

# **Hydrology and Water-Quality Characteristics of Muddy Creek and Wolford Mountain Reservoir near Kremmling, Colorado, 1990 through 2001**

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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 <sup>3</sup> /s)		0.02832	cubic meter per second
foot (ft)		0.3048	meter
yard (yd)		0.9144	meter
inch		2.54	centimeter
mile (mi)		1.609	kilometer
meter		39.37	inch
millimeter (mm)		0.03937	inch
square centimeter (cm <sup>2</sup> )		0.1550	square inch (in <sup>2</sup> )
square foot (ft <sup>2</sup> )		0.0929	square meter
square mile (mi <sup>2</sup> )		2.590	square kilometer (km <sup>2</sup> )

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

$$^{\circ}\text{F}=1.8^{\circ}\text{C}+32$$

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

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

MRL	Minimum Reporting Level
mg	milligrams
mg/L	milligrams per liter
mm	millimeters
NTU	nephelometric turbidity units
µg/L	micrograms per liter
µS/cm	microsiemens per centimeter at 25 degrees Celsius

# Hydrology and Water-Quality Characteristics of Muddy Creek and Wolford Mountain Reservoir near Kremmling, Colorado, 1990 through 2001

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## Abstract

A water-quality monitoring program was begun in March 1985 on Muddy Creek in anticipation of the construction of a reservoir water-storage project. Wolford Mountain Reservoir was constructed by the Colorado River Water Conservation District during 1992–94. The reservoir began to be filled in 1995.

Water quality generally was good in Muddy Creek and Wolford Mountain Reservoir throughout the period of record (collectively, 1990 through 2001), with low concentrations of nutrients (median total nitrogen less than 0.6 and median total phosphorus less than 0.05 milligrams per liter) and trace elements (median dissolved copper less than 2, median dissolved lead less than 1, and median dissolved zinc less than 20 micrograms per liter). Specific conductance ranged from 99 to 1,720 microsiemens per centimeter. Cation compositions at Muddy Creek sites were mixed calcium-magnesium-sodium. Anion compositions were primarily bicarbonate and sulfate. Suspended-sediment concentrations ranged from less than 50 milligrams per liter during low-flow periods to hundreds of milligrams per liter during snowmelt. Turbidity in prereservoir Muddy Creek generally was measured at less than 10 nephelometric turbidity units during low-flow periods and ranged to more than 360 nephelometric turbidity units during snowmelt. Compared to prereservoir conditions, turbidity in Muddy Creek downstream from the reservoir was substantially reduced because the reservoir acted as a sediment trap.

During most years, peak flows were slightly reduced by the reservoir or similar to peaks upstream from the reservoir. The upper first to fifteenth percentiles of flows were decreased by operation of the reservoir compared to prereservoir flows. Generally, the fifteenth to one-hundredth percentiles of flow were increased by operation of the reservoir outflow compared to prereservoir flows.

Nutrient transport in the inflow is proportional to the amount of inflow-water discharge in a given year. Some nitrogen was stored in the water column and gain/loss patterns for total nitrogen were somewhat related to reservoir storage. Nitrogen tended to move through the reservoir, whereas phosphorus was mostly trapped within the reservoir in bottom sedi-

ments. The reservoir gained phosphorus every year (1996–2001) and, as a percentage, more phosphorus was retained than nitrogen in years when both were retained in the reservoir due to stronger phosphorus tendencies for adsorption, coprecipitation, and settling. Only small amounts of phosphorus were available in the water column at the outflow, and reservoir water-column storage did not influence phosphorus outflow-loading patterns as much as settling further upstream in the reservoir.

From 1990 to 2001, upstream from the reservoir, concentrations and values of dissolved solids, turbidity, some major ions, and dissolved iron increased ( $p$ -value less than 0.10), and acid-neutralizing capacity decreased. From 1990 to 2001, there were no significant ( $p$ -value less than 0.10) trends in nutrient concentrations upstream from the reservoir. From 1990 to 2001, downstream from the reservoir, trends in concentrations and values of dissolved solids, turbidity, major ions, total ammonia plus organic nitrogen, dissolved and total-recoverable iron, and total-recoverable manganese were downward.

Upstream and downstream water-quality constituents for the prereservoir (1990 to 1995) period were compared. Concentrations and values of dissolved solids, major ions, turbidity, and manganese were greater ( $p$ -value less than 0.10) at the downstream site.

From 1995 to 2001 (postconstruction), upstream and downstream water-quality constituents also were compared. Concentrations of specific conductance and major ions increased at the downstream site when compared to the upstream site ( $p$ -value less than 0.10), except for acid-neutralizing capacity and silica, which decreased. Turbidity, concentrations of total-recoverable and dissolved manganese, and total-recoverable iron also were smaller downstream from the reservoir.

Results indicate that concentrations of dissolved solids increased downstream in Muddy Creek before the reservoir was constructed. This trend continued after construction, but the difference between upstream and downstream median concentrations of dissolved solids and major ion concentrations was less than in the prereservoir period.

Spring runoff temperatures and fall temperatures in Muddy Creek were lower than in the reservoir. Thus, inflows to

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the reservoir tended to settle near the thermocline. In summer, inflow-water temperature was similar to the surface layer, and flows were routed through the reservoir near the surface.

In winter, Muddy Creek stream temperatures were near 0°C, and surface water at the ice cover interface was 0°C, but the temperature in the reservoir subsurface probably increased with depth to 4°C in the bottom waters (water is most dense at about 4°C). Although no winter stratification measurements were made under the ice, the reservoir was assumed to be similar to other dimictic, montane reservoirs. Thus, inflow will tend to be routed just under the ice. Flow patterns within the reservoir could be important because residence time varies from season to season, and in the event of a chemical spill upstream, knowledge of timing and probable vertical location of the plume would be important for outflow gate configurations to manage the spill.

Near-bottom samples of ammonia and nitrite plus nitrate generally had larger concentrations than concurrent surface samples. Surface-sample concentrations of nitrite plus nitrate were substantially depleted throughout the growing season. Temporally, surface and bottom concentrations tended to decrease and stabilize for ammonia plus organic nitrogen and ammonia throughout the period of record. Nitrite plus nitrate seemed to increase in bottom samples with time. Spatial variation in nutrient concentrations from inflow to dam tended to decrease for total ammonia plus organic nitrogen and total phosphorus in surface samples, whereas bottom-sample concentrations of nitrite plus nitrate tended to increase from inflow to dam.

Spatially, total recoverable and dissolved iron and manganese and total recoverable aluminum show decreasing median concentrations from inflow to dam in surface samples. Bottom-sample median concentrations of total recoverable iron and aluminum decreased from inflow to dam. The spatial increases in manganese along the reservoir axis probably are related to redox reactions in the hypolimnion, which release manganese during periods of hypoxia.

Bacteria counts were low to not detected in the reservoir samples. Bacteria in Muddy Creek may be associated with suspended material that rapidly settles out in the reservoir.

Trophic conditions generally were upper oligotrophic to mesotrophic from 1995 to 2001 in Wolford Mountain Reservoir based on available Secchi depth, total phosphorus concentrations, and chlorophyll-*a* concentrations. Dissolved-oxygen concentrations generally were in the range of 3 to 7 milligrams per liter except in late summer when oxygen concentrations approached 1 milligram per liter or less in the hypolimnion.

Constituent concentrations generally were acceptable and met Colorado water-quality standards. Selenium concentrations exceeded chronic aquatic standards twice in Muddy Creek at the Kremmling site (prereservoir, 1982–95). Six selenium concentrations in near-bottom samples collected from the reservoir near the dam during 1995–97 exceeded chronic aquatic standards. Aquatic standards for iron and manganese were occasionally exceeded in Muddy Creek and in near-bottom samples from Wolford Mountain Reservoir.

## Introduction

Wolford Mountain Reservoir was constructed during 1992–94, and filling of the reservoir began in 1995. When water storage is created on a stream, changes can occur in downstream discharge patterns and water quality, and a new hydrologic environment is created in the resulting reservoir. Water-quality concerns such as changes to streamflow patterns, salinity, nutrient enrichment, oxygen depletion, and documentation of these changes prompted the Colorado River Water Conservation District (CRWCD) to initiate monitoring efforts both before construction of Wolford Mountain Reservoir and after construction. The U.S. Geological Survey (USGS), in cooperation with the CRWCD, began a monitoring program on Muddy Creek in March 1985 in anticipation of the construction of the Wolford Mountain Reservoir water-storage project (fig. 1).

## Purpose and Scope

The purpose of this report is to describe water quality of the inflow, reservoir, and outflow and to assess the effects of Wolford Mountain Reservoir on streamflow and downstream water quality from 1990 to 2001. Specific objectives include the following:

1. To characterize and compare the upstream/downstream and prereservoir (before construction of the reservoir) and postconstruction (after construction of the reservoir) streamflow, water-quality characteristics, and temporal and spatial trends of water-quality properties and constituents in Muddy Creek;
2. To describe limnology and water-quality characteristics of Wolford Mountain Reservoir (1995–2001); and
3. To compare water-quality data to Colorado water-quality standards and guidelines.

## Previous Studies

Two studies of the potential effects of the proposed Wolford Mountain Reservoir were done before construction of the reservoir. Ruddy (1987) analyzed sediment discharge in Muddy Creek and predicted the effect of sedimentation rate on the proposed Wolford Mountain Reservoir near Kremmling, Colo. Ruddy determined that at the rate of mean annual total-sediment discharge for water years 1983 to 1985 (years data were collected), water-storage capacity of the proposed Wolford Mountain Reservoir would decrease 10 percent after 100 years. Butler (1990) estimated water-quality conditions and potential downstream channel effects of Wolford Mountain Reservoir. Butler used a one-dimensional temperature model with a conservative constituent routine (for specific conductance) that predicted changes in thermal structure with outlet elevation and predicted that the reservoir would have a dampening effect on water temperature and specific conductance. Empirical models were used

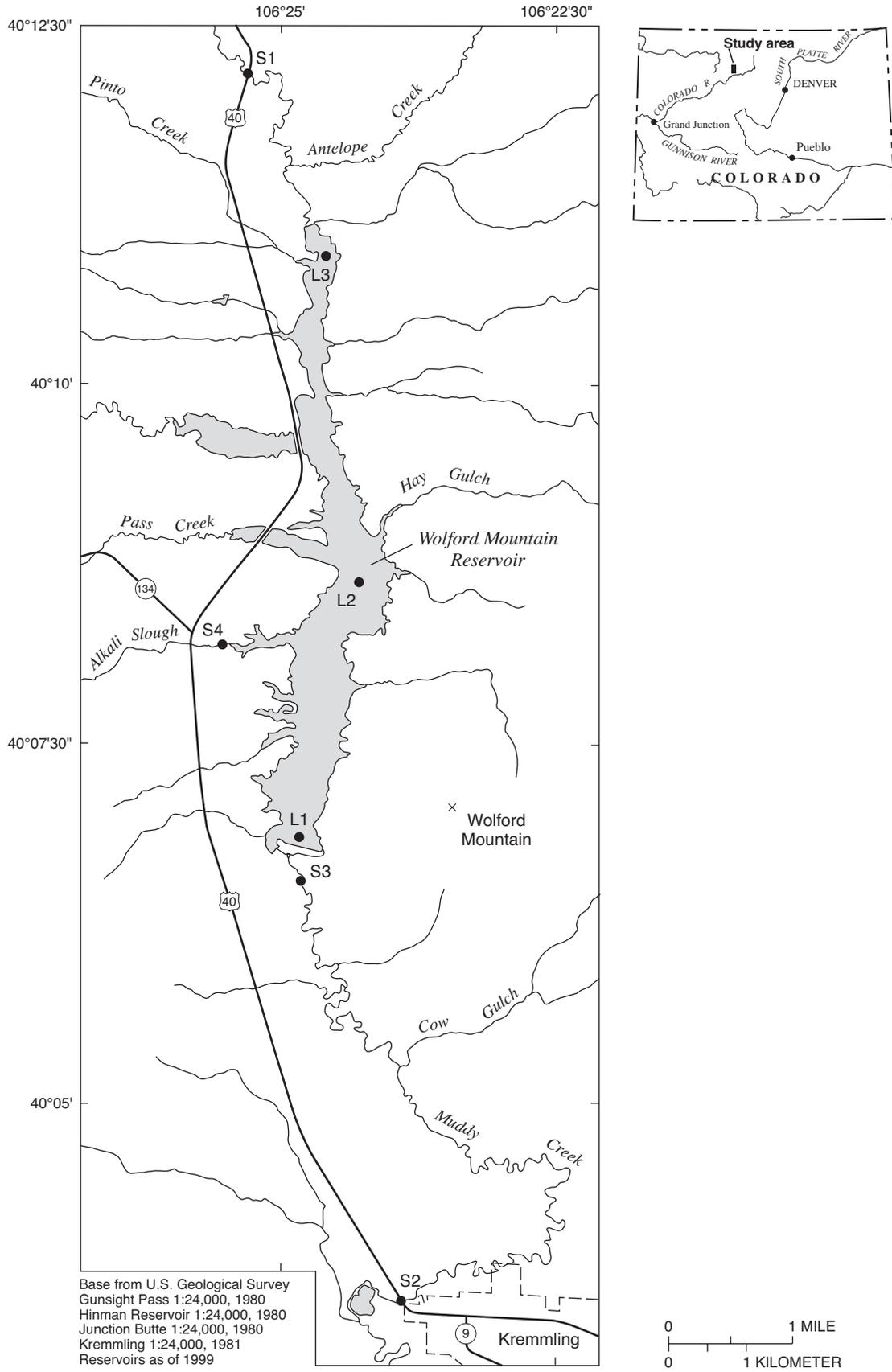


Figure 1. Location of study area and sampling sites.

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to estimate total phosphorus, total nitrogen, and chlorophyll-*a*. Sedimentation rates and channel degradation downstream from the dam were estimated using sediment discharge, particle-size, and streamflow data.

### Description and Background Information of Study Area

Muddy Creek and Wolford Mountain Reservoir are located in the mountains of north-central Colorado near Kremmling (fig. 1). The reservoir collects water from Muddy Creek, a watershed that encompasses about 270 mi<sup>2</sup>. Muddy Creek originates in the mountainous, forested terrain to the west and the northeast that sustain forestry activities and recreational land uses. These areas receive most of their annual precipitation (25 to 50 inches per year) as snowfall (Colorado Climate Center, 1984). Geology of the headwater area consists mostly of crystalline rocks in the Gore Range and volcanic rocks in the Rabbit Ears Range. The lower-elevation areas in the watershed are more arid (12 to 25 inches per year of precipitation) (Colorado Climate Center, 1984), sparsely vegetated rangeland underlain by marine shale (Tweto, 1979). Agricultural practices, such as irrigated hay and grass production and rangeland for livestock, occur in the lower elevation terrain. Domestic and livestock waste are factors with potential for affecting water quality in the Muddy Creek watershed.

Wolford Mountain Reservoir was constructed by the CRWCD and benefits people living on the eastern and western slopes of Colorado. The western slope receives water for development, compensatory storage for the Windy Gap Diversion (a pump-back facility operated by the Northern Colorado Water Conservancy District on the upper Colorado River), and greater instream flows on the Colorado River system for current users, for recreation, and for protection of endangered fish. The Denver Water Board releases water from Wolford Mountain Reservoir to satisfy senior downstream users during drought, thereby avoiding the release of water from further upstream during dry years (Colorado River Water Conservation District, 2000).

Wolford Mountain Reservoir was constructed during 1992–94. Filling of the reservoir began in 1995. The Ritschard Dam that retains Wolford Mountain Reservoir is about 7 miles upstream from the mouth of the Colorado River and 5 miles upstream from Kremmling. The dam is a zoned earth-filled type and is 120 ft high. The reservoir can store 68,000 acre-ft of water with an annual reliable yield of 28,000 acre-ft, and the reservoir covers approximately 1,550 surface acres at full storage (Colorado River Water Conservation District, 2000). There is no dead storage. The reservoir is about 4.5 miles in length and about one-quarter to one-half mile in width at full storage. The reservoir is long and narrow with an irregular shoreline and several shallow embayments on the western shore where larger tributaries enter the reservoir. Depths range from less than 10 ft in the inflow area to more than 100 ft near the dam, depending on water level. The major inflow to the reservoir is Muddy Creek. Pinto Creek, Pass Creek, Red Dirt Creek, and Alkali Slough are all intermittent tributaries to the reservoir.

Reservoir operations affect seasonal streamflow downstream from the storage reservoir. Release and storage patterns were similar over the period of record on a year-to-year basis (fig. 2). Generally, reservoir storage reaches maximum elevation in April through June of each year and decreases steadily through summer and winter until April of the following year when storage of new snowmelt begins. Elevation capacity (a plot that relates water-surface elevation to water volume in the reservoir) for Wolford Mountain Reservoir is shown in figure 3. Release operations for the reservoir generally are similar from year to year (1995–2001). Four gates are available for releasing water from the reservoir: the main (bottom), 7,420 ft, 7,440 ft, and 7,460 ft gates. Fall and winter releases (September to April) are usually made from the upper two gates. In late spring and summer (May to August), releases are made from the main and uppermost gates (Jack Osburn, Colorado River Water Conservation District, written commun., 2002).

### Acknowledgments

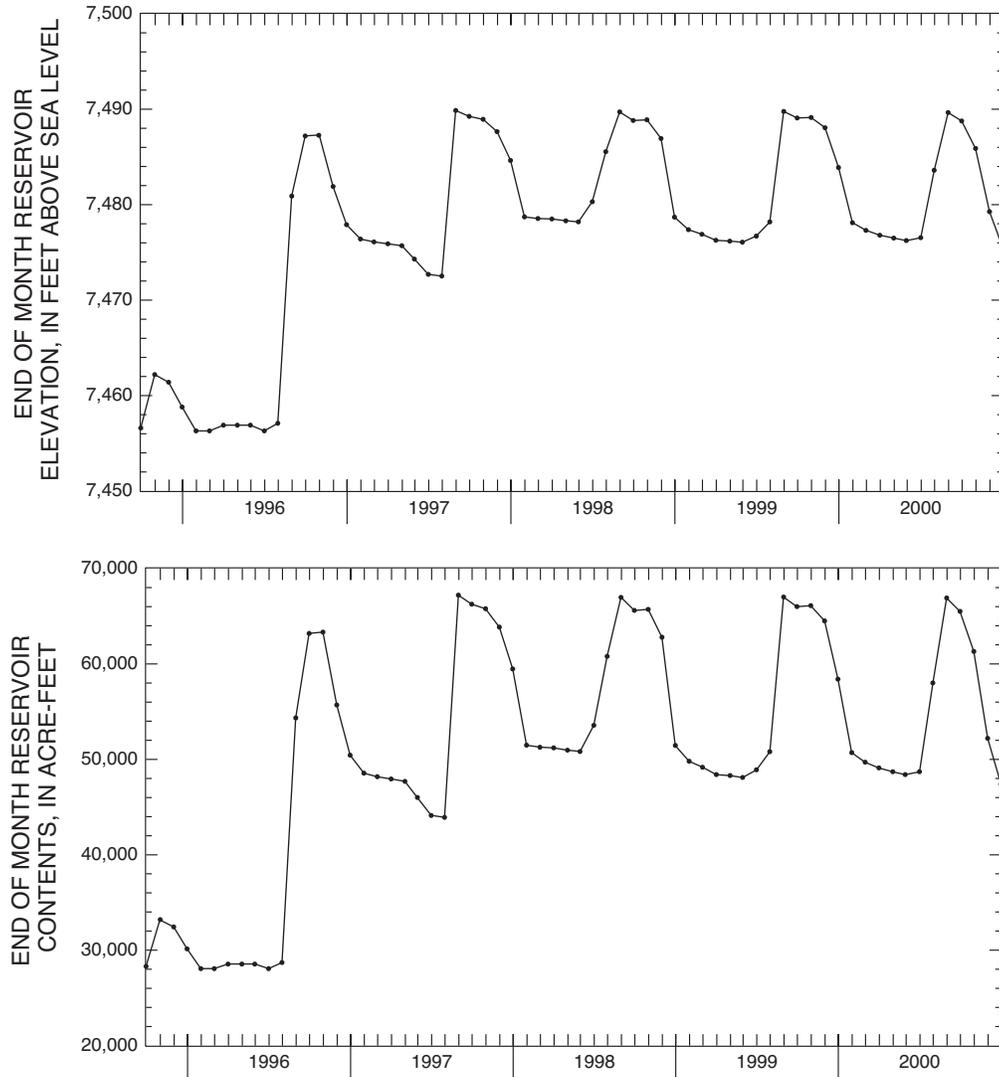
The authors thank Jack Osburn at the Colorado River Water Conservation District for providing reservoir operations data. Thanks also to the Lakewood Field Office of the U.S. Geological Survey Colorado District for data collection activities over many years and the Colorado District Publishing Section—Mary Kidd for editorial review, Sharon Powers for illustrations, and Alene Brogan for manuscript preparation.

### Methods of Investigation

Two types of methods are described in this section. The first, field methods, describes how data and samples were collected in streams and the reservoir, the processing of the samples, and the laboratory methods used. The second, data analysis methods, describes the statistical and analytical treatment of the data.

### Field Methods

Continuous-streamflow data were collected at three sites: Muddy Creek above Antelope Creek near Kremmling (S1) from April 1990 through September 2001, Muddy Creek at Kremmling (S2) from March 1985 through September 1995, and Muddy Creek below Wolford Mountain Reservoir near Kremmling (S3) from July 1995 through September 2001 (Table 1). Continuous water-quality monitors were operated at Muddy Creek above Antelope Creek (S1) from April 1990 through September 2001, Muddy Creek at Kremmling (S2) from April 1986 through September 1995, and Muddy Creek below Wolford Mountain Reservoir (S3) from October 1995 through September 2001. Continuous water temperature and specific conductance data were collected at the three sites (S1, S2, and S3), but dissolved oxygen was collected only at S3 below the reservoir.

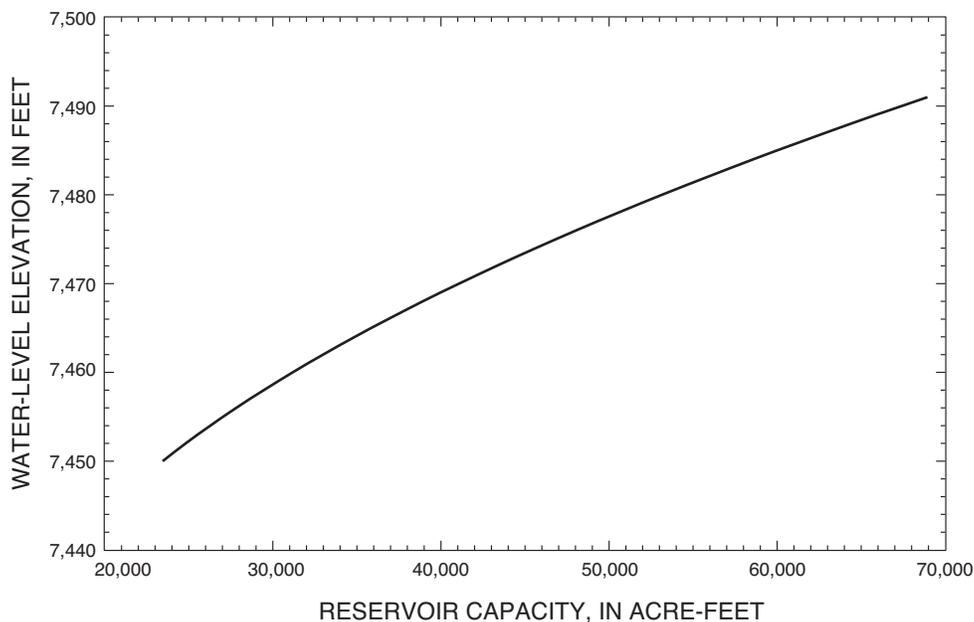


**Figure 2.** Water-surface elevation and contents of Wolford Mountain Reservoir, water years April 1995 through September 2000.

**Table 1.** Water-quality sampling sites.

Station number	Site code	Station name	Location description
09041090	S1	Muddy Creek above Antelope Creek near Kremmling	Approximately 1 mile upstream from reservoir 10.9 miles upstream from Kremmling.
400812106254800	S4	Alkali Slough #2 at Wolford Mountain Reservoir near Kremmling	Approximately 300 feet upstream from mouth at reservoir.
09041400	S3	Muddy Creek below Wolford Mountain Reservoir near Kremmling	About 200 yards downstream from reservoir, about 4 miles upstream from Kremmling.
09041500	S2	Muddy Creek at Kremmling	On northern edge of Kremmling about 3 miles upstream from confluence with Colorado River.
09041395	L1	Wolford Mountain Reservoir near Kremmling	Near the deepest part of the reservoir near the dam.
400841106240600	L2	Wolford Mountain Reservoir at midlake near Kremmling	At approximately midlake.
401110106244800	L3	Wolford Mountain Reservoir at inflow near Kremmling	Near the inflow of Muddy Creek to Wolford Mountain Reservoir.

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**Figure 3.** Wolford Mountain Reservoir elevation-capacity relation.

Continuous data from the monitoring stations (S1, S2, and S3) were supported by monthly site visits during the open-water season (generally from April to October) and bimonthly visits when ice cover was present. Measurements of streamflow were made using a current meter by procedures given in Buchanan and Somers (1969). The calibration of water temperature, specific conductance, and dissolved oxygen for the water-quality monitors were checked using an ASTM thermometer, field meters, and standard solutions, and adjusted, if needed, according to procedures given in Wagner and others (2000). Data from these visits were used to analyze and compute the continuous data from the monitoring stations according to procedures given in Rantz and others (1982), Kennedy (1983), and Wagner and others (2000).

Water-quality samples were collected at four stream sites near the Wolford Mountain Reservoir area. Three sites were located on Muddy Creek, the primary inflow to and outflow from the reservoir: Muddy Creek above Antelope Creek (S1) from April 1990 through September 2001, Muddy Creek below Wolford Mountain Reservoir (S3) from July 1995 through September 2001, and Muddy Creek at Kremmling (S2) from March 1985 through September 1995. Data and samples were collected approximately monthly in the streams and included field properties, major ions, nutrients, chlorophyll-*a*, fecal coliform, transparency, organic carbon, and suspended sediment. Trace-element samples were collected approximately twice per year during runoff and summer low flow. An intermittent stream, Alkali Slough #2 (site S4), was sampled from July 1996 through September 2001 twice per year in July and October.

In streams, field properties of specific conductance, water temperature, dissolved oxygen, and barometric pressure were made at streamside (U.S. Geological Survey, 1998). Turbidity and pH were measured from samples composited in a USGS

churn splitter. Samples for inorganic analysis (major ions, nutrients, and trace elements) were collected by equal-width-increment (EWI) methods using a DH-81 polyethylene sampler and bottle, and composited in a USGS churn splitter, from which separate aliquots were withdrawn for each required analytical bottle (U.S. Geological Survey, 1998).

Turbidity and pH were measured from samples composited in a USGS churn splitter. Samples for inorganic analysis (major ions, nutrients, and trace elements) were collected by EWI methods using a DH-81 polyethylene sampler and bottle, and composited in a USGS churn splitter, from which separate aliquots were withdrawn for each required analytical bottle (U.S. Geological Survey, 1998). The sample collection and processing equipment were cleaned to trace-element standards according to procedures in USGS (1998). Samples for dissolved constituents were filtered through a disposable 0.45- $\mu\text{m}$  capsule filter in an enclosed filter chamber using a peristaltic pump. Samples for trace-element analysis were preserved with trace-element grade nitric acid. Nutrient samples were chilled to approximately 4°C (U.S. Geological Survey, 1998).

Samples for organic analysis were collected in a baked glass bottle by dip methods at the centroid of flow. The total organic carbon samples were not filtered. Dissolved organic carbon samples were filtered through a 0.45- $\mu\text{m}$  filter. Carbon samples were chilled to less than 4°C until analyzed (U.S. Geological Survey, 1998).

Suspended-sediment samples were collected by EWI or equal-discharge-increment methods with a DH-48 hand sampler or DH-59 cable sampler (Guy and Norman, 1970) at sites S1 and S2, for analyses of concentration and particle-size percentage finer than 0.062 mm.

Water-quality samples were collected at three sites on Wolford Mountain Reservoir (fig. 1), at the dam (L1) from July

1995 through September 2001, at midlake (L2) from July 1995 through September 2001, and at the Muddy Creek inflow (L3) from July 1995 through September 2001. Data and samples collected in the reservoir included field properties (water temperature, specific conductance, pH, and dissolved oxygen), major ions, nutrients, chlorophyll-*a*, fecal coliform, transparency, organic carbon, and trace elements. Samples were collected from just below the surface and near the bottom of the reservoir at L1 and L2, but only at mid-depth at L3. Depth profiles of water temperature, specific conductance, pH, and dissolved oxygen were measured every 5 ft up to 30 ft of depth and every 10 ft for depths greater than 30 ft at every water-quality sampling visit. Samples and profile data were collected in June, July, August, and October each year.

Water-column samples and field-property profiles were collected in Wolford Mountain Reservoir (sites L1, L2, and L3). Water depth was determined by using a depth-finder in a boat. A multiparameter water-quality instrument was used to measure water temperature, specific conductance, pH, and dissolved oxygen. The transparency of the water was determined with a Secchi disk and measured in inches with a cloth tape or folding rule.

Samples for major ion, nutrient, and trace-element analyses were collected at the surface and just above the bottom 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). Field properties were determined from measurements taken in the lake or reservoir. Sample water for inorganic analyses was transferred to clean, acid-rinsed, deionized-water rinsed, and native-water rinsed polyethylene containers. Sample water 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 streamwater-quality section of this report (U.S. Geological Survey, 1998). Chlorophyll-*a* samples were collected and processed according to methods described in Britton and Greeson (1987).

Laboratory analysis of all samples collected for major ion, nutrient, and trace-element analysis were analyzed at the USGS National Water Quality Laboratory 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 same laboratory using standard analytical techniques described in Wershaw and others (1987) and Fishman (1993). Suspended-sediment and bed-material samples were analyzed according to methods described in Guy (1969) at the USGS Iowa Sediment Laboratory in Iowa City, Iowa. Laboratory methods and minimum reporting limits for samples collected during the study are listed in table 2. All data are published in the USGS annual data report for Colorado and are stored in the USGS National Water Quality Information System (NWIS).

## Data-Analysis Methods

For purposes of comparison, data sets were considered from 1990 to 2001 even though data were collected at S2 since March 1985. Data were collected at S1 from 1990 to 2001. Because data collection at the S2 site ended in 1995 and began at the S3 site in 1995, the two sites were combined for the purposes of time-series trend analysis to provide a complete 1990 to 2001 record. Reservoir sampling for the entire period of record (1995 to 2001) at sites L1, L2, and L3 were used in data analysis.

Hydrologic data were analyzed by using time-series plots, plots of daily mean statistics, and flow-duration curves. The purpose was to characterize seasonal and long-term flow patterns and compare flows upstream and downstream from Wolford Mountain Reservoir.

Streamwater-quality data for field properties, nutrients, major ions, trace elements, suspended sediment, and biological indicators were analyzed by discussions of general characteristics, upstream to downstream preresevoir/postconstruction comparisons, seasonality, and temporal trends through the use of time-series plots, statistics, boxplots, seasonal Kendall test results, and spatial differences by Wilcoxon signed rank test results.

To estimate the nutrient mass entering and leaving the reservoir in surface-water inflows and outflows each year, and to determine how the reservoir may have influenced downstream nutrient concentrations, total nitrogen and total phosphorus mass balances were calculated for each year from 1996 through 2001. Data were collected in 1996 only from April through December, and January through October in 2001. The general mass-balance equation used is:

$$\pm\text{UMS} = \text{IMS} - \text{OMS} \quad (1)$$

where

IMS is the mass in the surface-water inflow, in kilograms;

OMS is the mass in the surface-water outflow, in kilograms; and

UMS is the portion of the total mass that is unaccounted for (gained or lost), in kilograms.

Inflows as reported here are those measured in Muddy Creek above the reservoir, and outflows are those measured in Muddy Creek below the reservoir. Sources that are unaccounted for include inflow from intermittent and ephemeral streams, release from reservoir bottom sediment, runoff from surrounding land area, atmospheric deposition to the reservoir surface, changes in reservoir storage, and ground-water inflow, which could contribute to a positive unaccounted-for term. Sinks that are unaccounted for might include ground-water outflow, sedimentation, changes in reservoir storage, and biological uptake, which could contribute to a negative unaccounted-for term.

Inflow mass and outflow mass were calculated as the product of the concentration in a sample collected in a given month

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**Table 2.** Laboratory methods and minimum reporting limits for samples collected during the study.

[ICP, inductively coupled plasma; ICPMS, inductively coupled plasma mass spectrometry; IC, ion chromatography; AA, atomic absorption; GFAA, graphite furnace atomic absorption; HPLC, high-performance liquid chromatography; MF, membrane filtration; CVA, cold vapor atomic fluorescence; EWI, equal-width increment; mg/L, milligrams per liter; µg/L, micrograms per liter; °C, degrees Celsius; ft<sup>3</sup>/s, cubic feet per second; µS/cm, microsiemens per centimeter at 25°C; NTU, nephelometric turbidity units; T/d, tons per day]

Property or constituent	Units	Field method	Analytical method	Minimum reporting limit
Field properties				
Discharge	ft <sup>3</sup> /s	current meter	mid-interval	variable
Specific conductance	µS/cm	point	electrode	1
pH	units	EWI	electrode	0.1
Turbidity	NTU	EWI	nephelometry	.1
Dissolved oxygen	mg/L	point	electrode	.1
Secchi depth	inches	disk	observation	1
Major ions				
Hardness as CaCO <sub>3</sub>	mg/L	EWI	calculated	1
Calcium, dissolved	mg/L	EWI	ICP	.1
Magnesium, dissolved	mg/L	EWI	ICP	.1
Sodium, dissolved	mg/L	EWI	ICP	.1
Potassium, dissolved	mg/L	EWI	ICP	.1
Acid-neutralizing capacity, lab as CaCO <sub>3</sub>	mg/L	EWI	titration	1
Sulfate, dissolved	mg/L	EWI	IC	.1
Chloride, dissolved	mg/L	EWI	IC	.1
Fluoride, dissolved	mg/L	EWI	ion selective electrode	.1
Silica, dissolved	mg/L	EWI	ICP	.1
Dissolved solids, residue at 180°C	mg/L	EWI	residue on evaporation at 180°C	1
Dissolved solids, sum of constituents	mg/L	EWI	calculated	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
Phosphorus, total as P	mg/L	EWI	colorimetry	.001, .05
Phosphorus, dissolved as P	mg/L	EWI	colorimetry	.001
Phosphorus, dissolved orthophosphate as P	mg/L	EWI	colorimetry	.001
Biological				
Chlorophyll- <i>a</i> and - <i>b</i>	µg/L	point	HPLC	.1
Fecal coliform	col/100ml	EWI, point	MF	1
Trace Elements				
Aluminum, dissolved as Al	µg/L	EWI	ICPMS	1
Antimony, dissolved as Sb	µg/L	EWI	ICPMS	1
Arsenic, dissolved as As	µg/L	EWI	ICPMS, GFAA	1, 4
Barium, dissolved as Ba	µg/L	EWI	ICPMS	1
Beryllium, dissolved as Be	µg/L	EWI	ICPMS	1
Cadmium, total as Cd	µg/L	EWI	GFAA	1
Cadmium, dissolved as Cd	µg/L	EWI	ICPMS, GFAA	1

**Table 2.** Laboratory methods and minimum reporting limits for samples collected during the study.—Continued

[ICP, inductively coupled plasma; ICPMS, inductively coupled plasma mass spectrometry; IC, ion chromatography; AA, atomic absorption; GFAA, graphite furnace atomic absorption; HPLC, high-performance liquid chromatography; MF, membrane filtration; CVAf, cold vapor atomic fluorescence; EWl, equal-width increment; mg/L, milligrams per liter; µg/L, micrograms per liter; °C, degrees Celsius; ft<sup>3</sup>/s, cubic feet per second; µS/cm, microsiemens per centimeter at 25°C; NTU, nephelometric turbidity units; T/d, tons per day]

Property or constituent	Units	Field method	Analytical method	Minimum reporting limit
Chromium, dissolved as Cr	µg/L	EWI	ICPMS	1
Cobalt, dissolved as Co	µg/L	EWI	ICPMS	1
Copper, total as Cu	µg/L	EWI	ICP, GFAA	10, 1
Copper, dissolved as Cu	µg/L	EWI	ICP, ICPMS, GFAA	10, 1, 1
Iron, total as Fe	µg/L	EWI	AA, ICP	10
Iron, dissolved as Fe	µg/L	EWI	ICP, AA	3, 10
Lead, total as Pb	µg/L	EWI	GFAA	1
Lead, dissolved as Pb	µg/L	EWI	ICP, ICPMS, GFAA	10, 1, 1
Manganese, total as Mn	µg/L	EWI	AA, ICP	10
Manganese, dissolved as Mn	µg/L	EWI	ICP, ICPMS	10, 4, 1
Mercury, dissolved as Hg	µg/L	EWI	CVAf	0.1
Molybdenum, dissolved as Mo	µg/L	EWI	ICPMS	1
Nickel, dissolved as Ni	µg/L	EWI	ICPMS	1
Selenium, dissolved as Se	µg/L	EWI	ICPMS	1
Silver, dissolved as Ag	µg/L	EWI	ICPMS	1
Zinc, total as Zn	µg/L	EWI	ICP, AA	10, 31, 40
Zinc, dissolved as Zn	µg/L	EWI	ICP, ICPMS	20, 3
Uranium, dissolved as U	µg/L	EWI	ICPMS	1
<b>Sediment</b>				
Sediment, suspended, concentration	mg/L	EWI	gravimetric	1
Sediment, bedload, discharge	T/d	EWI	gravimetric	variable
Sediment, bedload, size fractions	percent	EWI	dry sieve	1

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and the volume of water entering or leaving the reservoir during that month. Monthly masses were summed to compute annual mass. The assumption that one concentration can represent the entire month may not always be valid, as inflow and outflow volumes, degrees of stratification, and biological activity changed between sampling dates. These uncertainties led to an unquantified amount of error in the mass balance for the reservoir. Therefore, the mass balances presented in this report should be used with caution.

Reservoir water-quality data for field properties, nutrients, major ions, trace elements, and biological indicators were analyzed through the evaluation of general characteristics, spatial variability, surface and bottom variability, and seasonality through the use of time-series plots, statistics, and boxplots. Stratification patterns were evaluated by analysis of field-property profiles to understand vertical variability in water temperature, specific conductance, pH, and dissolved oxygen. Nutrient budgets were used to evaluate loading and storage characteristics in the reservoir.

On the basis of data collected 1995–2001, Wolford Mountain Reservoir was classified using the method developed by Carlson (1977).

Trophic-state index (TSI) values were calculated from the following equations:

$$\text{TSI}(\text{SD}) = 60 - 14.41(\ln \text{SD}) \quad (2)$$

$$\text{TSI}(\text{TP}) = 14.42(\ln \text{TP}) + 4.15 \quad (3)$$

$$\text{TSE}(\text{CHLA}) = 9.81(\ln \text{CHLA}) + 30.6 \quad (4)$$

where

SD is Secchi-disc depth, in meters;

TP is total phosphorus concentration, in micrograms per liter;

CHLA is chlorophyll-*a* concentration, in micrograms per liter; and

ln is the natural logarithm of the indicated variable.

The indices are meant to normalize the three indicators so that any of the three could be used independently to describe the conditions in the water body. Secchi-disc depths and concentrations of total phosphorus and chlorophyll-*a* (surface only) were averaged for each year to compute mean values. The annual mean values then were used to compute annual TSI's.

Stream and reservoir water-quality data were evaluated by water-quality standards. In Colorado, water-quality standards specifies that hardness concentrations used to calculate the chronic trace-element standards be computed from 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 then is compared to the standard. For this report, however, each hardness concentration and standard value was determined from analysis of water samples collected at the time of sampling and compared to the sample concentration. The standards com-

parison in this report, therefore, should be regarded as a general indicator rather than a rigorous statistical comparison of State standards. Laboratory minimum reporting limits (MRL's) for trace elements such as ammonia, 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 laboratory 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).

### Data-Set Construction

In order to obtain a continuous record of water-quality data downstream from the reservoir, data from two sites (S2 and S3) were combined. In July, August, and September 1995, monthly samples were obtained from each of the two sites, although they were not concurrent (table 3). Although three samples were not enough to compare the data statistically, a qualitative analysis indicated that water quality at the two sites was similar for major ions but somewhat dissimilar for nutrients and metals. These differences may have been a greater consequence of the timing of sample collection than of the site locations because the greatest differences between sites were in July (samples taken on July 11 at 09041500 S2 and July 13 at 09041400 S3), whereas the smallest differences were in September (samples taken on September 19 at both sites). This comparison indicates that some caution should be used when interpreting results based on the combined data.

Water-quality samples were collected at the most upstream site, Muddy Creek above Antelope Creek near Kremmling (USGS station number 09041090 S1), from April 1990 through September 2001. To directly compare the results of trend analyses at the upstream and downstream sites, the combined downstream data set was limited to match the time interval of the upstream data set.

Before January 1993, the type of a small number of analyses done by the USGS National Water Quality Laboratory was changed: total ammonia was replaced with dissolved ammonia; total nitrate plus nitrite was replaced with dissolved nitrate plus nitrite; total nitrite was replaced with dissolved nitrite; and total orthophosphate was replaced with dissolved orthophosphate. Between 1990 and 2001, several samples were analyzed concurrently for total and dissolved constituents (table 4). A Wilcoxon signed-rank test indicated that there were no statistically significant differences between the total and dissolved concentrations at an  $\alpha$ -level of 0.01. Consequently, the total and dissolved constituent concentrations were combined in the final data sets both for the upstream and the downstream sites.

Trends in water quality were obtained using the seasonal Kendall trend (SKT) test with correction for serial correlation (Hirsch and Slack, 1984). The SKT is a nonparametric test for monotonic linear trend; it is resistant to outliers and is not dependent on the normality of the data set. In the test, data

**Table 3.** Comparison of samples taken concurrently at the two downstream sites —Muddy Creek at Kremmling (S2) and Muddy Creek below Wolford Mountain Reservoir near Kremmling (S3)—between August and September 1995.

[<, less than; --, sample not analyzed; mg/L, milligrams per liter; µg/L, micrograms per liter; µS/cm, microsiemens per centimeter; °C, degrees Celsius; NTU, nephelometric turbidity units]

Constituent	Concentration					
	S2			S3		
	07-11-95	08-15-95	09-19-95	07-13-95	08-16-95	09-19-95
Dissolved oxygen (mg/L)	7.8	7.7	8.3	9	7.5	7.8
pH, field (standard units)	8.3	8.3	8.3	7.9	8.1	8.2
Specific conductance (µS/cm @ 25°C)	462	575	562	446	564	530
Water temperature (°C)	15.5	15.0	15.0	12.5	12.0	16.0
Hardness, total (mg/L as CaCO <sub>3</sub> )	190	260	250	370	250	240
Calcium, dissolved (mg/L as Ca)	54	70	66	98	68	63
Magnesium, dissolved (mg/L as Mg)	14	20	20	30	19	19
Potassium, dissolved (mg/L as K)	1.8	1.9	2.2	2.6	1.9	2.1
Sodium, dissolved (mg/L as Na)	13	18	19	23	17	17
Acid-neutralizing capacity, alkalinity, lab, as CaCO <sub>3</sub>	93	111	122	130	105	115
Chloride, dissolved (mg/L as Cl)	2.1	2.2	2	2.4	2	1.7
Fluoride, dissolved (mg/L as F)	0.1	0.2	0.1	0.2	0.1	0.1
Silica, dissolved (mg/L as SiO <sub>2</sub> )	8.6	8.4	7.7	9.4	9.8	7.7
Sulfate, dissolved (mg/L as SO <sub>4</sub> )	130	180	160	290	170	150
Nitrogen, ammonia plus organic, dissolved (mg/L as N)	.3	.4	.3	.7	.5	.3
Nitrogen, ammonia plus organic, total (mg/L as N)	.4	.5	.5	.7	.5	.5
Nitrogen, ammonia, dissolved (mg/L as N)	.02	.15	.02	.28	.24	.02
Nitrogen, nitrite plus nitrate, dissolved (mg/L as N)	<.050	<.050	<.050	.06	<.050	<.050
Nitrogen, nitrite, dissolved (mg/L as N)	<.010	<.010	<.010	<.010	<.010	<.010
Phosphorus, dissolved (mg/L as P)	<.010	0.02	<.010	0.06	<.010	<.010
Phosphorus, dissolved orthophosphate (mg/L as P)	<.010	0.01	<.010	0.05	0.04	<.010
Phosphorus, total (mg/L as P)	<.010	0.02	0.04	0.11	0.04	0.05
Carbon, organic, dissolved (mg/L as C)	6.9	--	7.1	7.2	--	7.1
Carbon, organic, total (mg/L as C)	7.7	--	9	8.1	--	8.6
Dissolved solids, residue at 180°Celsius (mg/L)	314	390	375	288	376	355
Dissolved solids, sum of constituents (mg/L)	279	368	351	533	351	330
Turbidity (NTU)	6.2	12	13	2.2	1.6	1.9
Aluminum, total recoverable (µg/L as Al)	--	--	340	--	--	60
Arsenic, dissolved (µg/L as As)	--	--	1	--	--	<1
Arsenic, total recoverable (µg/L as As)	--	--	1	--	--	1
Barium, dissolved (µg/L as Ba)	--	--	<100	--	--	<100
Barium, total recoverable (µg/L as Ba)	--	--	<100	--	--	<100
Beryllium, total recoverable (µg/L as Be)	--	--	< 10	--	--	<10
Boron, dissolved (µg/L as B)	--	--	50	--	--	60
Cadmium, dissolved (µg/L as Cd)	--	--	<1.0	--	--	<1.0
Cadmium, total recoverable (µg/L as Cd)	--	--	<1.0	--	--	<1
Chromium, dissolved (µg/L as Cr)	--	--	<1.0	--	--	<1
Chromium, total recoverable (µg/L as Cr)	--	--	<1	--	--	<1
Cobalt, total recoverable(µg/L as Co)	--	--	<1	--	--	<1
Copper, dissolved (µg/L as Cu)	--	--	1	--	--	<1
Copper, total recoverable (µg/L as Cu)	--	--	2	--	--	<1
Iron, dissolved (µg/L as Fe)	60	110	40	160	160	50
Iron, total recoverable (µg/L as Fe)	--	--	660	--	--	130
Lead, dissolved (µg/L as Pb)	--	--	<1	--	--	<1
Lead, total recoverable (µg/L as Pb)	--	--	<1	--	--	<1

**12 Hydrology and Water-Quality Characteristics of Muddy Creek and Wolford Mountain Reservoir near Kremmling, Colorado, 1990 through 2001**

**Table 3.** Comparison of samples taken concurrently at the two downstream sites—Muddy Creek at Kremmling (S2) and Muddy Creek below Wolford Mountain Reservoir near Kremmling (S3)—between August and September 1995.—Continued

[<, less than; --, sample not analyzed; mg/L, milligrams per liter; µg/L, micrograms per liter; µS/cm, microsiemens per centimeter; °C, degrees Celsius; NTU, nephelometric turbidity units]

Constituent	Concentration					
	S2			S3		
	07-11-95	08-15-95	09-19-95	07-13-95	08-16-95	09-19-95
Lithium, total recoverable (µg/L as Li)	--	--	20	--	--	20
Manganese, dissolved (µg/L as Mn)	--	--	80	--	--	40
Manganese, total recoverable (µg/L as Mn)	--	--	110	--	--	40
Mercury, dissolved (µg/L as Hg)	--	--	<.1	--	--	<.1
Mercury, total recoverable (µg/L as Hg)	--	--	<.1	--	--	<.1
Molybdenum, dissolved (µg/L as Mo)	--	--	1.6	--	--	2
Molybdenum, total recoverable (µg/L as Mo)	--	--	1.6	--	--	2
Nickel, dissolved (µg/L as Ni)	--	--	3	--	--	2
Nickel, total recoverable (µg/L as Ni)	--	--	3	--	--	2
Selenium, dissolved (µg/L as Se)	--	--	3	--	--	3
Selenium, total recoverable (µg/L as Se)	--	--	3	--	--	4
Silver, dissolved (µg/L as Ag)	--	--	<1	--	--	<1
Silver, total recoverable (µg/L as Ag)	--	--	<1	--	--	<1
Strontium, dissolved (µg/L as Sr)	--	--	590	--	--	560
Zinc, dissolved (µg/L as Zn)	--	--	<10	--	--	<10
Zinc, total recoverable (µg/L as Zn)	--	--	<10	--	--	<10

**Table 4.** Comparison of concurrent total and dissolved analyses and results of Wilcoxon signed-rank test.

[2-sided test; <, less than; --, sample not analyzed; all concentrations in milligrams per liter; *p*-values significant at greater than 90 percent confidence shown in bold]

Date	Ammonia, total	Ammonia dissolved	Nitrite plus nitrate, total	Nitrite plus nitrate, dissolved	Nitrite, total	Nitrite, dissolved	Orthophosphate, total	Orthophosphate, dissolved
S3 09041400								
09-20-1989	0.04	0.03	<0.10	<0.10	--	--	<0.01	<0.01
05-9-1990	.03	.01	<.10	<.10	--	--	.04	<.01
09-25-1990	.05	.03	.20	<.10	--	--	<.01	<.01
05-30-1991	.05	.03	<.10	.052	.05	.01	.05	<.01
09-25-1991	.01	.01	<.10	<.05	.01	<.01	.02	<.01
09-3-1992	.02	.02	<.10	<.05	.02	<.01	.05	<.01
11-16-1992	.03	.02	.10	.13	<.01	.02	<.01	<.01
S1 09041900								
05-10-1990	.04	.01	<.10	<.10	--	<.01	.05	<.01
09-27-1990	.03	<.01	<.10	<.10	--	<.01	<.01	<.01
05-30-1991	.04	.02	.052	<.05	.03	<.01	.03	.03
09-25-1991	<.01	.01	<.05	<.05	<.01	<.01	.01	<.01
05-7-1992	<.01	.02	<.05	<.05	<.01	<.01	<.01	.01
09-3-1992	.03	.02	<.05	<.05	<.01	<.01	.02	<.01
11-18-1992	.03	.01	<.05	<.05	<.01	.02	<.01	<.01
<i>p</i> -value	<b>0.0110</b>		<b>0.3196</b>		<b>0.5295</b>		<b>0.0171</b>	

points are compared only to other points within the same season, reducing the effects of seasonality on concentrations.

Trends were calculated for unadjusted and flow-weighted concentrations. Monthly flow-weighted concentrations are concentrations that have been weighted to reflect flow conditions throughout an entire month, not just the conditions on the day that a sample was collected (fig. 4). Flow weighting can produce a more representative monthly concentration than a single observed concentration alone. When the relation between flow and concentration is not statistically significant, however, flow weighting will lead to biased values. As a result, flow-weighted concentration trend results in this report are provided only for those constituents that are significantly correlated with flow.

Flow-weighted concentrations were calculated using the ordinary least-squares (OLS) regression model equation:

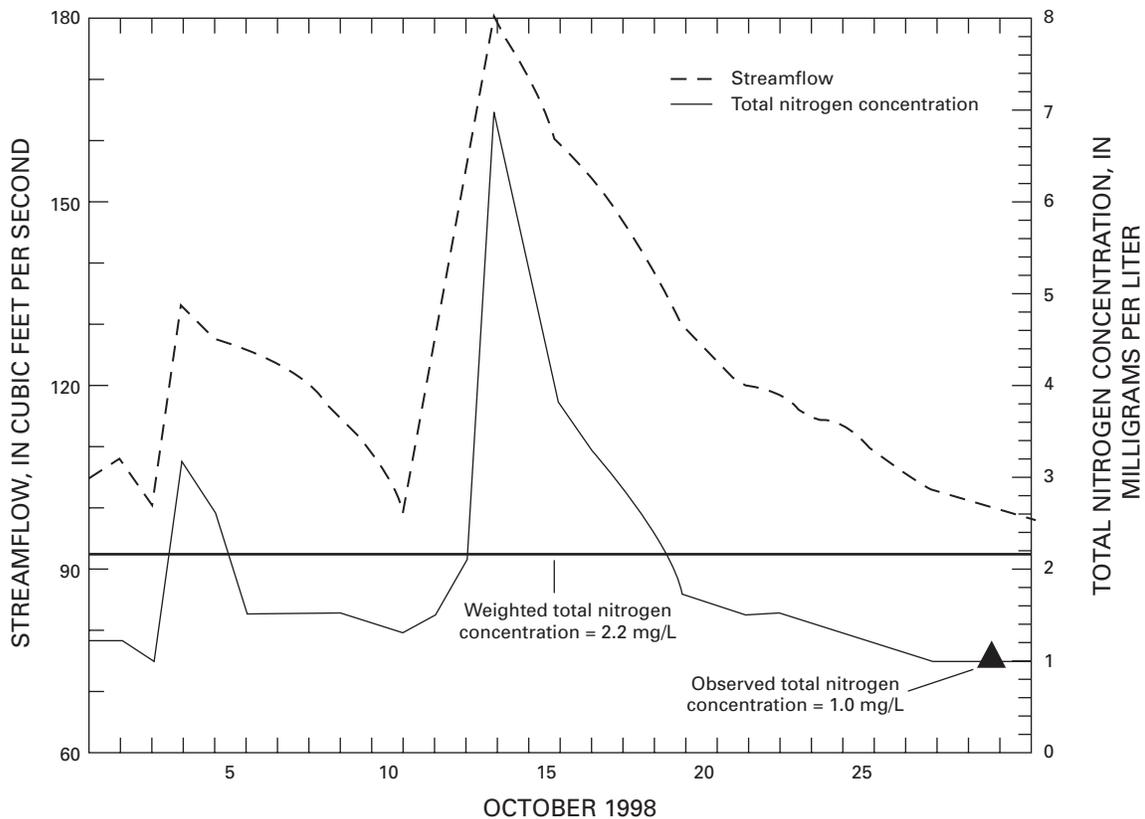
$$\ln(C_i) = \beta_0 + \beta_1 \ln(Q_i) \quad i = 1, 2, \dots, n \quad (5)$$

where

- ln is the natural log;
- $C_i$  is the  $i$ th observation of concentration;
- $Q_i$  is the  $i$ th observation of mean daily discharge;
- $\beta_0$  is the intercept;
- $\beta_1$  is the slope; and
- $n$  is the number of samples.

Log-normal transformations were used in an effort to achieve homoscedasticity and normality of the residuals, two major assumptions of OLS regression. If these assumptions were not met for a given constituent, the constituent was excluded from the flow-weighting procedure. For the downstream sites, mean daily discharges were combined by date into one data set the same way the water-quality values were, so that concentrations obtained at one site were matched up with discharges measured at the same site. Slope coefficients and intercepts for OLS regression equations cannot be computed accurately with a large amount of censored data (Helsel and Hirsch, 1992); consequently, constituents exceeding 10 percent of censored data were excluded from the flow-weighting procedure. Censored data for the constituents that remained were set equal to the detection limit in the OLS. The data set for each constituent remaining was tested for serial correlation using the "acf" function in S-Plus 2000© (Insightful Corp., 2000). If any values in the correlation matrix were above 0.20, serial correlation was deemed present at a level that would induce unacceptable type I error rates (Alden and others, 2000), and the corrected  $p$ -values from the SKT output were used.

The fitted OLS regression equation for each constituent was used to predict daily concentrations based on known mean daily discharge. The resulting concentrations were in log-normal space, so corrections for back-transformation bias were achieved using the equation:



**Figure 4.** Comparison of observed monthly concentration and a flow-weighted monthly concentration of total nitrogen (adapted from Langland and others, 1999).

## 14 Hydrology and Water-Quality Characteristics of Muddy Creek and Wolford Mountain Reservoir near Kremmling, Colorado, 1990 through 2001

$$C_i = \exp[\beta_0 + \beta_1 \ln(Q_i) + 0.5s^2] \quad i = 1, 2, \dots, n \quad (6)$$

where

$\ln$  is the natural log;

$C_i$  is the  $i$ th observation of concentration;

$Q_i$  is the  $i$ th observation of mean daily discharge;

$\beta_0$  is the intercept;

$\beta_1$  is the slope;

$s^2$  is the sample variance; and

$n$  is the sample size.

Monthly flow-weighted concentrations were calculated by taking the mean of the predicted daily concentrations each month. Flow-weighting procedures met criteria for most major ions at S2/S3 combined, and acid-neutralizing capacity (ANC), dissolved iron, and turbidity at S1. The SKT test then was run on the monthly flow-weighted concentrations using the "seaken" function in S-Plus 2000© (Insightful Corp., 2000).

For those constituents that were excluded from the flow-weighting procedure because they did not meet the correlation, censoring, normality, or homoscedasticity criteria, the SKT test was used on unadjusted (observed) concentrations. Further, constituents with censoring between 5 and 50 percent can lead to biased estimates of the trend slope when an arbitrarily chosen value is substituted for the censored value (Helsel and Hirsch, 1992). As a result, only the sign of the trend slope and not the magnitude was reported for constituents with censoring between 5 and 50 percent. The slope is reported in the tables in units of change per year in the median value. All censored data were set to the detection limit. When detection limits changed throughout the study period, all censored data were recensored to the highest reporting limit. This recensoring of the data caused a loss in statistical power, but leaving changes in reporting limits over time in a data set could have led to the detection of trends that did not exist.

The SKT test requires one value per season per year. At the upstream site (S1), samples were collected only from April through December in some years and monthly in others. Due to the variation in sampling frequency, the seasons for the SKT test were defined on the basis of the lowest sampling frequency (Helsel and Hirsch, 1992). Therefore, nine seasons were used for the upstream site. For the years in which monthly samples were collected, the data were adjusted to nine seasons by taking the value from the sample collected closest to the midpoint of each season. At the downstream sites, monthly samples were collected throughout the study period, so 12 seasons were used in the SKT test. When multiple samples were collected in a given month, the median for that month was used. As with the flow-weighted concentrations, the unadjusted concentrations were tested for serial correlation and, if necessary, the corrected  $p$ -values from the SKT output were used.

Spatial changes between the upstream and downstream sites were determined using a two-sided Wilcoxon rank-sum test to compare the two data sets before and after water storage began in the reservoir. The null hypothesis is that samples from both sites were from the same population, or accordingly, the

samples are not statistically different (Helsel and Hirsch, 1992). Using data with censoring greater than 50 percent can invalidate the results of the hypothesis test; as a result, constituents with censoring greater than 50 percent were excluded from the Wilcoxon statistical test.

The first part of the testing for spatial differences was to determine if upstream and downstream differences in water quality existed before construction of the reservoir so that pre-existing differences would not be mistaken for reservoir effects. Results of upstream/downstream differences at Muddy Creek above Antelope (S1) and Muddy Creek at Kremmling (S2) pre-reservoir, 1990 through 1995, were computed. Secondly, post-construction upstream/downstream differences, 1995 through 2001, also were computed.

## Hydrology

Hydrologic characteristics of the Muddy Creek watershed are important for understanding reservoir and streamflow water quality both upstream and downstream from the reservoir. Although some variation in hydrologic characteristics of Muddy Creek are due to natural changes, after 1995, when the dam was completed, the reservoir and control of outflows affected streamflow below the outlet of the dam. Daily mean discharge during the study was variable (fig. 5). The annual hydrograph for Muddy Creek was dominated by the magnitude and timing of snowmelt runoff. Snowpack melting represents about 88 percent of the average annual runoff 1990 through 2001 during April through June (figs. 6–8). Daily fluctuations in streamflow during snowmelt are largely due to diurnal variations in air temperatures that influence melting and to the location, duration, and intensity of rainstorms.

Maximum instantaneous streamflow was 955 ft<sup>3</sup>/s, June 20, 1994, before completion of the dam, when a localized storm dropped 3 inches of rain over a 1 to 2-mi<sup>2</sup> area in a tributary of Muddy Creek (Robert D. Jarrett, U.S. Geological Survey, written commun., 1994) (fig. 9). Attenuation of downstream peak streamflow was evident in the hydrograph. Minimum daily streamflow for the period of record at S1 was 0.96 ft<sup>3</sup>/s (fig. 7) and occurred in July 1994.

The effects of Wolford Mountain Reservoir on downstream streamflow can be seen in flow-duration curves for Muddy Creek above Antelope Creek (upstream from the reservoir, site S1) and Muddy Creek below Wolford Mountain Reservoir (downstream from the reservoir, site S3) (fig. 10). In most years (water years 1996 to 2001) since the reservoir began filling, peak flows downstream from the reservoir were similar or slightly reduced as a result of reservoir storage when compared to those upstream. The upper first to fifteenth percentiles of flows downstream were decreased compared to prereservoir flow patterns. The fifteenth to one-hundredth percentiles of outflow duration generally were increased by operation of the reservoir compared to inflow duration.

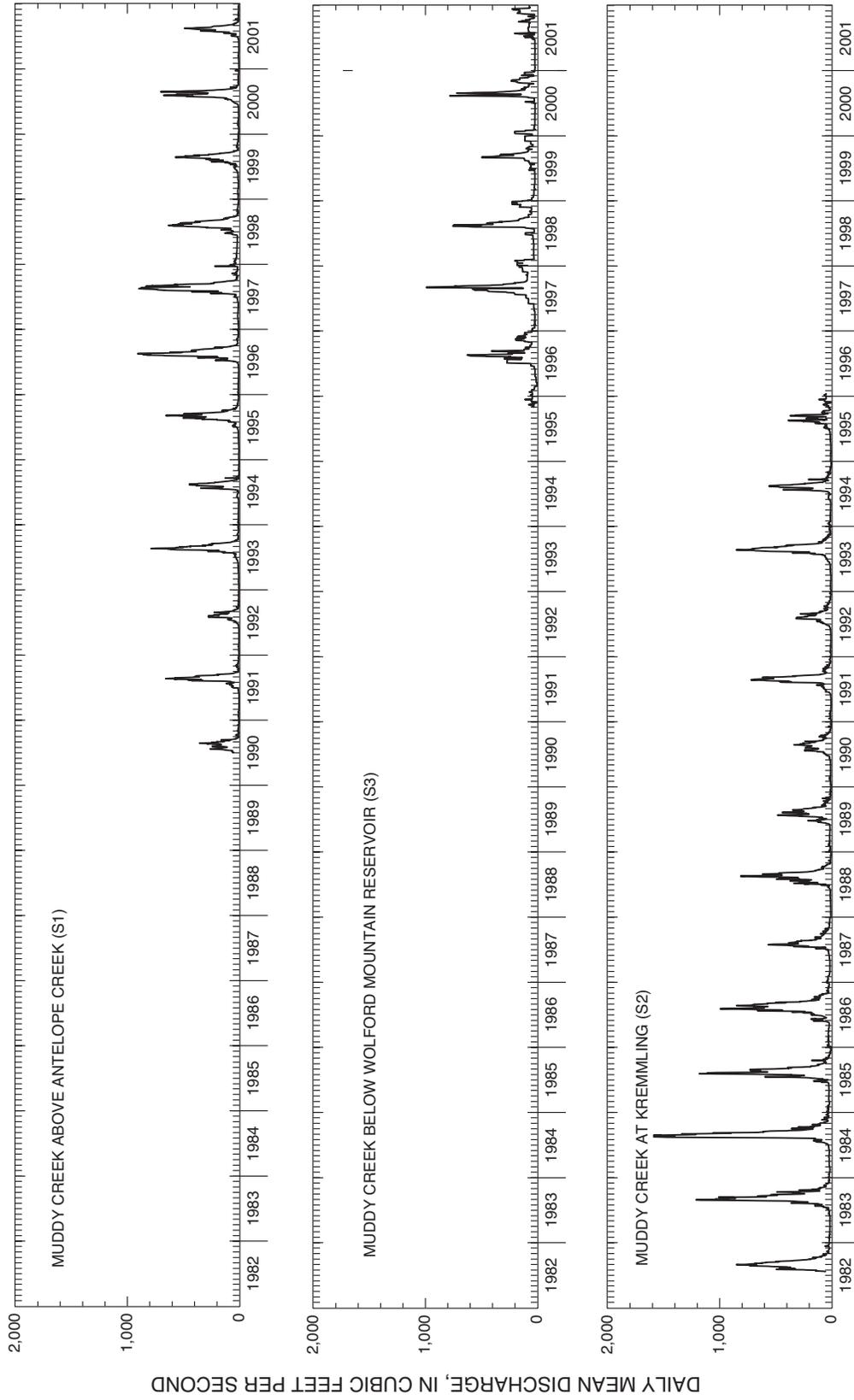


Figure 5. Daily mean discharge at stream gages along Muddy Creek.

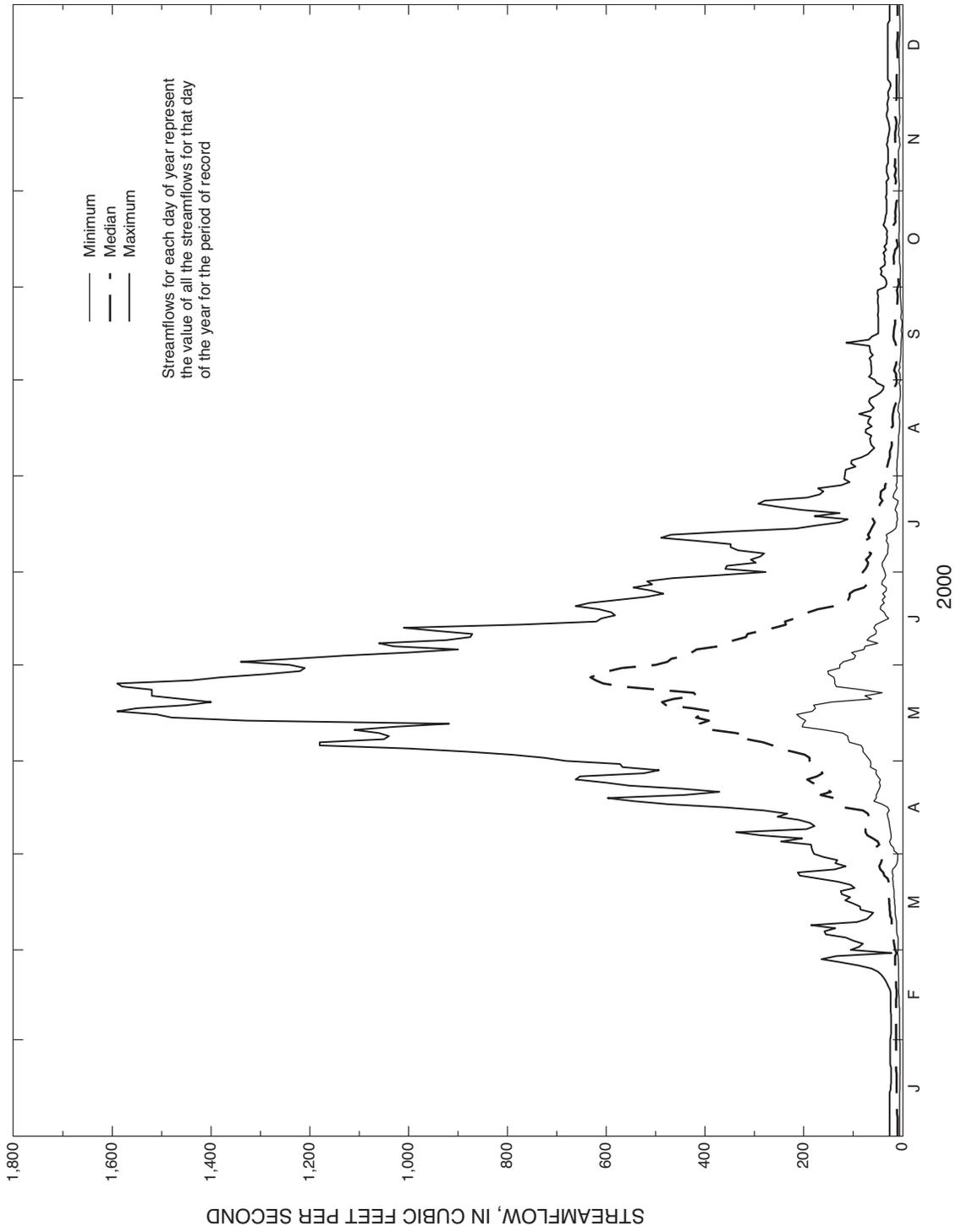


Figure 6. Daily streamflow statistics for period of record at Muddy Creek at Kremmling water years 1982–96.

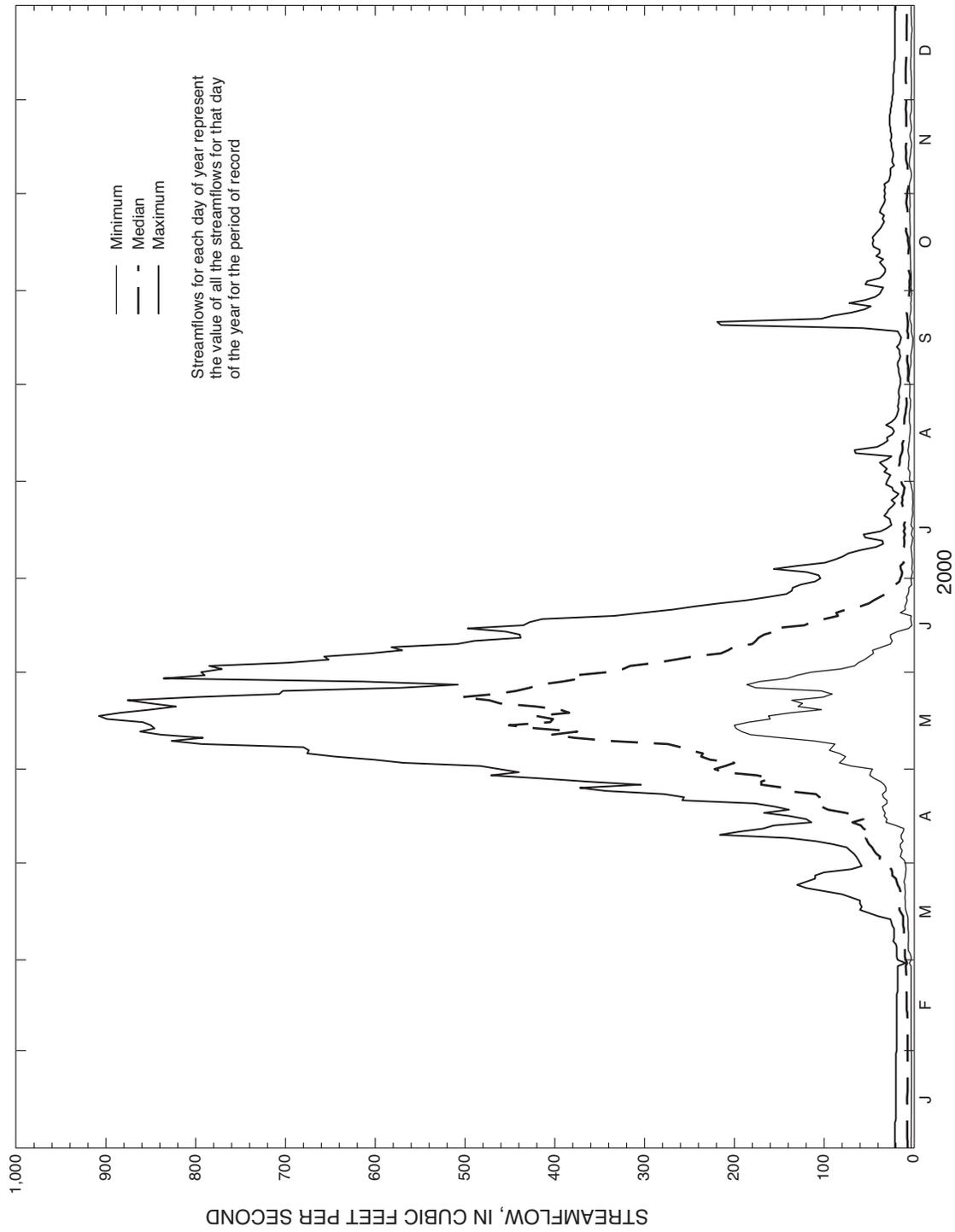


Figure 7. Daily streamflow statistics for period of record at Muddy Creek above Antelope Creek water years 1990–2002.

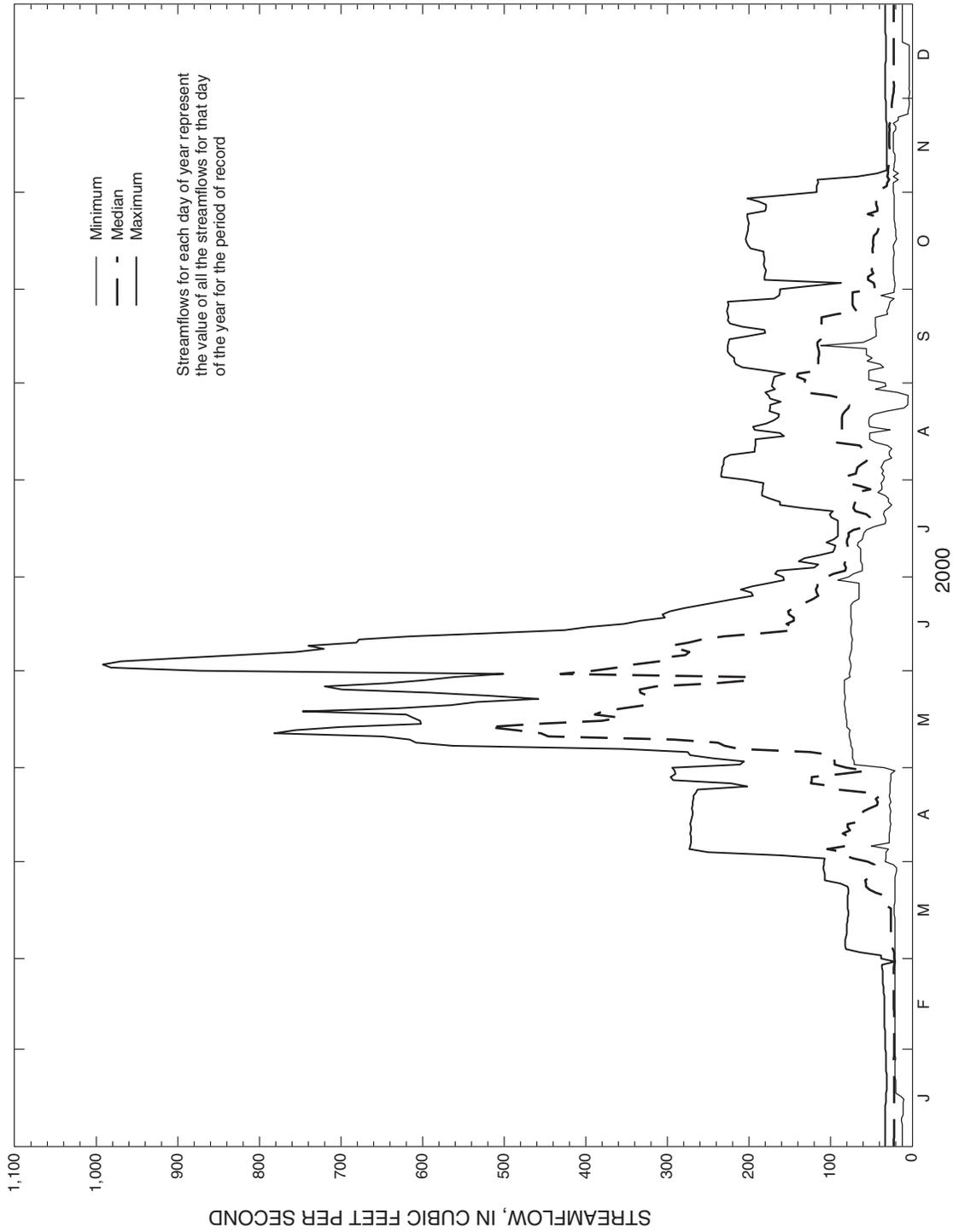
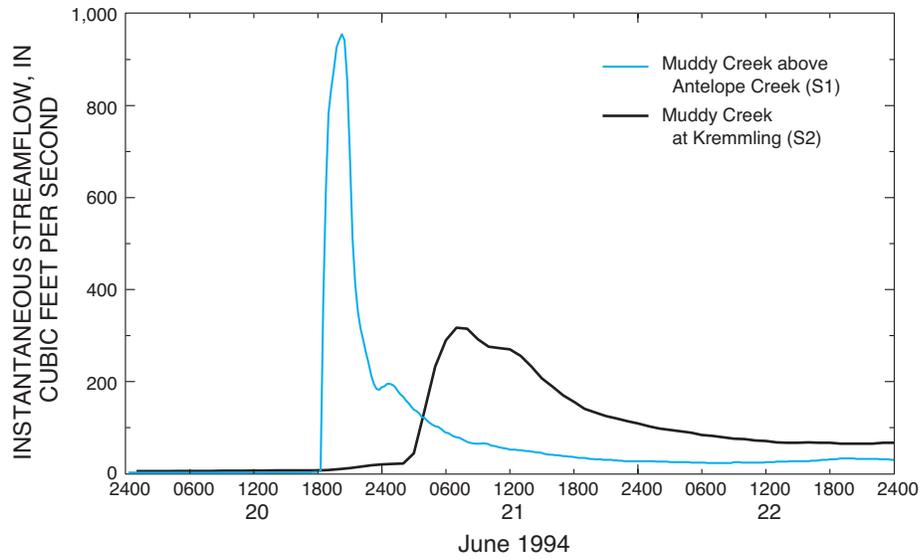
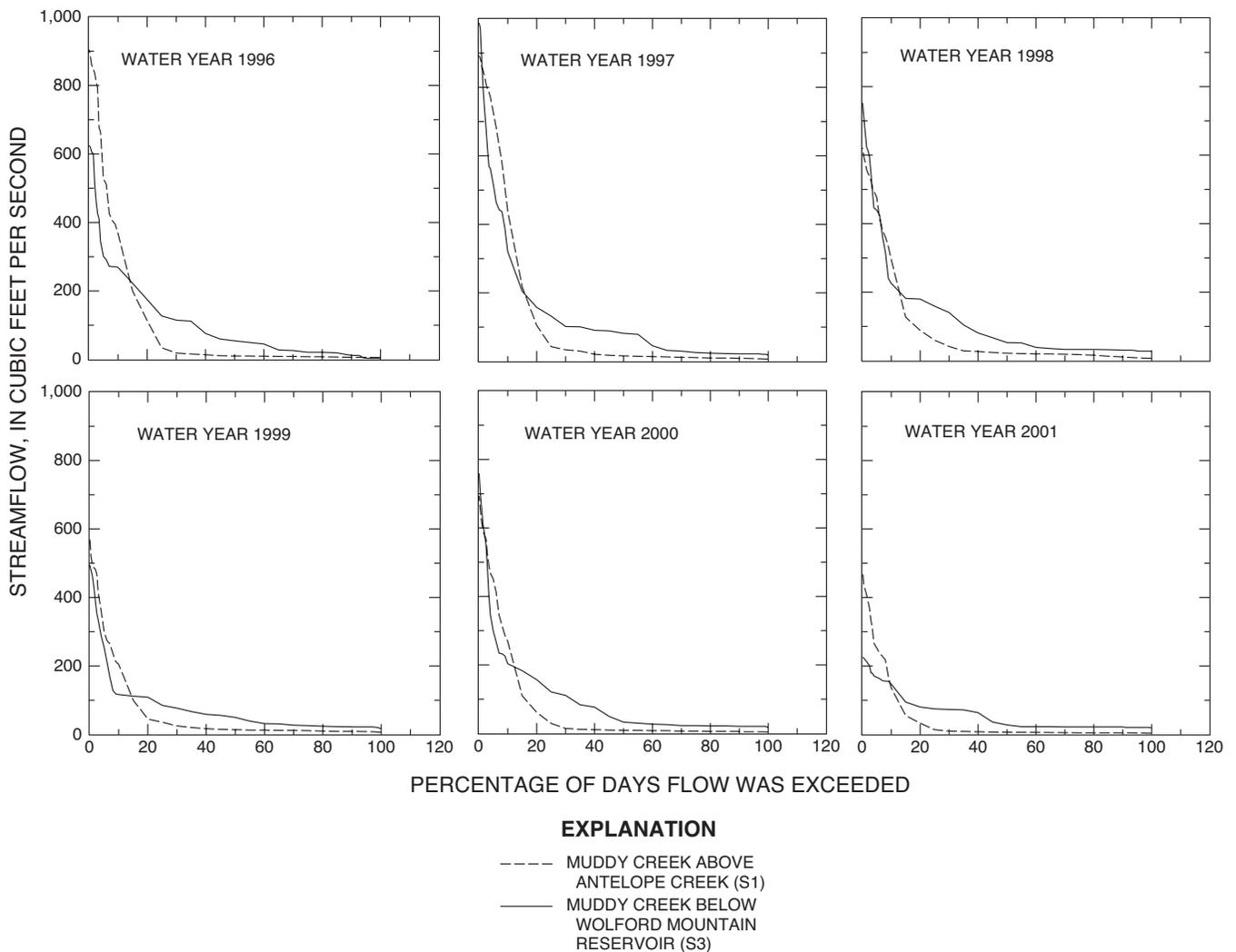


Figure 8. Daily streamflow statistics for period of record at Muddy Creek below Wolford Mountain Reservoir water years 1995–2002.



**Figure 9.** Instantaneous discharge hydrographs for two Muddy Creek gaging stations during a localized storm with maximum rainfall in the range of 3 inches total over a 1- to 2-square-mile area in a tributary of Muddy Creek.



**Figure 10.** Flow-duration curves for streamflow upstream and downstream from Wolford Mountain Reservoir, 1996 through 2001.

## Water Quality

This section presents chemical characteristics, sediment, and results of continuous water-quality monitoring of temperature, specific conductance, and dissolved oxygen (site S3 only) for streams. Chemical characteristics, profiles and stratification, nutrient mass balance, and trophic status of Wolford Mountain Reservoir are discussed after stream characteristics.

### Streamwater Quality

Seasonal and hydrologic factors such as precipitation distribution and bedrock geology affect variation in streamwater quality. Prereservoir water quality is an important baseline for evaluating postconstruction effects on water quality. Water-quality data available for analysis included field properties (water temperature, specific conductance, pH, dissolved oxygen, and turbidity), major ions, nutrients, trace elements, organic carbon, and suspended sediment. Continuous monitoring data for specific conductance, water temperature, and dissolved oxygen (site S3 only) also were collected and evaluated.

To determine the effects of water storage in Wolford Mountain Reservoir on downstream water quality in Muddy Creek, changes in water quality along Muddy Creek before and after completion of the reservoir in March 1995 were examined. Temporal changes in water quality, due to natural variations over the entire study period, were determined based on trends in water quality at site S1 (Muddy Creek above Antelope Creek) upstream from the reservoir. Spatial changes in water quality due to natural variations were determined based on differences in constituent concentrations at the upstream (S1) and downstream sites (S2) before the initial storage of water in the reservoir. Temporal changes due to both natural variations and water storage in the reservoir were determined based on trends in water quality at the downstream sites (S2 and S3). Spatial changes due to natural variations and water storage in the reservoir were determined based on differences in concentrations at the upstream (S1) and downstream sites (S2 and S3) after the initial storage of water in the reservoir. By analyzing all results together, the effects of water storage in the reservoir can be separated out from those due to natural variations.

### Field Properties

Summary statistics for field properties were compiled for S1, S2, and S3 (table 5). In the table, S1 is characterized for pre-reservoir (April 1990 to March 1995), postconstruction (April 1995 to September 2001), and both periods combined (1990 to 2001). S2 and S3, both downstream from the reservoir, are combined to create similar periods for comparison. Boxplots of selected constituents by site are in figure 11. Time-series plots of selected field properties from 1990 to present for upstream (S1), downstream (S3), and prereservoir down (S2) sites are

shown in figure 12. Specific conductance for S1, S2, and S3 ranged from 99 to 1,720  $\mu\text{S}/\text{cm}$  (site S2); however, the median ranged from about 434 to 658  $\mu\text{S}/\text{cm}$  from 1990 to 2001. Alkali Slough #2 (S4) had the largest specific conductance of 3,470  $\mu\text{S}/\text{cm}$  on April 12, 1995, probably due to the inflow of ground water in contact with saline marine shale and concentration by evapotranspiration. The lowest seasonal specific conductances (99 to 356  $\mu\text{S}/\text{cm}$ ) were measured during peak flow of snowmelt.

Seasonal variation in daily mean specific conductance is illustrated in figure 13 for 1990 to 2001 at S1, S2, and S3. Daily mean specific conductance at sites unaffected by the reservoir (S1 and S2 pre-1995) ranged from less than 200  $\mu\text{S}/\text{cm}$  during runoff to more than 1,500  $\mu\text{S}/\text{cm}$  in late summer or early fall at low flow. Site S3, Muddy Creek below Wolford Mountain Reservoir had less annual variation between high and low specific conductance due to the stabilizing effect of mixing water from different parts of the hydrograph into a single pool within the reservoir.

Temporal variability of specific conductance was tested by SKT (table 6). At site S1, no temporal trend in specific conductance was determined. At S2/S3, there was a significant ( $p$ -value less than 0.10) downward trend in specific conductance. The downward trend downstream from the reservoir site probably is caused by the mixing of a large volume of snowmelt runoff with a low specific conductance in the reservoir that is subsequently released throughout the year. These releases have lower specific conductance than typical Muddy Creek streamflow (prereservoir) at low flow.

Spatial variability of specific conductance was significant ( $p$ -value less than 0.10) in prereservoir and postconstruction periods (table 7). The specific conductivity preconstruction was 426  $\mu\text{S}/\text{cm}$  upstream compared to 941  $\mu\text{S}/\text{cm}$  downstream. Postconstruction was 435  $\mu\text{S}/\text{cm}$  upstream compared to 627  $\mu\text{S}/\text{cm}$  downstream. This difference indicates that the marine shales and irrigation return flows have always added dissolved solids in the reach between S1 and S2/S3 but the larger concentrations downstream have been moderated by dilution during the postconstruction period (1995 to 2001).

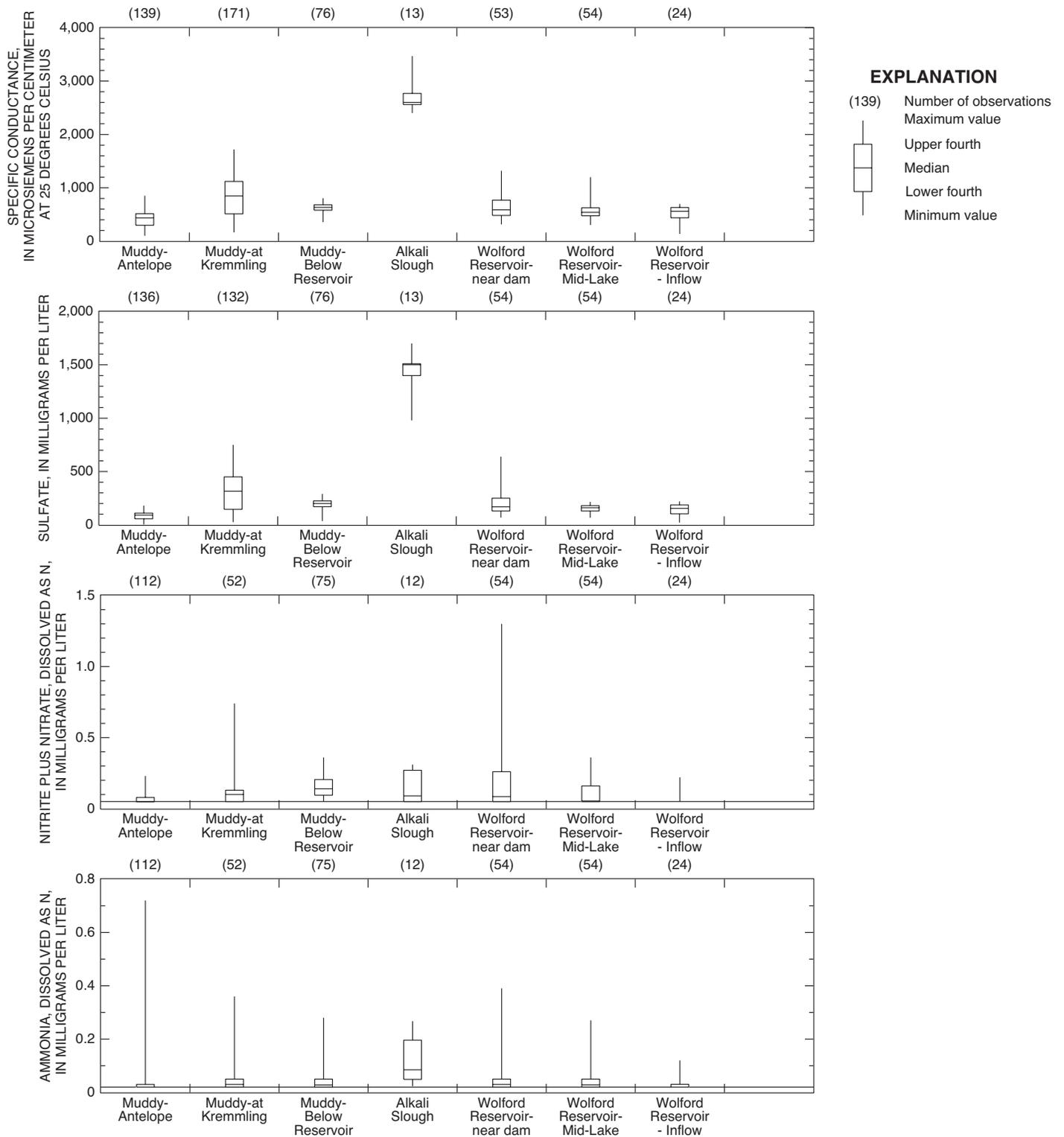
Prereservoir water temperatures at Muddy Creek above Antelope Creek (S1) reached 26.7°C during summer low flow on July 7, 1999, and were near 0°C during the winter. Seasonal variation in daily mean water temperature for 1990 to 2001 at S1, S2, and S3 is shown in figure 14. In winter, sites unaffected by the reservoir had daily mean and instantaneous water temperatures ranging from 0° to 2°C. In summer, daily mean water temperatures at sites unaffected by the reservoir (S1 and S2 pre-1995) ranged from about 14° to 22°C. Summer water temperatures at all three sites had a strong daily (diurnal) fluctuation that was influenced by air temperature. Spatial variability is illustrated by comparing S1 and S3 (fig. 12), which shows less annual variation between high and low water temperatures after the reservoir was filled (post-1995) due to stability of water temperatures within the reservoir.

**Table 5.** Statistical summary of field-property data at S1 and S2/S3 from April 1990 through March 1995 before storage began in the reservoir, S1 and S2/S3 combined from April 1990 through October 2001, and S1 and S2/S3 from April 1995 to September 2001 after storage began in the reservoir.

[ft<sup>3</sup>/s, cubic feet per second; <, less than; --, sample not analyzed; mg/L, milligrams per liter; μS/cm, microsiemens per centimeter; °C, degrees Celsius; NTU, nephelometric turbidity units]

Constituent or property	Minimum	25th percentile	Median	75th percentile	Maximum	Number of samples
<b>Site S1 1990 through 2001</b>						
Discharge, instantaneous (ft <sup>3</sup> /s)	3.20	8.99	39	203	811	323
Dissolved oxygen, (mg/L)	3.3	8.0	8.9	10.2	13	132
pH, field (standard units)	7.1	8.2	8.3	8.4	8.7	135
Specific conductance (μS/cm @ 25°C)	99	268	434	512	851	137
Turbidity (NTU)	0.5	3.5	5.4	30	180	128
<b>Site S2/S3 combined 1990 through 2001</b>						
Discharge, instantaneous (ft <sup>3</sup> /s)	1.3	20	52.35	111	1,000	174
Dissolved oxygen, (mg/L)	5.4	8.1	8.8	9.65	15.6	139
pH, field (standard units)	7.3	8.1	8.3	8.4	8.9	137
Specific conductance (μS/cm @ 25°C)	164	575	658	814	1,720	144
Turbidity (NTU)	.3	1.5	4.85	17.2	360	132
<b>Site S1 pre-reservoir 1990 through 1995</b>						
Discharge, instantaneous (ft <sup>3</sup> /s)	1.31	10.0	150	267	777	143
Dissolved oxygen, (mg/L)	3.3	7.9	8.6	9.8	12.6	51
pH, field (standard units)	7.6	8.1	8.2	8.4	8.6	54
Specific conductance (μS/cm @ 25°C)	99	219	426	525	851	57
Turbidity (NTU)	.5	3.2	5.6	26	110	53
<b>Site S2/S3 pre-reservoir combined 1990 through 1995</b>						
Discharge, instantaneous (ft <sup>3</sup> /s)	1.3	9.4	22	106	709	81
Dissolved oxygen, (mg/L)	5.8	7.8	8.9	10.6	12.6	64
pH, field (standard units)	7.5	8	8.2	8.4	8.9	55
Specific conductance (μS/cm @ 25°C)	164	624	941	1,200	1,720	60
Turbidity (NTU)	1.2	10.8	19	32.8	360	56
<b>Site S1 post-construction April 1995 through Sept 2001</b>						
Discharge, instantaneous (ft <sup>3</sup> /s)	3.20	8.50	16.0	85.0	811	180
Dissolved oxygen, (mg/L)	6.6	8.1	9.3	10.6	13	81
pH, field (standard units)	7.1	8.2	8.4	8.4	8.7	81
Specific conductance (μS/cm @ 25°C)	126	338	435	508	695	80
Turbidity (NTU)	.6	3.6	5.2	30	180	75
<b>Sites S2/S3 post-construction combined 1995 through 2001</b>						
Discharge, instantaneous (ft <sup>3</sup> /s)	3.50	28.0	58.0	111	1,000	93
Dissolved oxygen, (mg/L)	7.2	8.2	8.8	9.5	12.2	83
pH, field (standard units)	7.3	8.1	8.3	8.4	8.8	82
Specific conductance (μS/cm @ 25°C)	356	563	627	677	953	84
Turbidity (NTU)	.3	1.0	1.8	3.2	190	76

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**Figure 11.** Selected water-quality constituents.

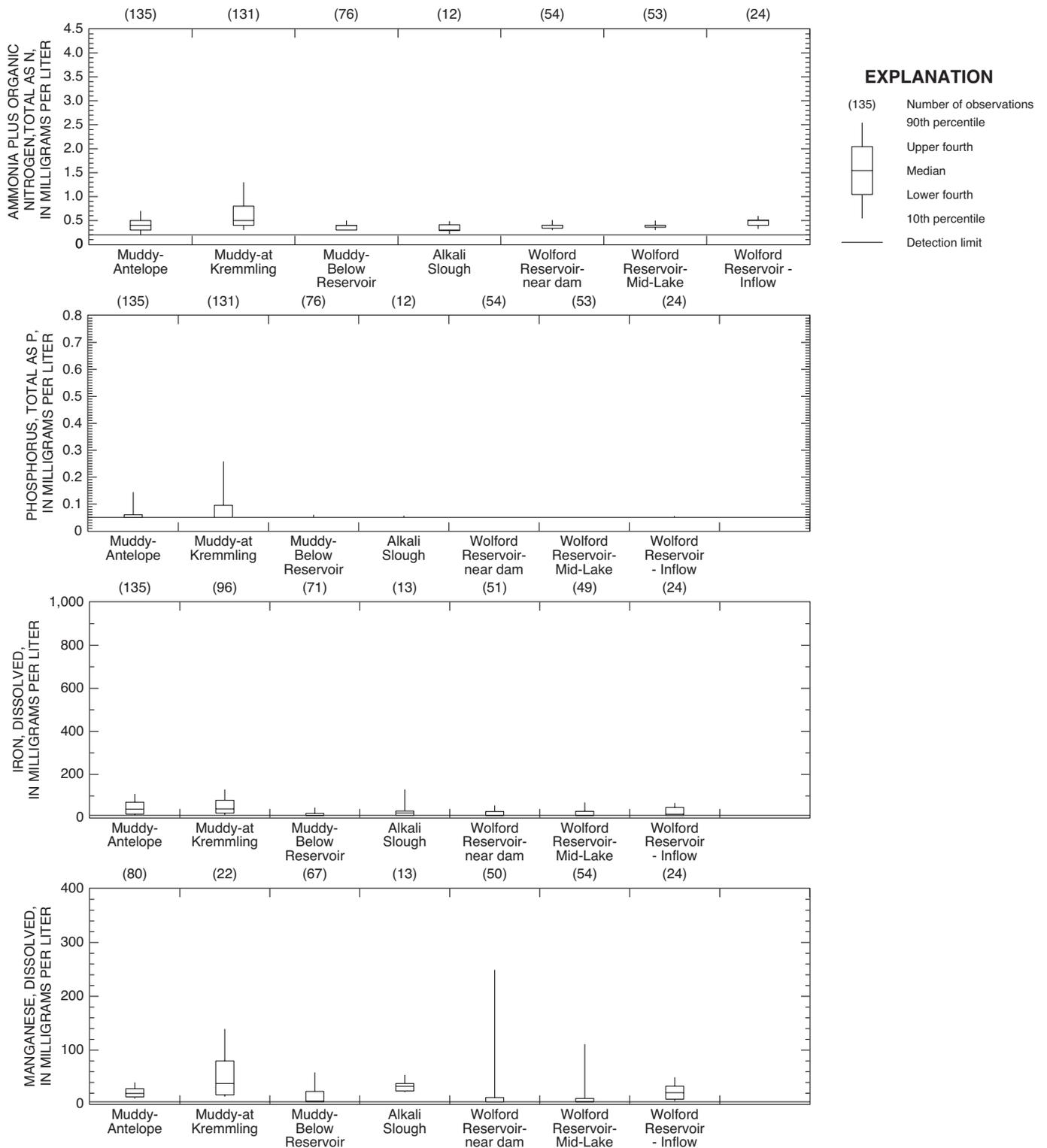
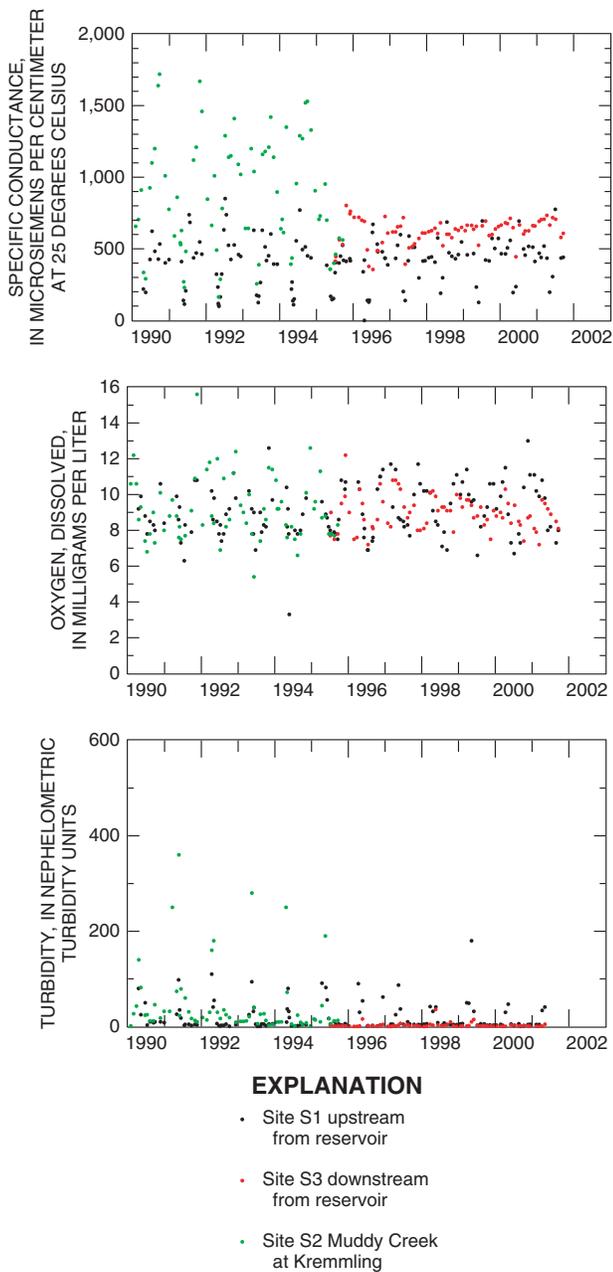


Figure 11. Selected water-quality constituents.—Continued.

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**Figure 12.** Time-series plots of field properties at Muddy Creek above Antelope Creek (upstream from reservoir) and Muddy Creek below Wolford Mountain Reservoir (directly below reservoir), and Muddy Creek at Kremmling (site located approximately 7 miles downstream from reservoir).

Continuous monitoring of stream pH was not done so it is not possible to describe variability of pH. At all sites, pH was near neutral to moderately alkaline ranging from 7.1 to 8.9 (table 5). During the reservoir period, median pH at S1 and S2/S3 was the same, 8.2. During the postconstruction period, pH was 8.4 at S1 and 8.3 at S3 (table 5).

At site S3, downstream from the reservoir, dissolved-oxygen concentration data were collected continuously from late

1995 to 2001 (fig. 15). Dissolved-oxygen concentration at all sites ranged from 3.3 to 15.6 mg/L (table 5). Daily minimum concentrations were usually greater than 5 mg/L and rarely less than 4 mg/L. Maximum daily dissolved-oxygen concentrations at S3 generally ranged from 7 to 12 mg/L. Seasonal lows generally occurred in late summer or early fall, coincident with summer hypoxia in the reservoir. Seasonal highs generally occurred during spring runoff. No multiyear temporal patterns were apparent in the S3 record. Meaningful interpretation of temporal and spatial variability for S1 and S2 is probably not possible due to the limited dissolved-oxygen data.

Turbidity, a measurement of the transparency of water, is related to fine-particle concentrations and sediment transport. Based on discrete sample data collected at S1 and S2, turbidity in prereservoir Muddy Creek was generally less than 10 NTU during low flow but ranged to more than 360 NTU during snowmelt. Turbidity in Muddy Creek downstream from the reservoir (S3) was substantially lower after 1995 [upstream (S1) median 5.2 NTU, downstream (S3) median 1.8 NTU] because the reservoir acts as a sediment trap (fig. 12). Turbidity was the best indicator of the spatial variability in particle transport because suspended-sediment concentrations were not sampled at S3.

**Major Ions**

Summary statistics for major ions were compiled for three streamwater-quality sites in this study (table 8). In the table, S1 is characterized for prereservoir (April 1990 to March 1995), postconstruction (April 1995 to September 2001), and both periods combined (1990 to 2001). S2 and S3 are combined to create similar periods for comparison. Boxplots of selected constituents by site are shown in figure 11. Time-series plots of selected major ions from 1990 to present for upstream (S1), downstream (S3), and prereservoir downstream (S2) sites are shown in figure 16.

Cation compositions at two sites (S1, 1990 to 2001; and S3, 1995 to 2001) were mixed calcium-magnesium-sodium, but calcium is predominant (fig. 17). Cation composition at S4 was mostly calcium. Anion composition at S1 was primarily bicarbonate and sulfate, whereas S4 was almost completely a sulfate composition. Downstream from the reservoir (S3) anion composition tended toward more sulfate. This difference likely was caused by a source of dissolved solids rich in calcium and sulfate in the marine shales of the reservoir drainage area such as Alkali Slough #2 (S4). Anion composition varies seasonally in response to runoff and low-flow conditions. During snowmelt (high flow), Muddy Creek above Antelope (S1) tends to have relatively large concentrations of bicarbonate, whereas low-flow samples tend to have relatively more sulfate. Seasonal variation of ANC (mostly bicarbonate under these pH conditions) exceeds that of sulfate, causing relative differences in composition (fig. 16). Another explanation could be a result of the decay of algae in the reservoir and the emission of CO<sub>2</sub>, which could increase bicarbonate concentrations in the outflow.

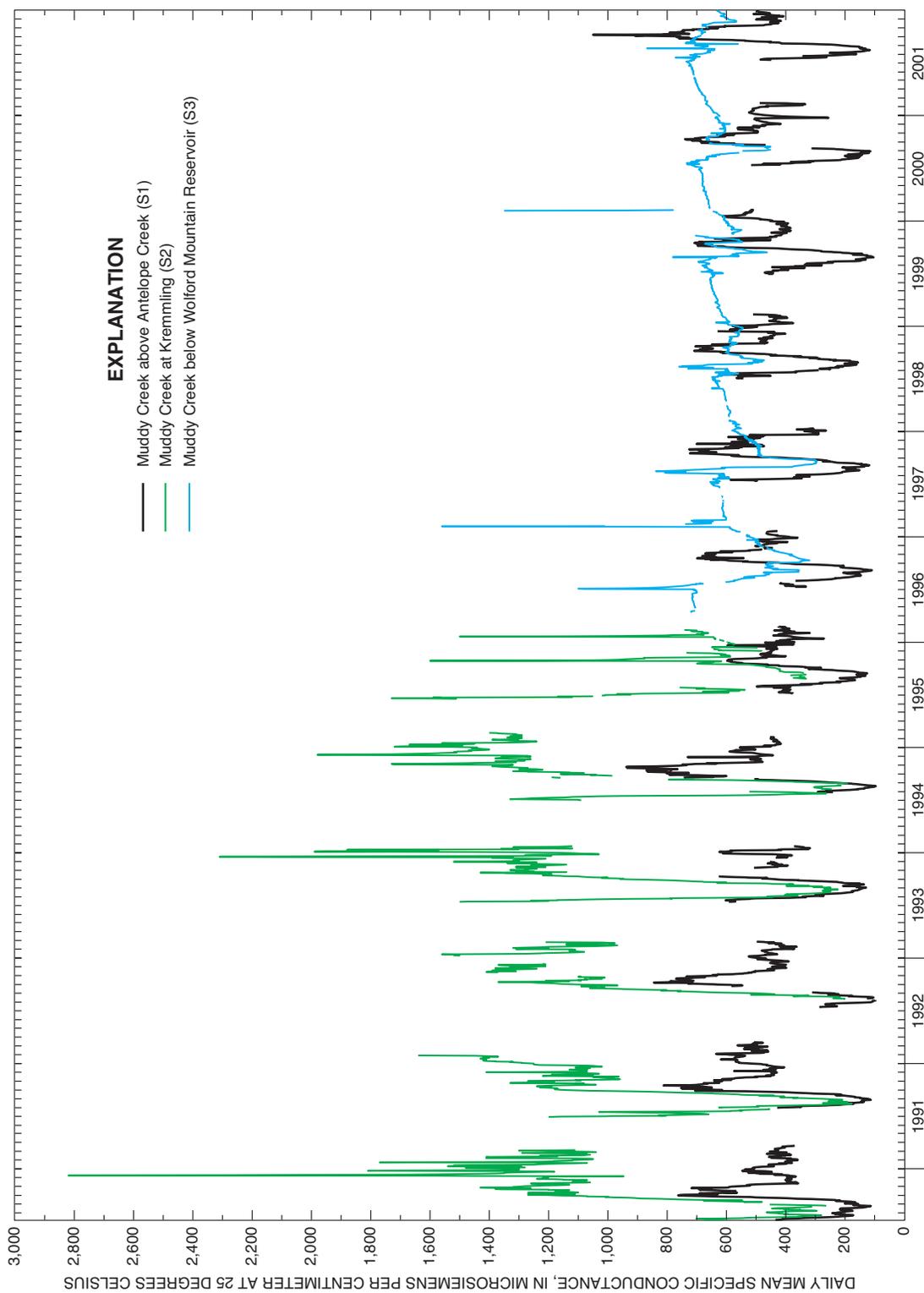


Figure 13. Daily mean specific conductance upstream and downstream from Wolford Mountain Reservoir.

**Table 6.** Summary of field-property temporal variation upstream from reservoir by seasonal Kendall test for Muddy Creek above Antelope Creek (S1) and downstream combined data from Muddy Creek at Kremmling (S2) and Muddy Creek below Wolford Mountain Reservoir (S3), 1990 through 2001.

[ >, greater than; --, slope not computed; mg/L, milligrams per liter;  $\mu$ S/cm, microsiemens per centimeter; °C, degrees Celsius; NTU, nephelometric turbidity units; slope, units per year; -, downward trend; unadj, not adjusted by flow-weighting; fwc, flow-weighted concentrations]

Constituent or property	<i>p</i> -value	Significance > 90-percent confidence	Slope	Type
<b>Site S1 April 1990 through September 2001</b>				
Oxygen, dissolved (mg/L)	0.6684	No	--	unadj
pH, field (standard units)	<b>.0750</b>	Yes	0.01	unadj
Specific conductance ( $\mu$ S/cm at 25°C)	.2698	No	2.33	unadj
Turbidity (NTU)	<b>.0427</b>	Yes	.32	fwc
<b>Site S2/S3 April 1990 through September 2001</b>				
Oxygen, dissolved (mg/L)	<b>.0229</b>	Yes	-.02	fwc
pH, field (standard units)	.6588	No	--	unadj
Specific conductance ( $\mu$ S/cm at 25°C)	<b>.0228</b>	Yes	-19.55	fwc
Turbidity (NTU)	<b>.0012</b>	Yes	-2.00	unadj

**Table 7.** Summary of prereservoir and postconstruction upstream/downstream field-property differences at Muddy Creek above Antelope (S1) and Muddy Creek at Kremmling (S2), 1990 through 1995, and differences at Muddy Creek above Antelope (S1) and Muddy Creek below Wolford Mountain Reservoir (S3), 1995 through 2001 by Wilcoxon signed-rank test.

[<, less than; 2-sided test; mg/L, milligrams per liter;  $\mu$ S/cm, microsiemens per centimeter; °C, degrees Celsius; NTU, nephelometric turbidity units; *p*-values significant at greater than 90-percent confidence shown in bold]

Constituent or property	<i>p</i> -value	Median	
		Upstream	Downstream
<b>April 1990 through March 1995</b>			
Oxygen, dissolved (mg/L)	0.5921	8.6	8.9
Specific conductance ( $\mu$ S/cm at 25°C)	<b>&lt;.0001</b>	426	941
Turbidity (NTU)	<b>.0006</b>	5.6	19
<b>April 1995 through-September 2001</b>			
Oxygen, dissolved (mg/L)	.1213	9.3	8.8
Specific conductance ( $\mu$ S/cm at 25°C)	<b>&lt;.0001</b>	435	627
Turbidity (NTU)	<b>&lt;.0001</b>	5.2	1.75

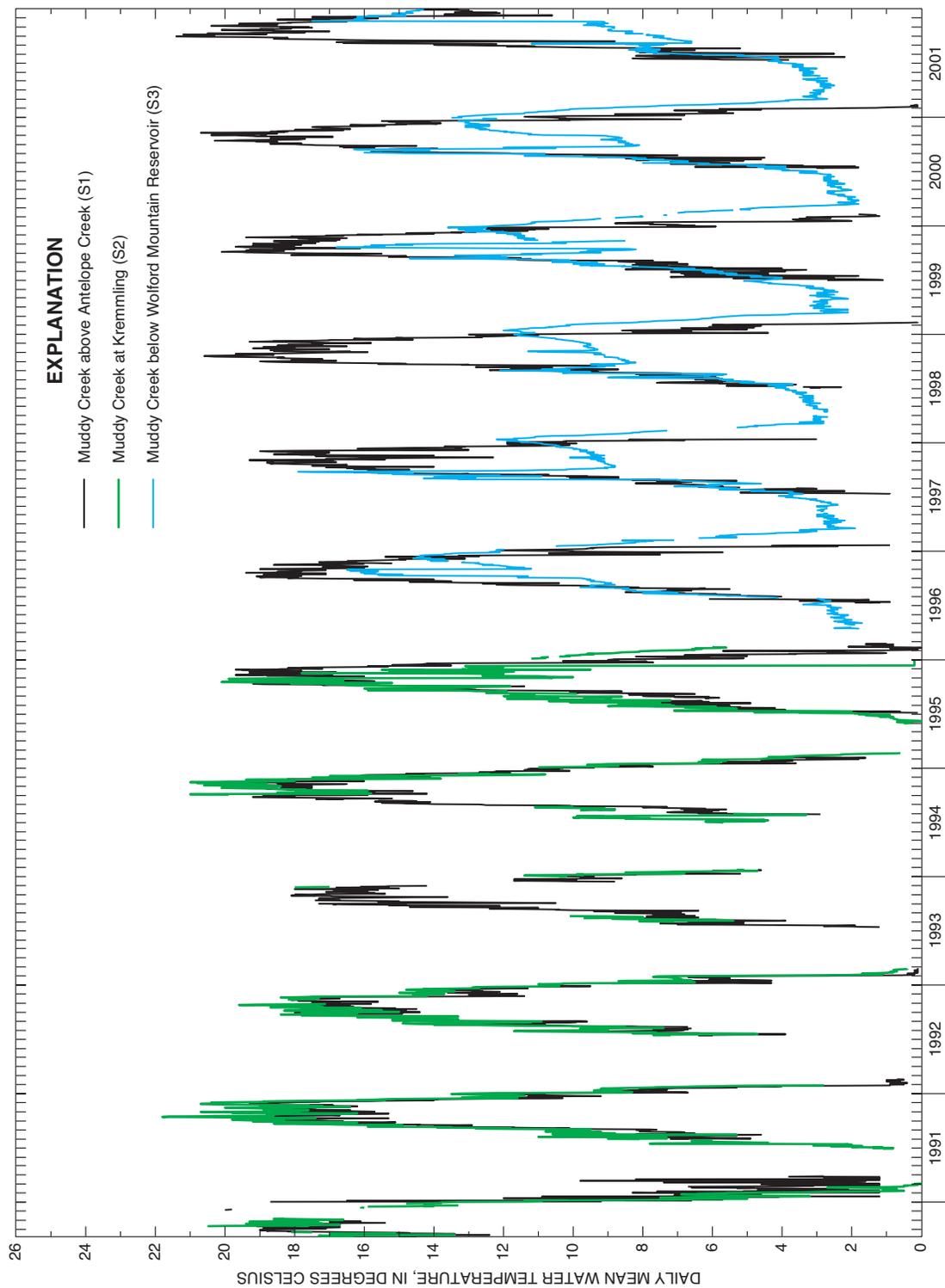


Figure 14. Daily mean water temperature upstream and downstream from Wolford Mountain Reservoir.

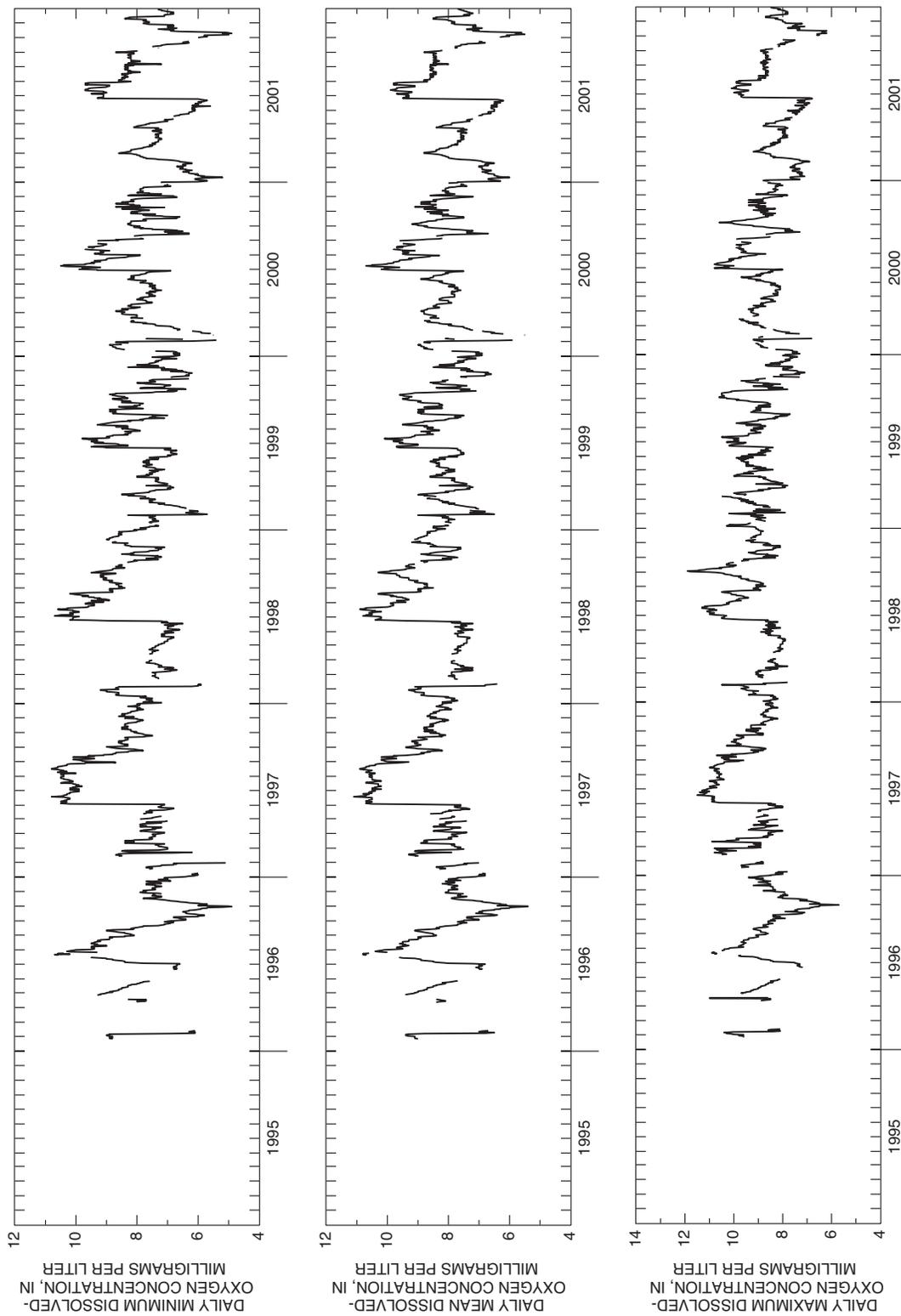


Figure 15. Daily minimum, mean, and maximum dissolved-oxygen concentrations at Muddy Creek below Wolford Mountain Reservoir.

Temporal variability in major ions was tested by SKT (table 9). At site S1 1990 to 2001, similar to the specific conductance results, calcium and sulfate (the predominant ionic species) had no significant temporal trend. Significant trends ( $p$ -value less than 0.01) were identified for ANC (downward), magnesium (upward), and silica (upward). For combined S2/S3 1990 to 2001 data, all major ions except calcium and ANC (no significant trends) had downward trends ( $p$ -value less than 0.10). These trends indicate that natural stream major-ion chemistry has not changed much during the period of record, and concentrations at downstream sites affected by the reservoir have decreased. As for specific conductance, the downward trend downstream from the reservoir site (table 6) probably was caused by the mixing of a large volume of relatively low-ionic strength water from runoff in the reservoir that subsequently was released throughout the year.

Spatial variability of almost all major ions was significant ( $p$ -value less than 0.10) in prereservoir and postconstruction periods (table 10). Median concentration for prereservoir upstream sulfate was 91.5 compared to 360 mg/L downstream. Median concentration for postconstruction upstream sulfate was 91.0 compared to 197 mg/L downstream. This similarity indicates that the marine shales and irrigation return flows have increased major ions in prereservoir and postconstruction periods in the reach between S1 and S2/S3, but the larger concentrations downstream have been moderated during the postconstruction period.

**Table 8.** Statistical summary of major-ion data at S1 and S2/S3 from April 1990 through March 1995 before storage began in the reservoir, S1 and S2/S3 combined from April 1990 through October 2001, and S1 and S2/S3 from April 1995 to September 2001 after storage began in the reservoir.

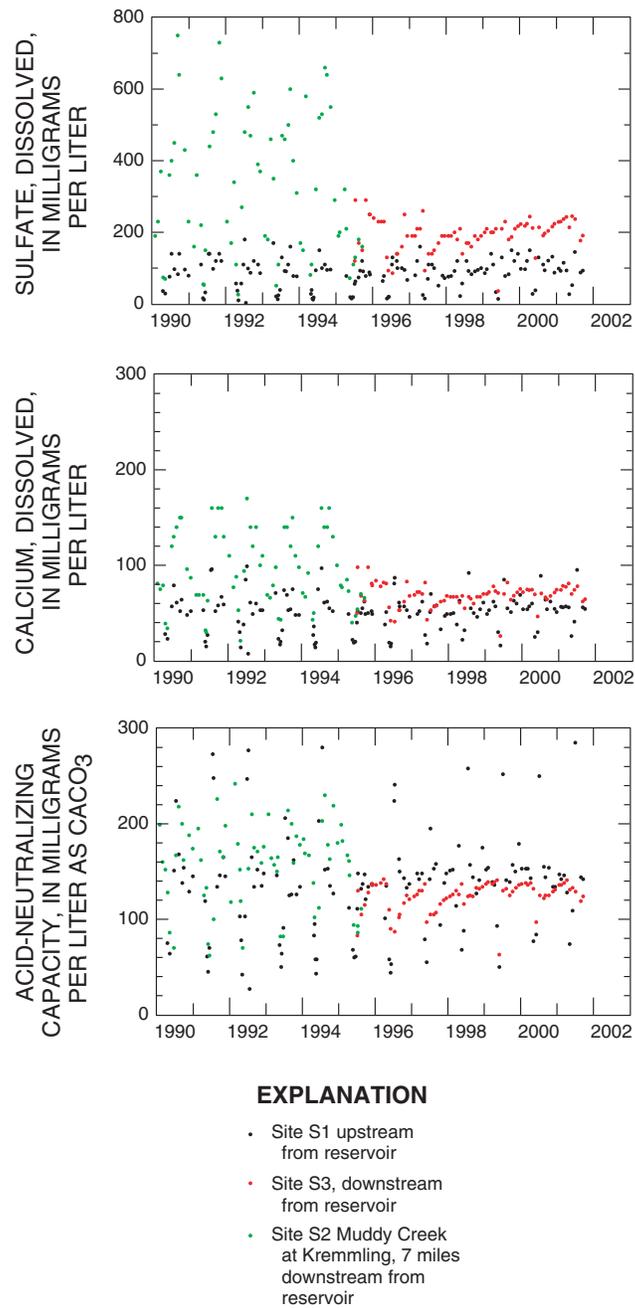
[<, less than; mg/L, milligrams per liter]

Constituent or property	Minimum	25th percentile	Median	75th percentile	Maximum	Number of samples
<b>Site S1 1990 through 2001</b>						
Hardness, total (mg/L as CaCO <sub>3</sub> )	24	140	190	220	370	133
Calcium, dissolved (mg/L as Ca)	7.4	38	52	60	99	133
Magnesium, dissolved (mg/L as Mg)	1.3	9.7	15	18	30	133
Potassium, dissolved (mg/L as K)	0.7	1.4	1.8	2.2	8.4	133
Sodium, dissolved (mg/L as Na)	2.5	11	17	20	48	133
Acid-neutralizing capacity, alkalinity, lab, as CaCO <sub>3</sub>	27	101	138	153	280	133
Chloride, dissolved (mg/L as Cl)	.2	1.0	1.8	2.3	14	133
Fluoride, dissolved (mg/L as F)	<.1	0.1	0.2	0.2	0.5	133
Silica, dissolved (mg/L as SiO <sub>2</sub> )	2	7.3	8.4	10	12	133
Sulfate, dissolved (mg/L as SO <sub>4</sub> )	3	56	91	110	180	133
Dissolved solids, sum of constituents (mg/L)	38	191	266	318	535	134
<b>Site S2/S3 combined 1990 through 2001</b>						
Hardness, total (mg/L as CaCO <sub>3</sub> )	71	250	290	390	790	140
Calcium, dissolved (mg/L as Ca)	21	64	72	92	170	140
Magnesium, dissolved (mg/L as Mg)	4.4	22	27	36	100	140
Potassium, dissolved (mg/L as K)	.5	2.2	2.4	2.8	7	140
Sodium, dissolved (mg/L as Na)	4.7	23	28	39	120	140
Acid-neutralizing capacity, alkalinity, lab, as CaCO <sub>3</sub>	62	122	133	162	242	140
Chloride, dissolved (mg/L as Cl)	.1	2.4	3	4.6	14	140
Fluoride, dissolved (mg/L as F)	<.1	.2	.2	.2	1	140
Silica, dissolved (mg/L as SiO <sub>2</sub> )	.1	7.4	8.1	9.1	14	140
Sulfate, dissolved (mg/L as SO <sub>4</sub> )	26	170	210	295	750	140
Dissolved solids, sum of constituents (mg/L)	107	375	434	595	1,220	139
<b>Site S1 pre-reservoir 1990 through 1995</b>						
Hardness, total (mg/L as CaCO <sub>3</sub> )	24	96	190	228	370	54
Calcium, dissolved (mg/L as Ca)	7.4	28	52	62	99	54
Magnesium, dissolved (mg/L as Mg)	1.3	6.5	14	17	30	54
Potassium, dissolved (mg/L as K)	.7	1.4	1.9	2.1	3.5	54
Sodium, dissolved (mg/L as Na)	2.5	6.7	16	20	48	54
Acid-neutralizing capacity, alkalinity, lab, as CaCO <sub>3</sub>	27	79	134	154	280	54
Chloride, dissolved (mg/L as Cl)	.2	.8	1.7	2.6	5.8	54
Fluoride, dissolved (mg/L as F)	<.1	.1	.2	.2	.5	54
Silica, dissolved (mg/L as SiO <sub>2</sub> )	4.7	7.0	8.1	9.2	12	54
Sulfate, dissolved (mg/L as SO <sub>4</sub> )	3	36	92	110	180	54
Dissolved solids, sum of constituents (mg/L)	38	134	264	317	535	54

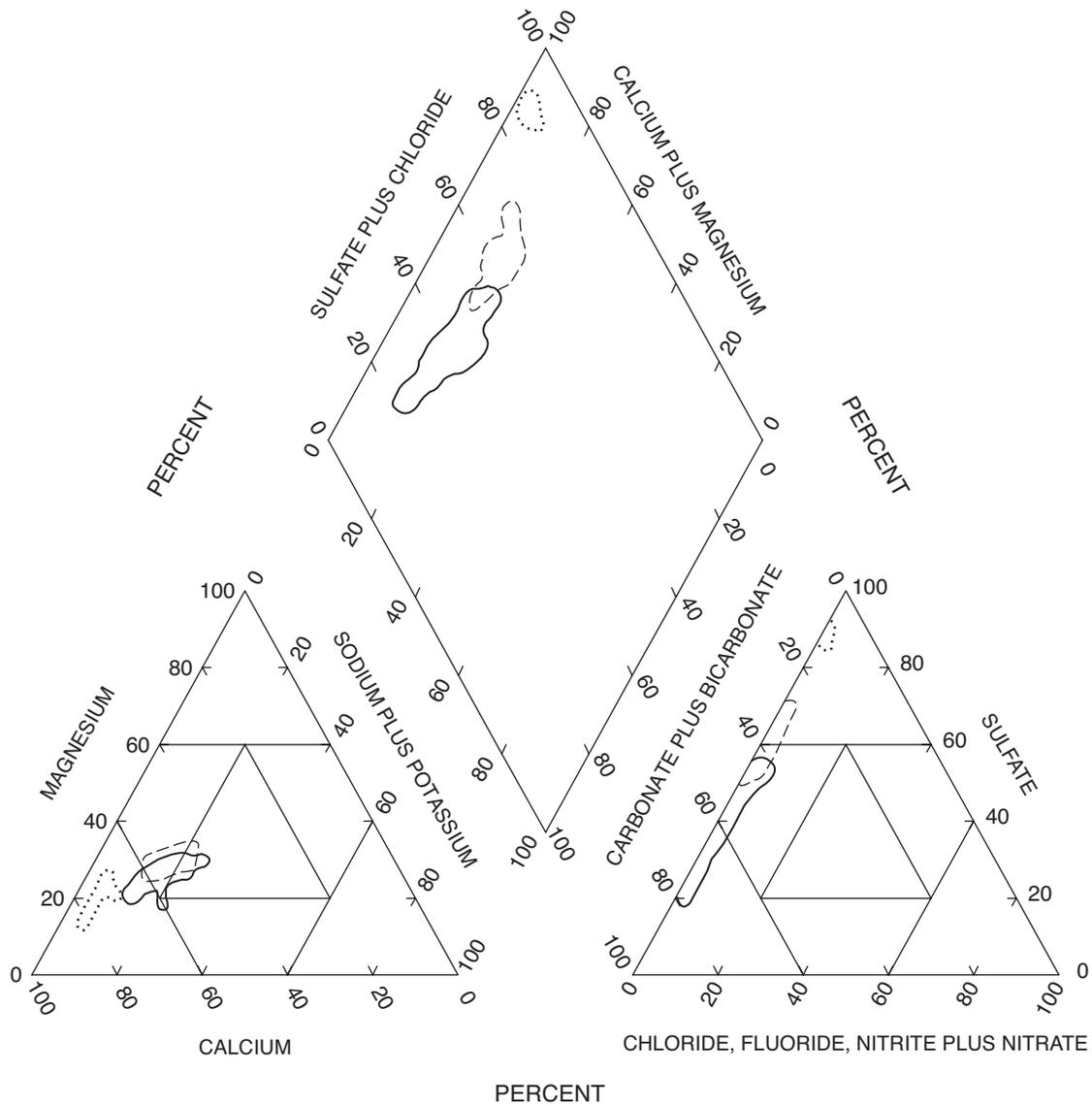
**Table 8.** Statistical summary of major-ion data at S1 and S2/S3 from April 1990 through March 1995 before storage began in the reservoir, S1 and S2/S3 combined from April 1990 through October 2001, and S1 and S2/S3 from April 1995 to September 2001 after storage began in the reservoir.—Continued

[<, less than; mg/L, milligrams per liter]

Constituent or property	Minimum	25th percentile	Median	75th percentile	Maximum	Number of samples
<b>Site S2/S3 pre-reservoir combined 1990 through 1995</b>						
Hardness, total (mg/L as CaCO <sub>3</sub> )	71	270	440	580	790	57
Calcium, dissolved (mg/L as Ca)	21	69	100	140	170	57
Magnesium, dissolved (mg/L as Mg)	4.4	24	45	55	100	57
Potassium, dissolved (mg/L as K)	1.1	2.4	2.9	3.6	7	57
Sodium, dissolved (mg/L as Na)	4.7	30	45	60	120	57
Acid-neutralizing capacity, alkalinity, lab, as CaCO <sub>3</sub>	62	150	167	188	242	57
Chloride, dissolved (mg/L as Cl)	.1	3.6	5	6.8	14	57
Fluoride, dissolved (mg/L as F)	<.1	.2	.3	.3	1	57
Silica, dissolved (mg/L as SiO <sub>2</sub> )	.4	6.7	8.5	10	14	57
Sulfate, dissolved (mg/L as SO <sub>4</sub> )	26	180	360	500	750	57
Dissolved solids, sum of constituents (mg/L)	107	429	670	857	1,220	56
<b>Site S1 post-construction April 1995 through Sept 2001</b>						
Hardness, total (mg/L as CaCO <sub>3</sub> )	51	160	190	220	330	79
Calcium, dissolved (mg/L as Ca)	15	44	52	57	92	79
Magnesium, dissolved (mg/L as Mg)	3.4	12	15	18	25	79
Potassium, dissolved (mg/L as K)	.7	1.5	1.8	2.2	8.4	79
Sodium, dissolved (mg/L as Na)	3.7	12	17	20	30	79
Acid-neutralizing capacity, alkalinity, lab, as CaCO <sub>3</sub>	44	113	141	152	258	79
Chloride, dissolved (mg/L as Cl)	.3	1.4	1.9	2.3	14	79
Fluoride, dissolved (mg/L as F)	<.1	.1	.2	.2	.3	79
Silica, dissolved (mg/L as SiO <sub>2</sub> )	2	7.9	8.7	10	12	79
Sulfate, dissolved (mg/L as SO <sub>4</sub> )	14	66	91	110	160	79
Dissolved solids, sum of constituents (mg/L)	77	237	268	317	441	80
<b>Sites S2/S3 post-construction combined 1995 through 2001</b>						
Hardness, total (mg/L as CaCO <sub>3</sub> )	88	250	270	300	390	83
Calcium, dissolved (mg/L as Ca)	26	63	69	74	98	83
Magnesium, dissolved (mg/L as Mg)	5.6	20	25	28	42	83
Potassium, dissolved (mg/L as K)	.5	2.1	2.3	2.5	3.2	83
Sodium, dissolved (mg/L as Na)	7.8	22	25	29	56	83
Acid-neutralizing capacity, alkalinity, lab, as CaCO <sub>3</sub>	63	118	128	136	161	83
Chloride, dissolved (mg/L as Cl)	.4	2.2	2.6	3.1	6.3	83
Fluoride, dissolved (mg/L as F)	<.1	.2	.2	.2	.3	83
Silica, dissolved (mg/L as SiO <sub>2</sub> )	.1	7.4	8.0	8.8	9.8	83
Sulfate, dissolved (mg/L as SO <sub>4</sub> )	36	170	197	223	320	83
Dissolved solids, sum of constituents (mg/L)	127	355	406	449	619	83



**Figure 16.** Time-series plots of selected major-ion constituents at Muddy Creek above Antelope Creek (upstream from reservoir) and Muddy Creek below Wolford Mountain Reservoir (directly below reservoir), and Muddy Creek at Kremmling (approximately 7 miles downstream from reservoir).



**EXPLANATION**

- Muddy Creek above Antelope Creek (site S1)
- - - Muddy Creek below Wolford Mountain Reservoir (site S3)
- ..... Alkali Slough #2 (site S4)

**Figure 17.** Major-ion composition of samples at selected sites.

**Table 9.** Summary of major-ion temporal variation upstream from reservoir by seasonal Kendall test for Muddy Creek above Antelope Creek (S1), and downstream combined data from Muddy Creek at Kremmling (S2) and Muddy Creek below Wolford Mountain Reservoir (S3), 1990 through 2001.

[>, greater than; --, slope not computed; mg/L, milligrams per liter; °C, degrees Celsius; slope, units per year; -, downward trend; unadj, not adjusted by flow-weighting; fwc, flow-weighted concentrations; *p*-values significant at greater than 90-percent confidence shown in bold]

Constituent or property	<i>p</i> -value	Significance > 90-percent confidence	Slope	Type
<b>Site S1 April 1990 through September 2001</b>				
Hardness, total (mg/L)	0.1755	No	1.25	unadj
Calcium, dissolved (mg/L)	.2358	No	0.30	unadj
Magnesium, dissolved (mg/L)	<b>.0284</b>	Yes	.15	unadj
Potassium, dissolved (mg/L)	.9817	No	--	unadj
Sodium adsorption ratio	.1139	No	--	unadj
Sodium, dissolved (mg/L)	.1883	No	.13	unadj
Sodium (percent)	.1743	No	--	unadj
Acid-neutralizing capacity, dissolved (mg/L as CaCO <sub>3</sub> )	.0416	Yes	-1.95	fwc
Chloride, dissolved (mg/L)	.5781	No	.01	unadj
Fluoride, dissolved (mg/L)	.8833	No	--	unadj
Silica, dissolved (mg/L)	.0425	Yes	.08	unadj
Sulfate, dissolved (mg/L)	.9823	No	--	unadj
Residue, dissolved, at 180°C (mg/L)	.0394	Yes	2.73	unadj
Dissolved solids, sum of constituents (mg/L)	.2167	No	1.50	unadj
<b>Site S2/S3 April 1990 through September 2001</b>				
Hardness, total (mg/L)	.0228	Yes	-9.25	fwc
Calcium, dissolved (mg/L)	.2128	No	-1.50	unadj
Magnesium, dissolved (mg/L)	.0226	Yes	-1.04	fwc
Potassium, dissolved (mg/L)	.0181	Yes	-.08	unadj
Sodium adsorption ratio	.2775	No	--	unadj
Sodium, dissolved (mg/L)	.0215	Yes	-1.20	fwc
Acid-neutralizing capacity, dissolved (mg/L as CaCO <sub>3</sub> )	.1676	No	-3.00	unadj
Chloride, dissolved (mg/L)	.0985	Yes	-.20	unadj
Fluoride, dissolved (mg/L)	.0219	Yes	-.00	unadj
Silica, dissolved (mg/L)	.0087	Yes	-.15	unadj
Sulfate, dissolved (mg/L)	.0215	Yes	-9.17	fwc
Residue, dissolved, at 180°C (mg/L)	.0228	Yes	-15.42	fwc
Dissolved solids, sum of constituents (mg/L)	.0228	Yes	-14.58	fwc

**Table 10.** Summary of upstream/downstream major-ion differences at Muddy Creek above Antelope (S1) and Muddy Creek at Kremmling (S2), 1990 through 1995, and differences at Muddy Creek above Antelope (S1) and Muddy Creek below Wolford Mountain Reservoir (S3), 1995 through 2001 by Wilcoxon signed-rank test.

[2-sided test; mg/L, milligrams per liter; *p*-values significant at greater than 90-percent confidence shown in bold]

Constituent	<i>p</i> -value	Median	
		Upstream	Downstream
<b>April 1990 through March 1995</b>			
Hardness, total (mg/L)	<b>&lt;0.0001</b>	190	440
Calcium, dissolved (mg/L)	<b>&lt;.0001</b>	52.5	100
Magnesium, dissolved (mg/L)	<b>&lt;.0001</b>	14	45
Potassium, dissolved (mg/L)	<b>&lt;.0001</b>	1.9	2.9
Sodium, dissolved (mg/L)	<b>&lt;.0001</b>	16	45
Acid-neutralizing capacity, dissolved (mg/L as CaCO <sub>3</sub> )	<b>0.0003</b>	134	167
Chloride, dissolved (mg/L)	<b>&lt;.0001</b>	1.7	5
Silica, dissolved (mg/L)	.3525	8.1	8.5
Sulfate, dissolved (mg/L)	<b>&lt;.0001</b>	91.5	360
Dissolved solids, sum of constituents (mg/L)	<b>&lt;.0001</b>	264	670
<b>April 1995 through September 2001</b>			
Hardness, total (mg/L)	<b>&lt;.0001</b>	190	270
Calcium, dissolved (mg/L)	<b>&lt;.0001</b>	52	69
Magnesium, dissolved (mg/L)	<b>&lt;.0001</b>	15	25
Potassium, dissolved (mg/L)	<b>&lt;.0001</b>	1.8	2.3
Sodium, dissolved (mg/L)	<b>&lt;.0001</b>	17	25
Acid-neutralizing capacity, dissolved (mg/L as CaCO <sub>3</sub> )	<b>&lt;.0001</b>	141	128
Chloride, dissolved (mg/L)	<b>&lt;.0001</b>	1.9	2.6
Silica, dissolved (mg/L)	<b>.0009</b>	8.7	8
Sulfate, dissolved (mg/L)	<b>&lt;.0001</b>	91	197
Dissolved solids, sum of constituents (mg/L)	<b>&lt;.0001</b>	268	406

## Nutrients

Summary statistics for nutrients and organic carbon were compiled for three streamwater-quality sites in this study (table 11). Boxplots of selected constituents by site are shown in figure 11. Time-series plots of selected nutrients and organic carbon from 1990 through 2001 for upstream (S1), downstream (S3), and prereservoir downstream (S2) sites are shown in figure 18.

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 in streams and reservoirs (causing eutrophication). Natural sources of nutrients include precipitation and biochemical processes in the watershed. Anthropogenic sources of nutrients include urban runoff, domestic effluent, livestock waste, and erosion caused by development.

Nutrient concentrations at Muddy Creek sites generally are low (fig. 18) (table 11). Data censoring levels changed somewhat throughout the period of record and, at times, were of insufficient precision or too high to fully characterize nutrient concentrations. Median concentrations of ammonia plus organic nitrogen were less than 0.4 mg/L at all Muddy Creek sites. Median concentrations of dissolved nitrite plus nitrate were generally less than 0.13 mg/L. Median concentrations of total phosphorus were less than 0.05 mg/L at all sites. Concentrations of nitrite and orthophosphorus were rarely greater than minimum reporting limits. The smallest nutrient concentrations were generally measured at Muddy Creek above Antelope Creek (S1). Largest nutrient concentrations tended to be at Muddy Creek at Kremmling (S2) and Muddy Creek below Wolford Mountain Reservoir (S3). Concentrations of dissolved organic carbon ranged from 3.6 to 10 mg/L at S1 and S2/S3. Concentrations of total organic carbon ranged from 3.5 to 21 mg/L.

**36 Hydrology and Water-Quality Characteristics of Muddy Creek and Wolford Mountain Reservoir near Kremmling, Colorado, 1990 through 2001**

**Table 11.** Statistical summary of nutrient and carbon data at S1 and S2/S3 from April 1990 through March 1995 before storage began in the reservoir, S1 and S2/S3 combined from April 1990 through October 2001, and S1 and S2/S3 from April 1995 to September 2001 after storage began in the reservoir.

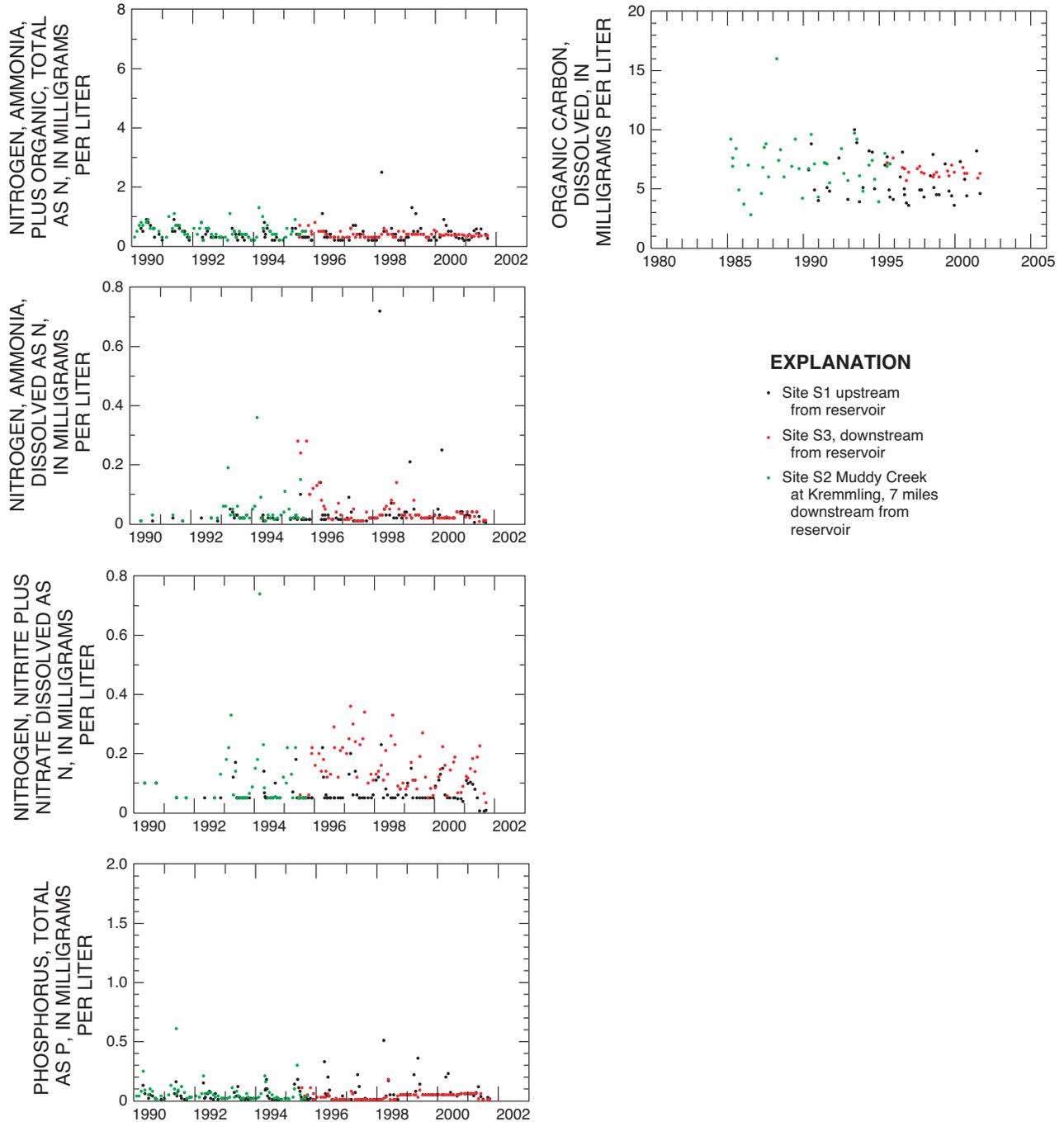
[<, less than; mg/L, milligrams per liter]

Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Number of samples
<b>Site S1 1990 through 2001</b>						
Nitrogen, ammonia plus organic, dissolved (mg/L as N)	<0.2	0.2	0.2	0.4	2	106
Nitrogen, ammonia plus organic, total (mg/L as N)	<.2	.3	.4	.5	2.5	131
Nitrogen, ammonia, dissolved (mg/L as N)	<.01	<.02	.02	.03	0.72	108
Nitrogen, nitrite plus nitrate, dissolved (mg/L as N)	<.05	<.05	<.05	.08	.23	108
Nitrogen, nitrite, dissolved (mg/L as N)	<.01	<.01	<.01	.01	.03	108
Phosphorus, dissolved (mg/L as P)	<.01	<.01	<.01	.05	.32	108
Phosphorus, dissolved orthophosphate (mg/L as P)	<.01	<.01	<.01	.01	.26	108
Phosphorus, total (mg/L as P)	<.01	<.01	.04	.06	.51	131
Carbon, organic, dissolved (mg/L as C)	3.6	4.4	5	7.2	10	43
Carbon, total (mg/L as C)	3.5	4.9	7.4	8.6	15	23
<b>Site S2/S3 combined 1990 through 2001</b>						
Nitrogen, ammonia plus organic, dissolved (mg/L as N)	.2	.3	.3	.4	1.2	112
Nitrogen, ammonia plus organic, total (mg/L as N)	.2	.3	.4	.5	1.3	139
Nitrogen, ammonia, dissolved (mg/L as N)	<.02	<.02	.03	.05	.36	139
Nitrogen, nitrite plus nitrate, dissolved (mg/L as N)	<.05	.08	.11	.19	.74	138
Nitrogen, nitrite, dissolved (mg/L as N)	<.01	<.01	<.01	.01	.07	134
Phosphorus, dissolved (mg/L as P)	<.01	<.01	.02	.05	.11	114
Phosphorus, dissolved orthophosphate (mg/L as P)	<.01	<.01	<.01	.02	.26	139
Phosphorus, total (mg/L as P)	<.01	.02	.04	.06	.61	140
Carbon, organic, dissolved (mg/L as C)	3.9	6.1	6.6	7.1	9.7	46
Carbon, total (mg/L as C)	4.1	6.3	8.2	9.6	21	24
<b>Site S1 pre-reservoir 1990 through 1995</b>						
Nitrogen, ammonia plus organic, dissolved (mg/L as N)	<.2	<.2	.2	.4	.5	28
Nitrogen, ammonia plus organic, total (mg/L as N)	<.2	.3	.4	.6	.9	53
Nitrogen, ammonia, dissolved (mg/L as N)	<.02	<.02	.02	.02	.05	29
Nitrogen, nitrite plus nitrate, dissolved (mg/L as N)	<.05	<.05	<.05	<.05	.17	29
Nitrogen, nitrite, dissolved (mg/L as N)	<.01	<.01	<.01	<.01	.02	29
Phosphorus, dissolved (mg/L as P)	<.01	<.01	<.01	.02	.04	29
Phosphorus, dissolved orthophosphate (mg/L as P)	<.01	<.01	<.01	<.01	.03	29
Phosphorus, total (mg/L as P)	<.01	.01	.02	.06	.18	52
Carbon, organic, dissolved (mg/L as C)	3.9	4.9	5.8	8.1	10	16
Carbon, total (mg/L as C)	3.5	4.9	7.4	8.6	15	18
<b>Site S2/S3 pre-reservoir combined 1990 through 1995</b>						
Nitrogen, ammonia plus organic, dissolved (mg/L as N)	<.2	.2	.3	.5	1.2	30
Nitrogen, ammonia plus organic, total (mg/L as N)	.2	.3	.4	.6	1.3	56
Nitrogen, ammonia, dissolved (mg/L as N)	.01	.02	.03	.06	.36	57
Nitrogen, nitrite plus nitrate, dissolved (mg/L as N)	<.05	.09	.1	.12	.74	56
Nitrogen, nitrite, dissolved (mg/L as N)	<.01	<.01	<.01	.02	.07	52
Phosphorus, dissolved (mg/L as P)	<.01	<.01	<.01	.02	.11	32
Phosphorus, dissolved orthophosphate (mg/L as P)	<.01	<.01	<.01	.02	.26	57

**Table 11.** Statistical summary of nutrient and carbon data at S1 and S2/S3 from April 1990 through March 1995 before storage began in the reservoir, S1 and S2/S3 combined from April 1990 through October 2001, and S1 and S2/S3 from April 1995 to September 2001 after storage began in the reservoir.—Continued

[<, less than; mg/L, milligrams per liter]

Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Number of samples
<b>Site S2/S3 pre-reservoir combined 1990 through 1995—Continued</b>						
Phosphorus, total (mg/L as P)	<.01	.02	.04	.07	.61	57
Carbon, organic, dissolved (mg/L as C)	3.9	5.7	6.8	7.4	9.7	18
Carbon, total (mg/L as C)	4.1	5.6	8.2	9.8	21	18
<b>Site S1 post-construction April 1995 through Sept 2001</b>						
Nitrogen, ammonia plus organic, dissolved (mg/L as N)	<.2	.2	.2	.3	2	79
Nitrogen, ammonia plus organic, total (mg/L as N)	.2	.2	.3	.5	2.5	79
Nitrogen, ammonia, dissolved (mg/L as N)	<.02	<.02	<.02	.03	.72	80
Nitrogen, nitrite plus nitrate, dissolved (mg/L as N)	<.05	<.05	.05	.08	.23	80
Nitrogen, nitrite, dissolved (mg/L as N)	.002	.01	.01	.01	.03	80
Phosphorus, dissolved (mg/L as P)	<.01	<.01	<.01	.05	.32	80
Phosphorus, dissolved orthophosphate (mg/L as P)	<.01	<.01	<.01	.02	.26	80
Phosphorus, total (mg/L as P)	<.01	<.01	.05	.07	.51	80
Carbon, organic, dissolved (mg/L as C)	3.6	4.4	4.9	6.6	8.2	27
Carbon, total (mg/L as C)	4.5	4.9	5	8.5	12	5
<b>Sites S2/S3 post-construction combined 1995 through 2001</b>						
Nitrogen, ammonia plus organic, dissolved (mg/L as N)	.2	.3	.3	.4	.7	82
Nitrogen, ammonia plus organic, total (mg/L as N)	.3	.3	.4	.5	.9	83
Nitrogen, ammonia, dissolved (mg/L as N)	<.02	<.02	.03	.05	.28	82
Nitrogen, nitrite plus nitrate, dissolved (mg/L as N)	.03	.08	.13	.2	.36	82
Nitrogen, nitrite, dissolved (mg/L as N)	<.01	<.01	<.01	.01	.03	82
Phosphorus, dissolved (mg/L as P)	<.01	<.01	.02	.05	.06	82
Phosphorus, dissolved orthophosphate (mg/L as P)	<.01	<.01	<.01	.02	.05	82
Phosphorus, total (mg/L as P)	<.01	<.01	.05	.05	.3	83
Carbon, organic, dissolved (mg/L as C)	5.7	6.3	6.4	6.9	8	28
Carbon, total (mg/L as C)	7.7	8.0	8.3	8.9	17	6



**Figure 18.** Time-series plots of selected nutrient and organic carbon constituents at Muddy Creek above Antelope Creek (upstream from reservoir) and Muddy Creek below Wolford Mountain Reservoir (directly downstream from reservoir), and Muddy Creek at Kremmling (site located approximately 7 miles downstream from reservoir).

Seasonal variability of nutrient concentrations generally was proportional to streamflow. Smallest concentrations for total ammonia plus organic nitrogen as N and total phosphorus as P occurred in late summer and winter low flow (July to March) (fig. 18). Largest concentrations were several times those at low flow and occurred during spring runoff (April to June). Concentrations of nitrite plus nitrate and ammonia tended to be largest in winter and early runoff and lowest during late summer and fall. Seasonal variability of organic carbon showed large concentrations in early runoff and high runoff and low concentrations during low-flow periods. Dissolved organic carbon is flushed from soils during runoff, and particulate carbon is transported during high flows when sediments enter Muddy Creek.

Temporal variability of nutrients were tested by SKT (table 12). Not all nutrient species had sufficient data greater than the MRL and, thus, were not tested. At site S1, an increasing temporal trend in total phosphorus was calculated, but insufficient data above MRL prevented the computation of slope. At S2/S3, there was a significant ( $p$ -value less than .10) downward trend in total ammonia plus organic nitrogen. This downward trend downstream from the reservoir site may have been caused by the settling of particulate organic nitrogen or biological uptake in the reservoir.

There were no statistically significant spatial trends for total ammonia plus organic nitrogen (table 13) indicating no statistical evidence of a difference in concentration between S1 and S2/S3. Other nutrient species had insufficient data above MRL for testing.

An inflow/outflow mass balance of total nitrogen and total phosphorus was computed to indicate how the reservoir is affecting the transport of nutrients in Muddy Creek. The annual (1996–2001) mass-balance results are summarized in table 14. Graphical presentation of selected components of the mass balance is in figures 19 to 21. A more detailed listing of calculations is in the “Hydrologic and Water-Quality Data” section at the back of this report in tables 15 and 16.

Analysis of nutrient mass balance in Wolford Mountain Reservoir provided insight into the effect of the reservoir on nutrient transport. The following interpretations are made about the nitrogen mass balance during the growing season:

1. Inflow and outflow water discharge (a component of the load calculation) peaked in 1997 and generally has decreased through 2001;
2. Inflow and outflow mass of nitrogen generally decreased from 1997 to 2001, following patterns of inflow and outflow water discharge;

3. Mass of nitrogen in outflow from the reservoir substantially exceeded nitrogen in inflow from 1997 to 1998 (years of larger outflow), whereas nitrogen was gained or approximately balanced in inflow and outflow during years of smaller outflows; and
4. Nitrogen mass in inflow generally was larger than mass in outflow during runoff and generally smaller than mass in outflow during low flow, indicating that some nitrogen was stored in the water column and gain/loss patterns for total nitrogen are related to reservoir storage.

The following observations can be made about the phosphorus mass balance:

1. Phosphorus was gained every year to the reservoir, and as a percentage, more phosphorus was retained than nitrogen in years when both were retained in the reservoir;
2. Phosphorus gained to the reservoir probably was related to settling or biological uptake;
3. Less phosphorus was gained to the reservoir in 1998, when outflow exceeded inflow by 27 percent;
4. Inflow mass of phosphorus generally followed patterns of inflow water discharge (fig. 19), which decreased from 1997 to 2001, but the outflow mass of phosphorus had a poor relation to outflow; and
5. Phosphorus mass in inflow generally was larger than mass in outflow during all seasons (fig. 21), indicating that little phosphorus is available in the water column at the outflow, and reservoir water-column storage did not affect phosphorus outflow loading patterns as much as settling.

These observations indicate that, in general, nutrient transport in the inflow was proportional to the amount of water discharge in a given year. Some nitrogen was stored in the water column, and gain/loss patterns for total nitrogen were somewhat related to reservoir storage. Mass of outflow nitrogen was more proportional to outflow volume than mass of outflow phosphorus to outflow volume. Nitrogen tended to move through the reservoir, whereas phosphorus was trapped mostly within the reservoir. Little phosphorus was available in the water column at the outflow, and reservoir water-column storage did not affect phosphorus outflow loading patterns as much as settling.

**40 Hydrology and Water-Quality Characteristics of Muddy Creek and Wolford Mountain Reservoir near Kremmling, Colorado, 1990 through 2001**

**Table 12.** Summary of nutrient temporal variation upstream from reservoir by seasonal Kendall test for Muddy Creek above Antelope Creek (S1), and downstream combined data from Muddy Creek at Kremmling (S2) and Muddy Creek below Wolford Mountain Reservoir (S3), 1990 through 2001.

[>, greater than; --, slope not computed; mg/L, milligrams per liter; slope, units per year; -, downward trend; *p*-values significant at greater than 90-percent confidence shown in bold; unadj, not adjusted by flow-weighting]

Constituent	<i>p</i> -value	Significance > 90-percent confidence	Slope	Type
<b>Site S1 April 1990 through September 2001</b>				
Nitrogen, ammonia plus organic, (mg/L as N) total	0.1375	No	--	unadj
Nitrogen, ammonia plus organic, (mg/L as N) dissolved	.3263	No	--	unadj
Nitrogen, ammonia, dissolved (mg/L as N)	.2296	No	--	unadj
Phosphorus, total (mg/L as P)	.0935	Yes	0	unadj
<b>Site S2/S3 April 1990 through September 2001</b>				
Nitrogen, ammonia plus organic, (mg/L as N) total	.0237	Yes	-0.02	unadj
Nitrogen, ammonia, dissolved (mg/L as N)	.6266	No	--	unadj
Phosphorus, total (mg/L as P)	.7377	No	--	unadj

**Table 13.** Summary of upstream/downstream differences in nitrogen Muddy Creek above Antelope (S1) and Muddy Creek at Kremmling (S2), 1990 through 1995, and differences at Muddy Creek above Antelope (S1) and Muddy Creek below Wolford Mountain Reservoir (S3), 1995 through 2001, by Wilcoxon signed-rank test.

[2-sided test; mg/L, milligrams per liter; *p*-values significant at greater than 90-percent confidence shown in bold]

Constituent	<i>p</i> -value	Median	
		Upstream	Downstream
<b>April 1990 through March 1995</b>			
Nitrogen, ammonia plus organic, (mg/L as N) total	0.2115	0.4	0.4
<b>April 1995 through September 2001</b>			
Nitrogen, ammonia plus organic, (mg/L as N) total	.1128	.3	.4

**Table 14.** Mass-balance calculations for total nitrogen and total phosphorus in Wolford Mountain Reservoir, 1996 to 2001.

[From equation 1: Unaccounted-for mass (UMS) = Inflow mass (IMS) - Outflow mass (OMS); negative UMS is mass lost, positive UMS is mass gained by the reservoir; inflow and outflow in acre-feet per year; mass in kilograms per year; N, total nitrogen; P, total phosphorus; inflow and outflow of Muddy Creek in acre-feet during calendar year; mass terms are in kilograms during calendar year]

**(A) Nitrogen**

Year	Inflow	Outflow	IMS	OMS	UMS
Total nitrogen mass, in kilograms					
<sup>a</sup> 1996	68,910	74,880	49,168	48,999	169
1997	82,273	104,080	66,363	71,681	-5318
1998	55,538	76,390	45,365	57,667	-12,302
1999	41,825	57,520	45,346	34,314	11,032
2000	47,978	62,820	43,784	40,481	3,303
<sup>b</sup> 2001	29288	39,450	21,935	23,319	-1,384
Total phosphorus mass, in kilograms					
<sup>a</sup> 1996	68,910	74,880	14,989	2,942	12,047
1997	82,273	104,080	15,144	1,483	13,661
1998	55,538	76,390	9,302	7,129	2,173
1999	41,825	57,520	11,788	2,355	9,433
2000	47,978	62,820	10,980	513	10,467
<sup>b</sup> 2001	29288	39,450	3,351	875	2,476

<sup>a</sup>April through December.

<sup>b</sup>January through October.

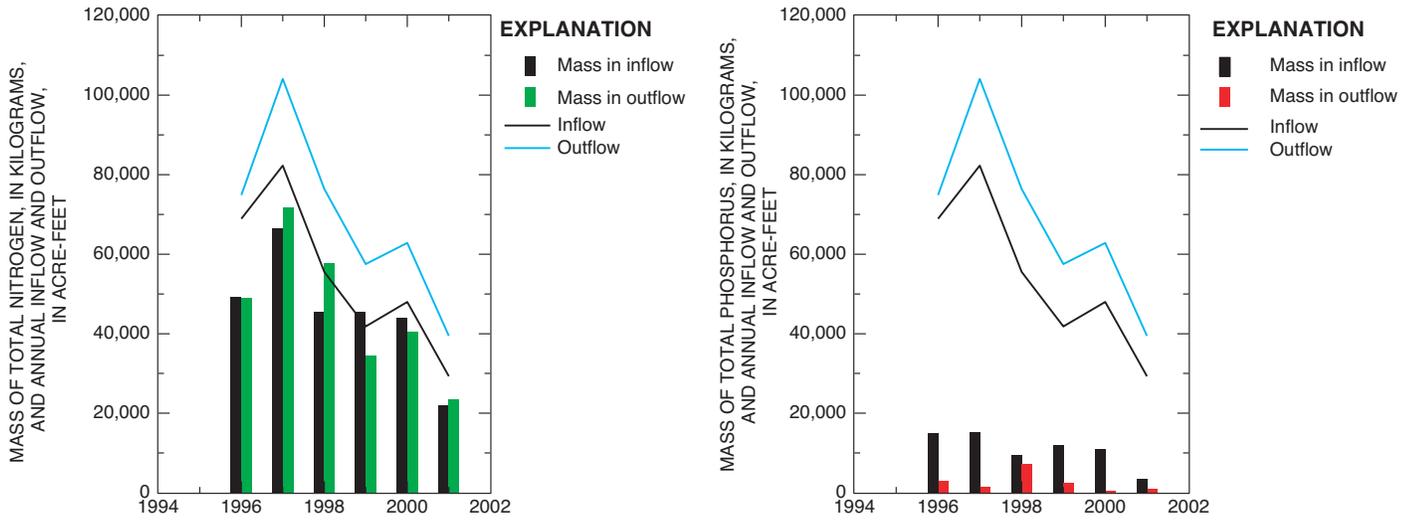


Figure 19. Nitrogen and phosphorus loads in Muddy Creek inflow and outflow to Wolford Mountain Reservoir (calendar years 1996 to 2001).

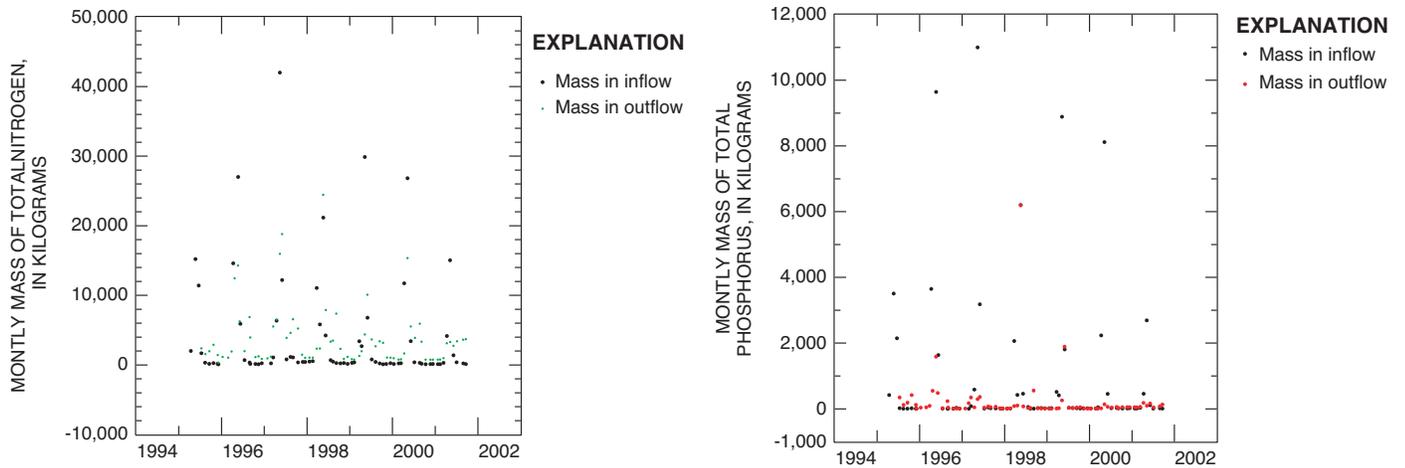


Figure 20. Monthly inflow and outflow mass of total nitrogen and total phosphorus (calendar years 1996 to 2001).

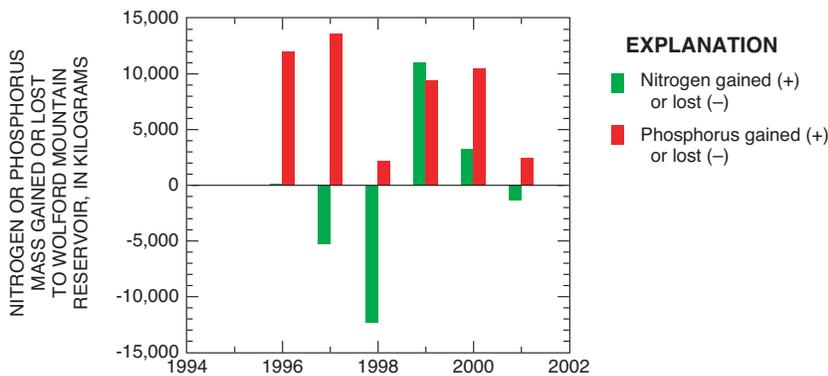


Figure 21. Total nitrogen and phosphorus load gained or lost in the reservoir mass balance (calendar years 1996 to 2001).

## Trace Elements

Summary statistics for trace-element concentrations were compiled for three streamwater-quality sites in this study (table 17). Boxplots of dissolved iron and dissolved manganese by site are shown in figure 11. Time-series plots of dissolved iron, dissolved manganese, and dissolved copper from 1990 to present for upstream (S1), downstream (S3), and prereservoir downstream (S2) sites are shown in figure 22.

For the purpose of this report, trace elements are metal and transition metal elements generally occurring in small (less than 1 mg/L) concentrations (table 17). Trace elements commonly detected at most sites in this study were aluminum, barium, copper, iron, manganese, nickel, selenium, and zinc. Trace elements infrequently detected at most sites were arsenic, boron, cadmium, chromium, cobalt, lead, molybdenum, and silver during the 1990 to 2001 period. For elements such as barium, copper, iron, manganese, and nickel, total-recoverable concentrations usually were larger than dissolved concentrations, indicating the presence of particulate-phase trace elements (greater than 0.45 microns). 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). Sources of the more toxic trace elements are generally associated with ore deposits or urban runoff. The relative lack of ore deposits and the relatively low density of urban development in the drainage area of Muddy Creek may limit concentrations of trace elements to relatively low concentrations.

Seasonal variability of concentrations of dissolved and total-recoverable iron and manganese seemed to be related to seasonal patterns of streamflow (proportional to flow) at S1 (unaffected by reservoir) and prereservoir S2/S3. After reservoir completion (1995), seasonal fluctuations in dissolved iron and manganese concentrations stabilized at S2/S3 (fig. 22).

Temporal variability in dissolved and total-recoverable iron and manganese was tested by SKT (table 18). At site S1 (1990 to 2001), dissolved iron had a significant ( $p$ -value less than 0.10) upward trend. At S2/S3 (1990 to 2001), dissolved and total-recoverable iron and manganese showed downward trends ( $p$ -value less than 0.10). This indicates that the downward trends downstream from the reservoir site probably were caused by settling in the reservoir and mixing of first-flush concentrations within the reservoir.

Spatial variability for iron and manganese is shown in table 19. Dissolved and total manganese increased significantly ( $p$ -value less than 0.10) from upstream to downstream during

the prereservoir period (April 1990 through March 1995).

These increases likely were caused by loads contributed by tributaries and ground-water inflow downstream. Total iron and dissolved and total-recoverable manganese medians were significantly decreased at the downstream site when compared to the upstream site in postconstruction (April 1995 through September 2001). These differences likely were caused by settling and mixing in the reservoir.

## Biological Indicators

Bacteria were sampled only from 1999 through 2001. Summary statistics were compiled for two streamwater-quality sites in this study (table 20). Time-series plots of bacteria data from 1999 to 2001 for upstream (S1) and downstream (S3) are shown in figure 23.

*E. coli* counts ranged from less than 1 to 130 colonies per 100 mL at S1 upstream from the reservoir and were not detected at S3 (table 20). Similarly, fecal coliform ranged from less than 1 to greater than 120 colonies per 100 mL at S1 and less than 1 to 1 at S3 with only two samples reported at 1 colony per 100 mL. The higher bacteria counts occurred at S1 during the summer season (fig. 23). The comparison of S1 and S3 data indicates that bacteria do not survive in the reservoir or rapidly settle out with suspended material and, therefore, were not detected in the outflow at S3.

## Suspended Sediment

Suspended sediment and turbidity were sampled at S1 and S2 because of concerns about the effect of substantial sediment loads to Wolford Mountain Reservoir. 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. Summary statistics of suspended-sediment concentrations are listed in table 21. Suspended-sediment concentrations ranged from small (4 mg/L) during low flow to as much as 2,800 mg/L during high snowmelt (table 21). Median concentrations of suspended sediment at S1 and S2 (prereservoir) were approximately equal. Starting in 1996, suspended sediment was not sampled downstream from the reservoir. In general, suspended-sediment discharge was positively correlated with streamflow in Muddy Creek (fig. 25).

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**Table 17.** Statistical summary of trace-element data at S1 and S2/S3 from April 1990 through March 1995, before storage began in the reservoir, S1 and S2/S3 combined from April 1990 through October 2001, and S1 and S2/S3 from April 1995 to September 2001 after storage began in the reservoir.

[<, less than; µg/L, micrograms per liter]

Constituent	Minimum	25 percentile	Median	75 percentile	Maximum	Number of samples
<b>Site S1 1990 through 2001</b>						
Aluminum, total recoverable (µg/L as Al)	60	132	213	851	2,660	22
Arsenic, dissolved (µg/L as As)	<1	<1	<1	1	2	23
Arsenic, total recoverable (µg/L as As)	<1	<1	1	2	3	21
Barium, dissolved (µg/L as Ba)	25	38	59	57	100	23
Barium, total recoverable (µg/L as Ba)	<100	<100	<100	100	200	23
Beryllium, total recoverable (µg/L as Be)	<10	<10	<10	<10	<10	23
Boron, dissolved (µg/L as B)	10	20	45	60	72	23
Cadmium, dissolved (µg/L as Cd)	<0.1	<1	<1	<1	<1	23
Cadmium, total recoverable (µg/L as Cd)	<0.1	<1	<1	<1	<1	23
Chromium, dissolved (µg/L as Cr)	<1	<1	<1	<1	<1	23
Chromium, total recoverable (µg/L as Cr)	<1	<1	<1	2	6	22
Cobalt, total recoverable (µg/L as Co)	<1	<1	<1	1	3	23
Copper, dissolved (µg/L as Cu)	<1	<1	1	1	6	23
Copper, total recoverable (µg/L as Cu)	1	1	2	5	35	23
Iron, dissolved (µg/L as Fe)	3	16	40	51	220	132
Iron, total recoverable (µg/L as Fe)	30	340	430	1,110	5,670	71
Lead, dissolved (µg/L as Pb)	<1	<1	<1	<1	5	23
Lead, total recoverable (µg/L as Pb)	<1	<1	<1	6	66	23
Lithium, total recoverable (µg/L as Li)	<10	<10	20	17	30	23
Manganese, dissolved (µg/L as Mn)	8	13	19	24	97	77
Manganese, total recoverable (µg/L as Mn)	19	26	40	54	450	74
Mercury, dissolved (µg/L as Hg)	0.1	0.1	0.1	0.1	0.2	22
Mercury, total recoverable (µg/L as Hg)	<.1	<.1	<.1	.2	1.2	22
Molybdenum, total recoverable (µg/L as Mo)	<1	<1	2	2	3	23
Nickel, total recoverable (µg/L as Ni)	1	2	3	4	10	23
Selenium, dissolved (µg/L as Se)	<1	<1	<1	<1	2	23
Selenium, total recoverable (µg/L as Se)	<1	<1	<1	1	3	21
Silver, dissolved (µg/L as Ag)	<1	<1	<1	<1	2	23
Silver, total recoverable (µg/L as Ag)	<1	<1	<1	<1	<1	23
Zinc, dissolved (µg/L as Zn)	3	4	7	10	20	23
Zinc, total recoverable (µg/L as Zn)	1	10	10	18	60	23
<b>Site S2/S3 combined 1990 through 2001</b>						
Aluminum, total recoverable (µg/L as Al)	38	60	90	720	8,200	23
Arsenic, dissolved (µg/L as As)	<1	<1	<1	1	2	24
Arsenic, total recoverable (µg/L as As)	<1	<1	<1	2	4	22
Barium, dissolved (µg/L as Ba)	30	50	57	70	120	25
Barium, total recoverable (µg/L as Ba)	<100	<100	<100	<100	300	24
Beryllium, total recoverable (µg/L as Be)	<10	<10	<10	<10	<10	24
Cadmium, dissolved (µg/L as Cd)	<1	<1	<1	<1	2	25
Cadmium, total recoverable (µg/L as Cd)	<1	<1	<1	<1	2	24
Chromium, dissolved (µg/L as Cr)	<1	<1	<1	<1	8	24

**Table 17.** Statistical summary of trace-element data at S1 and S2/S3 from April 1990 through March 1995, before storage began in the reservoir, S1 and S2/S3 combined from April 1990 through October 2001, and S1 and S2/S3 from April 1995 to September 2001 after storage began in the reservoir.—Continued

[<, less than; µg/L, micrograms per liter]

Constituent	Minimum	25 percentile	Median	75 percentile	Maximum	Number of samples
Chromium, total recoverable (µg/L as Cr)	<1	<1	<1	4	12	23
Cobalt, total recoverable (µg/L as Co)	<1	<1	<1	1	8	24
Copper, dissolved (µg/L as Cu)	<1	<1	<1	1	11	25
Copper, total recoverable (µg/L as Cu)	<1	<1	2	3	32	24
Iron, dissolved (µg/L as Fe)	<3	10	13	40	6,300	113
Iron, total recoverable (µg/L as Fe)	10	55	90	165	15,800	75
Lead, dissolved (µg/L as Pb)	<1	<1	<1	<1	18	25
Lead, total recoverable (µg/L as Pb)	<1	<1	<1	<1	40	24
Lithium, total recoverable (µg/L as Li)	10	20	24	32	110	24
Manganese, dissolved (µg/L as Mn)	1	4	6.9	29	370	79
Manganese, total recoverable (µg/L as Mn)	5	10	20	81	444	76
Mercury, dissolved (µg/L as Hg)	<.1	<.1	<.1	<.1	.2	23
Mercury, total recoverable (µg/L as Hg)	<.1	<.1	<.1	<.1	.3	23
Molybdenum, total recoverable (µg/L as Mo)	<1	2	2	3	3	24
Nickel, total recoverable µg/L as Ni)	2	3	4	5	26	24
Selenium, dissolved (µg/L as Se)	<1	2	2	3	6	24
Selenium, total recoverable (µg/L as Se)	2	2	3	4	7	22
Silver, dissolved (µg/L as Ag)	<1	<1	<1	<1	2	25
Silver, total recoverable (µg/L as Ag)	<1	<1	<1	<1	<1	24
Zinc, dissolved (µg/L as Zn)	<3	4	8	20	41	25
Zinc, total recoverable (µg/L as Zn)	<10	<10	<10	32	100	24
<b>Site S1 pre-reservoir 1990 through 1995</b>						
Aluminum, total recoverable (µg/L as Al)	100	140	220	1,300	2,500	9
Arsenic, dissolved (µg/L as As)	<1	<1	<1	<1	1	10
Arsenic, total recoverable (µg/L as As)	<1	<1	<1	2	3	10
Barium, dissolved (µg/L as Ba)	25	34	54	66	79	10
Barium, total recoverable (µg/L as Ba)	<100	<100	<100	<100	200	10
Beryllium, total recoverable (µg/L as Be)	<10	<10	<10	<10	<10	10
Cadmium, dissolved (µg/L as Cd)	<1	<1	<1	<1	<1	10
Cadmium, total recoverable (µg/L as Cd)	<1	<1	<1	<1	<1	10
Chromium, total recoverable (µg/L as Cr)	<1	<1	1	2	4	10
Cobalt, total recoverable (µg/L as Co)	<1	<1	<1	1	3	10
Copper, dissolved (µg/L as Cu)	<1	<1	1	2	6	10
Copper, total recoverable (µg/L as Cu)	1	2	2	5	35	10
Iron, dissolved (µg/L as Fe)	7	15	38	91	220	54
Iron, total recoverable (µg/L as Fe)	280	410	560	2,300	5,400	9
Lead, dissolved (µg/L as Pb)	<1	<1	<1	<1	5	10
Lead, total recoverable (µg/L as Pb)	<1	<1	2	4	66	10
Lithium, total recoverable (µg/L as Li)	<10	<10	20	20	30	10
Manganese, dissolved (µg/L as Mn)	9	12	16	24	46	10
Manganese, total recoverable (µg/L as Mn)	20	42	60	70	140	10
Mercury, dissolved (µg/L as Hg)	<.1	<.1	<.1	<.1	<.1	10
Mercury, total recoverable (µg/L as Hg)	<.1	<.1	<.1	<.1	1.2	10

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**Table 17.** Statistical summary of trace-element data at S1 and S2/S3 from April 1990 through March 1995, before storage began in the reservoir, S1 and S2/S3 combined from April 1990 through October 2001, and S1 and S2/S3 from April 1995 to September 2001 after storage began in the reservoir.—Continued

[<, less than; µg/L, micrograms per liter]

Constituent	Minimum	25 percentile	Median	75 percentile	Maximum	Number of samples
Molybdenum, total recoverable (µg/L as Mo)	<1	<1	1	2	3	10
Nickel, total recoverable (µg/L as Ni)	2	2	3	6	9	10
Selenium, dissolved (µg/L as Se)	<1	<1	<1	<1	2	10
Selenium, total recoverable (µg/L as Se)	<1	<1	<1	1	1	10
Silver, dissolved (µg/L as Ag)	<1	<1	<1	<1	2	10
Silver, total recoverable (µg/L as Ag)	<1	<1	<1	<1	<1	10
Zinc, dissolved (µg/L as Zn)	<3	<3	4	9	14	10
Zinc, total recoverable (µg/L as Zn)	<10	<10	10	20	60	10
<b>Site S2/S3 pre-reservoir combined 1990 through 1995</b>						
Aluminum, total recoverable (µg/L as Al)	310	613	950	2,080	8,200	8
Arsenic, dissolved (µg/L as As)	<1	<1	<1	1	2	9
Arsenic, total recoverable (µg/L as As)	<1	1	1	2	4	9
Barium, dissolved (µg/L as Ba)	30	48	70	88	120	10
Barium, total recoverable (µg/L as Ba)	<100	<100	100	200	300	9
Beryllium, total recoverable (µg/L as Be)	<10	<10	<10	<10	<10	9
Boron, dissolved (µg/L as B)	20	20	75	140	180	10
Cadmium, dissolved (µg/L as Cd)	<1	<1	<1	<1	2	10
Cadmium, total recoverable (µg/L as Cd)	<1	<1	<1	<1	2	9
Chromium, dissolved (µg/L as Cr)	<1	<1	<1	<1	8	10
Chromium, total recoverable (µg/L as Cr)	<1	<1	2	5	12	9
Cobalt, total recoverable (µg/L as Co)	<1	1	1	2	8	9
Copper, dissolved (µg/L as Cu)	<1	1	2	2	11	10
Copper, total recoverable (µg/L as Cu)	2	2	3	5	32	9
Iron, dissolved (µg/L as Fe)	<3	20	30	70	6,300	35
Iron, total recoverable (µg/L as Fe)	540	770	1,090	1,880	15,800	8
Lead, dissolved (µg/L as Pb)	<1	<1	<1	<1	<18	10
Lead, total recoverable (µg/L as Pb)	<1	1	2	5	40	9
Lithium, total recoverable (µg/L as Li)	10	20	60	70	110	9
Manganese, dissolved (µg/L as Mn)	13	20	56	89	200	10
Manganese, total recoverable (µg/L as Mn)	50	90	110	210	444	9
Mercury, dissolved (µg/L as Hg)	<.1	<.1	<.1	<.1	<.1	9
Mercury, total recoverable (µg/L as Hg)	<.1	<.1	<.1	<.1	<.1	9
Molybdenum, total recoverable (µg/L as Mo)	<1	<1	2	3	3	9
Nickel, total recoverable (µg/L as Ni)	3	4	5	8	26	9
Selenium, dissolved (µg/L as Se)	<1	2	2	4	6	9
Selenium, total recoverable (µg/L as Se)	2	2	3	4	7	9
Silver, dissolved (µg/L as Ag)	<1	<1	<1	1	2	10
Silver, total recoverable (µg/L as Ag)	<1	<1	<1	<1	<1	9
Zinc, dissolved (µg/L as Zn)	<3	<3	6	8	41	10
Zinc, total recoverable (µg/L as Zn)	<10	<10	20	40	100	9

**Table 17.** Statistical summary of trace-element data at S1 and S2/S3 from April 1990 through March 1995, before storage began in the reservoir, S1 and S2/S3 combined from April 1990 through October 2001, and S1 and S2/S3 from April 1995 to September 2001 after storage began in the reservoir.—Continued

[&lt;, less than; µg/L, micrograms per liter]

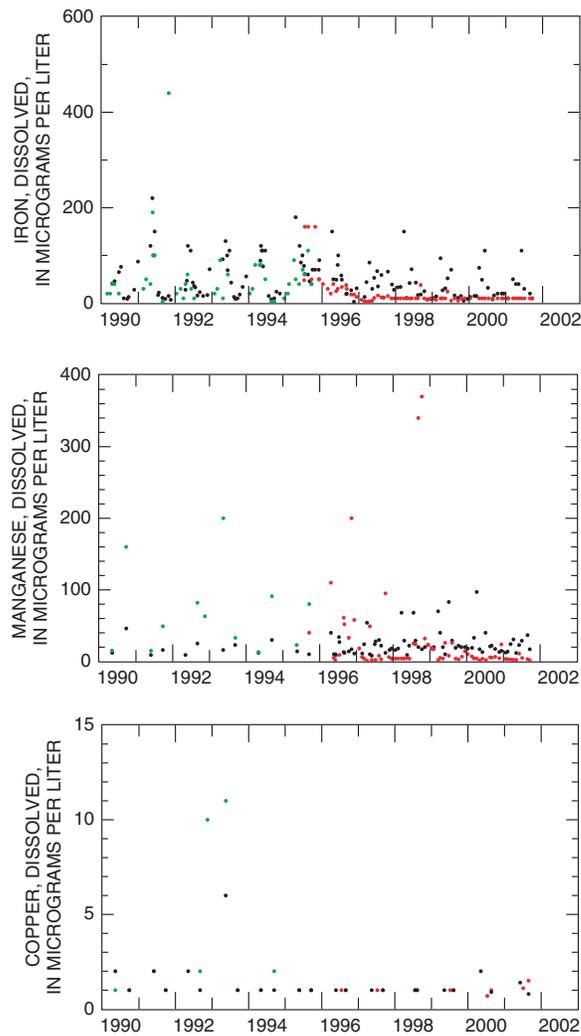
Constituent	Minimum	25 percentile	Median	75 percentile	Maximum	Number of samples
<b>Site S1 post-construction April 1995 through Sept 2001</b>						
Aluminum, total recoverable (µg/L as Al)	60	90	210	1,800	2,660	13
Arsenic, dissolved (µg/L as As)	<1	<1	<1	<1	1	13
Arsenic, total recoverable (µg/L as As)	<1	1	1	2	3	11
Barium, dissolved (µg/L as Ba)	31	42	68	77	100	13
Barium, total recoverable (µg/L as Ba)	<100	<100	<100	100	114	13
Beryllium, total recoverable (µg/L as Be)	<10	<10	<10	<10	<10	13
Cadmium, dissolved (µg/L as Cd)	<1	<1	<1	<1	<1	13
Cadmium, total recoverable (µg/L as Cd)	<1	<1	<1	<1	.5	13
Chromium, total recoverable (µg/L as Cr)	<1	<1	<1	3	6	13
Cobalt, total recoverable (µg/L as Co)	<1	<1	<1	2	3	12
Copper, dissolved (µg/L as Cu)	<1	<1	<1	1	2	13
Copper, total recoverable (µg/L as Cu)	1	1	2	5	10	13
Iron, dissolved (µg/L as Fe)	3	17	40	69	180	78
Iron, total recoverable (µg/L as Fe)	30	340	420	1,100	5,700	62
Lead, dissolved (µg/L as Pb)	<1	<1	<1	<1	<1	13
Lead, total recoverable (µg/L as Pb)	<1	<1	<1	5	11	13
Lithium, total recoverable (µg/L as Li)	<10	<10	14	20	30	13
Manganese, dissolved (µg/L as Mn)	8	13	20	28	97	67
Manganese, total recoverable (µg/L as Mn)	19	24	35	60	450	64
Mercury, dissolved (µg/L as Hg)	.1	.1	.1	.1	.2	12
Mercury, total recoverable (µg/L as Hg)	<.1	<.1	<.1	<.1	<.3	12
Molybdenum, total recoverable (µg/L as Mo)	<1	<1	2	3	3	13
Nickel, total recoverable (µg/L as Ni)	1	2	2	7	10	13
Selenium, dissolved (µg/L as Se)	<1	<1	<1	1	2	13
Selenium, total recoverable (µg/L as Se)	<1	<1	<1	<1	3	11
Silver, dissolved (µg/L as Ag)	<1	<1	<1	<1	<1	13
Silver, total recoverable (µg/L as Ag)	<1	<1	<1	<1	<1	13
Zinc, dissolved (µg/L as Zn)	<3	<3	<20	<20	<20	13
Zinc, total recoverable (µg/L as Zn)	<10	<10	<10	24	40	13
<b>Sites S2/S3 post-construction combined 1995 through 2001</b>						
Aluminum, total recoverable (µg/L as Al)	38	56	60	85	4,300	15
Arsenic, dissolved (µg/L as As)	<1	<1	<1	<1	1	13
Arsenic, total recoverable (µg/L as As)	1	1	1	2	3	13
Barium, dissolved (µg/L as Ba)	41	50	56	60	100	15
Barium, total recoverable (µg/L as Ba)	<100	<100	<100	<100	<100	15
Beryllium, total recoverable (µg/L as Be)	<10	<10	<10	<10	<10	15
Boron, dissolved (µg/L as B)	29	37	48	58	63	14
Cadmium, dissolved (µg/L as Cd)	<1	<1	<1	<1	<1	15
Cadmium, total recoverable (µg/L as Cd)	<1	<1	<1	<1	<1	15
Chromium, dissolved (µg/L as Cr)	<1	<1	<1	<1	2	14
Chromium, total recoverable (µg/L as Cr)	<1	<1	<1	<1	7	14
Cobalt, total recoverable (µg/L as Co)	<1	<1	<1	<1	4	15

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**Table 17.** Statistical summary of trace-element data at S1 and S2/S3 from April 1990 through March 1995, before storage began in the reservoir, S1 and S2/S3 combined from April 1990 through October 2001, and S1 and S2/S3 from April 1995 to September 2001 after storage began in the reservoir.—Continued

[<, less than; µg/L, micrograms per liter]

Constituent	Minimum	25 percentile	Median	75 percentile	Maximum	Number of samples
<b>Sites S2/S3 post-construction combined 1995 through 2001—Continued</b>						
Copper, dissolved (µg/L as Cu)	<1	<1	<1	<1	2	15
Copper, total recoverable (µg/L as Cu)	<1	<1	1	2	11	15
Iron, dissolved (µg/L as Fe)	<3	<10	<10	30	160	78
Iron, total recoverable (µg/L as Fe)	10	50	90	125	9,700	67
Lead, dissolved (µg/L as Pb)	<1	<1	<1	<1	<1	15
Lead, total recoverable (µg/L as Pb)	<1	<1	<1	<1	9	15
Lithium, total recoverable (µg/L as Li)	10	20	20	25	30	15
Manganese, dissolved (µg/L as Mn)	1	4	6	24	370	69
Manganese, total recoverable (µg/L as Mn)	5	10	20	37	390	67
Mercury, dissolved (µg/L as Hg)	<.1	<.1	<.1	<.1	.2	14
Mercury, total recoverable (µg/L as Hg)	<.1	<.1	<.1	<.1	.3	14
Molybdenum, total recoverable (µg/L as Mo)	1	2	2	2	3	15
Nickel, total recoverable (µg/L as Ni)	2	2	3	4	15	15
Selenium, dissolved (µg/L as Se)	1	2	2	3	3	15
Selenium, total recoverable (µg/L as Se)	2	2	3	3	4	13
Silver, dissolved (µg/L as Ag)	<1	<1	<1	<1	<1	15
Silver, total recoverable (µg/L as Ag)	<1	<1	<1	<1	<1	15
Zinc, dissolved (µg/L as Zn)	<3	5	20	20	20	15
Zinc, total recoverable (µg/L as Zn)	<3	6	10	10	60	15



**EXPLANATION**

- Site S1 upstream from reservoir
- Site S3 downstream from reservoir
- Site S2 Muddy Creek, at Kremmling

**Figure 22.** Time-series plots of selected trace-element constituents at Muddy Creek above Antelope Creek (upstream from reservoir) and Muddy Creek below Wolford Mountain Reservoir (directly downstream from reservoir), and Muddy Creek at Kremmling (approximately 7 miles downstream from reservoir).

**Table 18.** Summary of trace-element temporal variation upstream from reservoir by seasonal Kendall test for Muddy Creek above Antelope Creek (S1) and downstream combined data from Muddy Creek at Kremmling (S2) and Muddy Creek below Wolford Mountain Reservoir (S3), 1990 through 2001.

[<, less than; µg/L, micrograms per liter; slope, units per year; -, downward trend; *p*-values significant at greater than 90 percent confidence shown in bold; unadj, not adjusted by flow-weighting; fwc, flow-weighted concentrations]

Constituent	<i>p</i> -value	Significance > 90-percent confidence	Slope	Type
<b>Site S1 April 1990 through September 2001</b>				
Iron, dissolved (µg/L)	<b>0.0435</b>	Yes	0.82	fwc
Iron, total (µg/L)	.3447	No	-7.19	unadj
Manganese, dissolved (µg/L)	.6185	No	.15	unadj
Manganese, total (µg/L)	.8950	No	0	unadj
<b>Site S2/S3 April 1990 through September 2001</b>				
Iron, dissolved (µg/L)	<b>&lt;.0001</b>	Yes	0.	unadj
Iron, total (µg/L)	<b>.0004</b>	Yes	-29.	unadj
Manganese, dissolved (µg/L)	<b>.0403</b>	Yes	0.	unadj
Manganese, total (µg/L)	<b>.0207</b>	Yes	0.	unadj

**Table 19.** Summary of upstream/downstream trace-element differences at Muddy Creek above Antelope (S1) and Muddy Creek at Kremmling (S2), 1990 through 1995, and differences at Muddy Creek above Antelope (S1) and Muddy Creek below Wolford Mountain Reservoir (S3), 1995 through 2001 by Wilcoxon signed-rank test.

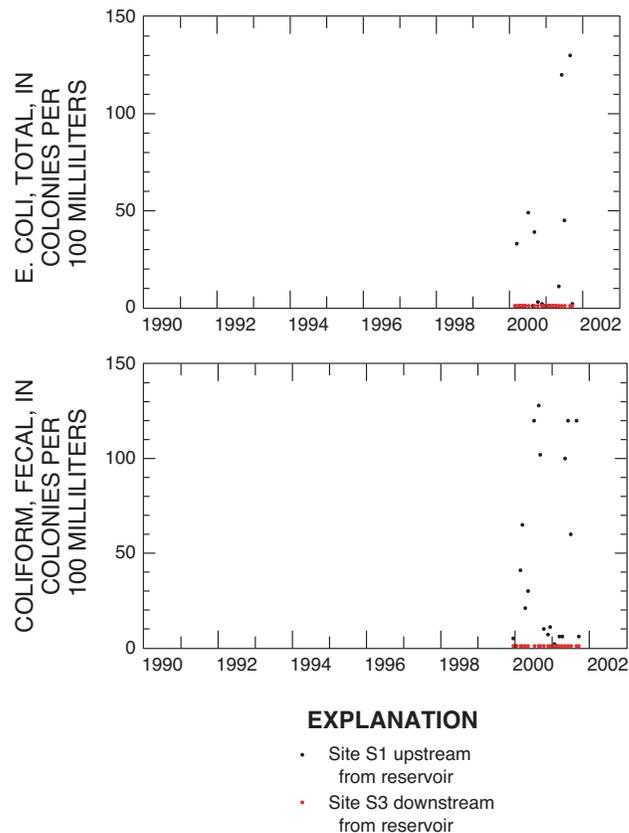
[<, less than; 2-sided test; µg/L, micrograms per liter; *p*-values significant at greater than 90-percent confidence shown in bold]

Constituent	<i>p</i> -value	Median	
		Upstream	Downstream
<b>April 1990 through March 1995</b>			
Iron, total (µg/L)	0.3704	560	1,090
Manganese, dissolved (µg/L)	<b>.0209</b>	16	56
Manganese, total (µg/L)	<b>.0138</b>	60	110
<b>April 1995 through September 2001</b>			
Iron, total (µg/L)	<b>&lt;.0001</b>	422	90
Manganese, dissolved (µg/L)	<b>&lt;.0001</b>	20	5.7
Manganese, total (µg/L)	<b>&lt;.0001</b>	35	20

**Table 20.** Statistical summary of bacteria data at S1 and S3 from December 1999 through September 2001, after storage began in the reservoir.

[<, less than; MF, membrane filtration; col/100 ml, colonies per 100 milliliters]

Constituent	Minimum	Median	Maximum	Number of samples
<b>Site S1 1999 through 2001</b>				
Coliform, fecal (col/100ml)	<1	1	>120	17
<i>E. coli</i> , urease, MF (col/100ml)	<1	25	130	20
<b>Site S3 1999 through 2001</b>				
Coliform, fecal (col/100ml)	<1	<1	1	21
<i>E. coli</i> , urease, MF (col/100ml)	<1	<1	<1	19



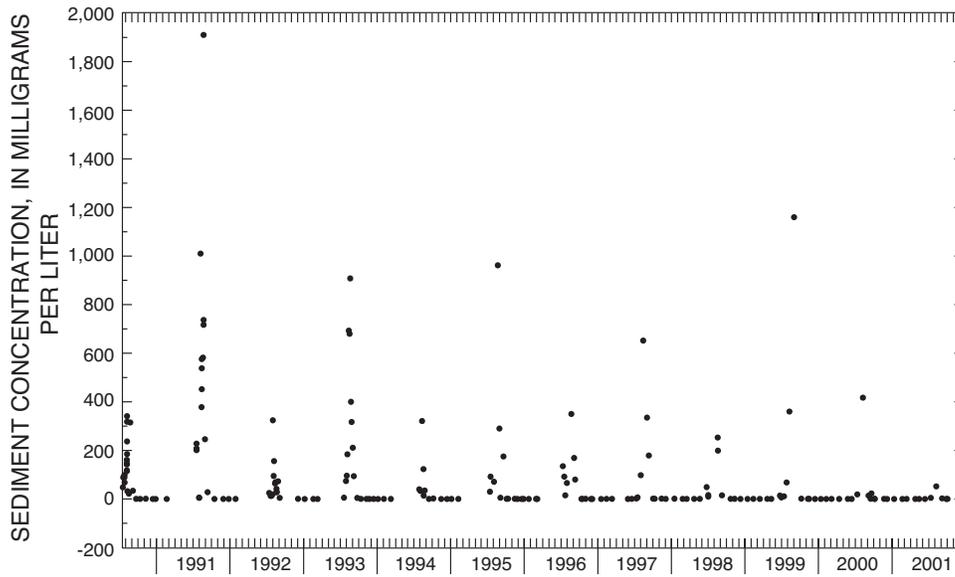
**Figure 23.** Time-series plots of bacteria data at Muddy Creek above Antelope Creek (upstream from reservoir) and Muddy Creek below Wolford Mountain Reservoir (directly downstream from reservoir), and Muddy Creek at Kremmling (site located approximately 7 miles downstream from reservoir 1999 through 2001).

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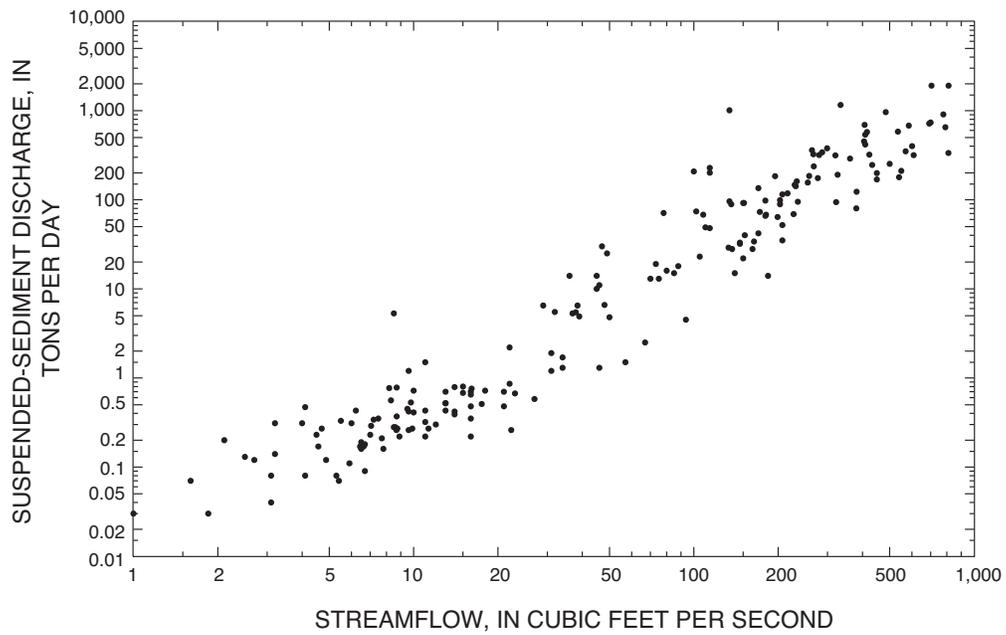
**Table 21.** Statistical summary of suspended-sediment data at S1 and S2 from April 1990 through March 1995 before storage began in the reservoir, S1 from April 1990 through October 2001, and S1 from April 1995 to September 2001 after storage began in the reservoir.

[mg/L, milligrams per liter; tons/d, tons per day]

Constituent	Minimum	25 percentile	Median	75 percentile	Maximum	Number of samples
<b>Site S1 1990 through 2001</b>						
Suspended-sediment concentration (mg/L)	4	15	53.9	204	2,800	191
Suspended-sediment discharge (tons/d)	0.03	0.4	6.5	107	1,910	191
<b>Site S1 pre-reservoir 1990 through 1995</b>						
Suspended-sediment concentration (mg/L)	4	35	113	265	2,800	93
Suspended-sediment discharge (tons/d)	.03	.67	42	208	1,910	93
<b>Site S1 post-construction April 1995 through Sept 2001</b>						
Suspended-sediment concentration ( mg/L)	4.3	11.3	19	96.8	1,290	98
Suspended-sediment discharge (tons/d)	.08	.342	0.77	22	1,160	98
<b>Sites S2 pre-reservoir 1990 through 1995</b>						
Suspended-sediment concentration (mg/L)	100	53	116	322	1,870	66
Suspended-sediment discharge (tons/d)	.19	2.2	11	158	2,540	66



**Figure 24.** Time-series of suspended-sediment concentration at Muddy Creek upstream from Antelope Creek (site S1).



**Figure 25.** Suspended-sediment transport curve for Muddy Creek upstream from Antelope Creek (site 1).

## Reservoir Water Quality

Wolford Mountain Reservoir is an important water resource for recreation, aquatic habitat, and water storage. Understanding chemical characteristics, field-property profiles and stratification patterns, mass balance of nutrients, and trophic status provides a basis for interpreting the effects of Wolford Mountain Reservoir on downstream water quality.

Variation in reservoir water quality is affected by seasonal and hydrologic factors. Water-quality data available for analysis included field properties, major ions, nutrients, trace elements, bacteria, and chlorophyll.

## Field Properties

Statistics for field properties (medians) were compiled for three reservoir water-quality sites (L1 near the dam, L2 at mid-lake, and L3 near the inlet) (table 22) for July 1995 to September 2001. Boxplots of selected constituents by site are shown in figure 11. Time-series plots of selected data collected at the surface and near the bottom at L1 are shown in figure 26.

In natural, snowmelt-dominated mountain streams, one of the primary processes controlling specific conductance and major-ion concentrations is dilution. In general, specific conductance in the reservoir is characterized by minimums ranging from 99 to 356  $\mu\text{S}/\text{cm}$  during peak snowmelt discharge and maximums ranging from 670 to 1,320  $\mu\text{S}/\text{cm}$  occurring during

winter low-flow conditions. In reservoirs, these fluctuations are dampened by mixing that occurs in the reservoir (fig. 26).

Median specific conductance in Wolford Mountain Reservoir was generally less than 600  $\mu\text{S}/\text{cm}$  (table 22). Water at Wolford Mountain Reservoir sampling sites are a blend of dilute high-elevation snowmelt runoff and more concentrated low-flow water, which have higher specific conductance related to exposure to marine shales and irrigation return flow or seepage. Median specific conductances generally were larger by at least 100  $\mu\text{S}/\text{cm}$  in the near-bottom samples at L1 and L2 (fig. 26). Median specific conductance at L3 near the reservoir surface was larger than at L1 or L2.

Water in Wolford Mountain Reservoir is subject to the cumulative effects of irrigation and evapotranspiration from the upper watershed. The reservoir is located at a lower elevation (higher evapotranspiration potential) and is exposed to saline, marine shale lithologies that may increase dissolved-solids content. All sampled reservoir waters had moderate specific conductivity and dissolved-solids content.

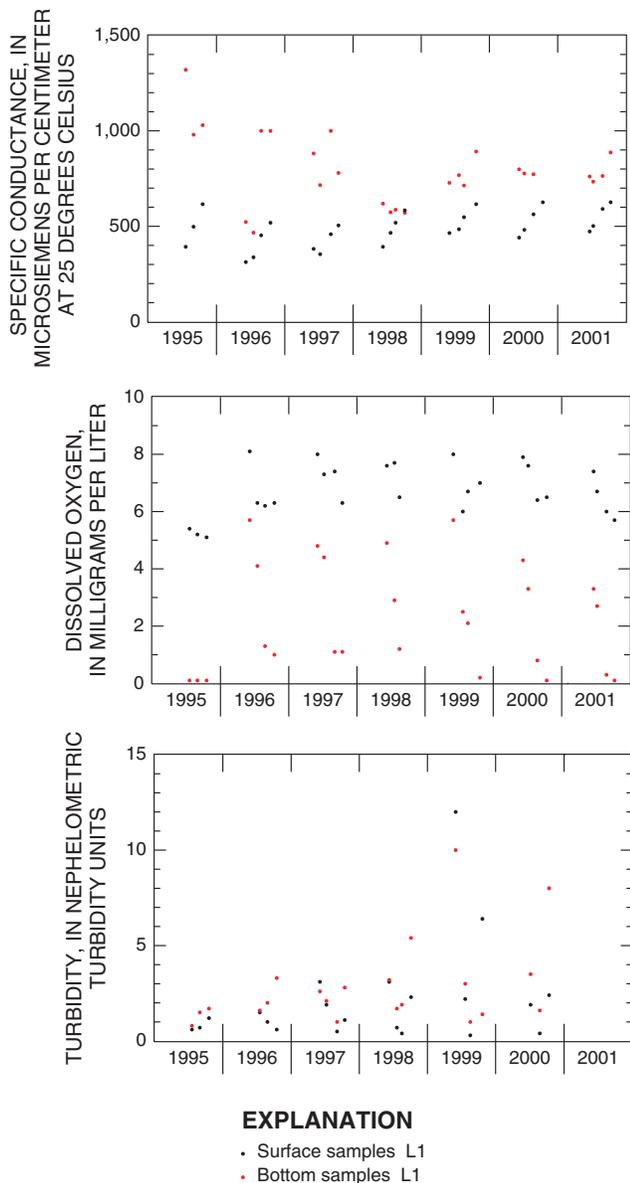
Water temperature varied seasonally; ice developed on the reservoir in winter, and temperatures approached 20°C in summer. The pH measured in the reservoir ranged from neutral to somewhat alkaline with median measurements of about 8.1 at all sites at the surface (table 22). Dissolved oxygen generally ranged from 4 to 8 mg/L, except in the hypolimnion of the reservoir, where seasonal stratification sometimes resulted in dissolved-oxygen concentrations approaching 1 mg/L or less. Dissolved-oxygen concentrations tended to be larger at the

**Table 22.** A comparison of spatial differences in field-measurement data from Wolford Mountain Reservoir, July 1995 to September 2001.

[--, constituent not measured; mg/L, milligrams per liter;  $\mu\text{S}/\text{cm}$ , microsiemens per centimeter; °C, degrees Celsius; NTU, nephelometric turbidity units]

Constituent or property	Sampling site	Median concentration or value	
		Near reservoir surface	Near reservoir bottom
Dissolved oxygen, (mg/L)	L1	6.6	1.7
	L2	6.8	2.6
	<sup>1</sup> L3	7.2	--
pH, field (standard units)	L1	8.1	7.5
	L2	8.1	7.7
	<sup>1</sup> L3	8.2	--
Specific conductance ( $\mu\text{S}/\text{cm}$ at 25°C)	L1	485	766
	L2	491	614
	<sup>1</sup> L3	558	--
Transparency, secchi (inches)	L1	113	--
	L2	110	--
	<sup>1</sup> L3	56	--
Turbidity (NTU)	L1	1.2	2
	L2	1.1	2.3
	<sup>1</sup> L3	2.7	--

<sup>1</sup>L3 near the reservoir inlet was sampled at mid-depth only.



**Figure 26.** Time-series plots of selected field properties from Wolford Mountain Reservoir, sampled near the dam (L1).

inflow and smallest near the dam in surface and bottom measurements (table 22). Turbidity was low at all sites but was highest at the L3 inflow site. Turbidity was higher in the near-bottom samples than the near-surface samples. Median transparency ranged from 56 to 113 inches below the surface. Transparency was largest at the dam and smallest at the inflow due to settling of suspended sediment at the inflow end of the reservoir (table 22).

Reservoir profiles of water temperature, specific conductance, pH, and dissolved oxygen were used to characterize stratification patterns of the reservoir. Profile measurements were collected in June, July, August, and October starting in July 1995 and continuing through 2001. Plots of profiles measured in 1999 at Wolford Mountain Reservoir (figs. 27–30) show how

these measurements generally vary with depth throughout the growing season.

Wolford Mountain Reservoir is probably dimictic (profile data generally did not extend to overturn periods in spring or fall), which means temperature stratification forms in summer and winter, and the lake contents mix during overturn in the spring and fall (Cole, 1994). Minor thermal stratification was evident in June and intensified through the summer. Specific conductance and pH data indicate moderate stratification with depth in June, but dissolved-oxygen concentrations were still relatively high (greater than 6 mg/L) and weakly stratified. In the fall (October 1999), the reservoir was in the process of overturn but was still stratified from summer heating. There was a very compact thermocline at the 60- to 70-ft interval (0.1°C/ft depth) relative to 0.02°C/ft depth in the 40- to 70-ft interval (fig. 28). During stratification, specific conductance generally increased with depth. This difference (fig. 26) may be due to seasonal routing differences through the reservoir but is also a result of mineral dissolution or ground-water inflow rich in dissolved solids. Dissolved oxygen commonly was depleted in the hypolimnion of the reservoir, and pH decreased with depth. The lowest dissolved-oxygen concentrations in the hypolimnion were measured in August when near-bottom oxygen concentrations approached zero.

Spatial stratification between L2 (a transitional zone) and L1 (a deeper lacustrine zone) was relatively minor as both sites had similar patterns for all profile measurements in the 1999 example (figs. 27–30). Site L3 at the inlet to the reservoir is a mixed riverine zone that is similar to Muddy Creek. Field-property data were collected at one mid-point depth at L3. The seasonal differences in water temperature at the inflow can affect routing of water within the reservoir because of water density variation 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. In Wolford Mountain Reservoir, spring-runoff temperatures and fall temperatures in Muddy Creek (essentially L3) are lower than in the reservoir (fig. 28). Thus, inflows tended to settle near the thermocline and plunge beneath the surface layer (epilimnion) in spring and fall of 1999. In summer, L3 water temperature was similar to the surface layer (fig. 28), and flows were routed through the reservoir near the surface.

In winter, stream temperatures were near 0°C, and surface water at the ice-cover interface was 0°C (profile not shown), but the temperature in the reservoir subsurface increased with depth to 4°C in the 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. Flow patterns could be important because it could drastically reduce residence time in the event of a chemical spill upstream, and knowledge of probable vertical location of the plume would be important for outflow gate configurations.

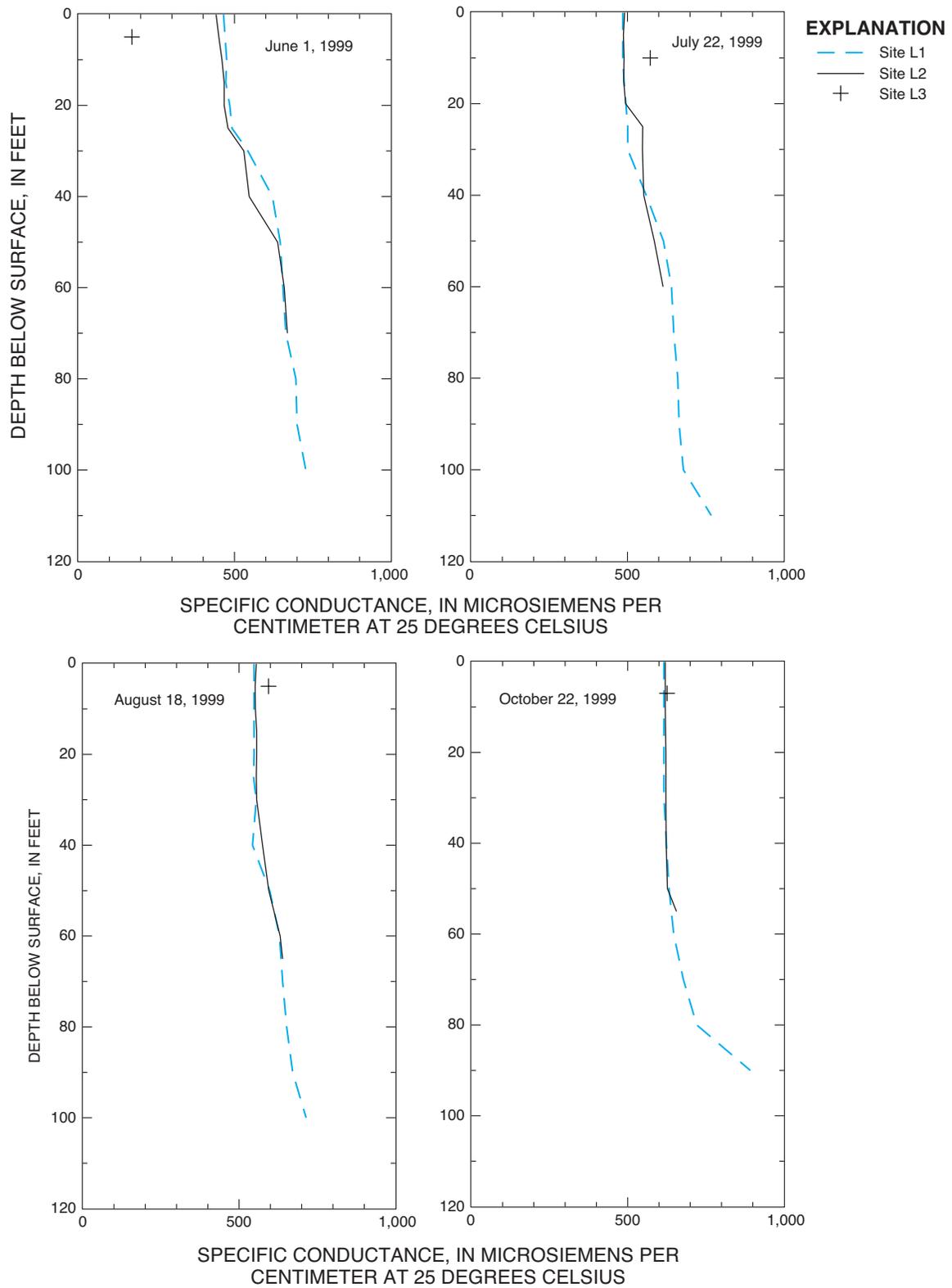


Figure 27. Specific-conductance profiles measured at Wolford Mountain Reservoir near the dam (L1) in 1999.

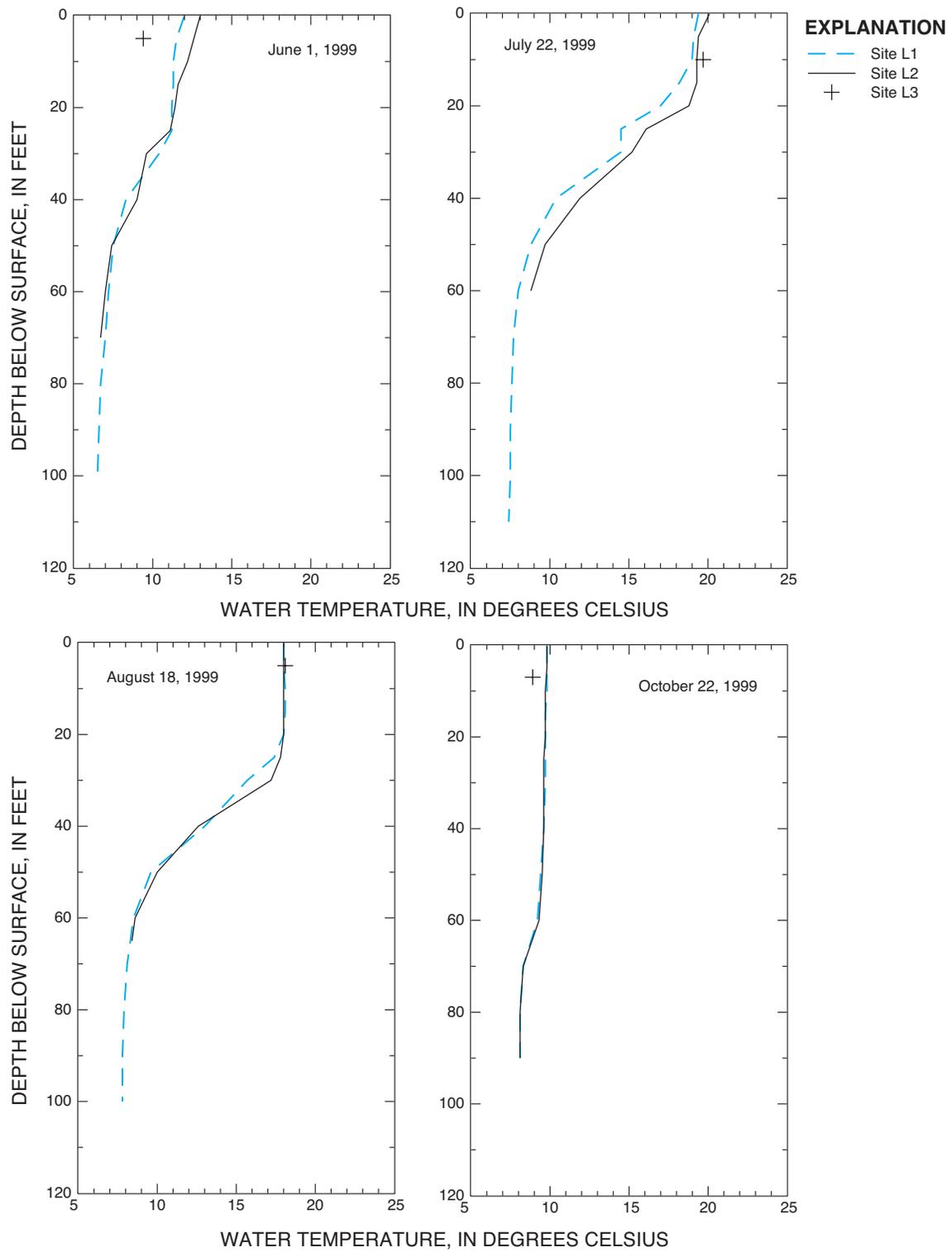


Figure 28. Water-temperature profiles measured at Wolford Mountain Reservoir near the dam (L1) in 1999.

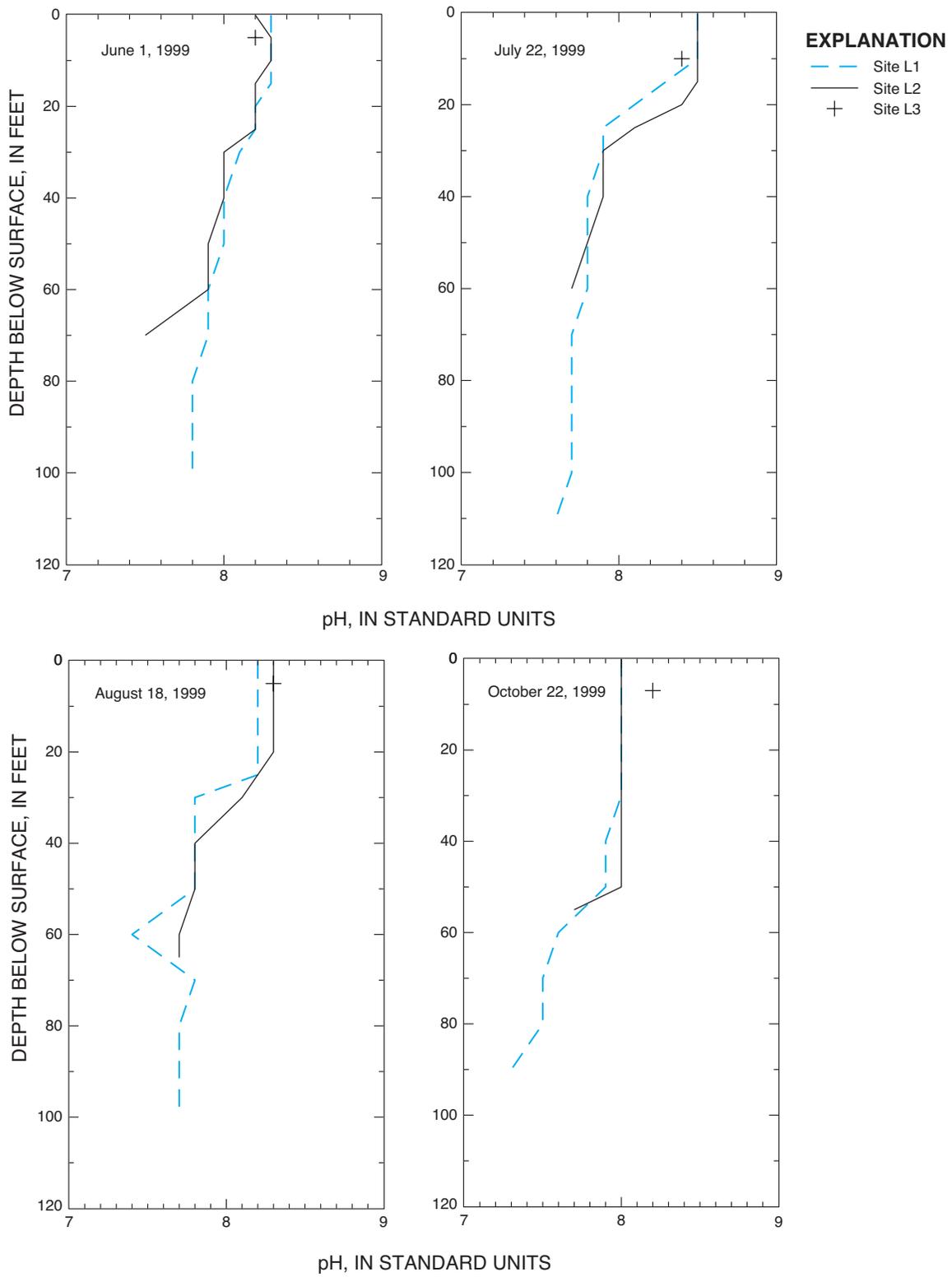


Figure 29. pH profiles measured at Wolford Mountain Reservoir near the dam (L1) in 1999.

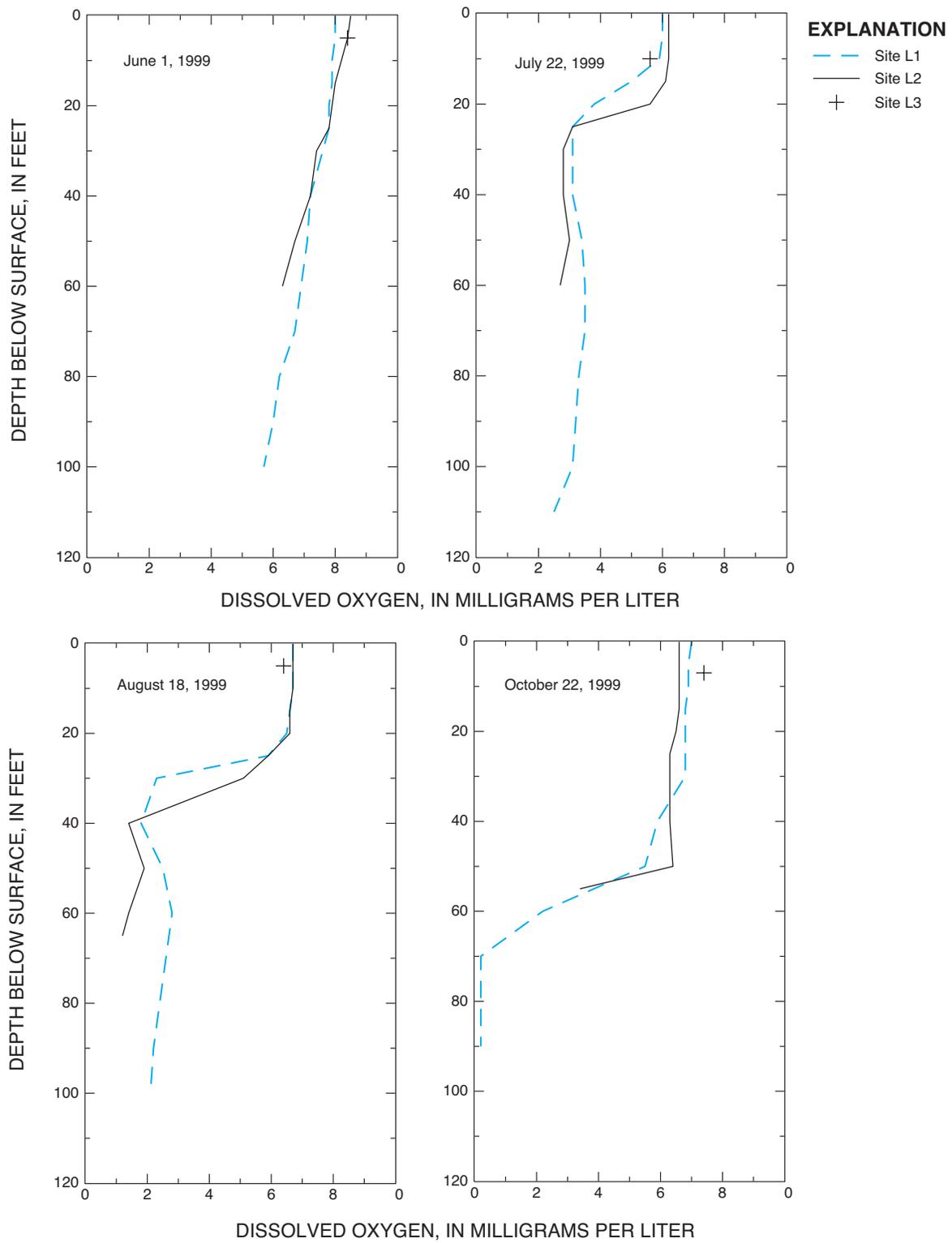
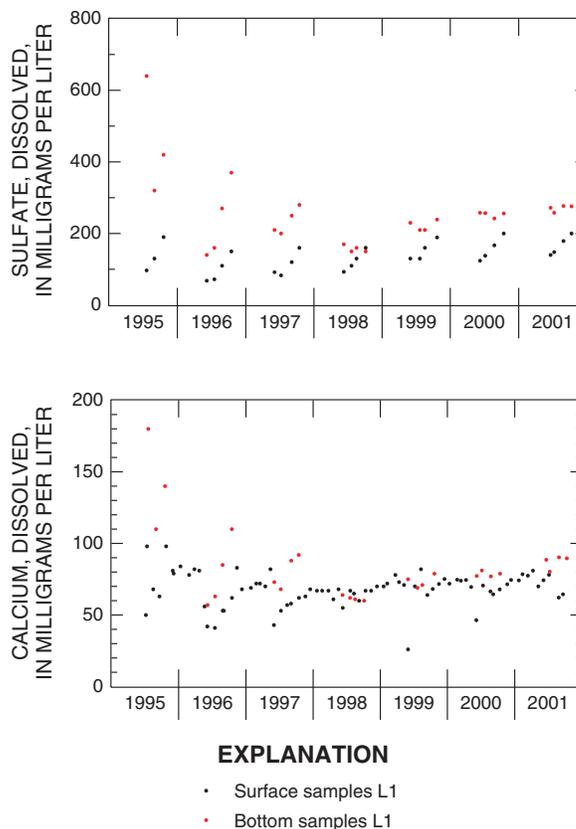


Figure 30. Dissolved-oxygen profiles measured at Wolford Mountain Reservoir near the dam (L1) in 1999.

### Major Ions

Statistics for median concentrations of major ions were compiled for three reservoir water-quality sites (L1 near the dam, L2 at midlake, and L3 near the inlet) (table 23) for July 1995 through September 2001. Boxplots of selected constituents by site are shown in figure 11. Time-series plots of selected major-ion data collected at the surface and near the bottom at L1 are shown in figure 31.

Major-ion composition of reservoir water was similar to the streamwater. Calcium was the predominant cation, whereas bicarbonate and sulfate were the primary anions. Concentrations of major ions in near-bottom samples usually were larger than those in surface samples (fig. 31) (table 23). A slight spatial trend decreasing from L3 to L1 is evident in median concentrations of surface samples (table 23); whereas, near-bottom median concentrations increased from inlet to dam. Similar patterns existed for specific conductance and dissolved solids. This pattern is probably a consequence of routing patterns during stratification. In summer, inflow is routed to the surface zone when specific conductance is higher in the inflow than in the main reservoir, which results in a chemical gradient that decreases from inlet to dam. During spring runoff, inflow is routed deeper within the reservoir when specific conductance is lower than in the deeper reservoir water, which results in a chemical gradient that increases from inlet to dam.



**Figure 31.** Time-series plots of selected major-ions from Wolford Mountain Reservoir, sampled near the dam (site L1).

**Table 23.** A comparison of spatial differences in major-ion data from Wolford Mountain Reservoir, July 1995 through September 2001.

[--, not sampled, mg/L, milligrams per liter]

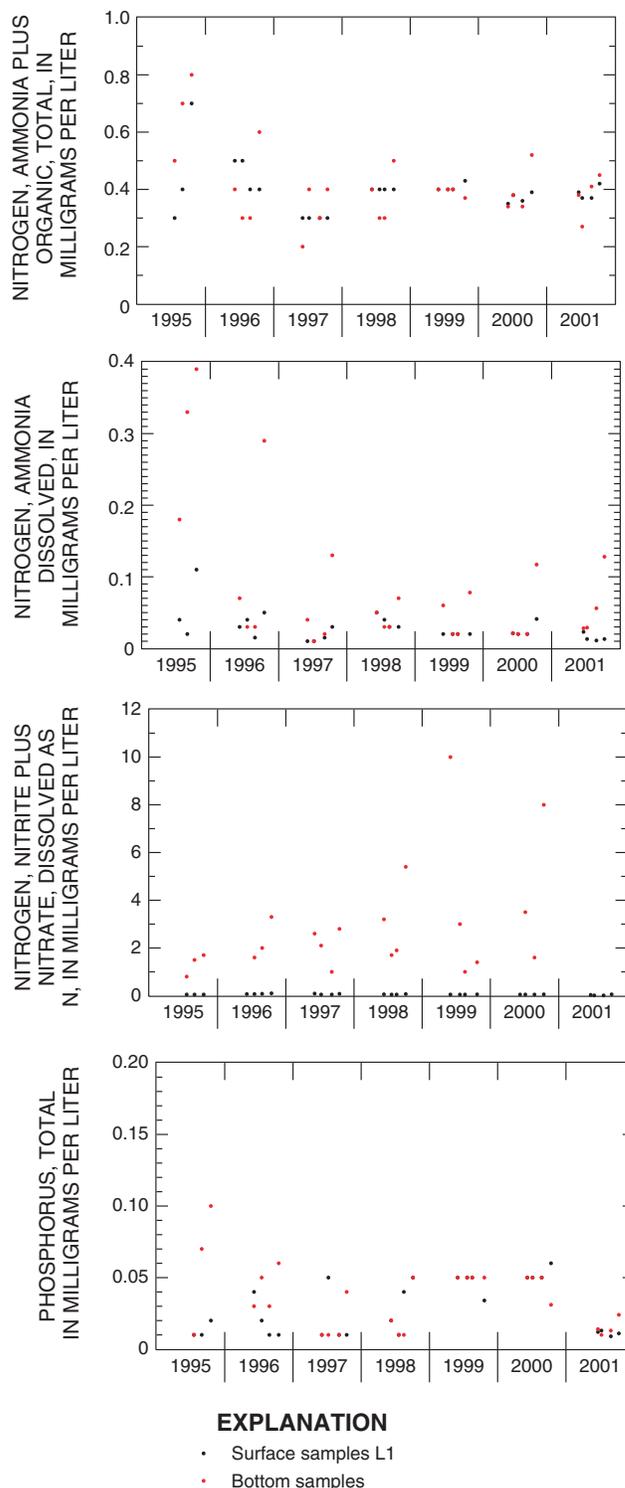
Constituent or property	Sampling site	Median concentration or value	
		Near reservoir surface	Near reservoir bottom
Hardness, total (mg/L as CaCO <sub>3</sub> )	L1	210	320
	L2	210	250
	<sup>1</sup> L3	245	--
Calcium, dissolved (mg/L as Ca)	L1	54	78.9
	L2	54	64
	<sup>1</sup> L3	61	--
Magnesium, dissolved (mg/L as Mg)	L1	19	28.1
	L2	19	22
	<sup>1</sup> L3	22	--
Potassium dissolved (mg/L as K)	L1	1.9	2.5
	L2	2	2.2
	<sup>1</sup> L3	2.0	--
Sodium, dissolved (mg/L as Na)	L1	19	27
	L2	18	21
	<sup>1</sup> L3	22	--
Acid-neutralizing capacity, alkalinity, lab, as CaCO <sub>3</sub>	L1	108	124
	L2	109	120
	<sup>1</sup> L3	126	--
Chloride, dissolved (mg/L as Cl)	L1	1.8	2.6
	L2	1.8	2
	<sup>1</sup> L3	1.9	--
Fluoride, dissolved (mg/L as F)	L1	0.1	0.2
	L2	.1	.2
	<sup>1</sup> L3	.2	--
Silica, dissolved (mg/L as SiO <sub>2</sub> )	L1	8	9.2
	L2	8	8.4
	<sup>1</sup> L3	7.9	--
Sulfate, dissolved (mg/L as SO <sub>4</sub> )	L1	130	250
	L2	130	170
	<sup>1</sup> L3	154	--
Dissolved solids, sum of constituents (mg/L)	L1	303	477
	L2	306	364
	<sup>1</sup> L3	347	--

<sup>1</sup> L3 near the reservoir inlet was sampled at mid-depth only.

### Nutrients

Statistics for median concentrations of nutrients were compiled for three reservoir water-quality sites (L1 near the dam, L2 at midlake, and L3 near the inlet) (table 24) for July 1995 through September 2001. Boxplots of selected constituents by site are shown in figure 11. Time-series plots of selected nutrient data collected at the surface and near the bottom at L1 are shown in figure 32.

Seasonal variation in nutrient concentrations differed in surface and near-bottom samples. Surface concentrations of total ammonia plus organic nitrogen, dissolved ammonia, dissolved nitrite plus nitrate, and total phosphorus showed few consistent seasonal patterns (fig. 32); whereas, near-bottom samples of the same nutrients had increased concentrations in fall samples. Near-bottom samples of ammonia and nitrite plus nitrate generally had larger concentrations than concurrent surface samples. (fig. 32). Surface-sample concentrations of nitrite plus nitrate were substantially depleted throughout the growing season. Temporally, surface and near-bottom concentrations tended to decrease and stabilize for ammonia plus organic nitrogen and ammonia throughout 1995 through 2001 (fig. 32). Nitrite plus nitrate seemed to increase in near-bottom samples with time (fig. 32). Spatial variation in nutrient concentrations from inflow to dam tended to decrease for total ammonia plus organic nitrogen and total phosphorus in surface samples; bottom-sample concentrations tended to increase from inflow to dam for nitrite plus nitrate.



**Figure 32.** Time-series plots of selected nutrients from Wolford Mountain Reservoir, sampled near the dam (site L1).

**Table 24.** A comparison of spatial differences in nutrient data from Wolford Mountain Reservoir, July 1995 through September 2001.

[&lt;, less than; --, not sampled; mg/L, milligrams per liter]

Constituent or property	Sampling site	Median concentration	
		Near reservoir surface	Near reservoir bottom
Nitrogen, ammonia plus organic, dissolved (mg/L as N)	L1	0.3	0.3
	L2	.3	.3
	<sup>1</sup> L3	.3	--
Nitrogen, ammonia plus organic, total (mg/L as N)	L1	.4	.4
	L2	.4	.4
	<sup>1</sup> L3	.5	--
Nitrogen, ammonia, dissolved (mg/L as N)	L1	.02	.04
	L2	.02	.03
	<sup>1</sup> L3	<.02	--
Nitrogen, nitrite plus nitrate, dissolved (mg/L as N)	L1	.05	.26
	L2	.05	.16
	<sup>1</sup> L3	<.05	--
Nitrogen, nitrite, dissolved (mg/L as N)	L1	<.01	<.01
	L2	<.01	<.01
	<sup>1</sup> L3	<.01	--
Phosphorus, dissolved (mg/L as P)	L1	<.01	<.01
	L2	<.01	<.02
	<sup>1</sup> L3	<.01	--
Phosphorus, dissolved orthophosphate (mg/L as P)	L1	<.01	.01
	L2	<.01	<.01
	<sup>1</sup> L3	<.01	--
Phosphorus, total (mg/L as P)	L1	<.05	<.05
	L2	<.05	<.05
	<sup>1</sup> L3	<.05	--

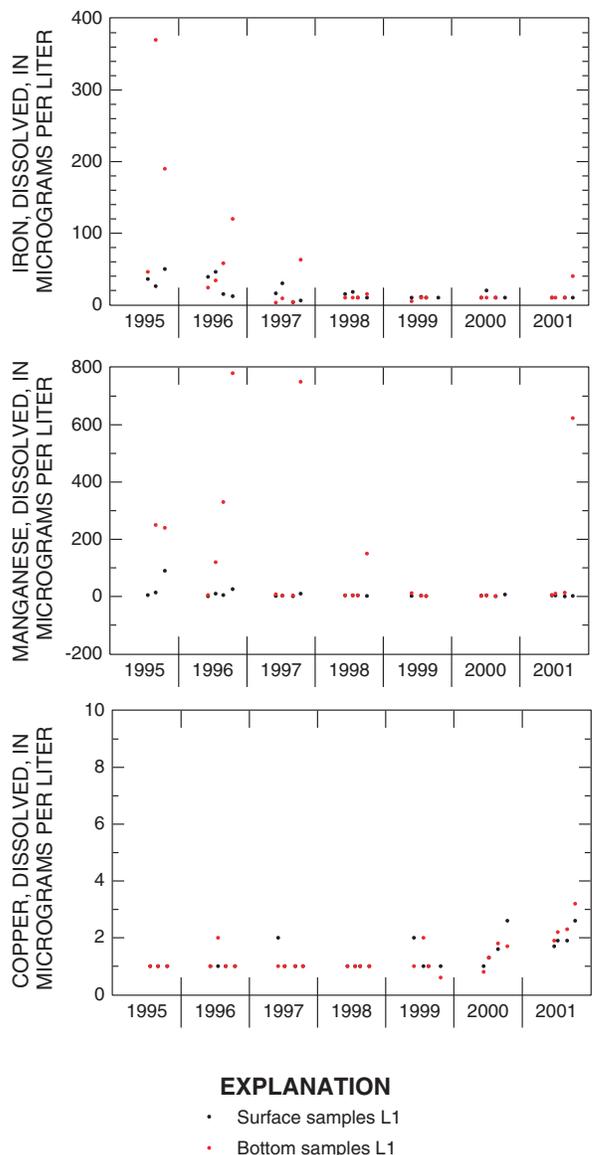
<sup>1</sup>L3 near the reservoir inlet was sampled at mid-depth only.

### Trace Elements

Statistics for median concentrations of trace elements were compiled for three reservoir water-quality sites (L1 near the dam, L2 at midlake, and L3 near the inlet) (table 25) for July 1995 through September 2001. Boxplots of dissolved copper, dissolved iron, and dissolved manganese by site are shown in figure 11. Time-series plots of selected trace-element data collected at the surface and near the bottom at L1 are shown in figure 33.

Variation was difficult to describe for trace elements with concentrations near the MRL. Dissolved iron, manganese, and copper tended to increase in bottom samples during late summer or fall (fig. 33). This increase is probably the result of increased hypoxia at the end of the growing season, which causes redox-related increases in iron and manganese concentrations. The increases in copper concentrations also may be related to redox potential in that some trace elements may be adsorbed to iron and manganese particulates that have been remobilized and reprecipitated.

Temporally, dissolved iron and manganese generally have decreased over the period of record (1995 to 2001) (fig. 33), whereas, the 2000 to 2001 data indicate increased copper concentrations. Spatially, total recoverable and dissolved iron and manganese, and total recoverable aluminum show decreasing median concentrations from inflow to dam (S3 to S1) in surface samples (table 25). Median concentrations of total recoverable iron and aluminum in near-bottom samples decreased from inflow to dam. The concentration increases in manganese along the reservoir axis probably are related to redox reactions in the hypolimnion, which release manganese from the bottom sediments during periods of hypoxia.



**Figure 33.** Time-series plots of selected trace elements from Wolford Mountain Reservoir, sampled near the dam (site L1).

**Table 25.** A comparison of spatial differences in trace-element data from Wolford Mountain Reservoir, July 1995 through September 2001.

[&lt;, less than; --, not sampled; µg/L, micrograms per liter]

Constituent	Sampling site	Median concentration	
		Near reservoir surface	Near reservoir bottom
Aluminum, total recoverable (µg/L as Al)	L1	40	54
	L2	43	70
	<sup>1</sup> L3	100	--
Arsenic, dissolved (µg/L as As)	L1	<1	<1
	L2	<1	<1
	<sup>1</sup> L3	<1	--
Arsenic, total recoverable (µg/L as As)	L1	<1	<1
	L2	<1	<1
	<sup>1</sup> L3	<1	--
Barium, dissolved (µg/L as Ba)	L1	55	58
	L2	54	56
	<sup>1</sup> L3	60	--
Barium, total recoverable (µg/L as Ba)	L1	<100	<100
	L2	<100	100
	<sup>1</sup> L3	83	--
Beryllium, total recoverable (µg/L as Be)	L1	<10	<10
	L2	<10	<10
	<sup>1</sup> L3	<10	--
Cadmium, dissolved (µg/L as Cd)	L1	<1	<1
	L2	<1	<1
	<sup>1</sup> L3	<1	--
Cadmium, total recoverable (µg/L as Cd)	L1	<1	<1
	L2	<1	<1
	<sup>1</sup> L3	<1	--
Chromium, dissolved (µg/l as Cr)	L1	<1	<1
	L2	<1	<1
	<sup>1</sup> L3	<1	--
Chromium, total recoverable (µg/l as Cr)	L1	<1	<1
	L2	<1	<1
	<sup>1</sup> L3	<1	--
Cobalt, total recoverable (µg/L as Co)	L1	<1	<1
	L2	<1	<1
	<sup>1</sup> L3	<1	--

**Table 25.** A comparison of spatial differences in trace-element data from Wolford Mountain Reservoir, July 1995 through September 2001.—Continued

[<, less than; --, not sampled; µg/L, micrograms per liter]

Constituent	Sampling site	Median concentration	
		Near reservoir surface	Near reservoir bottom
Copper, dissolved (µg/L as Cu)	L1	1	<1
	L2	1	1
	<sup>1</sup> L3	1	--
Copper, total recoverable (µg/L as Cu)	L1	1	1
	L2	1	1
	<sup>1</sup> L3	1	--
Iron, dissolved (µg/L as Fe)	L1	10	10
	L2	10	<10
	<sup>1</sup> L3	16	--
Iron, total recoverable (µg/L as Fe)	L1	62	95
	L2	70	140
	<sup>1</sup> L3	190	--
Lead, dissolved (µg/L as Pb)	L1	<1	<1
	L2	<1	<1
	<sup>1</sup> L3	<1	--
Lead, total recoverable (µg/L as Pb)	L1	<1	<1
	L2	<1	<1
	<sup>1</sup> L3	<1	--
Lithium, total recoverable (µg/L as Li)	L1	20	28
	L2	20	20
	<sup>1</sup> L3	20	--
Manganese, dissolved (µg/L as Mn)	L1	4	7
	L2	4	5
	<sup>1</sup> L3	21	--
Manganese, total recoverable (µg/L as Mn)	L1	10	65
	L2	10	36
	<sup>1</sup> L3	38	--
Mercury, dissolved (µg/L as Hg)	L1	<0.1	<0.1
	L2	<.1	<.1
	<sup>1</sup> L3	<.1	--
Mercury, total recoverable (µg/L as Hg)	L1	<.1	<.1
	L2	<.1	<.1
	<sup>1</sup> L3	<.1	--

**Table 25.** A comparison of spatial differences in trace-element data from Wolford Mountain Reservoir, July 1995 through September 2001.—Continued

[&lt;, less than; --, not sampled; µg/L, micrograms per liter]

Constituent	Sampling site	Median concentration	
		Near reservoir surface	Near reservoir bottom
Molybdenum, total recoverable (µg/L as Mo)	L1	2	3
	L2	2	2
	<sup>1</sup> L3	2	--
Nickel, total recoverable (µg/L as Ni)	L1	2	3
	L2	2	2
	<sup>1</sup> L3	2	--
Selenium, dissolved (µg/L as Se)	L1	2	3
	L2	2	2
	<sup>1</sup> L3	1	--
Selenium, total recoverable (µg/L as Se)	L1	2	3
	L2	2	2
	<sup>1</sup> L3	2	--
Silver, dissolved (µg/L as Ag)	L1	<1	<1
	L2	<1	<1
	<sup>1</sup> L3	<1	--
Silver, total recoverable (µg/L as Ag)	L1	<1	<1
	L2	<1	<1
	<sup>1</sup> L3	<1	--
Zinc, dissolved (µg/L as Zn)	L1	<6	<5
	L2	<6	<5
	<sup>1</sup> L3	<4	--
Zinc, total recoverable (µg/L as Zn)	L1	<10	<10
	L2	<10	<10
	<sup>1</sup> L3	<10	--

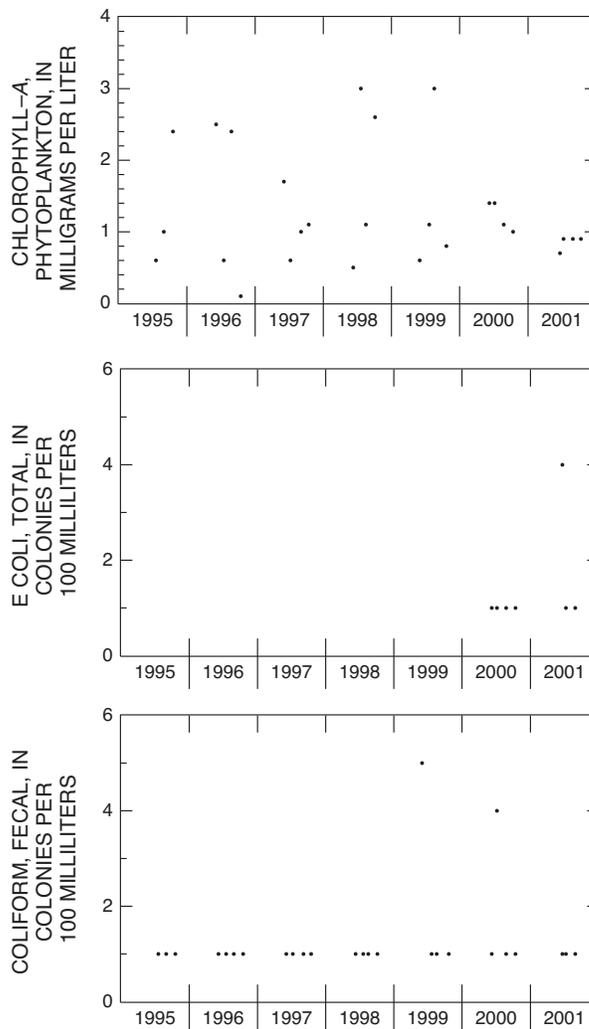
<sup>1</sup>L3 near the reservoir inlet was sampled at mid-depth only.

### Biological Indicators

Statistics for median concentrations of chlorophyll and bacteria were compiled for three reservoir water-quality sites (L1 near the dam, L2 at midlake, and L3 near the inlet) (table 26) for July 1995 to September 2001. Time-series plots of selected chlorophyll and bacteria data collected at the surface and near the bottom at L1 are shown in figure 34.

The median concentration for chlorophyll-*a* was 1 µg/L (table 26). Large variation in concentrations occurred during the growing season (fig. 34). Median concentrations at L1 and L2 were similar, indicating little spatial variation.

Bacteria counts were low to not detected in the reservoir samples (fig. 34) (table 26). Bacteria in Muddy Creek may be associated with suspended material that rapidly settles out in the reservoir.



**Figure 34.** Time-series plots of selected chlorophyll and bacteria data from Wolford Mountain Reservoir, sampled near the dam (site L1) 1995 through 2001.

**Table 26.** A comparison of spatial differences in biological data from Wolford Mountain Reservoir, July 1995 through September 2001.

[<, less than; --, constituent not measured; µg/L, micrograms per liter; col/100 ml, colonies per 100 milliliters; MF, membrane filtration; col, colonies]

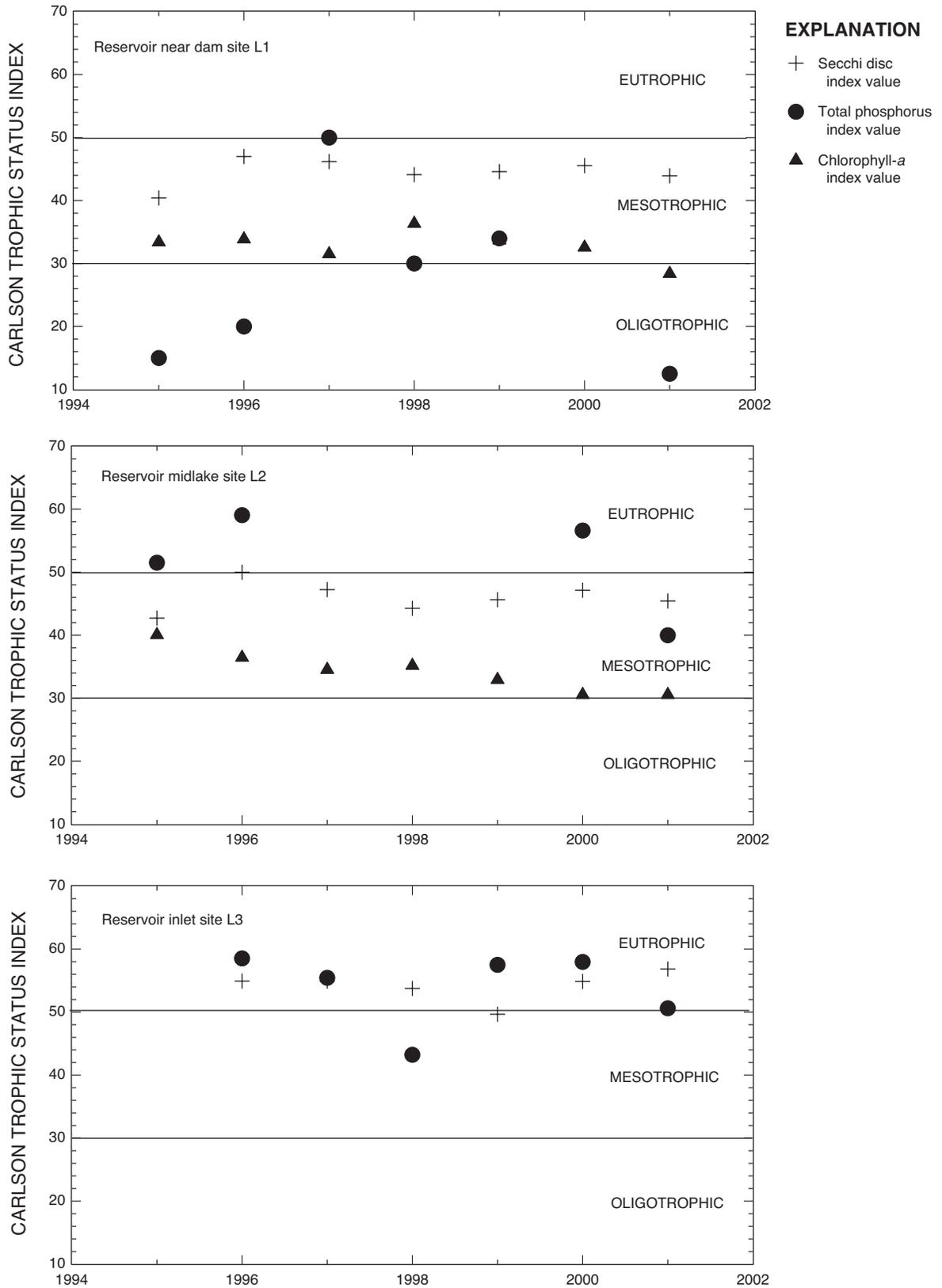
Constituent	Sampling site	Median concentration	
		Near reservoir surface	Near reservoir bottom
<i>E. coli</i> , urease, MF (col/100 ml)	L1	<1	--
	L2	1	--
	<sup>1</sup> L3	--	--
Coliform, fecal (col/100 ml)	L1	<1	--
	L2	1	--
	<sup>1</sup> L3	--	--
Chlorophyll- <i>a</i> (µg/L)	L1	1	--
	L2	1.3	--
	<sup>1</sup> L3	--	--
Chlorophyll- <i>b</i> (µg/L)	L1	<0.1	--
	L2	.1	--
	<sup>1</sup> L3	--	--

<sup>1</sup> L3 near the reservoir inlet was sampled at mid-depth only.

## Trophic Status

The relative fertility of a lake or reservoir can be evaluated by assessing the trophic status. Oligotrophic (nutrient-poor) lakes have characteristics such as high transparency, small organic-matter content, relatively large dissolved-oxygen concentrations, small 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, exhibiting some characteristics of both. On the basis of data collected 1995–2001, Wolford Mountain Reservoir was classified using the method developed by Carlson (1977). The annual mean values then were used to compute annual trophic-status index (TSI) values (fig. 35). Censored values of total phosphorus were common in the 1990's, therefore TSI's were not computed. The Carlson (1977) index 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. Most of the index values for the reservoir are in the upper

oligotrophic to mesotrophic ranges. Eutrophic conditions were indicated by some samples at L2 and L3 based on Secchi disc and total phosphorus. Computations based on chlorophyll-*a* at the dam (L1) indicated stable TSI's, whereas the midlake site showed decreasing TSI's. Generally, TSI's based on Secchi disc and total phosphorus were greater than those of chlorophyll-*a* on the same sampling date, and TSI's at the upstream end of the reservoir were greater than those computed for the site at the dam. This difference could be a result of turbid conditions caused by suspended sediment and turbidity from Muddy Creek that raise total-phosphorus and Secchi-depth TSI's relatively but do not affect (and may even decrease) the chlorophyll-*a* index due to reduced light penetration. Other cyclic factors such as grazing of phytoplankton by zooplankton can make interpretation of chlorophyll-*a* indices ambiguous. Use of TSI can give a qualitative indication of relative status of water bodies, but it should not be used exclusively to evaluate whether lakes and reservoirs are meeting the water-quality classifications.



**Figure 35.** Annual trophic status index (TSI) computations for Secchi depth, total phosphorus, and chlorophyll-*a* by the Carlson (1977) method.

## Water-Quality Standards

Based on all samples collected during 1990 to 2001, Colorado standards for chloride, dissolved chromium, dissolved copper, dissolved nickel, nitrate, sulfate, and dissolved zinc were not exceeded at any of the sampling sites in the study area (table 27). Dissolved oxygen generally met minimum standards (6 mg/L) except for brief periods in late summer most years, when oxygen concentrations dropped slightly below

6 mg/L at Muddy Creek below Wolford Mountain Reservoir (S3). Only in reservoir near-bottom samples was dissolved oxygen very low (less than 2 mg/L), but the reservoir water was well oxygenated in the mixed zone (epilimnion and metalimnion). The pH met standards at all sites. The standard for un-ionized ammonia was exceeded in only one sample at Muddy Creek below Wolford Mountain Reservoir (S3) in October 1995 during the first season of reservoir filling. Nutrients concentrated in the hypolimnion may have been released during mixing at fall overturn of the reservoir.

**Table 27.** Summary of exceedances of Colorado aquatic water-quality standards, 1990 to 2001.

[>, greater than;--, not sampled; TVS, table value standard equation; ch, chronic standard; ac, acute standard; f, fixed standard; s, surface; b, near-bottom]

Constituent or property	Type	Number of exceedances from 1990 to 2001							
		<sup>1</sup> Standard	S1	S2	S3	S4	L1	L2	L3
Dissolved oxygen, (mg/L)	f,ch	>6	0	0	8	0	<sup>2</sup> b	0	0
pH, field (standard units)	f,ch	6-9	0	0	0	0	0	0	0
Chloride, dissolved (mg/L as Cl)	f,ch	250	0	0	0	0	0	0	0
Sulfate, dissolved (mg/L as SO <sub>4</sub> )	f,ch	250	0	75	6	13	<sup>3</sup> b	0	0
Nitrogen, unionized ammonia, dissolved (mg/L as N)	ac	TVS	0	0	1	0	0	0	0
Nitrogen, unionized ammonia, dissolved (mg/L as N)	f,ch	0.02	0	0	0	0	0	0	0
Nitrogen, nitrite plus nitrate, dissolved (mg/L as N)	f,ch	10.	0	0	0	0	0	0	0
Nitrogen, nitrite, dissolved (mg/L as N)	f,ch	.05	0	0	0	0	0	0	0
Coliform, fecal (colonies/100ml)	f,ch	200	0	0	0	0	0	0	0
Arsenic, total recoverable (µg/L as As)	f,ac	50	0	0	0	0	0	0	0
Boron, dissolved (µg/L as B)	f,ch	750	0	0	0	0	--	--	--
Cadmium, total recoverable (µg/L as Cd)	ac	TVS	0	0	0	0	0	0	0
Cadmium, dissolved (µg/L as Cd)	ch	TVS	0	0	0	0	0	0	0
Chromium, total recoverable (µg/l as Cr)	f,ac	50	0	0	0	0	0	0	0
Copper, dissolved (µg/L as Cu)	ac	TVS	0	0	0	0	0	0	0
Copper, dissolved (µg/L as Cu)	ch	TVS	0	0	0	0	0	0	0
Iron, dissolved (µg/L as Fe)	f,ch	300	0	3	0	0	1	0	0
Iron, total recoverable (µg/L as Fe)	f, ch	1,000	21	10	0	1	0	0	3
Lead, dissolved (µg/L as Pb)	ac	TVS	0	0	0	0	0	0	0
Lead, dissolved (µg/L as Pb)	ch	TVS	2	1	0	0	0	0	0
Manganese, dissolved (µg/L as Mn)	f,ch	50	6	8	8	2	1s,8b	1s,7b	2
Mercury, total recoverable (µg/L as Hg)	f,ch	.01	0	0	0	0	0	0	0
Nickel, dissolved (µg/L as Ni)	ac	TVS	0	0	0	0	0	0	0
Nickel, dissolved (µg/L as Ni)	ch	TVS	0	0	0	0	0	0	0
Selenium, dissolved (µg/L as Se)	ac	TVS	0	0	0	12	0	0	0
Selenium, dissolved (µg/L as Se)	ch	TVS	0	2	0	12	6b	0	0
Silver, dissolved (µg/L as Ag)	ac	TVS	0	0	0	0	0	0	0
Silver, total recoverable (µg/L as Ag)	ch	TVS	1	1	0	0	0	0	0
Zinc, dissolved (µg/L as Zn)	ac	TVS	0	0	0	0	0	0	0
Zinc, dissolved (µg/L as Zn)	ch	TVS	0	0	0	0	0	0	0

<sup>1</sup>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.

<sup>2</sup>Dissolved-oxygen concentrations in the hypolimnion were frequently less than 6 mg/L during late-summer stratification.

<sup>3</sup>Sulfate concentrations often exceeded 250 mg/L in near-bottom samples.

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Selenium concentrations exceeded chronic standards twice at Muddy Creek at Kremmling site (S2). Six samples exceeded selenium chronic standards in near-bottom samples collected near the dam in Wolford Mountain Reservoir (L1) in 1995–97. Selenium concentrations in Alkali Slough #2 (S4) almost always exceeded computed chronic standards for selenium (12 samples). Acute standards for selenium at Alkali Slough #2 were exceeded six times. Concentrations of lead and silver occasionally exceeded chronic standards. Most of these concentrations probably were near the precision of the method of analysis at the time, increasing the chance that poor precision could overrepresent some concentrations. More recent data of greater precision indicate that silver was present only at very low concentrations. The fixed standard for dissolved iron of 300 µg/L was exceeded 3 times at Muddy Creek at Kremmling (S2) and once at Wolford Mountain Reservoir (L1). The total-recoverable iron fixed standard of 1,000 µg/L was exceeded at Muddy Creek above Antelope Creek (S1), Muddy Creek at Kremmling (S2) (10 samples), Alkali Slough #2 (S4) (1 sample), and Wolford Mountain Reservoir (L3) (3 samples). The fixed standard of 50 µg/L for dissolved manganese was exceeded in six samples from Muddy Creek above Antelope Creek (S1), eight samples from Muddy Creek at Kremmling (S2), eight samples from Muddy Creek below Wolford Mountain Reservoir (S3 all before 1999), and two samples from Alkali Slough #2 (S4). Wolford Mountain Reservoir concentrations of dissolved manganese exceed the standard in nine samples from near the dam (L1), eight samples from midlake (L2), and two samples from the inlet (L3). Exceedances generally occurred in late-summer near-bottom samples, and primarily during 1995 to 1996, a period of water-quality adjustment after initial filling of the reservoir. Manganese is a common problem constituent in the bottom waters of Colorado lakes and reservoirs and can cause problems for drinking-water treatment, staining of laundry when used for washing, and stream-bottom precipitates that can smother aquatic life.

### Summary and Conclusions

In March 1985, the U.S. Geological Survey, in cooperation with the Colorado River Water Conservation District (CRWCD), began a monitoring program on Muddy Creek in anticipation of the construction of Wolford Mountain Reservoir. A site upstream from the proposed reservoir (Muddy Creek above Antelope Creek, 09041090) and a site downstream (Muddy Creek at Kremmling, 09041500) were chosen to characterize preimpoundment conditions. Wolford Mountain Reservoir was constructed during 1992–94, and filling of the reservoir began in 1995. Water-quality monitoring of the reservoir began in July 1995 and in October 1995 at the reservoir outflow.

The purpose of this report was to describe inflow-, reservoir-, and outflow-water quality and assess the effects of Wolford Mountain Reservoir on downstream streamflow and water quality. Specific objectives were to:

1. Characterize and compare the upstream/downstream and preresevoir and postconstruction streamflow, water-quality characteristics, and temporal and spatial trends in Muddy Creek;
2. Describe limnological and water-quality characteristics of Wolford Mountain Reservoir (1995–2000); and
3. Compare water-quality data to Colorado water-quality standards and guidelines.

A summary of the primary conclusions of the study are as follows:

1. Water quality was generally good in Muddy Creek and Wolford Mountain Reservoir throughout the period of record (collectively 1982 to 2001). Specific conductance ranged from 99 to 1,720 µS/cm. Dissolved-oxygen concentrations generally were in the range of 3 to 7 mg/L, except in the hypolimnion where concentrations were near 1 mg/L or less in late summer and early fall. Cation compositions at Muddy Creek sites were mixed calcium-magnesium-sodium, but calcium typically was the predominant cation. Anion compositions were primarily bicarbonate and sulfate. After the reservoir was filled (post 1995), Muddy Creek downstream from the reservoir showed less annual variation in high and low water temperatures and specific conductance compared to preresevoir conditions. This change is likely due to the stabilizing effect of mixing within the reservoir. Turbidity in Muddy Creek downstream from the reservoir was substantially reduced after the reservoir was constructed as a result of sedimentation within the reservoir compared to preresevoir conditions. Concentrations of nutrients and trace elements generally were low (median total nitrogen less than 0.6 and median total phosphorus less than 0.05 milligrams per liter) and trace elements (median dissolved copper less than 2, median dissolved lead less than 1, and median dissolved zinc less than about 20 micrograms per liter) at all stream and reservoir sampling sites. The paucity of ore deposits and the low density of urban development in the Muddy Creek drainage probably limit trace-element concentrations to low concentrations.
2. The effects of Wolford Mountain Reservoir on streamflow are evident in flow-duration curves for Muddy Creek upstream and downstream from the reservoir. In most years, peak flows were the same or slightly reduced downstream from the reservoir due to storage effects. The upper first to fifteenth percentiles of flows were decreased compared to preresevoir flow patterns. Generally, the fifteenth to one-hundredth percentiles of flow were increased by operation of the reservoir outflow compared to preresevoir inflow.
3. Nutrient transport in the inflow is proportional to the amount of inflow-water discharge in a given year. Some nitrogen was stored in the water column, and gain/loss patterns for total nitrogen were somewhat related to reservoir storage. Nitrogen tended to be moved through

the reservoir, whereas phosphorus primarily was trapped within the reservoir in bottom sediments. Phosphorus was gained every year to the reservoir and, as a percentage, more phosphorus was retained than nitrogen in years when both were retained in the reservoir due to stronger phosphorus tendencies for adsorption, coprecipitation, and settling. Only small amounts of phosphorus were available in the water column at the outflow, and reservoir water-column storage did not affect phosphorus outflow-loading patterns as much as settling further upstream in the reservoir.

4. In most years, Carlson trophic-status index values for the reservoir were in the upper oligotrophic to mesotrophic ranges. Chlorophyll-*a*-based computations at the dam indicated stable Trophic Status Index (TSI) values, whereas the midlake site indicated decreasing TSI. Generally, the Secchi-depth and total-phosphorus TSI values were higher than those of chlorophyll-*a* on the same sampling date, and values at the upper end of the reservoir were higher than those computed for the reservoir site at the dam. This difference was probably a result of turbid conditions caused by inflow of suspended sediments and turbidity from Muddy Creek that raised the total-phosphorus and Secchi-depth TSI's or maybe decreased the chlorophyll-*a* index by reducing light penetration.
5. Statistically significant temporal trends ( $p$ -value less than 0.10) indicated by the seasonal Kendall test (SKT) for the upstream conditions (Muddy Creek above Antelope Creek, unaffected by the reservoir, 1990 to 2001) were for field properties of pH and turbidity; major ions and related calculated values that include magnesium, acid-neutralizing capacity (ANC), silica, and dissolved-solids residue; and the trace element dissolved iron. The trends all have positive slopes, except for the negative slope of ANC. No nutrients trends were significant ( $p$ -value less than 0.10). Trends ( $p$ -value less than 0.10) determined by SKT for the downstream conditions at Muddy Creek at Kremmling (unaffected by the reservoir) and Muddy Creek below Wolford Mountain Reservoir (affected by the reservoir, 1995 to 2001) had negative slopes indicating relatively decreasing concentrations for field properties, major ions, total ammonia plus organic nitrogen, and iron and manganese.
6. Spatial comparisons indicating statistically significant ( $p$ -value less than 0.10) upstream/downstream differences in water quality before construction of the reservoir were tested by nonparametric Wilcoxon signed-rank test for 1990 to 1995. Comparisons indicated that Muddy Creek was gaining dissolved solids, particulate matter (turbidity), and manganese as it flowed downstream before construction of the reservoir. Spatial comparisons indicating significant upstream/downstream differences also were determined for the period after construction of the reservoir (1995 to 2001). The

comparisons indicated increased specific conductance and major ion concentrations downstream from the reservoir compared to concentrations upstream from the reservoir, which were similar to the differences in values and concentrations that existed before construction. Turbidity, total-recoverable and dissolved manganese, and total-recoverable iron decreased downstream from the reservoir. The increase in most major ions indicates that Muddy Creek was still gaining dissolved solids after reservoir construction; however, the difference between median concentrations was less when compared to the prereservoir period. This decrease is probably due to mixing within the reservoir. Particulate matter (indicated by turbidity) and the trace elements manganese and iron decreased in Muddy Creek downstream as a result of the construction of the dam. This decrease is probably due to settling of suspended particles within the reservoir. *E. coli* and fecal coliform bacteria were found in Muddy Creek upstream from the reservoir (S1, up to more than 100 col/100mL). The comparison of upstream (S1) and downstream (S3) data indicate that bacteria do not survive in the reservoir or rapidly settle out with suspended material and, therefore, generally were not detected in the outflow at S3 or surface samples in the reservoir. Bacteria counts were low to not detected in the reservoir samples. Bacteria in Muddy Creek may be associated with suspended material that rapidly settles out in the reservoir.

7. Constituent concentrations generally met water-quality standards set by the State of Colorado. Selenium concentrations exceeded chronic standards twice at the Muddy Creek at Kremmling site (S2). Six samples exceeded selenium chronic standards in near-bottom samples collected from Wolford Mountain Reservoir near the dam (L1) in 1995–97.

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# **Hydrologic and Water-Quality Data**



**Table 15.** Nitrogen mass balance detailed computations.

[--, no sample or computation; mg/L, milligrams per liter; ac-ft, acre-feet; kg, kilograms; TN, total nitrogen]

Wolford 1996 Nitrogen Budget

Sample date	TN in (mg/L)	Water in (ac-ft)	TN mass in (kg)	TN out (mg/L)	Water out (ac-ft)	TN mass out (kg)
1/11/96	--	439	--	0.96	970	1,149
2/27/96	--	372	--	0.70	1,210	1,045
3/27/96	--	694	--	0.64	2,450	1,935
4/22/96	1.32	8,960	14,595	0.68	14,830	12,444
05/22/96	0.56	39,080	27,006	0.54	21,440	14,287
06/10/96	0.33	14,730	5,907	0.52	9,750	6,256
07/16/96	0.45	1,250	694	0.43	3,720	1,974
08/28/96	0.33	853	342	0.59	9,430	6,866
09/03/96	0.23	528	147	0.52	6,150	3,946
010/17/96	0.23	492	137	0.42	2,170	1,125
11/13/96	0.13	641	99	0.71	1,410	1,235
12/10/96	0.23	871	242	0.52	1,350	866

Gained/lost = inflow - outflow

Total inflow mass (kg)	49,168	April to December only
Total outflow mass (kg)	48,999	April to December only
Mass gained (+) or lost from (-) reservoir	169	April to December only

Wolford 1997 Nitrogen Budget

Sample date	TN in (mg/L)	Water in (ac-ft)	TN mass in (kg)	TN out (mg/L)	Water out (ac-ft)	TN mass out (kg)
1/28/97	0.30	674	250	0.50	1,520	938
2/27/97	0.33	559	228	0.55	1,730	1,174
3/18/97	0.80	1,090	1,076	0.96	4,660	5,520
4/16/97	0.76	6,780	6,359	0.70	7,530	6,504
05/14/97	0.84	40,520	42,001	0.54	23,960	15,966
06/02/97	0.46	21,480	12,193	0.52	29,300	18,801
07/10/97	0.43	1,530	802	0.53	5,950	3,891
08/13/97	0.55	1,690	1,147	0.65	5,740	4,604
09/03/97	0.33	2,690	1,079	0.64	8,310	6,563
010/16/97	0.13	2,350	362	0.40	10,600	5,232
11/26/97	0.23	1,570	436	0.43	2,770	1,470
12/16/97	0.26	1,340	430	0.41	2,010	1,017

Gained/lost = inflow - outflow

Total inflow mass (kg)	66,363
Total outflow mass (kg)	71,681
Mass gained (+) or lost from (-) reservoir	-5,319

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**Table 15.** Nitrogen mass balance detailed computations.—Continued

[--, no sample or computation; mg/L, milligrams per liter; ac-ft, acre-feet; kg, kilograms; TN, total nitrogen]

Wolford 1998 Nitrogen Budget

Sample date	TN in (mg/L)	Water in (ac-ft)	TN mass in (kg)	TN out (mg/L)	Water out (ac-ft)	TN mass out (kg)
1/22/98	0.31	1,250	478	0.43	1,980	1,051
2/19/98	0.42	1,040	539	0.44	1,910	1,037
3/25/98	2.73	3,280	11,050	0.56	3,380	2,336
4/21/98	0.55	8,570	5,816	0.71	2,700	2,366
05/20/98	0.58	29,570	21,164	0.71	27,900	24,444
06/09/98	0.46	7,460	4,235	0.53	12,060	7,887
07/22/98	0.63	886	683	0.66	4,110	3,347
08/11/98	0.43	897	470	0.63	4,490	3,491
09/09/98	0.43	509	267	0.53	11,270	7,371
010/14/98	0.26	711	228	0.59	3,180	2,315
11/12/98	0.28	809	280	0.38	1,850	868
12/14/98	0.23	556	154	0.60	1,560	1,155

Gained/lost = inflow - outflow

Total inflow mass (kg)	45,365
Total outflow mass (kg)	57,667
Mass gained (+) or lost from (-) reservoir	-12,303

Wolford 1999 Nitrogen Budget

Sample date	TN in (mg/L)	Water in (ac-ft)	TN mass in (kg)	TN out (mg/L)	Water out (ac-ft)	TN mass out (kg)
1/20/99	0.36	664	295	0.48	1,400	829
2/9/99	0.40	736	363	0.49	1,250	756
3/24/99	1.45	1,900	3,400	0.57	1,830	1,287
4/13/99	0.53	4,160	2,695	0.51	3,120	1,964
05/10/99	1.21	20,010	29,878	0.51	6,950	4,374
06/02/99	0.53	10,470	6,783	0.48	17,020	10,081
07/08/99	0.63	1,020	787	0.59	5,030	3,662
08/10/99	0.43	831	436	0.67	3,240	2,679
09/14/99	0.33	551	221	0.42	6,550	3,395
010/13/99	0.23	348	97	0.33	7,930	3,180
11/09/99	0.23	508	141	0.48	1,780	1,059
12/15/99	0.33	627	251	0.60	1,420	1,048

Gained/lost = inflow - outflow

Total inflow mass (kg)	45,346
Total outflow mass (kg)	34,314
Mass gained (+) or lost from (-) reservoir	11,033

**Table 15.** Nitrogen mass balance detailed computations.—Continued

[--, no sample or computation; mg/L, milligrams per liter; ac-ft, acre-feet; kg, kilograms; TN, total nitrogen]

Wolford 2000 Nitrogen Budget

Sample date	TN in (mg/L)	Water in (ac-ft)	TN mass in (kg)	TN out (mg/L)	Water out (ac-ft)	TN mass out (kg)
1/13/00	0.29	387	138	0.57	1,360	963
2/24/00	0.41	437	221	0.51	1,220	769
3/14/00	0.13	1,490	239	0.51	1,300	813
4/11/00	1.05	9,050	11,726	0.58	2,290	1,647
05/09/00	0.76	28,600	26,822	0.56	22,220	15,355
06/06/00	0.53	5,270	3,414	0.44	10,270	5,526
07/07/00	0.53	590	382	0.51	6,130	3,888
08/22/00	0.43	563	295	0.52	9,210	5,921
09/06/00	0.33	445	178	0.57	4,760	3,336
010/11/00	0.29	280	98	0.46	1,340	756
11/21/00	0.29	358	126	0.45	1,360	752
12/12/00	0.23	508	143	0.45	1,360	754

Gained/lost = inflow - outflow

Total inflow mass (kg)	43,784
Total outflow mass (kg)	40,481
Mass gained (+) or lost from (-) reservoir	3,304

Wolford 2001 Nitrogen Budget

Sample date	TN in (mg/L)	Water in (ac-ft)	TN mass in (kg)	TN out (mg/L)	Water out (ac-ft)	TN mass out (kg)
1/23/01	0.32	291	115	0.46	1,320	754
2/12/01	0.31	269	103	0.52	1,220	778
3/13/01	0.40	607	302	0.49	1,620	978
4/10/01	0.62	5,470	4,158	0.51	4,920	3,115
05/08/01	0.66	18,490	15,036	0.56	4,780	3,297
06/06/01	0.46	2,460	1,381	0.51	4,390	2,752
07/03/01	0.59	520	376	0.58	4,780	3,398
08/29/01	0.41	436	218	0.43	6,910	3,624
09/20/01	0.27	367	121	0.39	7,600	3,695
Oct estimate	0.27	378	125	0.39	1,910	929

Gained/lost = inflow - outflow

Total inflow mass (kg)	21,935	January to October only
Total outflow mass (kg)	23,319	January to October only
Mass gained (+) or lost from (-) reservoir	-1,384	January to October only

**Table 16.** Phosphorus mass balance detailed computations.

[mg/L, milligrams per liter; ac-ft, acre-feet; kg, kilograms]

Wolford 1996 Phosphorus Budget

Sample date	TP in (mg/L)	Water in (ac-ft)	TP mass in (kg)	TP out (mg/L)	Water out (ac-ft)	TP mass out (kg)
4/10/96	0.330	8,960	3,649	0.030	14,830	549
05/22/96	0.200	39,080	9,645	0.060	21,440	1,587
06/10/96	0.090	14,730	1,636	0.040	9,750	481
07/16/96	0.005	1,250	8	0.005	3,720	23
08/28/96	0.005	853	5	0.020	9,430	233
09/03/96	0.010	528	7	0.005	6,150	38
010/17/96	0.005	492	3	0.005	2,170	13
11/13/96	0.040	641	32	0.005	1,410	9
12/10/96	0.005	871	5	0.005	1,350	8

Gained/lost = inflow - outflow

Total inflow mass (kg)	14,989	April to December only
Total outflow mass (kg)	2,942	April to December only
Mass gained (+) or lost from (-) reservoir	12,047	April to December only

Wolford 1997 Phosphorus Budget

Sample date	TP in (mg/L)	Water in (ac-ft)	TP mass in (kg)	TP out (mg/L)	Water out (ac-ft)	TP mass out (kg)
1/28/97	0.005	674	3	0.005	1,520	9
2/26/97	0.080	559	108	0.080	1,730	171
3/18/97	0.060	1,090	502	0.060	4,660	345
4/16/97	0.005	6,780	250	0.005	7,530	46
05/14/97	0.220	40,520	11,000	0.010	23,960	296
06/02/97	0.120	21,480	3,181	0.010	29,300	362
07/10/97	0.005	1,530	9	0.005	5,950	37
08/13/97	0.020	1,690	42	0.010	5,740	71
09/03/97	0.005	2,690	17	0.005	8,310	51
010/16/97	0.005	2,350	14	0.005	10,600	65
11/20/97	0.005	1,570	10	0.005	2,770	17
12/16/97	0.005	1,340	8	0.005	2,010	12

Gained/lost = inflow - outflow

Total inflow mass (kg)	15,144
Total outflow mass (kg)	1,483
Mass gained (+) or lost from (-) reservoir	13,662

**Table 16.** Phosphorus mass balance detailed computations.—Continued

[mg/L, milligrams per liter; ac-ft, acre-feet; kg, kilograms]

Wolford 1998 Phosphorus Budget

Sample date	TP in (mg/L)	Water in (ac-ft)	TP mass in (kg)	TP out (mg/L)	Water out (ac-ft)	TP mass out (kg)
1/22/98	0.005	1,250	8	0.005	1,980	12
2/19/98	0.010	1,040	13	0.005	1,910	12
3/25/98	0.510	3,280	2,064	0.020	3,380	83
4/21/98	0.040	8,570	423	0.030	2,700	100
05/20/98	0.170	29,570	6,203	0.180	27,900	6,197
06/09/98	0.050	7,460	460	0.005	12,060	74
07/22/98	0.050	886	55	0.005	4,110	25
08/11/98	0.005	897	6	0.005	4,490	28
09/09/98	0.010	509	6	0.040	11,270	556
010/14/98	0.025	711	22	0.005	3,180	20
11/12/98	0.025	809	25	0.005	1,850	11
12/14/98	0.025	556	17	0.005	1,560	10

Gained/lost = inflow - outflow

Total inflow mass (kg) 9,302  
 Total outflow mass (kg) 7,129  
 Mass gained (+) or lost from (-) reservoir 2,173

Wolford 1999 Phosphorus Budget

Sample date	TP in (mg/L)	Water in (ac-ft)	TP mass in (kg)	TP out (mg/L)	Water out (ac-ft)	TP mass out (kg)
1/20/99	0.025	664	20	0.005	1,400	9
2/9/99	0.025	736	23	0.005	1,250	8
3/24/99	0.220	1,900	516	0.005	1,830	11
4/13/99	0.080	4,160	411	0.005	3,120	19
05/10/99	0.360	20,010	8,889	0.030	6,950	257
06/02/99	0.140	10,470	1,809	0.090	17,020	1,890
07/08/99	0.025	1,020	31	0.005	5,030	31
08/10/99	0.025	831	26	0.005	3,240	20
09/14/99	0.025	551	17	0.005	6,550	40
010/13/99	0.025	348	11	0.005	7,930	49
11/09/99	0.025	508	16	0.005	1,780	11
12/15/99	0.025	627	19	0.005	1,420	9

Gained/lost = inflow - outflow

Total inflow mass (kg) 11,788  
 Total outflow mass (kg) 2,355  
 Mass gained (+) or lost from (-) reservoir 9,433

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**Table 16.** Phosphorus mass balance detailed computations.—Continued

[mg/L, milligrams per liter; ac-ft, acre-feet; kg, kilograms]

Wolford 2000 Phosphorus Budget

Sample date	TP in (mg/L)	Water in (ac-ft)	TP mass in (kg)	TP out (mg/L)	Water out (ac-ft)	TP mass out (kg)
1/13/00	0.025	387	12	0.005	1,360	8
2/24/00	0.025	437	13	0.005	1,220	8
3/14/00	0.025	1,490	46	0.005	1,300	8
4/11/00	0.200	9,050	2,234	0.005	2,290	14
05/09/00	0.230	28,600	8,117	0.005	22,220	137
06/06/00	0.070	5,270	455	0.005	10,270	63
07/07/00	0.025	590	18	0.005	6,130	38
08/22/00	0.040	563	28	0.005	9,210	57
09/06/00	0.025	445	14	0.005	4,760	29
010/11/00	0.030	280	10	0.030	1,340	50
11/21/00	0.030	358	13	0.030	1,360	50
12/12/00	0.030	508	19	0.030	1,360	50

Gained/lost = inflow - outflow

Total inflow mass (kg)	10,980
Total outflow mass (kg)	513
Mass gained (+) or lost from (-) reservoir	10,467

Wolford 2001 Phosphorus Budget

Sample date	TP in (mg/L)	Water in (ac-ft)	TP mass in (kg)	TP out (mg/L)	Water out (ac-ft)	TP mass out (kg)
1/23/01	0.030	291	11	0.030	1,320	49
2/12/01	0.030	269	10	0.030	1,220	45
3/13/01	0.042	607	31	0.030	1,620	60
4/10/01	0.068	5,470	459	0.030	4,920	182
05/08/01	0.118	18,490	2,692	0.016	4,780	94
06/06/01	0.036	2,460	109	0.030	4,390	163
07/03/01	0.013	520	8	0.007	4,780	41
08/29/01	0.028	436	15	0.009	6,910	77
09/20/01	0.016	367	7	0.014	7,600	131
October estimate	0.016	378	7	0.014	1,910	33

Gained/lost = inflow - outflow

Total inflow mass (kg)	3,351	January to October only
Total outflow mass (kg)	875	January to October only
Mass gained (+) or lost from (-) reservoir	2,476	January to October only