at Clark and 09245000 Elkhead Creek near Elkhead, water years 1954–91.

Continuous Specific Conductance and Water Temperature

Daily mean discharge, specific conductance, and water temperature during water years 1997, 1999, and 2001 at stations 09246200 and 09246400 (fig. 8) shows the annual and seasonal distribution of these measurements. For both stations, water year 1997 was the year with the largest annual discharge, about 137,000 acre-ft, whereas water year 2001 was the year with the smallest annual discharge, about 54,000 acre-ft (fig. 5). Water year 1999 is included in figure 8 primarily because this was the only year during which continuous specific conductance and temperature measurements were obtained throughout the year; annual discharge was about 74,000 acre-ft during water year 1999 (fig. 5).

Specific conductance generally has an inverse relation to discharge in Elkhead Creek (fig. 8). During late fall and winter when discharge is small and derived mostly from ground water, specific conductance is large. During spring and early summer, when discharge is large and derived mostly from snowmelt, specific conductance is small. These results are because ground-water discharge has relatively high concentrations of dissolved solids, whereas snowmelt discharge has relatively low concentrations of dissolved solids. The range of daily mean specific conductance recorded at station 09246200 was about 110 to 960 µS/cm, and at station 09246400 was about 120 to 560 µS/cm (fig. 8).

The large increase in specific conductance at station 09246200 during late March to early April 1999 is very noticeable. The increase in specific conductance is during a time of

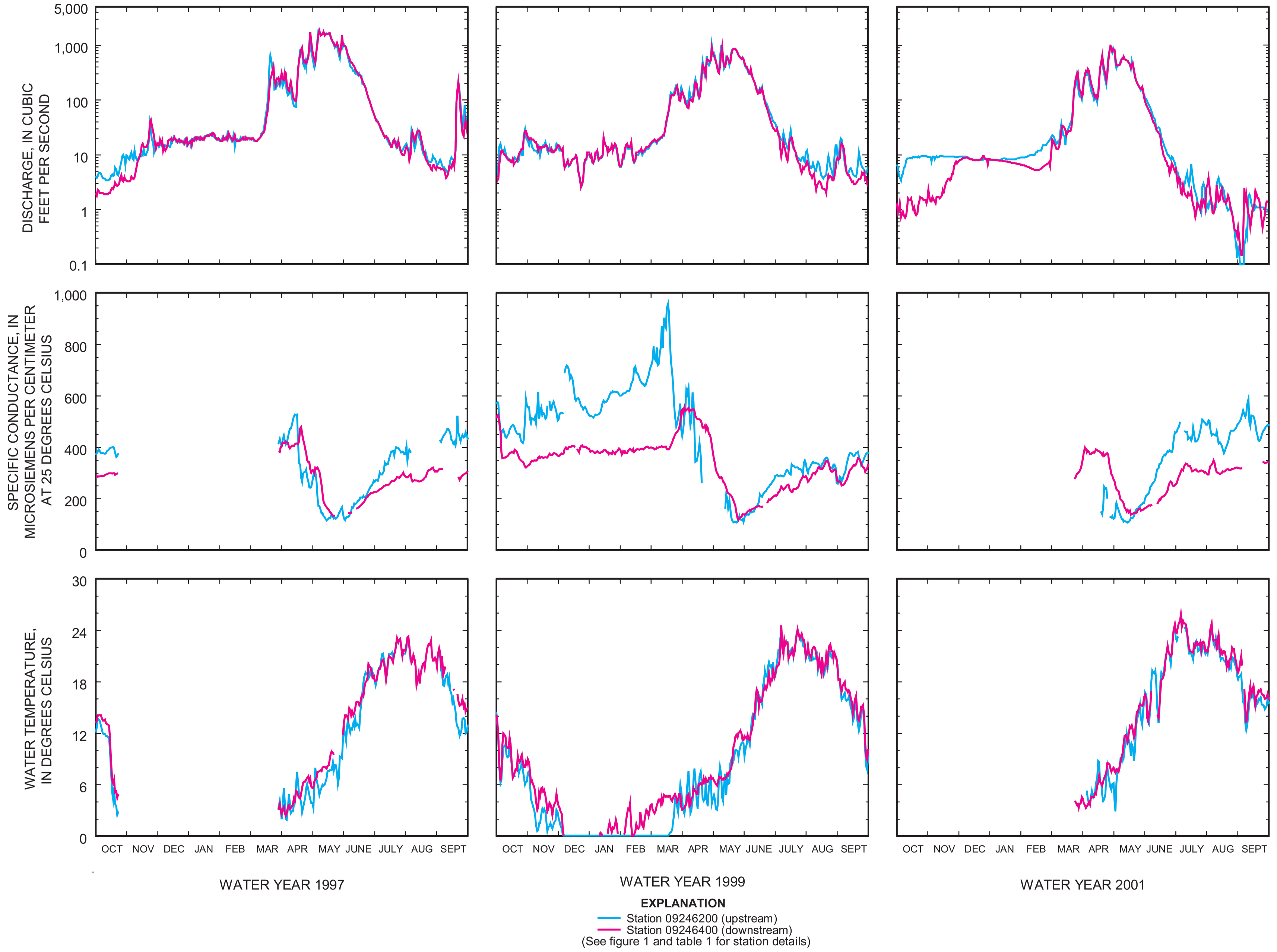


Figure 8. Daily mean discharge, specific conductance, and water temperature for Elkhead Creek at two stations upstream and downstream from Elkhead Reservoir, water years 1997, 1999, and 2001.

increasing discharge; some of this discharge could have been derived from low-elevation snowmelt that often contains higher concentrations of dissolved solids than high-elevation snowmelt, and some of the discharge could have been derived from melting stream ice that developed during winter. Assuming that reservoir residence time was a few days during this time, a corresponding, but smaller, increase in specific conductance is evident for the station (09246400) downstream from Elkhead Reservoir.

Seasonal variation in water temperature (fig. 8) generally follows the pattern of seasonal variation in air temperature, reaching minimum values during winter and maximum values during summer. During snowmelt, water temperature also is affected by snowpack temperature that often is considerably lower than air temperature. Daily mean temperatures recorded at station 09246200 ranged from about 0.0 to 24.3°C, and daily mean temperatures recorded at station 09246400 ranged from about 0.0 to 25.8°C (fig. 8).

The primary effect of Elkhead Reservoir on specific conductance and temperature at the downstream station (09246400) is a decrease in variability (fig. 8) that largely results from the moderating effect of mixing and storing accumulated inflow water with varying dissolved-solids concentrations and temperatures during the year. Although the variability in discharge at both stations was nearly the same during a given time period, the variability in specific conductance and temperature was less at station 09246400 than at station 09246200. The smaller downstream variability is especially evident during the March–May period during water year 1997 (fig. 8); the differences between the high and low daily values (peaks and valleys of the hydrographs) for specific conductance and temperature were greater at station 09246200 than the differences at station 09246400.

During winter of 1999, when specific conductance was relatively high at station 09246200, specific conductance was substantially lower and less variable at station 09246400 (fig. 8). Winter inflow to the reservoir commonly is colder than water in the reservoir, and likely stays near the bottom. On the other hand, outflow from the reservoir is derived from water that is a mix of inflow from throughout the year and thus has a lower specific conductance than the winter inflow. The reservoir also tends to moderate specific conductance at the downstream station in comparison to the upstream station during summer and fall. However, during the initial period of maximum snowmelt runoff, specific conductance at the downstream station is somewhat higher than at the upstream station because the outflow initially consists mostly of reservoir water that has a higher specific conductance than the inflow. Some time later, when the reservoir contents have been largely replaced by the low specific-conductance snowmelt inflow, values of specific conductance are about the same at the upstream and downstream stations until snowmelt begins to subside.

Elkhead Reservoir also has a moderating effect on temperature at the downstream station (09246400). However, the differences in temperature between stations 09246200 and 09246400 are not as substantial as the differences in specific conductance during most of the year, except during the winter. During snowmelt, the differences in temperature between stations 09246200 and 09246400 are not very large because the reservoir likely is spilling, owing to the relatively short residence time during which the large volume of relatively cold inflow is rapidly routed through the reservoir. During some parts of the winter, the moderating effects of the reservoir on temperature at station 09246400 are greatest, but the effects probably are somewhat diminished because of the distance, about 3 RM, from the reservoir outflow downstream to the station.

Temporal and Spatial Variability of Periodic Water-Quality Data

The following subsections of the report describe and compare the variability of water-quality data obtained at stations 09246200 and 09246400. Time-series plots of selected properties and constituents, with data for both stations plotted on the same graph, illustrate the annual and monthly variability and the differences between data for the stations 09246200 and 09246400. Data included in these descriptions and comparisons include field measurements, major ions, nutrients, biological indicators (organic carbon and coliforms), trace elements, and suspended sediment.

Field Measurements

Periodic field-measurement values made onsite at stations 09246200 and 09246400 (figs. 9–10) indicate considerable variability (annual and seasonal range); however, exceptionally high or low values were not measured. Within-year variability in the measured field property values seems to be about the same during each water year, and there are no large differences in variability from one year to the next (fig. 9). Some pattern of seasonal variation can be seen for the field measurements when the data are plotted on a monthly basis (fig. 10), except for atmospheric pressure. The seasonal pattern for instantaneous discharge, specific conductance, and temperature field-measurement values (fig. 10) is similar to that for the continuous data (fig. 8). The seasonal pattern for turbidity, a measurement of the transparency of water, is similar to that for discharge, primarily because turbidity often is related to fine-particle suspended sediment concentration that generally increases with increasing discharge. pH has a less-pronounced seasonal pattern (fig. 10) and appears to have a slight upward annual trend (fig. 9); the apparent upward trend will be discussed in the "Trends Analysis" section. Dissolved-oxygen concentration is highest during November–March, but percent saturation indicates a downward trend during those months; nevertheless, dissolved oxygen rarely was less than 7 mg/L, and percent saturation was less than 100 for only about 25 percent of the measurements (figs. 9–10).

Differences in the field-measurement values between station 09246200 and 09246400 can be seen in the graphs for

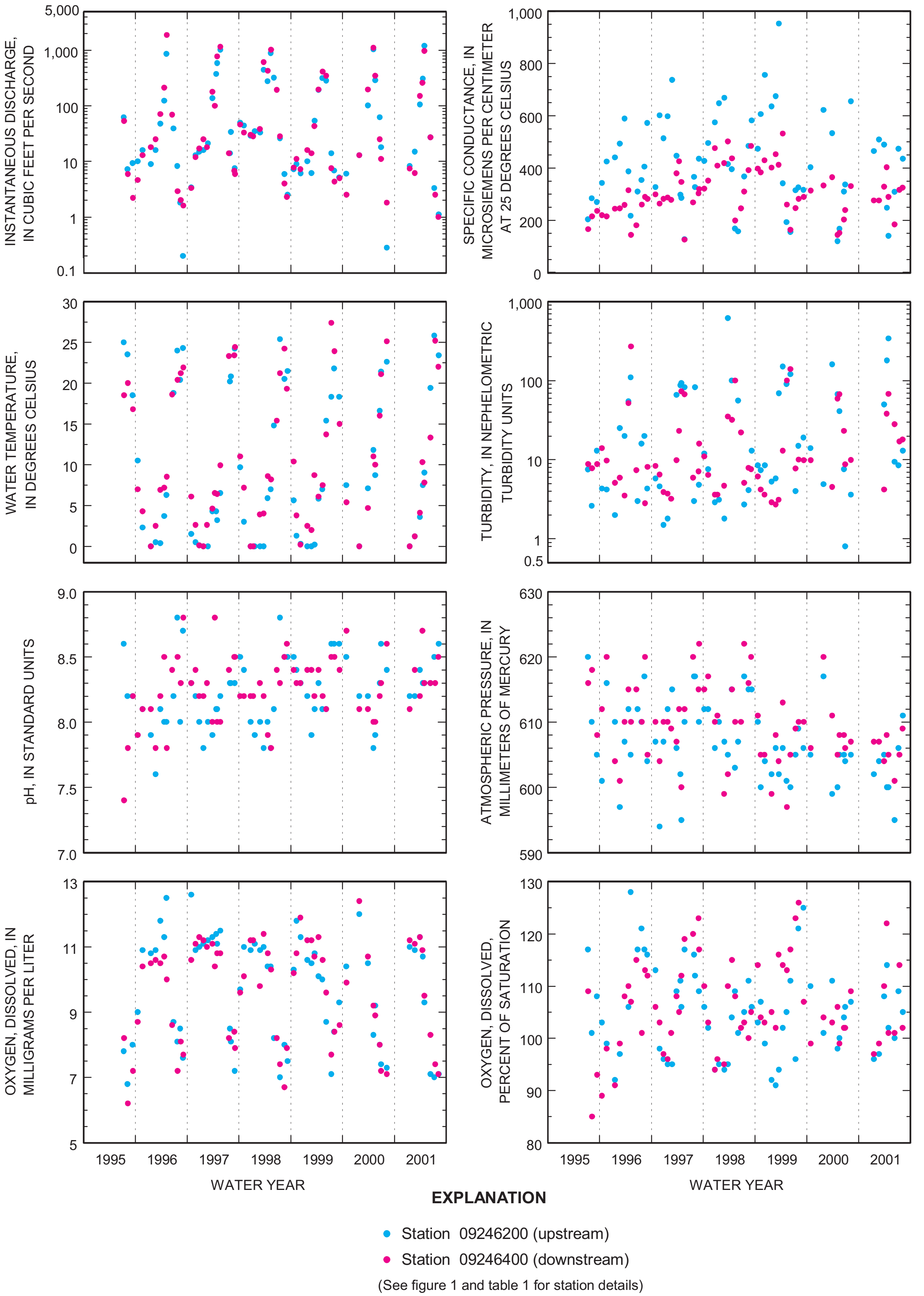


Figure 9. Annual variability of field measurements for Elkhead Creek at two stations upstream and downstream from Elkhead Reservoir, July 1995–September 2001.

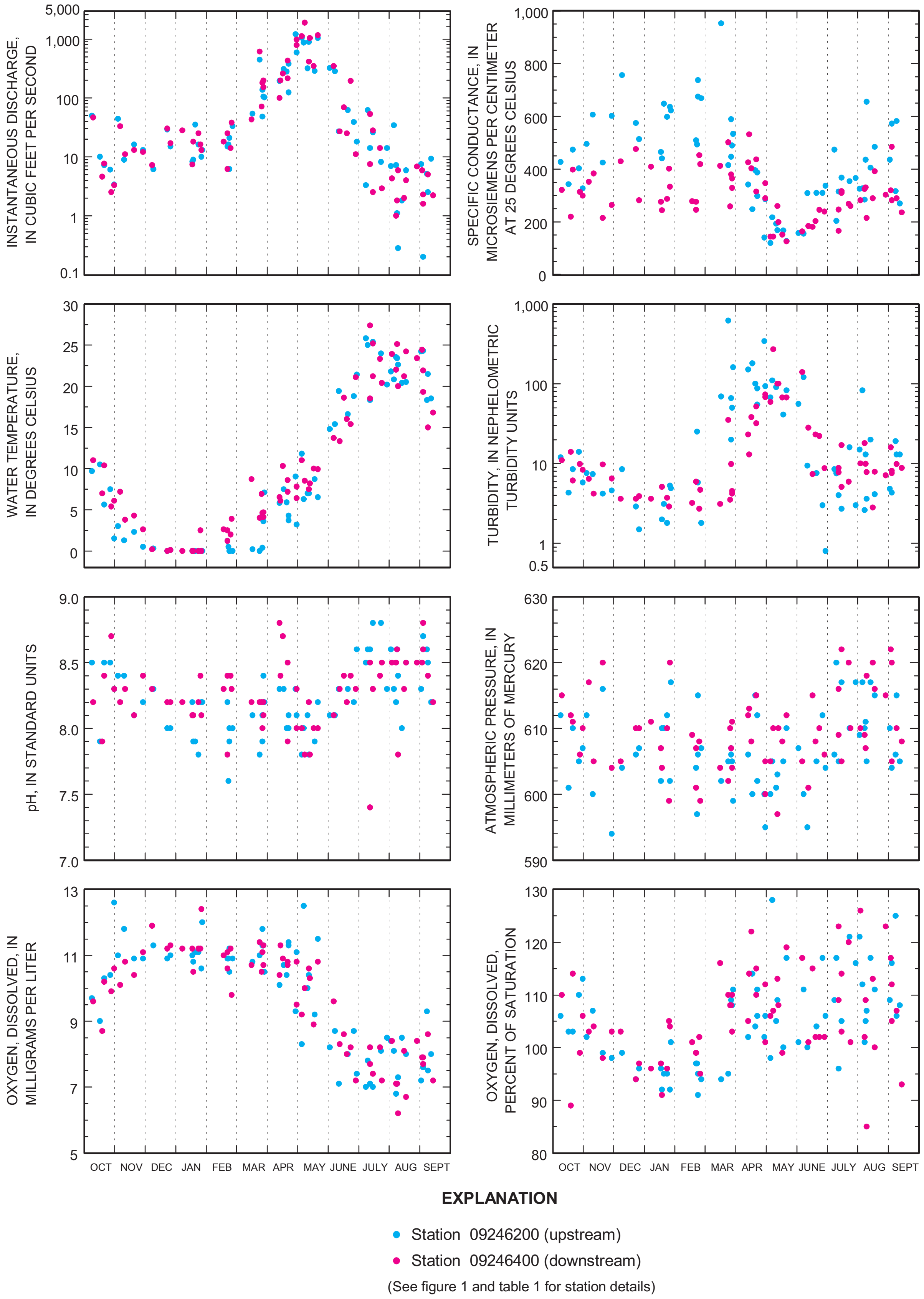


Figure 10. Monthly variability of field measurements for Elkhead Creek at two stations upstream and downstream from Elkhead Reservoir, July 1995–September 2001.

specific conductance, temperature, and turbidity (figs. 9–10) that indicate a larger variability in the measurement values at station 09246200 than at station 09246400. For specific conductance and temperature, the decrease in variability at the downstream station primarily is the result of the moderating effect of Elkhead Reservoir on those variables that was described in the "Continuous Specific Conductance and Water Temperature" section. For turbidity, the downstream decrease in variability also is due to the reservoir but in this case primarily is the result of settling of suspended sediment in the reservoir. Rank-sum tests (see p. 9) between the field-measurement values at stations 09246200 and 09246400 indicated that specific conductance was the only field measurement that differed statistically between the two stations; atmospheric pressure was not included in the rank-sum tests.

Major Ions

Concentrations of selected major ions in the periodic water-quality samples at stations 09246200 and 09246400 (figs. 11–12) also indicate considerable variability and some ions had a few (1–5) concentrations somewhat higher (calcium, magnesium, ANC, chloride, sulfate, and dissolved solids) or somewhat lower (silica) than the general tendency; however, these few higher and lower concentrations are not considered to be anomalous. Variability in the concentration values appears to be about the same during each water year, and there are no large differences in variability from one year to the next (fig. 11). Seasonal patterns in concentration are evident for the major ions when the data are plotted by month (fig. 12); the seasonal pattern for silica, however, is less pronounced than for the other constituents. The seasonal pattern for most major ions (fig. 12) is similar to the seasonal pattern of specific conductance (fig. 10), because specific conductance is related directly to concentration of dissolved ions.

The variability in concentration for nearly every major ion is larger at the upstream station, 09246200, than at the downstream station, 09246400 (figs. 11–12). There are two primary components in these differences: (1) maximum concentrations of the major ions generally are higher at station 09246200 than at station 09246400, and (2) minimum concentrations of the major ions generally are lower at station 09246200 than at station 09246400. These differences are evident during most of the year except during the snowmelt period, when the upstream and downstream concentrations are about the same. Concentration of silica differs somewhat from the trend in variability evident for the other major ions; reasons for this are not completely understood but may be related to the geochemical behavior of silica (Hem, 1985, p. 69–73). The difference in variability for the major ions between the upstream and downstream stations (figs. 11–12) results primarily from the moderating effects that Elkhead Reservoir has on water quality at the downstream station (see the "Continuous Specific Conductance and Water Temperature" section). Rank-sum tests (see p. 9) indicated a statistical difference between the concentration data for stations 09246200 and 09246400 for calcium, magnesium, sodium, ANC, sulfate, and dissolved solids, but not for chloride and silica, substantiating the upstream and downstream differences evident in figures 11–12.

Nutrients

Compounds of nitrogen and phosphorus are referred to as "major nutrients" because they are needed for plant growth. In excess quantities, nutrients can promote nuisance algae growth (eutrophication) in streams and reservoirs. Natural sources of nutrients include atmospheric deposition, precipitation, erosion, and biochemical processes in the basin. Anthropogenic sources of nutrients include urban runoff, domestic and septic-system effluent, livestock waste, and erosion caused by development.

Concentrations of selected nutrients in the periodic water-quality samples at stations 09246200 and 09246400 generally were low during most of the study period and did not differ substantially from one year to another (fig. 13). On a monthly basis, nutrient concentrations usually were lowest during late summer to spring (July–February) and were highest during snowmelt (March–June) (fig. 14); however, dissolved ammonia and dissolved ammonia plus organic nitrogen did not have very pronounced seasonal patterns. Nutrient concentrations during snowmelt often were several times larger than the concentrations during low flow. Many of the nutrient concentrations were less than the MRL, especially during July–February, and some nutrients had more than one MRL during the sampling period (table 2). Nutrient concentrations that were less than the MRL were set to one-half of the MRL for purposes of illustration in figures 13 and 14.

Except for a few values, concentrations of total ammonia plus organic nitrogen were about the same as the concentrations for dissolved ammonia plus organic nitrogen, indicating that these constituents were primarily in the dissolved phase (figs. 13–14; note different y-scales). Concentrations of dissolved ammonia also were low in comparison to concentrations of dissolved ammonia plus organic nitrogen, indicating that Elkhead Creek had very little ammonia (figs. 13–14). Concentrations of total nitrogen always were lower than about 1 mg/L, except for five of the samples (figs. 13–14). Total nitrogen consisted mostly of dissolved organic nitrogen and dissolved nitrite plus nitrate. Most of the dissolved orthophosphate concentrations were lower than the MRLs (table 2), which were exceeded only during March–June and had concentrations higher than about 0.02 mg/L in only five samples (fig. 14). When greater than the MRLs, total phosphorous varied exponentially from about 0.01 to about 1 mg/L, compared to a range of about 0.01 to 0.06 mg/L for dissolved phosphorus and orthophosphate (figs. 13–14). The higher concentrations of total phosphorus likely result from increased particulate phosphorus associated with increased sediment concentrations during snowmelt.

When nutrient concentrations exceeded the MRLs, substantial differences in nutrient concentrations between stations 09246200 and 09246400 generally are not evident, except that

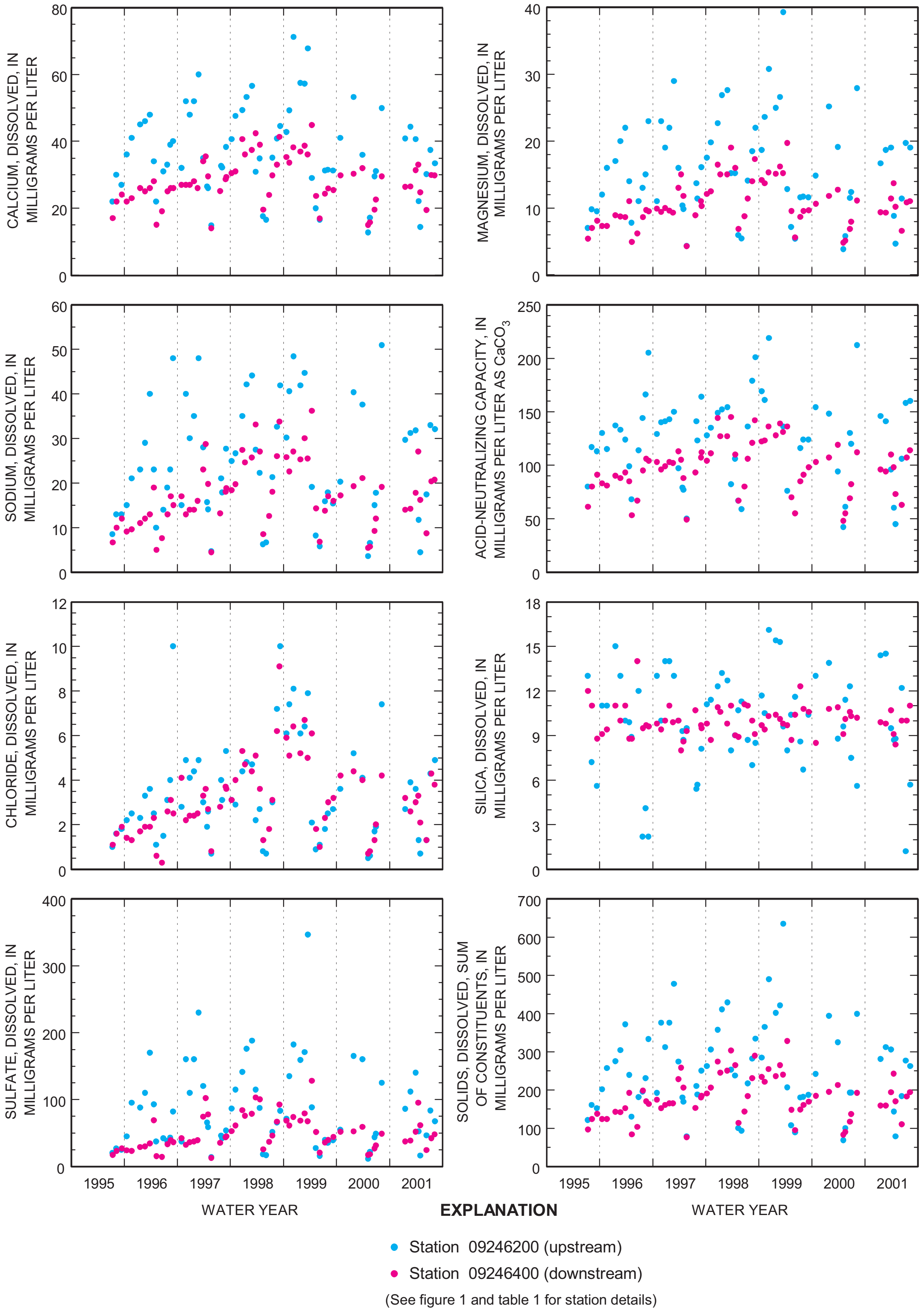


Figure 11. Annual variability of major-ion concentrations and acid-neutralizing capacity for Elkhead Creek at two stations upstream and downstream from Elkhead Reservoir, July 1995–September 2001.

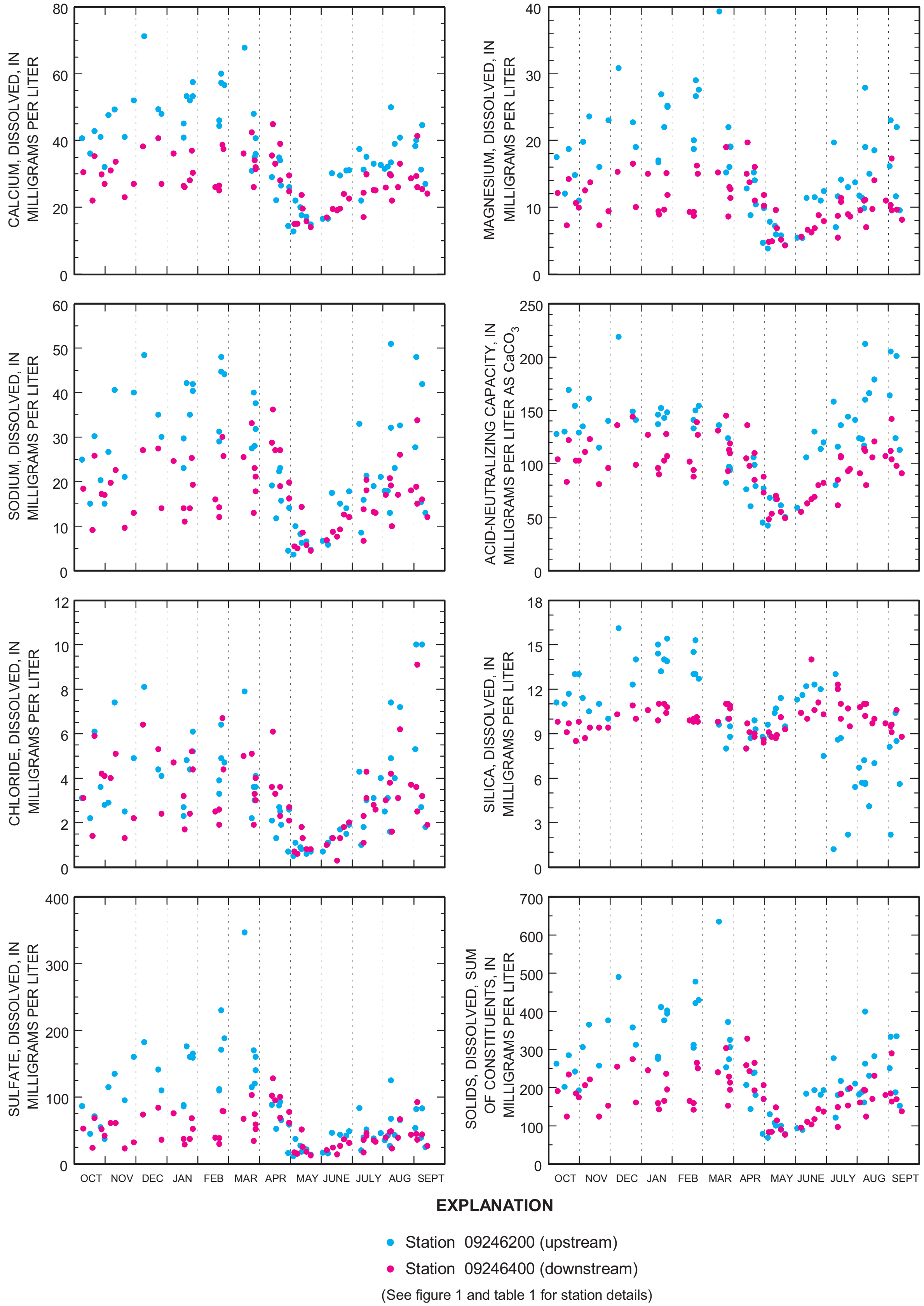
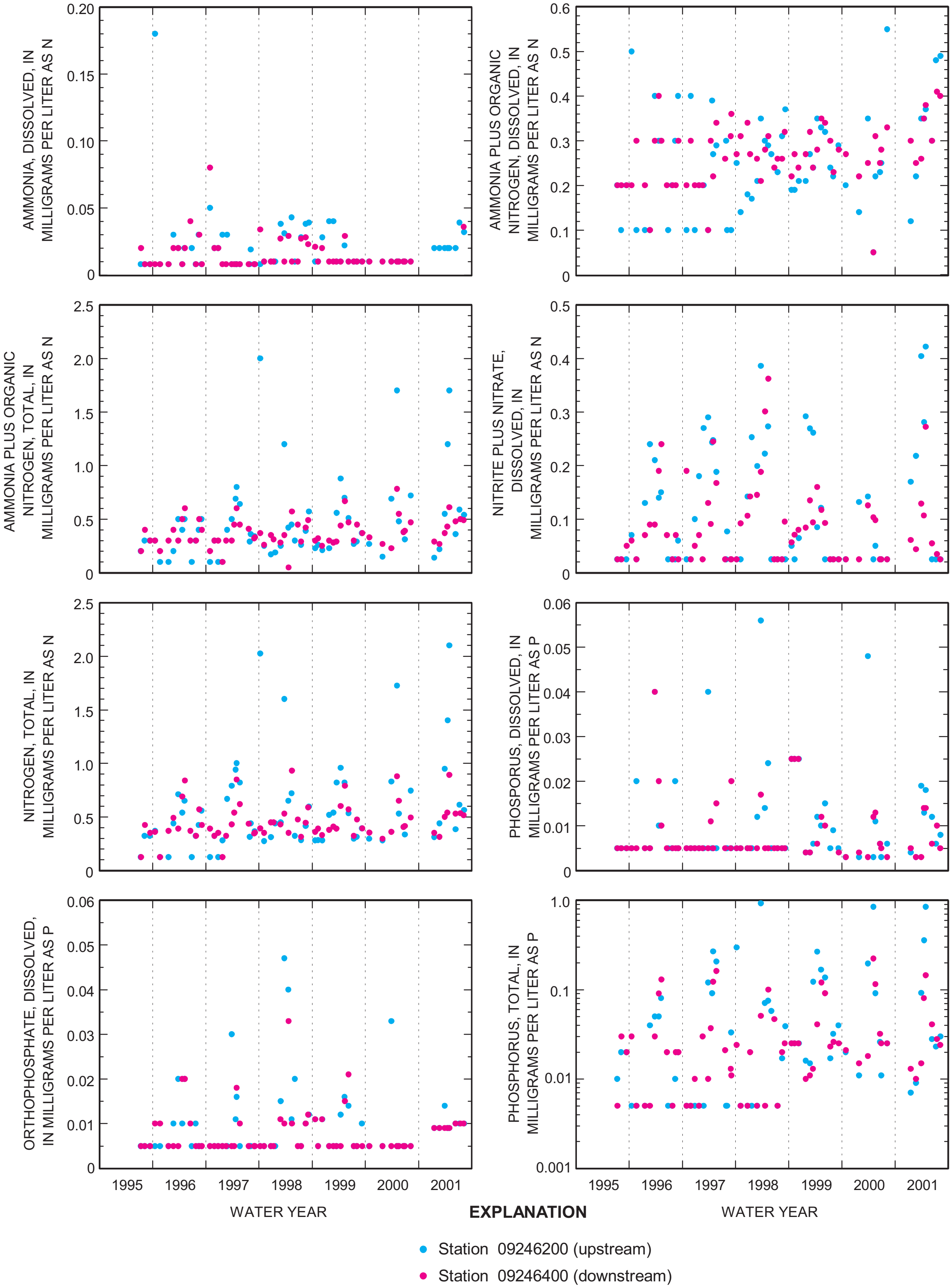


Figure 12. Monthly variability of major-ion concentrations and acid-neutralizing capacity for Elkhead Creek at two stations upstream and downstream from Elkhead Reservoir, July 1995–September 2001.



(See figure 1 and table 1 for station details)

Figure 13. Annual variability of nutrient concentrations for Elkhead Creek at two stations upstream and downstream from Elkhead Reservoir, July 1995–September 2001.

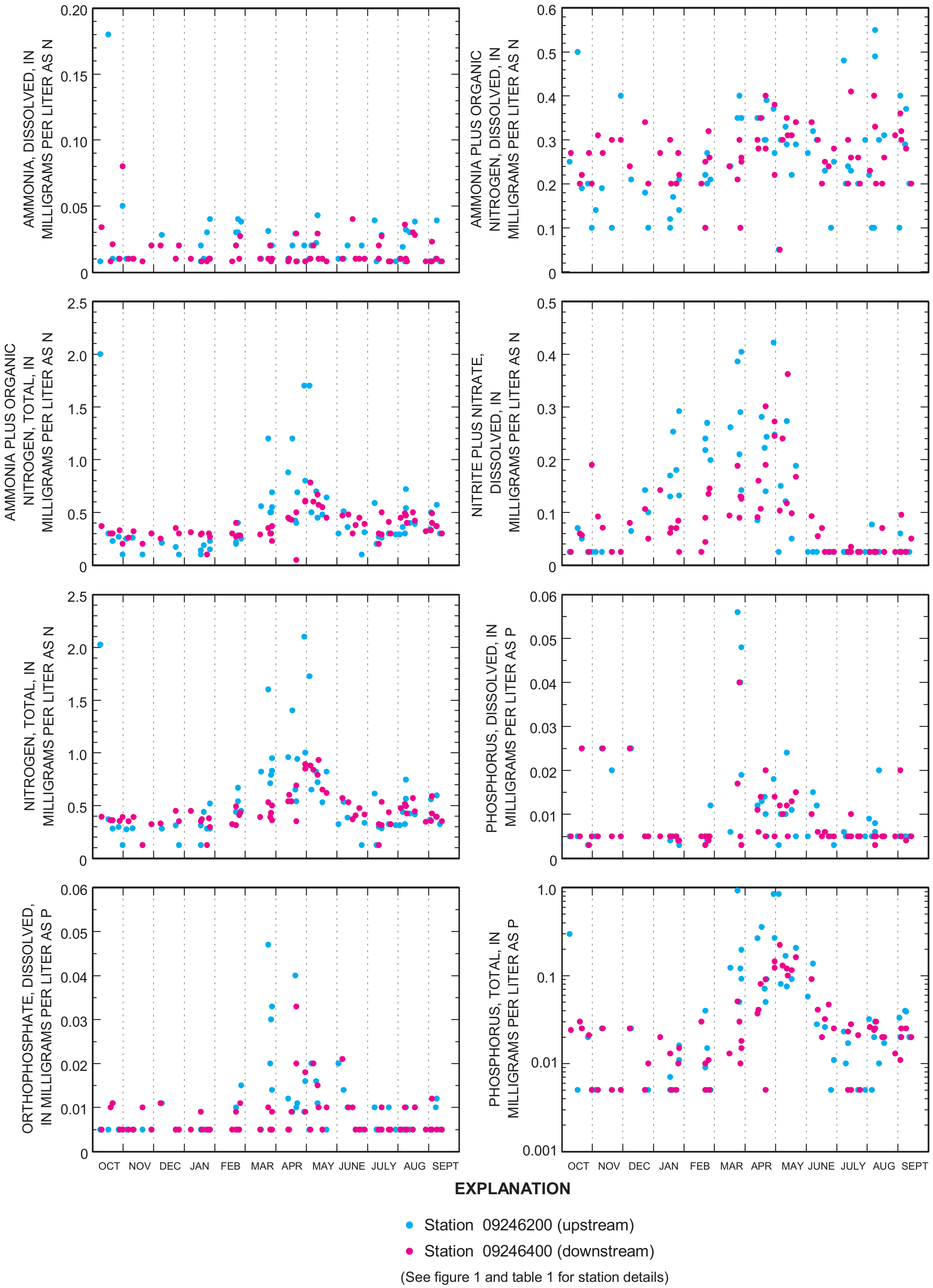


Figure 14. Monthly variability of nutrient concentrations for Elkhead Creek at two stations upstream and downstream from Elkhead Reservoir, July 1995–September 2001.

the few highest concentrations usually were at the upstream station (figs. 13–14). Nevertheless, rank-sum tests did not indicate a statistically significant difference between the nutrient concentrations at stations 09246200 and 09246400.

Biological Indicators

Annual variability in concentrations of dissolved and total organic carbon (DOC and TOC) in periodic water-quality samples at stations 09246200 and 09246400 was similar during the study period (fig. 15), and the variability on a monthly basis (fig. 16) does not indicate a very pronounced seasonal pattern. DOC and TOC concentrations usually were highest during high-flow periods and lowest during low-flow periods because dissolved organic carbon is flushed from soils during runoff and particulate carbon is transported during high flows when sediments enter Elkhead Creek. Rank-sum tests for DOC and TOC did not indicate a statistical difference between the concentration data for stations 09246200 and 09246400.

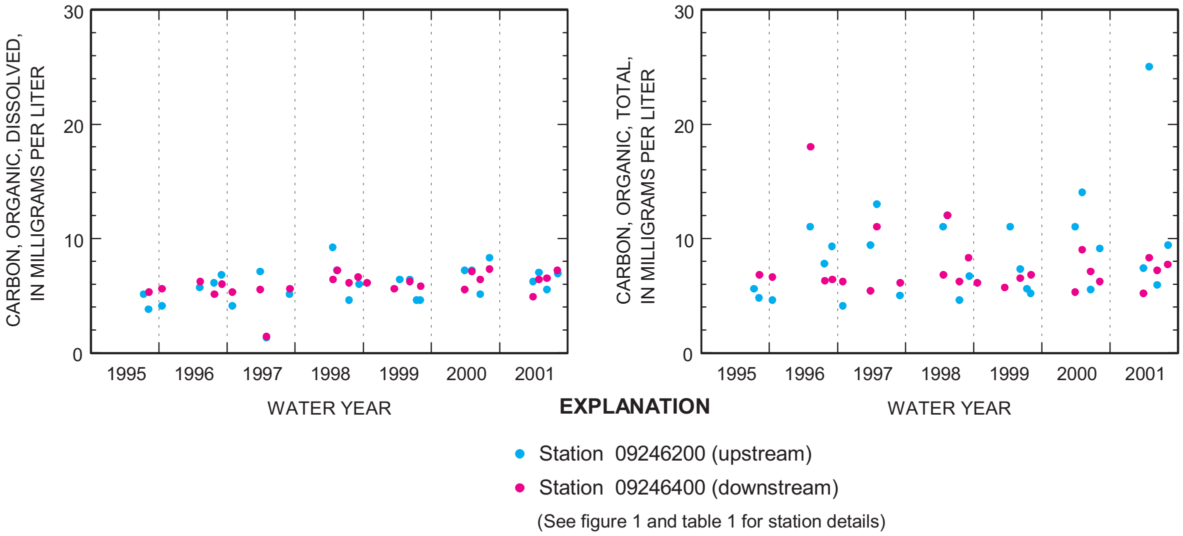


Figure 15. Annual variability of organic-carbon concentrations for Elkhead Creek at two stations upstream and downstream from Elkhead Reservoir, July 1995–September 2001.

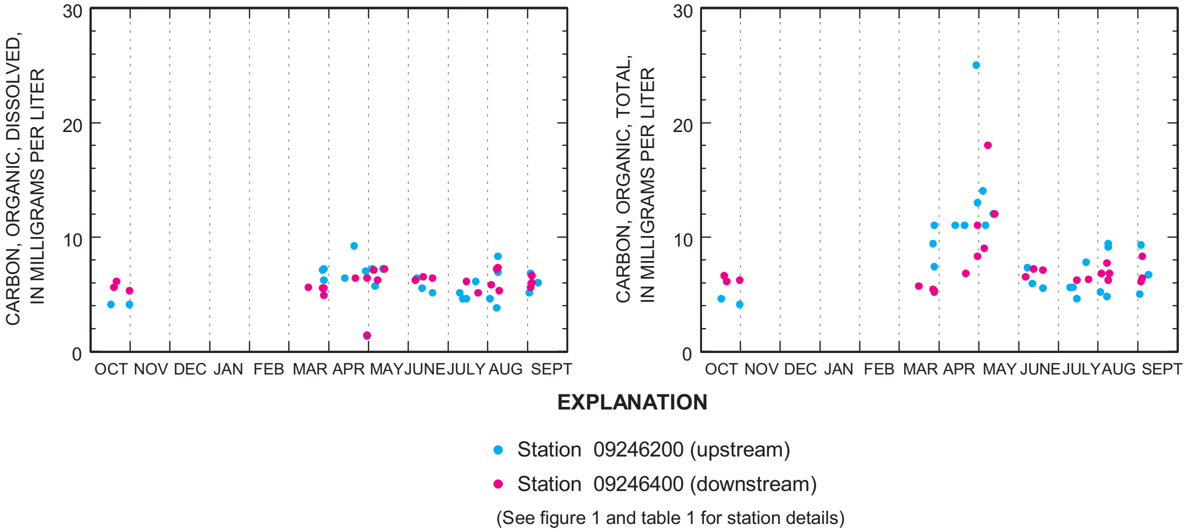


Figure 16. Monthly variability of organic-carbon concentrations for Elkhead Creek at two stations upstream and downstream from Elkhead Reservoir, July 1995–September 2001.

Analysis of samples for fecal coliform and *e. coli* bacteria was infrequent; at station 09246200, these bacteria were sampled during March 2000–September 2001, and at station 09246400, they were sampled during October 1996–September 2001. Also, sampling and laboratory analysis for coliforms usually were performed only during April–October. Summary statistics for the available data are listed in table 5. The bacteria counts generally are higher during the warm season (July–September) than during other seasons (table 5).

Trace Elements

For the purpose of this report, trace elements are metal and transition-metal elements that generally have small (less than 1 mg/L) concentrations. Trace elements are important indicators of water quality because, in large concentrations, they are toxic to aquatic life, and a large proportion of Colorado's regulated constituents are trace elements (Colorado Department of Public Health and Environment, Water Quality Control Division, 2002). Although small concentrations of trace elements may occur naturally, large concentrations of trace elements generally are associated with ore deposits, acid-mine drainage, or urban runoff. The lack of ore deposits, and hence, mining, and sparse urban development in the Elkhead Creek basin resulted in relatively low concentrations of trace elements.

Of the 16 dissolved and the 19 total-recoverable trace elements that were analyzed (table 2), only 8 trace elements (figs. 17–18) had a substantial number of concentrations that were higher than the MRL. Trace-element concentrations that were less than the MRL were set to one-half of the MRL for purposes of illustration; however, only a few of the analyses shown (figs. 17–18) were less than the MRL.

Because of the fewer number of samples per year and the large variability in concentration, it is difficult to discern differences in trace-element concentrations from one year to the next (fig. 17). Graphs of the data on a monthly basis (fig. 18) show some pattern of seasonal variation for most of the total-recoverable trace-element concentrations; however, the seasonal patterns for the dissolved trace-element concentrations are less evident. Trace-element concentrations, especially total-recoverable concentrations, are higher during runoff periods than during low flow, probably due to the presence of particulate-phase trace elements. Concentration of dissolved barium tends to be lower during runoff than during other periods (fig. 18); reasons for this are not known. Total-recoverable concentrations of copper are about five times higher than dissolved concentrations, whereas total-recoverable concentrations of iron and manganese are about one to two orders of magnitude higher than dissolved concentrations (figs. 17–18). Rank-sum tests did not indicate a statistical difference between the concentration data for stations 09246200 and 09246400 for any of the eight trace elements.

Suspended Sediment

Suspended sediment is defined as particles (mostly rock fragments, soil, and some organic material) suspended in the water column by the turbulence of the water. Suspended-sediment discharge usually is only a portion of the total sediment discharge, which also includes the bedload. Bedload is the sediment transported by bouncing, rolling, and skidding along the streambed; however, bedload was not measured at the two Elkhead Creek stations.

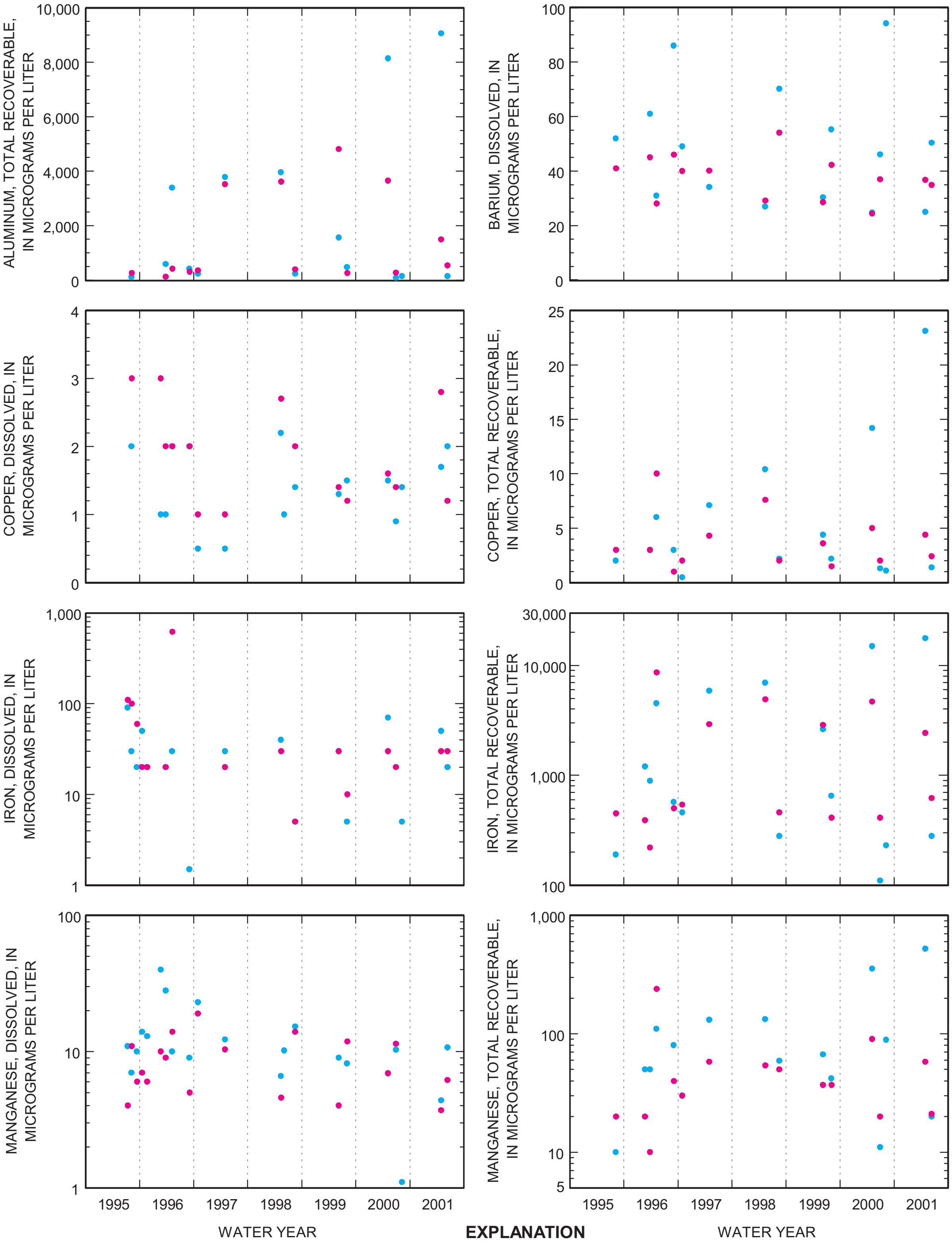
Annual variability in suspended-sediment concentration and instantaneous load at stations 09246200 and 09246400 was similar, and there were no substantial differences in the range of the values from one year to another (fig. 19). On a monthly basis, suspended-sediment concentration and instantaneous load have a pronounced seasonal pattern (fig. 20) that is similar to the pattern of monthly discharge (fig. 11). Suspended-sedi-

Table 5. Summary statistics for coliform bacteria for Elkhead Creek at two stations upstream and downstream from Elkhead Reservoir, water years 1996–2001.

Constituent	Number of samples	Value for indicated statistic				
		Maximum	75th Percentile	Median	25th Percentile	Minimum
Station 09246200 (upstream; see figure 1)						
Coliform, *e. coli* (colonies/100 milliliters)	7	53	47	21	18	16
Coliform, fecal (colonies/100 milliliters)	8	97	75	46	33	30
Station 09246400 (downstream; see figure 1)						
Coliform, *e. coli* (colonies/100 milliliters)	[1]17	83	52	31	20	1
Coliform, fecal (colonies/100 milliliters)	[2]19	100	60	35	18	1

[1] Nine plate counts were outside the ideal range of 20–80 colonies/100 milliliters.

[2] Ten plate counts were outside the ideal range of 20–60 colonies/100 milliliters.



EXPLANATION

● Station 09246200 (upstream)

● Station 09246400 (downstream)

(See figure 1 and table 1 for station details)

Figure 17. Annual variability of selected trace-element concentrations for Elkhead Creek at two stations upstream and downstream from Elkhead Reservoir, July 1995–2001.

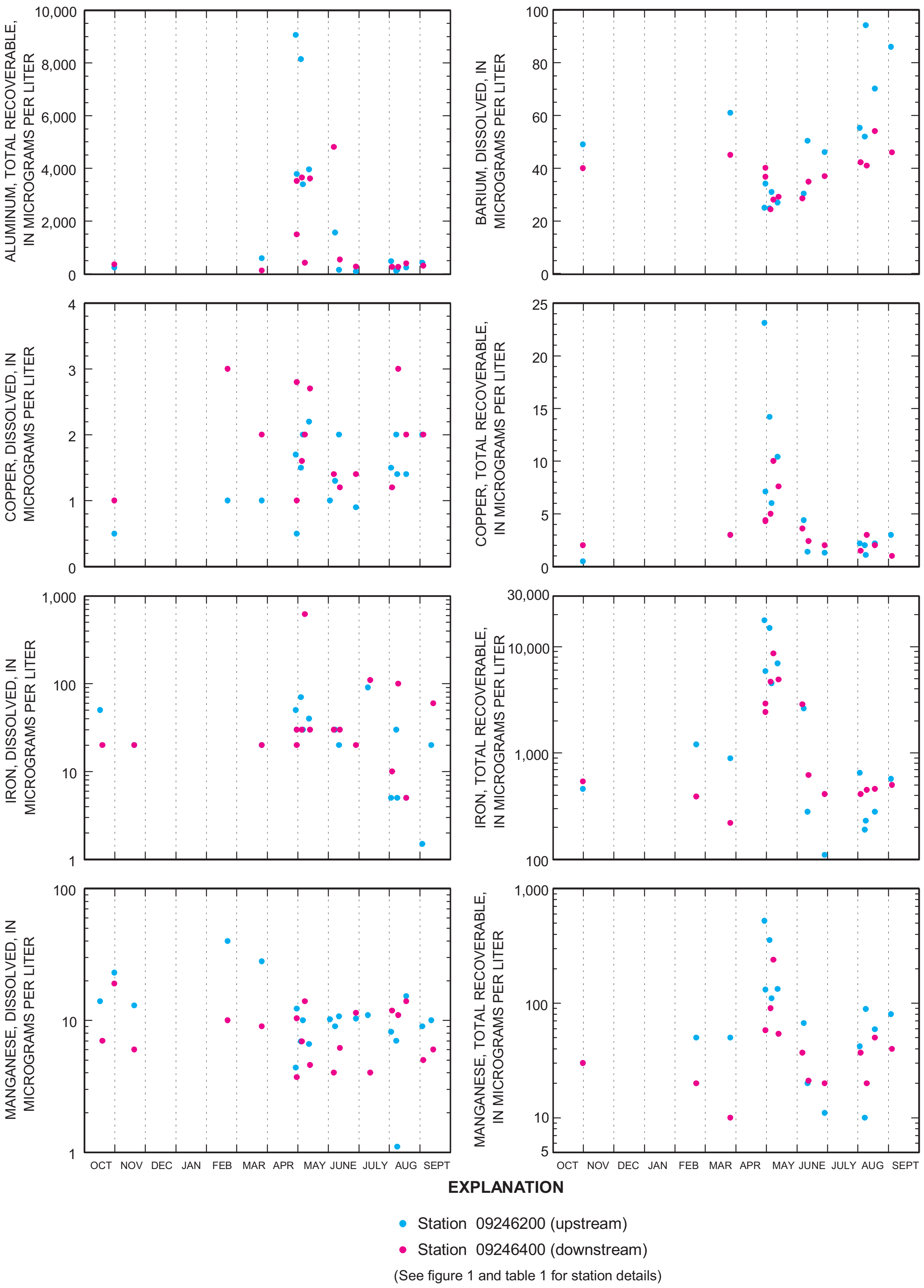


Figure 18. Monthly variability of selected trace-element concentrations for Elkhead Creek at two stations upstream and downstream from Elkhead Reservoir, July 1995–September 2001.

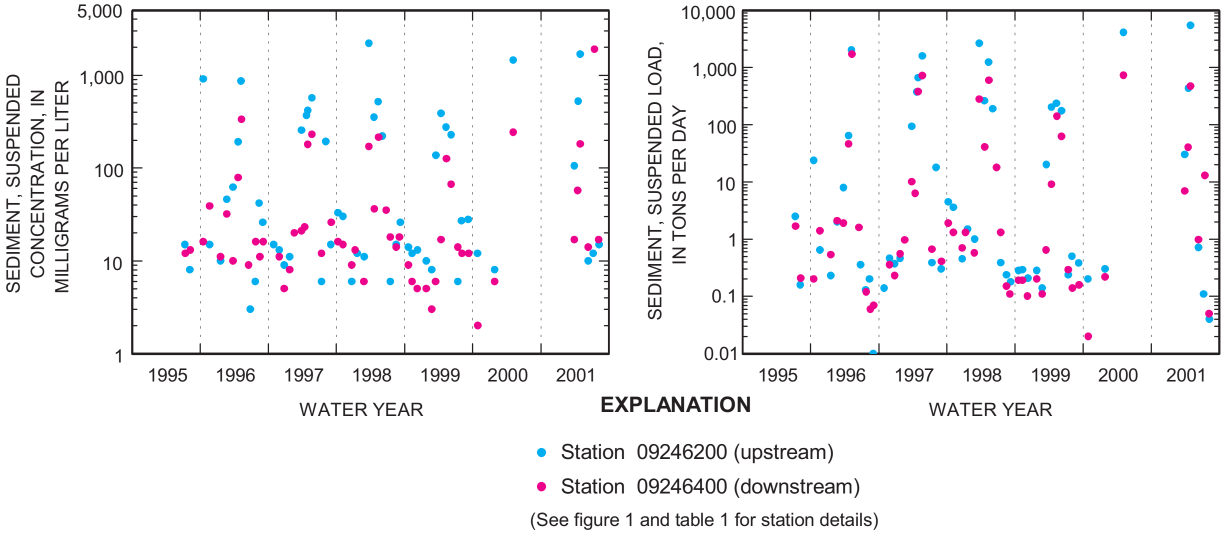


Figure 19. Annual variability of suspended-sediment concentration and load for Elkhead Creek at two stations upstream and downstream from Elkhead Reservoir, July 1995–September 2001.

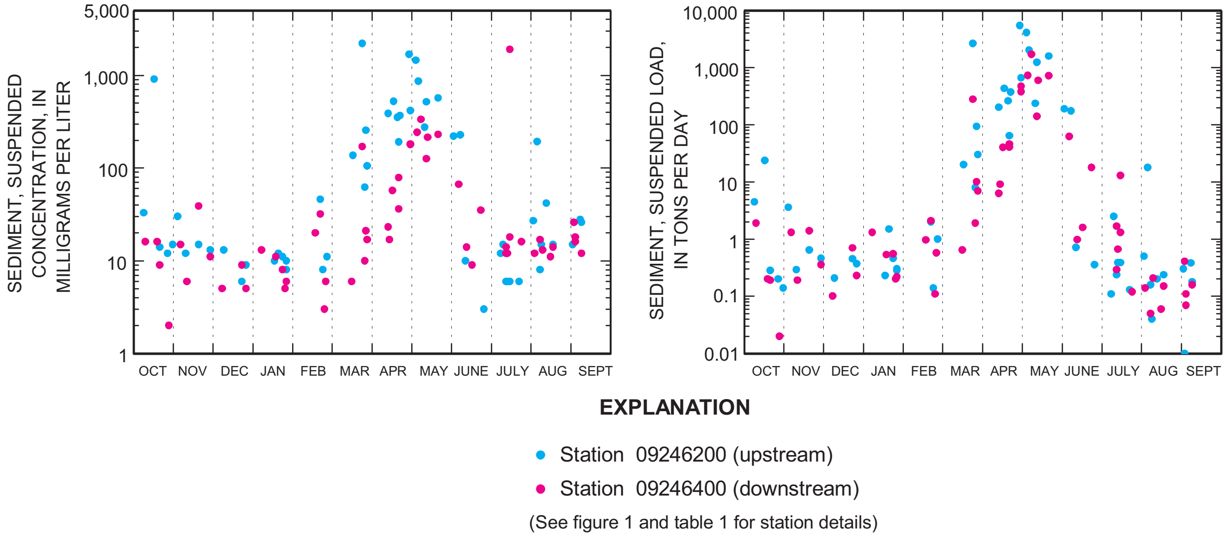


Figure 20. Monthly variability of suspended-sediment concentration and load for Elkhead Creek at two stations upstream and downstream from Elkhead Reservoir, July 1995–September 2001.

ment concentration and load generally are smaller and less variable at the downstream station, primarily because a large percentage of suspended sediment settles out in Elkhead Reservoir (Elliott and Gyetvai, 1999). This pattern is especially evident during March–June when discharge is largest due to snowmelt; suspended-sediment concentrations at station 09246400 were lower than the concentrations at station 09246200 by about an order of magnitude during this time (fig. 20). Surprisingly, rank-sum tests did not indicate a statistical difference, at a 0.05 significance level, between the concentration and load data at stations 09246200 and 09246400; however, at a 0.10 significance level, a difference in the concentration data was indicated. Possible reasons that no statistical difference at a 0.05 significance level was indicated in the suspended concentration at the two stations are (1) the variability of the data is large at both stations and covers about three orders of magnitude, (2) tributary inflow between the reservoir and station 09246400 could contribute additional suspended sediment, and (3) fine-sized particles could be routed through the reservoir, especially during snowmelt runoff.

Trend Analysis

Trend analyses results (tables 6 and 7) for stations 09246200 (upstream from Elkhead Reservoir) and 09246400

Table 6. Trend-analysis results for selected unadjusted water-quality field measurements and constituent concentrations for Elkhead Creek at two stations upstream and downstream from Elkhead Reservoir, July 1995–September 2001.

[mg/L, milligrams per liter; µS/cm, microsiemens per centimeter at 25°C; °C, degrees Celsius; T/d, tons per day; --, not applicable]

Measurement or constituent	Station 09246200 Elkhead Creek above Long Gulch near Hayden (upstream from reservoir)			Station 09246400 Elkhead Creek below Maynard Gulch near Craig (downstream from reservoir)		
	p-value (at 0.05 significance level)	[1]Trend	Trend slope, in percent per year	*p*-value (at 0.05 significance level)	[1]Trend	Trend slope, in percent per year
	Field measurements					
Atmospheric pressure (millimeters of mercury)	0.380	none	--	0.357	none	--
Discharge, instantaneous (cubic feet per second)	.572	none	--	.374	none	--
Oxygen, dissolved (mg/L)	.533	none	--	.248	none	--
Oxygen, dissolved (percent saturation)	.265	none	--	.595	none	--
pH, field (standard units)	.032	up	0.85	.196	none	--
Specific conductance (µS/cm at 25°C)	.857	none	--	.255	none	--
Temperature (°C)	.465	none	--	.165	none	--
Turbidity (nephelometric turbidity units)	[2].107	none	--	[2].895	none	--
	Major ions					
Acid-neutralizing capacity, lab (mg/L as $CaCO_3$)	.837	none	--	.225	none	--
Calcium, dissolved (mg/L as Ca)	.601	none	--	.191	none	--
Chloride, dissolved (mg/L as Cl)	.230	none	--	.126	none	--
Hardness (mg/L as $CaCO_3$)	.600	none	--	.301	none	--
Magnesium, dissolved (mg/L as Mg)	.869	none	--	.307	none	--
Potassium, dissolved (mg/L as K)	.631	none	--	.782	none	--
Silica, dissolved (mg/L as Si)	.235	none	--	.428	none	--
Sodium, dissolved (mg/L as Na)	.304	none	--	.168	none	--
Solids, dissolved, sum of constituents (mg/L)	.645	none	--	.302	none	--
Sulfate, dissolved (mg/L as SO_4)	.342	none	--	.254	none	--
	Nutrients					
Nitrogen, ammonia, dissolved (mg/L as N)	.952	none	--	.647	none	--
Nitrogen, ammonia + organic, dissolved (mg/L as N)	.519	none	--	.005	up	4.68
Nitrogen, ammonia + organic, total (mg/L as N)	.107	none	--	.095	none	--
Nitrogen, nitrite + nitrate, dissolved (mg/L as N)	.224	none	--	.145	none	--
Nitrogen, total (mg/L as N)	.045	up	7.34	.279	none	--
Phosphorus, dissolved (mg/L as P)	.778	none	--	.312	none	--
Phosphorus, orthophosphate, dissolved (mg/L as P)	.775	none	--	.234	none	--
Phosphorus, total (mg/L as P)	.125	none	--	.302	none	--
	Suspended sediment					
Sediment, suspended concentration (mg/L)	[2].914	none	--	[2].462	none	--
Sediment, suspended load (T/d)	[2].697	none	--	[2].305	none	--

[1] Seasonal Kendall procedure was used for field-measurements, major-ions, and suspended-sediment trend tests; Tobit procedure was used for nutrients trend tests.

[2] Trend analysis made using 6 seasons; 12 seasons used for all other analyses.

Table 7. Trend-analysis results for selected flow-adjusted water-quality field measurements and constituent concentrations for Elkhead Creek at two stations upstream and downstream from Elkhead Reservoir, July 1995–September 2001.

[mg/L, milligrams per liter; µS/cm, microsiemens per centimeter at 25°C; °C, degrees Celsius; --, not applicable]

Measurement or constituent	Station 09246200 Elkhead Creek above Long Gulch near Hayden (upstream from reservoir)			Station 09246400 Elkhead Creek below Maynard Gulch near Craig (downstream from reservoir)		
	p-value (at 0.05 significance level)	[1]Trend	Trend slope, in percent per year	*p*-value (at 0.05 significance level)	[1]Trend	Trend slope, in percent per year
	Field measurements					
Oxygen, dissolved (mg/L)	0.058	none	--	0.482	none	--
Oxygen, dissolved (percent saturation)	.188	none	--	.579	none	--
pH, field (standard units)	.026	up	0.91	.062	none	--
Specific conductance (µS/cm at 25°C)	.762	none	--	.232	none	--
Temperature (°C)	.108	none	--	.558	none	--
Turbidity (nephelometric turbidity units)	[2].075	none	--	[2].872	none	--
	Major ions					
Acid neutralizing capacity, lab (mg/L as $CaCO_3$)	.676	none	--	.446	none	--
Calcium, dissolved (mg/L as Ca)	.401	none	--	.313	none	--
Chloride, dissolved (mg/L as Cl)	.750	none	--	.200	none	--
Hardness (mg/L as $CaCO_3$)	.779	none	--	.538	none	--
Magnesium, dissolved (mg/L as Mg)	.869	none	--	.307	none	--
Potassium, dissolved (mg/L as K)	.548	none	--	.774	none	--
Silica, dissolved (mg/L as Si)	.157	none	--	.208	none	--
Sodium, dissolved (mg/L as Na)	.876	none	--	.203	none	--
Solids, dissolved, sum of constituents (mg/L)	.958	none	--	.359	none	--
Sulfate, dissolved (mg/L as SO_4)	.733	none	--	.199	none	--
	Nutrients					
Nitrogen, ammonia, dissolved (mg/L as N)	.728	none	--	.672	none	--
Nitrogen, ammonia + organic, dissolved (mg/L as N)	.797	none	--	.004	up	4.91
Nitrogen, ammonia + organic, total (mg/L as N)	.027	up	8.11	.033	up	4.49
Nitrogen, nitrite + nitrate, dissolved (mg/L as N)	.243	none	--	.473	none	--
Nitrogen, total (mg/L as N)	.016	up	8.75	.049	up	3.57
Phosphorus, dissolved (mg/L as P)	.805	none	--	.560	none	--
Phosphorus, orthophosphate, dissolved (mg/L as P)	.790	none	--	.344	none	--
Phosphorus, total (mg/L as P)	.005	up	20.7	.011	up	12.4
	Suspended sediment					
Sediment, suspended concentration (mg/L)	[2].726	none	--	[2].146	none	--

[1] Seasonal Kendall procedure was used for field-measurements, majo- ions, and suspended-sediment trend tests; Tobit procedure was used for nutrients trend tests.

[2] Trend analysis made using 6 seasons; 12 seasons used for all other analyses.

(downstream from Elkhead Reservoir) indicated only a few upward trends in the data; no downward trends were indicated. For unadjusted data, upward trends were indicated for pH and total nitrogen at station 09246200 and for dissolved ammonia plus organic nitrogen at station 09246400. For flow-adjusted data, upward trends were indicated for pH, total ammonia plus organic nitrogen, total nitrogen, and total phosphorus at station 09246200 and for dissolved ammonia plus organic nitrogen, total ammonia plus organic nitrogen, total nitrogen, and total phosphorus at station 09246400. The reasons for the upward trends are not clear, especially in regard to the nutrients, because trends in the same constituents upstream and downstream from the reservoir seem to indicate some sort of an effect. It is not known if there have been any changes in land use, such as increased urban development or increased ranching activity, in the Elkhead Creek basin during 1995–2001 that could have increased nutrients. The length of the available record was just at the minimum for trend analysis; analysis of additional years may be needed to verify the upward trends indicated for 1995–2001.

Loads Analysis

The methods used for load computation (see “Statistical Testing and Load Computation” section, p. 8–9) are based on the assumption of a linear relation between the logarithms of discharge and constituent loads. Prior to the actual load computations, the relation between the instantaneous discharge and instantaneous load were evaluated for the constituents for which loads were to be computed. The relation for a selected number of the constituents (fig. 21) showed a generally linear relation between instantaneous discharge and instantaneous load; the relations were similar for the other constituents. In figure 21, instantaneous load is the product of the instantaneous discharge and the constituent concentration (from the periodic water-quality samples); it was not necessary to convert instantaneous load to a consistent set of units to evaluate the relations between discharge and load. Because of the generally linear relations between instantaneous discharge and instantaneous load, annual and monthly load computations were made.

In the equations (R.L. Runkel, U.S. Geological Survey, written commun., 2002) to which the load-computation regressions are fit, logarithm of discharge is the independent variable, logarithm of load is the dependent variable, and the equations may contain additional dependent time variables; because of this, the fitted regressions could not be plotted on the graphs shown in figure 21. For the 21 constituents for which loads were computed, the R^2 for the regressions ranged from 0.906 to 0.998, except for one constituent (dissolved ammonia at station 09246200), for which the R^2 was 0.862.

Annual loads for major ions during water years 1996–2001 (fig. 22) were consistently larger at station 09246400 (downstream from Elkhead Reservoir) than at station 09246200 (upstream from Elkhead Reservoir), except for silica and sulfate; annual discharge also was larger at station 09246400, but only slightly. The larger annual loads for the major ions at station 09246400 could have resulted from a number of factors: (1) discharge was larger at the downstream station; (2) evaporation from Elkhead Reservoir that concentrates dissolved constituents; (3) unmeasured tributary discharge to Elkhead Creek downstream from the reservoir that had high concentrations of dissolved constituents; and (4) ground-water discharge to Elkhead Creek, including irrigation return flow, downstream from the reservoir that also had high concentrations of dissolved constituents.

Mean monthly loads of major ions for water years 1996–2001 generally were much larger at both stations during snowmelt (March–June) than during the remainder of the year (fig. 23). Because discharge was so small during the low-flow months compared to the high-flow months, major-ion loads during the low-flow months were just a fraction of the loads during the high-flow months (fig. 23), and the loads during the high-flow months were the primary component of the annual loads (fig. 22). In addition, mean monthly loads of major ions during snowmelt usually were larger at station 09246400 than at station 09246200, except for a few instances during March and April. Conversely, mean monthly loads during the remainder of the year (July–February) usually were smaller at station 09246400 than at station 09246200 (fig. 23), even though discharge was about the same at both stations. Because geology in the vicinity of the upstream station is not much different than that in the vicinity of the downstream station (Tweto, 1976), the larger upstream loads during July–February at station 09246200 (fig. 23) likely resulted from the base-flow discharge during this time that was derived largely from ground water, which likely had higher concentrations of dissolved solids (fig. 12). By comparison, the smaller downstream loads during July–February at station 09246400 (fig. 23) likely resulted from the reservoir outflow discharge, which contained lower concentrations of dissolved solids than did the inflow (fig. 12) because of the mixing and moderating effects of Elkhead Reservoir.

The annual load pattern for nutrients was quite different from the annual load pattern for major ions, in that nutrient annual loads at station 09246400, downstream from Elkhead Reservoir, usually were smaller than the annual loads at station 09246200, upstream from the reservoir (fig. 24); however, this was not the case for dissolved nitrite plus nitrate. For dissolved nutrients, the annual and mean monthly loads at stations 09246200 and 09246400 were not substantially different, and the loads were proportional to the discharge volumes. However, for total phosphorus, and to a lesser extent, total nitrogen, loads at station 09246400 were substantially smaller than the loads at station 09246200 (fig. 24). Most of the annual nutrient loads were transported during April–June (fig. 25) and, as in the case of the annual loads, the loads for total nitrogen and phosphorus during those months were substantially smaller at the downstream station. The differences in total nitrogen and phosphorus

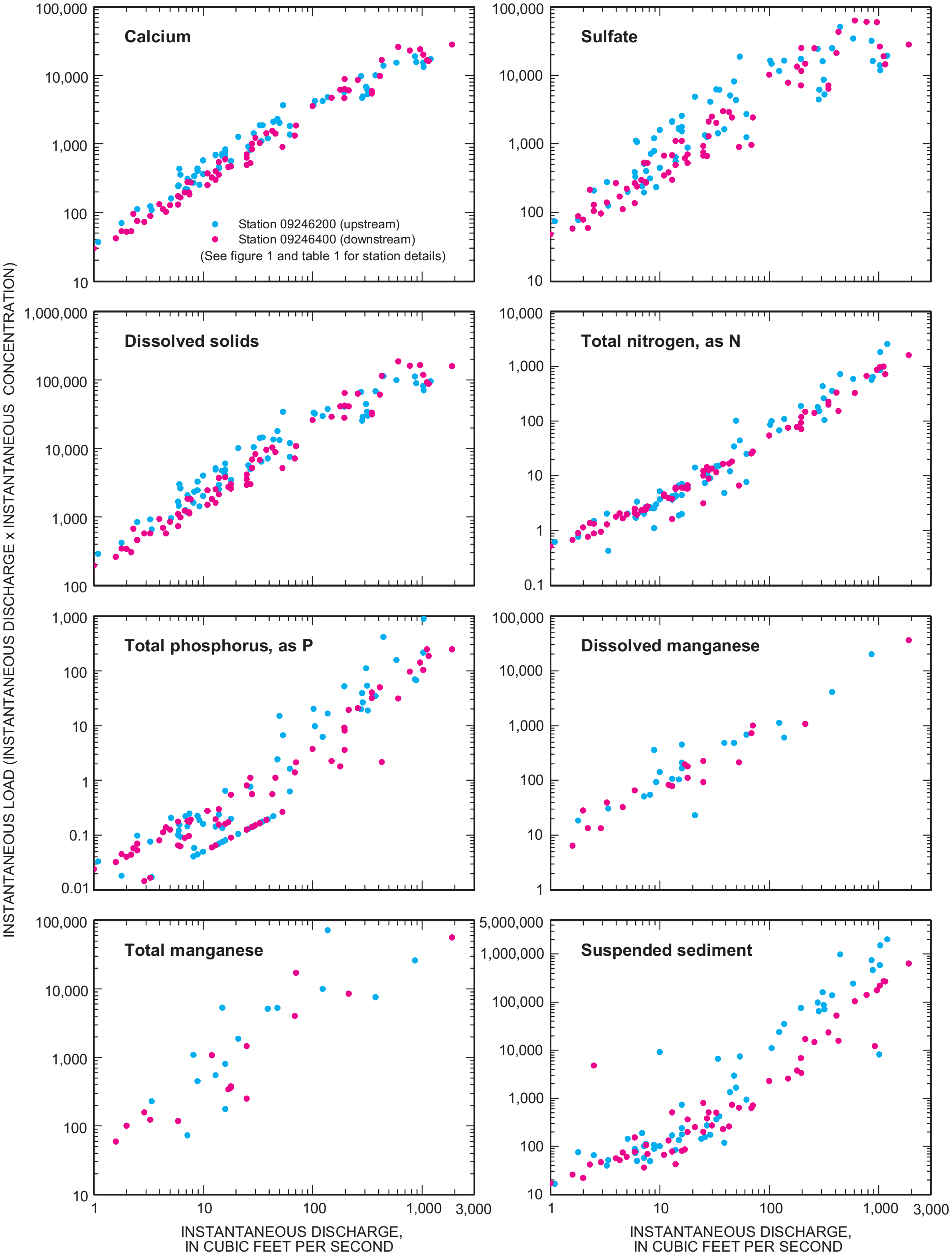


Figure 21. Relation between instantaneous load and instantaneous discharge for selected constituents for Elkhead Creek at two stations upstream and downstream from Elkhead Reservoir, July 1995–September 2001. (Instantaneous load was not converted to a consistent set of units).

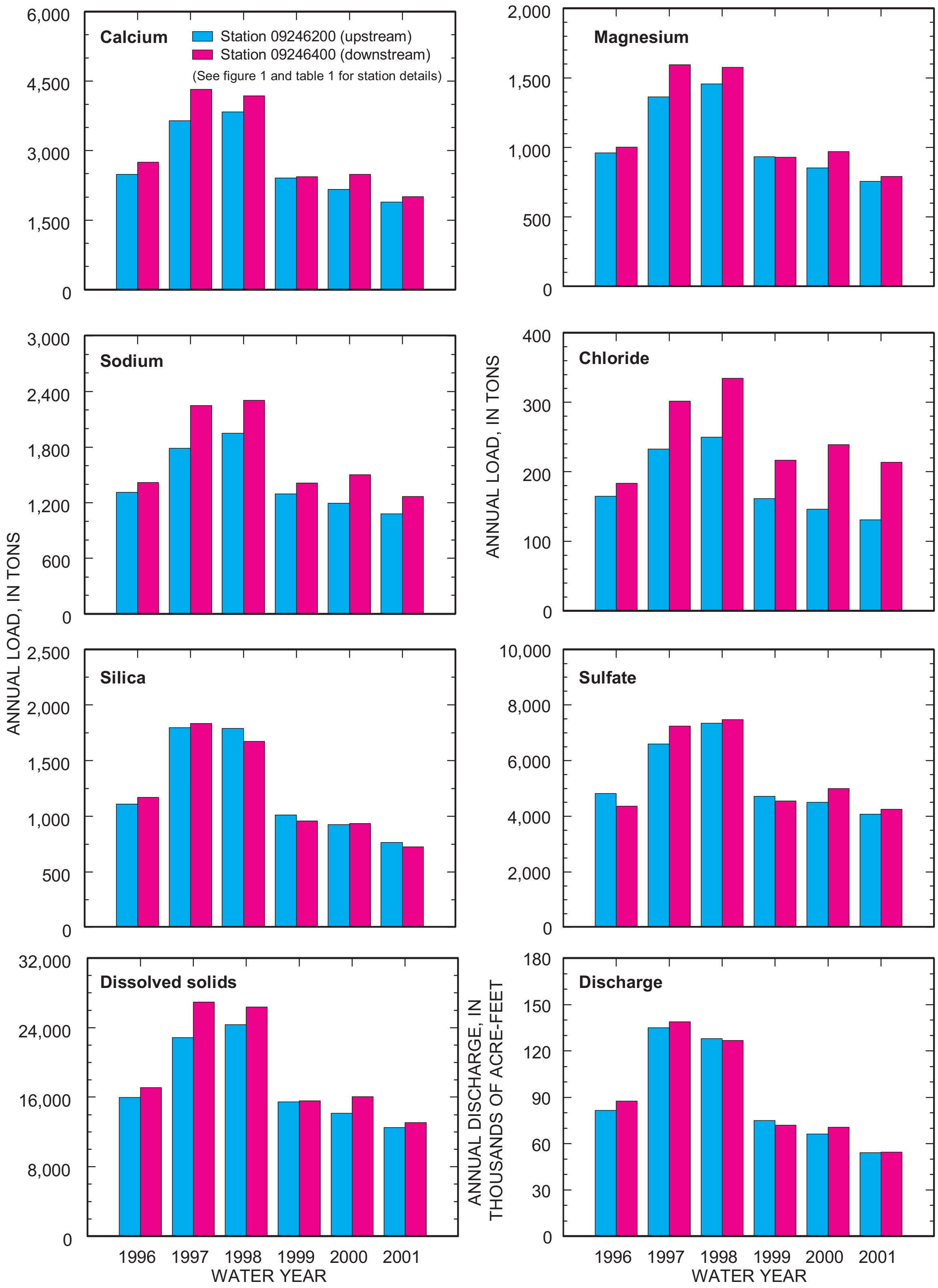


Figure 22. Annual dissolved-major-ion loads and discharge for Elkhead Creek at two stations upstream and downstream from Elkhead Reservoir.

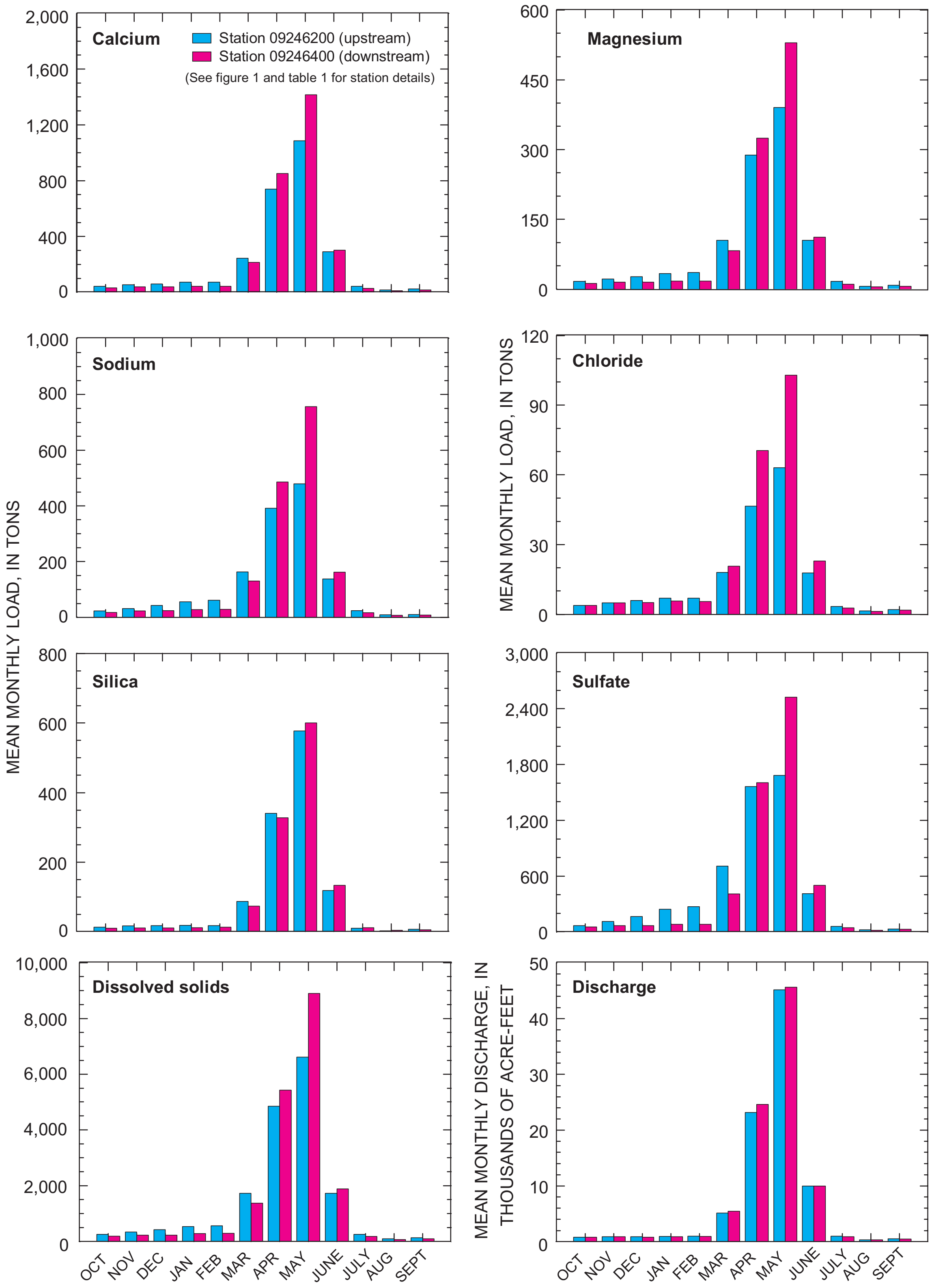


Figure 23. Mean monthly dissolved-major-ion loads and discharge for Elkhead Creek at two stations upstream and downstream from Elkhead Reservoir, water years 1996–2001.

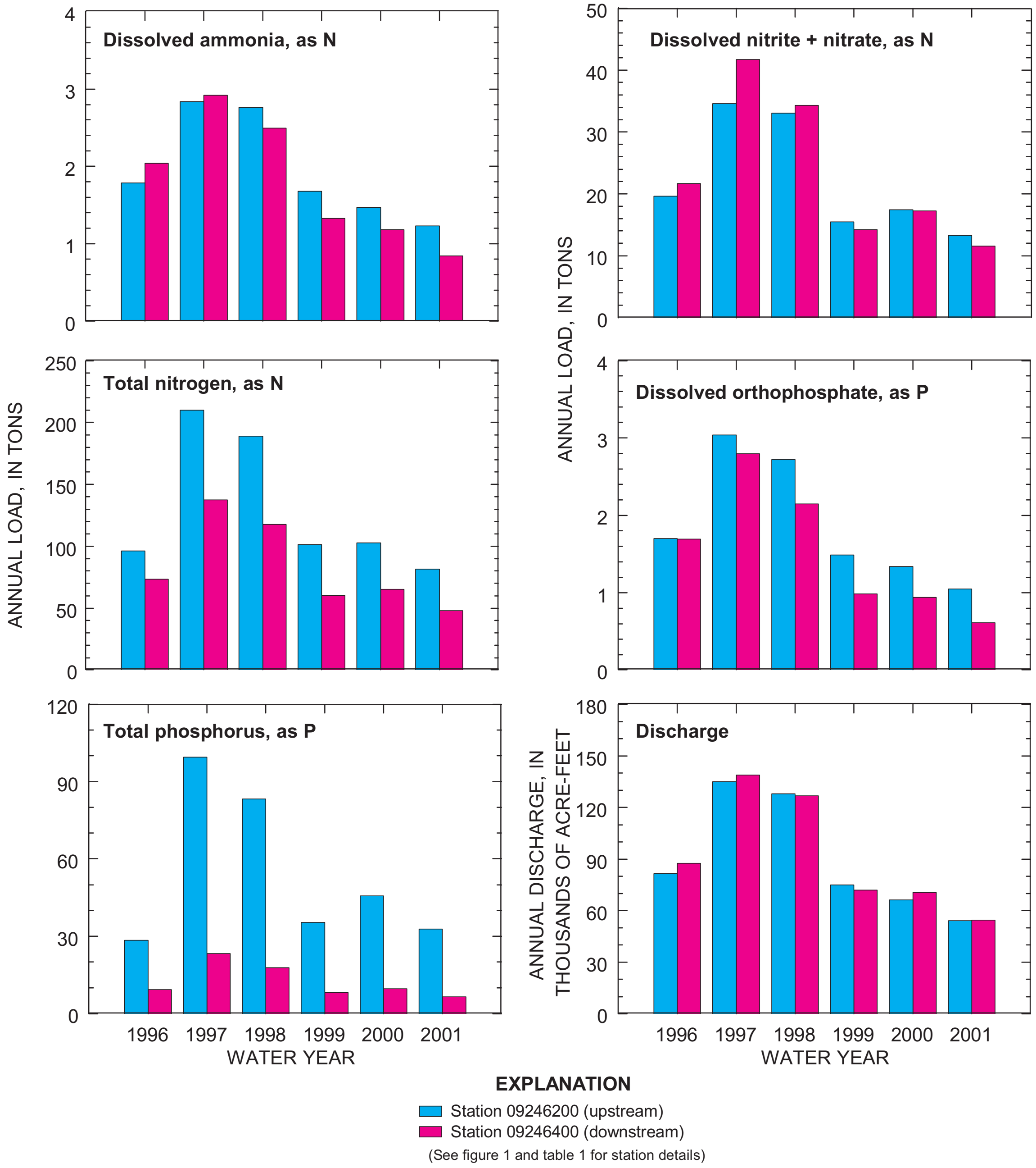


Figure 24. Annual nutrient loads and discharge for Elkhead Creek at two stations upstream and downstream from Elkhead Reservoir.

loads between the upstream and downstream station (figs. 24–25) indicated that particulate nitrogen tended to move through the reservoir, whereas particulate phosphorus mostly was retained within the reservoir, either because of biological uptake, settling within the reservoir, or both. Also, nutrient loads during July–February (fig. 25), often were relatively smaller than the major-ion loads (fig. 23) during those months; consequently, nutrient loads during March–June were a larger component of the annual nutrient load than in the case of the loads for the major ions (figs. 22–23).

Annual loads for dissolved barium, copper, and iron were larger at the downstream station than at the upstream station, and in the case of dissolved iron, the downstream increase in load was substantial (fig. 26). Much of the dissolved-iron load at the downstream station probably resulted from increased hypoxia near the reservoir bottom, which caused redox-related increases in dissolved iron (M.R. Stevens, U.S Geological Survey, written commun., 2003). Some of the increase in downstream dissolved copper load also could be attributed to the same cause. Typically, dissolved manganese load upstream and downstream from a reservoir shows the same pattern as that

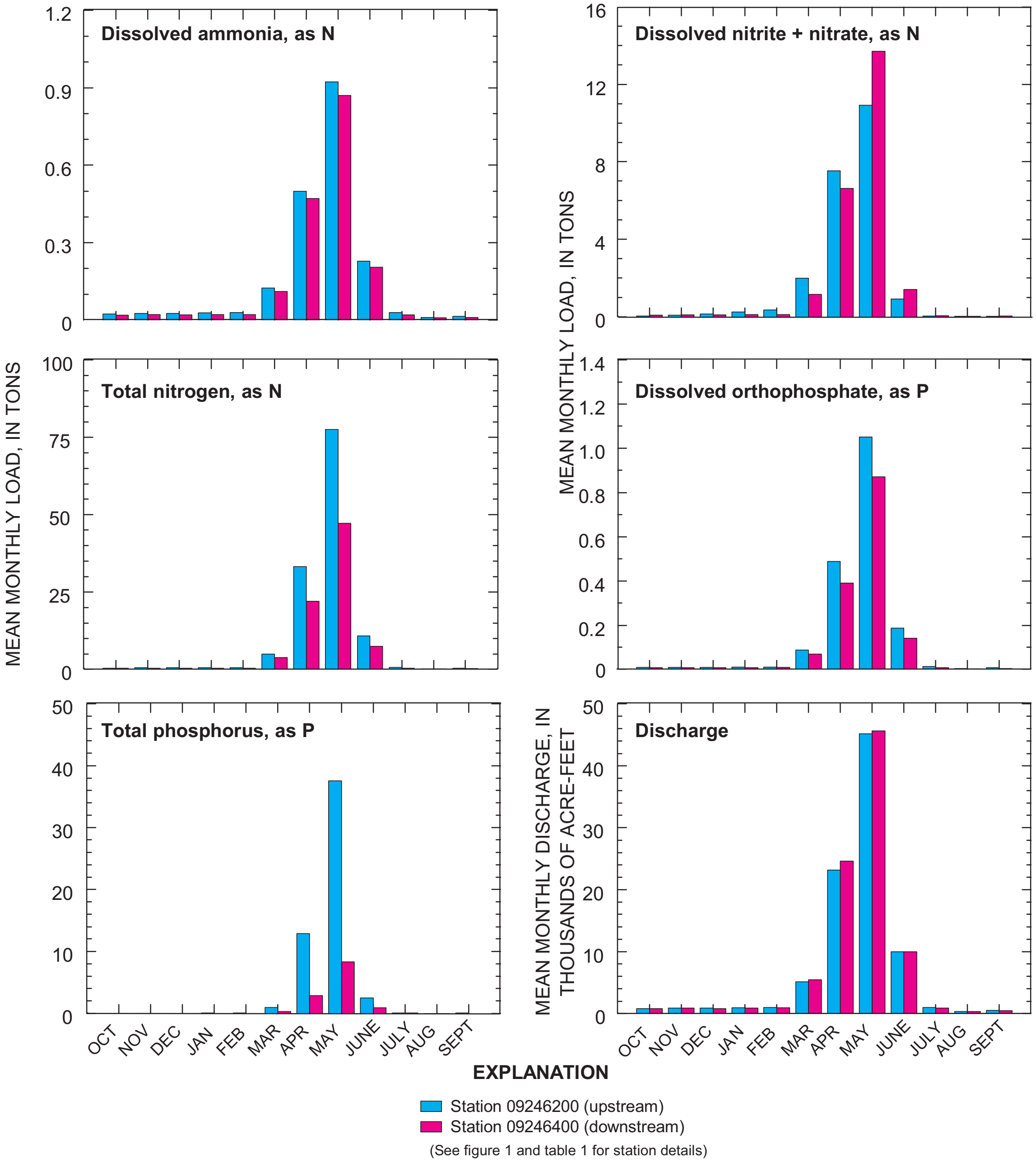


Figure 25. Mean monthly nutrient loads and discharge for Elkhead Creek at two stations upstream and downstream from Elkhead Reservoir, water years 1996–2001.

seen for dissolved copper and iron; however, dissolved manganese loads were smaller at the downstream station (fig. 26). Reasons for this are not known. There was little difference between the upstream and downstream loads of dissolved barium.

Annual loads for total-recoverable copper, iron, and manganese at both stations were substantially larger than the dissolved loads (fig. 26; y-axes scales). Also, annual loads for total aluminum, copper, iron, and manganese at the downstream station were consistently and substantially less than the annual loads at the upstream station (fig. 26), indicating that large amounts of the total concentrations that were related to suspended sediment and other particulates settled out in Elkhead Reservoir. The comparisons between annual upstream and downstream loads and between dissolved and total loads (fig. 26) just described also apply to the mean monthly loads (fig. 27). As in the case of major ions and nutrients, monthly trace-element loads were substantially larger during April–June, owing to the much larger discharge during those months (fig. 25; “Discharge” graph).

Annual and mean monthly suspended-sediment loads for stations 09246200 and 09246400 (figs. 28–29) show that most

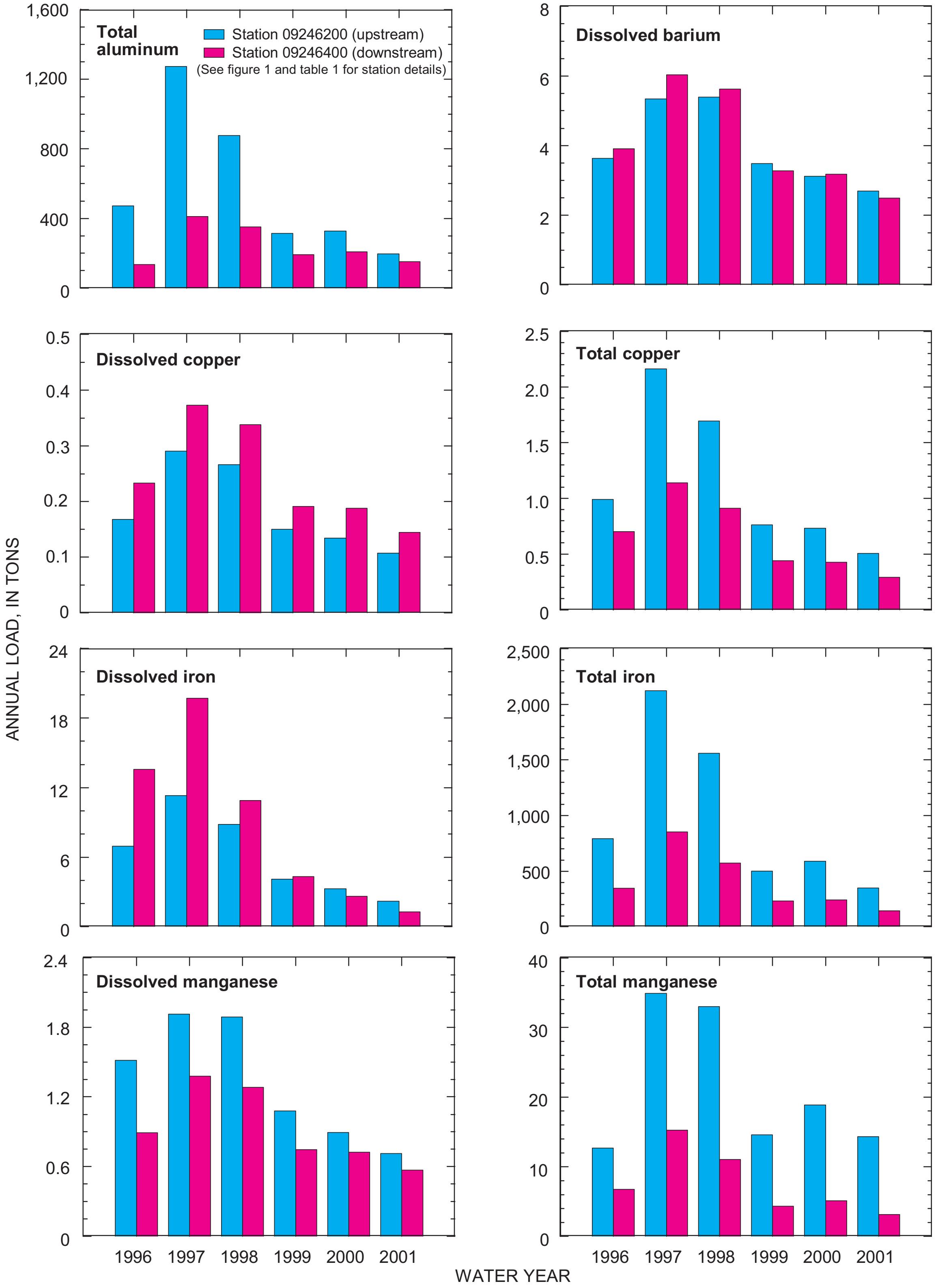


Figure 26. Annual trace-element loads for Elkhead Creek at two stations upstream and downstream from Elkhead Reservoir.

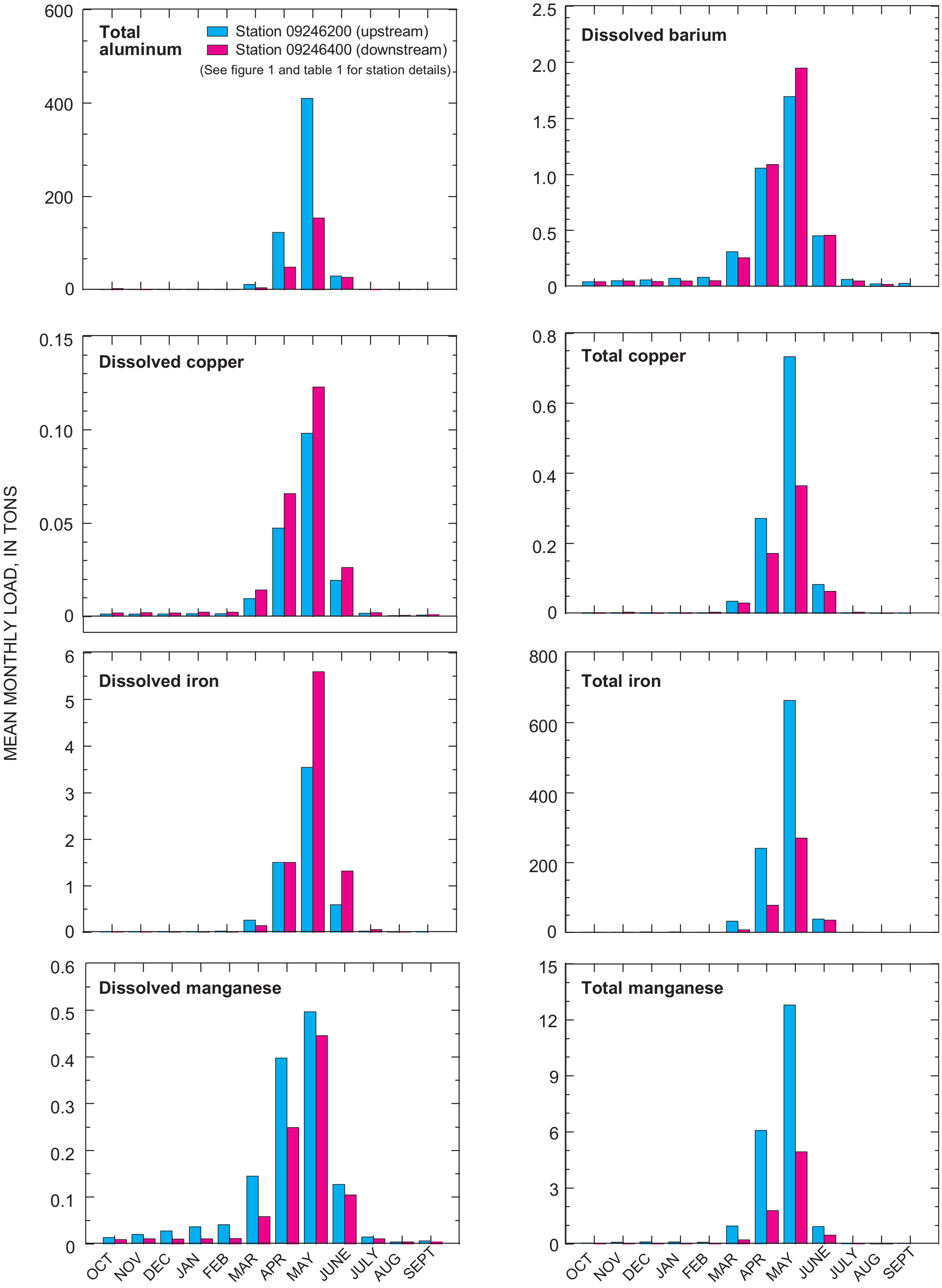


Figure 27. Mean monthly trace-element loads for Elkhead Creek at two stations upstream and downstream from Elkhead Reservoir, water years 1996–2001.

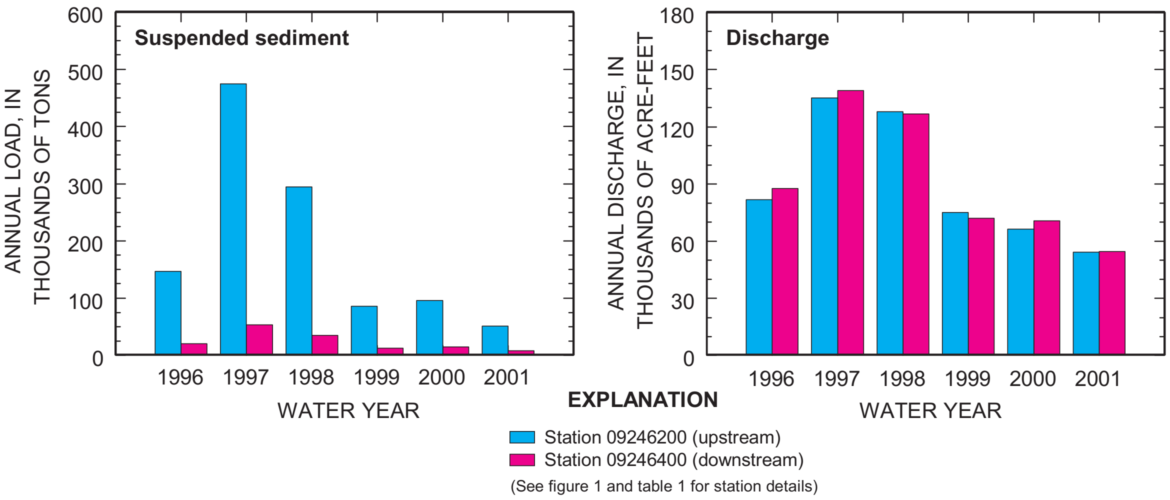


Figure 28. Annual suspended-sediment load and discharge for Elkhead Creek at two stations upstream and downstream from Elkhead Reservoir.

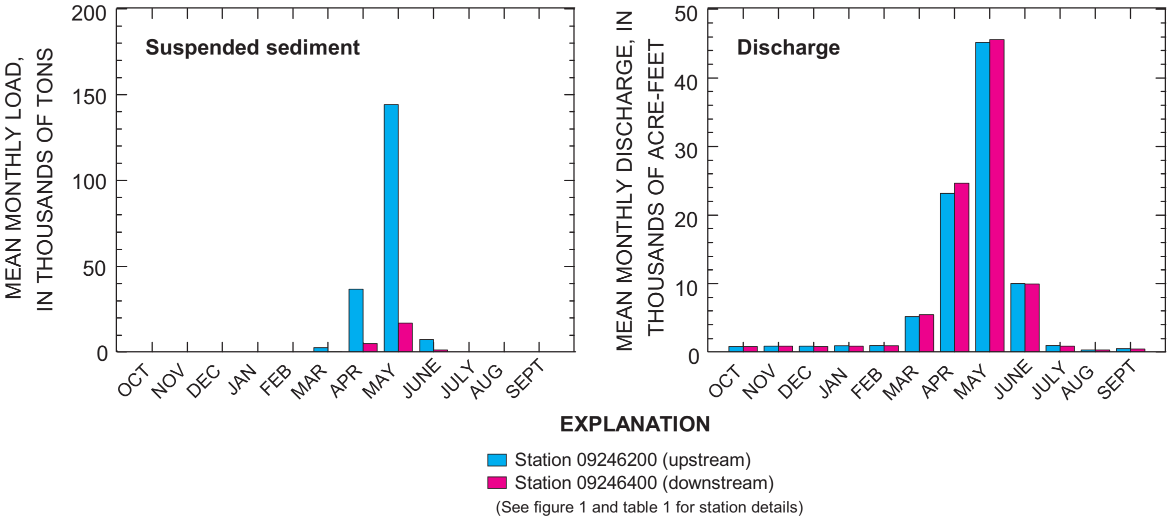


Figure 29. Mean monthly suspended-sediment load and discharge for Elkhead Creek at two stations upstream and downstream from Elkhead Reservoir, water years 1996–2001.

suspended sediment transported into Elkhead Reservoir remained in the reservoir. Mean annual load for water years 1996–2001 was about 191,000 tons at station 09246200 compared to about 24,000 tons at station 09246400 and is about an 87-percent decrease in downstream suspended-sediment load. Elliott and Gyetvai (1999, p. 31–33) estimated that in 1993, the volume of a sediment delta at the inlet to Elkhead Reservoir was about 163 acre-ft and had a mass of about 345,000 tons, and that the estimated deposition rate during 1975–93 was about 18,170 tons per year. It is not known if the 1996–2001 mean load at station 09246200 is representative of the mean load during a longer period back to completion of Elkhead Dam; however, the mean annual rate of sediment deposition at the delta estimated by Elliott and Gyetvai (1999, p. 31–33) is about one-tenth of the mean annual load at station 09246200 during 1996–2001.

The estimate of the sediment delta mass together with the estimated annual deposition rate (Elliott and Gyetvai, 1999, p. 31–33) and the estimate of the annual loads shown in figure 28 are subject to some error; other differences in these estimates could be attributable to movement of unknown quantities of sediment to other locations in the reservoir or smaller suspended-sediment loads at station 09246200 before 1996. A comprehensive analysis of the sediment transport characteristics at station 09246200 and of the rate and total quantity of sediment deposition in Elkhead Reservoir is needed to fully understand the differences; however, that analysis is beyond the scope of this report.

Water Quality of Elkhead Reservoir

Water in Elkhead Reservoir is subject to the cumulative effects of inflow that is exposed to sedimentary lithologies, return flow from irrigation, and evapotranspiration in the upstream basin, as well as evaporation from the reservoir itself; all of these factors may affect water quality. Water quality in the reservoir also is affected considerably by the process of snowmelt runoff in Elkhead Creek, resulting in reservoir water that is a mixture of diluted high-elevation snowmelt runoff and more concentrated low-flow water. Understanding vertical stratification patterns, chemical characteristics, and trophic state provides a basis for assessing conditions in Elkhead Reservoir and effects of impoundment on downstream water quality. Data analysis is organized by the topics of field measurements, nutrients, and chlorophyll, followed by a discussion of trophic state and nutrient limitation. Major-ion and trace-element samples were not collected from Elkhead Reservoir in conjunction with the 1995–2001 data-collection program.

Depth-Profile Measurements

Median depth-profile measurements of temperature, specific conductance, pH, and dissolved oxygen were compiled for three reservoir water-quality sites (ER1b at the inlet, ER2b at midlake, and ER3b near the dam) (table 8) for July 1995 to August 2001. Boxplots of selected field measurements by site are shown in figure 30. Time-series plots of selected data collected near the surface and near the bottom at ER3b are shown in figures 31–32.

Water temperature in the reservoir varied seasonally, ranging from near 0^{o}C during winter when ice develops on the reservoir to about 20°C during summer (fig. 31). Temperatures were less variable and had a lower median at depth in comparison to near the surface (fig. 30; table 8). Specific conductance in Elkhead Reservoir varied from minimums of 138 to 169 µS/cm, during peak snowmelt inflow, to maximums of 424 to 610 µS/cm, during early spring (April) before snowmelt. Variations in specific conductance in Elkhead Reservoir (fig. 30) are less extreme than in Elkhead Creek (figs. 8–9) because of the moderating effect of mixing the seasonal high- and low-flow discharges in the reservoir. Median specific conductance was highest in the near-bottom samples at ER1b and highest in the near-surface samples at ER2b and ER3b (fig. 30). Variability between minimum and maximum seasonal specific conductance was largest in near-bottom samples at site ER3b (fig. 31). Median specific conductance in Elkhead Reservoir was no higher than 274 µS/cm at all sampling sites (table 8).

The pH measured in the reservoir ranged from neutral to somewhat alkaline with median measurements between 7.2 and 8.0 (table 8). Median dissolved-oxygen concentration ranged from 7.1 to 7.7 mg/L (table 8), except in the hypolimnion at sites ER2b and ER3b, where median dissolved-oxygen concentration ranged from 4.8 to 5.6 mg/L (table 8); seasonal stratification at these two sites sometimes resulted in individual dissolved-oxygen concentrations approaching 1 mg/L or less in near-bottom samples (fig. 30; sites ER2b–B and ER3b–B). Dissolved-oxygen concentrations tended to be largest at the inlet and smallest near the dam in near-surface and near-bottom measurements (table 8). Median transparency ranged from 36 to 52 inches below the surface. This range is less than the transparency at many montane reservoirs (Crowfoot and others, 2002), and likely is caused by turbidity from inflow of suspended sediments. Median transparency was smallest at the inlet and was largest near the dam (table 8) due to settling of suspended sediment as water moves through the reservoir; also, transparency usually was larger after snowmelt (fig. 32).

Stratification Patterns

Vertical stratification patterns within the water column of Elkhead Reservoir were characterized by using depth profiles of temperature, specific conductance, pH, and dissolved oxygen that were measured during April–May, July–August, and September–October starting in July 1995 and continuing through 2001, except for 2000 when no data were collected at the reservoir. Variation of measured water temperature, specific conductance, pH, and dissolved oxygen with depth and throughout the growing season at Elkhead Reservoir for water year 1996, a typical year, is shown in figures 33–36.

Elkhead Reservoir was dimictic in water year 1996, which means temperature stratification formed in summer and late winter, and the lake contents mixed during overturn in the spring and fall (fig. 33, October and May profiles) (Cole, 1994). Thermal stratification was evident in July and intensified into September 1996 when the thermocline (at site ER3b) was at the 18- to 27-ft depth interval and had a rate of change of about –0.8°C/ft compared to about a –0.1°C/ft rate of change in the 27- to 60-ft depth interval (fig. 33).

Seasonal differences in inflow temperature can affect routing of water within the reservoir because water density varies with temperature (Ford, 1990). Water of a given temperature at the inflow will tend to flow as a density current to depths within the reservoir of similar temperature. Spring and fall water temperatures in Elkhead Creek upstream from Elkhead Reservoir (figs. 8–10) were lower than temperatures in the reservoir (fig. 33). Thus, inflows tended to plunge beneath the surface layer (epilimnion) and settle near the thermocline and during spring and fall of water year 1996. During summer, water temperature in Elkhead Creek upstream from the reservoir (figs. 8–10) was similar to the upper reservoir layer (fig. 33), and flows were routed through the reservoir near the surface.

During winter, stream temperatures were near 0^{o}C, and surface water at the ice-cover interface was 0^{o}C (profile not shown), but temperature in the reservoir subsurface increased

Table 8. Comparison of near-surface and near-bottom median water-quality field measurements and constituent concentrations for Elkhead Reservoir, July 1995–August 2001.

[°C, degrees Celsius; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter; µg/L, micrograms per liter; <, less than; --, constituent not measured; site ER1b is at inlet; site ER2b is near midlake; site ER3b is near dam]

Measurement or property	Sampling site (fig. 1)	Median concentration or value	
		Near reservoir surface	Near reservoir bottom
Field measurements			
Water temperature (°C)	ER1b	14.8	13.0
	ER2b	14.2	9.2
	ER3b	14.4	7.8
Specific conductance (µS/cm at 25°C)	ER1b	247	274
	ER2b	234	200
	ER3b	233	200
pH, field (standard units)	ER1b	8.0	8.0
	ER2b	8.0	7.4
	ER3b	7.9	7.2
Dissolved oxygen, (mg/L)	ER1b	7.2	7.7
	ER2b	7.1	5.6
	ER3b	7.1	4.8
Transparency, Secchi depth (inches)	ER1b	36	--
	ER2b	49	--
	ER3b	52	--
Nutrients			
Nitrogen, ammonia plus organic, dissolved (mg/L as N)	ER1b	.3	.3
	ER2b	.3	.3
	ER3b	.3	.3
Nitrogen, ammonia plus organic, total (mg/L as N)	ER1b	.4	.4
	ER2b	.4	.3
	ER3b	.3	.3
Nitrogen, ammonia, dissolved (mg/L as N)	ER1b	.006	.005
	ER2b	.004	.008
	ER3b	.006	.004
Nitrogen, nitrite plus nitrate, dissolved (mg/L as N)	ER1b	.006	.005
	ER2b	.020	.099
	ER3b	.020	.172

Table 8. Comparison of near-surface and near-bottom median water-quality field measurements and constituent concentrations for Elkhead Reservoir, July 1995–August 2001.—Continued

[°C, degrees Celsius; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter; µg/L, micrograms per liter; <, less than; --, constituent not measured; site ER1b is at inlet; site ER2b is near midlake; site ER3b is near dam]

Measurement or property	Sampling site (fig. 1)	Median concentration or value	
		Near reservoir surface	Near reservoir bottom
	Nutrients—Continued		
Nitrogen, nitrite, dissolved (mg/L as N)	ER1b	0.002	0.002
	ER2b	.002	.002
	ER3b	.002	.002
Phosphorus, dissolved (mg/L as P)	ER1b	.009	.008
	ER2b	.006	.009
	ER3b	.008	.016
Phosphorus, dissolved orthophosphate (mg/L as P)	ER1b	.002	.002
	ER2b	.001	.003
	ER3b	.002	.008
Phosphorus, total (mg/L as P)	ER1b	.028	.028
	ER2b	.017	.041
	ER3b	.018	.058
	Chlorophyll		
Chlorophyll-*a* (µg/L)	ER1b	1.1	.9
	ER2b	1.1	.4
	ER3b	.6	.1
Chlorophyll-*b* (µg/L)	ER1b	<.1	<.1
	ER2b	<.1	<.1
	ER3b	<.1	<.1

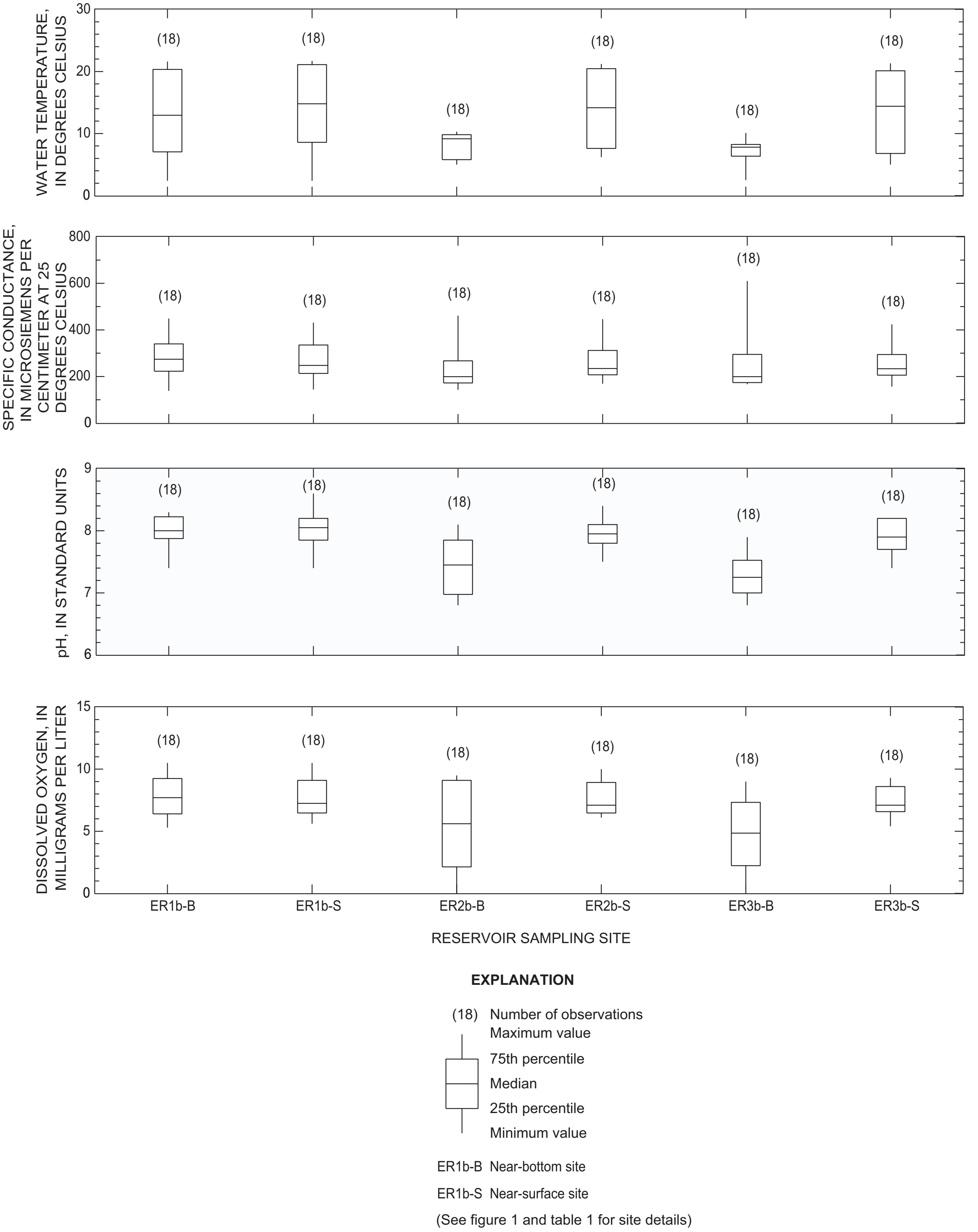


Figure 30. Field measurements for Elkhead Reservoir, July 1995–August 2001.

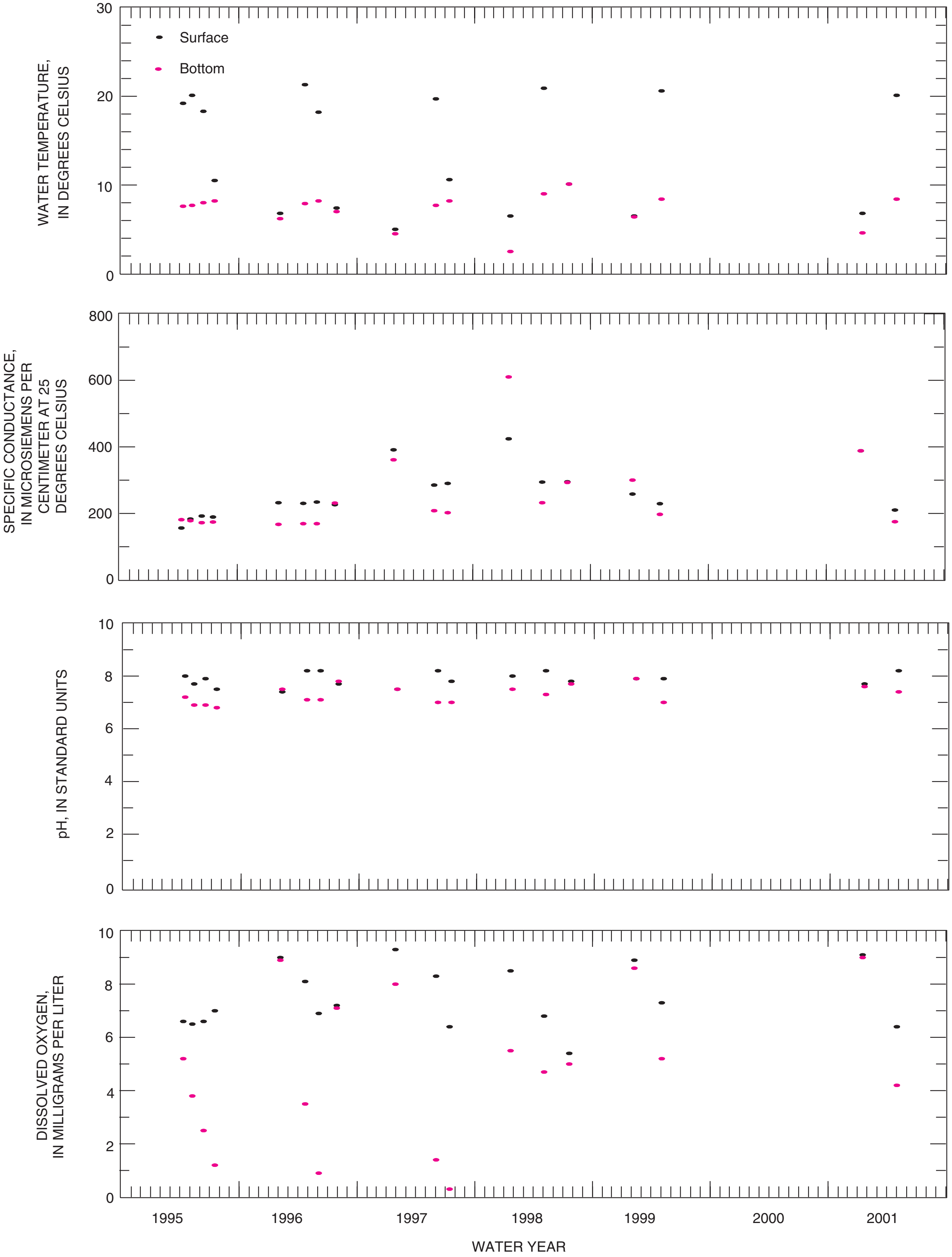


Figure 31. Annual and seasonal variability of field measurements for Elkhead Reservoir at site ER3b, July 1995–August 2001.

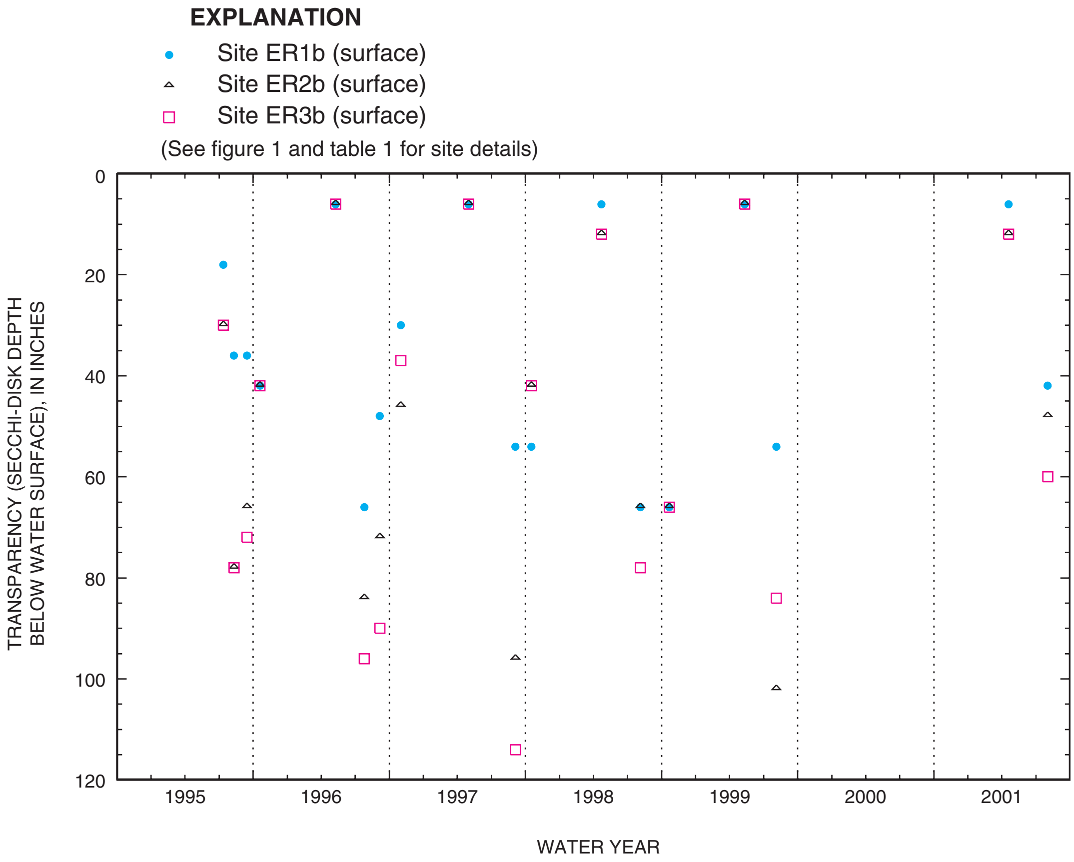


Figure 32. Annual and seasonal variability of water transparency for Elkhead Reservoir, July 1995–August 2001.

with depth to 4°C in the near-bottom waters (water is most dense at about 4°C). Winter stratification is assumed to be similar to other dimictic, montane reservoirs such as Lake Granby, Shadow Mountain Lake, and Grand Lake (Crowfoot and others, 2002). Thus, inflow will tend to be routed just under the ice. Routing information could be important in the event of a chemical spill upstream because it may help to determine the residence time of the spill plume, and knowledge of probable vertical location of the plume would be important for outflow gate configurations.

During stratification, specific conductance generally was highest in the epilimnion, resulting from warm and relatively concentrated water from Elkhead Creek that was routed through the reservoir in the relatively warm epilimnion (fig. 34). The pH in the epilimnion generally increased from May to September (fig. 35), probably as a result of algal productivity. In the hypolimnion (lowermost layer of water), pH decreased slightly with depth in the July and September profiles, probably as a result of biomass decay processes and a lack of circulation during stratification.

Dissolved-oxygen concentrations were greater than 6 mg/L in the epilimnion during all sampling periods in water year 1996 (fig. 36). Dissolved-oxygen concentrations in the hypolimnion were lowest in September when near-bottom oxygen concentrations approached zero at the mid-lake and near-dam sites (fig. 36). A decrease in dissolved-oxygen concentrations in the metalimnion (middle layer of water), in the about 15- to 25-ft depth interval (fig. 36; July and September) probably is not caused by interflow because other field measurements (figs. 33–35) did not show evidence of a large interflow circulation during summer and fall. The pattern of only decreased dissolved-oxygen concentration during July, August, and September occurred to some extent during most years at site ER3b (dam) and to a lesser extent at site ER2b (mid-lake). This dissolved-oxygen pattern is described as a metalimnitec oxygen minima and partly results from oxygen consumption by decaying plankton settling in the thermocline (Cole and Hannan, 1990).

Spatial differences between ER2b (a transitional zone) and ER3b (a deeper lacustrine zone) were relatively minor as both sites had similar depth-profile patterns for field measurements during water year 1996 (figs. 33–36). Dissolved-oxygen concentrations were lowest in the hypolimnion at the mid-lake site (ER2b) in July and September 1996 rather than in the deepest part of the reservoir at the near-dam site (ER3b). During summer stratification, the midlake hypoxia (oxygen depletion) probably is greater because the hypoxic zone usually begins at the point of sedimentation of the inflow oxygen demand where reservoir bottom layers are not effectively reaerated (Cole and Hannan, 1990). This sedimentation zone can shift depending on

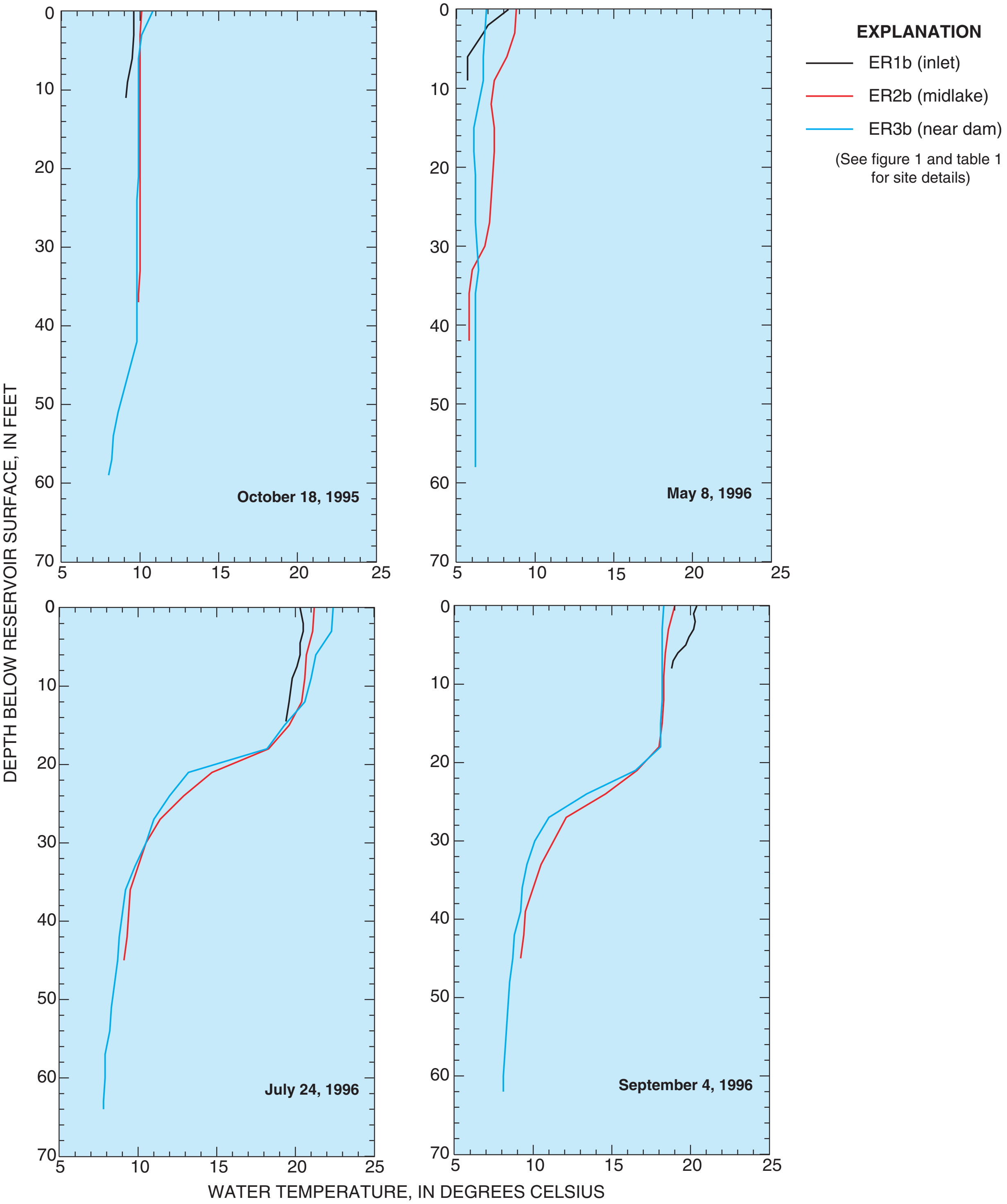


Figure 33. Water-temperature profiles for Elkhead Reservoir, water year 1996.

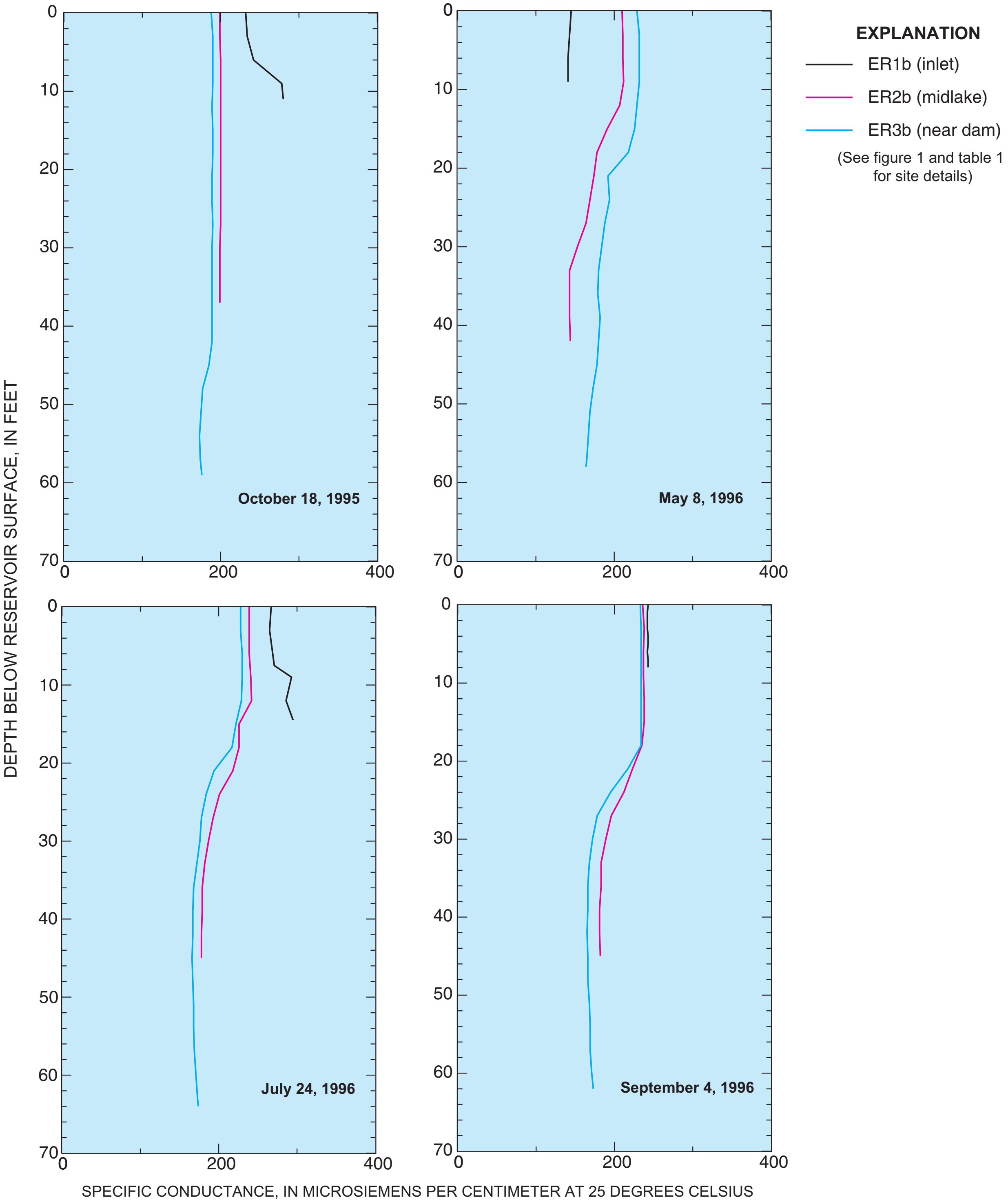


Figure 34. Specific-conductance profiles for Elkhead Reservoir, water year 1996.

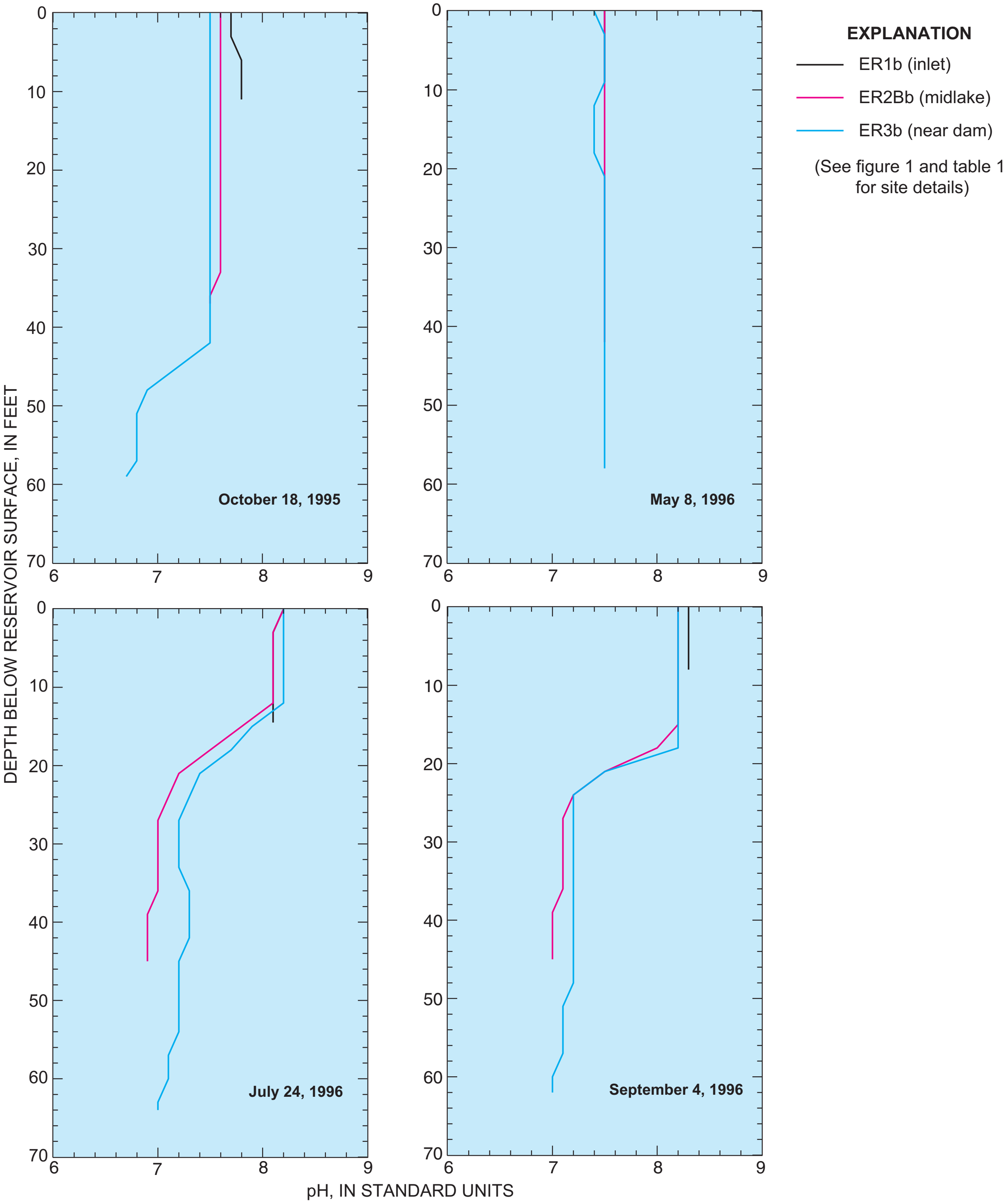


Figure 35. pH profiles for Elkhead Reservoir, water year 1996.

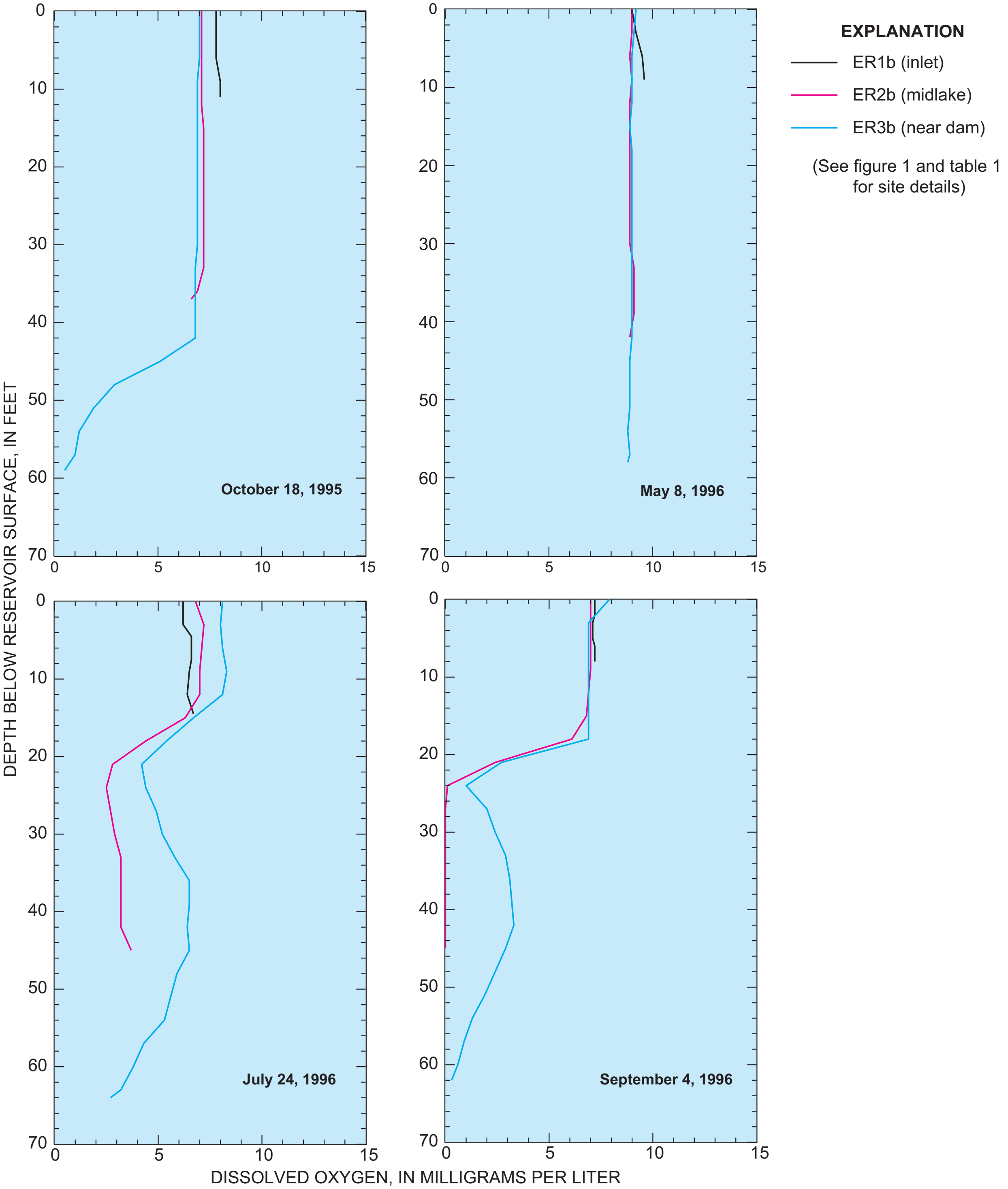


Figure 36. Dissolved-oxygen profiles for Elkhead Reservoir, water year 1996.

the rate of inflow; high inflow pushes the zone farther into the reservoir, whereas during low inflow the zone retreats back towards the inflow. As the hypoxia deepens, the hypoxic zone moves upstream and downstream in the reservoir (Cole and Hannan, 1990).

Nutrients and Chlorophyll

Median nutrient concentrations during July 1995–August 2001 at the three reservoir water-quality sites are listed in table 8. Boxplots of selected constituents by site are shown in figure 37, and time-series plots of nutrient concentrations near the surface and near the bottom at ER3b are shown in figure 38.

Seasonal variation in nutrient concentrations was similar in near-surface and near-bottom samples. Near-surface and near-bottom concentrations of total ammonia plus organic nitrogen, dissolved ammonia, dissolved nitrite plus nitrate, and dissolved phosphorus increased in concentration during runoff (April–May) (fig. 38). Concentrations of total phosphorus in near-surface samples generally were highest during runoff, whereas total phosphorus concentrations in near-bottom samples generally were highest during July or September. These spikes in total phosphorus concentration probably were caused by inflow of phosphorus-rich suspended sediment during runoff in the case of the near-surface samples, and bottom release during late summer hypoxia in the case of the near-bottom samples. Near-bottom samples of ammonia and nitrite plus nitrate generally had higher concentrations than concurrent near-surface samples (fig. 38). Concentrations of nitrite plus nitrate in near-surface samples were depleted substantially, presumably by biological uptake, during July, September, and October compared to near-bottom samples (fig. 38). Median nitrite plus nitrate in near-surface samples and near-bottom samples tended to increase from the inlet to near the dam (table 8). Median concentrations of orthophosphorus, dissolved phosphorus, and total phosphorus in near-bottom samples increased from the inlet to near the dam (table 8).

Median chlorophyll-*a* and -*b* concentrations during July 1995–August 2001 at the reservoir water-quality sites are listed in table 8. Boxplots of chlorophyll-*a* concentration by site are shown in figure 37, and time-series plots of chlorophyll-*a* concentrations at the surface are shown in figure 38.

Median concentration of chlorophyll-*a* ranged from 0.6 μg/L at site ER3b to 1.1 μg/L at sites ER1b and ER2b (table 8). The largest chlorophyll-*a* concentration was 4.6 μg/L at site ER1b on August 2, 2001 (fig. 37). Variations in concentrations were large during the growing season with peak seasonal concentrations during runoff or late summer and fall (fig. 38). Spatial variation in median concentrations indicated greater productivity at the inlet and midlake and a decline along the flow path in the reservoir (table 8). Maximum chlorophyll-*b* concentration was 0.9 μg/L (site ER1b), and chlorophyll-*b* concentrations exceeded the MRL of 0.1 μg/L in only 9 percent of samples.

Trophic State

The relative fertility of a lake or reservoir can be evaluated by assessing the trophic state. Oligotrophic (nutrient poor) lakes have characteristics such as high transparency, low organic-matter content, relatively high dissolved-oxygen concentrations, low nutrient concentrations, and small algal biomass. Eutrophic (nutrient rich) lakes have the opposite characteristics (Woods, 1992). Mesotrophic lakes are intermediate in the continuum between oligotrophic and eutrophic lakes. Elkhead Reservoir was classified using the trophic state index (TSI) method developed by Carlson (1977), which assumes phosphorus limitation. The boundary between oligotrophic (nutrient poor) and mesotrophic (moderate nutrients) is a TSI of 30. The boundary between mesotrophic and eutrophic (nutrient rich) is a TSI of 50. TSI values were computed for each value of Secchi-disk depth and total phosphorus and chlorophyll-*a* concentration. All TSI values at each site during each year then were averaged to derive the annual TSI value (fig. 39). If the concentration of total phosphorus was censored (less than MRL), the total phosphorus TSI was not computed.

On the basis of data collected 1995–2001, trophic state for Elkhead reservoir ranged from oligotrophic to eutrophic (fig. 39). TSI's computed from Secchi-disk depth and total phosphorus concentrations showed a general upward trend from 1995 to 2001, whereas TSI's computed from chlorophyll-*a* concentrations showed little trend (fig. 39). TSI's based on Secchi-disk depth and total phosphorus concentration were greater than those based on chlorophyll-*a* on the same sampling date, and TSI's for site ER1b (inlet) were greater than those for site ER3b (dam). This difference is a result of turbid conditions caused by suspended sediment from Elkhead Creek that resulted in a relative increase in total-phosphorus and Secchi disk TSI's and a relative decrease in the chlorophyll-*a* TSI due to reduced light penetration. Other cyclic factors such as grazing of phytoplankton by zooplankton can make interpretation of chlorophyll-*a* TSI ambiguous. Use of the TSI can give a qualitative indication of relative state of water bodies; however, a TSI should not be used exclusively to evaluate whether lakes and reservoirs are meeting water-quality classifications.

Nutrient Limitation

Nutrient limitation results based on N:P ratios for Elkhead Reservoir for water years 1995 through 2001 are listed in table 9. Some nutrient concentrations were less than the MRL, but in many cases this did not prevent assessment of the ranges in ratios. If ammonia concentration was less than the reporting limit, the proportion of ammonia generally was too small to affect the N:P ratio. If the orthophosphorus or nitrite plus nitrate concentration was less than the MRL, an evaluation of the possible concentrations usually would allow a determination of the range for the N:P ratio, which determined the limiting nutrient. For Elkhead Reservoir, 52 percent of the samples indicated phosphorus limitation (N:P greater than 10) (table 9); 9 percent

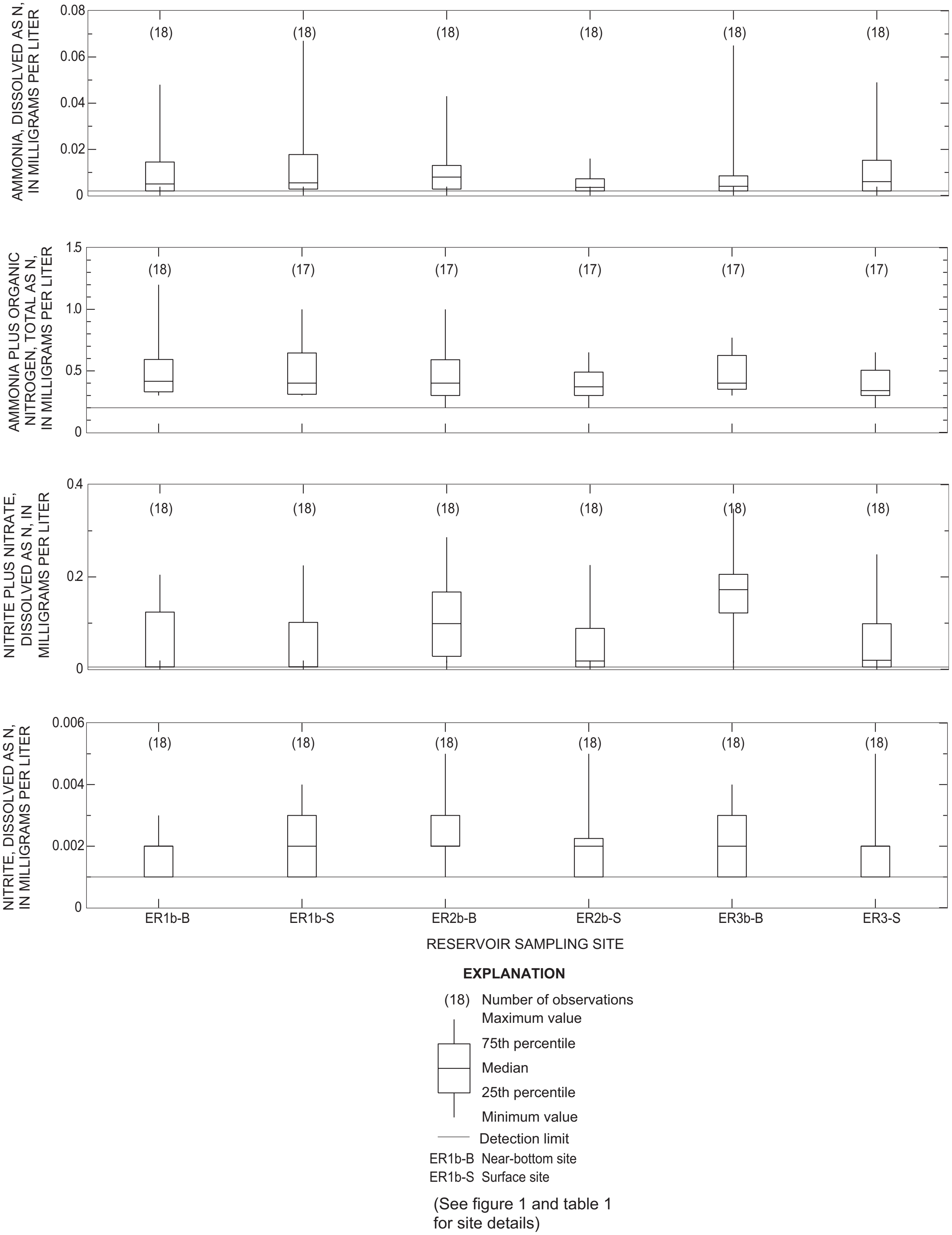


Figure 37. Selected nutrient and chlorophyll-*a* concentrations for Elkhead Reservoir, July 1995–August 2001.

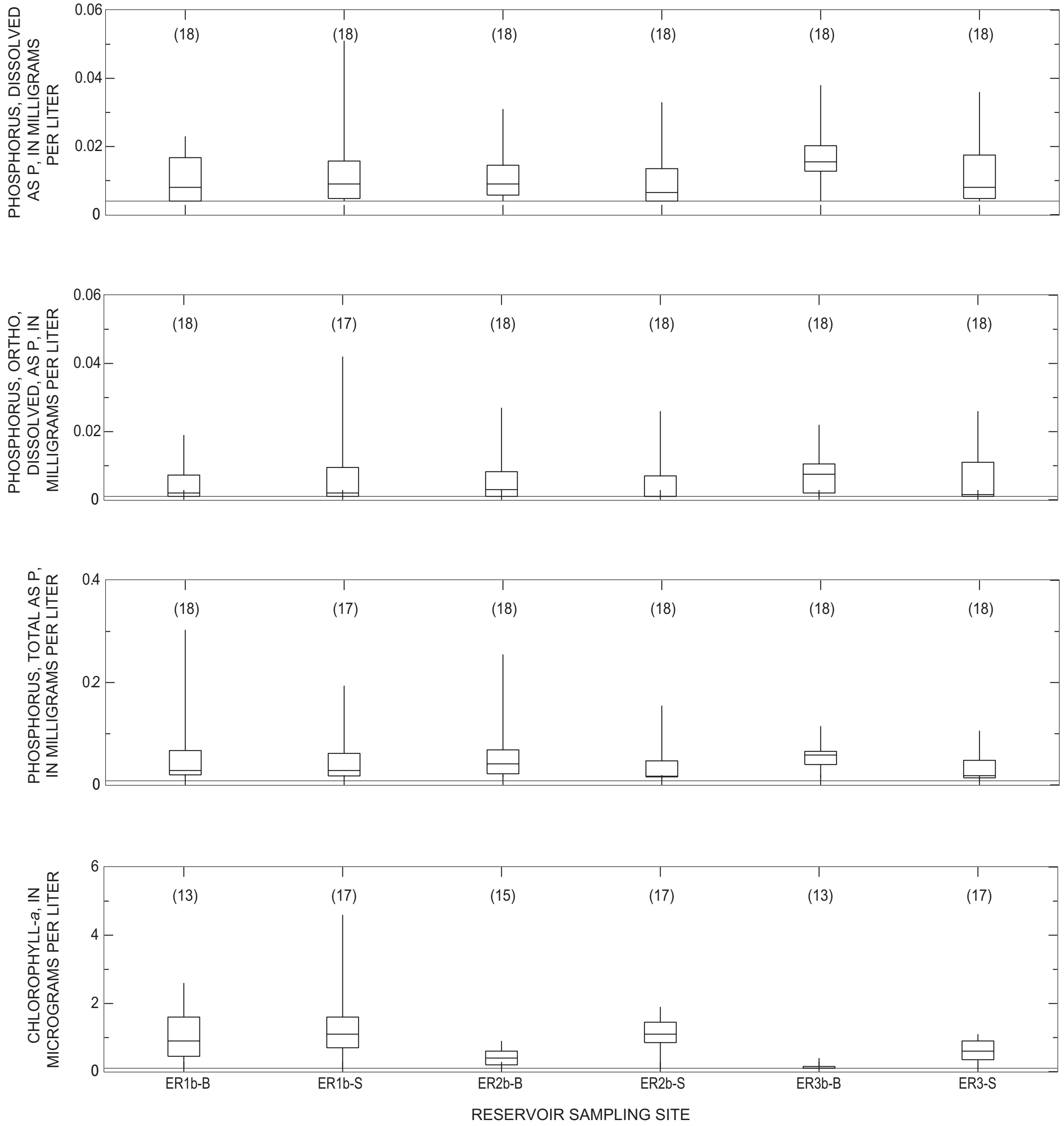


Figure 37. Selected nutrient and chlorophyll-*a* concentrations for Elkhead Reservoir, July 1995–August 2001.—Continued

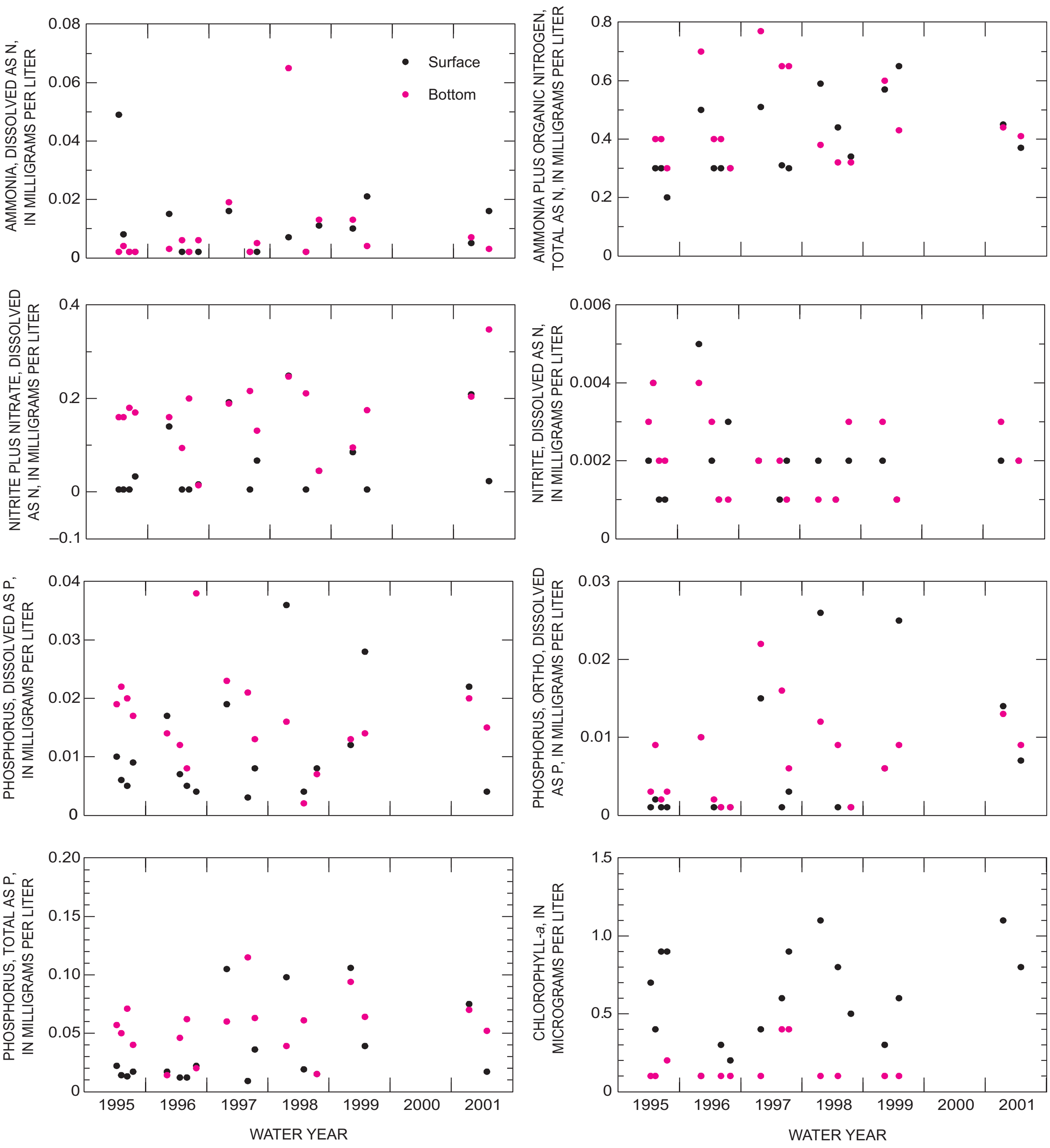


Figure 38. Annual and seasonal variability of selected nutrient and chlorophyll-*a* concentrations for Elkhead Reservoir at site ER3b, July 1995–August 2001.

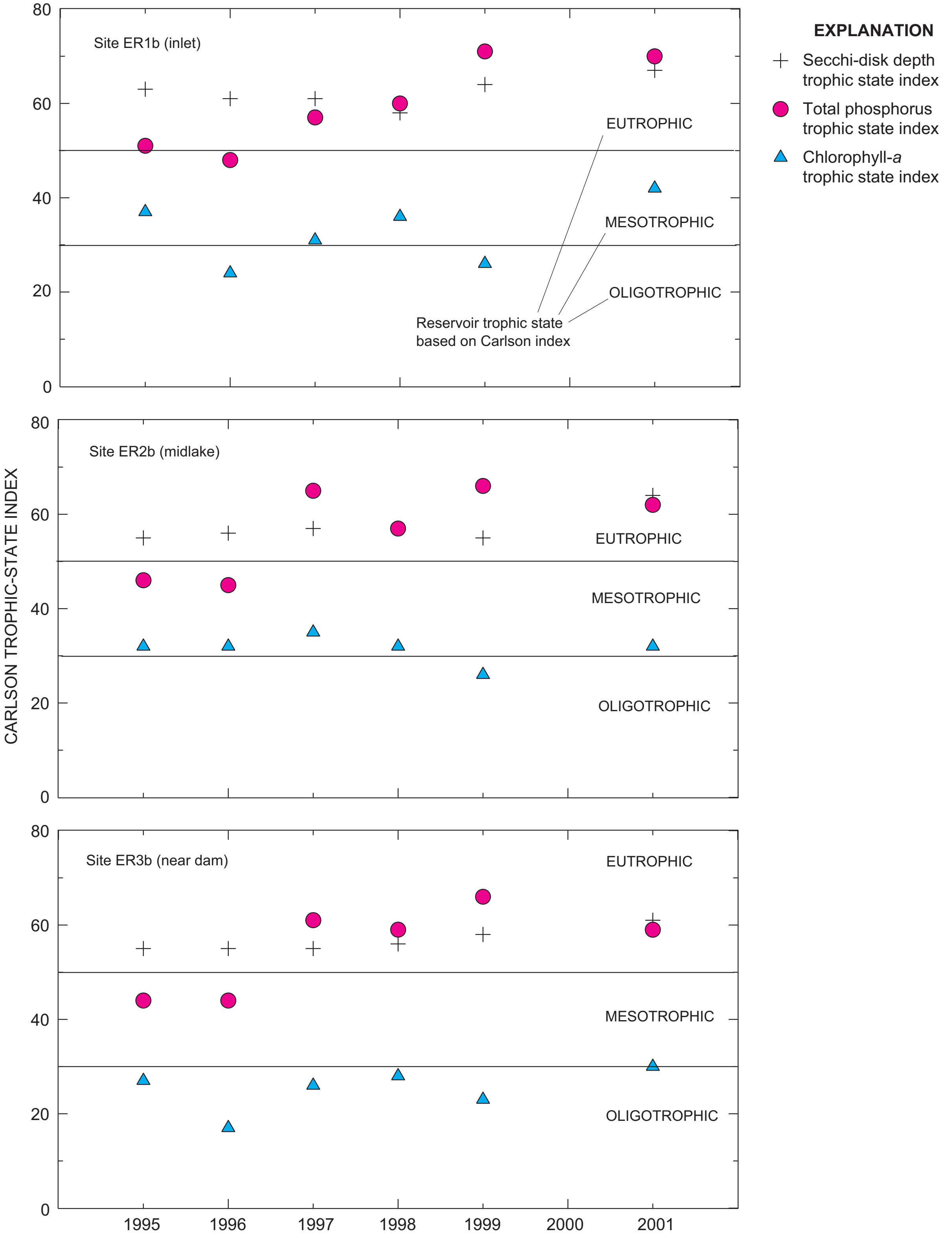


Figure 39. Carlson trophic-state indexes for Secchi-disk depth, total phosphorus, and chlorophyll-*a* for Elkhead Reservoir, 1995–2001.

Table 9. Limiting nutrient for algal growth for Elkhead Reservoir based on mass ratio of nitrogen to phosphorus, water years 1995–2001.

[Limiting nutrient, algal growth limited by concentration of nitrogen or phosphorus; P, phosphorus; N, nitrogen; --, no data; site ER1b is at inlet; site ER2b is near midlake; site ER3b is near dam]

Date	[1]Limiting nutrient for indicated site on Elkhead Reservoir (see figure 1 and table 1 for site details)		
	ER1b	ER2b	ER3b
07/12/95	P	P	P
08/09/95	P	N or P	N or P
09/13/95	--	--	--
10/18/95	N	P	P
05/08/96	P	P	P
07/24/96	--	--	--
09/04/96	--	--	--
10/30/96	P	P	P
04/30/97	P	P	P
09/03/97	N or P	N or P	N
10/15/97	P	P	P
04/22/98	N or P	N or P	P
08/04/98	--	--	--
10/21/98	P	P	P
05/11/99	P	P	P
08/04/99	N or P	N or P	N
04/18/01	P	P	P
08/02/01	N	N	N or P

[1] Limiting nutrient computation is based on calculation of mass ratio of dissolved inorganic nitrogen, as N, to dissolved orthophosohorus, as P.

of the samples indicated nitrogen limitation (N:P less than 5); 17 percent of samples had N:P ratios between 5 and 10, indicating N or P limitation; and for 22 percent of the samples, limitation status could not be determined because of concentrations below the MRL. In August of 1995, 1999, and 2001, a tendency toward either N limitation or the N or P limitation range was computed. From site to site, overall percentage type of limitation and the limitation type on each sampling date were somewhat similar (table 9), indicating some uniformity of limitation status throughout the reservoir at any given date and over the long term.

Water-Quality Standards

Based on all samples collected during 1995 to 2001, Colorado water-quality standards (Colorado Department of Public Health and Environment, Water Quality Control Commission, 2002) for pH, chloride, un-ionized ammonia, nitrite, nitrate (nitrite plus nitrate evaluated), fecal coliform, total-recoverable arsenic, dissolved boron, dissolved and total-recoverable cadmium, total-recoverable chromium, dissolved copper, dissolved lead, dissolved manganese, dissolved nickel, dissolved selenium, dissolved and total-recoverable silver, and dissolved zinc were not exceeded at any of the sampling sites in the study area (table 10). Dissolved oxygen in streams generally met the minimum standard (6 mg/L) except for a couple of instantaneous measurements in which dissolved-oxygen concentrations were slightly below 6 mg/L. Dissolved-oxygen concentrations in near-bottom reservoir samples sometimes were very low (less than 2 mg/L) during stratification. Elkhead Reservoir generally was well oxygenated in the mixed zone (epilimnion) where the reservoir standard (equal to or greater than 6 mg/L) is applied. The mean dissolved-oxygen concentration in the epilimnion was less than 6 mg/L only in the July 12, 1995, and August 4, 1998, profile measurements at site ER1b; the August 4, 1998, profile measurements at site ER2b; and the October 21, 1998,

Table 10. Estimated number of exceedances of Colorado aquatic water-quality standards for Elkhead Creek and Elkhead Reservoir, July 1995–September 2001.

[ac, acute standard; ch, chronic standard; f, fixed standard; s, surface; TVS, table value standard equation; mg/L, milligrams per liter; mL, milliliter; µg/L, micrograms per liter; >, greater than; <, less than; --, not sampled]

Constituent or property	Type	[2]Standard	[1]Number of exceedances from July, 1995 to August, 2001 at indicated station or site				
			09246200	09246400	ER1b	ER2b	ER3b
Dissolved oxygen (mg/L)	f, ch	>6	1	2	[3]2 (s)	[3]1 (s)	[3]1 (s)
pH, field (standard units)	f, ch	6 - 9	0	0	0	0	0
Chloride, dissolved (mg/L as Cl)	f, ch	250	0	0	--	--	--
Sulfate, dissolved (mg/L as SO_4)	f, ch	250	1	0	--	--	--
Nitrogen, nitrite, dissolved (mg/L as N)	f, ch	.05	0	0	0	0	0
Nitrogen, nitrite plus nitrate, dissolved (mg/L as N)	f, ch	10	0	0	0	0	0
Nitrogen, un-ionized ammonia, dissolved (mg/L as N)	ac	TVS	0	0	0	0	0
Nitrogen, un-ionized ammonia, dissolved (mg/L as N)	f, ch	0.02	0	0	0	0	0
Coliform, fecal (colonies/100 mL)	f, ch	200	0	0	--	--	--
Arsenic, total recoverable (µg/L as As)	f, ac	50	0	0	--	--	--
Boron, dissolved (µg/L as B)	f, ch	750	0	0	--	--	--
Cadmium, dissolved (µg/L as Cd)	ch	TVS	0	0	--	--	--
Cadmium, total recoverables (µg/L asCd)	ac	TVS	0	0	--	--	--
Chromium, total recoverable (µg/L as Cr)	f, ac	50	0	0	--	--	--
Copper, dissolved (µg/L as Cu)	ac	TVS	0	0	--	--	--
Copper, dissolved (µg/L as Cu)	ch	TVS	0	0	--	--	--
Iron, dissolved (µg/L as Fe)	f, ch	300	0	1	--	--	--
Iron, total recoverable (µg/L as Fe)	f, ch	1,000	7	6	--	--	--
Lead, dissolved (µg/L as Pb)	ac	TVS	0	0	--	--	--
Lead, dissolved (µg/L as Pb)	ch	TVS	0	0	--	--	--
Manganese, dissolved (µg/L as Mn)	f, ch	50	0	0	--	--	--
Mercury, total recoverable (µg/L as Hg)	f, ch	0.01	2	2	--	--	--
Nickel, dissolved (µg/L as Ni)	ac	TVS	0	0	--	--	--
Nickel, dissolved (µg/L as Ni)	ch	TVS	0	0	--	--	--
Selenium, dissolved (µg/L as Se)	ac	TVS	0	0	--	--	--
Selenium, dissolved (µg/L as Se)	ch	TVS	0	0	--	--	--
Silver, dissolved (µg/L as Ag)	ac	TVS	0	0	--	--	--
Silver, total recoverable (µg/L as Ag)	ch	TVS	0	0	--	--	--
Zinc, dissolved (µg/L as Zn)	ac	TVS	0	0	--	--	--
Zinc, dissolved (µg/L as Zn)	ch	TVS	0	0	--	--	--

[1] See figure 1 and table 1 for station and site details.

[2] Colorado Department of Public Health and Environment, Water Quality Control Commission, 2002, Classifications and numeric standards for Upper Colorado River Basin and North Platte River (Planning Region 12) Regulation No. 33: Denver, Colorado Department of Health, Water Quality Control Commission Report, 3.8.0 (5 CCR 1002-33), variously paginated.

[3] Dissolved-oxygen concentrations in the epilimnion and metalimnion only.

profile measurements at site ER3b. Thus, by State standards, dissolved-oxygen concentrations in the reservoir are sufficient to sustain aquatic life. The sulfate fixed standard of 250 mg/L was exceeded in a single sample in Elkhead Creek upstream from the reservoir in March 1999 and was associated with low streamflow conditions.

The fixed standard for dissolved iron of 300 µg/L (Colorado Department of Public Health and Environment, Water Quality Control Commission, 2002) was exceeded once at station 09246400 (table 10). The total-recoverable iron fixed standard of 1,000 µg/L was exceeded seasonally during high flow at station 09246200 (seven times) and at station 09246400 (six times). The high total-recoverable iron concentrations were associated with samples containing high suspended-sediment concentrations. The 0.01-µg/L standard for total-recoverable mercury was exceeded twice at both stations. More mercury exceedances might have been estimated if the 0.01 µg/L MRL (table 2) that was initiated in 2001 had been available for samples analyzed during 1995–2000. The source of mercury in all the samples from Elkhead Creek is unknown.

Summary

Elkhead Creek is in northwestern Colorado and flows into the Yampa River about 4 mi east of Craig; Elkhead Reservoir is about 9 river miles upstream from the confluence. In anticipation of the possible enlargement of the 13,700-acre-ft Elkhead Reservoir, the U.S. Geological Survey, in cooperation with the Colorado River Water Conservation District, began a data-collection program in 1995 to obtain baseline streamflow and water-quality information for Elkhead Creek and water-quality and trophic-state information for Elkhead Reservoir. Interpretations of these data can be used to evaluate the existing effects of the reservoir on discharge and water quality in Elkhead Creek and will provide a benchmark for comparisons to data obtained following reservoir enlargement. This report presents the results of analyzing discharge and water-quality data for Elkhead Creek and water-quality data for Elkhead Reservoir collected from July 1995 through September 2001.

In the study area, Elkhead Creek is a meandering, alluvial stream dominated by snowmelt in mountainous headwaters that produces most of the annual discharge volume and discharge peaks during late spring and early summer. During most of water year 1996 (a typical year), daily mean discharge at station 09246400 (downstream from the reservoir) was similar to daily mean discharge at station 09246200 (upstream from the reservoir). Flow-duration curves for stations 09246200 and 09246400 were nearly identical for discharges larger than about 10 ft^3/s. There was some divergence in the flow-duration curves for discharges less than 10 ft^3/s, primarily because of the effects of upstream diversion on low-flow discharge at station 09246200, and the effects of reservoir regulation on low-flow discharge at station 09246400. Although larger daily mean discharges at station 09246400 were not affected substantially by Elkhead Reservoir, the instantaneous peak discharges at station 09246400 were attenuated in comparison to the instantaneous peak discharges at station 09246200.

Specific conductance generally had an inverse relation to discharge in Elkhead Creek. During late fall and winter when discharge was small and derived mostly from ground water, specific conductance was high, whereas during spring and early summer, when discharge was large and derived mostly from snowmelt, specific conductance was low. Continuous records of specific conductance and temperature indicated that there is a decrease in variability at the downstream station (09246400) in these variables that largely results from the moderating effect of mixing and storing the seasonally varied inflows in Elkhead Reservoir. The range of daily mean specific-conductance values recorded at station 09246200 was about 110 to 960 µS/cm, and the range of daily mean specific-conductance values recorded at station 09246400 was about 120 to 560 µS/cm.

Seasonal variation in temperature generally followed the pattern of seasonal variation in air temperature, reaching minimum values during winter and maximum values during summer. Daily mean water temperatures recorded at station 09246200 ranged from about 0.0 to 24.3°C, and at station 09246400 they ranged from about 0.0 to 25.8°C.

Graphical analysis of concentrations of major ions, nutrients, trace elements, organic carbon, and suspended sediment indicated no substantial within-year variability and no substantial differences in variability from one year to the next. Analysis on a monthly basis indicated a seasonal pattern for most of the constituents. The seasonal concentration pattern for most of the dissolved constituents followed the seasonal pattern of specific conductance, whereas some nutrients, some trace elements, and suspended sediment followed the seasonal pattern of discharge.

Analysis (rank-sum tests) for statistical differences between the field measurements and constituent concentrations at stations 09246200 (upstream from the reservoir) and 09246400 (downstream from the reservoir) indicated a difference only for specific conductance, calcium, magnesium, sodium, acid-neutralizing capacity, sulfate, and dissolved solids, but not for chloride and silica. Trend analysis indicated upward temporal trends for pH, total ammonia plus organic nitrogen, total nitrogen, and total phosphorus at station 09246200; upward temporal trends for dissolved and total ammonia plus organic nitrogen, total nitrogen, and total phosphorus were indicated at station 09246400. No downward trends were indicated.

Annual loads for dissolved constituents during water years 1996–2001 were consistently larger at station 09246400 than at station 09246200, except for silica and sulfate. The larger annual loads at station 09246400 could have resulted from a number of factors: (1) discharge was larger at the downstream station; (2) evaporation from Elkhead Reservoir that concentrates dissolved constituents; (3) unmeasured tributary discharge to Elkhead Creek downstream from the reservoir that had high concentrations of dissolved constituents; and (4) ground-water discharge to Elkhead Creek, including irrigation return flow, downstream from the reservoir that also had high concentrations of dissolved constituents. Mean monthly loads for dissolved constituents followed the seasonal pattern of discharge, indicating that most of the annual loads were transported during March–June.

Annual dissolved nutrient loads at stations 09246400 and 09246200 were not substantially different; however, loads for total phosphorus, and to a lesser extent, total nitrogen, were substantially less at the downstream station than at the upstream station. This indicates that particulate nitrogen tended to move through the reservoir, whereas particulate phosphorus mostly was retained within the reservoir, either because of biological uptake, settling within the reservoir, or both.

Annual loads for dissolved barium, copper, and iron were larger at the downstream station than at the upstream station, and annual loads for total-recoverable copper, iron, and manganese at both stations were substantially larger than the dissolved loads. Annual loads for total aluminum, copper, iron, and manganese at the downstream station were consistently and substantially less than the annual loads at the upstream station, indicating that large amounts of the total concentrations that were related to suspended sediment and other particulates settled out in Elkhead Reservoir.

Annual and mean monthly loads for suspended sediment at station 09246400 were substantially less that at station 09246200. Mean annual suspended-sediment load for water years 1996–2001 was about 191,000 tons at station 09246200, compared to about 24,000 tons at station 09246400, equal to about an 87-percent decrease in the downstream suspended-sediment load.

Temperature in Elkhead Reservoir varied seasonally, from about 0°C during winter when ice develops on the reservoir to about 20°C during summer. Specific conductance varied from minimums of 138 to 169 μS/cm during snowmelt inflow to maximums of 424 to 610 μS/cm during early spring low flow (April). Measured pH in the reservoir ranged from neutral to somewhat alkaline with median measurements of 7.2 to 8.0 at all sites near the surface. Median dissolved oxygen ranged from 7.1 to 7.2 mg/L in epilimnion (near-surface) samples, whereas in hypolimnion (near bottom) samples, median dissolved-oxygen concentrations were smaller (4.8 to 5.6 mg/L) because of seasonal stratification.

Reservoir profiles indicate Elkhead Reservoir was dimictic in 1996. During stratification, specific conductance was generally largest in the epilimnion, resulting from warm and relatively concentrated water from Elkhead Creek that was routed through the reservoir in the relatively warm epilimnion. The pH in the epilimnion generally increased from May to September, probably a result of algal productivity. In the hypolimnion, pH decreased slightly with depth in the July and September profiles, probably a result of biomass decay processes and a lack of circulation during stratification. Dissolved-oxygen concentrations were greater than 6 mg/L in the epilimnion during all sampling periods in water year 1996. The lowest dissolved-oxygen concentrations in the hypolimnion were measured in September, when near-bottom oxygen concentrations approached zero at the midlake and near-dam sites.

Concentrations of total ammonia plus organic nitrogen, dissolved ammonia, dissolved nitrite plus nitrate, and dissolved phosphorus in surface and near-bottom samples from Elkhead Reservoir were highest during snowmelt runoff (April–May). Total phosphorus concentrations in near-surface samples generally were largest during runoff, whereas total phosphorus concentrations in near-bottom samples generally were largest during July or September. Concentrations of nitrite plus nitrate in near-surface samples were substantially depleted by biological uptake during July, September, and October, compared to concentrations in near-bottom samples. Variations in near-surface concentration of chlorophyll-*a* were large during the growing season with peak seasonal concentrations during runoff and late summer and fall. Spatial variation in median concentrations indicated greater productivity at the inlet and midlake and a decline along the reservoir flowpath.

Trophic state of Elkhead Reservoir was classified using Carlson's trophic state index. Trophic state for Elkhead reservoir ranged from oligotrophic to eutrophic. For Elkhead Reservoir, 52 percent of the samples indicated phosphorus nutrient limitation, 9 percent of the samples indicated nitrogen limitation, 17 percent of samples had N:P ratios between 5 and 10 indicating N or P limitation, and for 22 percent of the samples limitation status could not be determined because of concentrations below the MRL.

Based on all samples collected during 1995 to 2001, the Colorado minimum standard for dissolved oxygen in streams (6 mg/L) was not met in two periodic samples for which dissolved-oxygen concentrations were slightly less than 6 mg/L. The total-recoverable iron fixed standard of 1,000 mg/L was exceeded seasonally during high flow at station 09246200 (seven times) and at station 09246400 (six times). The large iron concentrations were associated with samples containing large suspended-sediment concentrations.

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