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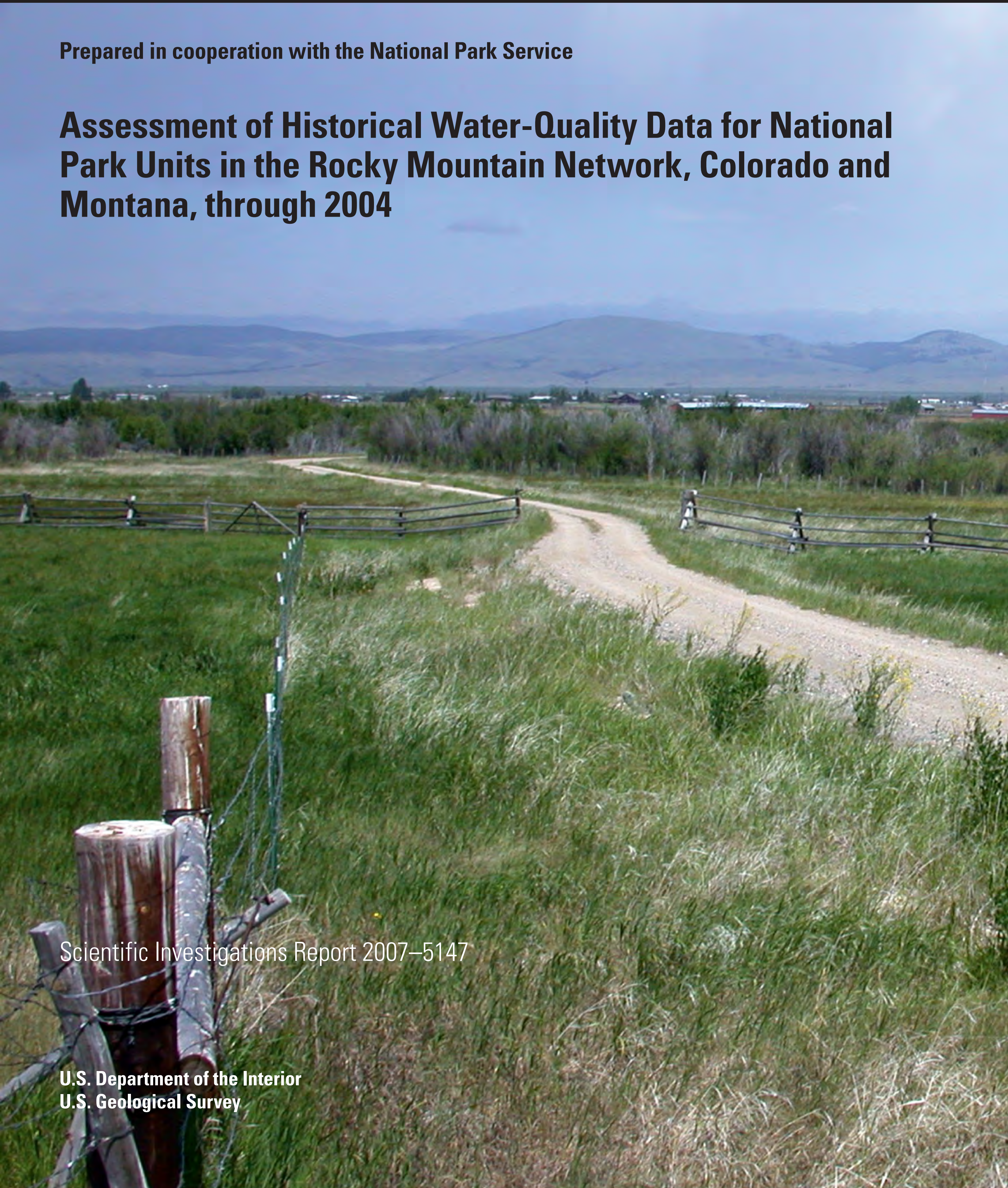
Assessment of Historical Water-Quality Data for National Park Units in the Rocky Mountain Network, Colorado and Montana, through 2004



Scientific Investigations Report 2007–5147

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

Cover. Grant-Kohrs Ranch National Historic Site, Montana, by W. Schweiger, National Park Service.

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Conversion Factors, Abbreviations, and Datums

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
meter (m)	1.094	yard (yd)
kilometer (km)	0.6214	mile (mi)
	Area	
square meter (m^2)	0.0002471	acre
hectare (ha)	2.471	acre
square kilometer (km^2)	247.1	acre
square meter (m^2)	10.76	square foot (ft^2)
hectare (ha)	0.003861	square mile (mi^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
liter (L)	33.82	ounce, fluid (fl. oz)
liter (L)	2.113	pint (pt)
liter (L)	1.057	quart (qt)
liter (L)	0.2642	gallon (gal)
cubic meter (m^3)	264.2	gallon (gal)
cubic meter (m^3)	0.0002642	million gallons (Mgal)
liter (L)	61.02	cubic inch (in^3)
cubic meter (m^3)	35.31	cubic foot (ft^3)
cubic meter (m^3)	1.308	cubic yard (yd^3)
cubic meter (m^3)	0.0008107	acre-foot (acre-ft)
	Flow rate	
cubic meter per second (m^3/s)	70.07	acre-foot per day (acre-ft/d)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
liter per second (L/s)	15.85	gallon per minute (gal/min)
	Mass	
gram (g)	0.03527	ounce, avoirdupois (oz)
kilogram (kg)	2.205	pound avoirdupois (lb)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) by

$$°F=(1.8×°C)+32.$$

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

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

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

Water year, as used in this report, refers to the period October 1 through September 30 and is designated by the year in which it ends.

Abbreviations, acronyms, and symbols used in this report

CASNET	Clean Air Status and Trends
CDPHE	Colorado Department of Public Health and Environment
ESTREND	Estimate Trend
FLBS	Flathead Lake Biological Station
FLFO	Florissant Fossil Beds National Monument
GLAC	Glacier National Park
GRKO	Grant-Kohrs Ranch National Historic Site
GRSA	Great Sand Dunes National Park and Preserve
I&M	Inventory and Monitoring Program
LIBI	Little Bighorn Battlefield National Monument
LVWS	Loch Vale Watershed
MTDEQ	Montana Department of Environmental Quality
NADP	National Atmospheric Deposition Program
NPS	National Park Service
NURE	National Uranium Resource Evaluation
NWIS	National Water Information System
ROMN	Rocky Mountain Network
ROMO	Rocky Mountain National Park
STORET	Storage and Retrieval System
TVS	Table Value Standard
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
VNRP	Voluntary Nutrient Reduction Program

cm	centimeter
col/100 mL	colonies per 100 milliliters
ft^3/s	cubic feet per second
$ft^3/s/yr$	cubic feet per second per year
kg N/ha/yr	kilograms of nitrogen per hectare per year
km	kilometer
km^2	square kilometers
L/min	liters per minute
L/s	liters per second

m	meter
m/km	meters per kilometer
mg/L	milligrams per liter
mg/L/yr	milligrams per liter per year
μeq/L/yr	microequivalents per liter per year
μg/L	micrograms per liter
μS/cm	microsiemens per centimeter
°C	degrees Celsius
<	less than
>	greater than
≤	less than or equal to

Assessment of Historical Water-Quality Data for National Park Units in the Rocky Mountain Network, Colorado and Montana, through 2004

By M. Alisa Mast

Abstract

This report summarizes historical water-quality data for six National Park units that compose the Rocky Mountain Network. The park units in Colorado are Florissant Fossil Beds National Monument, Great Sand Dunes National Park and Preserve, and Rocky Mountain National Park; and in Montana, they are Glacier National Park, Grant-Kohrs Ranch National Historic Site, and Little Bighorn Battlefield National Monument. This study was conducted in cooperation with the Inventory and Monitoring Program of the National Park Service to aid in the design of an effective and efficient water-quality monitoring plan for each park. Data were retrieved from a number of sources for the period of record through 2004 and compiled into a relational database. Descriptions of the environmental setting of each park and an overview of the park's water resources are presented. Statistical summaries of water-quality constituents are presented and compared to aquatic-life and drinking-water standards. Spatial, seasonal, and temporal patterns in constituent concentrations also are described and suggestions for future water-quality monitoring are provided.

Introduction

In 1992, the National Park Service (NPS) initiated the Inventory and Monitoring (I&M) program to help develop a stronger scientific basis for stewardship and management of natural resources across the National Park system (*http://science.nature.nps.gov/im/index.cfm*, accessed November 2006). A primary goal of I&M is to complete basic inventories in parks with extensive natural resources and to provide resource managers with scientifically sound information on their status and trends in a readily accessible form. Another I&M goal is to design and implement a program to monitor the 'vital signs' of park resources (National Park Service, 2005). Vital signs are selected physical, chemical, and biological elements and processes of park ecosystems that represent the overall health or condition of the park. Vital signs can be used as early warning signals to detect changes that could impair the long-term health of natural systems. Early detection of potential problems allows park managers to take steps to restore ecological health of park resources before serious damage occurs (National Park Service, 2005). To achieve these goals, the I&M program organized the 270 parks in the National Park system into 32 networks, which link parks that share similar geographic and natural-resource characteristics. Parks within a network share funding and staff to improve efficiency and reduce costs and partner with universities and State and Federal agencies to assist with basic park resource inventories and monitoring.

One of the 32 networks is the Rocky Mountain Network (ROMN), which consists of six parks located along a northwest–southeast axis that follows the Continental Divide in the central Rocky Mountains (fig. 1). The six parks are Florissant Fossil Beds National Monument, Great Sand Dunes National Park and Preserve, and Rocky Mountain National Park in Colorado; and Glacier National Park, Grant-Kohrs Ranch National Historic Site, and Little Bighorn Battlefield National Monument in Montana. Twelve high-priority vital signs have been selected for monitoring in the six ROMN parks (*http://www1.nature.nps.gov/im/units/romn/vital_signs.cfm*, accessed April 2007). The vital signs include (1) wet and dry deposition, (2) weather and climate, (3) water chemistry, (4) surface-water dynamics, (5) freshwater communities, (6) invasive/exotic aquatic biota, (7) ground-water dynamics, (8) wetland communities, (9) invasive/exotic plants, (10) vegetation composition, structure, and soils, (11) focal species, and (12) landscape dynamics. One-half of the identified vital signs are related to aquatic resources because they are central to the park missions, and their protection is given high priority in each park's resource management plan, particularly in Glacier National Park, Great Sand Dunes National Park and Preserve, and Rocky Mountain National Park. Rocky Mountain National Park, for example, has 156 high-elevation lakes and more than 700 kilometers (km) of streams in Class I wilderness (Britten and others, 2006), which provide habitat for numerous aquatic plants and animals, including the Federally listed greenback cutthroat trout and boreal toad.

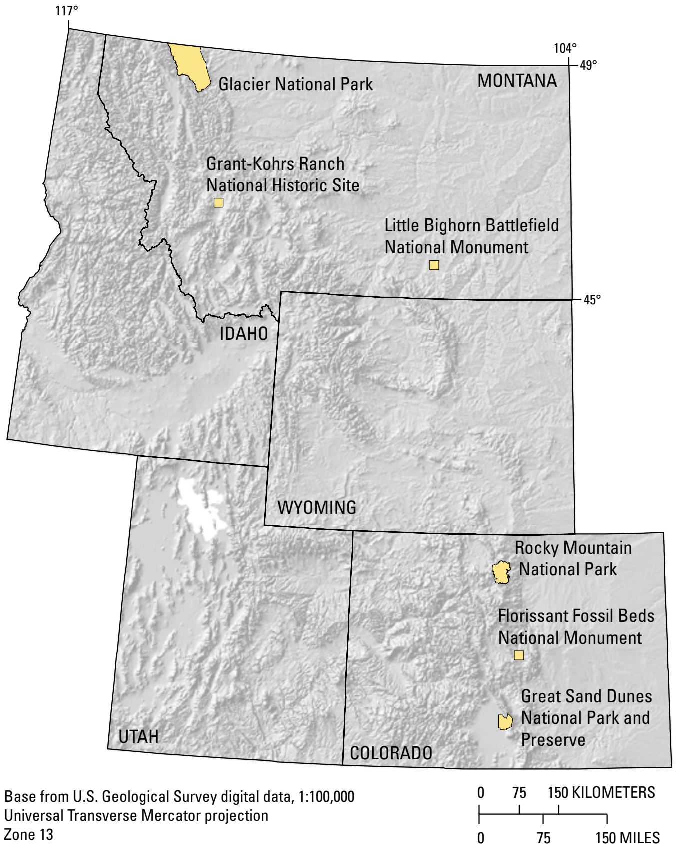

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Figure 1. Location of the six National Park units in the Rocky Mountain Network, Colorado and Montana.

The ROMN staff currently (2007) is in the process of establishing protocols and developing an integrated monitoring plan for aquatic vital signs (including water quality), which is scheduled for implementation during 2009 to 2010. The general goal of the monitoring plan is to characterize the current status of and determine trends in the ecological condition of aquatic resources. Trend information is essential to assess the effectiveness of management and restoration activities and to provide early warning of environmental change. Water-quality monitoring also must be linked to Federal and State regulatory frameworks established under the 1977 Clean Water Act. As one of the first steps in the planning process, the U.S. Geological Survey (USGS), in cooperation with the NPS, conducted a study to compile, review, and summarize historical water-quality data for each park unit in the network. The main objective of this study was to provide a framework of information to aid in the design of an effective and efficient water-quality monitoring program for each of the six ROMN parks.

Purpose and Scope

The purpose of this report is to present summaries and hydrologic interpretations of water-quality data collected at surface- and ground-water sites in the six park units in the ROMN. This report uses available water-quality data for the period of record through water year 2004 and focuses on field properties, major constituents, nutrients, and dissolved trace elements. The majority of the data were obtained from the USGS National Water Information System (NWIS) and the U.S. Environmental Protection Agency (USEPA) Storage and Retrieval System (STORET) databases. Descriptions of the environmental setting of each park and an overview of the park's water resources are provided. Statistical summaries of water-quality constituents are presented and compared to aquatic-life and drinking-water standards. Spatial, seasonal, and temporal patterns in constituent concentrations also are described and suggestions are made for design of a water-quality monitoring plan in each park. Hydrologic interpretations are considered preliminary because data sets generally are small and data were collected periodically for different study objectives. Other limitations to interpreting data from different sources include use of different analytical laboratories and methods, differences in laboratory reporting levels, and differences in field and laboratory quality-assurance procedures.

Acknowledgments

The author thanks Mike Britten, Brent Frakes, and E. William Schweiger of the NPS I&M Program for their support of this project. Technical reviews of the report were provided by Julianne Brown of the USGS and E. William Schweiger of the NPS.

Methods of Data Analysis

Water-quality data were retrieved in electronic format from a number of difference sources, compiled into a relational database, and checked for general accuracy. Results for selected surface- and ground-water sites from each park unit were analyzed by statistical and graphical methods for hydrologic interpretation.

Data Sources and Compilation

Most of the water-quality data analyzed in this report were retrieved from the NWIS (*http://waterdata.usgs.gov/nwis*, accessed August 2007) and STORET *(http://www.epa.gov/storet/dbtop.html*, accessed August 2007) databases for the period of record through 2004. Additional datasets were obtained from several USGS and NPS researchers and graduate students provided they were available in electronic format. Study areas were defined for each park unit based on the park boundary, a buffer area (up to 1 km) around the boundary, and headwater areas of streams flowing through but not originating in the park (see Grape Creek drainage in fig. 2 for example). All water-quality data for surface- and ground-water sites located within the defined study areas were retrieved from the different data sources and compiled into a relational database using the Access software, herein referred to as the "ROMN database." In the database, data are stored in three core tables that include a site attribute table, a sampling event table, and a water-quality results table. Additional related information is stored in a number of lookup tables and ancillary tables. Data in the results table are stored using 5-character numeric codes called parameter codes that define a specific type of data (*http://nwis.waterdata.usgs.gov/usa/nwis/pmcodes*, accessed November 2006). For example, the parameter code for field pH in unfiltered water is 00400 and for laboratory pH in unfiltered water is 00403. Parameter codes were grouped into 18 water-quality categories, such as field properties, nutrients, and major constituents, to facilitate retrieval of information from the database. All data were screened for outliers and checked against expected ranges for constituent concentrations (National Park Service, 1998); suspect values were moved to a separate table in the database. All USGS trace-element data were retained in the database although it is documented that dissolved concentrations in samples collected before 1992 may have been contaminated during sample collection and processing (USGS Office of Water Quality Technical Memorandum 91.10, available at *http://water.usgs.gov/admin/memo/QW/index.html*, accessed November 2006). Because field and laboratory quality-assurance data are not available for the majority of the retrieved records, a more comprehensive review of data quality was not possible.

The final ROMN database contained water-quality data collected at 1,696 surface-water sites and 240 ground-water sites from 1941 to 2004 (table 1). For these 1,936 sites, there were a total of 35,534 samples with more than 400,000 individual results most of which were field properties (33 percent), and major-constituent (28 percent), nutrient (12 percent), and trace-element (13 percent) analyses. The number of sites, samples, and results in the ROMN database by park unit and location relative to the park boundary are shown in table 1. More than 80 percent of the retrieved results were for Glacier National Park and Rocky Mountain National Park, which are the largest parks in the ROMN network.

Data-Analysis Procedures

For this report, a subset of water-quality properties and constituents from the ROMN database were used for data analysis; primarily field properties, major constituents, nutrients, and trace elements. In addition, only data for sites located within or immediately adjacent to the park unit boundaries were selected. In some cases, results for the same constituent are stored under different parameter codes because of differences in analytical methods, sampling techniques, reporting units, or data sources. For these constituents, the results were aggregated into a single parameter to obtain a more complete and continuous record for data analysis. For example, pH often is reported under three different parameter codes; field pH (P0400), laboratory pH (00403), and pH in standard units (00406). In this case, results for parameter codes 00403 and 00406 were combined with parameter code 00400 for samples where field pH was not reported. Nutrients also are commonly reported under multiple parameter codes. Guidelines used for aggregating common nutrient species are described by Mueller and others (1995). Total dissolved solids were computed for samples with complete major constituent analyses by summing the concentrations of the individual constituents. For this report, 'dissolved' constituents refer to concentrations measured in filtered samples and 'total' constituents refer to concentrations measured in unfiltered samples. Based on the range of pH in surface and ground water samples from the parks, the bicarbonate anion was assumed to be the dominant form of alkalinity.

Descriptive summary statistics for surface-water and ground-water quality were computed and tabulated and compared to aquatic-life standards and drinking-water regulations. Because data were compiled from different sources and periods of record, the datasets often contained more than one laboratory reporting level for a given constituent, particularly for nutrients and trace elements. The original censored values including 'zero' values were retained in the database, which sometimes resulted in minimum values less than minimum censored values in the water-quality summary tables. For the three parks in Colorado, water-quality standards and clas-

Table 1. Number of water-quality sites, samples, and results retrieved and compiled for park units in the Rocky Mountain Network, Colorado and Montana, through 2004.

[Colo., Colorado; Mont., Montana; first number is number of sites, samples or results inside park boundary; number in parentheses is number of sites, samples or results outside park boundary]

Park unit	Surface water			Ground water		
	Sites	Samples	Results	Sites	Samples	Results
Florissant Fossil Beds National Monument, Colo.	8 (5)	43 (17)	476 (198)	2 (0)	2 (0)	88 (0)
Great Sand Dunes National Park and Preserve, Colo.	46 (16)	387 (44)	8,340 (675)	20 (25)	26 (28)	597 (509)
Rocky Mountain National Park, Colo.	548 (120)	12,796 (7,731)	144,814 (94,399)	45 (18)	346 (20)	4,573 (1,022)
Glacier National Park, Mont.	527 (273)	3,147 (7,767)	58,623 (48,956)	22 (0)	74 (0)	2,480 (0)
Grant-Kohrs Ranch National Historic Site, Mont.	4 (117)	138 (1,335)	2,825 (23,798)	18 (15)	199 (59)	1,616 (866)
Little Bighorn Battlefield National Monument, Mont.	2 (30)	5 (1,284)	253 (15,806)	3 (72)	6 (80)	202 (2,161)

sifications were obtained from the Colorado Department of Public Health and Environment (CDPHE) (*http://www.cdphe.state.co.us/regulations/wqccregs/*, accessed November 2006). For the three parks in Montana, water-quality standards and classifications were obtained from the Montana Department of Environmental Quality (MTDEQ) (*http://www.deq.state.mt.us/wqinfo/Standards/Index.asp*, accessed November 2006). Some trace elements have table value standards (TVS), which are site-specific standards based on stream hardness. For these constituents, the standard was calculated based on the median hardness for the water bodies of interest. Both chronic and acute standards typically are established for trace elements. Chronic standards, which usually are lower than the acute standards, were used for comparison with trace-element concentrations in surface water.

Temporal trends in water-quality constituent concentrations were tested using the Estimate Trend (ESTREND) computer program (Schertz and others, 1991), which uses the nonparametric seasonal Kendall test or the Tobit procedure if more than 5 percent of the data are censored. Temporal trends were tested only on sites with less than 50 percent censored data, and with at least 5 years of quarterly data. If discharge data were available, concentrations were adjusted for flow-related variability, which not only improves the power of the statistical test, but decreases the possibility that the observed trends were an artifact of the sampling discharge record (Hirsch and others, 1982; Schertz and others, 1991). Flow adjustment was not made if the concentration-discharge model was not significant at the 90 percent confidence level (Schertz and others, 1991) or if more than 5 percent of the data were censored. Trends were calculated using unadjusted and flow-adjusted concentrations and were considered statistically significant at the 99 percent confidence level (p-value ≤ 0.01). The ESTREND procedure also computes a trend slope, which represents the median rate of change in concentration or discharge for the selected period of record.

Assessment of Historical Water-Quality Data

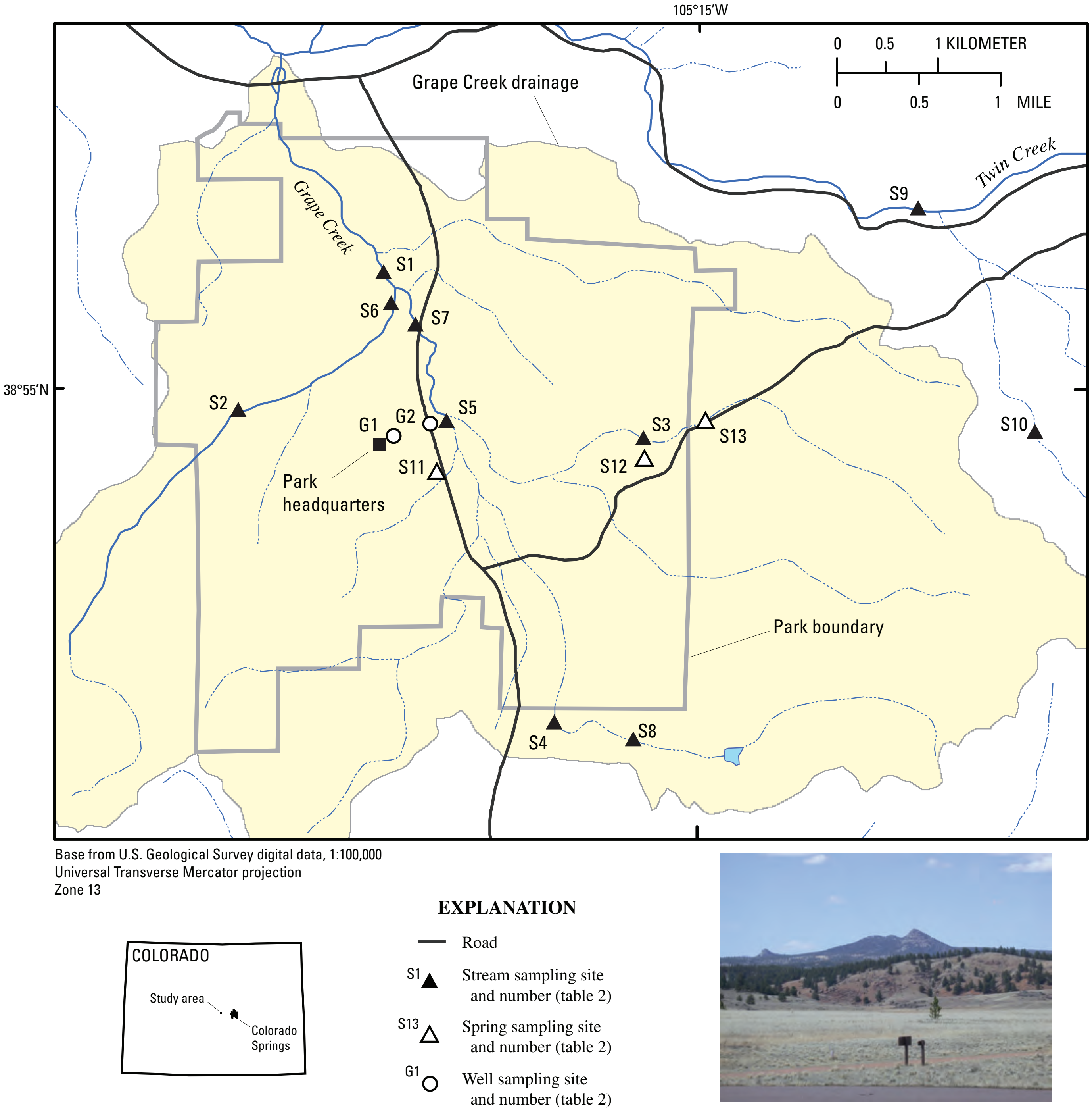
Historical data were assessed to describe water-quality conditions for the six park units in the ROMN. Results for each of the parks are discussed separately in the following sections of this report. Each section provides a brief description of the environmental setting of the park and an overview of the park's water resources. Statistical summaries of selected water-quality constituents are presented and compared to aquatic-life and drinking-water standards. Spatial, seasonal, and temporal patterns in constituent concentrations were examined to help identify natural and anthropogenic factors controlling water quality in each of the six parks. Suggestions are provided for consideration in designing water-quality monitoring plans.

The discussion of water quality in this report primarily focuses on field properties, major constituents, nutrients, and dissolved trace elements. The most commonly measured field properties are water temperature, dissolved oxygen, pH, and specific conductance, which are referred to as "core field properties" by the NPS. Water temperature is important because it controls the rate of chemical reactions, which in turn affects biological activity in aquatic environments. Dissolved oxygen is necessary for the survival of many aquatic organisms, and pH is important because it determines the solubility and biological availability of chemical constituents such as nutrients and trace elements. Specific conductance is proportional to the concentration of major dissolved constituents, the most common of which are bicarbonate, calcium, chloride, fluoride, magnesium, potassium, silica, sodium, and sulfate. The sum of the concentrations of these dissolved constituents is referred to as dissolved solids concentration. The primary source of major dissolved constituents in surface and ground water is weathering of minerals in soil, bedrock, and unconsolidated material. Atmospheric deposition can be a substantial source of dissolved chloride and sulfate particularly in areas with crystalline bedrock, which typically has low chlorine and sulfur contents. Human activities also can affect major-constituent concentrations; for example, mine wastes are a source of sulfate, and sewage effluent and road salt can be sources of sodium and chloride. Major nutrients are compounds of nitrogen and phosphorus that are needed for plant growth. Excess nutrients in surface water can cause overgrowth of algae, which can lead to degradation of aquatic habitat. Sewage effluent, livestock waste, and fertilizer typically are the largest sources of nutrients to surface and ground water. In areas with minimal human activities, such as National Parks, atmospheric deposition of nitrogen derived from fossil fuel combustion and agriculture can be an important source of nutrients to lakes and streams. Trace elements generally are associated with mining and urban activities, and are important indicators of water quality because elevated concentrations can be toxic to aquatic life.

Florissant Fossil Beds National Monument

Environmental Setting

Florissant Fossil Beds National Monument (FLFO) is located on the eastern slope of the Colorado Front Range approximately 48 km west of Colorado Springs, Colorado (fig. 2). The park covers 24.2 square kilometers (km^2), ranges in elevation from 2,500 to 2,700 meters (m), and is characterized by an open mountain valley surrounded by rounded rocky hills. Vegetation is dominated by Arizona Fescue and Mountain Muly herbaceous cover along the valley floor and ponderosa pine woodland and Colorado blue spruce/Douglas fir forest on the surrounding hills (Britten and others, 2006). Climate is characterized by cool winters with warm summers. Mean monthly air temperatures near the park headquarters



Base from U.S. Geological Survey digital data, 1:100,000
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Photograph of Florissant Fossil Beds National Monument
by W. Schweiger, National Park Service

Figure 2. Location of water-quality sampling sites near Florissant Fossils Beds National Monument, Colorado.

range from -5.3 °C in January to 15.3 °C in July (*http://www.wrcc.dri.edu/summary/climsmco.html*, accessed May 2006). Annual average precipitation is 38 centimeters (cm) most of which falls during afternoon thundershowers between May and September. The area receives about 145 cm of snowfall each year, mostly between October and April.

Bedrock is the Pikes Peak Granite, which is a pink to reddish-tan coarse-grained granite and quartz monzonite that forms hills and ridges in the monument (Wobus and Epis, 1978). Along the valley floor, the granite is overlain by the Eocene Florissant Formation, which in most places is mantled by a thin layer of Quaternary alluvium and colluvium. The Florissant Formation is composed of andesitic tuff and volcanic mudflow breccia interlayered with tuffaceous shale and mudstone that were deposited in an ancient lake. These lake sediments contain abundant plant, insect, and tree fossils for which FLFO is renowned (*http://www2.nature.nps.gov/geology/parks/flfo/*, accessed May 2006).

Land-use activities in FLFO are related to visitor use and park administration including the visitor center and park headquarters, 9.7 km of roads, and two picnic areas. Land adjacent to the monument is privately owned and is used as rangeland. According to the park's resource management plan, rapid expansion of subdivisions adjacent to the monument and anticipated increases in visitor use pose the largest threats to natural resources in the park (National Park Service, 2006). In the1930s and 1940s, ranchers and farmers constructed 44 earthen dams in park drainages, which were intended to provide erosion control and facilitate water retention and diversion for agriculture. By 2001, removal of five dams was completed to restore the drainages to their natural condition; however, there are no immediate plans to remove the remaining dams (National Park Service, 2006). Surface water in the monument is not used for irrigation, and drinking water is obtained from a ground-water well located near the park headquarters (G1, fig. 2). The well is 50 m deep and capable of pumping an estimated 15 to 23 liters per minute (L/min) (National Park Service, 2006). The ground water has high dissolved solid concentrations and must be treated to make it potable. The park also has water rights for a second well (G2, fig. 2), which is 18 m deep and capable of pumping 2 to 4 L/min and is used for sanitation purposes only (National Park Service, 2006). Water supply in the park is monitored for health-based contaminants according to the Colorado Drinking Water Program (*http://www.cdphe.state.co.us/wq/drinkingwater/index.html*, accessed August 2007). Wastewater in FLFO is handled by a septic system located near the park headquarters.

Water Resources

The main drainage in FLFO is Grape Creek (fig. 2), which flows north into Twin Creek, a tributary of the South Platte River. The lower reaches of Grape Creek are perennial, but its tributaries are intermittent. Flow characteristics of Grape Creek are not well characterized because the creek has not been gaged, nor have any streams of similar size in adjacent areas. The only available hydrologic data for Grape Creek are seven instantaneous measurements at site S1 (fig. 2) during the summer months (June to September), which ranged from 0.14 to 2.6 cubic feet per second (ft^3/s), and three measurements at site S4, which ranged from 0.09 to 0.22 ft^3/s. The closest streamflow-gaging station on a stream of similar size and elevation is Fountain Creek at Green Mountain Falls (USGS station 07099990), which is located 18 km east of FLFO. The Fountain Creek drainage ranges in elevation from 2,359 to 3,000 m and drains a 43-km^2 area. By comparison, Grape Creek (above the confluence with Twin Creek) ranges in elevation from 2,485 to 2,930 m, and drains an area of 55 km^2. The range of daily streamflow values for Fountain Creek from 2001 to 2005 is shown in figure 3. The smallest streamflows were observed during winter (November to February) and represent base flow from ground-water discharge. The largest streamflows generally are observed in late spring and early summer (April, May, and June) as a result of snowmelt runoff. Thundershowers contribute to streamflows through the summer months (July to September). Runoff during the snowmelt period (April, May, and June) at Fountain Creek accounts for more than 40 percent of the annual streamflow.

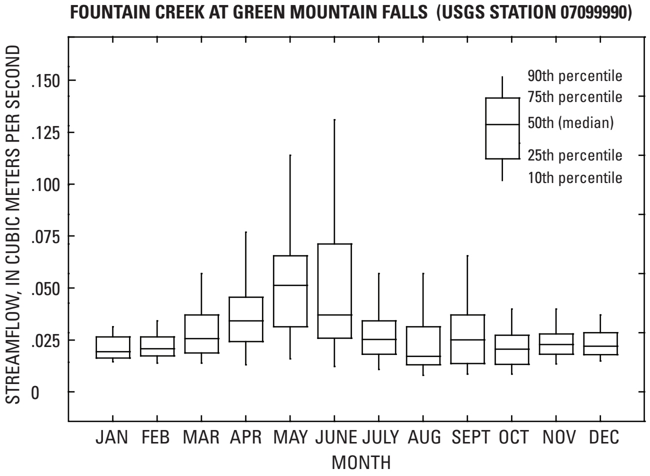


Figure 3. Daily streamflow range at Fountain Creek at Green Mountain Falls (USGS streamflow-gaging station 07099990) near Florissant Fossils Beds National Monument, Colorado, 2001–2005.

Although there are a number of ground-water fed seeps and springs in FLFO, the ground-water resources have not been studied and are poorly characterized. Because surficial deposits of alluvium and soils generally are thin in the foothills of the Front Range (Bossong and others, 2003), it is likely that aquifers in the granitic bedrock are the dominant ground-water resource in the park. Crystalline bedrock, such as granite, generally has low intergranular porosity, so open space that may contain water consists mostly of fractures and fracture networks (Bossong and others, 2003).

Water-resource issues for FLFO include effects of park facilities and visitor use inside the park, and land-use activities such as grazing and residential development in the headwaters of Grape Creek (National Park Service, 2006). The water-quality constituents most likely to be affected by these activities include nutrients, sediment, and bacteria. Climate change may have long-term effects on streamflows and ground-water resources in the park.

Surface-Water Quality

Water-quality data are available for 13 surface-water sites in and adjacent to FLFO, including 10 streams and 3 springs (table 2, fig. 2). Sites S1-S4 were sampled by the NPS from 1995 to 1997 to characterize seasonal variation in core field properties (water temperature, specific conductance, dissolved oxygen, and pH). Sites S4 and S5 were sampled in the early 1990s as part of the USEPA Environmental Monitoring and Assessment Program (*http://www.epa.gov/emap/remap/index.html*, accessed May 2006) and sites S6-S13 were sampled once each in 1976 as part of the National Uranium Resource Evaluation (NURE) program (*http://pubs.usgs.gov/of/1997/ofr-97-0492/*, accessed May 2006). The ROMN database includes 60 water-quality samples collected at these 13 surface-water sites, most of which are field properties (39 percent), and major-constituent (23 percent), nutrient (8 percent), and trace-element (29 percent) analyses. The period of record and number of samples collected in each of these property or constituent categories are summarized in table 3.

Water-quality data for the 13 surface-water sites in and adjacent to FLFO are summarized in table 4. Stream water in FLFO is a well buffered calcium-bicarbonate type; specific conductance ranged from 130 to 525 microsiemens per centimeter (µS/cm) and alkalinity ranged from 66 to 180 milligrams per liter (mg/L). The dominant cations in stream water were calcium (20 to 84 mg/L) and sodium (7.6 to 17 mg/L), and the dominant anion was bicarbonate (based on pH and alkalinity). The predominance of these major dissolved constituents is attributed to weathering of carbonate minerals in the Florissant Formation and plagioclase in the Pikes Peak Granite. Other major anions were sulfate, which ranged from 6.7 to 73 mg/L, and chloride, which ranged from 4.0 to 20 mg/L. Although these anions were less abundant than bicarbonate, concentrations were substantially larger than those measured at a nearby precipitation station (*http://nadp.sws.uiuc.edu/*, accessed May 2006) indicating they also are derived primarily from weathering of rocks and soils. Perhaps the most unusual result was the fluoride concentration measured at site S5, which ranged from 2.2 to 2.5 mg/L. This concentration range is elevated compared to most natural waters, which typically are less than 1 mg/L (Hem, 1985). A potential source of fluoride to surface water in FLFO is the Pikes Peak Granite, which is enriched in fluoride (up to 0.5 weight percent) compared to most granitic rocks (Hawley and Wobus, 1977). Fluoride in the granite is present primarily in the minerals fluorite, topaz, biotite, and muscovite.

Nutrients measured in surface-water samples from FLFO include ammonia, nitrite, nitrate, orthophosphate, and total

Table 2. Water-quality sampling sites near Florissant Fossil Beds National Monument, Colorado.

[no., number; FLFO, Florissant Fossil Beds National Monument; ST, stream; SP, spring; GW, ground water; Identification numbers beginning with FLFO from USEPA STORET and identification numbers beginning with 3854 from USGS NWIS]

Site no. (fig. 2)	Identification no.	Station name	Latitude	Longitude	Type	No. of samples	Period of record
S1	FLFO_NPS_GC2	Grape Creek #2	38° 55’ 37”	105° 17’ 08”	ST	12	1995–97
S2	FLFO_NPS_CAVE	Stock pond downstream Sanborn’s Camp	38° 54’ 53”	105° 18’ 07”	ST	11	1995–97
S3	FLFO_NPS_BRK	Barksdale Picnic Area	38° 54’ 42”	105° 15’ 21”	ST	11	1995–97
S4	FLFO_NPS_HUTCH	Grape Creek upstream of FLFO	38° 53’ 13”	105° 15’ 59”	ST	13	1992, 95–97
S5	FLFO_EPA_CO005M	Grape Creek in FLFO	38° 54’ 50”	105° 16’ 42”	ST	5	1992–95
S6	FLFO_NURE_26	C20346	38° 55’ 27”	105° 17’ 06”	ST	1	1976
S7	FLFO_NURE_25	C20332	38° 55’ 21”	105° 16’ 55”	ST	1	1976
S8	FLFO_NURE_47	C20348	38° 53’ 01”	105° 15’ 27”	ST	1	1976
S9	FLFO_NURE_27	C20031	38° 55’ 59”	105° 13’ 29”	ST	1	1976
S10	FLFO_NURE_63	C20033	38° 54’ 47”	105° 12’ 42”	ST	1	1976
S11	FLFO_NURE_08	C20333	38° 54’ 33”	105° 16’ 46”	SP	1	1976
S12	FLFO_NURE_07	C20347	38° 54’ 38”	105° 15’ 21”	SP	1	1976
S13	FLFO_NURE_06	C20032	38° 54’ 49”	105° 14’ 57”	SP	1	1976
G1	385445105170201	SC0130712ABBAA (visitor center well)	38° 54’ 44”	105° 17’ 03”	GW	1	1992
G2	385449105164501	SC01307113CDDD	38° 54’ 48”	105° 16’ 46”	GW	1	1991

Table 3. Period of record and types of analyses conducted for surface-water samples collected near Florissant Fossil Beds National Monument, Colorado.

[value in cell is the number of samples analyzed in each category for the year; --, no data]

	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
Field properties	8	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	2	--	2	18	12	16	--	--	--	--	--	--	--
Major constituents	8	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	2	--	2	9	2	2	--	--	--	--	--	--	--
Nutrients	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	2	--	2	7	2	2	--	--	--	--	--	--	--
Trace elements	8	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	2	--	2	2	--	--	--	--	--	--	--	--	--

phosphorus. Nitrogen compounds in all samples were low, and only a few had concentrations above laboratory reporting levels (table 4). For example, only 2 of 12 samples had detectable ammonia, and 4 of 11 samples had detectable nitrate. These low nitrogen concentrations reflect minimal human-related activities in the Grape Creek drainage basin. In contrast to nitrogen, all analyzed samples had detectable levels of phosphorus species with dissolved orthophosphate ranging from 0.14 to 0.22 mg/L and total phosphorus ranging from 0.06 to 0.28 mg/L. Concentrations of the two phosphorus species were similar, indicating most of the phosphorus is present in the dissolved form. Although anthropogenic sources of phosphorus in the basin are minimal, most of the samples had phosphorus concentrations above levels typically present in undeveloped streams (Clark and others, 2000). Phosphorus to FLFO streams likely comes from natural sources, such as weathering of phosphorous-bearing minerals in lake-bed sediments and/or volcanic deposits of the Florissant Formation.

Trace elements measured in surface-water samples from FLFO are shown in table 4. Concentrations were less than laboratory reporting levels in 60 percent of the samples and only iron, manganese, and zinc had a substantial number of detected concentrations greater than 10 micrograms per liter (µg/L). The largest trace element concentrations were measured at eight sites (S6–S13, fig. 2) sampled by the NURE program. The reason for larger concentrations in the NURE samples is unclear; however, because of the age of the data (more than 25 years old) and the lack of published quality-assurance information for water samples (Sharp and Aamodt, 1978), the NURE data should be interpreted with care. Other constituents measured in FLFO surface-water samples included dissolved organic carbon (4.3 to 11 mg/L), fecal coliform [7 and 21 colonies per 100 milliliters (col/100 mL)] and total coliform (0 to 3,000 col/100 mL). Concentrations of these constituents were in the range expected for small streams draining undeveloped basins.

Because there are few water-quality data available for FLFO, little can be described about spatial and seasonal variations in water quality within the park. The most complete data set available includes core field properties (water temperature, dissolved oxygen, pH, and specific conductance), which were measured at four sites from 1995 to 1997 (fig. 4). Dissolved oxygen concentrations ranged from 5.0 to 12.3 mg/L and did not show a consistent seasonal pattern at any of the four sites. The largest concentrations typically were measured at S2, which is a small stock pond along a tributary. Elevated dissolved oxygen at this site may be because of photosynthesis by aquatic vegetation in the pond, causing dissolved oxygen concentrations and pH in surface water to increase during the day. pH values ranged from 6.56 to 9.40 and were lowest at site S3, downstream from the spring, and highest at site S2, a manmade stock pond, which also had the largest dissolved oxygen concentration. All four sites showed similar seasonal patterns with lower concentrations in the spring and higher in the fall. Specific conductance at the four sites ranged from 184 to 510 µS/cm and was highest at site S1, which is the furthest downstream site. Specific conductance at sites S1 and S4 indicated similar seasonal patterns of lower concentrations in spring because of dilution of stream water by snowmelt. By contrast, specific conductance showed little seasonal variation at site S3, probably because it is fed by discharge from a nearby ground-water spring. None of the surface-water sites had a sufficient period of record to test for water-quality changes with time using ESTREND.

Comparison to Water-Quality Standards. Water-quality use classifications and standards for all stream segments in Colorado are established by the Colorado Water Quality Control Commission (Colorado Department of Public Health and Environment, 2006). Grape Creek and its tributaries are classified under segment 2a of the Upper South Platte River Basin. None of the reaches within this segment were listed in 2006 as impaired for water quality (*http://www.cdphe.state.co.us/op/wqcc/SpecialTopics/303(d)/303dtmdlpro.html*, accessed May 2006). The designated uses for this segment are cold-water aquatic life class 1, recreation 1a, agriculture, and water supply. Streams designated for cold-water aquatic life class 1 (the most sensitive use) should have temperatures less than 20 °C, dissolved oxygen greater than 6.0 mg/L (7.0 mg/L during spawning), and pH values in the 6.5 to 9.0 range. In FLFO, 48 of 50 stream temperatures were less than the 20 °C standard, 34 of 38 dissolved oxygen measurements were greater than the 6.0 mg/L standard, and 40 of 50 pH values were within the 6.5 to 9.0 pH range. Most of the values that exceeded the aquatic-life standards were from site S2, which is a manmade stock pond on Grape Creek. Concentrations of nutrients and major constituents (chloride and sulfate) in all samples were below the water-supply and cold-water aquatic life standards, except for one stream sample that exceeded the ammonia

Table 4. Summary of selected water-quality data for surface-water sites in Florissant Fossil Beds National Monument, Colorado, 1976 to 1997.

[no., number; chronic aquatic-life (and water-supply) standards from Colorado Department of Public Health and Environment (2006); <, less than; >, greater than; --, not reported; °C, degrees Celsius; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter at 25 °C; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorous; col/100 mL, colonies per 100 milliliters; µg/L, micrograms per liter; some nutrients and trace elements have multiple reporting limits]

Constituent or property	No. sites	No. analyses (no. censored)	Minimum value	Median value	Maximum value	Aquatic-life (water-supply) standard
Field properties						
Temperature, water (°C)	13	50	5.6	12.8	22.2	<20
Oxygen, dissolved (mg/L)	5	38	5.0	8.0	12.3	>6.0 (>3.0)
pH (standard units)	13	50	6.56	7.72	9.40	6.5–9.0 (5.0–9.0)
Specific conductance (µS/cm)	13	50	130	273	525	--
Major constituents						
Alkalinity (mg/L as $CaCO_3$)	5	15	66	140	180	--
Calcium, dissolved (mg/L)	10	14	20	44	84	--
Chloride, dissolved (mg/L)	5	13 (3)	[a]4.0	5.8	20	([b]250)
Fluoride, dissolved (mg/L)	1	4	2.2	2.3	2.5	(2.0)
Magnesium, dissolved (mg/L)	10	14	3.7	7.3	16	--
Potassium, dissolved (mg/L)	2	6	2.4	6.8	7.8	--
Silica, dissolved (mg/L)	0	0	--	--	--	--
Sodium, dissolved (mg/L)	2	6	7.6	12	17	--
Sulfate, dissolved (mg/L)	2	6	6.7	35	73	([b]250)
Nutrients, carbon, and microorganisms						
Ammonia, dissolved (mg/L as N)	3	12 (10)	<0.04	<0.10	0.43	0.02
Nitrate, dissolved (mg/L as N)	3	11 (7)	<.05	<1.0	<1.0	(10)
Nitrite, dissolved (mg/L as N)	1	1 (1)	<.02	--	--	.05 (1.0)
Orthophosphate, dissolved (mg/L as P)	1	4	.14	.19	.22	--
Phosphorus, total (mg/L as P)	5	11	.06	.17	.28	--
Organic carbon, dissolved (mg/L)	1	4	4.3	5.5	10	--
Fecal coliform (col/100 mL)	2	2	7	--	21	--
Total coliform (col/100 mL)	2	4	0	153	3,000	--
Trace elements						
Aluminum, dissolved (µg/L)	1	4 (4)	<30	<30	<30	[c]87
Arsenic, dissolved (µg/L)	1	4 (2)	<4	4.3	6	[c]50 (10)
Cadmium, dissolved (µg/L)	1	4 (4)	<0.5	<.5	<.5	[d].6 (5)
Chromium, dissolved (µg/L)	9	12 (9)	<1.5	<25	37	11 (50)
Cobalt, dissolved (µg/L)	8	8 (8)	<55	<55	<55	--
Copper, dissolved (µg/L)	9	12 (9)	<.6	<4	<4	[d]13 (1,300)
Iron, dissolved (µg/L)	9	12	14	108	1,225	[c]1,000 ([b]300)
Lead, dissolved (µg/L)	9	12 (12)	<4	<200	<200	[d]4.2 (50)
Manganese, dissolved (µg/L)	9	12 (3)	<3	15	353	[d]1,930 ([b]50)
Nickel, dissolved (µg/L)	9	12 (9)	<12	<25	110	[d]77 (100)
Selenium, dissolved (µg/L)	1	4 (4)	<5	<5	<5	4.6 (50)
Silver, dissolved (µg/L)	1	4 (4)	<.3	<.3	<.3	[d].7 ([b]100)
Uranium, dissolved (µg/L)	8	8	.78	2.0	16.2	[d]2,520 (30)
Zinc, dissolved (µg/L)	9	12 (4)	<4	114	371	[d]186 ([b]5,000)

[a] Minimum reported value less than minimum censored value.

[b] Secondary standard based on aesthetic properties such as taste, odor, and staining.

[c] Total recoverable concentration.

[d] Table value standard calculated for a hardness of 160 mg/L.

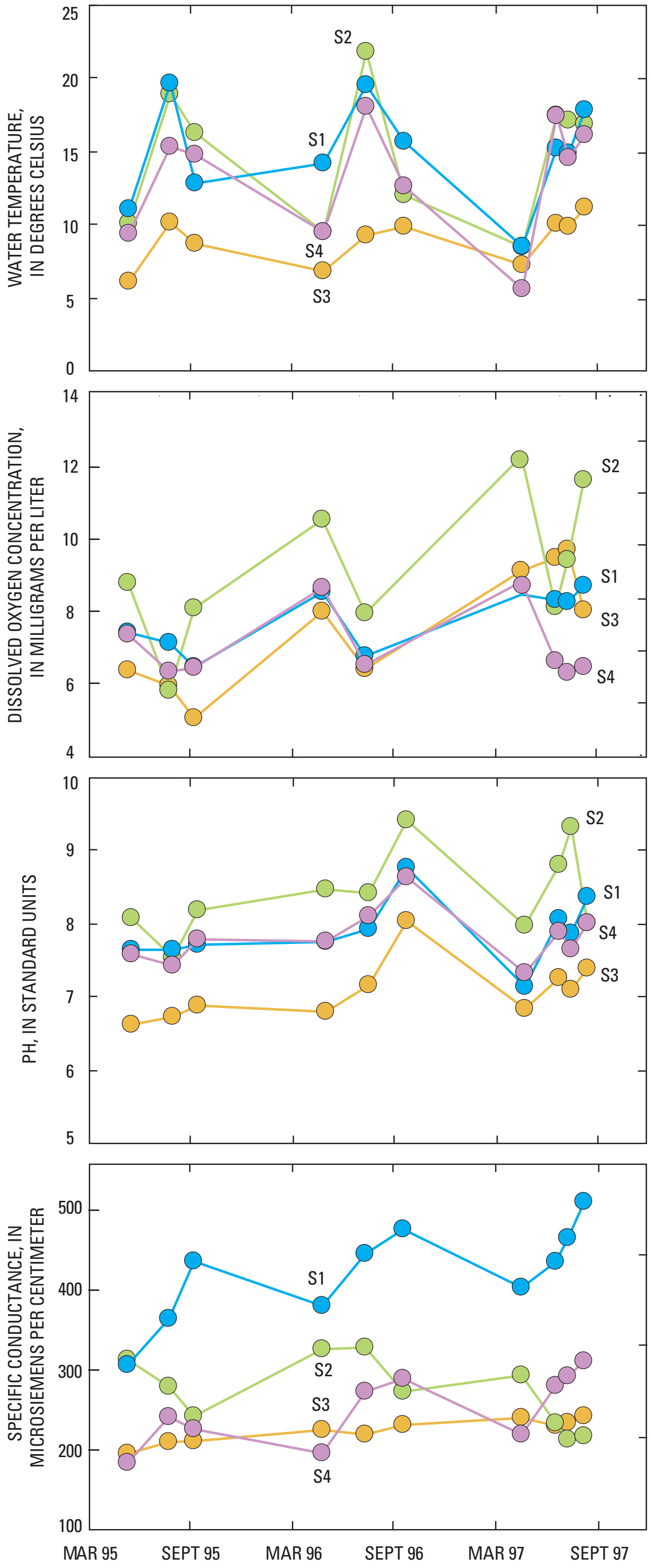


Figure 4. Seasonal variation in water quality at selected sites in Florissant Fossil Beds National Monument, Colorado.

standard. There were only two fecal coliform measurements (7 and 21 col/100 mL), but neither exceeded the 200 col/100 mL standard for recreation 1a. Two samples collected in the Grape Creek drainage at sites S8 and S13 exceeded the chronic aquatic-life standards for chromium, iron, nickel and zinc, which were calculated from table value standards for a median hardness of 160 mg/L. However, these samples were collected more than 25 years ago as part of the NURE program and quality-assurance information was not published so the data should be interpreted with care.

Ground-Water Quality

Water-quality data are available for two ground-water wells (G1 and G2, fig. 2) in FLFO. Site G1 is a well used for drinking water at the park visitor center and was sampled by the USGS on July 15, 1992; site G2 was sampled by the USGS on June 20, 1991. Major dissolved constituents in the two ground-water samples were present in the same proportions as in surface-water samples, although concentrations were as much as two times higher (table 5). As observed in surface-water samples, fluoride concentrations in ground-water samples were greater than 1.0 mg/L, which may reflect the high-fluoride content of the bedrock. The fluoride concentration at site G1 was 3.1 mg/L, which was above the Colorado water-supply standard of 2.0 mg/L, but below the USEPA maximum contaminant level of 4.0 mg/L (*http://www.epa.gov/safewater/contaminants/index.html*, accessed May 2006). Nutrient concentrations in ground-water samples were well below the water-supply standards for nitrate and nitrite. Most of the 13 trace elements had concentrations at or close to laboratory reporting levels with the exception of iron, lithium, manganese, and zinc. Site G2 had elevated iron (2,122 µg/L) and manganese (493 µg/L) concentrations that exceeded the secondary standards for drinking water. Elevated iron and manganese in ground water often is because of dissolution of oxide minerals in aquifer materials when dissolved oxygen concentrations become depleted (Hem, 1985). The high lithium concentrations were unusual and, similar to fluoride, likely are related to contributions from natural weathering sources.

Summary and Suggestions for Vital Signs Monitoring

Review of historical water-quality records indicates that few data are available for FLFO and most of what is available is more than a decade old. From 1976 to 1997, 60 water-quality samples were collected at 13 surface-water sites. The majority of results for these 60 samples were field properties (39 percent), and major-constituent (23 percent), nutrient (8 percent), and trace-element (29 percent) analyses. Only five of the sites were sampled more than once during the period of record, and mostly for field properties only. None of the streams in FLFO have been gaged for streamflow and manual

Table 5. Summary of selected water-quality data for ground-water sites in Florissant Fossil Beds National Monument, Colorado.

[water-supply standards from Colorado Department of Public Health and Environment (2006); <, less than; --, not reported; µS/cm, microsiemens per centimeter at 25 °C; mg/L, milligrams per liter; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorous; µg/L, micrograms per liter]

Constituent or property	G1 (fig. 2) 7/15/1992	G2 (fig. 2) 6/20/1991	Water-supply standard
	Field properties		
pH (standard units)	7.30	7.25	5.0–9.0
Specific conductance (µS/cm)	496	871	--
	Major constituents		
Alkalinity (mg/L as $CaCO_3$)	218	349	--
Calcium, dissolved (mg/L)	62	98	--
Chloride, dissolved (mg/L)	8.5	39	[a]250
Fluoride, dissolved (mg/L)	3.1	1.1	2.0
Magnesium, dissolved (mg/L)	12	25	--
Potassium, dissolved (mg/L)	4.4	10	--
Silica, dissolved (mg/L)	23	54	--
Sodium, dissolved (mg/L)	21	52	--
Sulfate, dissolved (mg/L)	32	67	[a]250
	Nutrients		
Ammonia (mg/L as N)	0.03	0.28	--
Nitrate (mg/L as N)	<.05	.096	10
Nitrite (mg/L as N)	<.01	<.01	1.0
Orthophosphate, dissolved (mg/L as P)	<.01	.09	--
Phosphorus, total (mg/L as P)	<.01	.09	--
	Trace elements		
Cadmium, dissolved (µg/L)	<1	<1	5
Chromium, dissolved (µg/L)	<5	<5	50
Cobalt, dissolved (µg/L)	<3	<3	--
Copper, dissolved (µg/L)	<10	<10	1,000
Iron, dissolved (µg/L)	200	2,122	[a]300
Lead, dissolved (µg/L)	<10	13	50
Lithium, dissolved (µg/L)	75	142	--
Manganese, dissolved (µg/L)	130	493	[a]50
Molybdenum, dissolved (µg/L)	<10	<10	--
Nickel, dissolved (µg/L)	<10	<10	100
Silver, dissolved (µg/L)	<1	<1	[a]100
Vanadium, dissolved (µg/L)	<6	<6	--
Zinc, dissolved (µg/L)	410	<3	[a]5,000

[a] Secondary standard based on aesthetic properties such as taste, odor, and staining.

discharge measurements were made only periodically at two sites in the park. Surface water in the area is a calcium-bicarbonate type and dissolved solids primarily are derived from weathering of the underlying granite and lake-bed sediments. Land-use activities likely have a minor effect on water quality, although there is concern about future increases in visitor use and residential development in areas upstream from the park. Because of a lack of long-term monitoring sites, it was not possible to identify temporal trends in water quality. Designated uses for streams in FLFO are cold-water aquatic life class 1, recreation 1a, agriculture, and water supply; the available water-quality data indicate most sites meet Colorado water-quality standards for cold-water aquatic life class 1 (the most sensitive use). Water-quality data are available for one sample at each of the two ground-water wells in the park. One of the wells exceeded the drinking-water standard for fluoride and the other well exceeded secondary standards for manganese and iron. Elevated fluoride in FLFO is attributed to natural weathering of fluoride-rich bedrock that underlies the park.

Issues of concern for water resources in the park include visitor use, land-use activities adjacent to the park, and climate change. Based on a review of the historical data, the following suggestions are provided for consideration in designing a water-quality monitoring plan for FLFO.

- Establish a long-term water-quality monitoring station or “sentinel site” on Grape Creek at the northern park boundary. Monitor for core field properties, major constituents, nutrients, bacterial indicators, and suspended sediment during different hydrologic conditions. Because of the small drainage area of Grape Creek, water samples collected at the sentinel site should be representative of water-quality conditions in the park.

- Establish a continuous streamflow-monitoring station collocated with the Grape Creek sentinel site. Streamflow monitoring is important for interpreting trends in water quality and for monitoring the effects of human stressors, such as residential development and climate change, on water resources.

- Sites upstream from the sentinel site, including ground-water springs, could be sampled periodically to address special issues or to achieve a better understanding of the factors controlling water quality in the park.

- Ground-water levels or spring discharge could be used to monitor the effects of human stressors on water resources.

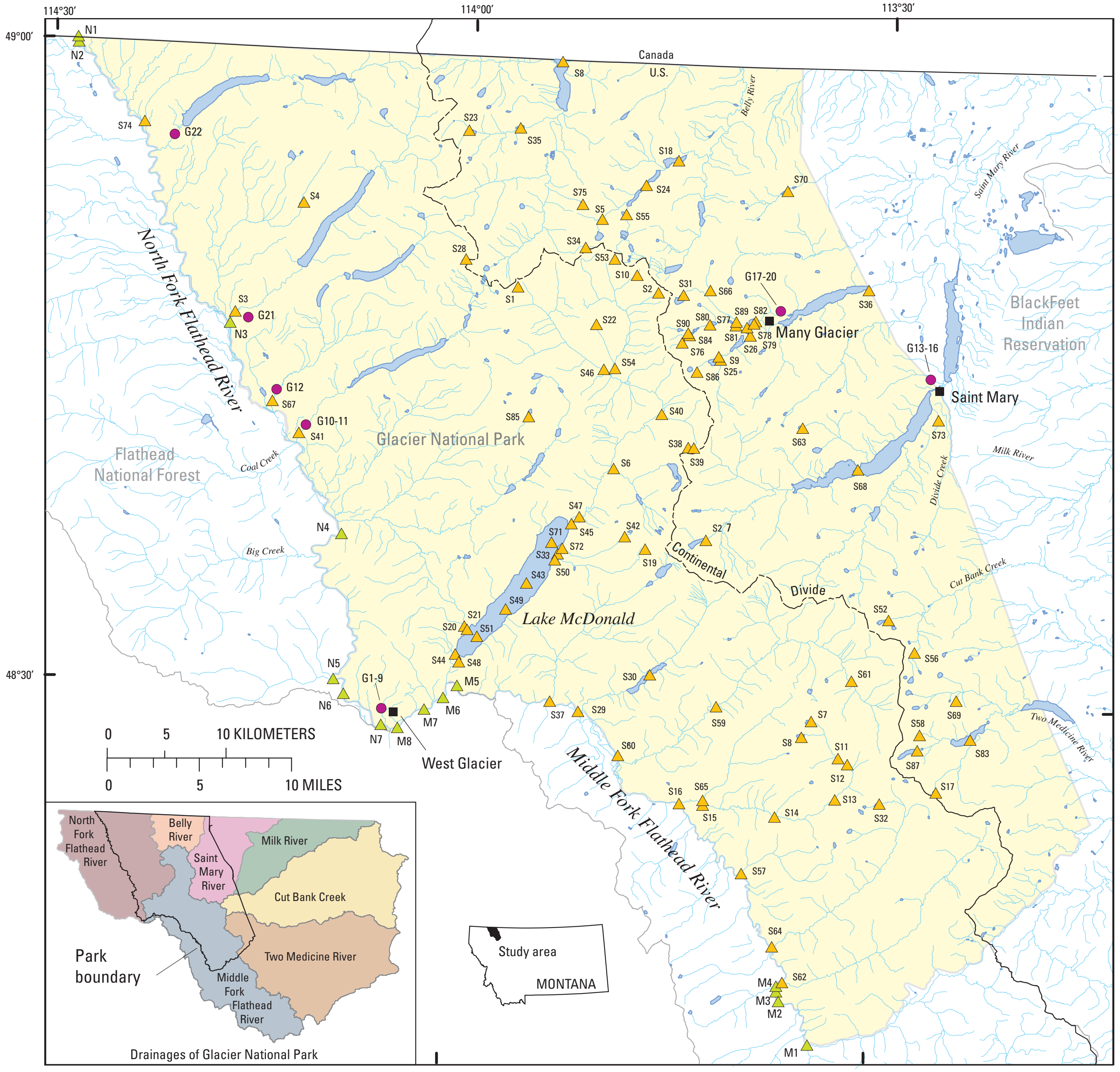
Glacier National Park

Environmental Setting and Geology

Glacier National Park (GLAC) is located in the northern Rocky Mountains in northwestern Montana and is bounded to the north by Canada (fig. 5). The North and Middle Forks of the Flathead River border the park on the west and south, and the park is bisected by the Continental Divide. The park covers 4,100 km^2, ranges in elevation from 949 to 3,180 m, and is characterized by horn-shaped peaks, broad U-shaped valleys, numerous glacial lakes, and several active glaciers. Five large bioregions are present in GLAC including alpine tundra, subalpine forest, montane forest, aspen parkland, and fescue grassland. Coniferous forests dominate much of the landscape with lodgepole pine, Douglas fir, and western larch growing on drier sites and western hemlock and western red cedar inhabiting wetter sites (White and others, 1998). The climate in GLAC is one of long, cold, snowy winters and relatively short, warm summers. The west side of the park is affected by Pacific air masses that result in a milder and moister climate than the east side, which is dominated by colder Continental air masses. Winter temperatures are warmer on the west side than the east, but summer temperatures are similar (Finklin, 1986). Annual precipitation differs substantially between west-side and east-side locations in the park and ranges from as little as 30 cm at low elevations on the east side to as much as 350 cm at higher elevations on the west side (Finklin, 1986). Most precipitation in winter falls as snow that accumulates in a seasonal snowpack between November and April.

GLAC is underlain by the Proterozoic Belt Supergroup, which consists of thick sequences of argillite, quartzite, and carbonate rocks (Ross, 1959). Although the rocks are thoroughly consolidated and recrystallized, they contain well-preserved sedimentary features such as ripple marks, mud cracks, and stromatolite fossils. The primary units in the Supergroup are the Altyn Limestone, Appekunny Argillite, Grinnell Argillite, Helena Dolomite, and Missoula Group. Sediments in the Belt Supergroup were folded and faulted during the Paleocene producing the Lewis overthrust, which is a large thrust fault that is exposed along the eastern edge of the park (Ross, 1959). During the Pleistocene, valley glaciers and ice fields covered the region carving the glacial topography seen today. As the glaciers retreated, the stream and river valleys were filled with poorly sorted glacial till, outwash, and alluvium derived from the sedimentary bedrock. In 2005, GLAC had 27 active glaciers that are direct remnants from a period of glacier formation ending about 11,000 years ago. The glaciers in the park have been shrinking because of climate change, and at current rates it is estimated that all glaciers in the park will be gone by the year 2030 (Fagre and others, 2005).

Land-use activities in the park are related to tourism and park administration including the road system, campgrounds, picnic areas, boat launches, liveries, visitor centers, lodges, and park administrative buildings and residences. The park has approximately 1.8 million visitors each year, mostly between June and September (Britten and others, 2006). More than 90 percent of park lands are designated wilderness, and human activities in these areas are limited. Water supply in the park is obtained from a system of 7 surface-water sources and 20 ground-water sources. Water supplies are tested twice monthly during the high-use season for indicator bacteria and nitrogen species according to water-supply regulations set by



Base from National Hydrography Dataset, 1:100,000
Universal Transverse Mercator projection
Zone 12

EXPLANATION

S64 ▲	Stream and lake sampling site and number (table 6)
M1 ▲	Mainstem sampling site and number (table 8)
G1-9 ●	Observation well and number (table 12)
■	Developed area


Photograph of Lake McDonald by Karen Holzer, U.S. Geological Survey

Figure 5. Location of water-quality sampling sites in Glacier National Park, Montana.

the MTDEQ. Results of water-supply testing are available at *http://www.deq.state.mt.us/wqinfo/pws/reports.asp* (accessed November 2006). Treatment facilities at West Glacier, Saint Mary, and Many Glacier (fig. 5) and several small septic systems handle wastewater for park facilities. Prescribed burns are conducted periodically in the park to improve habitat and to reduce fuels. An average of 14 natural wildfires have burned 20 km^2 in the park each year since 1988 (*http://www.nps.gov/archive/glac/resources/fires.htm*, accessed November 2006). GLAC is bounded by largely undeveloped National Forest land to the west and south and by the Blackfeet Indian Reservation to the east. Land-use activities in areas adjacent to GLAC include timber harvesting, low-density residential development, road networks, ranching, and mineral exploration (Hauer and others, 2007).

Water Resources

GLAC is straddled by the Continental Divide and encompasses the headwaters of three continental river systems; the Columbia (North Fork and Middle Fork Flathead River), the Missouri (Milk River, Cut Bank Creek, Two Medicine River), and the Saskatchewan (Belly River and Saint Mary River). Drainages on the west side of the park flow into the North and Middle Forks of the Flathead River, which form the southern and western park boundaries (fig. 5). Drainages on the east side of the park form the headwaters of the Belly, Saint Mary, and Two Medicine Rivers. The park contains more than 2,500 km of perennial streams (Britten and others, 2006) that flow through glacially carved drainages, some of which still contain active glaciers in their headwaters. The park contains more than 650 lakes; the largest is Lake McDonald on the west side of the park, which is 16 km long and has a maximum depth of 144 m (fig. 5).

The USGS has operated as many as 25 streamflow-gaging stations inside or adjacent to the boundaries of the park (*http://mt.water.usgs.gov/pub/MTStations.pdf*, accessed November 2006). Of these, six stations currently (2007) are active including Swiftcurrent Creek above Swiftcurrent Lake (USGS station 05014300; site S78 in figure 5), Swiftcurrent Creek at Many Glacier (USGS station 05014500; S81), Lake Sherburne (USGS station 05015500; S36), Middle Fork Flathead River (USGS station 12358500; M6), Flathead River at Flathead (USGS station 12355000; N2), and North Fork Flathead River (USGS station 12355500; N6). Swiftcurrent Creek above Swiftcurrent Lake (S78) is part of the USGS Hydrologic Benchmark Network, a National program for monitoring streamflow and water quality in areas that are minimally affected by human activities (Murdoch and others, 2005). The longest continuously operating station in the park is Swiftcurrent Creek at Many Glacier (S81), which began operation in 1912. The range of daily streamflows at Swiftcurrent Creek at Many Glacier from 1986 to 2005 is shown in figure 6. Peak streamflow occurs during spring snowmelt in late May or June during which time streamflow increases by two to three orders of magnitude over winter streamflows. More than 60 percent of the annual streamflow occurs from mid May through mid July. Streamflow decreases steadily through the remainder of the year reaching a minimum in December, January, and February when streamflow is sustained by slow release of ground water and storage in lakes.

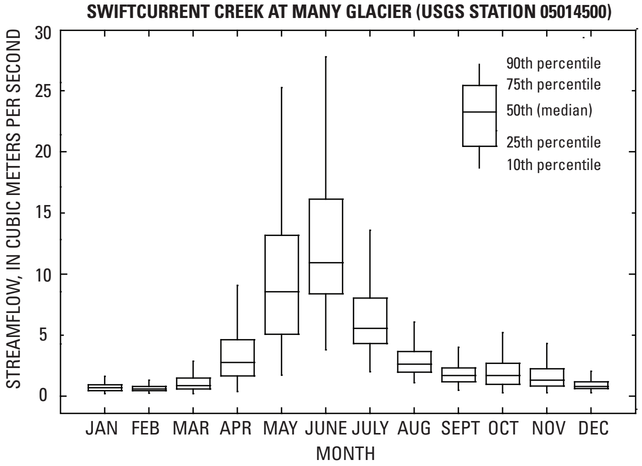


Figure 6. Daily streamflow range at Swiftcurrent Creek at Many Glacier (S81) in Glacier National Park, Montana, 1986–2005.

In mountainous areas such as GLAC, there generally are two different ground-water systems; bedrock aquifers in the mountain block, and shallow localized aquifers in alluvium and glacial till along stream and river channels. In GLAC, the hydrologic characteristics of mountain block aquifers are virtually unknown, and sparse information is available for shallow alluvial aquifers. The NPS had observation wells (fig. 5) installed in the vicinity of three wastewater treatment facilities in the park and several campgrounds and ranger stations. All the wells were shallow (3.1 to 24.4 m) and were completed in unconsolidated alluvial or glacial deposits composed of clay, silt, sand, and gravel (Boettcher, 1973). Because of the poorly sorted nature of these deposits, the water-bearing characteristics vary widely from place to place. Aquifer tests on several of the campground wells indicated yields between 0.25 to 3.2 liters per second (L/s) (Boettcher, 1973). Weekly to monthly water-level measurements were made at observation wells at West Glacier, Saint Mary, and Many Glacier wastewater treatment facilities (Moreland and Wood, 1982). Water levels for the Many Glacier wells (G17 to G20) from May 1980 to August 1982 are shown in figure 7. Water levels varied substantially during the year and peaked in June indicating alluvial aquifers are recharged primarily by snowmelt and respond quickly to changes in streamflow.

The park has a National Atmospheric Deposition Program (NADP) station located at West Glacier that has been operated by the NPS since 1980. The NADP is a national network of precipitation monitoring sites that measures weekly precipitation chemistry and precipitation amount; data for the network are available at *http://nadp.sws.uiuc.edu/* (accessed November 2006). The site at GLAC is used to monitor the

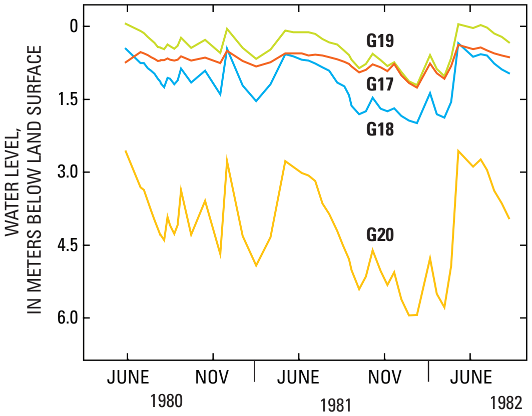


Figure 7. Periodic water-level measurements at selected shallow ground-water wells in Glacier National Park, Montana.

effect of air pollution on ecological resources including vegetation, water quality, and soils (*http://www2.nature.nps.gov/air/index.cfm*, accessed November 2006). The park also has a Clean Air Status and Trends (CASNET) site at 976 m, not far from the West Glacier NADP station. CASTNET is a national network of air monitoring sites that provide estimates of dry deposition of sulfur and nitrogen compounds and concentrations of ground-level ozone (*http://www.epa.gov/castnet/*, accessed November 2006). The CASNET site in GLAC is operated by the NPS and was added to the network in 1990.

Water-quality concerns for GLAC may include effects of visitor use, park facilities, and road networks on nutrients, sediment, and bacteria. Sedimentation and erosion associated with flooding following prescribed burns and large-scale wildfires also may be a concern. Land-use activities outside the park boundary such as timber harvesting, road networks, and mineral exploration may affect water quality of the Middle and North Forks of the Flathead River (Hauer and others, 2007). Long-term increases in atmospheric deposition of contaminants (particularly nitrogen) may pose a threat to high-elevation lakes and streams (Williams and others, 1996). Climate change is causing the rapid retreat of park glaciers, and may have long-term effects on surface- and ground-water resources in the park (Fagre and others, 2005).

Surface-Water Quality

For this report, water-quality data were compiled for 90 surface-water sites originating within the boundaries of GLAC including 54 stream sites and 36 lake sites (table 6, fig. 5). The types of analyses and numbers of samples collected for the period of record for these 90 sites are summarized in table 7. The ROMN database contains water-quality data for 1,144 samples at these sites collected over the period 1963 to 2004, the majority of which were field properties (19 percent), and major-constituent (30 percent), nutrient (26 percent), trace-element (8 percent), and organic carbon (7 percent) analyses.

Most of the surface-water sites were sampled 1 to 3 times each during the period of record, although there were 14 sites that were sampled 20 or more times (table 6). The majority of these sites were sampled by the USEPA, Flathead Lake Biological Station (FLBS), or the USGS. The USEPA collected 102 samples from 10 sites (S20, S21, S33, S43, S44, S45, S50, S51, S71, S72) during water year 1975 as part of a lake eutrophication study. Five lake sites (S1, S17, S19, S24, S30) were sampled by USEPA in 1985 as part of the Western Lake Survey (Landers and others, 1987). The FLBS collected 149 samples from 14 lake sites (S7, S17, S27, S28, S42, S49, S52, S68, S69, S75, S82, S83, S85, S88) from 1984–1990 as part of a cooperative monitoring program with the NPS. The objective of the program was to document annual variability in water quality, physical characteristics, and phytoplankton and zooplankton communities for selected lakes in the park (Ellis and others, 1992; Ellis and others, 2003). In a separate study, the FLBS collected 357 samples during 1992 to 1994 from 14 stream sites (S2, S6, S10, S21, S22, S34, S38, S39, S40, S46, S47, S48, S53, S54) in the McDonald Creek drainage and 2 sites on Lake McDonald (S50, S51). The samples were collected from 1992 to 1998 and were analyzed primarily for nutrient species in a cooperative study with the NPS (Hauer and others, 2003). The USGS collected water-quality data for 478 samples from 55 stream and lake sites from 1963 to 2004. More than 70 percent of these samples were collected at 14 sites (S9, S25, S26, S31, S66, S76–S81, S86, S89, S90) in the Swiftcurrent Creek drainage on the east side of the park as part of the USGS Hydrologic Benchmark Network (Clark and others, 1999) including 129 samples from Swiftcurrent Creek at Many Glacier (S81) and 187 samples from Swiftcurrent Creek above Swiftcurrent Lake (S78). The USGS began a project in 2004 to assess the effects of the 2003 wildfires on water quality in the park. As part of this project, major constituent and nutrient data have been collected as frequently as weekly at Coal Creek (S15) and Pinchot Creek (S65) sites, and intermittently at 14 additional stream sites (S8, S11–S14, S16, S29, S37, S57, S59–S62, S64). Five lakes (S1, S17, S18, S24, S30) were sampled by the USEPA in 1985 during the Western Lake Survey (Landers and others, 1987) and six lake sites (S17, S18, S19, S24, S30, S55) were sampled by the USGS during a lake survey in 1999 (Clow and others, 2002). Ten lake sites (S4, S5, S35, S42, S55, S58, S63, S70, S75, S84) were sampled during the summers of 2002 or 2003 by the USGS to document the distribution and occurrence of organochlorine compounds and pesticides in lake sediments (Mast and others, 2006). Miscellaneous field measurements were made by the USGS at sites S3, S41, S67, and S74 in the late 1980s.

In addition to the 90 stream and lake sites originating inside the park boundary, water-quality samples were collected at 7 sites on the main stem of the North Fork of the Flathead River and 8 sites on the Middle Fork of the Flathead River, which flow along the park boundary (fig. 5 and table 8). On the North Fork, the USGS collected water-quality samples at sites N2 and N6. Site N1, which is in Canada just upstream from site N2, was sampled monthly by Environment

Table 6. Surface-water sampling sites in Glacier National Park, excluding sites on the North and Middle Forks of the Flathead River, Montana.

[no., number; LK, lake; ST, stream; GNP, Glacier National Park; Cr, Creek; ab, above; nr, near; identification numbers and station names from USEPA STORET and USGS NWIS]

Site no. (fig. 4)	Identification no.	Station name	Latitude	Longitude	Type	No. samples	Period of record
S1	4C3-004	(No Name)	48° 49’ 10”	113° 56’ 25”	LK	1	1985
S2	484908113462400	Ahern Creek at Highline Trail	48° 49’ 08”	113° 46’ 24”	ST	1	1992
S3	12355220	Akokala Creek near Polebridge, Mont.	48° 47’ 18”	114° 17’ 06”	ST	3	1989
S4	485244114115400	Akokala Lake	48° 52’ 44”	114° 11’ 54”	LK	1	2002
S5	485230113503300	Atsina Lake near Mokowanis Cascade in GNP	48° 52’ 30”	113° 50’ 37”	LK	2	2003
S6	484048113490800	Avalanche Creek at Going To The Sun Road	48° 40’ 48”	113° 49’ 08”	ST	42	1993–98
S7	482913113343100	Beaver Woman Lake	48° 29’ 13”	113° 34’ 31”	LK	9	1984–89
S8	482333113345501	Buffalo Woman Lake	48° 28’ 28”	113° 35’ 11”	LK	1	2004
S9	484604113414500	Cataract Cr near Many Glacier	48° 46’ 04”	113° 41’ 48”	ST	1	1992
S10	484955113475800	Cattlequeen Creek at Highline Trail	48° 49’ 55”	113° 47’ 58”	ST	1	1992
S11	482734113321801	Coal Creek 4 at Confluence	48° 27’ 31”	113° 32’ 33”	ST	1	2004
S12	482715113315201	Coal Creek 5	48° 27’ 15”	113° 31’ 52”	ST	1	2004
S13	482537113324001	Coal Creek 6	48° 25’ 35”	113° 32’ 40”	ST	1	2004
S14	482441113365401	Coal Creek 7	48° 24’ 41”	113° 36’ 54”	ST	1	2004
S15	482518113420100	Coal Creek above Pinchot Creek	48° 25’ 18”	113° 41’ 60”	ST	38	2003–04
S16	482509113434500	Coal Creek near West Glacier	48° 25’ 09”	113° 43’ 40”	ST	2	2004
S17	4C3-013	Cobalt Lake	48° 26’ 04”	113° 25’ 33”	LK	11	1984–90, 99
S18	485551113443600	Cosley Lake GNP	48° 55’ 22”	113° 45’ 18”	LK	1	1999
S19	4C3-010	Feather Woman Lake	48° 37’ 04”	113° 46’ 42”	LK	2	1985, 99
S20	3008F1	Fern Creek	48° 33’ 07”	113° 59’ 19”	ST	13	1974–75
S21	483259113590600	Fish Creek at Fish Creek Campground	48° 32’ 59”	113° 59’ 06”	ST	58	1974–75, 93–98
S22	484732113504500	Flattop Cr at Flattop Campground	48° 47’ 32”	113° 50’ 45”	ST	2	1992, 99
S23	485625114001500	Frances Lake	48° 56’ 25”	114° 00’ 19”	LK	1	2000
S24	4C3-062	Glenns Lake	48° 54’ 10”	113° 47’ 33”	LK	2	1985, 99
S25	484614113415500	Grinnell Cr below Grinnell Lake nr Many Glacier	48° 46’ 14”	113° 41’ 59”	ST	1	1992
S26	484718113394400	Grinnell Creek above Swiftcurrent Lake	48° 47’ 15”	113° 39’ 46”	ST	1	2000
S27	483734113422500	Gunsight Lake	48° 37’ 34”	113° 42’ 25”	LK	9	1984–90
S28	485022114001200	Gyrfalcon Lake	48° 50’ 22”	114° 00’ 12”	LK	9	1984–90
S29	482919113510300	Harrison Creek near West Glacier	48° 29’ 19”	113° 51’ 03”	ST	2	2004
S30	4C3-011	Harrison Lake	48° 31’ 10”	113° 46’ 03”	LK	3	1985, 99
S31	484903113443500	Iceberg Cr near Many Glacier	48° 49’ 03”	113° 44’ 38”	ST	1	1992
S32	482527113292700	Isabel Lake	48° 25’ 27”	113° 29’ 30”	LK	1	2000
S33	3008D1	Jackson Creek	48° 36’ 42”	113° 52’ 53”	ST	14	1974–75

Table 6. Surface-water sampling sites in Glacier National Park, excluding sites on the North and Middle Forks of the Flathead River, Montana.—Continued

[no., number; LK, lake; ST, stream; GNP, Glacier National Park; Cr, Creek; ab, above; nr, near; identification numbers and station names from USEPA STORET and USGS NWIS]

Site no. (fig. 4)	Identification no.	Station name	Latitude	Longitude	Type	No. samples	Period of record
S34	485108113514200	Kootenai Creek at Fifty Mile Camp	48° 51’ 08”	113° 51’ 42”	ST	1	1992
S35	485639113563600	Lake Janet near Olson Mountain in GNP	48° 56’ 39”	113° 56’ 39”	LK	2	2003
S36	6320LA01	Lake Sherburne	48° 49’ 35”	113° 31’ 27”	LK	2	1980
S37	482943113530500	Lincoln Creek near West Glacier	48° 29’ 45”	113° 53’ 05”	ST	2	2004
S38	484154113435300	Logan Creek at Headwater Spring	48° 41’ 54”	113° 43’ 53”	ST	3	1994, 98
S39	484154113433000	Logan Creek at Logan Pass	48° 41’ 54”	113° 43’ 30”	ST	1	1994
S40	484325113455100	Logan Creek at The Snowshoe Cabin	48° 43’ 25”	113° 45’ 51”	ST	32	1993–98
S41	12355320	Logging Creek near Polebridge, Mont.	48° 41’ 55”	114° 11’ 34”	ST	4	1989
S42	483736113481100	Lower Snyder Lake	48° 37’ 36”	113° 48’ 11”	LK	10	1984–90, 2002
S43	300802	Mc Donald Reservoir	48° 35’ 15”	113° 55’ 02”	LK	16	1975
S44	483133113595000	McDonald Cr below Lake McDonald	48° 31’ 33”	113° 59’ 48”	ST	14	1974–75
S45	3008A2	McDonald Creek	48° 38’ 08”	113° 51’ 59”	ST	14	1974–75
S46	484526113500700	McDonald Creek ab Confluence with Mineral Cr	48° 45’ 26”	113° 50’ 07”	ST	41	1993–98
S47	483828113512800	McDonald Creek at Bridge above Lake McDonald	48° 38’ 28”	113° 51’ 28”	ST	46	1993–98
S48	483133113594800	McDonald Creek at Bridge below Lake McDonald	48° 31’ 33”	113° 59’ 48”	ST	45	1993–98
S49	483400113562600	McDonald Lake	48° 34’ 00”	113° 56’ 26”	LK	16	1984–90
S50	483713113532200	McDonald Lake at Midlake—North	48° 37’ 13”	113° 53’ 22”	LK	43	1975, 93–94
S51	483240113582200	McDonald Lake at Midlake—South	48° 32’ 40”	113° 58’ 22”	LK	42	1975, 93–94
S52	483406113291800	Medicine Grizzly Lake	48° 34’ 06”	113° 29’ 18”	LK	9	1984–90
S53	485038113493700	Mineral Creek at Highline Trail	48° 50’ 38”	113° 49’ 37”	ST	1	1992
S54	484530113491800	Mineral Creek at Foot Bridge near Mouth	48° 45’ 30”	113° 49’ 18”	ST	44	1992–98
S55	485245113485000	Mokowanis Lake in Glacier National Park	48° 52’ 45”	113° 48’ 53”	LK	3	1999, 2003
S56	483237113271800	Morning Star Lake	48° 32’ 37”	113° 27’ 22”	LK	1	2000
S57	482154113390600	Muir Creek near West Glacier	48° 21’ 57”	113° 39’ 06”	ST	2	2004
S58	482844113265000	Noname Lake	48° 28’ 44”	113° 26’ 50”	LK	1	2002
S59	482946113411701	Nyack Creek 2	48° 29’ 46”	113° 41’ 17”	ST	1	2004
S60	482720113480800	Nyack Creek near West Glacier	48° 27’ 19”	113° 48’ 06”	ST	2	2004
S61	483111113314701	Nyack Creek 3, Upper Nyack	48° 31’ 11”	113° 31’ 47”	ST	1	2004
S62	481656113355600	Ole Creek near West Glacier	48° 16’ 54”	113° 35’ 59”	ST	2	2004
S63	484300113355000	Otokomi Lake	48° 43’ 00”	113° 35’ 50”	LK	1	2002

Table 6. Surface-water sampling sites in Glacier National Park, excluding sites on the North and Middle Forks of the Flathead River, Montana.—Continued

[no., number; LK, lake; ST, stream; GNP, Glacier National Park; Cr, Creek; ab, above; nr, near; identification numbers and station names from USEPA STORET and USGS NWIS]

Site no. (fig. 4)	Identification no.	Station name	Latitude	Longitude	Type	No. samples	Period of record
S64	481835113365100	Park Creek near West Glacier	48° 18’ 35’’	113° 36’ 47’’	ST	3	2004
S65	482520113420100	Pinchot Creek above Coal Creek	48° 25’ 21’’	113° 41’ 59’’	ST	38	2003–04
S66	484920113424000	Ptarmigan Cr above Falls near Many Glacier	48° 49’ 20’’	113° 42’ 44’’	ST	1	1992
S67	12355300	Quartz Creek near Polebridge, Mont.	48° 43’ 21’’	114° 13’ 33’’	ST	4	1989
S68	484108113314800	Saint Mary Lake	48° 41’ 08’’	113° 31’ 48’’	LK	15	1984–90
S69	Lake 6182	Sky 2 Lake	48° 30’ 24’’	113° 24’ 19’’	LK	1	1984
S70	485407113372500	Slide Lake in Glacier National Park	48° 54’ 07’’	113° 37’ 28’’	LK	2	2003
S71	3008C1	Snyder Creek	48° 36’ 58’’	113° 52’ 34’’	ST	14	1974–75
S72	3008E1	Sprague Creek	48° 36’ 24’’	113° 53’ 05’’	ST	14	1974–75
S73	05013600	Saint Mary River near St. Mary Mont.	48° 43’ 34’’	113° 26’ 12’’	ST	5	1978, 95
S74	12355100	Starvation Cr near Flathead British Columbia	48° 56’ 15’’	114° 23’ 30’’	ST	16	1985–87
S75	485309113515800	Stoney Indian Lake ab Pass Creek	48° 53’ 09’’	113° 52’ 02’’	LK	11	1984–90, 2003
S76	484649113443200	Swiftcurrent Cr ab Bullhead Lake nr Many Glacier	48° 46’ 49’’	113° 44’ 36’’	ST	2	1992, 2000
S77	484754113411700	Swiftcurrent Cr ab Fishercap Lake nr Many Glacier	48° 47’ 54’’	113° 41’ 20’’	ST	1	1992
S78	05014300	Swiftcurrent Cr ab Swiftcurrent Lk at Many Glacier	48° 47’ 43’’	113° 40’ 48’’	ST	187	2000–04
S79	484739113395800	Swiftcurrent Cr ab Swiftcurrent Lk nr Many Glacier	48° 47’ 39’’	113° 40’ 02’’	ST	1	1992
S80	484742113423500	Swiftcurrent Cr at Redrock Falls	48° 47’ 42’’	113° 42’ 40’’	ST	1	2000
S81	05014500	Swiftcurrent Creek at Many Glacier, Mont.	48° 47’ 57’’	113° 39’ 24’’	ST	129	1963–70, 1984–04
S82	484750113393200	Swiftcurrent Lake	48° 47’ 50’’	113° 39’ 32’’	LK	11	1985, 88–90
S83	482836113231500	Two Medicine Lake	48° 28’ 36’’	113° 23’ 15’’	LK	20	1984–90
S84	484709113441900	Upper Bullhead Lake	48° 47’ 10’’	113° 44’ 06’’	LK	1	2002
S85	484305113551800	Upper Dutch Lake	48° 43’ 05’’	113° 55’ 18’’	LK	9	1984–90
S86	484528113432600	Upper Grinnell Cr nr Many Glacier	48° 45’ 28’’	113° 43’ 29’’	ST	1	1992
S87	482802113264600	Upper Two Medicine Lake	48° 28’ 00’’	113° 26’ 57’’	LK	1	2000
S88	485950113535000	Waterton Lake	48° 59’ 50’’	113° 53’ 50’’	LK	14	1984–90
S89	484753113404500	Wilber Cr ab Fishercap Lake nr Many Glacier	48° 47’ 53’’	113° 40’ 48’’	ST	2	1992, 2000
S90	484717113440800	Windmaker Cr near Many Glacier	48° 47’ 17’’	113° 44’ 11’’	ST	1	1992

Canada as part of a network of sites in British Columbia to detect the existence of any significant trends in water quality (*http://www.ec.gc.ca/water/en/manage/qual/e_keymap.htm*, accessed November 2006). The MTDEQ collected samples at sites N3–N7 as part of a statewide water-quality monitoring network and the U.S. Forest Service sampled site N7. On the Middle Fork, the USGS collected water-quality samples at sites M1 and M6, the MTDEQ collected samples at all eight Middle Fork sites, and the U.S. Forest Service collected samples at sites M1 and M7. The ROMN database also contains major-constituent and trace-element data for 331 sites sampled in 1976 and 1978 as part of the NURE program (*http://pubs.usgs.gov/of/1997/ofr-97-0492/*, accessed November 2006). Because of the age (more than 25 years old) and unknown quality of NURE data and the availability of more recent datasets, results for NURE sites in GLAC are not discussed as part of this report.

Surface water in GLAC is fairly dilute and moderately buffered. Specific conductance ranged from 6.1 to 178 µS/cm, and alkalinity ranged from 2.0 to 93 mg/L (table 9). The dominant anion in surface water was bicarbonate (based on pH and alkalinity), and the dominant cations were calcium (median 14 mg/L) and magnesium (median 4.0 mg/L). The predominance of these constituents is attributed to weathering of carbonate minerals in the Proterozoic sedimentary rocks. Other major anions were sulfate, which ranged from 0.16 to 9.2 mg/L, and chloride, which ranged from less than 0.01 to 3.7 mg/L. The relatively low chloride concentrations (median 0.1 mg/L) indicate that atmospheric deposition probably is the dominant source of chloride in surface water (Clark and others, 1999). Although considerably less abundant than bicarbonate, sulfate concentrations were substantially higher (median 2.3 mg/L) than chloride, indicating weathering of sedimentary rocks also likely contributes sulfate to surface water. Summaries of water quality for the main stems of the North Fork and Middle Fork of the Flathead River are shown separately in table 10. These two rivers have much larger drainage areas than streams within the park boundary and, in addition, have a large percentage of their drainage area outside the park boundary. The ratio of major constituents in river-water samples was similar to samples collected from streams and lakes within the park, although major-constituent concentrations were up to three times higher in the North and Middle Forks of the Flathead River.

The most temporally intensive dataset available in the park is for Swiftcurrent Creek above Swiftcurrent Lake (S78). This site has been sampled at least monthly, and as frequent as weekly during snowmelt, since 2001 as part of the USGS Hydrologic Benchmark Network. Seasonal variations in alkalinity, calcium, and sulfate concentrations at S78 are shown in figure 8 for 2001 through 2004. Major constituent concentrations decrease in spring and reach a minimum in late May or early June at peak snowmelt discharge. Concentrations increase steadily through the summer and fall as snowmelt declines and ground water provides a greater percentage of streamflow. Although major constituents followed the same

Table 7. Period of record and types of analyses conducted for surface-water samples in Glacier National Park, excluding sites on the North and Middle Forks of the Flathead River, Montana.

[value in cell is number of samples analyzed in each category for the year; --, no data]

	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983
Field properties	1	2	1	3	4	8	--	1	--	--	--	--	48	--	--	7	--	2	--	3	3
Major constituents	1	2	1	3	4	8	--	--	--	--	--	--	--	--	--	2	--	--	--	--	--
Nutrients	1	2	1	3	4	8	--	--	--	--	--	21	102	--	--	2	--	--	--	--	--
Trace elements	1	2	1	1	4	8	--	1	--	--	--	--	--	--	--	--	--	--	--	--	--
Carbon	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Organics	1	2	1	3	4	7	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Microorganisms	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	2	--	--	--	--	--

	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
Field properties	28	38	28	32	29	35	23	8	19	61	78	49	30	41	33	14	16	99	55	30	118
Major constituents	27	31	19	19	22	18	18	--	12	31	40	33	27	32	28	8	7	95	47	21	110
Nutrients	27	31	19	19	21	18	18	--	18	67	89	52	47	52	44	8	7	95	47	21	116
Trace elements	27	31	19	19	21	18	18	--	12	--	--	2	--	--	--	8	7	--	5	6	85
Carbon	2	31	19	19	22	18	18	--	--	43	59	52	47	52	43	8	1	24	22	21	100
Organics	--	5	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	3	--
Microorganisms	10	5	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--

Table 8. Water-quality sampling sites on the North Fork and Middle Fork of the Flathead River in Glacier National Park, Montana.

[no., number; ab, above; nr, near]

Site no. (fig. 5)	Identification no.	Station name	Latitude	Longitude	No. samples	Period of record
		North Fork Flathead River				
N1	08NP001	Flathead River at Flathead British Columbia[a]	49° 00’ 06”	114° 28’ 31”	292	1965, 70, 74–93, 99–2004
N2	12355000	Flathead River at Canada-U.S. Border[b]	49° 00’ 02”	114° 28’ 35”	442	1979–95, 2002–04
N3	BSC01002	North Fork Flathead River at Polebridge[c]	48° 46’ 57”	114° 16’ 48”	23	1978–81
N4	BSC01001	North Fork Flathead River at Camas Creek[c]	48° 37’ 15”	114° 08’ 15”	48	1978–85
N5	FBC01019	North Fork Flathead River at Canyon Creek[c]	48° 30’ 27”	114° 08’ 39”	12	1984–85
N6	12355500	North Fork Flathead River near Columbia Falls[b]	48° 29’ 44”	114° 07’ 39”	222	1970, 73–79, 82–2004
N7	FL7013	North Fork Flathead River at Blankenships[c]	48° 28’ 05”	114° 04’ 20”	36	1981–82, 85–87
		Middle Fork Flathead River				
M1	12355900	Middle Fork Flathead River ab Bear Creek near Essex[b]	48° 14’ 01”	113° 34’ 02”	5	1970, 75–77, 80
M2	BSC03001	Middle Fork Flathead River nr Walton Ranger Station[c]	48° 16’ 28”	113° 36’ 12”	55	1975–79
M3	5719MI02	Middle Fork Flathead River near Goat Lick[c]	48° 15’ 57”	113° 36’ 18”	38	1975–77
M4	5719MI03	Middle Fork Flathead River at Essex[c]	48° 16’ 36”	113° 37’ 03”	38	1975–77, 80
M5	C07MFKFR01	Middle Fork Flathead R nr West Glacier Golf Course[c]	48° 30’ 20”	113° 59’ 40”	4	2001–2004
M6	12358500	Middle Fork Flathead River near West Glacier[b]	48° 29’ 43”	114° 00’ 36”	212	1949–50, 70, 78–2004
M7	6016MI01	Middle Fork Flathead River near West Glacier[c]	48° 29’ 31”	114° 01’ 56”	21	1973, 78–79
M8	FL6017	Middle Fork Flathead River at Blankenships[c]	48° 28’ 03”	114° 04’ 07”	36	1981–82, 86–87

[a] Identification number and station name from Environment Canada.

[b] Identification number and station name from USGS NWIS.

[c] Identification number and station name from USEPA STORET.

general pattern, there were some subtle differences in seasonal patterns. Alkalinity and calcium increased slightly in March at the start of the snowmelt period, then declined to their minimum concentrations in late April. In contrast, sulfate did not show an increase in March, and concentrations reached their minimum a few weeks later in June. These subtle variations likely reflect differences in weathering and biological processes that control surface-water quality.

General spatial patterns in water quality are illustrated by comparing lakes and streams in GLAC to the North Fork and Middle Fork of the Flathead River (fig. 9). pH generally was between 7.5 and 8.5 and fairly uniform among surface-water types, reflecting the predominance of carbonate minerals in the bedrock and buffering of surface waters by the carbonate system. Specific conductance, which is proportional to dissolved solids, was higher at the mainstem sites compared to lakes and streams in the park. This reflects longer hydrologic flow paths and greater opportunity for rock-water interactions in the larger river basins. Differences in geology and land-use activities also may be important factors. The most dilute surface waters were small lakes (less than 0.05 km^2) situated at high elevations (above 1,500 m). Of the sampled lakes in the park, the most dilute were sites S17, S19, S42, and S85, which had specific conductance values less than 10 µS/cm and pH values below 7.0. They also had alkalinities below 10 mg/L indicating some lakes in the park may be sensitive to acidification by deposition of atmospheric contaminants. However, less than 5 percent of lakes in the park have been sampled so the population of sensitive lakes is not well defined. Research is currently (2007) underway to identify and quantify the extent of sensitive lakes in GLAC through application of statistical models based on watershed characteristics (Nanus, 2005; Nanus and others, 2005).

Nutrients measured in streams and lakes inside GLAC include ammonia, nitrate, nitrite, organic nitrogen, orthophosphate, and dissolved and total phosphorus (table 9). Concentrations of most nutrients were close to or below detection with the exception of nitrate, which was detected in nearly all samples in concentrations ranging from less than 0.001 to 1.2 mg/L. Concentrations at some sites were higher than expected considering that atmospheric deposition is the primary source of inorganic nitrogen to surface-water systems in GLAC (Clark and others, 1999). Some of the highest nitrate concentrations (0.12 to 0.84 mg/L) were measured in Coal Creek above Pinchot Creek (S15) during the 2004 snowmelt period. Elevated nitrate at this site is attributed to leaching of nitrogen from soil and ash following a large wildfire that burned more than 80 percent of the drainage basin in 2003. Post-fire leaching of nutrients to surface water, particularly nitrate, is a commonly observed response in the first or second year following a fire (Ranalli, 2004). Elevated nitrate (range 0.034 to 1.20 mg/L) also was reported at Logan Creek at the Snowshoe Cabin (S40), although this drainage was not affected by recent wildfires. Hauer and others (2007) suggested that elevated nitrate may be caused by alders, which increase the nitrogen content of soil through symbiotic nitrogen fixation. The

Table 9. Summary of selected water-quality data for surface-water sites in Glacier National Park excluding the Middle and North Forks of the Flathead River, Montana, 1980 to 2004.

[no. number; chronic aquatic-life (and human-health) standards from *www.deq.state.mt.us/wqinfo/Standards/Index.asp*; <, less than; >, greater than; --, not reported; °C, degrees Celsius; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter at 25 °C; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorous; µg/L, micrograms per liter; some nutrients and trace elements have multiple reporting limits]

Constituent or property	No. sites	No. analyses (no. censored)	Minimum value	Median value	Maximum value	Aquatic-life (human-health) standard
			Field properties			
Temperature, water (°C)	44	235	0.0	7.0	19.0	<19.4
Oxygen, dissolved (mg/L)	0	0	--	--	--	>4.0
pH (standard units)	63	457	5.54	7.93	8.66	[a]6.5–9.0
Specific conductance (µS/cm)	55	576	6.1	101	178	--
			Major constituents			
Alkalinity (mg/L as $CaCO_3$)	63	457	2.0	49	93	--
Calcium, dissolved (mg/L)	58	444 (1)	<.1	14	25	--
Chloride, dissolved (mg/L)	59	454 (117)	<.01	.1	3.7	--
Fluoride, dissolved (mg/L)	30	128 (110)	[b].01	<.2	.31	(4)
Magnesium, dissolved (mg/L)	59	451 (1)	<.1	4.0	10	--
Potassium, dissolved (mg/L)	59	452 (34)	[b].03	.16	.42	--
Silica, dissolved (mg/L)	59	447 (2)	[b].20	2.2	7.6	--
Sodium, dissolved (mg/L)	59	453 (5)	[b].02	.46	1.3	--
Sulfate, dissolved (mg/L)	58	449 (3)	[b].16	2.3	9.2	--
			Nutrients and carbon			
Ammonia, dissolved (mg/L as N)	65	650 (361)	[b]0.001	0.006	0.094	[c]2.8
Nitrate, dissolved (mg/L as N)	73	808 (16)	<.001	.12	1.2	(10)
Nitrite, dissolved (mg/L as N)	17	94 (27)	<.0001	.0003	.002	(1.0)
Organic nitrogen, dissolved (mg/L as N)	14	75	.018	.057	.20	--
Orthophosphate, dissolved (mg/L as P)	41	513 (136)	[b].0003	.0009	.01	--
Phosphorus, dissolved (mg/L as P)	14	144 (36)	<.0006	.0014	.007	--
Phosphorus, total (mg/L as P)	46	581 (54)	[b].0009	.0038	.35	--
Carbon, dissolved organic (mg/L)	53	514	.06	.87	6.4	--
			Trace elements			
Aluminum, dissolved (µg/L)	14	141	1	14	96	87
Arsenic, dissolved (µg/L)	13	90 (90)	<1	<1	<1	[d]150 (10)
Barium, dissolved (µg/L)	15	93 (1)	<1	52	119	(2,000)
Cobalt, dissolved (µg/L)	14	91 (91)	<1	<1	<3	--
Copper, dissolved (µg/L)	14	79 (76)	<1	<1	2.8	[c,d]5.2 (1,300)
Iron, dissolved (µg/L)	26	161 (101)	<1	<100	<100	[d]1,000 ([e]300)
Lead, dissolved (µg/L)	13	82 (60)	<1	<1	2	[c,d]1.3 (15)
Manganese, dissolved (µg/L)	17	18 (9)	<1	1	4	([e]50)
Mercury, dissolved (µg/L)	13	65 (65)	<1	<1	<1	[d]0.91 (.05)
Molybdenum, dissolved (µg/L)	14	129 (126)	<1	<1	<10	--
Selenium, dissolved (µg/L)	13	65 (65)	<1	<1	<1	[d]5 (50)

[a] Natural pH outside this range must be maintained without change.

[b] Minimum reported value less than minimum censored value.

[c] Table value standard calculated for a hardness of 50 mg/L for trace elements or pH of 7.9 at 20 °C for ammonia.

[d] Total recoverable concentration.

[e] Secondary standard based aesthetic properties such as taste, odor, and staining.

Table 10. Summary of selected water-quality data for sampling sites on the North Fork and Middle Fork of the Flathead River in Glacier National Park, Montana, 1980 to 2004.

[no. number; chronic aquatic-life (and human-health) standards from *www.deq.state.mt.us/wqinfo/Standards/Index.asp*; <, less than; >, greater than; --, not reported; °C, degrees Celsius; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter at 25°C; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorous; col/100 mL, colonies per 100 milliliters; µg/L, micrograms per liter; some trace elements have multiple reporting limits]

Constituent or property	River Section	No. sites	No. analyses (no. censored)	Minimum value	Median value	Maximum value	Aquatic-life (human-health) standard
Field properties							
Temperature, water (°C)	North Fork	5	834	0.0	6.0	18.9	<19.4
	Middle Fork	4	194	.0	7.5	18.2	
Oxygen, dissolved (mg/L)	North Fork	3	167	8.4	10.2	14.3	>4.0
	Middle Fork	3	9	8.1	10.3	14.4	
pH (standard units)	North Fork	5	522	7.30	8.30	8.60	[a]6.5–9.0
	Middle Fork	3	29	6.93	8.10	8.60	
Specific conductance (µS/cm)	North Fork	3	523	138	251	310	--
	Middle Fork	4	195	120	172	273	
Major constituents							
Alkalinity (mg/L as $CaCO_3$)	North Fork	3	479	76	134	154	--
	Middle Fork	1	3	106	109	114	
Calcium, dissolved (mg/L)	North Fork	6	394	19	41	50	--
	Middle Fork	3	25	16	23	36	
Chloride, dissolved (mg/L)	North Fork	3	494 (1)	<.1	.4	3.6	--
	Middle Fork	2	13 (3)	[b].07	.2	.9	
Fluoride, dissolved (mg/L)	North Fork	3	518 (14)	[b].02	.08	1.5	(4)
	Middle Fork	2	13 (10)	[b].04	<.1	.2	
Magnesium, dissolved (mg/L)	North Fork	6	394	2.9	8.5	12	--
	Middle Fork	3	25	4.1	6.1	9.1	
Potassium, dissolved (mg/L)	North Fork	6	370	.2	.3	.9	--
	Middle Fork	3	25	.2	.3	1.6	
Silica, dissolved (mg/L)	North Fork	4	195	1.5	2.6	5.7	--
	Middle Fork	2	13	3.3	4.0	5.3	
Sodium, dissolved (mg/L)	North Fork	6	374	.4	.9	7.0	--
	Middle Fork	3	25	.5	.8	9.9	
Sulfate, dissolved (mg/L)	North Fork	3	519 (1)	[b].8	5.1	19	--
	Middle Fork	2	14	1.8	4.0	10	
Nutrients, carbon, and microorganisms							
Ammonia, dissolved (mg/L as N)	North Fork	2	102 (13)	<0.01	0.015	0.28	[c]1.52
	Middle Fork	0	0	--	--	--	
Nitrate, dissolved (mg/L as N)	North Fork	7	599 (44)	[b].003	.016	1.34	(10)
	Middle Fork	3	35	.01	.10	.26	
Nitrite, dissolved (mg/L as N)	North Fork	4	107 (97)	<.001	<.005	.08	(1.0)
	Middle Fork	1	20 (16)	<.001	.<002	.01	
Orthophosphate, dissolved (mg/L as P)	North Fork	3	116 (105)	<.001	<.003	.024	--
	Middle Fork	1	20 (16)	<.001	<.007	.007	
Phosphorus, dissolved (mg/L as P)	North Fork	5	111 (87)	<.001	<.002	.020	--
	Middle Fork	2	8	.001	.005	.014	
Phosphorus, total (mg/L as P)	North Fork	7	579 (107)	<.001	.006	.42	--
	Middle Fork	2	31 (5)	[b].001	.008	.20	
Carbon, dissolved organic (mg/L)	North Fork	5	42	.0	1.3	7.0	--
	Middle Fork	2	10	.04	.9	2.0	
Fecal coliform (col/100 mL)	North Fork	2	94 (5)	<1	3	120	--
	Middle Fork	1	24 (10)	<1	1	75	
Fecal strep (col/100 mL)	North Fork	2	94	1	3	170	--
	Middle Fork	1	24	1	3	93	

Table 10. Summary of selected water-quality data for sampling sites on the North Fork and Middle Fork of the Flathead River in Glacier National Park, Montana, 1980 to 2004.—Continued

[no. number; chronic aquatic-life (and human-health) standards from *www.deq.state.mt.us/wqinfo/Standards/Index.asp*; <, less than; >, greater than; --, not reported; °C, degrees Celsius; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter at 25°C; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorous; col/100 mL, colonies per 100 milliliters; µg/L, micrograms per liter; some trace elements have multiple reporting limits]

Constituent or property	River Section	No. sites	No. analyses (no. censored)	Minimum value	Median value	Maximum value	Aquatic-life (human-health) standard
			Trace elements				
Aluminum, total (µg/L)	North Fork	1	154 (1)	<0.2	33	4,000	[d]87
	Middle Fork	0	0	--	--	--	
Arsenic, total (µg/L)	North Fork	3	421 (21)	<.1	.3	2.6	150 ([d]10)
	Middle Fork	2	11 (11)	<1	<2	<2.6	
Barium, total (µg/L)	North Fork	2	165 (1)	[b]24	55	223	([d]2,000)
	Middle Fork	0	0	--	--	--	
Cadmium, total (µg/L)	North Fork	3	191 (127)	[b].004	<.1	6	[c]0.2 ([d]5)
	Middle Fork	2	11 (10)	<.1	<.11	.14	
Chromium, total (µg/L)	North Fork	3	150 (30)	[b].18	.4	10	[c]68 ([d]100)
	Middle Fork	1	12 (8)	<.8	<1	4.4	
Cobalt, total µg/L)	North Fork	2	165 (29)	[b].008	.1	2.3	--
	Middle Fork	0	0	--	--	--	
Copper, total (µg/L)	North Fork	3	211 (30)	[b].1	1	12	[c]7.3 ([d]1,300)
	Middle Fork	1	10 (3)	<.6	1.9	12	
Iron, total (µg/L)	North Fork	2	401	4.5	42	5,960	1,000 ([d,e]300)
	Middle Fork	1	4	10	25	40	
Lead, total (µg/L)	North Fork	3	211 (128)	<.005	<.2	57	[c]2.2 ([d]15)
	Middle Fork	1	10 (6)	[b].3	<1	4.2	
Manganese, total (µg/L)	North Fork	2	422 (88)	[b].06	5	180	([d,e]50)
	Middle Fork	0	0	--	--	--	
Molybdenum, total (µg/L)	North Fork	1	154 (1)	<.1	.3	1.1	--
	Middle Fork	0	0	--	--	--	
Nickel, total (µg/L)	North Fork	3	240 (102)	<.05	.4	8	[c]41
	Middle Fork	1	10 (6)	[b].38	<1	6.3	
Selenium, total (µg/L)	North Fork	3	387 (50)	<.05	.2	1	5 ([d]50)
	Middle Fork	1	1	0	--	--	
Zinc, total (µg/L)	North Fork	3	211 (29)	<.05	1.9	211	[c]94 ([d]2,000)
	Middle Fork	1	10 (5)	<1	2.3	<40	

[a] Natural pH outside this range must be maintained without change.

[b] Minimum reported value less than minimum censored value.

[c] Table value standard calculated for a hardness of 75 mg/L for trace elements or pH of 7.1 at 20 °C for ammonia.

[d] Dissolved concentration.

[e] Secondary standard based aesthetic properties such as taste, odor, and staining.

Logan Creek drainage has a particularly high density of alders because the landscape is dominated by steep avalanche terrain (Hauer and others, 2007). Summaries of nutrient concentrations for mainstem sites on the North and Middle Forks of the Flathead River are shown separately in table 10. Nutrient concentrations generally were low and were similar between the two forks of the river.

Processes controlling seasonal and spatial patterns in surface-water nutrients can be inferred from a few datasets available for the park. Frequent sampling at Swiftcurrent Creek above Swiftcurrent Lake (S78) on the east side of the park reveals a complicated seasonal pattern in stream-water nitrate (fig. 8). Concentrations increase rapidly during snowmelt in April and May due to preferential release of nitrate from the snowpack in addition to flushing of soils by infiltrating melt water. As melting subsides, stream-water concentrations begin to decline and reach a minimum in August near the end of the growing season. Nitrate concentrations increase through the winter probably because of greater contributions of nutrient-enriched ground water to streamflow coupled with decreasing biological demand during snow-covered months. The cause of the slight decline in nitrate during March before snowmelt is not clear, but might be related to early season breakup of ice cover on streams.

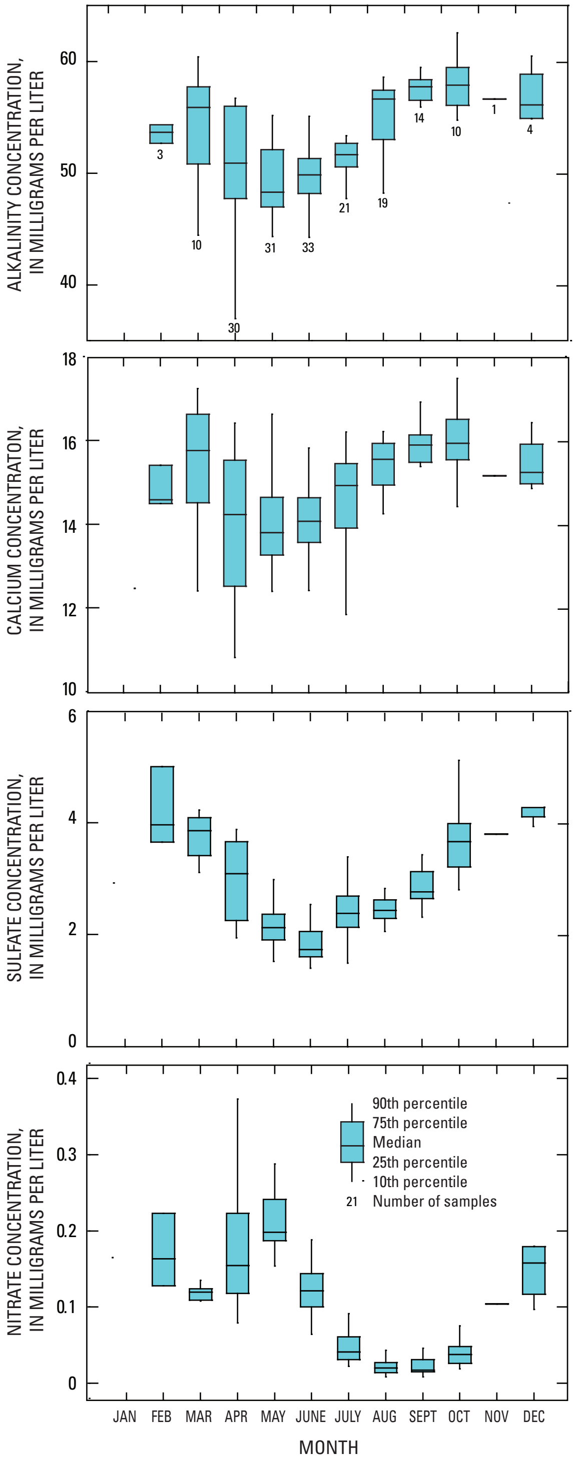


Figure 8. Seasonal variation in water quality at Swiftcurrent Creek above Swiftcurrent Lake at Many Glacier (S78) in Glacier National Park, Montana, 2001–2004.

Some general spatial patterns are apparent in a comparison of nutrients among streams and lakes in the park and the Middle and North Forks of the Flathead River (fig. 9). Orthophosphate was elevated in the North Fork and Middle Forks compared to lakes and streams in the park. Because phosphorus typically is associated with sediment, the higher concentrations probably reflect greater sediment loads in the larger river systems. This explanation is reasonable considering timber harvesting and road network land-use activities in areas outside the park boundary. Two west-side tributaries to the North Fork, Big Creek and Coal Creek, were 303(d) listed in 2006 as impaired for aquatic life and cold water fishery because of sedimentation from forest road networks and timber harvesting (*http://www.deq.state.mt.us/CWAIC/default.aspx*). By contrast, nitrate was lowest in the North Fork of the Flathead River, perhaps reflecting greater capacity of soils and forests to utilized atmospheric nitrogen in this drainage. Nitrate was elevated in park streams relative to lakes, partly reflecting the elevated concentrations in Coal Creek above Pinchot Creek (S15) and Logan Creek at Snowshoe Cabin (S40) discussed previously. Nitrate concentrations in park lakes ranged from less than 0.001 to 0.2 mg/L, and most of the values above 0.1 mg/L were measured in Lake McDonald, which has lake shore developments and is used intensively by visitors (Ellis and others. 1992). Concentrations in high-elevation lakes were low (less than 0.1 mg/L) throughout the park indicating rates of atmospheric nitrogen deposition have not yet exceeded biological uptake. There is concern, however, that increased deposition of nitrogen to high-elevation aquatic ecosystems could eventually result in decreases in lake clarity, episodic acidification of surface water, and changes in species composition of aquatic organisms (Porter and others, 2005). Most high-elevation lakes and streams in GLAC have physical characteristics that make them sensitive to increases in atmospheric deposition of nitrogen (Burns, 2004).

Concentrations for 11 trace elements were reported for lakes and streams sampled inside the park. At most of these sites only dissolved trace-element concentrations were measured; summaries are presented in table 9. The majority of concentrations were less than laboratory reporting levels and only aluminum and barium had a substantial number of detected concentrations above 10 µg/L. Aluminum concentrations ranged from 1 to 96 µg/L and were somewhat higher than expected given the neutral pH range of the samples. Given the high clay content of the sedimentary bedrock, higher concentrations could be related to colloidal aluminum not removed by sample filtration. Relatively high concentrations of barium (range less than 1 to 199 µg/L) were reported for lakes sampled in the 1980s as part of a baseline water-quality study (Ellis and others, 1992). Many barium concentrations were above the mean concentration of 45 µg/L for large rivers in North America (Hem, 1985) indicating a weathering source in the sedimentary bedrock. This result also may reflect the low sulfate concentration of lakes as barium concentrations in natural waters are controlled partially by the solubility of barium sulfate (Hem, 1985).

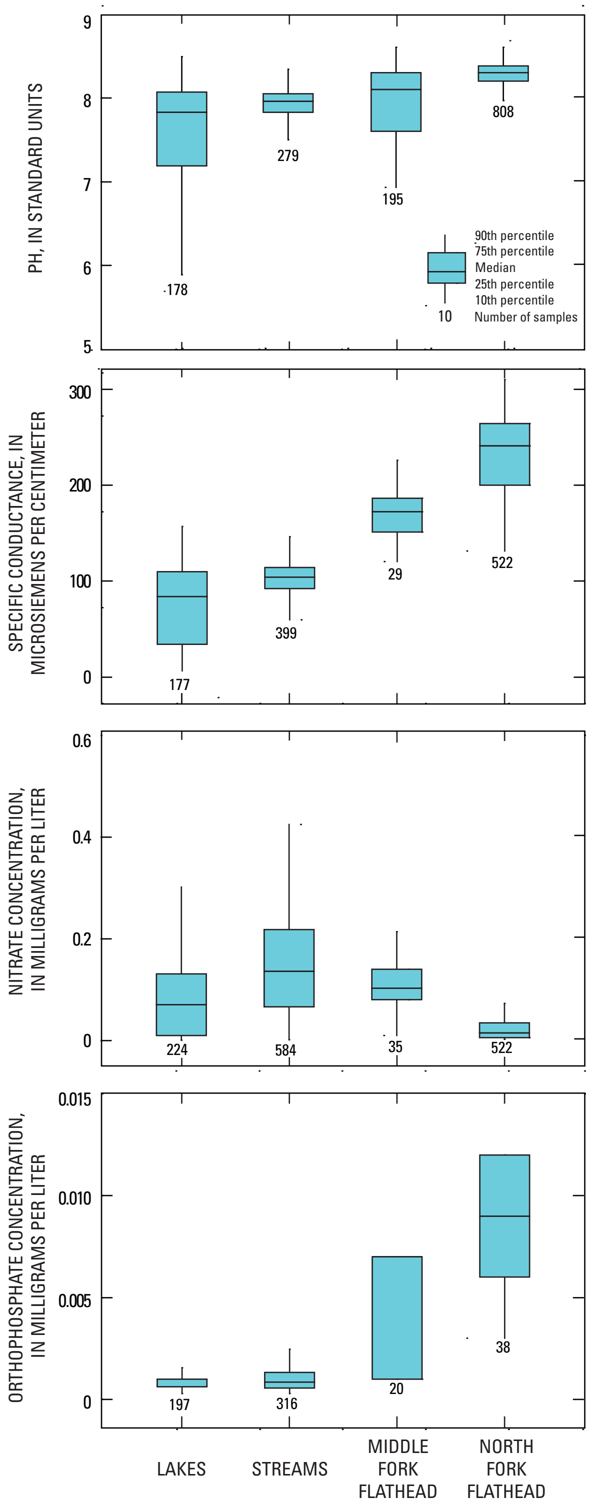


Figure 9. Spatial variation in surface-water quality at selected sites in Glacier National Park, Montana.

In contrast to sites in the park, trace elements in unfiltered samples primarily were measured at sites along the North and Middle Forks of the Flathead River (table 10). This occurrence is because Montana aquatic-life standards are defined for total recoverable rather than dissolved trace elements. The majority of available trace-element data (more than 90 percent) is for the North Fork of the Flathead River at the U.S.-Canada border (N1 and N2). With the exception of aluminum and iron, trace-element concentrations were low, which is not unexpected given the neutral pH of river water and the lack of mining and urban sources upstream from the site. Concentrations of trace elements were highest in April, May, and June reflecting greater sediment transport by rivers during snowmelt. Aluminum and iron concentrations exceeded 500 µg/L in 10 percent of samples, nearly all of which were collected during high-flow conditions in spring.

Five surface-water sites in GLAC had sufficient data to test for trends in water quality with time, including one site on the Middle Fork (M6), three sites on the North Fork (N1, N2, N6), and one site on Swiftcurrent Creek (S81). All sites were tested for trends in discharge and specific conductance, and two sites on the North Fork also were tested for trends in major constituents and selected nutrients (table 11). None of the sites had significant trends in discharge or specific conductance. Statistically significant trends ($p \leq 0.01$) were detected only for sulfate and total phosphorus at Flathead River at the Canada-U.S. border (N2). The magnitude and direction of the sulfate trend were similar for the unadjusted and flow-adjusted concentrations indicating the trend is not related to variations in stream discharge. The cause of the downward trend in sulfate is not clear, particularly considering that a similar trend was not detected in sulfate at site N1. Although the period of record was slightly different, these two sites are located within 100 m of each other on opposite sides of the Canada-U.S. border. A possible explanation could be that the trend is an artifact of changes in analytical methods. Mast and Turk (1999) observed similar sulfate trends at streams in the USGS Hydrologic Benchmark Network, which were attributed to documented changes in the analytical method for sulfate used by USGS laboratories between 1980 and 1990 (Fishman and others, 1994). A small downward trend in total phosphorus also was detected at site N2 although the significance of the trend declined slightly after flow adjustment. The magnitude of the trend was small [-0.001 milligrams per liter per year (mg/L/yr)] and, as with sulfate, was not detected at site N1. Trends in phosphorus concentrations might reflect changes in land-use activities outside the park boundary that result in sedimentation to the river. Alternatively, the trend might reflect a change in the reporting level for total phosphorus that occurred in 1988.

Comparison to Water-Quality Standards. Water-use classifications and water-quality standards for all stream segments in Montana are established by the MTDEQ (*http://www.deq.state.mt.us/wqinfo/Standards/Index.asp,* accessed November 2006). The main stems of the North and Middle Forks of the Flathead River above their junction are classified as A-1,

Table 11. Results of the seasonal Kendall test for trends in streamflow and unadjusted and flow-adjusted constituent concentrations for selected surface-water stations in Glacier National Park, Montana.

[--, not calculated or flow model not significant at $p \leq 0.1$; ft^3/s/yr, cubic feet per second per year; μS/cm/yr, microsiemens per centimeter per year; mg/L/yr, milligrams per liter per year; trends in bold are significant at $p \leq 0.01$]

	Unadjusted		Flow-adjusted		
Constituent or property	**Trend**	**p-value**	**Trend**	**p-value**	**Period of record**
Middle Fork Flathead River near West Glacier, Montana (M6 in fig. 5)					
Streamflow (ft^3/s/yr)	-3.4	0.724	--	--	1982–2004
Specific conductance (μS/cm/yr)	-.46	.114	-0.50	0.135	1982–2004
Swiftcurrent Creek at Many Glacier, Montana (S81 in fig. 5)					
Discharge (ft^3/s/yr)	.22	0.913	--	--	1982–2004
Specific conductance (μS/cm/yr)	-.42	.161	-0.56	0.070	1982–2004
North Fork Flathead River near Columbia Falls, Montana (N6 in fig. 5)					
Discharge (ft^3/s/yr)	-2.6	0.845	--	--	1982–2004
Specific conductance (μS/cm/yr)	.50	.070	0.37	0.041	1982–2004
Flathead River at Canada-U.S. Border (N2 in fig. 5)					
Discharge (ft^3/s/yr)	1.29	0.592	--	--	1974–93
pH (standard units/yr)	.00	.845	--	--	1974–93
Specific conductance (μS/cm/yr)	.00	.917	0.39	0.307	1974–93
Alkalinity (mg/L/yr)	.00	.777	.11	.632	1974–93
Calcium (mg/L/yr)	.00	.567	.09	.030	1974–93
Chloride (mg/L/yr)	.00	.947	--	--	1974–93
Magnesium (mg/L/yr)	.00	.896	.01	.251	1974–93
Potassium (mg/L/yr)	.00	.650	.00	.608	1974–93
Sodium (mg/L/yr)	.01	.014	--	--	1974–93
Sulfate (mg/L/yr)	-.06	.013	**-.07**	.005	1974–93
Nitrate (mg/L as N/yr)	.001	.049	--	--	1974–93
Phosphorus, total (mg/L as P/yr)	**-.001**	.010	-.001	.014	1974–93
Flathead River at British Columbia (N1 in fig. 5)					
Discharge (ft^3/s/yr)	-3.0	0.469	--	--	1979–95
pH (standard units/yr)	.00	.683	--	--	1979–95
Specific conductance (μS/cm/yr)	1.08	.022	0.74	0.132	1979–95
Alkalinity (mg/L/yr)	.50	.089	.23	.014	1979–95
Calcium (mg/L/yr)	.15	.098	.05	.352	1979–95
Chloride (mg/L/yr)	.00	.055	--	--	1979–95
Magnesium (mg/L/yr)	.05	.101	.05	.131	1979–95
Potassium (mg/L/yr)	.00	.016	--	--	1979–95
Sodium (mg/L/yr)	.00	.933	--	--	1979–95
Sulfate (mg/L/yr)	.07	.133	.07	.133	1979–95
Nitrate (mg/L as N/yr)	.000	.544	--	--	1979–95
Phosphorus, total (mg/L as P/yr)	.000	.515	.000	.984	1980–95

which is surface water suitable for domestic water supply; bathing, swimming, and recreation; growth and propagation of salmonid fishes and associated aquatic life, waterfowl and furbearers; and agricultural and industrial water supply. All surface waters located wholly within the boundaries of GLAC are designated as Outstanding Resource Waters, which offers the highest level of protection in the State. For these water bodies, any new or increased point source discharge that would result in a permanent change in water quality is prohibited. As mentioned previously, Big Creek and Coal Creek, two west-side tributaries of the North Fork outside the park were on the State's 303(d) list in 2006 for sedimentation and siltation related to road networks and timber harvesting. Along the east boundary of the park, Divide Creek was listed as partially impaired in 2006 for cold water fisheries and aquatic life because of road construction and land development around Saint Mary (fig. 5).

Montana aquatic-life and human-health standards are compared to surface-water quality for GLAC in tables 9 and 10. For the more than 900 water-quality samples collected inside the park, only a few samples exceeded the aquatic-life standards for aluminum and lead. For the North and Middle Forks of the Flathead River there were several exceedances of trace-element standards, most notably for aluminum (29 percent) and iron (5 percent) in the North Fork. Concentrations of total metals were elevated in these samples because nearly all of them were collected during snowmelt when sediment loads are greater. Because Montana uses total rather than dissolved concentrations for trace-element standards, the standards were exceeded during periods of high sediment transport. There also were a few exceedances for cadmium, copper, lead, manganese, and zinc in samples collected by the USGS during the 1980s. As mentioned previously, sampling methods used by the USGS before 1992 resulted in contamination of dissolved trace elements and data collected before this time have limited qualitative value and should be interpreted with caution.

Ground-Water Quality

Water-quality data were collected at 22 ground-water wells within the boundaries of GLAC (table 12). For these 22 wells, there are 74 samples with 2,480 individual data results including field properties (14 percent), and major-constituent (45 percent), nutrient (4 percent), and trace-element (29 percent) analyses. Five of the wells (G10, G11, G12, G21, G22) were sampled once each by the USGS in 1972 as part of a study to evaluate ground-water supplies at campgrounds and ranger stations in the park (Boettcher, 1973). The remaining 17 wells were sampled four times each during 1980–81. These are shallow observation wells completed in alluvium and located in the vicinity of park wastewater facilities in West Glacier, Saint Mary, and Many Glacier (table 12). They were sampled to determine if effluent from the wastewater treatment facilities was affecting the water quality of the alluvial aquifer (Moreland and Wood, 1982). No ground-water-quality data are available for the park for the past 25 years.

Ground-water samples had low to moderate concentrations of dissolved solids and were well buffered (table 13). Specific conductance ranged from 59 to 445 µS/cm, and alkalinity ranged from 33 to 290 mg/L. The major cation in ground water was calcium and the dominant anion was bicarbonate (as indicated by pH and alkalinity). The predominance of these ions is due to weathering of carbonate minerals in sedimentary rocks that occur as fragments in alluvium and till. Chloride was low (median 0.7 mg/L), characteristic of an atmospheric source (Hem, 1985), whereas sulfate was slightly higher (median 5.8 mg/L) indicating an additional source from weathering. Nutrient concentrations were low in all the well samples; nitrate ranged from 0.01 to 1.1 mg/L, orthophosphate from 0.02 to 0.04 mg/L and total phosphorus from 0.003 to 0.13 mg/L. Nutrients and major constituents in wells sampled during 1980 and 1981 did not appear to be affected by nearby wastewater treatment facilities (Moreland and Wood, 1982). However, many of the wells were upgradient from the facilities, or were completed in aquifers that were not hydrologically connected to the percolation ponds (Moreland and Wood, 1982). Of the trace elements, iron and manganese were present in the largest concentrations. This likely is because of reductive dissolution of aquifer sediments, although this cannot be verified because dissolved oxygen was not measured. A few samples had detectable concentrations of other trace elements most notably for copper, lead, and zinc. These detections were somewhat unexpected given the neutral pH measured in these well water samples and the fact that alluvial material is composed of unmineralized sedimentary rock types. A possible explanation for the detected trace-element concentrations is contamination of samples during collection and processing. It has been documented that samples collected for dissolved trace elements by the USGS before 1992 were sometimes contaminated during sampling and field processing (*http://water.usgs.gov/admin/memo/QW/qw91.10.html*, accessed November 2006). The contamination was most pronounced for arsenic, boron, beryllium, cadmium, chromium, copper, lead, and zinc. Because of the contamination issue, trace-element data for ground-water wells in GLAC must be viewed as questionable, and should be interpreted with caution. None of the wells had sufficient data to determine trends in ground-water quality or water levels with time.

Comparison to Water-Quality Standards. Although the sampled wells in the park are not used for water supplies, samples were compared to water-supply standards that are established by the MTDEQ for ground water (*http://www.deq.state.mt.us/wqinfo/Standards/Index.asp*, accessed November 2006). Primary drinking-water standards are developed for human health, and secondary standards are based on aesthetic properties such as taste, odor, and staining. Several of the samples collected during 1980 and 1981 had constituent concentrations that exceeded the human-health standards for cadmium and lead (table 13). One sample exceeded the secondary standard for manganese, and three exceeded the secondary standard for iron. As mentioned previously, sampling methods used by the USGS before 1993 could have resulted in contamination of

Table 12. Ground-water sampling sites in Glacier National Park, Montana.

[no., number; well depth in meters; WTF, wastewater treatment facility CG, campground; RS, ranger station; identification numbers and station names from USGS NWIS]

Site no. (fig. 5)	Identification no.	Station name	Latitude	Longitude	Well depth	Location	Period of record
G1	483029113595901	32N19W26BCCC01	48° 30’ 28”	114° 00’ 02”	4.0	West Glacier WTF	1980–81
G2	483031114001601	32N19W27ADCD01	48° 30’ 02”	114° 00’ 19”	8.7	West Glacier WTF	1980–81
G3	483036114000401	32N19W27ADDA01	48° 30’ 35”	114° 00’ 07”	3.1	West Glacier WTF	1980–81
G4	483037114000501	32N19W27ADAD03	48° 30’ 36”	114° 00’ 08”	3.2	West Glacier WTF	1980–81
G5	483038114000601	32N19W27ADAD02	48° 30’ 37”	114° 00’ 09”	3.2	West Glacier WTF	1980–81
G6	483039114000701	32N19W27ADAD01	48° 30’ 38”	114° 00’ 10”	2.3	West Glacier WTF	1980–81
G7	483039114000801	32N19W27ADAA01	48° 30’ 38”	114° 00’ 11”	3.5	West Glacier WTF	1980–81
G8	483039114001301	32N19W27ADAB01	48° 30’ 38”	114° 00’ 16”	10.0	West Glacier WTF	1980–81
G9	483045113595401	32N19W26BBCD01	48° 30’ 44”	113° 59’ 57”	12.0	West Glacier WTF	1980–81
G10	484153114113300	34N20W20DDA 01	48° 41’ 52”	114° 11’ 36”	12.5	Logging Creek CG	1972
G11	484155114112600	34N20W21BCB 01	48° 41’ 54”	114° 11’ 29”	10.4	Logging Creek CG	1972
G12	484321114132500	34N20W07DBB 01	48° 43’ 20”	114° 13’ 28”	13.7	Quartz Creek CG	1972
G13	484427113254801	35N14W34CCCA01	48° 44’ 26”	113° 25’ 51”	10.3	Saint Mary WTF	1980–81
G14	484434113260701	35N14W33DDBA01	48° 44’ 33”	113° 26’ 10”	22.9	Saint Mary WTF	1980–81
G15	484437113255601	35N14W33DADD01	48° 44’ 36”	113° 25’ 59”	24.4	Saint Mary WTF	1980–81
G16	484439113260101	35N14W33DADC01	48° 44’ 38”	113° 26’ 04”	23.9	Saint Mary WTF	1980–81
G17	484803113384301	35N16W12DCCA01	48° 48’ 02”	113° 38’ 46”	10.9	Many Glacier WTF	1980–81
G18	484804113383901	35N16W12CBBB01	48° 48’ 03”	113° 38’ 42”	11.6	Many Glacier WTF	1980–81
G19	484806113384501	35N16W12CCAB01	48° 48’ 05”	113° 38’ 48”	9.1	Many Glacier WTF	1980–81
G20	484808113384101	35N16W12CACC01	48° 48’ 07”	113° 38’ 44”	10.6	Many Glacier WTF	1980–81
G21	484817114190900	35N21W09CCA 01	48° 48’ 16”	114° 19’ 12”	6.1	Polebridge RS	1972
G22	485609114204400	37N21W29DDC 01	48° 56’ 08”	114° 20’ 47”	14.0	Kintla Lake CG	1972

dissolved trace elements, so data collected before this time have limited qualitative value and should be interpreted with caution.

Summary and Suggestions for Vital Signs Monitoring

The historical water-quality data review identified 1,144 samples collected at 54 streams and 36 lakes in GLAC from 1963 to 2004. The majority of results for these samples were field properties (19 percent), and major-constituent (30 percent), nutrient (26 percent), trace-element (8 percent), and organic carbon (7 percent) analyses. Most of the surface-water sites were sampled 1 to 3 times each during the period of record, although there were 14 sites that were sampled 20 or more times. For the 15 main-stem sites along the North and Middle Forks of the Flathead River, there were 1,515 samples collected from 1949 to 2004. Streamflow-gaging stations currently (2007) are operated by the USGS at six stations in the park including Swiftcurrent Creek at Many Glacier, which has been operated since 1912 and is the longest continuously operating station in the park. Surface water is a moderately dilute calcium-bicarbonate type, and dissolved solids primarily are derived from weathering of carbonate minerals in the sedimentary bedrock. Wildfire was determined to be an important control on stream-water nutrients in areas of the park burned during 2003. Five sites had sufficient data to test for temporal trends in water quality. The only detected trends were attributed to analytical method-related factors, rather than environmental change. All streams and lakes located entirely within the boundaries of GLAC are designated as Outstanding Resource Waters, which offers the highest level of protection in Montana. Historical data indicates water quality in the park meets Montana aquatic-life and human-health standards. Ground-water quality and resources in the park are not well characterized, and no water-quality data are available for the park for the past 25 years.

Some water-quality issues in GLAC include effects of visitor use and park facilities, atmospheric deposition of pollutants to high-elevation lakes, and land-use activities in areas

Table 13. Summary of selected water-quality data for ground-water sites in Glacier National Park, Montana, 1972 to 1981.

[no., number; human-health standards from *www.deq.state.mt.us/wqinfo/Standards/Index.asp*; <, less than; --, not reported; °C, degrees Celsius; µS/cm, microsiemens per centimeter at 25 °C; mg/L, milligrams per liter; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorous; µg/L, micrograms per liter; some trace elements have multiple reporting limits]

Constituent or property	No. sites	No. analyses (no. censored)	Minimum value	Median value	Maximum value	Human-health standard
Field properties						
Temperature, water (°C)	22	72	3.0	7.5	15	--
pH (standard units)	22	67	6.90	7.50	8.20	--
Specific conductance (µS/cm)	22	72	59	301	445	--
Major constituents						
Alkalinity (mg/L as $CaCO_3$)	22	74	33	185	290	--
Calcium, dissolved (mg/L)	22	74	7.4	43	69	--
Chloride, dissolved (mg/L)	22	73	.1	.7	3.0	--
Fluoride, dissolved (mg/L)	22	74 (1)	[a].01	.06	.2	4.0
Magnesium, dissolved (mg/L)	22	74	2.1	11	29	--
Potassium, dissolved (mg/L)	22	74	.1	.5	3.0	--
Silica, dissolved (mg/L)	22	74	3.8	5.8	28	--
Sodium, dissolved (mg/L)	22	74	.5	1.3	5.2	--
Sulfate, dissolved (mg/L)	22	74	.6	5.8	39	--
Nutrients						
Nitrate, dissolved (mg/L as N)	22	74	0.01	0.15	1.1	10
Orthophosphate, dissolved (mg/L as P)	5	5	.02	.02	.04	--
Phosphorus, total (mg/L as P)	13	26 (1)	[a].003	.018	.13	--
Trace elements						
Aluminum, dissolved (µg/L)	17	39 (14)	<20	50	150	--
Cadmium, dissolved (µg/L)	17	39 (28)	<2	<2	9	5
Chromium, dissolved (µg/L)	17	39 (20)	<2	<2	20	100
Copper, dissolved (µg/L)	17	39 (7)	<2	5	12	1,300
Iron, dissolved (µg/L)	22	74 (26)	<2	20	2,300	[b]300
Lead, dissolved (µg/L)	17	39 (31)	<10	<40	290	15
Lithium, dissolved (µg/L)	22	69 (49)	<2	<2	10	--
Manganese, dissolved (µg/L)	22	74 (25)	<0	<2	240	[b]50
Molybdenum, dissolved (µg/L)	17	39 (22)	<10	20	38	--
Nickel, dissolved (µg/L)	17	39 (31)	<10	<10	<60	100
Silver, dissolved (µg/L)	17	39 (27)	<2	<2	9	100
Titanium, dissolved (µg/L)	17	39 (10)	<1	4	20	--
Vanadium, dissolved (µg/L)	17	39 (24)	<1	<1	28	--
Zinc, dissolved (µg/L)	17	39 (22)	<3	<3	540	2,000
Zirconium, dissolved (µg/L)	17	39 (34)	<4	<4	<50	--

[a] Minimum reported value less than minimum censored value.

[b] Secondary standard based on aesthetic properties such as taste, odor, and staining.

outside the park draining the North and Middle Forks of the Flathead River. Climate change may have long-term effects on water resources in the park. Based on historical data review, the following suggestions are provided for consideration in designing a water-quality monitoring plan for GLAC.

- Maintain long-term water-quality monitoring at Swiftcurrent Creek above Swiftcurrent Lake (S78) and establish as a sentinel site for the east side of the park. The site is currently sampled as frequently as 20 times per year for major constituents and nutrients as part of the USGS Hydrologic Benchmark Network and a USGS streamflow-gaging station has been operated here since 2001.

- Consider adding a sentinel site on the west side of the park such as Avalanche Creek (S6) or McDonald Creek above Lake McDonald (S47). Both sites were sampled for nutrients and were gaged for streamflow from 1993 through 1998 by the NPS.

- Conduct periodic surveys of high-elevation lakes in the park to monitor the effects of atmospheric deposition of contaminants. Lakes could be selected on the basis of historical water-quality data and statistical models that estimate lake sensitivity to nitrogen and sulfur deposition (Nanus and others, 2005).

- Establish a network of streamflow-gaging stations and ground-water wells in the park to monitor the effect of climate change on water resources.

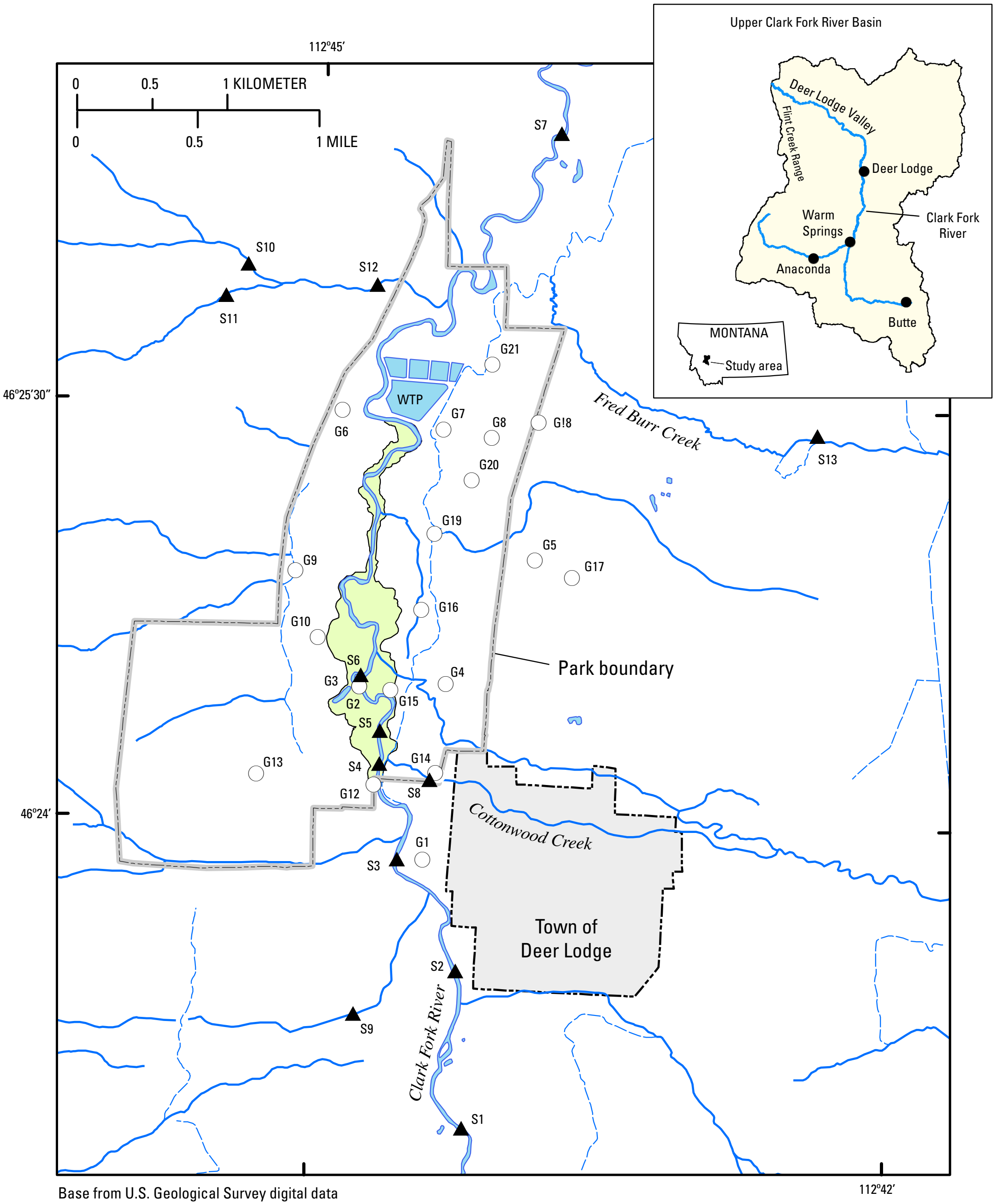
Grant-Kohrs Ranch National Historic Site

Environmental Setting and Land Use

Grant-Kohrs Ranch National Historic Site (GRKO) is located at the north end of the Deer Lodge Valley (fig. 10), which is an intermontane basin in western Montana bounded by low mountains to the east and the rugged Flint Creek Range to the west. The park covers an area of 6.5 km^2 and is situated in the floodplain of the Clark Fork River, which bisects the park from south to north. Only a small area in the southwest corner of the park extends onto terraces above the floodplain. Vegetation in riparian areas is dominated by redtop and willows, and drier areas of the park are used for pasture and for cultivation of hay (Britten and others, 2006). The climate is semiarid and typical of colder short-grass prairies. Mean monthly air temperatures at Deer Lodge range from –6.3 ºC in January to 16.4 ºC in July (*http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?mtdeer*, accessed June 2006). Annual average precipitation is 27 cm, most of which occurs as rain in late spring and early summer. The area receives about 92 cm of snow each year between October and April. Bedrock underlying the northern part of the Deer Lodge Valley includes a thick sequence of Tertiary sediments composed of grayish to pale orange sandy or silty mudstones interspersed with sand, gravel, and pebble conglomerate beds (Berg, 2004). In GRKO, the Tertiary sediments are covered by Quaternary alluvium and colluvium, and alluvial terrace deposits composed of poorly sorted gravel, sand, silt, and clay derived from Tertiary and older strata in the surrounding highlands (Berg, 2004).

GRKO is managed as a working cattle ranch and the site preserves 90 historic structures associated with its operation (*http://www.nps.gov/grko/parkmgmt/planning.htm,* accessed June 2006). Land-use activities primarily are related to cattle grazing, hay cultivation, and cultural feature operation and maintenance. The park has as many as 25 water-right claims to surface water from the river and its tributaries for flood irrigation of park lands. GRKO obtains drinking water from the town of Deer Lodge municipal system, and wastewater is handled by the Deer Lodge wastewater treatment facility, located just inside the northern park boundary (fig. 10). Since 2000, the ranch has used secondary treated sewage effluent from the wastewater treatment facility to irrigate some of the hayfields during summer months. For example, in June, July, and August of 2000 and 2001, 0.48 km^2 of park land was irrigated with 310 and 650 million liters of effluent, respectively (Johnson, 2002). This arrangement is part of the Clark Fork River Voluntary Nutrient Reduction Program (VNRP), which was developed by stakeholders to reduce nutrient pollution in the upper and middle reaches of the Clark Fork River (*http://www.tristatecouncil.org/programs/cfrwatershed.html,* accessed June 2006). The Clark Fork River has some of the most productive stream water in western Montana, and some of the highest densities of attached algae are present in the reach just downstream from GRKO. In 2000, the NPS studied the fate of sewage effluent nutrients (primarily nitrogen) applied to soils in GRKO by a sprinkler irrigation system (Johnson, 2002). The study determined that most of the applied nitrogen was retained by plants and in the soil, but that as much as 40 percent of the nitrogen might be leached to the shallow ground-water system.

GRKO also is within the Clark Fork River Superfund Site (*http://www.epa.gov/region08/superfund/sites/mt/milltowncfr/cfrou.html*, accessed June 2006), which is contaminated with arsenic and heavy metals (copper, cadmium, lead, and zinc) related to historic mining, milling, and smelting activities in the headwaters of the Clark Fork River. Tailings from these operations were transported downstream and deposited along the floodplain of the Clark Fork River by at least six major floods in the late 1800s and early 1900s (Smith and others, 1998). Sedimentation ponds were later built to prevent movement of tailings from headwater areas; however, the river continues to be contaminated by erosion of previously deposited tailings, and by direct leaching of metals from tailings into surface and ground water. Copper is the primary metal of concern because it is the most toxic to aquatic life and plants in the river floodplain (Lambing, 1991). An NPS study in 2000 estimated the volume of contaminated geologic resources in GRKO (Moore and Woessner, 2000) to include 12,600 m^2 of exposed tailings and as much as 1,660,000 cubic meters (m^3) of contaminated soil. In April, 2004, a Record of Decision was issued by the USEPA for the remediation of contaminated areas within Reach A of the Clark Fork River, which includes GRKO



Base from U.S. Geological Survey digital data
Universal Transverse Mercator Projection
Zone 12

EXPLANATION

🟦	Wastewater treatment plant (WTP)
🟩	Tailings deposits
– – –	Irrigation ditch
S2 ▲	Surface-water sampling site and number (table 14)
W8 ○	Ground-water well and number (table 18)

Photograph of Grant-Kohrs Ranch National Historic Site by W. Schweiger, National Park Service

Figure 10. Location of water-quality sampling sites near Grant-Kohrs Ranch National Historic Site, Montana.

(*http://www.epa.gov/region8/superfund/sites/mt/milltowncfr/cfrrodhome.html,* accessed June 2006). The remediation will include removal of larger tailing deposits (>37 m^2 in area and 60 cm deep) followed by revegetation of the excavated area. Smaller tailing deposits (generally what are present in GRKO) and impacted soil and vegetation will be remediated in place using lime addition, soil mixing, and revegetation.

Water Resources

GRKO is situated along a 5-km reach of the Clark Fork River downstream from the town of Deer Lodge, between Cottonwood Creek and Fred Burr Creek. The Clark Fork River begins near the town of Warm Springs and flows northward through the broad and meandering floodplain of the Deer Lodge Valley with an average gradient of 3.8 meters per kilometer (m/km). The river has four west-side perennial tributaries that flow from the Flint Creek Range, and several small east-side tributaries that flow only during spring snowmelt. During the summer months, water from the Clark Fork River and its west-side tributary streams is diverted for irrigation (Smith and others, 1998), some of which returns to the river channel as surface- or ground-water return flow.

The USGS has operated as many as 22 streamflow-gaging stations (10 were active in 2006) in the upper Clark Fork River Basin (*http://mt.water.usgs.gov/pub/MTStations.pdf*, accessed June 2006), including the Clark Fork River at Deer Lodge (USGS streamflow-gaging station 12324200) just 500 m upstream from GRKO, which has been in operation since 1979 (site S3, fig. 10). In addition to discharge, station 12324200 also has continuous water temperature measurements for 2001 to 2006 and suspended-sediment concentrations for 1985 to 2006 (*http://waterdata.usgs.gov/nwis/inventory/?site_no=12324200*, accessed June 2006). The range of daily streamflow values for the Clark Fork River at Deer Lodge from 1979 to 2005 is shown in figure 11. Peak flows typically occur in late May and early June as a result of spring rains and melting of mountain snowpacks. Runoff during snowmelt (April, May, and June) represents 37 percent of the mean annual runoff of 7.5 cm for the Clark Fork River at Deer Lodge. The lowest flows are in late July and August due to declining runoff and increasing rates of evapotranspiration combined with diversion of water for irrigation. Increased flows also can occur in late winter and early spring because of valley snowmelt and breakup of ice cover on the river, and in summer during thunderstorms (Hornberger and others, 1997).

Ground-water resources in the upper Clark Fork River Basin are described by Nimick (1993) and Konizeski and others (1962). Shallow aquifers in Quaternary and Tertiary valley-fill deposits are the primary water source for domestic supplies and irrigation. The direction of ground-water flow generally is from upland areas towards the Clark Fork River. Recharge to these shallow aquifers is by infiltration of precipitation, losses from irrigation ditches and irrigated lands, and infiltration from streams during periods of increased streamflow. The alluvial aquifer is localized along the river and major tributaries and is composed of medium to well-sorted unconsolidated gravel. Wells in alluvial deposits have a median depth of 11 m, and rarely are deeper than 21 m. Wells yield varies considerably ranging from 0.19 to 37 L/s with a median of 2.5 L/s. Coarse-grained beds and lenses of sand and gravel are the primary units that yield water to wells in the Tertiary aquifer. Wells completed in the Tertiary aquifer generally were deeper (median 33 m) and had lower yields (median 1.3 L/s) than wells in the alluvial aquifer. Water-level data are available for several shallow alluvial wells in GRKO. Nimick (1993) reported intermittent water-level measurements for two observation wells (G2 and G3, fig. 10) within GRKO during 1986 and 1987 and at several additional wells just outside the east park boundary. Monthly water-level data were collected during 2000 at 16 monitoring wells (G6-G21, fig. 10) installed as part of a NPS study (Moore and Woessner, 2000). The hydrograph in figure 12 shows water levels at selected wells during 2000. Water levels at many of the wells were higher in late spring and early summer, likely reflecting increased precipitation rates and streamflow during this time of year.

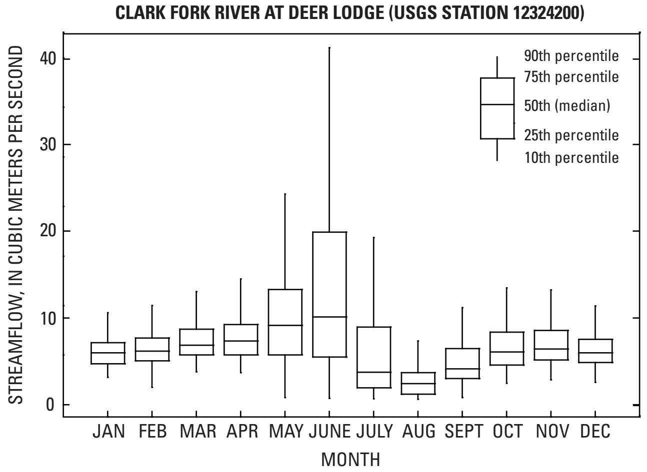


Figure 11. Daily streamflow range at Clark Fork River at Deer Lodge (S3) near Grant-Kohrs Ranch National Historic Site, Montana, 1979–2005.

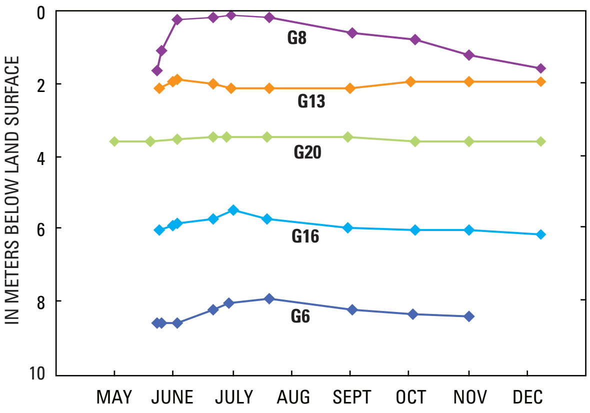


Figure 12. Ground-water level measurements at selected monitoring wells in Grant-Kohrs Ranch National Historic Site, Montana, 2000.

Surface-Water Quality

Water-quality data were collected at 13 surface-water sites in and immediately adjacent to GRKO, including 7 sites along the main stem of the Clark Fork River and 6 tributary streams (table 14, fig. 10). Water-quality samples collected at site S3 (Clark Fork River at Deer Lodge) are part of a long-term study being conducted by the USGS to quantify the concentrations, transport, and accumulation of metals in the water, bed sediment, and aquatic insects in the upper Clark Fork River Basin (S9 also sampled as part of this program). These data are being used to identify elevated metal concentrations that could pose an environmental risk, determine source areas of metals, and detect trends with time as remediation of the Superfund site proceeds (Dodge and others, 2005). Water-quality samples were collected intermittently at sites S1, S2, S4, S5, S7, and S8 between 1973 and 1996 as part of a surface-water monitoring program operated by the MTDEQ (*http://www.deq.state.mt.us/wqinfo/monitoring/index.asp*, accessed June 2006). Diurnal data sets were collected at site S6 (2 km downstream from S3) during July 21–23, 1994, and February 15–17, 1995, by the University of Montana to study diel cycles in arsenic, cadmium, nickel, manganese, and zinc concentrations (Brick and Moore, 1996). Four tributary sites (S10 to S13) were sampled once each during 1976 and 1977 as part of the NURE program (*http://pubs.usgs.gov/of/1997/ofr-97-0492/*, accessed June 2006). The ROMN database includes 881 samples collected at these 13 surface-water sites from 1968 to 2004. The majority of results for these 881 samples were field properties (24 percent), and major-constituent (24 percent), nutrient (9 percent), and trace-element (30 percent) analyses.

Because only a few samples were collected at tributary streams, the following discussion focuses on the water quality of the Clark Fork River. The period of record and types of analyses conducted at the main-stem sites are presented in table 15; water-quality data for 1980 to 2004 are summarized in table 16. The Clark Fork River samples showed a wide range in composition with specific conductance ranging from 208 to 1,890 µS/cm and alkalinity ranging from 7 to 199 mg/L. Calcium was the dominant cation (median 72 mg/L) and bicarbonate (based on pH and alkalinity; median 142 mg/L) and sulfate (median 120 mg/L) were the dominant anions. Calcium and bicarbonate (based on pH and alkalinity) are most likely derived from weathering of carbonate rocks that are common in the basin and as fragments in the valley fill and alluvium. By contrast, most sulfate probably is released from oxidation of sulfide minerals in mine wastes located in waste piles and tailings ponds in the headwater valleys of the Clark Fork and in flood-plain deposits along the river. Concentrations of major dissolved constituents in the river varied seasonally as shown by specific conductance values at site S3 (fig. 13). Concentrations are lowest during increased flow in May and June, when there are large contributions of dilute snowmelt to the river. Concentrations vary little from September through April when streamflow is sustained primarily by ground-water discharge.

Nutrient data for the Clark Fork included ammonia, nitrate, and orthophosphate concentrations, most of which were collected at site S1, which is located upstream from the town of Deer Lodge, and at site S6, which is located inside

Table 14. Surface-water sampling sites near Grant-Kohrs Ranch Ranch National Historic Site, Montana.

[no., number; MS, main-stem site on Clark Fork River, TR, tributary stream to Clark Fork River; Mont., Montana; NHS, National Historic Site]

Site no. (fig. 10)	Identification number	Station name	Latitude	Longitude	Type	Period of record
S1	3526CL01	Clark Fork River[a]	46° 22’ 54”	112° 44’ 07”	MS	1973–96
S2	3526CL10	Clark Fork River[a]	46° 23’ 30”	112° 44’ 02”	MS	1978
S3	12324200	Clark Fork at Deer Lodge, Mont.[b]	46° 23’ 51”	112° 44’ 34”	MS	1968–71, 79, 82–04
S4	3626CL01	Clark Fork River[a]	46° 24’ 09”	112° 44’ 20”	MS	1977–80, 85, 88, 91
S5	3626CL02	Clark Fork River[a]	46° 24’ 18”	112° 44’ 25”	MS	1977–78, 86–87
S6	GRKO_BRICK_1	Clark Fork River at Grant-Kohrs NHS[a]	46° 24’ 31”	112° 44’ 45”	MS	1994–95
S7	3626CL03	Clark Fork River[a]	46° 26’ 25”	112° 43’ 35”	MS	1977–80
S8	3626CO01	Cottonwood Creek[a]	46° 24’ 09”	112° 44’ 21”	TR	1978, 88–89
S9	462320112443701	Tin Cup Joe Creek at Deer Lodge, Mont.[b]	46° 23’ 19”	112° 44’ 40”	TR	1996
S10	GRKO_NURE_041	M25833[a]	46° 25’ 59”	112° 45’ 23”	TR	1977
S11	GRKO_NURE_042	M25834[a]	46° 25’ 52”	112° 45’ 30”	TR	1977
S12	GRKO_NURE_043	M24922[a]	46° 25’ 55”	112° 44’ 43”	TR	1977
S13	GRKO_NURE_080	M24438[a]	46° 25’ 19”	112° 42’ 28”	TR	1976

[a] Station name and identification number from USEPA STORET.

[b] Station name and identification number from USGS NWIS.

Table 15. Period of record and types of analyses conducted on surface-water samples collected along the main stem of the Clark Fork River near Grant-Kohrs Ranch National Historic Site, Montana.

[value in cell is number of samples analyzed in each category for the year; --, not data]

	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
Field properties	9	14	30	7	--	1	8	5	3	13	33	25	20	11	17	23	34	32	36	33	29	35	37	37	28	24	67	64	15	18	16	20	20	17	15	19	15
Major constituents	9	13	30	7	--	1	7	4	2	13	32	22	16	11	12	13	17	17	23	22	19	23	22	22	19	15	64	64	8	8	8	8	8	8	7	9	7
Nutrients	9	13	12	6	--	1	7	5	3	13	25	25	17	11	12	12	12	12	19	17	16	15	15	14	14	6	53	48	1	--	--	--	--	--	--	--	--
Trace elements	9	13	30	7	--	1	26	5	2	8	23	12	16	11	12	13	25	22	23	26	20	23	22	21	19	9	63	62	7	8	8	8	8	8	7	9	7
Organics	9	13	18	3	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Carbon	7	12	11	5	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	1	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Microorganisms	9	11	13	6	--	--	--	1	--	--	--	3	8	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--

the park but upstream from the wastewater treatment plant. Although concentrations were fairly low, there were detectable levels of nutrients in nearly all the river samples. From 1987 to 1995, nitrate concentrations ranged from 0.02 to 0.94 mg/L and orthophosphate concentrations ranged from 0.001 to 0.024 mg/L. Nitrate showed a strong seasonal pattern at site S1, with winter concentrations as much as five times higher than summer concentrations (fig. 13). Orthophosphate concentrations at site S1 also were elevated in winter relative to summer. Higher nutrient concentrations in winter probably are caused by greater contributions of nutrient-enriched ground water to streamflow coupled with decreased biological demand during colder winter months. Major sources of nitrogen and phosphorus to the river upstream from sites S1 and S6 include point sources such as the municipal wastewater treatment plant in the town of Butte, and seepage from septic systems and nonpoint sources such as animal wastes and irrigated agricultural land (*http://www.tristatecouncil.org/documents/02vnrp_eval.pdf*, accessed June 2006).

Trace elements detected in river water included arsenic, cadmium, copper, iron, lead, manganese, and zinc, which are metals associated with the Superfund mine tailings (Lambing, 1991). All of the main-stem samples had detectable levels of dissolved arsenic, which ranged from 6.0 to 39 µg/L, and dissolved copper, which ranged from 3 to 120 µg/L (table 16). Dissolved cadmium and lead were present in lower concentrations, and were detected in about 25 percent of samples. The highest dissolved trace-element concentrations were for manganese, which ranged from 1 to 400 µg/L and had a median concentration of 50 µg/L. The maximum dissolved copper (120 µg/L) and zinc (230 µg/L) concentrations were measured during an intense rainstorm on July 12, 1989, that flushed metal salts from tailings into the river and caused a fishkill (Lambing, 1991). Trace-element concentrations in the Clark Fork River at S3 showed strong seasonal patterns that were opposite to those observed for major constituents. For example, the highest concentrations of dissolved arsenic and copper concentrations at site S3 occurred during spring runoff, when major dissolved constituents were at a minimum (fig. 13). One possible explanation for this pattern is greater amounts of suspended sediment in the river during high-flow conditions (Lambing, 1991). Elevated suspended sediment, which often exceeds 50 mg/L during spring runoff, is caused by erosion of mine tailings from stream banks and floodplain deposits. Another potential source of dissolved metals is flushing of salts that accumulate in tailings and contaminated soils during the winter months. In addition to seasonality, metal concentrations also showed substantial diel cycles in the Clark Fork River (Brick and Moore, 1996). Daily variations in dissolved manganese and zinc concentrations and pH at site S6 are shown in figure 14. Metal concentrations increased during the night, reaching the highest concentrations at sunrise. Concentrations began to decrease during the late morning, reaching the lowest concentrations during late afternoon. A similar diel pattern has been documented in a wide variety of pH neutral streams in the Northern Rocky Mountains, which typically is attributed to sorption of

Table 16. Summary of selected water-quality data for main-stem sites on the Clark Fork River near Grant-Kohrs Ranch National Historic Site, Montana, 1980 to 2004.

[no. number; chronic aquatic-life (and human-health) standards from *www.deq.state.mt.us/wqinfo/Standards/Index.asp*; >, greater than; --, not reported; °C, degrees Celsius; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter at 25 °C; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorous; µg/L, micrograms per liter]

Constituent or property	No. analyses (no. censored)	Minimum value	Median value	Maximum value	Aquatic-life (human-health) standard
Field properties					
Temperature, water (°C)	637	0.0	9.6	26.5	--
Oxygen, dissolved (mg/L)	94	6.2	10.4	12.4	>4.0
pH (standard units)	351	6.70	8.27	8.91	[a]6.5–9.0
Specific conductance (µS/cm)	534	208	524	1,890	--
Major constituents					
Alkalinity (mg/L as $CaCO_3$)	304	7.0	142	199	--
Calcium, dissolved (mg/L)	418	28	72	134	--
Chloride, dissolved (mg/L)	308	.5	8.6	18	--
Fluoride, dissolved (mg/L)	82	.0	.7	1.0	(4.0)
Magnesium, dissolved (mg/L)	413	4.7	15	27	--
Potassium, dissolved (mg/L)	90	1.9	3.7	6.7	--
Silica, dissolved (mg/L)	131	9.1	13	21	--
Sodium, dissolved (mg/L)	307	3.5	19	28	--
Sulfate, dissolved (mg/L)	215	11	120	350	--
Nutrients					
Ammonia, dissolved (mg/L as N)	90	0.00	0.01	0.23	[b]3.15
Nitrate, dissolved (mg/L as N)	185	.02	.18	.94	[c].3 (10)
Orthophosphate, dissolved (mg/L as P)	89	.001	.006	.024	[c].02
Trace elements					
Arsenic, dissolved (µg/L)	146	6	13	39	(10)
Cadmium, dissolved (µg/L)	144 (108)	[d].02	.1	5	(5)
Copper, dissolved (µg/L)	251	3	8	120	(1,300)
Iron, dissolved (µg/L)	247 (25)	[d]3	13	190	([e]300)
Lead, dissolved (µg/L)	148 (108)	[d].04	.6	50	(15)
Manganese, dissolved (µg/L)	243	1	50	400	([e]50)
Zinc, dissolved (µg/L)	247	.9	11	230	(2,000)
Aluminum, total (µg/L)	122	18	100	1,129	[f]87
Arsenic, total (µg/L)	321	2	4	240	150
Cadmium, total (µg/L)	287 (89)	[d].06	1	8	[b].5
Copper, total (µg/L)	442	2	25	1,500	[b]20
Iron, total (µg/L)	434	27	310	29,000	1,000
Lead, total (µg/L)	291 (8)	[d].5	6	200	[b]10
Manganese, total (µg/L)	417	8	120	4,600	--
Zinc, total (µg/L)	444 (2)	[d]5	40	1,700	[b]260

[a] Natural pH outside this range must be maintained.

[b] Table value standard calculated for a hardness of 250 mg/L for trace elements or pH of 8.3 at 20 °C for ammonia.

[c] For reduction of nuisance algae growth, standards are for total nitrogen and total phosphorus.

[d] Minimum reported value less than minimum censored value.

[e] Secondary standard based aesthetic properties such as taste, odor, and staining.

[f] Dissolved concentration.

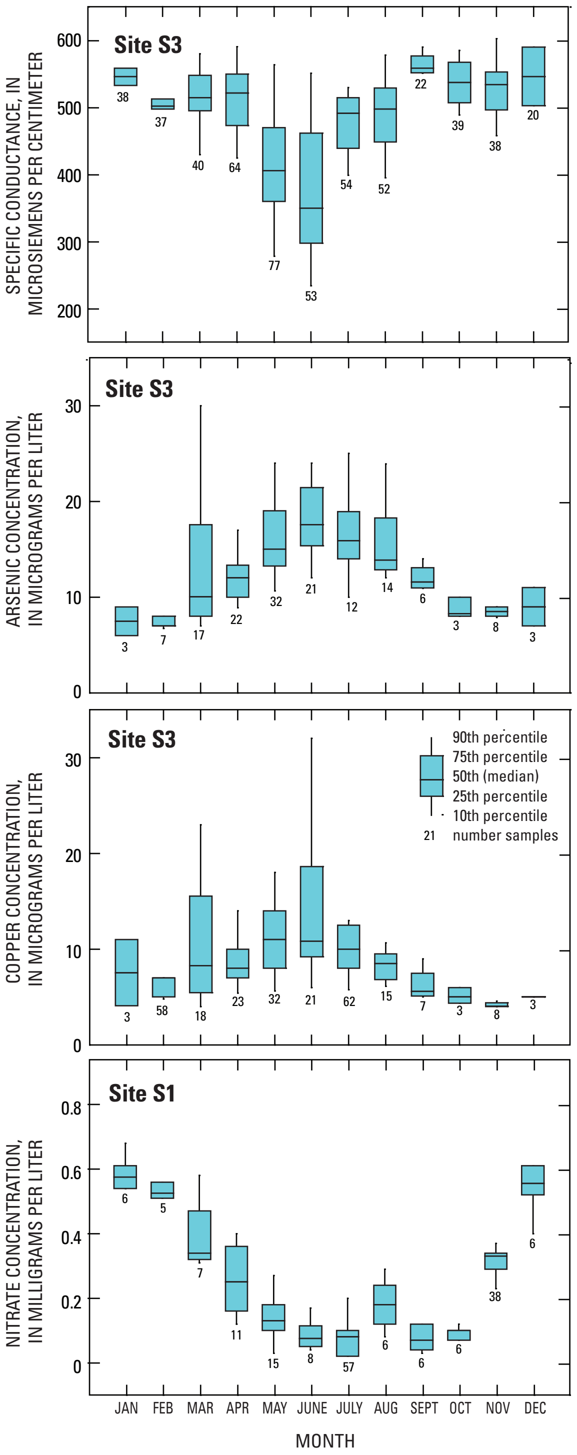


Figure 13. Seasonal variation in water quality at sites S1 and S3 on the Clark Fork River near Grant-Kohrs Ranch National Historic Site, Montana, 1982–2004.

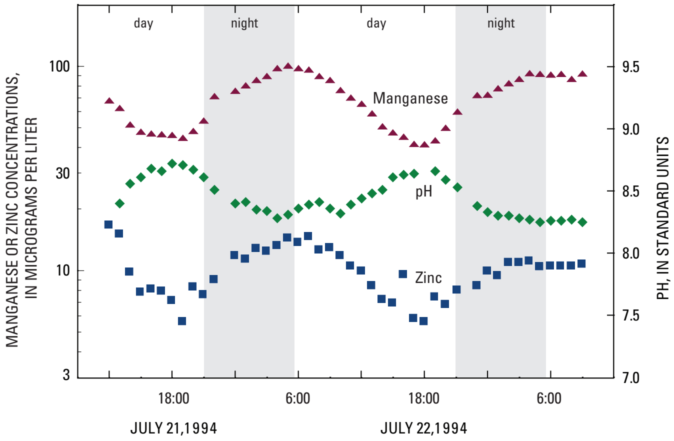


Figure 14. Diurnal variations in pH, manganese, and zinc at Clark Fork River (S6) in Grant-Kohrs Ranch National Historic Site, Montana, July 21–23, 1994.

metals between stream water and streambed sediments and aquatic plants (Nimick, 2003). Daily cycles in stream-water temperature and pH seem to control the amount of each metal that is adsorbed or desorbed (Nimick, 2003).

The Clark Fork River at sites S1 and S3 had sufficient data to test for temporal trends in water quality. At site S3, trends were tested for discharge, pH, calcium, magnesium, and dissolved arsenic, copper, iron, manganese, and zinc concentrations from 1989 to 2004 using four seasons per year (table 17). A statistically significant upward trend was detected for pH, and a downward trend was detected for zinc at site S3. The magnitude and significance of the pH trend were the same between unadjusted and flow-adjusted concentrations, indicating patterns in discharge were not driving the trend. The flow model for zinc was not statistically significant; therefore flow-adjusted concentrations were not tested. Total recoverable trace-element concentrations at this site also were tested, but none of the constituents (including zinc) had significant trends. At site S1, discharge and major constituents were tested from 1980 to 1992 using 12 seasons per year (table 17). A strong downward trend was detected in streamflow, which reflects an extended period of drought during the late 1980s. A statistically significant upward trend was detected in alkalinity; however, the trend changed direction and decreased in significance after flow-adjustment, indicating it was largely driven by the downward trend in streamflow. By contrast, there was a significant downward trend in the flow-adjusted calcium concentrations that was not detected in the unadjusted concentrations perhaps because it was offset by the decline in streamflows. A strong downward trend was detected in unadjusted sulfate concentrations but the flow-adjusted concentrations were not tested because the flow model was weak. The magnitudes of the calcium (-1.4 mg/L/yr) and sulfate (-4.0 mg/L/yr) trends were fairly large and were similar on an equivalent basis [-70 microequivalents per liter per year (µeq/L/yr) for calcium compared to -83 µeq/L/yr for sulfate] indicating they reflect real changes in stream-water quality. Because sulfate and

Table 17. Results of the seasonal Kendall test for trends in streamflow and unadjusted and flow-adjusted constituent concentrations for two stations on the Clark Fork River near Grant-Kohrs Ranch National Historic Site, Montana.

[--, not calculated or flow model not statistically significant at $p \leq 0.1$; $ft^3/s/yr$, cubic feet per second per year; mg/L/yr, milligrams per liter per year; µg /L/yr, micrograms per liter per year; trends in bold are significant at $p \leq 0.01$]

Parameter	Unadjusted trend	Unadjusted p-value	Flow-adjusted trend	Flow-adjusted p-value	Period of record
Clark Fork at Deer Lodge (S3 from fig. 10)					
Discharge ($ft^3/s/yr$)	-0.67	0.709	--	--	1989–2004
pH (standard units/yr)	**.01**	.007	**0.01**	0.007	1989–2004
Calcium (mg/L/yr)	.25	.375	-.29	.170	1989–2004
Magnesium (mg/L/yr)	-.01	.651	.04	.511	1989–2004
Arsenic, dissolved (µg/L/yr)	.04	.512	.06	.484	1989–2004
Copper, dissolved (µg/L/yr)	-.19	.025	-.09	.355	1989–2004
Iron, dissolved (µg/L/yr)	.00	.770	--	--	1989–2004
Manganese, dissolved (µg/L/yr)	.13	.647	--	--	1989–2004
Zinc, dissolved (µg/L/yr)	**-.52**	.008	--	--	1989–2004
Clark Fork River (S1 from fig. 10)					
Discharge ($ft^3/s/yr$)	**-20.4**	0.000	--	--	1980–1992
Alkalinity (mg/L/yr)	**2.0**	.008	-1.1	0.022	1980–1992
Calcium (mg/L/yr)	-.63	.120	**-1.4**	.008	1980–1992
Chloride (mg/L/yr)	.20	.039	-.04	.399	1980–1992
Magnesium (mg/L/yr)	.08	.489	-.18	.072	1980–1992
Sodium (mg/L/yr)	.29	.060	-.11	.307	1980–1992
Sulfate (mg/L/yr)	**-4.0**	.009	--	--	1980–1992

zinc are associated with mine wastes, it is likely the observed trends in water quality reflect remediation and restoration efforts in the headwater areas of the Clark Fork drainage during the 1980s and early 1990s (*http://www.epa.gov/region8/superfund/mtsf.html*, accessed June 2006); however, a detailed analysis of these trends with respect to specific remediation efforts is beyond the scope of this report. Continued monitoring will be important for assessing future remediation activities related to Superfund, and in particular, those activities that might occur inside the boundaries of GRKO.

Comparison to Water-Quality Standards. Water-use classifications and water-quality standards for all stream segments in Montana are established by the MTDEQ (*http://www.deq.state.mt.us/wqinfo/Standards/Index.asp*, accessed June 2006). The main stem of the Clark Fork River in the vicinity of GRKO (Clark Fork River downstream from Cottonwood Creek) has a beneficial use classification of C-1, which is suitable for bathing, swimming, and recreation; growth and propagation of salmonid fishes and associated aquatic life, waterfowl, and furbearers; and agricultural and industrial water supply. This reach of the Clark Fork River is on the most recent (2006) 303(d) list for the State of Montana (*http://www.deq.state.mt.us/CWAIC*, accessed June 2006) and is severely impaired for aquatic life and cold water fishery, and partially impaired for primary contact recreational use. The sources of the impairment are mill tailings, which have caused elevated copper, lead, and zinc concentrations, and agriculture and municipal point source discharge, which have resulted in elevated nitrogen, phosphorus, and sediment concentrations. In addition, discharge in the river during August and September is less than the minimum necessary for maintenance of a salmonid fishery. Contaminated sediments and siltation also have cause partial impairment for primary contact recreational use.

Aquatic-life and human-health standards established by the MTDEQ for surface water are compared to available water-quality data for the main-stem sites in table 16. Aquatic-life standards for copper, cadmium, lead, and zinc are dependent on hardness and standards were calculated using a median hardness of 250 mg/L. Comparing total trace-element concentrations to aquatic-life standards indicates exceedances for all the trace elements listed, with copper exceeding the standards the most frequently (60 percent of samples). Comparing dissolved trace-element concentrations to human-health standards indicates numerous exceedances for arsenic and manganese, and a few for lead. This reach of the river, however, is classified as C-1 and drinking water is not a beneficial use.

Standards for total nitrogen and phosphorus in the Clark Fork River have been established by the VNRP to reduce nuisance algae growth in the Clark Fork River downstream from Warm Springs in summer and to restore nutrient-impaired water uses along the river. (*http://www.ci.missoula.mt.us/wastewater/VNRP.htm*, accessed June 2006). The numeric standards are 0.02 mg/L for total phosphorus and 0.3 mg/L for total nitrogen, which are applicable from June 21 through September 21 (*http://www.deq.state.mt.us/dir/Legal/Chapters/CH30-06.pdf*, accessed June 2006). Assuming most nitrogen is present as dissolved nitrate, more than 40 percent of the nitrate concentrations in the main-stem samples exceeded the total nitrogen standard; however, none of the exceedances occurred during the summer months. Total phosphorus was not measured; however, 5 percent of samples had orthophosphate concentrations that exceeded the total phosphorus standard (20 μg/L) and, similar to nitrate, none of the exceedances occurred during summer months.

Ground-Water Quality

Water-quality data are available for 79 samples collected at 20 ground-water wells in or immediately adjacent to GRKO (table 18, fig. 10). Sites G1 to G4 were sampled between 1985 and 1989 as part of a cooperative study between the USGS and Montana Bureau of Mines and Geology to describe hydrologic conditions along the upper Clark Fork (Nimick, 1993). Samples collected at these wells were analyzed at the Montana Bureau of Mines and Geology Analytical Laboratory (*http://www.mbmg.mtech.edu/analytical.htm*, accessed June 2006). Site G5 was sampled and analyzed by the Montana Bureau of Mines and Geology in 1980 and sites G6 to G21 were installed and sampled in 2000 by the University of Montana as a cooperative project with the NPS to investigate metal-contaminated ground water in GRKO (Moore and Woessner, 2000).

Water-quality results for the 79 ground-water samples from GRKO are summarized in table 19. All of the samples had moderately high levels of major constituents with dissolved solids (calculated) ranging from 213 to 536 mg/L. Calcium was the dominant cation and bicarbonate was the dominant anion (based on pH and alkalinity) reflecting dissolution of carbonates rocks that occur as fragments in the alluvial deposits. Although sulfate was less abundant than bicarbonate, it ranged from 16 to 101 mg/L and accounted for as much as 35 percent of the total anion charge in some of the wells. Because there are no large sources of sulfate in the bedrock and alluvium, most sulfate in ground water likely is from oxidation of sulfide minerals in mine tailings that contaminate the floodplain. Wells with the highest sulfate concentrations also had elevated arsenic concentrations, which supports the idea that sulfate is derived from mine wastes. Another possible source of sulfate (and chloride) is wastewater effluent used to irrigate hayfields during the summer as part of the VNRP. Johnson (2002) reported concentrations as high as 47 mg/L for sulfate and 28 mg/L for chloride from effluent collected at sprinkler heads during 2000. None of the ground-water sites had a sufficient period of record to test for changes in water quality with time.

Despite agricultural activities in the park and tailings deposits in the floodplain, concentrations of nutrients and trace elements in the shallow ground-water samples generally were low. Nitrate concentrations ranged from less than 0.01 to 2.2 and were greater than 1.0 mg/L in only 15 percent of the samples. Nimick (1993) suggested that nitrate concentrations above 1.0 mg/L in the upper Clark Fork River basin probably indicate a nitrate source that is related to agricultural activities. In GRKO, an additional source of nitrate to ground water is treated sewage effluent used for irrigation, although, an NPS study in 2000 did not find significant differences between nitrate concentrations in background wells compared to wells in irrigated fields (Johnson, 2002). Of the 10 trace elements reported, dissolved concentrations commonly were close to or less than the laboratory reporting levels. The most frequent detections were for aluminum (48), arsenic (32 percent), copper (32 percent), iron (97 percent), manganese (97 percent), and zinc (100 percent). A likely source of arsenic, copper, and zinc is leaching of mine tailings that contaminate the floodplain sediments and soils. Because these wells are along the floodplain, metals also could come from percolation of contaminated river water into the underlying alluvial aquifer.

Comparison to Water-Quality Standards. Although ground-water wells in the park are not used as a water supply, samples were compared to human-health standards established by the MTDEQ (*http://www.deq.state.mt.us/wqinfo/Standards/Index.asp*, accessed June 2006). Primary drinking-water standards are developed for human health, and secondary standards are based on aesthetic properties such as taste, odor, and staining. Arsenic concentrations in 12 samples (ranging from 11 to 39 μg/L) from four wells exceeded the human health standard of 10 μg/L. None of the other trace-element concentrations exceeded the human-health standards, although one sample exceeded the secondary standard for iron and 18 exceeded the secondary standard for manganese. Elevated manganese concentrations probably are related to leaching of metals from tailings deposits in the floodplain or infiltration of river water into the alluvial aquifer.

Summary and Suggestions for Vital Signs Monitoring

Data for surface-water quality at GRKO are available for 881 samples collected at 7 main-stem sites on the Clark Fork River and 6 tributary streams from 1968 to 2004. The majority of results for these 881 samples were field properties (24 percent), and major-constituent (24 percent), nutrient (9 percent), and trace-element (30 percent) analyses. One-half of the water-quality samples were collected at the Clark Fork River at Deer Lodge (site S3), which has been sampled intensively since 1982. A streamflow-gaging station has been operated by the USGS at this station since 1979. Water in the Clark

Table 18. Ground-water sampling sites near Grant-Kohrs Ranch National Historic Site, Montana.

[no., number; well depth in meters; GKW, Grant-Kohrs well; MW, monitoring well; station names beginning with 08 from USGS NWIS; station names beginning with GKW or MW from Moore and Woessner (2000)]

Site no. (fig. 10)	Identification no.	Station name	Latitude	Longitude	Well depth	Period of record	No. of samples
G1	462352112442201	08N09W33CCDD01	46° 23’ 51”	112° 44’ 25”	50.0	1985	1
G2	462429112444301	08N09W32AADD01	46° 24’ 28”	112° 44’ 46”	2.9	1986–87	2
G3	462429112444302	08N09W32AADD02	46° 24’ 28”	112° 44’ 46”	18.1	1987, 89	2
G4	462457112434901	08N09W28DBDC01	46° 24’ 56”	112° 43’ 52”	18.0	1985	1
G5	462430112441601	08N09W33BAC 01	46° 24’ 29”	112° 44’ 19”	1.8	1980	1
G6	462528112445300	GKW-1	46° 25’ 04”	112° 44’ 39”	10.2	2000	5
G7	462454112450700	GKW-2	46° 25’ 22”	112° 44’ 06”	13.1	2000	4
G8	462439112445900	GKW-3	46° 24’ 53”	112° 45’ 06”	3.8	2000	2
G9	462426112450900	GKW-4	46° 24’ 39”	112° 44’ 59”	10.2	2000	6
G10	462408112444100	GKW-5	46° 24’ 26”	112° 45’ 09”	5.8	2000	3
G12	462410112442100	GKW-7	46° 24’ 09”	112° 45’ 17”	4.3	2000	5
G13	462428112443600	GKW-8	46° 24’ 09”	112° 44’ 20”	4.4	2000	6
G14	462446112442700	GKW-9	46° 24’ 28”	112° 44’ 36”	3.0	2000	6
G15	462525112442100	GKW-10	46° 25’ 28”	112° 44’ 53”	5.8	2000	4
G16	462523112440600	GKW-11	46° 25’ 24”	112° 44’ 21”	7.3	2000	4
G17	462453112434000	MW1	46° 25’ 37”	112° 44’ 07”	8.7	2000	5
G18	462527112435200	MW2	46° 24’ 53”	112° 43’ 40”	5.5	2000	5
G19	462502112442400	MW3	46° 25’ 26”	112° 43’ 51”	4.4	2000	1
G20	462514112441200	MW4	46° 25’ 02”	112° 44’ 23”	5.1	2000	8
G21	462539112440700	MW5	46° 25’ 13”	112° 44’ 12”	4.9	2000	8

Fork River is a calcium-bicarbonate-sulfate type, and major constituents primarily are derived from weathering of rock fragments in the alluvial fill except sulfate, which is released from oxidation of pyrite present in mine wastes. Arsenic, cadmium, copper, lead, manganese, and zinc, which are trace elements associated with mine wastes from historical mining activities, commonly were measured at detectable levels in the river. Nutrients in the river were mainly human-derived related to wastewater discharge and agriculture. Statistically significant downward trends were detected in dissolved calcium, sulfate, and zinc in the Clark Fork River that were attributed to remediation and restoration efforts during the 1980s and early 1990s. The Clark Fork River in the vicinity of GRKO has a beneficial-use classification of C-1 (suitable for bathing, swimming and recreation; growth and propagation of salmonid fishes and associated aquatic life, waterfowl, and furbearers; and agricultural and industrial water supply) and is listed as severely impaired for aquatic life and cold-water fishery and partially impaired for primary-contact recreational use. The sources of impairment are mine wastes, agriculture, and municipal wastewater discharge.

Data for ground-water quality at GRKO are available for 79 samples collected at 20 shallow ground-water wells from 1980 to 2000. The majority of results for these 77 samples were field properties (14 percent), and major-constituent (28 percent), nutrient (9 percent), and trace-element (39 percent) analyses. Most of the samples were collected in 2000 as part of a NPS ground-water study. Ground water is a calcium-bicarbonate type with moderately high dissolved solids (213 to 536 mg/L). Nutrient concentrations in ground water were low, indicating minimal effects from agricultural activities in the park. Samples from 4 of the 21 ground-water wells exceeded the human-health standard for arsenic, although none of the wells are used as a water supply.

Nutrient input from the sewage irrigation program and trace-element and sediment contamination related to mine tailings and their remediation are the primary water-quality issues for the reach of the Clark Fork River in GRKO. Based on a review of the historical data, the following suggestions are provided for consideration in designing a water-quality monitoring plan for GRKO.

- Maintain long-term water-quality monitoring at the Clark Fork River at Deer Lodge (USGS streamflow-gaging station 12324200) and establish as a sentinel site. The site is sampled 10–20 times per year by the USGS for trace elements, sediment, and hardness in

Table 19. Summary of selected water-quality data for ground-water sites in Grant-Kohrs Ranch National Historic Site, Montana, 1980 to 2000.

[no., number; human-health standards from *www.deq.state.mt.us/wqinfo/Standards/Index.asp*; <, less than; --, not reported; °C, degrees Celsius; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter at 25 °C; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorous; µg/L, micrograms per liter; some nutrients and trace elements have multiple reporting limits]

Constituent or property	No. sites	No. analyses (no. censored)	Minimum value	Median value	Maximum value	Human-health standard
Field properties						
Temperature, water (°C)	18	52	7.6	11.6	17.4	--
Oxygen, dissolved (mg/L)	3	3	4.6	5.6	6.4	--
pH (standard units)	19	53	6.45	7.31	7.68	--
Specific conductance (µS/cm)	19	53	242	457	799	--
Major constituents						
Alkalinity (mg/L as $CaCO_3$)	15	77	110	240	335	--
Calcium, dissolved (mg/L)	19	76	27	72	91	--
Chloride, dissolved (mg/L)	20	78	3.0	9.2	26	--
Fluoride, dissolved (mg/L)	5	7	.1	.7	1.0	4.0
Magnesium, dissolved (mg/L)	19	76	4.4	23	31	--
Potassium, dissolved (mg/L)	19	76	1.6	4.5	8.4	--
Silica, dissolved (mg/L)	4	6	44	64	79	--
Sodium, dissolved (mg/L)	19	76	11	19	32	--
Sulfate, dissolved (mg/L)	20	78	16	46	101	--
Nutrients						
Nitrate, dissolved (mg/L as N)	19	77 (12)	<0.01	0.5	2.2	10
Orthophosphate, dissolved (mg/L as P)	4	5 (4)	<.1	<.1	.2	--
Phosphorus, dissolved (mg/L as P)	18	75 (5)	<.01	.05	.16	--
Trace elements						
Aluminum, dissolved (µg/L)	18	75 (39)	<10	<10	280	--
Arsenic, dissolved (µg/L)	18	75 (51)	[a]3	<5	39	10
Cadmium, dissolved (µg/L)	18	75 (72)	<1	<1	5	5
Chromium, dissolved (µg/L)	18	75 (71)	<2	<5	5	100
Copper, dissolved (µg/L)	18	75 (51)	<2	<3	7	1,300
Iron, dissolved (µg/L)	17	72 (2)	<2.0	36	707	[b]300
Lead, dissolved (µg/L)	17	73 (70)	<10	<10	<40	15
Manganese, dissolved (µg/L)	17	72 (2)	<1	13	605	50[2]
Zinc, dissolved (µg/L)	18	75	1	3	120	2,000

[a] Minimum reported value less than minimum censored value.

[b] Secondary standard based aesthetic properties such as taste, odor, and staining.

support of remediation efforts at the Clark Fork Superfund site. The addition of analyses for nutrients, major constituents, and bacteria could be considered. There is a USGS streamflow-gaging station at this site that has been in operation since 1979.

- Establish a second water-quality monitoring site downstream from GRKO for periodic monitoring of nutrients, trace elements, sediment, and bacteria.
- Initiate routine monitoring of water levels and water quality (nutrients and trace elements) at a subset of shallow ground-water wells in the park. This information would be useful for monitoring the effects of the sewage irrigation program as well as future remediation efforts related to Superfund on ground-water resources.

Great Sand Dunes National Park and Preserve

Environmental Setting and Geology

Great Sand Dunes National Park and Preserve (GRSA) is located along the eastern edge of the broad, flat San Luis Valley in south-central Colorado (fig. 15). The covers 168 km^2 and ranges in elevation from 2,293 m at the edge of the San Luis valley up to 4,123 m along the crest of the Sangre de Cristo Mountains, which form the eastern park boundary. The predominant feature of the park is a 63 km^2 dune field in which some of the dunes are as much as 230 m high. Vegetation surrounding the dune field is dominated by grassland and shrub communities (Britten and others, 2006). East of the dunes, the lower flanks of the Sangre de Cristo Mountains are covered by pinion pine/juniper woodlands that grade into spruce/fir/aspen forests at higher elevations. The climate is characterized by cold winters with hot dry summers. Mean monthly air temperatures range from -6 °C in January to 15 °C in August at the park headquarters (*http://www.wrcc.dri.edu/summary/climsmco.html*, accessed July 2006). Annual average precipitation at the park headquarters is 26 cm, most of which falls during afternoon thundershowers in July, August, and September. Higher elevation areas in the eastern part of the park receive substantial snowfall that accumulates in a seasonal snowpack between November and April.

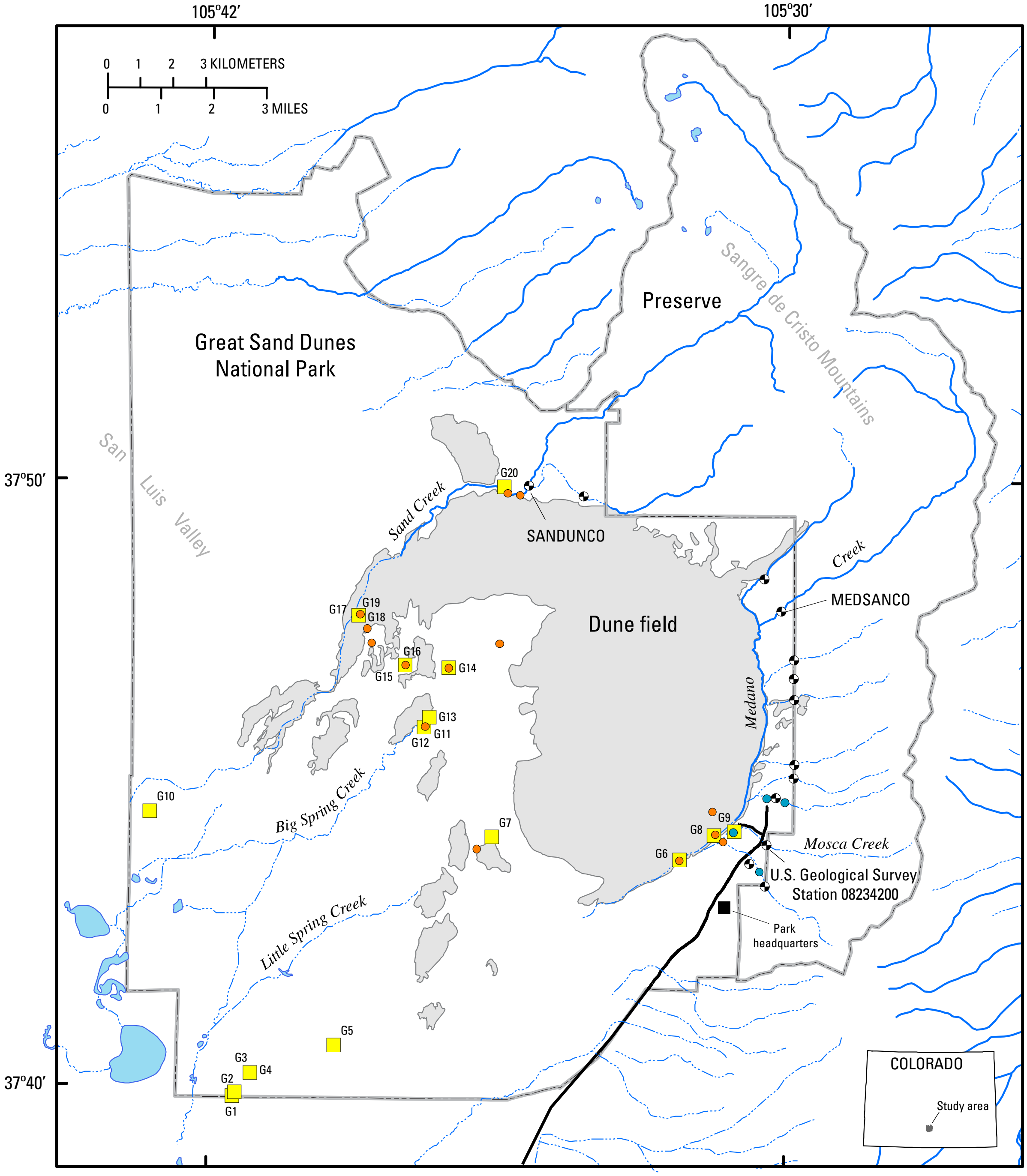
Bedrock in the Sangre de Cristo Mountains to the east of the dunes is Precambrian gneiss and micaceous schist (*http://www2.nature.nps.gov/geology/parks/grsa/*, accessed July 2006). Flat lying areas west of the mountains, including the dunes, are underlain by the Quaternary Alamosa Formation, which consists of unconsolidated gravel, sand, clay, and conglomerate. In the dune field itself, eolian deposits are subdivided into three provinces: the dune field, which is an area of actively forming reversing and star dunes; the sand sheet, which is composed of vegetation-stabilized dunes; and the Sabkha, which is a playa area where sand deposits are hardened by evaporate minerals (Chatman and others, 1997).

Land-use activities in GRSA are related to visitor use including the park headquarters and administrative area, a visitor center, an 88-site campground and recreational vehicle dump station, four picnic areas, and seasonal residences (Chatman and others, 1997). Some of the most intense visitor use is in a public wading area in the lower reach of Medano Creek. Land adjacent to the park mostly is public-owned and largely undeveloped. Water for park facilities is obtained from four ground-water wells located in the vicinity of park headquarters. Wastewater is treated at various locations in the park through septic tank-leach field combinations.

Water Resources

The two primary drainages in GRSA are Sand Creek, which flows around the northwest side of the dunes, and Medano Creek, which flows around the southeast side (fig. 15). The streams play a vital role in maintaining the dune fields because they deposit sand on the upwind side of the dune field where it is transported back to the dunes by prevailing winds (Chatman and others, 1997). Both streams begin high in the Sangre de Cristo Mountains and are fed primarily by snowmelt. As they flow around the edge of the dune field they begin losing water through the sand into a shallow unconfined ground-water aquifer. All the water in both creeks, except what is lost to evapotranspiration, eventually infiltrates into the unconfined aquifer, which flows under the dunes and eventually discharges at Big Spring and Little Spring Creeks on the west side of the dune field. Ground-water dating using chlorofluorocarbons indicates it takes more than 60 years for the ground water to flow under the dune field (Rupert and Plummer, 2004). A deeper confined aquifer, which also underlies the dune field, is separated from the unconfined aquifer by a 2.4-m thick clay layer at a depth of 90 m (Rupert and Plummer, 2004). There are insufficient data to determine whether or not the unconfined and confined aquifers are hydrologically connected (Rupert and Plummer, 2004). A more complete description of the surface- and ground-water hydrology of GRSA can be found in Chatman and others (1997).

The USGS operated a streamflow-gaging station on Mosca Creek (USGS station 08234200) a tributary of Medano Creek from 1967 to1970 (fig. 15). Streamflow-gaging stations have been operated on the two major perennial streams, Sand Creek (station SANDUNCO) and Medano Creek (station MEDSANCO), since 1992 (fig. 15). The gaging stations are operated by the Colorado Division of Water Resources for the NPS as part of a Federal water rights agreement. The range of daily streamflows by month at Medano Creek (station MEDSANCO) is shown in figure 16. Streamflow typically peaks in late May to early June during spring snowmelt, and the lowest streamflows are in fall and winter (November to February) when flow is sustained primarily by ground water. Afternoon thundershowers contribute to streamflow through the summer months (July to September) and can cause flash flooding. The NPS also has weirs on 10 other streams or springs in the park



Base from U.S. Geological Survey digital data, 1:100,000
Universal Transverse Mercator projection
Zone 13

EXPLANATION

━━ Paved road

G5 🟨 Ground-water sampling site and number (table 23)

● Water-supply well

● Monitoring well

◐ Streamflow-gaging station

Photograph of dune field by W. Schweiger, National Park Service

Figure 15. Location of streamflow-gaging stations and ground-water wells in Great Sand Dunes National Park and Preserve, Colorado.

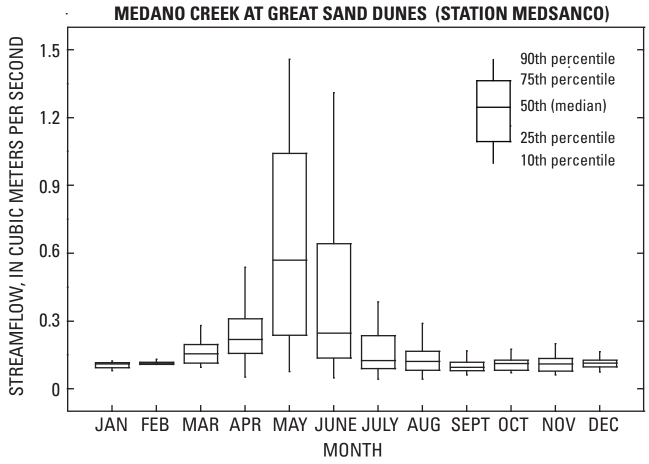


Figure 16. Daily streamflow range at Medano Creek (station MEDSANCO) in Great Sand Dunes National Park and Preserve, Colorado, 1992–2004.

that have water rights. Manual measurements have been made periodically by the NPS at these sites since 1992.

The NPS initiated a ground-water monitoring program in 1990 and has installed 22 monitoring wells ranging from 2.4 to 120 m deep. Locations of some of the NPS monitoring wells are shown in figure 15, and detailed descriptions of the wells are provided by Chatman and others (1997). The purpose of the original program was to monitor the effects of a proposed project to mine ground water from the San Luis Valley (Chatman and others, 1997). Water-level measurements are made manually at some of the wells and continuously at others; water-level data for the wells are stored in an NPS database (Andrew Valdez, National park Service, oral commun., 2006). There also are four water-supply wells located east of the dune field near the park headquarters (fig. 15). The NPS monitors these wells for nutrients, chlorine, and fecal indicator bacteria to meet Colorado drinking-water regulations. Descriptions of the water-supply wells are given in Chatman and others (1997), and water-quality records starting in 1991 are available from the NPS. Additional water-level measurements were made at 120 shallow observation wells in 1998 to study the disappearance of interdunal wetlands in GRSA (Wurstera and others, 2002).

The main water-resource issue identified by NPS is the lack of high-quality data that are needed to adequately describe the water budget for GRSA (Chatman and others, 1997). This information is needed to protect ground-water levels, surface-water levels, and streamflow on, across, and under GRSA, which is necessary for the preservation of the dunes and the adjacent wetlands. The primary threats to maintaining the balance of natural hydrologic processes are ground-water and surface-water withdrawals and long-term changes in climate. One of the main water-quality issues identified by the NPS was fecal contamination of Medano Creek in public wading areas (Chatman and others, 1997). Other issues identified include maintenance of a potable water supply and determining effects of primitive camping zones and abandoned mine sites, landfills, and a firing range on water quality. Deposition of atmospheric contaminants such as nitrogen and sulfur could pose a risk to high-elevation lakes and streams in the Sangre De Cristo Mountains.

Surface-Water Quality

Water-quality samples were collected over the period 1964 to 2001 at 46 surface-water sites within the boundaries of GRSA including 40 streams, 4 springs, and 2 interdunal ponds (table 20, fig. 17). Data are available for 387 samples at these sites, the majority of which are field properties (29 percent), and major-constituent (21 percent), nutrient (9 percent), and trace-element (12 percent) analyses (table 21). Surface-water sites typically were sampled 1 to 3 times each during the period of record, although there were eight sites that were sampled 10 or more times (table 20). The agencies responsible for sample collection at these sites are summarized below. Water-quality data from 1966 to 1970 were collected by the USGS at Mosca Creek (S1) around the time that the USGS gaging station at that site was operational. Fifteen sites (S1, S4, S21–S31, S36, and S46) were sampled once each in 1976 as part of the NURE program (*http://pubs.usgs.gov/of/1997/ofr-97-0492/*, accessed July 2006*)*. Twenty sites (S1, S4, S13, S19, S20, and S32–S46) were sampled during1990 to 1996 for the NPS through a grant from the non-profit citizens support group Friends of the Dunes. Twenty-eight samples were collected at Medano Creek (S14) from 1992 to 1996 as part of the USGS National Water Quality Assessment Program (*http://water.usgs.gov/nawqa/*, accessed July 2006). Two hundred fifty samples were collected by the USGS at 15 sites (S1, S3-S9, S11, S12, and S14–S18) during 1999 and 2000 to characterize baseline water-quality conditions in support of achieving Outstanding Waters Designation for several streams and springs in GRSA (Ferguson, 2003). Four sites (S2, S10, S14, and S18) were sampled during 2000 and 2001 as part of a USGS ground-water study (Rupert and Plummer, 2004).

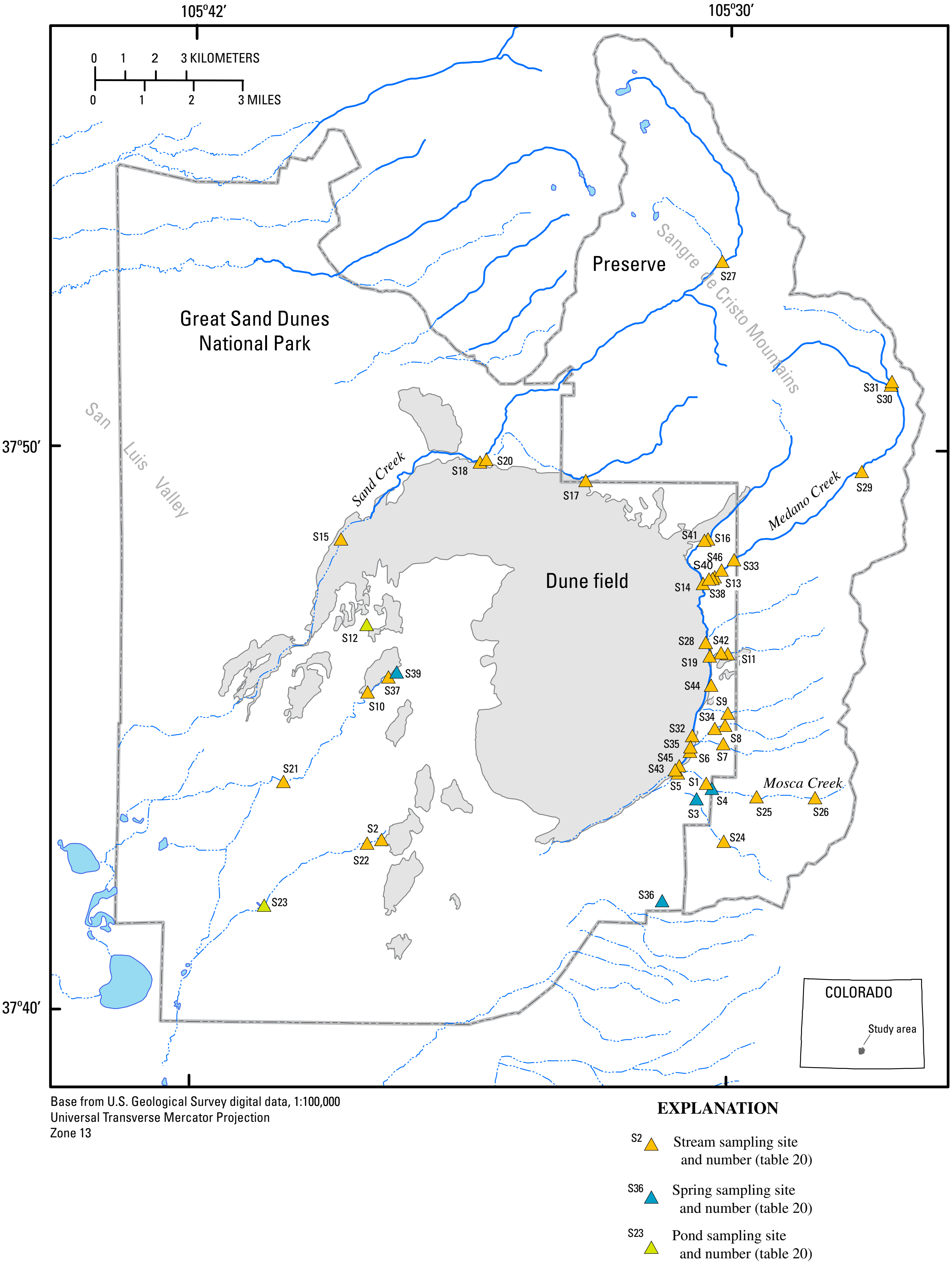
Field properties and major-dissolved constituents for the 46 surface-water sites in GRSA are summarized in table 22. Surface water in GRSA was moderately concentrated and well buffered. Specific conductance ranged from 40 to 725 µS/cm, and alkalinity ranged from 17 to 156 mg/L. The dominant anion in surface-water samples was bicarbonate (based on pH and alkalinity), and the dominant cations were calcium (4.0 to 50 mg/L), magnesium (1.1 to 9.4 mg/L), and sodium (1.0 to 19 mg/L). The predominance of these constituents is attributed to weathering of silicate minerals in the Precambrian bedrock of the Sangre de Cristo Mountains. Other major anions were sulfate, which ranged from 0.6 to 28 mg/L, and chloride, which ranged from 0.17 to 7.2 mg/L. The relatively low chloride concentrations (median 0.79 mg/L) indicate that atmospheric deposition is probably the main source of chloride in surface water. Although considerably less abundant than bicarbonate, sulfate concentrations were slightly higher (median 4.1 mg/L)

Table 20. Surface-water sampling sites in Great Sand Dunes National Park and Preserve, Colorado.

[no., number; ST, stream; SP, spring; LK, lake or pond; Cr, Creek; Colo., Colorado; GRSA, Great Sand Dunes National Monument; identification numbers beginning with GRSA from USEPA STORET all others from USGS NWIS]

Site no. (fig. 17)	Identification no.	Station name	Latitude	Longitude	Type	Period of record
S1	08234200	Mosca Creek near Mosca, Colo.	37° 44’ 05’’	105° 30’ 29’’	ST	[a]1966–70, 76, 90–93, 99–2000
S2	374303105374401	Little Spring Creek near Source	37° 43’ 03’’	105° 37’ 44’’	ST	2001
S3	374348105304001	Morris Gulch Spring at GRSA, Colo.	37° 43’ 48’’	105° 30’ 42’’	SP	[a]1964, 99–2000
S4	374404105302701	Mosca Spring at GRSA, Colo.	37° 44’ 04’’	105° 30’ 29’’	SP	[a]1964, 76, 91, 99–2000
S5	374416105310501	Medano Cr below Mosca Cr at GRSA, Colo.	37° 44’ 16’’	105° 31’ 07’’	ST	[a]1999–2000
S6	374439105304901	Medano Cr below Garden Cr at GRSA, Colo.	37° 44’ 39’’	105° 30’ 51’’	ST	[a]1999–2000
S7	374447105301101	Garden Creek at Boundary at GRSA, Colo.	37° 44’ 47’’	105° 30’ 06’’	ST	1999–2000
S8	374507105300201	Buck Cr at Boundary at GRSA, Colo.	37° 45’ 07’’	105° 30’ 04’’	ST	[a]1999–2000
S9	374520105295801	Sawmill Cany at Boundary GRSA, Colo.	37° 45’ 20’’	105° 30’ 00’’	ST	1999
S10	374540105380201	Big Spring Creek below Indian Spring	37° 45’ 40’’	105° 38’ 04’’	ST	2000–01
S11	374623105295901	Castle Creek at Boundary at GRSA, Colo.	37° 46’ 23’’	105° 30’ 01’’	ST	1999–2000
S12	374652105380401	West Elk Interdunal Pond at GRSA, Colo.	37° 46’ 52’’	105° 38’ 06’’	LK	1999–2000
S13	374745105301701	Medano Creek at GRSA	37° 47’ 45’’	105° 30’ 19’’	ST	1978, 95
S14	374752105300801	Medano Creek near Mosca, Colo.	37° 47’ 52’’	105° 30’ 10’’	ST	[a]1992–96, 99–2001
S15	374823105383901	Sand Creek at Baca Boundary at GRSA, Colo.	37° 48’ 23’’	105° 38’ 41’’	ST	1999–2000
S16	374825105302601	Little Medano Cr at Mouth at GRSA, Colo.	37° 48’ 25’’	105° 30’ 28’’	ST	1999–2000
S17	374927105331101	Cold Cr at Boundary at GRSA, Colo.	37° 49’ 27’’	105° 33’ 13’’	ST	1999–2000
S18	374946105353301	Sand Cr at North Boundary at GRSA, Colo.	37° 49’ 46’’	105° 35’ 35’’	ST	[a]1999–2001
S19	GRSA_BOR_CASTLE	Castle Cr between Park Boundary and Dunes	37° 46’ 23’’	105° 30’ 09’’	ST	1991
S20	GRSA_BOR_SAND	Sand Creek at Jeep Trail Crossing	37° 49’ 48’’	105° 35’ 26’’	ST	1991
S21	GRSA_NURE_02	C29077	37° 44’ 03’’	105° 39’ 56’’	ST	1976
S22	GRSA_NURE_03	C29079	37° 42’ 59’’	105° 38’ 03’’	ST	1976
S23	GRSA_NURE_05	C29083	37° 41’ 52’’	105° 40’ 20’’	LK	1976
S24	GRSA_NURE_13	C29061	37° 43’ 03’’	105° 30’ 04’’	ST	1976
S25	GRSA_NURE_14	C29469	37° 43’ 50’’	105° 29’ 21’’	ST	1976
S26	GRSA_NURE_15	C29470	37° 43’ 50’’	105° 28’ 02’’	ST	1976
S27	GRSA_NURE_16	C29679	37° 53’ 21’’	105° 30’ 11’’	ST	1976
S28	GRSA_NURE_17	C29283	37° 46’ 35’’	105° 30’ 30’’	ST	1976
S29	GRSA_NURE_19	C29654	37° 49’ 37’’	105° 27’ 02’’	ST	1976
S30	GRSA_NURE_20	C29655	37° 51’ 10’’	105° 26’ 23’’	ST	1976
S31	GRSA_NURE_21	C29656	37° 51’ 14’’	105° 26’ 22’’	ST	1976
S32	GRSA_SLV_BEND	Medano Creek at a Large Bend	37° 44’ 55’’	105° 30’ 47’’	ST	1995
S33	GRSA_SLV_BOUND	Medano Creek at Park Boundary	37° 48’ 03’’	105° 29’ 52’’	ST	1995
S34	GRSA_SLV_BUCK	Buck Creek between Boundary and Dunes	37° 45’ 03’’	105° 30’ 17’’	ST	1990–93
S35	GRSA_SLV_CAMPTR	Medano Creek at Campground Trail	37° 44’ 43’’	105° 30’ 50’’	ST	1995
S36	GRSA_SLV_DENSP	Denton Spring	37° 41’ 59’’	105° 31’ 26’’	SP	1976, 91, 93
S37	GRSA_SLV_DRAIN	Drainage Creek above Indian Spring	37° 46’ 02’’	105° 37’ 30’’	ST	1993
S38	GRSA_SLV_FLUME	Medano Creek at Flume	37° 47’ 43’’	105° 30’ 21’’	ST	1995
S39	GRSA_SLV_INDSP	Indian Spring	37° 46’ 00’’	105° 37’ 31’’	SP	1990, 91, 93
S40	GRSA_SLV_LIMED	Little Medano Cr and Medano Cr Confluence	37° 47’ 37’’	105° 30’ 34’’	ST	1995
S41	GRSA_SLV_LITMED	Little Medano Creek	37° 48’ 23’’	105° 30’ 33’’	ST	1990–91
S42	GRSA_SLV_MEDCAS	Medano Creek at Castle Creek	37° 46’ 20’’	105° 30’ 25’’	ST	1990, 92, 93
S43	GRSA_SLV_NBOARD	Medano Creek at North Boardwalk	37° 44’ 23’’	105° 31’ 04’’	ST	1995
S44	GRSA_SLV_SANDPI	Medano Creek at Sand Pit	37° 45’ 49’’	105° 30’ 22’’	ST	1995
S45	GRSA_SLV_SBOARD	Medano Creek at South Boardwalk	37° 44’ 19’’	105° 31’ 10’’	ST	1991, 95
S46	GRSA_SLV_SHOCKY	Medano Creek at Shockey’s Crossing	37° 47’ 42’’	105° 30’ 26’’	ST	1976, 90–91, 95

[a]Sampled 10 or more times during period of record.



Base from U.S. Geological Survey digital data, 1:100,000
Universal Transverse Mercator Projection
Zone 13

Figure 17. Location of surface-water sampling sites in Great Sand Dunes National Park and Preserve, Colorado.

Table 21. Period of record and types of analyses conducted on surface-water samples collected in Great Sand Dunes National Park and Preserve, Colorado.

[value in cell is number of samples analyzed in each category for the year; --, no data]

	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Field properties	2	--	1	15	23	13	14	--	--	--	--	--	15	--	1	--	--	--	--	--	--	--	--	--	--	--	--	10	4	15	13	15	2	--	--	132	70	4	--
Major constituents	2	--	--	1	5	--	--	--	--	--	--	--	--	--	1	--	--	--	--	--	--	--	--	--	--	--	6	10	4	15	13	12	2	--	--	41	35	4	--
Nutrients	2	--	--	1	5	--	--	--	--	--	--	--	--	--	1	--	--	--	--	--	--	--	--	--	--	--	--	10	1	14	12	11	2	--	--	41	33	--	--
Trace elements	2	--	--	--	--	--	--	--	--	--	--	--	15	--	1	--	--	--	--	--	--	--	--	--	--	--	6	10	4	15	12	11	2	--	--	41	35	4	--
Carbon	--	--	--	--	--	--	--	--	--	--	--	--	--	--	1	--	--	--	--	--	--	--	--	--	--	--	--	--	1	6	--	1	--	--	--	--	--	--	--
Microorganisms	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	30	--	--	--	117	49	--	--
Pesticides	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	1	--	--	4	1	--	--	--	--	--	--
Isotopes	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	12	4	--

than chloride indicating geologic as well as atmospheric sources of sulfate.

Spatial variation in selected water-quality constituents at eight surface-water sites in GRSA are shown in figure 18. Sites S18, S16, and S14 are located on larger perennial streams that originate at high elevations (above 3,600 m) in the Sangre de Cristo Mountains. Sites S8 and S1 are on smaller streams on the east side of the park that originate at lower elevations (below 3,000 m) and are intermittent in their upper reaches. Sites S3 and S4 are springs on the east side of the park and site S12 is a shallow interdunal pond on the sand sheet. The median specific conductance at the eight sites ranged from 68 to 279 µS/cm and was lowest for the perennial streams. This reflects greater contributions of dilute snowmelt and surface runoff from high-elevation areas compared to the springs, which are dominated by ground-water discharge. The two intermittent streams (S8 and S1) were similar to the springs indicating they are likely fed by similar ground-water sources. The ratio of major dissolved constituents was similar among all the sites with the exception of the interdunal pond (S12), which had a lower calcium to alkalinity ratio perhaps reflecting a different ground-water source. This explanation is reasonable considering site S12 is the only site located downgradient from the dune field. Median pH at the eight sites ranged from 7.4 to 8.1 and was not notably different among the eight sites except for site S12, which had a wider range of values than the other sites. Median dissolved oxygen concentrations ranged from 7.4 to 13.4 mg/L and, similar to pH, were elevated at site S12 relative to other sites. Because site S12 is a shallow pond, these differences could result from photosynthesis by aquatic vegetation, which produces oxygen and consumes carbon dioxide causing increases in dissolved oxygen concentrations and pH in surface water during the day.

Seasonal variations in selected major-dissolved constituents at Medano Creek (S14) are shown in figure 19. Concentrations were highest during low-flow conditions in winter and then decrease by more than a factor of two in May and June during peak snowmelt. Similar seasonal patterns were observed at other stream (S1, S8, and S18) and spring (S3 and S4) sites although dilution during snowmelt was less pronounced in springs reflecting a greater contribution of ground water. Medano Creek (S14) was the only surface-water site that had sufficient data to test for changes in water quality with time but only for field properties. No statistically significant trends were detected for specific conductance ($p = 0.581$), pH ($p = 0.576$), or dissolved oxygen ($p = 0.311$) at this site during 1992 to 2000.

Nutrients measured in surface-water samples from GRSA include ammonia, nitrate, nitrite, organic nitrogen, orthophosphate, and total phosphorus (table 22). Inorganic nitrogen species were measured at 16 surface-water sites, whereas phosphorus species were measured only at 3 sites. Nitrogen compounds in all samples were low, and most had concentrations below laboratory reporting levels. For example, 34 percent of samples had ammonia concentrations below laboratory reporting levels, 74 percent for nitrate, and 96 percent for

Table 22. Summary of selected water-quality data for surface-water sites in Great Sand Dunes National Park and Preserve, Colorado, 1964 to 2001.

[No. number; chronic aquatic-life (and water-supply) standards from Colorado Department of Public Health and Environment (2003); <, less than; >, greater than; --, not reported; bd, below detection; °C, degrees Celsius; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter at 25 °C; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorous; col/100 mL, colonies per 100 milliliters; µg/L, micrograms per liter; some nutrients and trace elements have multiple reporting limits]

Constituent or property	No. sites	No. analyses (no. censored)	Minimum value	Median value	Maximum value	Aquatic-life (water-supply) standard
		Field properties				
Temperature, water (°C)	29	312	0.0	10.0	31.5	<20
Oxygen, dissolved (mg/L)	16	228	5.7	8.0	18.9	>6.0
pH (standard units)	37	280	6.4	7.8	9.5	6.5–9.0 (5.0–9.0)
Specific conductance (µS/cm)	37	273	40	125	725	--
		Major constituents				
Alkalinity (mg/L as $CaCO_3$)	15	110	17	45	156	--
Calcium, dissolved (mg/L)	27	140	4.0	12	50	--
Chloride, dissolved (mg/L)	12	74	.17	.79	7.2	([a]250)
Fluoride, dissolved (mg/L)	12	50	.1	.2	1.0	--
Magnesium, dissolved (mg/L)	27	140	1.1	3.4	9.4	--
Potassium, dissolved (mg/L)	17	60	.40	.74	16	--
Silica, dissolved (mg/L)	12	56	5.6	12	42	--
Sodium, dissolved (mg/L)	17	66	1.0	2.9	19	--
Sulfate, dissolved (mg/L)	23	126	.6	4.1	28	([a]250)
		Nutrients, carbon, and microorganisms				
Ammonia, dissolved (mg/L as N)	16	109 (37)	<0.002	0.005	0.192	0.02
Nitrate, dissolved (mg/L as N)	16	108 (80)	[b].013	<.05	.13	(10)
Nitrite, dissolved (mg/L as N)	16	109 (105)	<.01	<.01	.01	.05 (1.0)
Organic nitrogen, dissolved (mg/L as N)	2	34 (32)	<.20	<.20	.42	--
Orthophosphate, dissolved (mg/L as P)	3	40 (25)	<.01	<.01	.02	--
Phosphorus, dissolved (mg/L as P)	2	35 (22)	<.01	<.01	.03	--
Organic carbon, dissolved (mg/L)	2	5	1.9	2.8	5.6	--
Fecal coliform (col/100 mL)	9	166 (31)	<1	4.5	2,500	[c]200
Fecal streptococci (col/100 mL)	9	166 (1)	<1	138	17,000	--
		Trace elements				
Arsenic, dissolved (µg/L)	13	19 (12)	bd	0.0	22	[d]50 (10)
Cadmium, dissolved (µg/L)	25	90 (81)	bd	<.5	<2.5	[e]0.2 (5)
Copper, dissolved (µg/L)	25	93 (53)	bd	<1.3	95	[e]4 (1,300)
Iron, dissolved (µg/L)	16	58 (11)	bd	84	270	[d]1,000 ([a]300)
Lead, dissolved (µg/L)	25	93 (91)	bd	<1.0	23	[e]1 (50)
Manganese, dissolved (µg/L)	27	130 (24)	bd	7.8	386	50 ([a]50)
Mercury, dissolved (µg/L)	12	12 (12)	bd	bd	<.20	--
Nickel, dissolved (µg/L)	11	11 (11)	bd	.0	<5.0	[e]25 (100)
Selenium, dissolved (µg/L)	25	93 (81)	bd	<1.0	20	4.6 (50)
Silver, dissolved (µg/L)	24	88 (88)	bd	<.2	<4.0	[e]0.08 ([a]100)
Uranium, dissolved (µg/L)	17	17 (2)	0.42	[b].4	11	[e]592 (30)
Zinc, dissolved (µg/L)	24	90 (56)	bd	<10	44	[e]61 ([a]5,000)

[a] Secondary standard based on aesthetic properties such as taste, odor, and staining.

[b] Minimum reported value less than minimum censored value.

[c] Primary contact recreation.

[d] Total recoverable concentration.

[e] Table value standard calculated for a hardness of 160 mg/L.

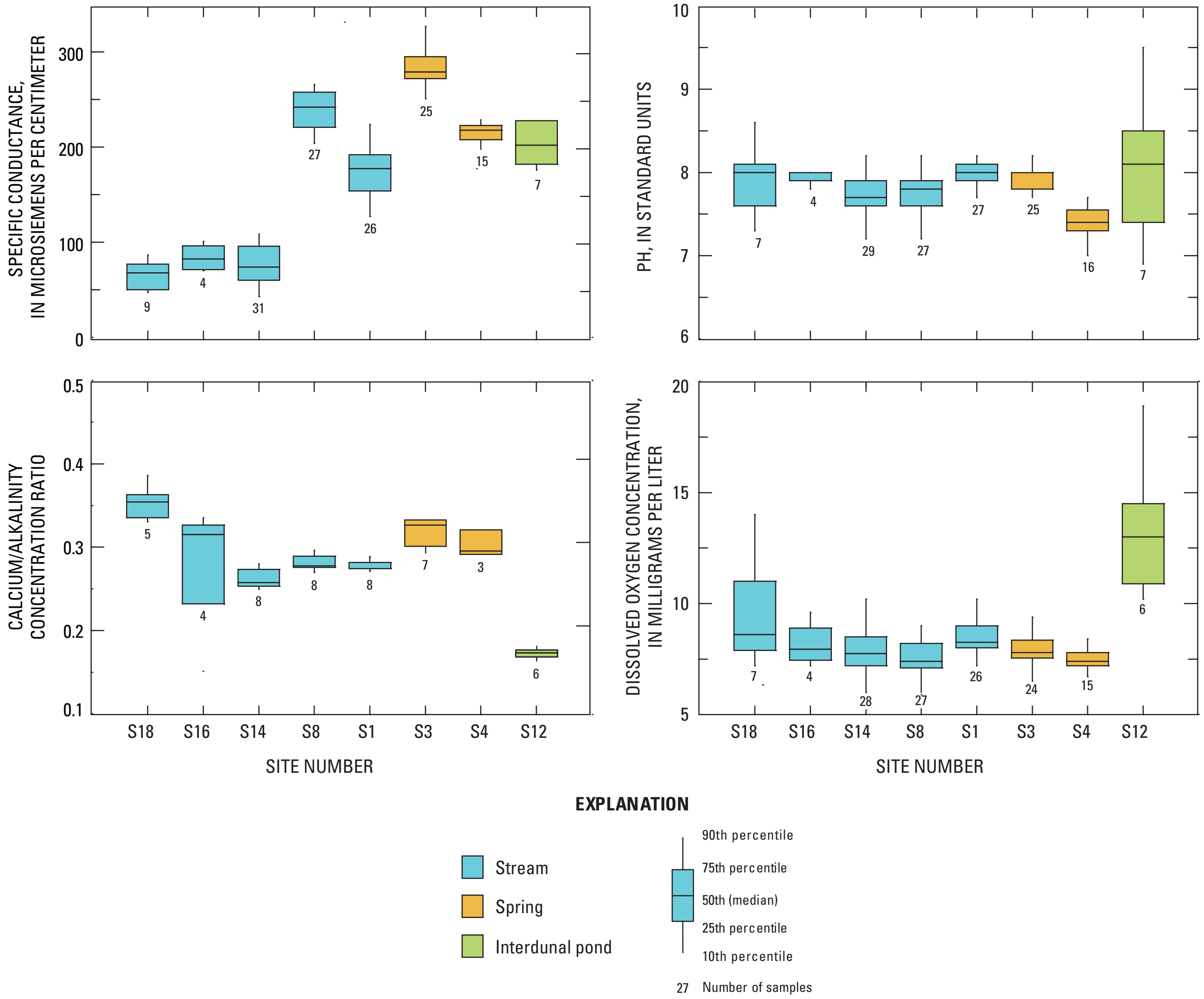


Figure 18. Spatial variation in water quality at selected sites in Great Sand Dunes National Park and Preserve, Colorado.

nitrite. Detected ammonia concentrations were less than 0.05 mg/L except for one sample collected at a shallow interdunal pond (S12), which had a concentration of 0.192 mg/L. Detected concentrations of nitrate ranged from 0.013 to 0.13 mg/L and were elevated during winter months (0.07 to 0.13 mg/L) relative to summer months (0.02 to 0.07 mg/L) likely because of greater ground-water inputs combined with lower biological demand. The major source of inorganic nitrogen to streams in GRSA is atmospheric deposition (Burns, 2004), which originates from fossil fuel combustion and agriculture. Low nitrate concentrations at the stream sites, which are all at lower elevations of the park, indicate most atmospherically deposited nitrogen is retained by soils and vegetation. A recent study of several high-elevation lakes in GRSA, however, showed elevated nitrate concentrations (up to 0.3 mg/L) during the growing season (Nanus, 2005). These results may indicate that nitrogen deposition is exceeding biological uptake and that high-elevation areas in the park may be in the early stages of nitrogen saturation (Burns, 2004). Orthophosphate and total phosphorous concentrations also were low with 72 percent of samples below the reporting levels, and all detected concentrations less than or equal to 0.03 mg/L.

Dissolved concentrations of 12 trace elements for sites with four or more samples are summarized in table 22. Most concentrations were less than laboratory reporting levels and only iron (78 percent) and manganese (33 percent) had a substantial number of detected concentrations above 10 µg/L. Detected iron concentrations ranged from 7 to 270 µg/L, and were highest in Medano Creek (51 to 250 µg/L). High dissolved iron in Medano Creek was somewhat unexpected given

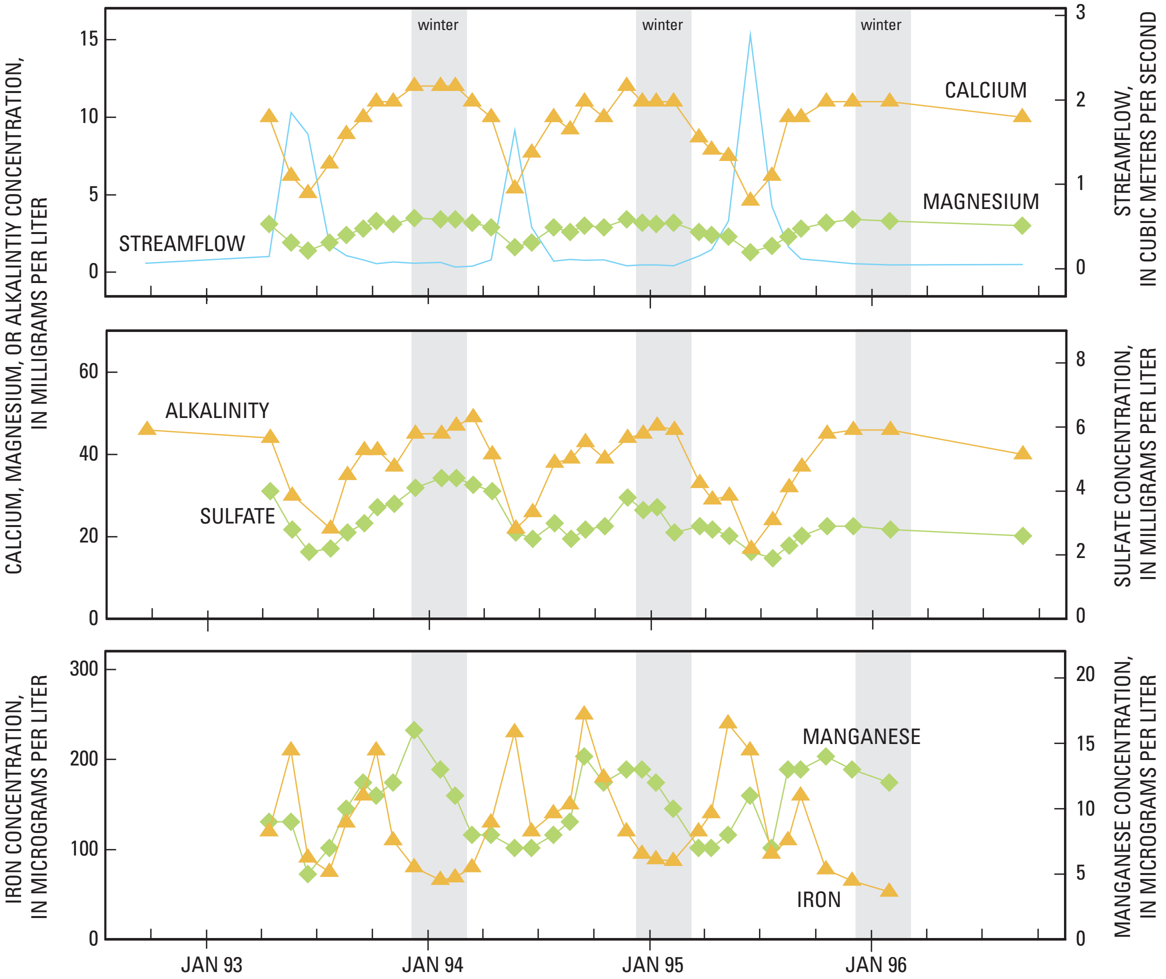


Figure 19. Seasonal variation in selected constituent concentrations at Medano Creek near Mosca (S14) in Great Sand Dunes National Park and Preserve, Colorado.

that stream pH is neutral, which indicates that some colloidal iron is not removed by sample filtration. Detected manganese concentrations ranged from 1.8 to 386 µg/L and were highest in Buck Creek (7 to 386 µg/L). The source of manganese may be mineralized quartz veins that occur throughout the Sangre de Cristo Mountains. These veins were prospected for gold, lead, and zinc in the late 1880s and there are several prospect pits located in the southern part of the park (Chatman and others, 1997). Seasonal patterns for iron and manganese at Medano Creek (S14) are shown in figure 19. Iron showed a strong seasonal pattern with concentrations peaking during snowmelt and again in early fall. Higher concentrations during runoff could be related to increased colloidal iron in the stream during snowmelt or flushing of organically-complexed iron from soils. The reason for the peak in iron concentrations during fall is unclear. In contrast to iron, manganese concentrations were lowest during snowmelt and peaked during baseflow conditions in winter, indicating manganese is related to inputs of ground water to streamflow.

Other constituents measured in surface-water samples collected in GRSA include dissolved organic carbon (1.9 to 5.6 mg/L), fecal coliform (less than 1 to 2,500 col/100 mL) and fecal streptococci (less than 1 to 17,000 col/100 mL). Fecal coliform and fecal streptococci are considered indicator bacteria for the presence of fecal contamination because they are present in large numbers in the feces and intestinal tracts of humans and other warm-blooded animals. Fecal coliform and total coliform were measured seasonally at nine sites in GRSA during 1999 and 2000. The highest concentrations of fecal coliform were measured in Medano Creek (S5), which had a median concentration of 420 col/100 mL. The higher concentrations relative to other sampling sites in the park may be related to visitor use as most park facilities are located in the vicinity of Medano Creek. In addition, wading in the lower reaches of Medano Creek is a popular activity of park visitors during the summer months. Fecal streptococci were substantially higher in Morris Gulch Spring (S3) and Mosca Spring (S4) than the other seven sites, and indicated a strong seasonal pattern with peak concentrations in June and July (1,100 to 17,000 col/100 mL). Despite elevated fecal streptococci counts, the fecal coliform counts at these two sites were low (less than 1 to 66 col/100 mL). Fecal streptococci are sometimes used as an indicator of nonhuman fecal contamination, the increased concentrations may be caused by wildlife that use the springs as a source of drinking water.

Comparison to Water-Quality Standards. Water-quality use classifications and standards for all stream segments in Colorado are established by the Colorado Water Quality Control Commission (Colorado Department of Public Health and Environment, 2003). Standards for the Closed Basin-San Luis Valley (segment 10), which includes Sand Creek and Medano Creek and all tributaries and wetlands, from the source to the mouth, are listed in table 22. None of the reaches within this segment were listed in 2006 as impaired for water quality (*http://www.cdphe.state.co.us/op/wqcc/SpecialTopics/303(d)/303dtmdlpro.html*, accessed July 2006). The designated uses for this segment are cold-water aquatic life class 1, recreation 1a, agriculture, and water supply. Streams designated for cold-water aquatic life class 1 (the most sensitive use) should have temperatures less than 20 °C, dissolved oxygen greater than 6.0 mg/L (7.0 mg/L during spawning), and pH values ranging from 6.5 to 9.0. For surface-water samples in GRSA, 296 of 312 temperature measurements were below the 20 °C standard, 223 of 228 dissolved oxygen measurements were above the 6.0 mg/L standard, and 277 of 280 pH values were within the 6.5 to 9.0 range. Most of the sites that exceeded the 20 °C temperature standard are on the edge of the dune field where temperatures on the sand surface can reach 60 °C during hot summer days (Chatman and others, 1997). The six dissolved oxygen measurements below 6.0 mg/L were made in summer at sites along the edge of the dune field where water temperatures commonly exceed 20 °C. The three pH values that were outside the standard range were measured at Denton Spring (S36; pH 6.4), Indian Spring (S39; pH 9.1), and West Elk interdunal pond (S12; pH 9.5). The instream standard for fecal coliform is 200 col/100 mL for recreation class 1a, which was exceeded in 10 of 166 measurements. Most of the exceedances were samples collected from Medano Creek during the summer months (June–August). All park facilities, campgrounds, and picnic grounds are located along the lower reach of Medano Creek. Ammonia was the only nutrient species that exceeded the aquatic-life standard (0.02 mg/L). The highest concentration (0.192 mg/L) was measured at a shallow interdunal pond (S12). Exceedances in other samples ranged from 0.02 to 0.05 mg/L. Of the trace elements there were a few exceedances for copper (3 of 93), lead (1 of 93), selenium (5 of 93), and manganese (11 of 130). The manganese exceedances were limited to three sites: Buck Creek (S8), a shallow interdunal pond (S12), and Indian Spring (S39). As mentioned previously, elevated manganese, particularly in Buck Creek, may be related to mineralized veins in the Sangre de Cristo Mountains. Elevated manganese at the interdunal pond and Indian Spring site is more likely caused by reductive dissolution of aquifer materials as both of these sites are fed by ground water discharging downgradient from the dune field.

GRSA is pursuing “Outstanding Natural Waters” designation for several surface-water segments in the park, which would provide the highest level of regulatory protection provided under the Clean Water Act and Colorado regulations. To quality for this designation, water bodies must have exceptional recreational or ecological significance unmodified by human activities, and existing water quality must meet specified standards for 12 properties and constituents (pH, dissolved oxygen, *E. coli* bacteria, nitrate, ammonia, cadmium, copper, lead, manganese, selenium, silver, and zinc) (Colorado Department of Public Health and Environment, 2006). The regulations state that the 85th percentile of existing water-quality data shall not exceed State criteria for ammonia, nitrate, and dissolved metals, the 50th percentile for total recoverable metals, the 15th percentile for dissolved oxygen, the geometric mean for *E. coli*, and the range between the 15th and 85th percentiles for pH. Data collected by the USGS in 1999 and 2000 to describe baseline conditions indicate that surface water in the park meets water-quality criteria for determining Outstanding Waters Designation (Ferguson, 2003).

Ground-Water Quality

Water-quality results for 20 samples collected at 20 ground-water wells (table 23, fig. 15) within the boundaries of GRSA between 1946 and 2000 are summarized in table 24. Sites G3 and G10 were sampled for specific conductance in 1946; sites G1, G2, and G6 were sampled for major constituents in 1968; and G4 and G5 were sampled for major constituents and nutrients in 1980. The most complete data set is for 13 wells (G8–G9, G11–G20) sampled by the USGS in 2000 as part of a study to determine ground-water flow direction, water quality, recharge sources, and age in GRSA. These samples were analyzed for major constituents, organic carbon, chlorofluorocarbons, and isotopes of hydrogen, oxygen, and carbon. The results of this ground-water study, which are summarized below, are published in Rupert and Plummer (2004). The water quality of the unconfined aquifer was dominated by calcium, sodium, and bicarbonate. Specific conductance ranged from 69 to 333 µS/cm, and alkalinity ranged from 27 to 125 mg/L. As ground water traveled under the dune field through the unconfined aquifer, the percentage of calcium decreased and the percentage of sodium increased because of cation exchange with clays. Water quality of the confined aquifer was similar, except that magnesium and dissolved oxygen were depleted relative to concentrations in the unconfined aquifer. Age dating of the ground water indicates it takes more than 60 years for water in the unconfined aquifer to flow from the mountain front to the western edge of the dune field. Ground water in the deeper confined aquifer was estimated to be approximately 30,000 years old. Insufficient data exist to quantify the hydrologic connection between the unconfined and confined aquifers. Available data for ground-water wells are insufficient to describe seasonal patterns or temporal trends in water quality because

Table 23. Ground-water sampling sites in Great Sand Dunes National Park and Preserve, Colorado.

[no., number; well depth in meters; identification numbers and station names from USGS NWIS]

Site no. (fig. 15)	Identification no.	Station name	Latitude	Longitude	Well depth	Period of record
G1	373915105414501	NA04001232CCC1	37° 39’ 48”	105° 41’ 27”	17.1	1968
G2	373915105414502	NA04001232CCC2	37° 39’ 48”	105° 41’ 27”	3.4	1968
G3	373953105412301	NA04001121CC	37° 39’ 52”	105° 41’ 25”	14.6	1946
G4	374012105410401	NA04001232BAA	37° 40’ 12”	105° 41’ 06”	9.1	1980
G5	374040105392001	NA04001233AAA1	37° 40’ 40”	105° 39’ 21”	11.9	1980
G6	374345105321001	SC02707334DD	37° 43’ 45”	105° 32’ 12”	107	1968
G7	374407105360401	SC04001212AAA	37° 44’ 07”	105° 36’ 06”	3.1	2000
G8	374410105312701	SC02707303ABB	37° 44’ 09”	105° 31’ 28”	4.0	2000
G9	374414105310201	SC02607334DDC	37° 44’ 13”	105° 31’ 04”	107	2000
G10	374431105431101	NA04001101CA	37° 44’ 30”	105° 43’ 13”	15.6	1946
G11	374557105372901	SC04101235ABB2	37° 45’ 56”	105° 37’ 31”	107	2000
G12	374558105372801	SC04101235ABB1	37° 45’ 57”	105° 37’ 30”	23.0	2000
G13	374605105372301	SC04101226DCD	37° 46’ 05”	105° 37’ 24”	4.0	2000
G14	374655105365901	SC04101223DDD	37° 46’ 54”	105° 37’ 01”	8.0	2000
G15	374657105375401	SC04101223CCD1	37° 46’ 56”	105° 37’ 55”	23.0	2000
G16	374657105375402	SC04101223CCD2	37° 46’ 56”	105° 37’ 55”	3.5	2000
G17	374746105385201	SC04101215CDC	37° 47’ 45”	105° 38’ 53”	32.0	2000
G18	374746105385202	SC04101215CDC1	37° 47’ 45”	105° 38’ 53”	9.5	2000
G19	374746105385203	SC04101215CDC2	37° 47’ 45”	105° 38’ 53”	120	2000
G20	374954105355101	SC02501236ADD	37° 49’ 54”	105° 35’ 53”	12.0	2000

none of the wells in GRSA have been sampled more than once during the period of record. The water quality of the 20 wells was compared to water-supply standards established by the CDPHE (Colorado Department of Public Health and Environment, 2006), although none of these wells are used for water supply. For the reported constituents, the pH of one sample was just above the water supply standard and one sample (G13) exceeded the secondary drinking-water standards for iron and manganese. Elevated iron and manganese concentrations in ground water can be caused by reductive dissolution of oxide minerals present in the aquifer sediments when the dissolved oxygen concentration becomes depleted.

Summary and Suggestions for Vital Signs Monitoring

Review of historical records identified 387 water-quality samples collected at 46 surface-water sites in GRSA from 1964 to 2001. The majority of results for these 387 samples were field properties (29 percent), and major-constituent (21 percent), nutrient (9 percent), and trace-element (12 percent) analyses. Surface-water sites typically were sampled 1 to 3 times each during the period of record, although there were eight sites that were sampled 10 or more times. Streamflow-gaging stations have been operated at the two primary perennial streams, Medano Creek and Sand Creek, since 1992. Surface water is a calcium-bicarbonate type and dissolved solids primarily are derived from weathering of crystalline bedrock in the Sangre De Cristo Mountains. Visitor use and park facilities likely have a minimal effect on water quality, except perhaps in the lower reaches of Medano Creek. Preliminary data indicate that lakes at high elevations in the park may be in early stages of nitrogen saturation because of atmospheric nitrogen deposition. Sufficient data were available to test for temporal trends in water quality only for field properties at one site, which showed no trends. The designated uses for this segment are cold-water aquatic life class 1, recreation 1a, agriculture, and water supply. Available water-quality data indicate most surface-water sites meet Colorado water-quality standards for Outstanding Natural Waters designation, which the NPS is pursuing for streams in GRSA. Twenty water-quality samples have been collected at 20 ground-water wells in the park from 1946 to 2000. Most of these samples were collected in 2000 by the USGS as part of a study to determine ground-water flow direction, water quality, recharge sources, and age in GRSA.

Table 24. Summary of selected water-quality data for ground-water sites in Great Sand Dunes National Park and Preserve, 1946 to 2000.

[no., number; water-supply standards published by Colorado Department of Public Health and Environment (2006); <, less than; --, not reported; °C, degrees Celsius; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter at 25 °C; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorous; µg/L, micrograms per liter]

Constituent or property	No. sites	No. analyses (no. censored)	Minimum value	Median value	Maximum value	Water-supply standard
Field properties						
Temperature, water (°C)	6	6	9.5	11.7	14.5	--
Oxygen, dissolved (mg/L)	13	13	0.2	4.1	7.4	--
pH (standard units)	17	17	6.5	7.7	9.1	5.0–9.0
Specific conductance (µS/cm)	20	20	68	156	499	--
Major constituents						
Alkalinity (mg/L as $CaCO_3$)	17	17	28	64	213	--
Calcium, dissolved (mg/L)	17	17	2.4	15	40	--
Chloride, dissolved (mg/L)	17	17	.44	1.3	11	[a]250
Fluoride, dissolved (mg/L)	17	17	.00	.43	1.4	2.0
Magnesium, dissolved (mg/L)	17	17	.39	2.7	8.6	--
Potassium, dissolved (mg/L)	17	17	.70	4.6	18	--
Silica, dissolved (mg/L)	17	17	13	40	69	--
Sodium, dissolved (mg/L)	17	17	1.9	11	84	--
Sulfate, dissolved (mg/L)	17	17	.44	5.3	53	[a]250
Other constituents						
Nitrate, dissolved (mg/L as N)	2	2	0.09	--	0.40	10
Nitrogen, total (mg/L as N)	2	2	.46	--	.74	--
Phosphorus, total (mg/L as P)	2	2	.05	--	.13	--
Carbon, organic (mg/L)	13	13 (3)	<.15	0.45	5.2	--
Iron, dissolved (µg/L)	15	15 (10)	<10	<10	3,365	[a]300
Manganese, dissolved (µg/L)	15	15 (7)	[b]1.8	<3.2	116	[a]50

[a] Secondary standard based on aesthetic properties such as taste, odor, and staining.

[b] Minimum reported value less than minimum censored value.

Water-quality issues for the park include effects of visitor use and atmospheric deposition of contaminants, maintenance of potable water supplies, and attainment of Outstanding Natural Waters designation. The primary threats to water resources in the park are surface- and ground-water withdrawals and long-term climate changes. Based on a review of the historical data, the following suggestions are provided for consideration in designing a water-quality monitoring plan for GRSA.

- Establish a long-term water-quality monitoring station or "sentinel site" on Medano Creek at the streamflow-gaging station. Monitor for core field properties, major constituents, and nutrients during different hydrologic conditions.
- Monitor the lower reaches of Medano Creek for bacterial indicators during the summer tourist season.
- Periodically conduct water-quality surveys of high-elevation lakes and streams in the park to monitor the effects of deposition of atmospheric contanimants.
- Additional surface-water sites, including ground-water springs, could be sampled periodically to address special issues or to achieve a better understanding of the factors controlling water quality.
- Maintain the existing network of streamflow-gaging stations and ground-water wells for monitoring the effects of human stressors on water resources.

Little Bighorn Battlefield National Monument

Environmental Setting

The Little Big Horn Battlefield National Monument (LIBI) is located within the Little Bighorn River Valley in south-central Montana near the town of Crow Agency (fig. 20). The monument covers 3.08 km^2, ranges in elevation from 933 to 1,050 m, and sits on terraces above the floodplain of the Little Bighorn River. Only a small area (approximately 0.20 km^2) along the western boundary of the monument extends into the floodplain of the river. The landscape is characterized by rolling hills covered by grasslands (74 percent) and shrublands (11 percent) interspersed with pockets of coniferous trees (10 percent) (Britten and others, 2006). The dominant grasses are bluebunch wheatgrass and blue grama-needlegrass, and the main shrubs are hawthorn, chokeberry, silver sage, and big sagebrush. Climate is typical of colder short-grass prairies. Mean monthly air temperatures at Crow Agency range from -6.8 °C in January to 22.2 °C in July (*http://www.wrcc.dri.edu/summary/climsmmt.html*, accessed June 2006). Average annual precipitation is 39 cm; May (6.1 cm) and June (6.0 cm) are the wettest months. The area receives about 105 cm of snowfall each year between October and April.

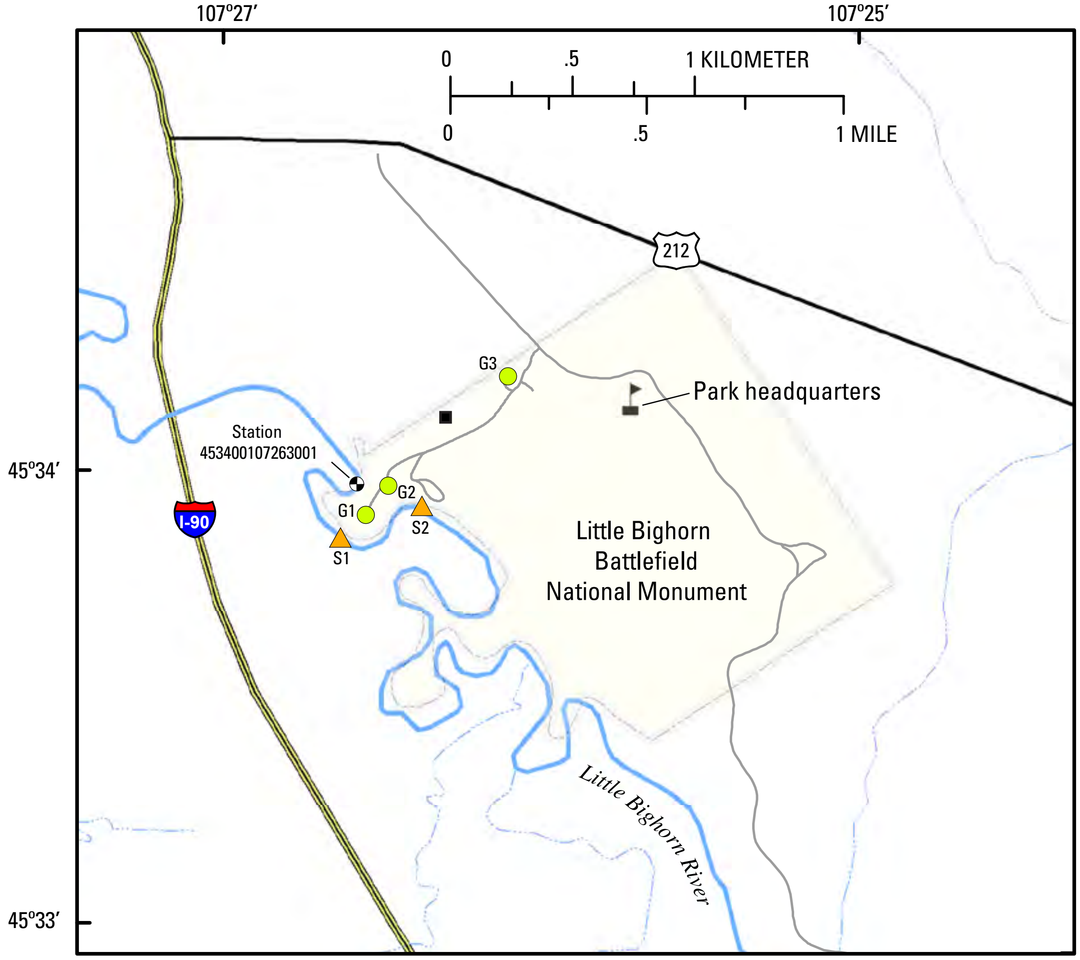
LIBI is underlain by Upper Cretaceous sedimentary rocks of the Judith River Formation and Bearpaw Shale. The Judith River Formation is fine-grained sandstone interbedded with shales and forms an important aquifer in the area (Tuck, 2003). The Bearpaw Shale is a dark grey fossiliferous shale that is nearly impermeable with respect to ground water. Along the floodplain, the Cretaceous sediments are covered by Quaternary alluvium, which is composed of unconsolidated gravel, sand, silt, and clay. The alluvium, which typically is less than 9 m thick, forms the principal aquifer in the Little Bighorn River Basin (Tuck, 2003).

Land-use activities in LIBI are related to visitor use (nearly 400,000 visitors per year), which peaks in July and August (Britten and others, 2006). The monument has a visitor center, several administrative buildings and residences, numerous cultural features, three trails, and 15 km of roads. A shallow alluvial well adjacent to the Little Bighorn River is the primary water supply for the monument. The water supply is tested regularly for fecal indicators, nitrogen species, and organic compounds according to water-supply regulations mandated by the MTDEQ; results of the tests are available at *http://www.deq.state.mt.us/wqinfo/pws/reports.asp* (accessed June 2006). Wastewater for the park is handled by a septic system. Land surrounding the monument is within the Crow Indian Reservation. The primary land use in the reservation is irrigated agriculture along the valley floor for cultivation of alfalfa, pasture grass, corn, and sugar beets (Tuck, 2003). The higher terraces and foothill areas primarily are used as rangeland for cattle. Effects of these agricultural activities on nutrient, bacteria, and sediment are the main water-quality issues for the Little Bighorn River.

Water Resources

LIBI is situated along the lower reaches of the Little Bighorn River (fig. 20), which drains an area of about 3,370 km^2. The river originates in the Bighorn Mountains in Wyoming, and drains north for about 130 km through foothills and a broad alluvial valley. Lodge Grass and Pass Creeks are the main perennial tributaries, and Owl and Reno Creeks are the largest ephemeral tributaries. LIBI is bounded on the west by the Little Bighorn River, but there are no perennial or ephemeral streams flowing through the monument. The Little Bighorn River is an important source of water for irrigation in the valley, and as a water supply for LIBI and the town of Crow Agency. The USGS has operated as many as 17 streamflow-gaging stations in the Little Bighorn River Basin (*http://mt.water.usgs.gov/pub/MTStations.pdf*, accessed June 2006); however, only 4 of these stations were active in 2006. The NPS operates a streamflow-gaging station on the Little Bighorn River (station 453400107263001) along the western edge of the monument (fig. 20). This gage, which started operation in November 1999, is maintained by the NPS as part of a Federal water-rights agreement. The range of daily streamflow values at station 453400107263001 from 1999–2005 is shown by month in figure 21. The streamflow pattern shows that discharge peaks in May and June during snowmelt. Intense rainstorms and saturated or frozen soils are additional factors contributing to increased runoff during the spring. Streamflow decreases rapidly through July and is lowest in August and September because of low precipitation rates and high evapotranspiration rates. During summer months, water also is diverted from the river for irrigation.

An excellent description of ground-water hydrology in the Little Bighorn River Basin is presented by Tuck (2003) from which the following discussion is summarized. Quaternary alluvium and the Cretaceous Judith River Formation compose the two main aquifers in the basin and the primary water source for domestic and stock supplies. The alluvial aquifer, which is limited to areas adjacent to the river and major tributaries, is composed of unconsolidated alluvial deposits that have moderate to low permeability. Recharge to the alluvium is by infiltration of precipitation primarily during fall before the ground freezes and in early spring when evapotranspiration is minimal. Other sources of recharge include inflow from the underlying Judith River Formation, canal leakage, excess irrigation water, bank storage, and inflow from ephemeral tributaries. The direction of ground-water flow generally is from the valley margins, where it is recharged, towards the Little Bighorn River, where it discharges into the river contributing as much as 18 percent of the annual daily mean streamflow. The fine-grained sediment comprosing the Judith River aquifer results in lower permeability than the overlying alluvial aquifer. Recharge to the Judith River aquifer primarily is by infiltration of precipitation with additional inputs from infiltration of streamflow across outcrops, canal leakage, and bank storage. The direction of ground-water



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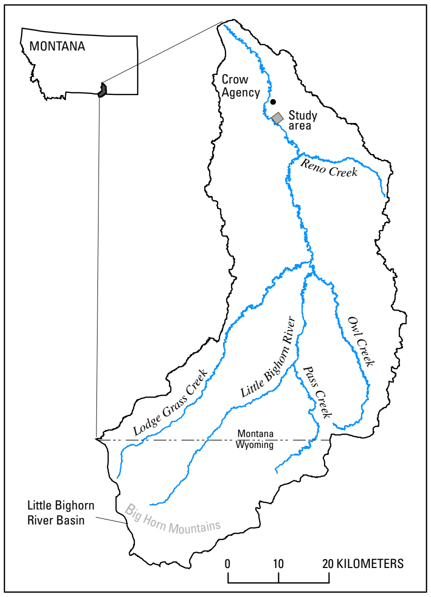


Photograph of Little Bighorn Battlefield National Monument
by W. Schweiger, National Park Service

Figure 20. Location of water-quality sampling sites near Little Bighorn Battlefield National Monument, Montana.

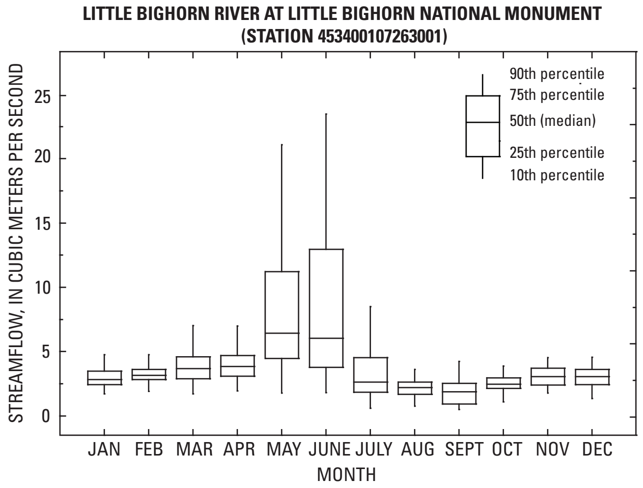


Figure 21. Daily streamflow range at Little Bighorn River (station 453400107263001) in Little Bighorn National Battlefield Monument, Montana, 1999–2005.

flow is from outcrop areas west of the river towards the Little Bighorn River, where it discharges to the alluvial aquifer and directly to the river.

Water levels in 32 ground-water wells in the basin were measured monthly to bimonthly by the USGS during 1994 to 1995 to document seasonal changes in water levels (Tuck, 2003). Water-level data for these wells are available from the USGS NWIS web interface at *http://nwis.waterdata.usgs.gov/usa/nwis/gwlevels* (accessed June 2006). Annual water-level measurements were made by USGS at one well in LIBI (G3, fig. 20) from 1977 to 1999 as part of a state-wide ground-water monitoring network. The hydrograph for this well shows that ground-water levels were highest in the early part of the record because of above average precipitation during most of the 1970s (fig. 22).

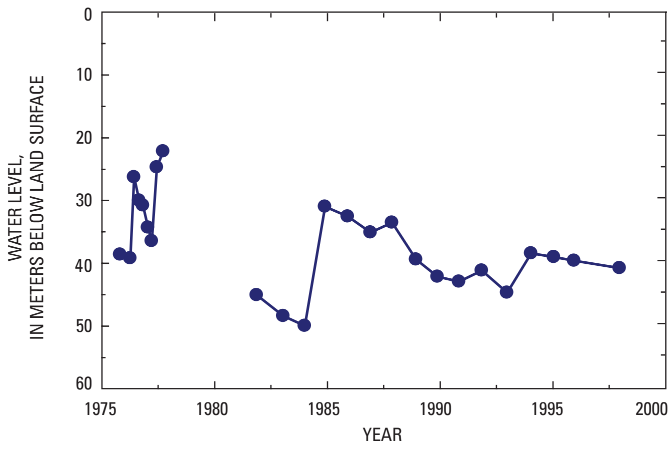


Figure 22. Ground-water level measurements at site G3 in Little Bighorn National Battlefield Monument, Montana.

The park also has a NADP station (fig. 20), which has been operated jointly by the USGS and NPS since 1984. The NADP is a national network of precipitation monitoring sites that measures weekly precipitation chemistry and precipitation amount; data for the network are available at *http://nadp.sws.uiuc.edu/* (accessed June 2006). The site at LIBI was established to represent atmospheric deposition in shortgrass prairie ecosystems.

Surface-Water Quality

LIBI is bounded on the west by the Little Bighorn River, but there are no perennial or ephemeral streams originating within the park. The only surface-water stations in LIBI are sites S1 and S2 both of which are on the Little Bighorn River adjacent to the west boundary of the monument (fig. 20). There were four water-quality samples collected at site S1 during 1999 and 2000 that were analyzed for field properties, major constituents, nutrients, trace elements, and suspended sediment. These samples were collected by the USGS for the NPS and analyzed at the USGS National Water Quality Laboratory (*http://nwql.usgs.gov/,* accessed June 2006). Site S2 was sampled in 1977 by the USGS and analyzed at the Montana Bureau of Mines and Geology analytical laboratory (*http://www.mbmg.mtech.edu/analytical.htm*, accessed June 2006).

Water-quality data for the two sampling sites on the Little Bighorn River adjacent to the monument are summarized in table 26. Surface water was fairly concentrated and well buffered; specific conductance ranged from 489 to 786 µS/cm, and alkalinity ranged from 155 to 241 mg/L. Calcium was the dominant cation, and bicarbonate (based on alkalinity and pH) and sulfate were the dominant anions. These dissolved constituents are likely derived from weathering of carbonate minerals and gypsum in the marine sedimentary rocks that are common in the area (Vuke and others, 2000). Of the five samples, major-constituent concentrations generally were highest on March 22, 2000, which probably reflects a greater contribution of ground water to the river during low-flow conditions before spring runoff. Nutrient concentrations were low and close to laboratory reporting levels in all five samples except for the sample collected on May 19, 2000. Because this sample was collected during increased streamflow conditions (1,970 ft^3/s), the elevated nitrogen concentrations may be caused by runoff from agricultural areas upstream from the sampling site. The high total phosphorus concentration (1.97 mg/L) in this sample probably is related to the elevated suspended-sediment concentration (2,662 mg/L) because erosion can transport considerable amounts of suspended phosphorus to surface waters (Mueller and others, 1995). Dissolved trace-element concentrations were less than 20 µg/L in all five samples. Low trace-element concentrations reflect neutral stream-water pH values (range 7.7 to 8.5) and the lack of urban and mining areas upstream from the sampling sites. Neither surface-water site had a sufficient period of record to test for changes in water quality with time.

Table 25. Water-quality sampling sites near Little Bighorn Battlefield National Monument, Montana.

[no., number; Well depth in meters; --, no data; ST, stream; GW, ground water; AL, alluvial; JR; Judith River; identification numbers and station names from NWIS]

Site no. (fig. 20)	Identification number	Station name	Latitude	Longitude	Type	Well depth	Aquifer
S1	453350107263301	Little Bighorn River near Bighorn Battlefield	45° 33’ 50”	107° 26’ 33”	ST	--	--
S2	453355107261801	Little Bighorn River	45° 33’ 55”	107° 26’ 18”	ST	--	--
G1	453354107262801	03S35E18DCCB01	45° 33’ 54”	107° 26’ 28”	GW	3	AL
G2	453358107262401	03S35E18DCBD01	45° 33’ 58”	107° 26’ 24”	GW	37	JR
G3	453413107260201	03S35E18DABD01	45° 34’ 13”	107° 26’ 02”	GW	122	JR

Comparison to Water-Quality Standards. Water-use classifications and water-quality standards for all stream segments in Montana are established by the MTDEQ (*http://www.deq.state.mt.us/wqinfo/Standards/Index.asp*, accessed June 2006). The Little Bighorn River and tributaries below Grass Creek are classified as B-2, which is surface water suitable for domestic water supply, recreation, aquatic life (salmonid fishes), and agricultural and industrial water supply. No stream reaches in this segment are on the most recent (2006) 303(d) list for the State of Montana (*http://www.deq.state.mt.us/wqinfo/*, accessed June 2006). Aquatic-life and human-health standards established by the State of Montana for surface waters are listed in table 26. The sample collected on May 19, 2000, had constituent concentrations that exceeded trace-element standards for total cadmium, copper, iron, and lead. Concentrations of total trace elements were elevated in this sample likely because it was collected during a period of elevated sediment transport.

Ground-Water Quality

Water-quality data are available for six samples collected at three ground-water wells in LIBI (fig. 20) that were analyzed for field properties, major constituents, nutrients, trace elements, and pesticides. Site G1 is a shallow well located in the alluvial aquifer in the floodplain of the Little Bighorn River. Sites G2 and G3 are deeper wells that penetrate into the Cretaceous Judith River Formation. All three wells were sampled in 1977 by the USGS as part of a state-wide ground-water study conducted by the Montana Bureau of Mines and Geology (*http://www.mbmg.mtech.edu/*, accessed June 2006). The USGS also sampled site G1 in 1999 and 2000 and site G2 in 1945.

The water-quality results for samples collected at ground-water wells within the boundaries of LIBI are summarized in table 27. All of the samples had elevated concentrations of dissolved constituents with dissolved solids greater than 800 mg/L. Sodium was the dominant cation, and alkalinity and sulfate were the dominant anions. Elevated dissolved solids result from weathering of salts and soluble minerals in marine shales that underlie the drainage basin (Vuke and others, 2000). Comparison of major constituents in ground water at the three well sites indicates that dissolved solid concentrations increase with well depth, primarily because of increasing sodium and sulfate concentrations (fig. 23). A possible explanation for the observed change in ground-water quality is that calcium, released from dissolution of gypsum, is progressively exchanged for sodium on clays in the marine shale as ground water moves downgradient through the aquifer.

Despite elevated dissolved solids, concentrations of other constituents in the six ground-water samples generally were quite low. Nutrient concentrations were low in all the ground-water samples (table 27). Nitrate concentrations were well below the 2 mg/L background level defined for ground water by Mueller and Helsel (1996). These low nutrient concentrations indicate that rangeland and agricultural lands adjacent to the monument did not appear to be affecting nutrient levels in the LIBI wells at the time of sampling. Of the eight trace elements measured in ground water, only iron, lithium, and manganese were detected at concentrations above 10 μg/L. Elevated iron and manganese concentrations in ground water can be caused by reductive dissolution of oxide minerals present in aquifer materials. Lithium concentration tended to increase with well depth similar to sodium, indicating that lithium may be released by cation exchange with clays in the marine shales. Concentrations of the pesticides and organochlorine compounds measured at site G1 on May 18, 2000, were all below the laboratory reporting levels for these compounds. None of the wells in LIBI had a sufficient period of record to test for changes in ground-water quality with time.

Comparison to Water-Quality Standards. Although wells in LIBI are not used for water supply, they were compared to human-health standards established by the MTDEQ (*http://www.deq.state.mt.us/wqinfo/Standards/Index.asp*, accessed June 2006). None of the wells had constituent concentrations that exceeded the human-health standards, although four samples exceeded the secondary manganese standard of 50 μg/L, and three exceeded the secondary iron standard of 300 μg/L. Secondary standards are based on aesthetic properties such as taste, odor, and staining. Elevated iron and manganese concentrations can affect the taste of drinking water and cause staining and scaling of plumbing systems. All of the wells also exceeded the USEPA secondary drinking-water standard for sulfate (250 mg/L) and dissolved solids (500 mg/L).

Table 26. Summary of selected water-quality data for the Little Bighorn River adjacent to Little Bighorn Battlefield National Monument, Montana.

[chronic aquatic-life and human-health standards from *www.deq.state.mt.us/wqinfo/Standards/Index.asp*; <, less than; >, greater than; --, not reported; ft^3/s, cubic feet per second; °C, degrees Celsius; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter at 25 °C; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorous; µg/L, micrograms per liter]

Constituent or property	S1 (fig. 20) 7/21/1999	S1 (fig. 20) 9/1/1999	S1 (fig. 20) 3/22/2000	S1 (fig. 20) 5/19/2000	S2 (fig. 20) 6/28/1977	Aquatic-life (human-health) standards
Field properties						
Discharge, instantaneous (ft^3/s)	148	109	144	1,970	--	--
Temperature, water (°C)	22	15.5	3.5	13.5	28	--
Oxygen, dissolved (mg/L)	8.2	8.5	11.8	7.7	--	>4.0
pH (standard units)	8.5	8.5	8.4	7.7	8.4	[a]6.5–9.0
Specific conductance (µS/cm)	489	542	786	568	519	--
Sediment, suspended (mg/L)	28	47	11	2,662	--	--
Major constituents						
Alkalinity (mg/L as $CaCO_3$)	179	184	241	155	180	--
Calcium, dissolved (mg/L)	47	57	65	48	54	--
Chloride, dissolved (mg/L)	1.9	2.7	2.9	1.6	1.7	--
Fluoride, dissolved (mg/L)	.15	.18	.19	.23	.1	(4)
Magnesium, dissolved (mg/L)	24	27	34	20	26	--
Potassium, dissolved (mg/L)	1.3	2.5	2.1	4.7	2.0	--
Silica, dissolved (mg/L)	5.9	5.3	4.6	7.6	5.5	--
Sodium, dissolved (mg/L)	19	24	45	36	24	--
Sulfate, dissolved (mg/L)	83	117	183	129	99	([b]250)
Nutrients						
Ammonia, dissolved (mg/L as N)	<0.02	0.032	<0.02	0.116	--	[c]0.9
Nitrate, dissolved (mg/L as N)	<.05	<.05	<.05	.148	0.023	(10)
Nitrite, dissolved (mg/L as N)	<.01	<.01	<.01	.023	--	(1.0)
Organic nitrogen, dissolved (mg/L as N)	--	.42	--	.45	--	--
Nitrogen, total (mg/L as N)	.162	.45	.16	.561	--	--
Orthophosphate, dissolved (mg/L as P)	.011	<.01	<.01	.013	--	--
Phosphorus, total (mg/L as P)	<.05	<.05	<.05	1.97	--	--
Trace elements						
Arsenic, dissolved (µg/L)	<1	<1	<0.9	0.8	--	(10)
Cadmium, dissolved (µg/L)	<1	<1	<.14	<.14	--	(5)
Copper, dissolved (µg/L)	3.0	6.8	.6	.7	--	(1,300)
Iron, dissolved (µg/L)	<10	<10	16.5	12.5	--	([b]300)
Lead, dissolved (µg/L)	<1	<1	<1	<1	--	(15)
Manganese, dissolved (µg/L)	2.2	4.7	15.1	1.6	--	([b]50)
Zinc, dissolved (µg/L)	1.7	8.1	1.8	3.1	--	(2,000)
Arsenic, total (µg/L)	<1	1.4	<2.6	9.7	--	150
Cadmium, total (µg/L)	<1	<1	<.1	.6	--	[c].5
Copper, total (µg/L)	1.3	9.2	1.4	34	--	[c]20
Iron, total (µg/L)	244	418	198	31,470	--	1,000
Lead, total (µg/L)	<1	1.5	<1	33	--	[c]9.7
Manganese, total (µg/L)	15	23	19	1,143	--	--
Zinc, total (µg/L)	40	40	11	121	--	[c]252

[a] Natural pH outside this range must be maintained.

[b] Secondary standard based on aesthetic properties such as taste, odor, and staining.

[c] Table value standard calculated for a hardness of 240 mg/L for trace elements or pH of 8.4 at 20 °C for ammonia.

Table 27. Summary of selected water-quality data for ground-water sites in the Little Bighorn Battlefield National Monument, Montana.

[human-health standards from *www.deq.state.mt.us/wqinfo/Standards/Index.asp*; <, less than; --, not reported; °C, degrees Celsius; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter at 25 °C; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorous; µg/L, micrograms per liter]

Constituent or property	G1 (fig. 20)			G2 (fig. 20)		G3 (fig. 20)	Human-health standard
	6/29/1977	7/21/1999	5/18/2000	12/19/1945	6/28/1977	10/28/1977	
Field properties							
Temperature, water (°C)	10	13	9	--	10	13	--
Oxygen, dissolved (mg/L)	--	5.8	.46	--	--	--	--
pH (standard units)	7.8	7.6	7.4	--	8.7	--	--
Specific conductance (µS/cm)	1,070	1,380	1,060	--	2,670	7,910	--
Major constituents							
Alkalinity (mg/L as $CaCO_3$)	310	331	296	378	380	670	
Calcium, dissolved (mg/L)	60	63	55	12	4.8	110	
Chloride, dissolved (mg/L)	8.3	9.6	4.9	32	26	94	--
Fluoride, dissolved (mg/L)	.3	.3	.3	--	.2	.8	4.0
Magnesium, dissolved (mg/L)	27	26	24	9	1.3	120	--
Potassium, dissolved (mg/L)	2	2.3	1.7	--	2.0	7.0	--
Silica, dissolved (mg/L)	12	14	13	11	9.2	11	--
Sodium, dissolved (mg/L)	150	206	145	--	640	1,900	--
Sulfate, dissolved (mg/L)	270	387	270	950	940	3,800	[a]250
Nutrients							
Ammonia, dissolved (mg/L as N)	--	0.13	0.076	--	--	--	--
Nitrate, dissolved (mg/L as N)	0.12	<.05	<.05		0.023	0.33	10
Nitrite, dissolved (mg/L as N)	--	<.01	<.01	--	--	--	1.0
Organic nitrogen, dissolved (mg/L as N)	--	.12	.08	--	--	--	--
Orthophosphate, dissolved (mg/L as P)	--	.019	.012	--	--	--	--
Phosphorus, total (mg/L as P)	--	<.05	<.05	--	--	--	--
Trace elements							
Arsenic, dissolved (µg/L)	--	<1.0	0.77	--	--	--	10
Cadmium, dissolved (µg/L)	--	<1.0	<.14	--	--	--	5
Copper, dissolved (µg/L)	--	1.6	<1.3	--	--	--	1,300
Iron, dissolved (µg/L)	340	625	230	1,000	90	20	[a]300
Lead, dissolved (µg/L)	--	<1	<1	--	--	--	15
Lithium, dissolved (µg/L)	40	--	--	--	140	600	--
Manganese, dissolved (µg/L)	90	230	145	--	<10	130	[a]50
Zinc, dissolved (µg/L)	--	8.9	8.2	--	--	--	2,000
Pesticides and organochlorine compounds							
Aldrin, µg/L	--	--	<0.001	--	--	--	0.02
alpha-Endosulfan (µg/L)	--	--	<.001	--	--	--	62
Chlordane, technical (µg/L)	--	--	<.1	--	--	--	1
Dieldrin (µg/L)	--	--	<.001	--	--	--	.02
Endrin (µg/L)	--	--	<.001	--	--	--	2
Heptachlor epoxide (µg/L)	--	--	<.001	--	--	--	.04
Heptachlor (µg/L)	--	--	<.001	--	--	--	.08
Lindane (µg/L)	--	--	<.001	--	--	--	2
Mirex (µg/L)	--	--	<.01	--	--	--	14
p,p'-DDD (µg/L)	--	--	<.001	--	--	--	.0031
p,p'-DDE (µg/L)	--	--	<.001	--	--	--	.0022
p,p'-DDT (µg/L)	--	--	<.001	--	--	--	.0022
p,p'-Ethyl-DDD (µg/L)	--	--	<.1	--	--	--	--
p,p'-Methoxychlor (µg/L)	--	--	<.01	--	--	--	40
PCBs (µg/L)	--	--	<.1	--	--	--	0.5
Polychlorinated naphthalenes (µg/L)	--	--	<.1		--	--	--
Toxaphene (µg/L)	--	--	<1	--	--	--	0.3

[a] Secondary standard based on aesthetic properties such as taste, odor, and staining.

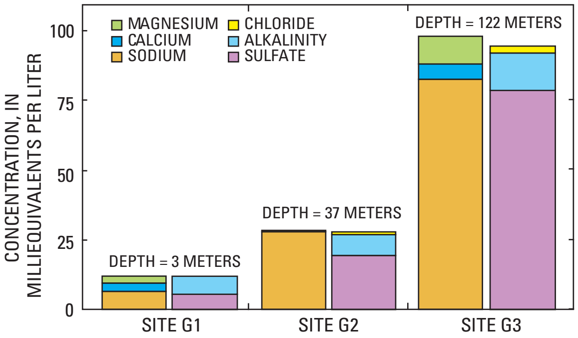


Figure 23. Variation in water quality with depth at selected ground-water wells in Little Bighorn National Battlefield Monument, Montana, 1977.

Summary and Suggestions for Vital Signs Monitoring

Review of historical records reveals few water-quality data are available for LIBI. From 1945 to 2000, a total of 11 samples were collected at 2 sites on the Little Bighorn River and 3 ground-water wells. Each site was sampled one to three times during the period of record with the exception of site S1 on the Little Bighorn River, which was sampled four times during 1999 and 2000. A streamflow-gaging station has been operated by the NPS on the Little Bighorn River (station 453400107263001) along the park boundary since November 1999, and water levels were measured annually at one well in the park during 1977 to 1999. Surface water is a calcium-bicarbonate-sulfate type and major constituents primarily are derived from natural weathering processes. Agricultural activities upstream from the park may affect nutrient and sediment concentrations in surface water, particularly during periods in increased streamflow. Because of a lack of long-term monitoring data, it was not possible to identify temporal trends in the water quality of the river. The reach of river in the park is classified as B-2, which is suitable for domestic water supply, recreation, aquatic life (salmonid fishes), and agricultural and industrial water supply. The available water-quality data indicate the river in this reach meets Montana aquatic-life and human-health standards, except perhaps during periods of high sediment transport. The standard comparison, however, is based on relatively few samples and additional data would be needed to characterize water-quality conditions during high flow. Ground water is a sodium-bicarbonate-sulfate type with elevated dissolved solid concentrations (more than 800 mg/L). Nutrient concentrations in ground water were low, indicating minimal effects from agricultural activities outside the park. None of the ground-water samples exceeded human-health standards, although several exceeded the secondary standards for manganese and iron.

Effects of agricultural activities outside the park on nutrient, bacteria, and sediment concentrations likely are the main water-quality issues for the Little Bighorn River. Based on a review of the historical data, the following suggestions are provided for consideration in designing a water-quality monitoring plan for LIBI.

- Establish a long-term water-quality monitoring station or “sentinel site” at the Little Bighorn River (station 453400107263001). Monitor for core field properties, nutrients, sediment, and indicator bacteria during different hydrologic conditions and occasionally for major constituents and trace elements.

- Maintain the NPS streamflow-gaging station at the Little Bighorn River (station 453400107263001).

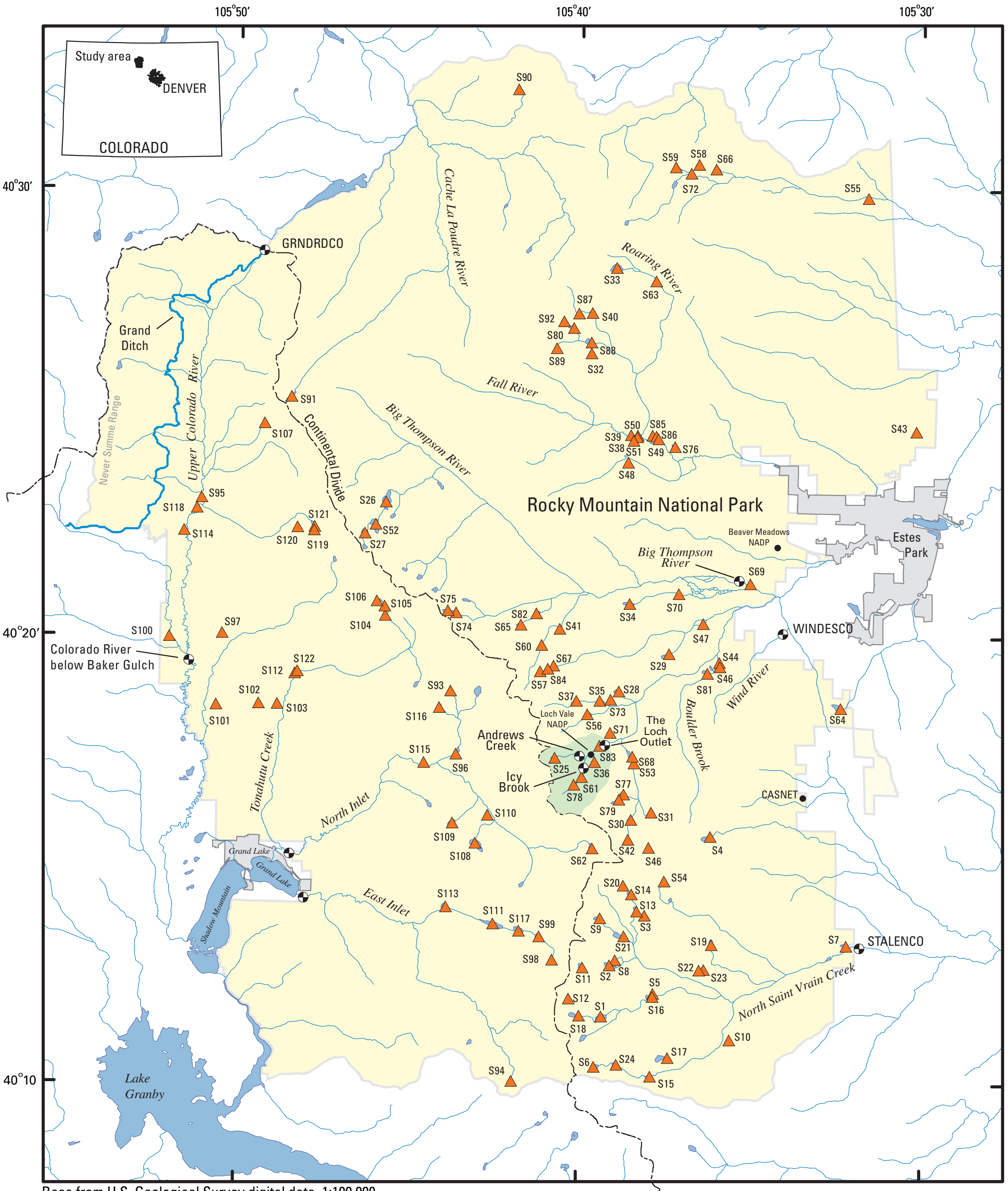
- Establish routine water-quality and water-level monitoring at existing ground-water wells. This information would be useful for investigating the effects of human stressors such as agriculture and climate change on ground-water resources.

Rocky Mountain National Park

Environmental Setting and Geology

Rocky Mountain National Park (ROMO) is located in the Colorado Front Range in north-central Colorado approximately 80 km northeast of Denver, Colorado (fig. 24). The park covers 1,075 km^2 and is characterized by steep, mountainous terrain with elevations ranging from 2,323 m at the eastern park boundary to 4,343 m along the Continental Divide. Three major bioregions are present in ROMO including alpine tundra, subalpine forest, and montane forest (Baron, 1992). Vegetation is dominated by spruce-fir forests between 2,860 and 3,300 m and alpine tundra communities at higher elevations (Baron, 1992). The area is characterized by a continental climate with long, cold winters and a short growing season (1 to 3 months). Mean monthly air temperatures at 2,500 m ranges from -4.4 °C in January to 15.5 °C in July (*http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?coalle*, accessed November 2006) and at 3,160 m ranges from -6.0 °C in January to 13.8 °C in July (Baron, 1992). Precipitation varies considerably with elevation, with mean annual precipitation ranging from 40 cm at 2,500 m to 100 cm at 3,160 m (*http://nadp.sws.uiuc.edu/*, accessed November 2006). More than one-half of the precipitation occurs as snow that accumulates in a seasonal snowpack between October and April. Winter precipitation is associated with synoptic weather systems with westerly airflow, and summer precipitation is associated with convective air masses originating primarily from the southwest and southeast (Baron and Denning, 1993).

Bedrock in ROMO predominantly is granite, gneiss, and schist of Proterozoic age (Braddock and Cole, 1990). The mineralogy of the Proterozoic rocks is similar, and consists of quartz, biotite, plagioclase, microcline and sillimanite. Some Tertiary lava flows crop out in the northwestern corner of the park. During the Pleistocene, valley glaciers covered the region carving the alpine cirques, glacial moraines, and U-shaped valleys that give the park its spectacular scenery.



Base from U.S. Geological Survey digital data, 1:100,000
Universal Transverse Mercator projection
Zone 13

0 5 10 KILOMETERS
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EXPLANATION

▭ Town

🟩 Loch Vale Watershed

S2 ▲ Lake and pond sampling site and number (table 28)

◐ Streamflow-gaging station

• NADP/CASNET station

Big Thompson River below Moraine Park

Figure 24. Location of lake and pond sampling sites in Rocky Mountain National Park, Colorado.

The Pinedale glaciation, the last of three separate Pleistocene advances, left extensive till deposits at elevations between 2,400 and 3,200 m (Madole, 1976). Several Neoglacial advances during the Holocene formed moraines, rock glaciers, talus, and debris flows present at higher elevations (3,300 to 3,750 m) in the park. The few small glaciers that exist in the park today are remnants of the most recent glaciation, but have been receding since the mid-1800s (Baron, 1992).

Approximately 95 percent of ROMO is designated or recommended as wilderness, and human activities are limited in these areas. Land-use activities in other areas of the park are related to tourism and park administration, and include the road system, campgrounds, picnic areas, liveries, visitor centers, and administrative buildings and park housing. The park has approximately 3 million visitors each year, most of whom visit the park between July and September (Britten and others, 2006). Water supply for the park is obtained from a system of 4 surface-water sources and 15 ground-water sources. The CDPHE requires monitoring for microbiological, chemical, physical, and radiological contaminants in public water systems (*http://www.cdphe.state.co.us/wq/drinkingwater/index.html*, accessed November 2006). The monitoring frequency is dependent on the type of water system, the water source, and the presence of contaminant-generating activities in the area surrounding the water source. The park has a few small septic systems but the majority of wastewater is treated by municipal treatment facilities outside of the park boundary in Estes Park and Grand Lake.

ROMO holds Federal reserved water rights for surface and ground water dating back to 1915 for purposes of conserving and maintaining park resources in an unimpaired condition. One exception is the Grand Ditch water diversion project, which was constructed before the establishment of ROMO. The project consists of a 24-km long drainage ditch that is carved into the eastern slope of the Never Summer Range (fig. 24). The ditch intercepts streamflow from 13 upstream drainage areas from mid June to mid September, and diverts the water to the east side of the Continental Divide (Woods and others, 2006). The seasonal diversion of surface water causes substantial declines in water levels in wetlands downstream from the ditch (Woods and others, 2006). In May 2003, the ditch breached because of ice and debris blockage and 46,000 cubic meters of sediment was washed into the upper Colorado River drainage causing damage to wetlands, forests, trails, bridges, and campsites. Four water-storage reservoirs including Bluebird Lake (S1 in fig. 24), Lawn Lake (S63), Pear Lake (S17), and Sandbeach Lake (S19) existed in the park before its establishment in 1915. In July 1982, the dam on Lawn Lake failed, resulting in substantial property damage to downstream communities and the loss of three lives. As a result, the dams were removed from all four reservoirs during 1988 to 1990 and 2002 and lakes were restored to pre-dam levels (*http://www.nps.gov/romo/naturescience/hydrologicactivity.htm*, accessed November 2006).

Air pollution is arguably the main natural resource issue for ROMO. The park is situated less than 70 km to the west of the Front Range urban corridor, which contains the most concentrated population density in the Rocky Mountain region, as well as directly west of large expanses of cropland and pasture on the plains of eastern Colorado. These urban and agricultural areas are sources of air pollution that are causing visibility degradation, increased ozone levels, and acidic deposition (nitrogen and sulfur) in the park (*http://www.nps.gov/romo/naturescience/airquality.htm*, accessed November 2006). Perhaps the most serious of these air-pollution issues is atmospheric deposition of nitrogen to high-elevation areas of the park. Nitrogen deposition rates have been increasing in the park during the past two decades, and current year levels [3–4 kilograms of nitrogen per hectare per year (kg N/ha/yr)] are 15–20 times greater than the estimated natural background level (Baron, 2006). Ecosystem effects from nitrogen deposition have been documented on the east side of the park and include changes in the type and abundance of aquatic plant species (diatoms), chronically elevated levels of nitrate in surface waters, elevated levels of nitrogen in spruce tree chemistry, and accumulation of nitrogen in forest soils (Burns, 2004). ROMO has proposed that a reduction in the deposition rate to 1.5 kg N/ha/yr would be needed to restore healthy ecosystems and is currently working on emission reduction strategies with the State of Colorado and USEPA to achieve this management goal. Additional information on the effects of atmospheric deposition in ROMO is available on the CDPHE web site at *http://www.cdphe.state.co.us/ap/rmnp.html* (accessed November 2006).

Water Resources

Drainages on the east side of ROMO form the headwaters of the Big Thompson River, Saint Vrain Creek, and Cache La Poudre River; those on the west side drain into the Upper Colorado River system. The park contains nearly 800 km of perennial streams and more than 150 lakes, most of which are above 3,000 m in the subalpine and alpine zones (Britten and others, 2006). The USGS has operated as many as 14 streamflow-gaging stations in or adjacent to the boundaries of the park. Of these, four stations currently (2007) are active including Andrews Creek in Loch Vale (USGS station 401723105400000), Icy Brook in Loch Vale (USGS station 401707105395000), Big Thompson River at Moraine Park (USGS station 402114105350101), and the Colorado River below Baker Gulch (USGS station 09010500) (fig. 24). The Big Thompson River at Moraine Park is part of the USGS Hydrologic Benchmark Network, a National program for monitoring streamflow and water quality in areas that are minimally affected by human activities (Murdoch and others, 2005).

The Andrews Creek and Icy Brook gages are operated as part of the USGS Water, Energy, and Biogeochemical Budgets Program (Baedecker and Friedman, 2000; Clow and others, 2000). These two gages are located in the Loch Vale Watershed (LVWS), which is an ecological research area that was established by the NPS in 1981 to study biogeochemical and hydrologic processes in alpine and subalpine ecosystems (Baron, 1992). The NPS also has a gage in LVWS at the outlet of The Loch that has been in operation since 1983. LVWS is a 6.6-km^2 watershed that drains subalpine and alpine terrain on the east side of the Continental Divide (fig. 24). The watershed contains two alpine streams (Andrews Creek and Icy Brook), three lakes (Sky Pond, Lake of Glass, and The Loch), and two small glaciers. More details about LVWS and its research programs are presented in Baron (1992) and Clow and others (2000) and at the following two web sites—*http://www.nrel.colostate.edu/projects/lvws/* and *http://co.water.usgs.gov/lochvale/index.html* (accessed November 2006).

The Colorado Division of Water Resource operates several gages just outside the park boundary including North Saint Vrain Creek near Allenspark (station STALENCO), Wind River near Estes Park (station WINDESCO), and Grand River Ditch at La Poudre Pass (station GRNDRDCO) (fig. 24). Data for these stations are available at *http://water.state.co.us/pubs/datasearch.asp* (accessed November 2006). The Northern Colorado Water Conservation District operates seasonal gages near the mouth of East Inlet Creek and North Inlet Creek on the west side of the park (*http://www.ncwcd.org/datareports/westflow.asp*, accessed November 2006).

The longest continuously operated station in the park is the Colorado River below Baker Gulch (USGS station 09010500), which began operation in 1953 (fig. 24). The range of daily streamflow values for this station from 1986 to 2005 is shown in figure 25. Peak streamflow occurs in late May or early June during spring snowmelt, and streamflow increases by two to three orders of magnitude over winter streamflows. Nearly 65 percent of the annual streamflow occurs in May and June. Streamflows decrease rapidly after June, and reaches a minimum in late winter when streamflow is sustained by slow release of ground water.

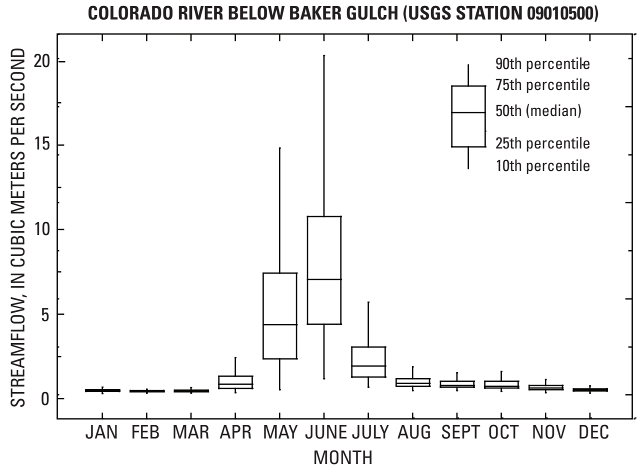

Figure 25. Daily streamflow range at Colorado River near Baker Gulch (USGS streamflow-gaging station 09010500) in Rocky Mountain National Park, Colorado, 1986–2005.

In mountainous areas such as ROMO there generally are two different ground-water systems; bedrock aquifers in the mountain block, and shallow localized aquifers in alluvium and glacial till. In ROMO, the hydrologic characteristics of mountain block aquifers are virtually unknown and there have been only a few published studies of shallow aquifer systems, most of which have been related to wetlands. Bachman (1994) made water-level measurements at 20 shallow wells (less than 1.9 m) in LVWS from 1991 to 1993 to study ground-water movement in subalpine wetlands. Cooper and others (1998) measured water levels at 50 shallow wells (less than 2.5 m) in a wetland along Tonahutu Creek from 1987 to 1994 to determine the effect of hydrologic restoration activities in the wetland. Woods and others (2006) measured water levels in 18 shallow wells (less than 1.6 m) in a small wetland along the upper Colorado River to study controls on wetland water levels and the effect of the upstream water diversions related to the Grand Ditch. These studies concluded that seepage of surface water was an important wetland water source, and suggested these systems could be sensitive to climate variability or changes in hydrology related to water diversions. Clow and others (2004) estimated ground-water occurrence and contributions to streamflow using hydrogeomorphologic mapping, seismic refraction measurements, tracer tests, and porosity and permeability estimates in LWVS. The study concluded that talus deposits formed at the base of cliffs are the primary ground-water reservoir in alpine areas, and that discharge from these deposits accounts for more than 75 percent of streamflow during summer storms and the winter base-flow period. The second largest ground-water reservoir in alpine areas was determined to be ice stored in permafrost in talus and rock glaciers.

The park has two NADP stations, one in LVWS at an elevation of 3,159 m and one at Beaver Meadows at an elevation of 2,490 m (fig. 24). The NADP is a national network of precipitation monitoring sites that measures weekly precipitation chemistry and precipitation amount; data for the network are available at *http://nadp.sws.uiuc.edu/* (accessed November 2006). The sites in ROMO were established in the early 1980s to monitor the effects of air pollution on ecological resources including vegetation, water quality, and soils (*http://www2.nature.nps.gov/air/index.cfm*, accessed November 2006). The park also has a CASNET station located near the south-eastern park boundary at 2,800 m. CASTNET is a national network of air monitoring sites that provide estimates of dry deposition of sulfur and nitrogen compounds and concentrations of ground-level ozone (*http://www.epa.gov/castnet/*, accessed November 2006). The CASNET station in ROMO is operated by the NPS and was added to the network in 1995.

Surface-Water Quality

Water-quality data were collected and compiled for 493 surface-water sites within the boundaries of ROMO including 122 lakes and ponds, 83 springs, and 288 streams. For

Table 28. Lake and pond sampling sites in Rocky Mountain National Park, Colorado.

[no., number; identification numbers and station names from USEPA STORET and USGS NWIS]

Site no. (fig. 24)	Identification number	Station name	Latitude	Longitude	Elevation (meters)	Type	No. samples
S1	4E1-051	Bluebird Lake	40° 11’ 30”	105° 39’ 17”	3,348	Lake	4
S2	4E1-030	Box Lake	40° 12’ 47”	105° 38’ 55”	3,276	Lake	2
S3	ROMO_JR_CAP29	Castle Lake North of the Outlet	40° 13’ 47”	105° 38’ 04”	3,414	Lake	1
S4	401533105360800	Chasm Lake	40° 15’ 33”	105° 36’ 10”	3,591	Lake	16
S5	ROMO_JR_CAP30	Chickadee Pond near Southwest Corner	40° 12’ 02”	105° 37’ 49”	3,055	Pond	1
S6	401025105392000	Cony Lake	40° 10’ 24”	105° 39’ 27”	3,505	Lake	1
S7	401307105320900	Copeland Lake	40° 13’ 07”	105° 32’ 11”	2,533	Lake	7
S8	401137105384900	Eagle Lake	40° 12’ 40”	105° 39’ 05”	3,298	Lake	1
S9	401343105392201	Falcon Lake	40° 13’ 43”	105° 39’ 22”	3,376	Lake	2
S10	4E1-038	Finch Lake	40° 10’ 60”	105° 35’ 35”	3,023	Lake	25
S11	401237105394600	Frigid Lake	40° 12’ 37”	105° 39’ 52”	3,600	Lake	1
S12	401155105401700	Isolation Lake	40° 11’ 55”	105° 40’ 17”	3,655	Lake	1
S13	401352105381801	Lion Lake #1	40° 13’ 52”	105° 38’ 18”	3,375	Lake	5
S14	401415105382701	Lion Lake #2	40° 14’ 15”	105° 38’ 27”	3,481	Lake	2
S15	401013105374900	Lower Hutcheson	40° 10’ 11”	105° 37’ 54”	3,316	Lake	2
S16	401158105375001	Ouzel Lake	40° 11’ 58”	105° 37’ 50”	3,056	Lake	4
S17	401036105372301	Pear Lake	40° 10’ 36”	105° 37’ 23”	3,225	Lake	5
S18	401132105395801	Pipit Lake	40° 11’ 32”	105° 39’ 58”	3,486	Lake	3
S19	4E1-033	Sandbeach Lake	40° 13’ 08”	105° 36’ 07”	3,136	Lake	7
S20	401424105383301	Snowbank Lake	40° 14’ 24”	105° 38’ 33”	3,513	Lake	3
S21	401319105384001	Thunder Lake	40° 13’ 19”	105° 38’ 40”	3,225	Lake	4
S22	ROMO_JR_CAP38	Twin Lakes (Lower)	40° 12’ 34”	105° 36’ 20”	3,000	Lake	1
S23	ROMO_JR_CAP39	Twin Lakes (Upper)	40° 12’ 34”	105° 36’ 28”	3,000	Lake	1
S24	ROMO_JR_CAP40	Upper Hutcheson Lake	40° 10’ 26”	105° 38’ 52”	3,414	Lake	1
S25	401723105394803	Andrews Tarn	40° 17’ 18”	105° 40’ 43”	3,471	Lake	7
S26	4E1-014	Arrowhead Lake	40° 22’ 60”	105° 45’ 42”	3,398	Lake	2
S27	402222105461100	Azure Lake	40° 22’ 18”	105° 46’ 19”	3,505	Lake	1
S28	401843105384700	Bear Lake	40° 18’ 47”	105° 38’ 52”	2,883	Lake	14
S29	401938105372200	Bierstadt Lake	40° 19’ 38”	105° 37’ 24”	2,871	Lake	4
S30	4E1-025	Black Lake	40° 15’ 55”	105° 38’ 29”	3,239	Lake	32
S31	401602105375300	Blue Lake	40° 16’ 05”	105° 37’ 54”	3,399	Lake	4
S32	ROMO_JR_CAP04	Chipmunk Lake	40° 26’ 21”	105° 39’ 43”	3,250	Lake	1
S33	GA04	Crystal Lake	40° 28’ 16”	105° 39’ 00”	3,511	Lake	2
S34	402046105382800	Cub Lake	40° 20’ 45”	105° 38’ 34”	2,621	Lake	2
S35	401835105392300	Dream Lake	40° 18’ 35”	105° 39’ 25”	3,018	Lake	23
S36	401715105394201	Embryo Pond	40° 17’ 15”	105° 39’ 42”	3,169	Lake	5
S37	401835105395800	Emerald Lake	40° 18’ 35”	105° 40’ 06”	3,078	Lake	44
S38	ROMO_USFW_FAN	Fan Lake	40° 24’ 32”	105° 38’ 33”	2,605	Pond	7
S39	402430105381700	Fan Lake #2	40° 24’ 31”	105° 38’ 21”	2,603	Pond	1
S40	GB10	Fay Lakes	40° 27’ 15”	105° 39’ 42”	3,353	Lake	2
S41	402011105403801	Fern Lake	40° 20’ 11”	105° 40’ 36”	2,903	Lake	7
S42	401533105382900	Frozen Lake	40° 15’ 33”	105° 38’ 31”	3,530	Lake	7
S43	402438105301000	Gem Lake	40° 24’ 38”	105° 30’ 12”	2,688	Lake	1
S44	401927105355500	Glacier Basin Primenet	40° 19’ 27”	105° 35’ 56”	2,627	Pond	8
S45	401925105355500	Glacier Basin PRIMENET New	40° 19’ 25”	105° 35’ 55”	2,621	Pond	12
S46	401518105375500	Green Lake	40° 15’ 18”	105° 37’ 58”	3,520	Lake	6
S47	402019105362200	Hallowell Park	40° 20’ 19”	105° 36’ 24”	2,548	Pond	1
S48	402357381053822	Hidden Valley	40° 23’ 57”	105° 38’ 40”	2,548	Pond	1
S49	402427105374900	Horseshoe Park	40° 24’ 27”	105° 37’ 51”	2,606	Pond	3

Table 28. Lake and pond sampling sites in Rocky Mountain National Park, Colorado.—Continued

[no., number; identification numbers and station names from USEPA STORET and USGS NWIS]

Site no. (fig. 24)	Identification number	Station name	Latitude	Longitude	Elevation (meters)	Type	No. samples
S50	ROMO_USFW_HP1	Horseshoe Park Lake #1	40° 24’ 29”	105° 38’ 22”	2,602	Pond	7
S51	ROMO_USFW_HP3	Horseshoe Park Lake #3	40° 24’ 24”	105° 38’ 28”	2,602	Pond	3
S52	402236105455200	Inkwell Lake	40° 22’ 30”	105° 45’ 60”	3,493	Lake	1
S53	ROMO_JR_CAP13	Jewell Lake	40° 17’ 11”	105° 38’ 24”	3,036	Lake	4
S54	4E1-032	Keplinger Lake	40° 14’ 33”	105° 37’ 30”	3,564	Lake	2
S55	402950105313700	Kettle Tarn	40° 29’ 51”	105° 31’ 38”	2,810	Pond	19
S56	4E1-022	Lake Haiyaha	40° 18’ 17”	105° 39’ 47”	3,117	Lake	37
S57	401915105410900	Lake Helene	40° 19’ 14”	105° 41’ 10”	3,219	Lake	2
S58	403033105363801	Lake Husted	40° 30’ 35”	105° 36’ 36”	3,381	Lake	43
S59	403028105371301	Lake Louise	40° 30’ 29”	105° 37’ 14”	3,362	Lake	35
S60	ROMO_JR_CAP24	Lake Odessa (North End)	40° 19’ 49”	105° 41’ 07”	3,055	Lake	2
S61	401655105395401	Lake Of Glass	40° 16’ 53”	105° 39’ 53”	3,298	Lake	153
S62	4E1-026	Lake Powell	40° 15’ 17”	105° 39’ 37”	3,520	Lake	2
S63	ROMO_JR_CAP15	Lawn Lake	40° 27’ 59”	105° 37’ 51”	3,353	Lake	3
S64	402657110232200	Lily Pond	40° 18’ 26”	105° 32’ 22”	2,900	Pond	9
S65	402017105414400	Loomis Lake	40° 20’ 16”	105° 41’ 44”	3,118	Lake	1
S66	403029105360400	Lost Lake	40° 30’ 29”	105° 36’ 06”	3,266	Lake	8
S67	401921105404600	Marigold Pond Outflow	40° 19’ 21”	105° 40’ 46”	3,255	Pond	2
S68	4E1-060	Mills Lake	40° 17’ 20”	105° 38’ 27”	3,032	Lake	65
S69	402113105346000	Moraine Park, Lower	40° 21’ 13”	105° 35’ 02”	2,454	Pond	1
S70	402059105370500	Moraine Park, Upper	40° 20’ 59”	105° 37’ 07”	2,474	Pond	13
S71	401752105390601	Mystery Pond (No Name)	40° 17’ 52”	105° 39’ 06”	3,092	Pond	1
S72	403023105364800	North Fork Ponds	40° 30’ 23”	105° 36’ 50”	3,350	Pond	1
S73	ROMO_JR_CAP23	Nymph Lake near Longs Peak Viewpod	40° 18’ 37”	105° 39’ 06”	2,969	Lake	1
S74	402032105433801	Rainbow Lake (Lower)	40° 20’ 32”	105° 43’ 38”	3,580	Lake	1
S75	402035105435201	Rainbow Lake (Upper)	40° 20’ 35”	105° 43’ 52”	3,613	Lake	1
S76	402416105371400	Sheep Lake	40° 24’ 16”	105° 37’ 16”	2,593	Lake	3
S77	401629105384000	Shelf Lake	40° 16’ 29”	105° 38’ 42”	3,420	Lake	3
S78	401642105400601	Sky Pond	40° 16’ 39”	105° 40’ 07”	3,319	Lake	267
S79	401622105384800	Solitude Lake	40° 16’ 22”	105° 38’ 50”	3,475	Lake	3
S80	402653105400600	Spectacle Lakes Southeast	40° 26’ 55”	105° 40’ 14”	3,456	Lake	1
S81	401910105360800	Sprague Lake	40° 19’ 12”	105° 36’ 17”	2,646	Lake	2
S82	402032105411500	Spruce Lake	40° 20’ 32”	105° 41’ 17”	2,707	Lake	11
S83	4E1-061	The Loch	40° 17’ 33”	105° 39’ 37”	3,105	Lake	342
S84	401918105405300	Two Rivers Lake	40° 19’ 17”	105° 40’ 57”	3,261	Lake	2
S85	ROMO_NPS_FLD_3	Unnamed Pond F-Lawn Lake Alluvial Fan	40° 24’ 30”	105° 37’ 48”	2,606	Pond	10
S86	ROMO_NPS_FLD_4	Unnamed Pond Q-Lawn Lake Alluvial Fan	40° 24’ 26”	105° 37’ 45”	2,606	Pond	10
S87	GB04	Upper Fay Lakes	40° 27’ 15”	105° 40’ 05”	3,425	Lake	1
S88	402636105394100	Ypsilon Lake, Rocky Mountain National Park	40° 26’ 36”	105° 39’ 43”	3,200	Lake	8
S89	4E1-013	Chiquita Lake	40° 26’ 28”	105° 40’ 44”	3,459	Lake	5
S90	4E1-053	Mirror Lake	40° 32’ 15”	105° 41’ 54”	3,361	Lake	4
S91	402522105482800	Poudre Lake	40° 25’ 20”	105° 48’ 29”	3,281	Lake	6
S92	4E1-012	Spectacle Lakes (Northwest)	40° 27’ 04”	105° 40’ 32”	3,459	Lake	3
S93	4E1-035	(No Name)	40° 10’ 04”	105° 41’ 56”	3,312	Lake	2
S94	4E1-019	(No Name)	40° 18’ 47”	105° 43’ 47”	3,373	Lake	2
S95	402305105510400	Beaver Ponds Picnic Area	40° 23’ 05”	105° 51’ 06”	2,743	Pond	1
S96	401723105433500	Bench Lake	40° 17’ 23”	105° 43’ 37”	3,094	Lake	2
S97	402005105502600	Chickaree Lake	40° 20’ 03”	105° 50’ 28”	2,808	Lake	2
S98	4E1-029	Fifth Lake	40° 12’ 47”	105° 40’ 46”	3,312	Lake	7

Table 28. Lake and pond sampling sites in Rocky Mountain National Park, Colorado.—Continued

[no., number; identification numbers and station names from USEPA STORET and USGS NWIS]

Site no. (fig. 24)	Identification number	Station name	Latitude	Longitude	Elevation (meters)	Type	No. samples
S99	4E1-054	Fourth Lake	40° 13’ 18”	105° 41’ 09”	3,166	Lake	9
S100	493853118011201	Gaskil Pond	40° 19’ 58”	105° 52’ 00”	2,682	Pond	4
S101	401827105503600	Green Mountain Trail	40° 18’ 27”	105° 50’ 38”	2,664	Pond	1
S102	401829105492100	Green Mountain Trailhead Pond	40° 18’ 29”	105° 49’ 23”	2,855	Pond	1
S103	401830105484900	Green Mtn. Trail Pond #3	40° 18’ 29”	105° 48’ 50”	2,871	Pond	1
S104	402029105453900	Haynach Lake #5	40° 20’ 28”	105° 45’ 42”	3,350	Lake	1
S105	402040105454100	Haynach Lakes #2-4	40° 20’ 41”	105° 45’ 43”	3,365	Lake	1
S106	4E1-018	Haynach Lakes (Northwest)	40° 20’ 47”	105° 45’ 57”	3,373	Lake	3
S107	402445105491400	Lake Irene	40° 24’ 45”	105° 49’ 16”	3,231	Lake	9
S108	4E1-027	Lake Nanita	40° 15’ 23”	105° 43’ 02”	3,288	Lake	6
S109	401552105433300	Lake Nokoni	40° 15’ 50”	105° 43’ 42”	3,286	Lake	6
S110	401601105423800	Lake Solitude	40° 16’ 01”	105° 42’ 40”	2,969	Lake	1
S111	4E1-028	Lake Verna	40° 13’ 35”	105° 42’ 30”	3,105	Lake	10
S112	401910105481800	Lilly Pond at Big Meadows	40° 19’ 10”	105° 48’ 20”	2,871	Pond	1
S113	401324105435400	Lone Pine Lake	40° 13’ 58”	105° 43’ 53”	3,078	Lake	7
S114	402221105513400	Never Summer Ranch	40° 22’ 21”	105° 51’ 36”	2,707	Pond	3
S115	401713105443100	Ptarmigan Pond	40° 17’ 11”	105° 44’ 32”	2,816	Pond	1
S116	4E1-058	Snowdrift Lake	40° 18’ 25”	105° 44’ 06”	3,373	Lake	3
S117	401246105414900	Spirit Lake	40° 13’ 25”	105° 41’ 45”	3,127	Lake	7
S118	402251105511200	Timber Creek Campground	40° 22’ 51”	105° 51’ 14”	2,722	Pond	16
S119	4E1-057	Timber Lake	40° 22’ 27”	105° 47’ 47”	3,373	Lake	10
S120	402228105481800	Timber Lake Pond #4	40° 22’ 26”	105° 48’ 17”	3,322	Pond	1
S121	402224105474700	Timber Lake Ponds 2 and 3	40° 22’ 22”	105° 47’ 48”	3,383	Pond	1
S122	401911105481701	Toad Pond at Benchmark	40° 19’ 11”	105° 48’ 19”	2,880	Pond	1

the 122 lake and pond sites (table 28, fig. 24), there were 1,515 samples collected from 1974 to 2004 with more than 25,000 individual results, most of which were field properties (26 percent), and major-constituent (40 percent) and nutrient (16 percent) analyses. The types of analyses and numbers of lake and pond samples collected during the period of record are summarized in table 29. Most of the sites (56 percent) were sampled 1 to 3 times during the period of record, but 11 sites were sampled more than 20 times each (table 27). Nearly one-half of the 1,515 samples were collected at sites in LVWS for ecological research including Andrews Tarn (S25), Embryo Pond (S36), Lake of Glass (S61), Sky Pond (S78), and The Loch (S83). Lakes at other locations in the park were sampled as part of studies by the USGS, NPS, U.S. Fish and Wildlife Service, and USEPA, some of which are mentioned below. The USEPA sampled 23 lakes in 1985 as part of the Western Lake Survey (Landers and others, 1987). The USGS resampled these lakes in 1999, in addition to 24 others, as part of a survey of lakes in high-elevation National Parks (Clow and others, 2002; Clow and others, 2003). The U.S. Fish and Wildlife Service sampled 12 lakes in 1982 as part of an acidic deposition study (Gibson and others, 1983) that were resampled in 1997 as part of a USGS research project (J. Baron, U.S. Geological Survey, written commun., 2005). The LVWS research project monitored four lake sites (S37, S56, S58, S59) outside of LVWS periodically from 1981-2003 (*http://www.nrel.colostate.edu/projects/lvws/*, accessed November 2006) and conducted a synoptic survey of 17 lakes in 1998 (J. Baron, U.S. Geological Survey, written commun., 2005). Several small ponds in wetland areas were sampled during 2001 through 2004 as part of the USGS Amphibian Research and Monitoring Initiative (*http://armi.usgs.gov/*, accessed November 2006). The USGS sampled 10 lakes during 2002 and 2003 to document the occurrence of organochlorine compounds and pesticides in lake sediments (Mast and others, 2006).

For the 83 spring sites (not shown on fig. 24), there were 739 samples collected from 1991 to 2004 with 11,645 results most of which were field properties (23 percent), and major-constituent (45 percent), nutrient (13 percent), and trace-element (7 percent) analyses. All but 12 of the spring sites were in LVWS and more than 75 percent of the 739 samples were collected at three LVWS sites—Andrews Spring 1 (USGS station 401727105400000), Spring 19 (USGS station 401707105394800), and Spring 2N (USGS station 401707105394800).

For the 288 stream sites (not shown on fig. 24), there were 5,597 samples collected from 1955 to 2004 with more than 100,000 individual results, most of which were field

Table 29. Period of record and types of analyses conducted at lake and pond sampling sites in Rocky Mountain National Park, Colorado.

[value in cell is number of samples analyzed in each category for the year; --, no data]

	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
Field properties	2	--	--	--	--	--	--	44	115	109	118	145	80	102	103	24	18	17	18	16	14	17	30	79	24	107	123	100	32	11	25
Major constituents	2	--	--	--	--	--	--	44	115	108	95	114	61	86	92	18	18	15	18	16	14	17	13	29	24	107	123	100	32	11	25
Nutrients	2	--	--	--	--	--	--	44	115	109	118	145	80	100	100	18	18	15	18	16	14	17	13	27	24	107	123	99	32	11	25
Trace elements	2	--	--	--	--	--	--	--	22	108	93	143	79	104	101	20	18	15	17	10	--	2	1	--	--	100	112	87	26	10	25
Carbon	--	--	--	--	--	--	--	--	--	13	14	51	27	50	39	5	11	15	17	12	13	9	11	7	5	102	118	28	32	11	24
Organics	--	--	--	--	--	--	--	--	--	--	--	23	--	31	19	15	--	--	--	--	--	--	--	--	--	--	--	--	--	3	--

properties (22 percent), and major-constituent (43 percent), nutrient (15 percent), and trace-element (5 percent) analyses. Most of the sites (191) were sampled 1 to 3 times during the period of record, but 33 sites were sampled 20 or more times each. More than 60 percent of the 5,625 stream samples were collected in LVWS; the most frequently samples sites were Andrews Creek (USGS station 401723105400000), Icy Brook (USGS station 401707105395000), and The Loch Outlet (USGS station 401733105392404). The water quality of streams in ROMO, and in particular LVWS, has been described extensively in the scientific literature, from which a few of the studies are mentioned here. Baron and Campbell (1997), Campbell and others (1995), and Campbell and others (2000) discuss processes controlling chemical concentrations and fluxes for streams in LVWS. Clow and Sueker (2000) and Sueker and others (2001) examined the relations between basin physical characteristics and solute fluxes and mineral weathering rates for several streams in the park. Mast and others (1995) and Sueker and others (2000) used hydrograph separation techniques based on isotopes of water to determine hydrologic pathways and sources of water during snowmelt. Baron (2006) and Sullivan and others (2005) discuss the effects of sulfur and nitrogen deposition on surface water in LVWS. Mast and others (2005) describe total mercury and methylmercury concentrations and fluxes for selected streams in LVWS. A complete list of publications for LVWS and other surface-water studies in ROMO is available online at *http://www.nrel.colostate.edu/projects/lvws/pages/publications/publications.htm* (accessed November 2006).

Because a large percentage of stream and spring samples were collected in LVWS, and results for many of these are published in the scientific literature, the discussion in this report primarily focuses on the water quality of lakes and ponds in ROMO (table 29). Field properties and major-dissolved constituents for the lakes in ROMO are summarized in table 30. Lake water in ROMO is dilute (median specific conductance 13 µS/cm) and weakly buffered (median alkalinity 2.9 mg/L) because of the slowly weathering crystalline bedrock and rapid hydrologic flushing rates. The dominant anion in surface water was bicarbonate (based on pH and alkalinity), and the dominant cations were calcium (median 1.5 mg/L) and sodium (median 0.50 mg/L). The predominance of these constituents is attributed to weathering of plagioclase and trace amounts of calcite in the granite and gneiss (Baron, 1992). Concentrations of sulfate (median 1.4 mg/L) and chloride (median 0.13 mg/L) also were quite low and similar to concentrations measured in local precipitation (Baron, 1992). Mineral weathering may contribute a small amount of sulfate in some lakes in ROMO although probably not more than 25 percent (Clow and others, 2002). Seasonal variations in selected major-constituent concentrations are shown in figure 26 for Sky Pond (S78) at the surface (0.2 m) and near the bottom of the lake (6.0 m). Sky Pond is an alpine lake that is ice covered for 7 months each year and has a maximum depth of 7.3 m and a surface area of 0.03 km^2. The lake thermally stratifies under ice cover; however, wind mixing generally prevents

Table 30. Summary of selected water-quality data for lake and pond sampling sites in Rocky Mountain National Park, Colorado, 1981 to 2004.

[no. number; chronic aquatic-life (and water-supply) standards from Colorado Department of Public Health and Environment (2006); <, less than; >, greater than; --, not reported; °C, degrees Celsius; mg/L, milligrams per liter; μS/cm, microsiemens per centimeter at 25 °C; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorous; μg/L, micrograms per liter]

Constituent or property	No. sites	No. samples (no. censored)	Minimum value	Median value	Maximum value	Aquatic-life (water-supply) standard
		Field properties				
Temperature, water (°C)	98	1,028	-0.2	6.0	33	<20
Oxygen, dissolved (mg/L)	13	51	.2	7.1	9.2	>6.0
pH (standard units)	112	1,328	5.45	6.61	9.40	6.5–9.0 (5.0–9.0)
Specific conductance (μS/cm)	101	1,305	1.0	13	773	--
		Major constituents				
Alkalinity (mg/L as $CaCO_3$)	105	1,134	0.10	2.9	75	--
Calcium, dissolved (mg/L)	109	1,227	.09	1.5	142	--
Chloride, dissolved (mg/L)	112	1,228 (7)	<.01	.13	17	([a]250)
Fluoride, dissolved (mg/L)	61	683 (31)	<.01	.098	1.5	--
Magnesium, dissolved (mg/L)	109	1,247	.039	.21	15	--
Potassium, dissolved (mg/L)	109	1,250	.02	.17	17	--
Silica, dissolved (mg/L)	106	1,099 (3)	<.01	1.7	27	--
Sodium, dissolved (mg/L)	109	1,248	.11	.50	18	--
Sulfate, dissolved (mg/L)	109	1,223 (3)	<.01	1.4	267	([a]250)
		Nutrients and organic carbon				
Ammonia, dissolved (mg/L as N)	111	433 (219)	<0.002	<0.007	11.8	0.02
Nitrate, dissolved (mg/L as N)	113	1,275 (132)	[b].002	.16	21	(10)
Nitrite, dissolved (mg/L as N)	9	480 (152)	<.01	.01	.05	.05 (1.0)
Orthophosphate, dissolved (mg/L as P)	50	851 (424)	<.001	.003	.036	--
Phosphorus, dissolved (mg/L as P)	30	59 (18)	<.005	.01	.16	--
Organic carbon, dissolved (mg/L)	93	614 (2)	<.1	1.2	76	--
		Trace elements				
Aluminum, dissolved (μg/L)	8	443 (0)	0.02	20	160	--
Iron, dissolved (μg/L)	20	644 (4)	<2	32	800	[c]1,000 ([a]300)
Manganese, dissolved (μg/L)	38	595 (25)	<1	3	520	50 ([a]50)
Strontium, dissolved (μg/L)	96	363	2	7	442	--

[a] Secondary standard based on aesthetic properties such as taste, odor, and staining.

[b] Minimum reported value less than minimum censored value.

[c] Total recoverable concentration.

stratification during the open water season (Baron, 1992). Concentrations of weathering-derived constituents (calcium and alkalinity) decrease rapidly in spring and reach a minimum in mid summer as the lake is diluted by large inflows of dilute snowmelt. Concentrations increase steadily through the fall and early winter as snowmelt declines and shallow ground water contributes a greater percentage of flow to lakes and streams. Some of the increase in concentrations during early winter also may be caused by ice formation, which converts more than one-half of the lake volume of water (Baron, 1992). Chloride, which largely is derived from atmospheric sources, showed a slightly different seasonal pattern. Concentrations decrease in early summer due to snowmelt dilution then began to increase in late summer and early fall because of evaporation and ground-water inputs. Once the lake became ice-covered, concentrations remained remarkably constant indicating

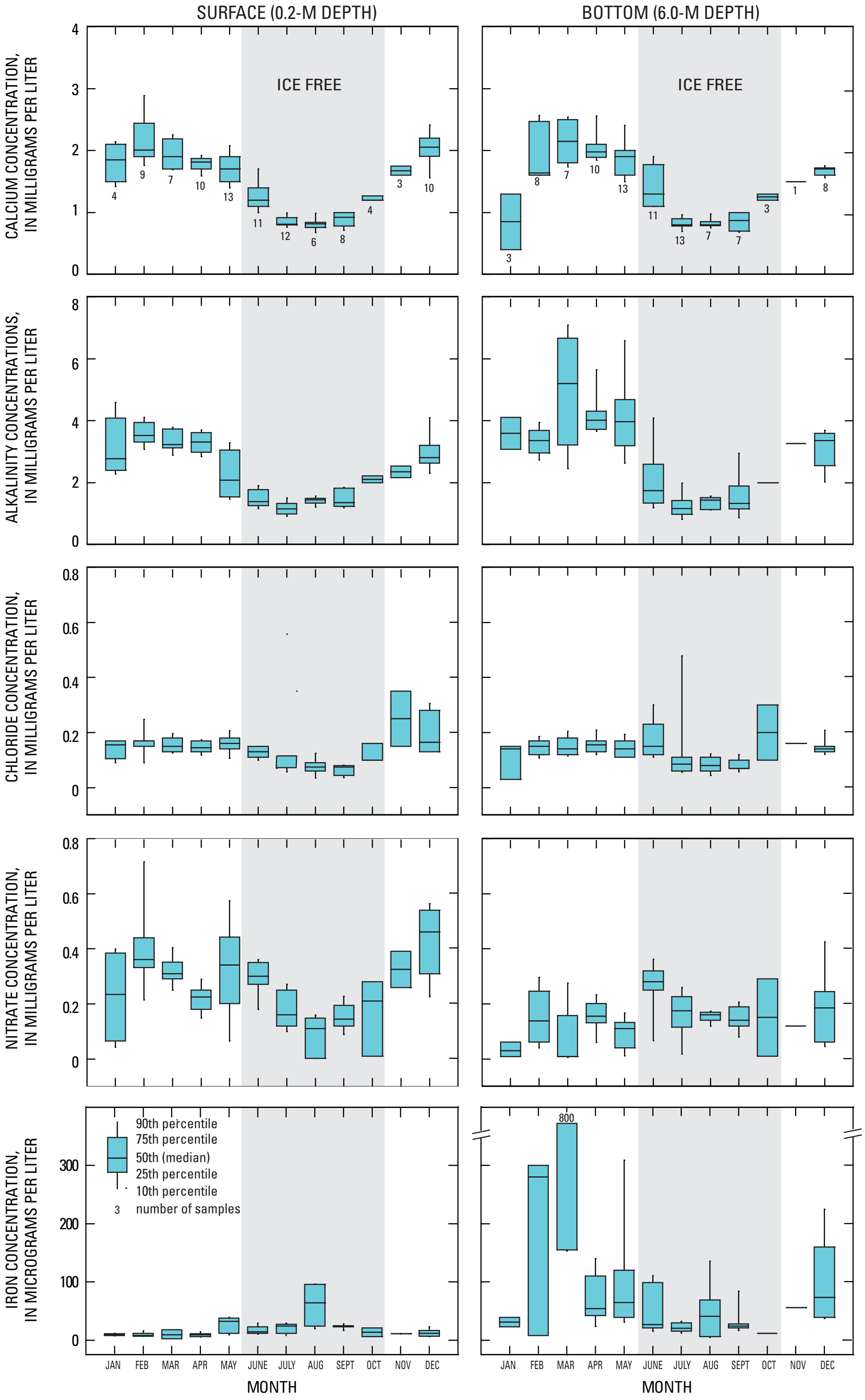

Figure 26. Seasonal variation in selected constituent concentrations in water samples from the surface and bottom of Sky Pond (S78) in Rocky Mountain National Park, Colorado, 1982–2004.

chloride was minimally affected by in-lake biological and geochemical processes. Concentrations of major constituents were similar between the two sampling depths (0.2 and 6.0 m) except for alkalinity, which was elevated in the subsurface during early spring. This likely was caused by dissolved oxygen depletion in water at the bottom of the lake during winter (Baron, 1992), Low dissolved oxygen concentrations in lake water allow buildup of bicarbonate, iron, and manganese that are generated by anaerobic respiration reactions in the lake sediments.

Spatial patterns in major constituents are illustrated by comparing lakes on different sides of the Continental Divide (fig. 27). Probabilities (p-values) shown on the figure are for statistical comparison of east- and west-side lakes using the Wilcoxon signed-rank test. Of the 86 lakes used for the comparison (small wetland ponds were excluded), 63 were on the east side of he divide and 23 were on the west side. The greater number of east-side lakes largely reflects the geographic distribution of lakes in the park. East-side lakes span a wider range in elevation than west-side lakes; however, there was no statistical difference in the two groups. Calcium concentrations indicated very little difference between the two groups of lakes, indicating weathering processes are fairly uniform. Sulfate concentrations, which primarily are derived from atmospheric sources, also had little difference, indicating rates of sulfur deposition are not substantially different on the two sides of the Continental Divide. None of the other major constituents indicated statistically significant differences in concentrations between east and west-side lakes.

Nutrients measured in lake-water samples from ROMO include ammonia, nitrate, nitrite, orthophosphate, and dissolved phosphorus (table 30). Ammonia concentrations ranged from less than .002 to 11.8 mg/L and 95 percent of samples had concentrations less than 0.1 mg/L. The highest ammonium concentrations (0.3 to 11.8 mg/L) were collected at Kettle Tarn (S55), which is a shallow wetland pond that provides important amphibian habitat. Elevated concentrations were measured following a drought in 2002 and are attributed to the development of anoxic conditions that caused mineralization of organic matter at the sediment/water interface (D. Campbell, U.S. Geological Survey, oral commun., 2006). Samples collected at Kettle Tarn in 2004 also had very high nitrate concentrations (more than 15 mg/L), which probably resulted from conversion of ammonia to nitrate (nitrification) once oxidizing conditions were restored in the pond.

Nitrate concentrations for other sites in ROMO ranged from 0.002 to 0.81 mg/L, some of which were the largest reported for high-elevation lakes in the Rocky Mountains (Burns, 2004). As mentioned previously, elevated nitrate in surface water is attributed to atmospheric deposition of nitrogen, which is released to the atmosphere by fossil fuel combustion and agricultural activities. When the availability of inorganic nitrogen exceeds biological demand, the ecosystem reaches nitrogen saturation and nitrate begins leaching to surface waters (Williams and others, 1996). The degree to which nitrogen saturation is occurring in ROMO is illustrated by temporal and spatial patterns in surface-water nitrate concentrations. Concentrations are lowest in summer when biological demand is high, then increase rapidly through fall and early winter once the growing season ends (fig. 26). Concentrations peak again in late April and early May because of elution from the snowpack and flushing of soils during the early stages of snowmelt (Campbell and others, 1995). This seasonal pattern is typical of watersheds in the northeastern U.S. that receive much higher loadings of atmospheric nitrogen (Burns, 2004). Nitrate concentrations in east-side lakes were found to be significantly higher than west-side lakes indicating ecosystems on the east side may be at a more advanced stage of nitrogen saturation

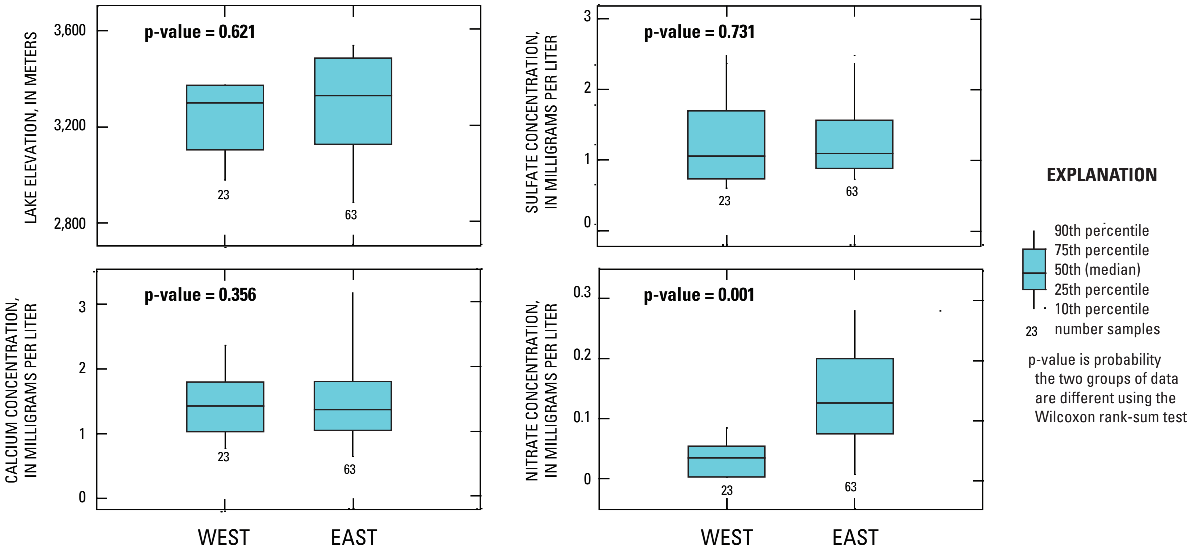

Figure 27. Comparison of water-quality data for selected lakes on the east and west sides of the Continental Divide in Rocky Mountain National Park, Colorado.

(fig. 27). Some studies indicate this may reflect higher deposition rates east of the Continental Divide because of proximity to nitrogen source areas (Baron and others, 2000). Other studies have shown that variations in vegetation and soil cover, and the distribution of talus deposits explain most of the spatial variation in nitrate concentrations (Clow and Sueker, 2000; Sueker and others, 2001). In contrast to nitrogen, phosphorus species showed much lower concentrations. More than 99 percent of orthophosphate concentrations were below 0.01 mg/L, and 90 percent of total phosphorous concentrations were below 0.05 mg/L.

Concentrations for only four trace elements were reported for lakes and ponds sampled in ROMO: aluminum, iron, manganese, and strontium (table 30). Aluminum concentrations ranged from 0.02 to 160 µg/L and concentrations generally were higher during the snow-free season particularly during snowmelt. Higher aluminum concentrations during runoff could be related to increased suspended sediment in surface water or flushing of organically complexed aluminum from soils. Iron concentrations ranged from less than 2 to 800 µg/L and manganese ranged from less than 1 to 520 µg/L. The majority of iron and manganese concentrations above 50 µg/L were reported for bottom-water samples collected from lakes during late winter and early spring (fig. 26). This occurrence is caused by depletion of dissolved oxygen at the bottom of the lake during winter stratification, which allows buildup of iron and manganese generated by anaerobic respiration reactions in the lake sediments. Strontium concentrations ranged from 2 to 442 µg/L and were highest in samples collected from shallow pond sites. These samples also had fairly high concentrations of major constituents, including chloride, indicating they may have been elevated by evaporative processes in the ponds and surrounding wetlands. Strontium also was found to be strongly correlated with calcium, indicating it is derived from the same source. Using strontium isotopes as a tracer, Clow and others (1997) determined that weathering of plagioclase, calcite, and eolian dust was the main process controlling calcium (and strontium) concentrations in surface water in LVWS.

Sufficient data to test for trends in water quality with time were available for one lake site and three stream sites, all of which are in LVWS (table 31, fig. 24). All sites were tested for trends in discharge and major-constituent and nitrate concentrations, except for Sky Pond, which was not gaged for streamflow. Sky Pond and The Loch, which had the longest records, were tested from 1984 to 2004, and Andrews Creek and Icy Brook were tested from 1992 to 2004. Statistically significant (p-value ≤ 0.01) upward trends were detected for several constituents although none of the sites had trends in discharge. From 1984 to 2004, Sky Pond and The Loch had upward trends in unadjusted alkalinity and sodium, and The Loch also showed upward trends in unadjusted calcium, magnesium, and nitrate concentrations that were similar in magnitude to trends detected using flow-adjusted concentrations. Andrews Creek had significant trends in calcium, magnesium, potassium, sodium, sulfate, and nitrate that were similar between unadjusted and flow-adjusted concentrations from 1992 to 2004. Icy Brook had similar trends during the same period in unadjusted calcium, magnesium, and sodium concentrations that were not significant in the flow-adjusted concentrations.

Three of the four sites had statistically significant increases in surface-water nitrate concentrations, which could reflect long-term increases in atmospheric deposition of nitrate and ammonia. Baron (2006) determined that total nitrogen deposition in LVWS has increased by 2.5 percent per year since 1984 because of increases in nitrogen emissions from fossil fuel and agricultural sources. The magnitude of the deposition trend was similar to nitrate in The Loch, which increased about 3 percent per year since 1984. Increases in strong acid anions (nitrate and sulfate) because of acidic deposition often are offset by declines in the acid neutralizing capacity (or alkalinity) of streams (Galloway and others, 1983). Interestingly, none of the streams showed declines in alkalinity and The Loch actually had a slight upward trend from 1984 to 2004. The increase in stream-water nitrate appeared to be associated with increases in cation concentrations, particularly calcium and magnesium This could reflect leaching of base cations from the soil by acidic compounds (sulfuric and nitric acids), which is a common watershed response to acidic precipitation (Galloway and others, 1983).

An alternative explanation for the observed trends in stream-water quality could be patterns in climate, particularly precipitation amount. Although there were no detected trends in discharge, only daily discharge associated with each water-quality sample was tested, which is probably insufficient for detecting long-term trends in streamflow. From 1995 to 2004, annual precipitation amount at the NADP station in LVWS showed a statistically significant ($p = .010$) downward trend, reaching a minimum in 2002 during a regional drought (fig. 28). A time-series plot of calcium for The Loch shows that most of the increase in concentration occurred over the last decade, which is coincident with the decline in annual precipitation (fig. 28). Because seasonality strongly affects chemical concentrations in most high-elevation streams, the seasonal patterns of concentrations may differ from year to year, depending on the amounts of snowfall and summer rainfall as well as other climate variables, such as temperature (Campbell and others, 1995). To some degree, both acidic deposition and precipitation amount are likely driving water-quality trends, and continued monitoring will be crucial for sorting out the relative importance of these processes.

Comparison to Water-Quality Standards. Water-quality use classifications and standards for all stream segments in Colorado are established by the CDPHE (Colorado Department of Public Health and Environment, 2003). All tributaries, wetlands, lakes, and reservoirs in ROMO are included in segment 1 of the Upper Colorado River Basin, segment 1 of the Saint Vrain Creek, segment 1 of the Big Thompson River, and segment 1 of the Cache La Poudre River (Colorado Department of Public Health and Environment, 2006). The classified uses for these segments are cold-water aquatic life class 1, recreation 1a, agriculture, and water supply. None of these segments were listed in 2006 as impaired by the

Table 31. Results of the seasonal Kendall test for trends in streamflow and unadjusted and flow-adjusted constituent concentrations for Rocky Mountain National Park, Colorado.

[--, not calculated or flow model not statistically significant at $p \leq 0.1$; ft^3/s/yr, cubic feet per second per year; mg/L/yr, milligrams per liter per year; ; N, nitrogen; trends in bold are significant at $p \leq 0.01$]

Parameter	Unadjusted		Flow-adjusted		Period of record
	trend	p-value	trend	p-value	
Sky Pond (S78)					
pH (standard units/yr)	0.018	0.057	--	--	1984–2004
Alkalinity (mg/L/yr)	**.026**	.007	--	--	1984–2004
Calcium (mg/L/yr)	.016	.051	--	--	1984–2004
Chloride (mg/L/yr)	<.001	.152	--	--	1984–2004
Magnesium (mg/L/yr)	.003	.027	--	--	1984–2004
Potassium (mg/L/yr)	<.001	.951	--	--	1984–2004
Silica (mg/L/yr)	.022	.056	--	--	1984–2004
Sodium (mg/L/yr)	**.010**	.003	--	--	1984–2004
Sulfate (mg/L/yr)	.027	.047	--	--	1984–2004
Nitrate (mg as N/L/yr)	.006	.030	--	--	1984–2004
The Loch (S83)					
Streamflow (ft^3/s/yr)	<0.01	0.751	--	--	1984–2004
pH (standard units/yr)	.015	.035	--	--	1984–2004
Alkalinity (mg/L/yr)	**.025**	.010	**0.021**	0.004	1984–2004
Calcium (mg/L/yr)	**.024**	.001	**.022**	.004	1984–2004
Chloride (mg/L/yr)	.003	.015	.002	.037	1984–2004
Magnesium (mg/L/yr)	**.005**	.001	**.004**	.001	1984–2004
Potassium (mg/L/yr)	.002	.095	.001	.171	1984–2004
Silica (mg/L/yr)	.021	.059	.021	.078	1984–2004
Sodium (mg/L/yr)	**.013**	.001	**.011**	.001	1984–2004
Sulfate (mg/L/yr)	.032	.032	.031	.020	1984–2004
Nitrate (mg as N/L/yr)	**.008**	.001	--	--	1984–2004
Andrews Creek (USGS station 401723105400000)					
Streamflow (ft^3/s/yr)	-0.003	0.610	--	--	1992–2004
pH (standard units/yr)	-.011	.094	-0.012	0.050	1992–2004
Alkalinity (mg/L/yr)	.005	.349	.003	.644	1992–2004
Calcium (mg/L/yr)	**.043**	.001	**.045**	.003	1992–2004
Chloride (mg/L/yr)	.003	.049	.003	.043	1992–2004
Magnesium (mg/L/yr)	**.007**	.003	**.007**	.004	1992–2004
Potassium (mg/L/yr)	**.004**	.009	.004	.012	1992–2004
Silica (mg/L/yr)	.034	.013	.026	.039	1992–2004
Sodium (mg/L/yr)	.013	.011	**.012**	.008	1992–2004
Sulfate (mg/L/yr)	**.063**	.009	**.064**	.003	1992–2004
Nitrate (mg as N/L/yr)	**.023**	.001	**.024**	.001	1992–2004
Icy Brook (USGS station 401707105395000)					
Streamflow (ft^3/s/yr)	<0.01	0.589	--	--	1992–2004
pH (standard units/yr)	-.010	.229	--	--	1992–2004
Alkalinity (mg/L/yr)	.030	.044	--	--	1992–2004
Calcium (mg/L/yr)	**.045**	.004	0.047	0.018	1992–2004
Chloride (mg/L/yr)	.002	.219	--	--	1992–2004
Magnesium (mg/L/yr)	**.007**	.006	.007	.024	1992–2004
Potassium (mg/L/yr)	.003	.125	--	--	1992–2004
Silica (mg/L/yr)	-.005	.643	--	--	1992–2004
Sodium (mg/L/yr)	**.015**	.002	.015	.021	1992–2004
Sulfate (mg/L/yr)	.061	.030	.074	.070	1992–2004
Nitrate (mg as N/L/yr)	.016	.017	--	--	1992–2004

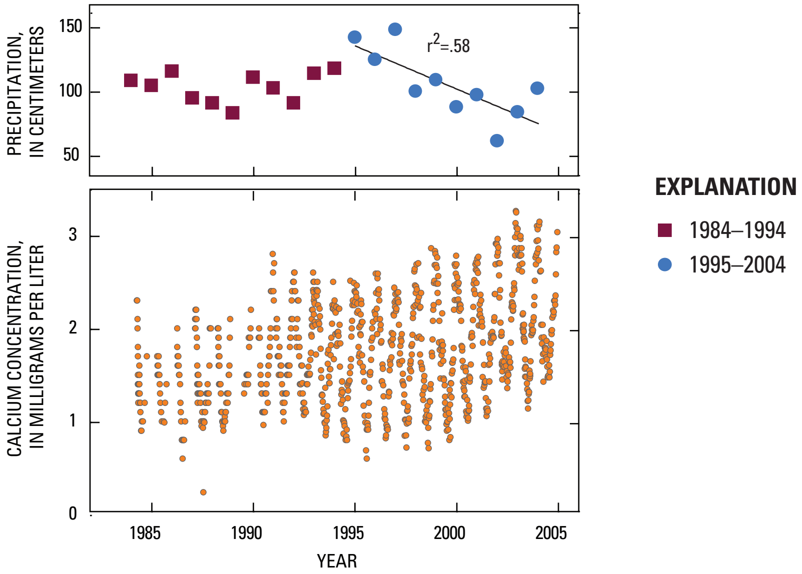

Figure 28. Temporal trends in annual precipitation at Loch Vale NADP station and calcium concentrations at The Loch (S33) in Rocky Mountain National Park, Colorado.

CDPHE (*http://www.cdphe.state.co.us/op/wqcc/SpecialTopics/303(d)/303dtmdlpro.html*, accessed November 2006). Overall, the water quality of the park is excellent; however, there were several samples that exceeded the aquatic-life standards for pH, ammonia, nitrate, and manganese (table 30). About 30 percent of samples had pH values that were less than the lower pH limit of 6.5. These low pH values reflect the naturally low alkalinity of lakes in the park. Several samples exceeded the standard for ammonium and nitrate, all of which were collected at the Kettle Tarn site. As mentioned previously, the unusually high nutrient concentrations at this site likely are related to development of anoxic conditions in the pond that occurred during the 2002 drought. Subsurface water samples from a few high-elevation lakes exceeded the manganese standard of 50 µg/L likely due to depletion of dissolved oxygen at the bottom of the lake during winter stratification.

There is a growing body of scientific data that indicates atmospheric deposition of nitrogen compounds has caused increases in nitrate concentrations of surface water and impairment of aquatic and terrestrial ecosystems. Current (2007) levels of nitrate in surface water do not exceed numeric standards that have been adopted for the classified uses; however, the standards do not directly apply to terrestrial or aquatic effects, other than cold-water fisheries. All surface water within the park boundary has “Outstanding Natural Waters” designation, which provides the highest level of regulatory protection provided under the Clean Water Act and Colorado regulations (Colorado Department of Public Health and Environment, 2006). Outstanding waters are protected under the Antidegradation Rule, which states that these waters shall be maintained and protected at their existing quality. The traditional program implementing this protection, however, regulates pollutants coming from point source discharges. Atmospheric deposition is not defined as point-source discharge, and the State of Colorado has not previously applied the Antidegredation Rule to non-point atmospheric sources (*http://www2.nature.nps.gov/air/Pubs/pdf/2005romoPolicyOptions.pdf*, accessed November 2006).

Ground-Water Quality

Water-quality data were collected at 30 ground-water wells within the boundaries of ROMO (table 32). For these 30 wells, there are 76 samples with 1,121 individual data results, most of which are field properties (20 percent), and major-constituent (51 percent) and nutrient (13 percent) analyses. Seven of the wells (G1–G7) were sampled once each by the USGS before 1980, although the purpose for the sampling could not be determined. These wells are located at relatively low elevations (below 2,800 m) in the vicinity of park facilities, and probably are supply wells. The remaining 23 wells are located in the LVWS and were sampled by the USGS as part of the Water, Energy, and Biogeochemical Budgets Program. All the wells in LVWS are shallow (0.3 to 1.8 m) observation wells that were installed in high-elevation wetlands (above 3,100 m) situated at the base of talus slopes (Bachman, 1994).

Water-quality summaries for the two groups of wells (LVWS and supply wells) in ROMO are presented in table 33. Ground water in LVWS is dilute and weakly buffered. Specific conductance ranged from 17 to 50 µS/cm, and alkalinity ranged from 3.3 to 22 mg/L. The major cations were calcium and sodium, and the dominant anion was bicarbonate (based on pH and alkalinity). Low dissolved solids in these wells are attributed to chemically resistant bedrock and short hydrologic residence times that are characteristic of high-elevation areas. Chloride (median 0.14 mg/L) and sulfate (median 2.9 mg/L)

Table 32. Ground-water sampling sites in Rocky Mountain National Park, Colorado.

[--, no data; identification numbers and station names from USGS NWIS]

Site no. (fig. 24)	Identification number	Station name	Latitude	Longitude	Well depth (meters)	Period of record	Number of samples
			Supply wells				
G1	401609105502000	Harbison Utility Well	40° 16’ 09”	105° 50’ 29”	--	1974	1
G2	401621105332500	SB00407334BBD	40° 16’ 21”	105° 33’ 25”	--	1971	1
G3	401807105503800	Onahu Well	40° 18’ 07”	105° 50’ 38”	--	1974	1
G4	401820105503300	Green Mountain Well 2	40° 18’ 20”	105° 50’ 33”	--	1974	1
G5	402252105511500	Timber Creek Campground	40° 22’ 52”	105° 51’ 15”	--	1974	1
G6	402253105510501	SB00507624ADC	40° 22’ 53”	105° 51’ 05”	30	1973	1
G7	402412105353001	B00507317ADB	40° 24’ 12”	105° 35’ 30”	31	1965	1
			Loch Vale wells				
G8	401707105394502	Well A020	40° 17’ 07”	105° 39’ 45”	1.3	1994	1
G9	401707105394503	Well A030	40° 17’ 07”	105° 39’ 45”	1.2	1994	1
G10	401711105394401	Well B010	40° 17’ 11”	105° 39’ 44”	1.3	1994, 2003	3
G11	401711105394402	Well B020	40° 17’ 11”	105° 39’ 44”	1.4	1994	2
G12	401711105394403	Well B030	40° 17’ 11”	105° 39’ 44”	1.3	1994	2
G13	401711105394404	Well B040	40° 17’ 11”	105° 39’ 44”	1.6	1994	2
G14	401711105394405	Well B050	40° 17’ 11”	105° 39’ 44”	1.3	1994	2
G15	401713105394601	Well C010	40° 17’ 13”	105° 39’ 46”	1.3	1994–95, 2003	14
G16	401713105394602	Well C020	40° 17’ 13”	105° 39’ 46”	1.1	1994	1
G17	401713105394603	Well C030	40° 17’ 13”	105° 39’ 46”	1.1	1994	1
G18	401713105394604	Well C040	40° 17’ 13”	105° 39’ 46”	1.0	1994	1
G19	401713105394605	Well C050	40° 17’ 13”	105° 39’ 46”	1.3	1994	1
G20	401713105394606	Well C060	40° 17’ 13”	105° 39’ 46”	1.3	1994	1
G21	401713105394607	Well C070	40° 17’ 13”	105° 39’ 46”	1.0	1994	1
G22	401713105394608	Well C080	40° 17’ 13”	105° 39’ 46”	1.3	1994	1
G23	401713105394609	Well C090	40° 17’ 13”	105° 39’ 46”	1.8	1994	1
G24	401713105394610	Well C100	40° 17’ 13”	105° 39’ 46”	1.4	1994	1
G25	401713105394611	Well C110	40° 17’ 13”	105° 39’ 46”	1.5	1994	1
G26	401713105394612	Well C120	40° 17’ 13”	105° 39’ 46”	1.1	1994	1
G27	401713105394613	Well C130	40° 17’ 13”	105° 39’ 46”	1.1	1994	1
G28	401723105400014	Well ASC1	40° 17’ 23”	105° 40’ 00”	.9	1996–2002	15
G29	401723105400015	Well ASC2	40° 17’ 23”	105° 40’ 00”	1.4	1996–2003	13
G30	401723105401600	Well AGT-1	40° 17’ 23”	105° 40’ 16”	.3	1996	2

concentrations also were low and likely are derived primarily from atmospheric sources. Nitrate concentrations ranged from 0.003 to 0.22 mg/L and were substantially lower than surface water in LVWS, which may reflect longer hydrologic residence times and greater capacity for nutrient uptake by the organic-rich sediments underlying the wetland. The water quality of the water-supply wells (G1–G7) was similar in composition to the LVWS wells, except that concentrations were as much as 10 times higher. These wells are deeper than those in LVWS and likely have much longer hydrologic residence times, resulting in greater opportunity for ground water to react with aquifer materials. None of the wells had sufficient data to determine seasonal patterns or temporal trends in ground-water quality. Ground-water samples collected from LVWS did not exceed any Colorado water-supply standards. One sample from the water-supply wells exceeded the secondary standard for iron, and two exceeded the secondary standard for manganese. Secondary standards are based on aesthetic properties such as taste, odor, and staining.

Summary and Suggestions for Vital Signs Monitoring

Review of historical water-quality records identified more than 7,800 samples collected at 122 lakes, 288 streams,

Table 33. Summary of selected water-quality data for ground-water sites in Rocky Mountain National Park, Colorado, 1971 to 2003.

[water-supply standards published by Colorado Department of Public Health and Environment (2006); <, less than; --, not reported; °C, degrees Celsius; µS/cm, microsiemens per centimeter at 25 °C; mg/L, milligrams per liter; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorous; µg/L, micrograms per liter]

Constituent or property	Loch Vale wells Minimum value	Loch Vale wells Median value	Loch Vale wells Maximum value	Supply wells Minimum value	Supply wells Median value	Supply wells Maximum value	Water-supply standard
Field properties							
Temperature, water (°C)	9.0	9.5	9.7	5.5	6.0	9.5	--
pH (standard units)	5.44	6.31	6.87	--	--	--	5.0–9.0
Specific conductance (µS/cm)	17	25	50	96	121	218	--
Major constituents							
Alkalinity (mg/L as $CaCO_3$)	3.3	5.6	22	35	62	100	--
Calcium, dissolved (mg/L)	1.7	2.4	4.5	11	16	30	--
Chloride, dissolved (mg/L)	.02	.14	.43	2.3	7.0	23	[a]250
Magnesium, dissolved (mg/L)	.23	.42	.93	1.9	2.4	7.3	--
Potassium, dissolved (mg/L)	.02	.06	.49	.9	1.5	2.0	--
Silica, dissolved (mg/L)	3.2	5.9	26	19	21	27	--
Sodium, dissolved (mg/L)	.54	1.0	3.1	4.1	7.0	13	--
Sulfate, dissolved (mg/L)	.46	2.9	5.2	3.0	6.1	9.0	[a]250
Other constituents							
Nitrate, dissolved (mg/L as N)	0.003	0.005	0.22	0.1	0.2	1.8	10
Orthophosphate, dissolved (mg/L as P)	--	--	--	<.01	<.01	.01	--
Carbon, organic (mg/L)	1.4	2.2	7.5	--	--	--	--
Iron, dissolved (µg/L)	--	--	--	20	60	1,300	[a]300
Manganese, dissolved (µg/L)	--	--	--	10	10	720	[a]50

[a] Secondary standard based on aesthetic properties such as taste, odor, and staining.

and 83 springs in ROMO from 1955 to 2004. More than one-half of the samples were collected at sites in LVWS for ecological research. Five streamflow-gaging stations currently (2007) are operated in the park, including Colorado River below Baker Gulch (USGS station 09010500), which began operation in 1953 and is the longest continuously operating station in the park. Surface water is a dilute calcium-sodium-bicarbonate type and dissolved solids primarily are derived from weathering of plagioclase and trace amounts of calcite in the crystalline bedrock. Nitrogen deposition rates have been increasing in the park during the past two decades, and current levels are estimated to be 15 to 20 times greater than the natural background level. Prolonged nitrogen deposition has caused nitrogen saturation resulting in chronically elevated levels of nitrate in some lakes and streams on the east side of the Continental Divide. Four sites had sufficient data to test for temporal trends in water quality. Upward trends were detected for nitrate (in three of the four sites tested) and base cations (all four sites), which were attributed to long-term increases in nitrogen deposition and declines in precipitation amount. All streams and lakes located entirely within the boundaries of ROMO are designated as Outstanding Natural Waters, which offers the highest level of protection. Ground-water quality and resources in the park are not well characterized and few water-quality data are available for this resource.

The primary water-quality issue in ROMO is the effect of atmospheric nitrogen deposition on high-elevation lakes and streams. Climate change may have long-term effects on water resources in the park. Based on a review of the historical data, the following suggestions are provided for consideration in designing a water-quality monitoring plan for ROMO.

- Establish long-term water-quality monitoring stations or “sentinel sites” at different elevations to capture gradients in deposition. Big Thompson at Moraine Park (USGS station 402114105350101) is suggested as a lower elevation site. This site has a USGS streamflow-gaging station and is sampled weekly to monthly as part of the USGS Hydrologic Benchmark Network for major constituents and nutrients. Andrews Creek or The Loch in LVWS is suggested as a possible high-elevation sentinel site.

- Conduct periodic surveys of high-elevation lakes in the park to monitor the effects of atmospheric deposition of pollutants.

- Conduct monitoring at selected surface-water sites to determine the effects of visitor use, park facilities, and roads on nutrients, sediment, and bacteria.
- Establish a network of streamflow-gaging stations and ground-water wells in the park to monitor the effect of climate change on water resources.

Summary

Historical data were assessed to describe water-quality conditions six National Park units that compose the Rocky Mountain Network. The park units in Colorado are Florissant Fossil Beds National Monument, Great Sand Dunes National Park and Preserve, and Rocky Mountain National Park; and in Montana they are Glacier National Park, Grant-Kohrs Ranch National Historic Site, and Little Bighorn Battlefield National Monument. This study was done in cooperation with the Inventory and Monitoring Program of the National Park Service to aid in the design of an effective and efficient water-quality monitoring plan for each park. Results for each of the parks are discussed separately in the report. Each section provides a brief description of the environmental setting of the park and an overview of the park's water resources. Statistical summaries of selected water-quality constituents are presented and compared to aquatic-life and drinking-water standards. Spatial, seasonal, and temporal patterns in constituent concentrations were examined to help identify natural and anthropogenic factors controlling water quality in each of the six parks. Suggestions are provided for consideration in designing water-quality monitoring plans. Issues of concern for water resources in the park include visitor use, land-use activities adjacent to the park, and climate change.

Florissant Fossil Beds National Monument is located on the eastern slope of the Colorado Front Range approximately 48 kilometers west of Colorado Springs, Colorado. Surface water in the area is a calcium-bicarbonate type, and dissolved solids primarily are derived from weathering of the underlying granite and lake-bed sediments. Land-use activities likely have a minor effect on water quality, although there is concern about future increases in visitor use and residential development in areas upstream from the park. Because of a lack of long-term monitoring sites, it was not possible to identify temporal trends in water quality. Water-quality data are available for one sample at each of the two ground-water wells in the park. One of the wells exceeded the drinking-water standard for fluoride and the other well exceeded secondary standards for manganese and iron. Elevated fluoride in the ground water is attributed to natural weathering of fluoride-rich bedrock that underlies the park. Issues of concern for water resources in the park include visitor use, land-use activities adjacent to the park, and climate change.

Glacier National Park is located in the northern Rocky Mountains in northwestern Montana and is bounded to the north by Canada. The North and Middle Forks of the Flathead River border the park on the west and south, and the park is bisected by the Continental Divide. Surface water is a moderately dilute calcium-bicarbonate type, and dissolved solids primarily are derived from weathering of carbonate minerals in the sedimentary bedrock. Wildfire was determined to be an important control on stream-water nutrients in areas of the park burned during 2003. Five sites had sufficient data to test for temporal trends in water quality. The only detected trends were attributed to analytical-method-related factors, rather than environmental change. Ground-water quality and resources in the park are not well characterized, and no water-quality data are available for the park for the past 25 years. Some water-quality issues in the park include effects of visitor use and park facilities, atmospheric deposition of pollutants to high-elevation lakes, and land-use activities in areas outside the park draining the North and Middle Forks of the Flathead River. Climate change may have long-term effects on water resources in the park.

Grant-Kohrs Ranch National Historic Site is located at the north end of the Deer Lodge Valley in western Montana. One-half of the water-quality samples were collected at the Clark Fork River at Deer Lodge. Water in the Clark Fork River is a calcium-bicarbonate-sulfate type and major constituents primarily are derived from weathering of rock fragments in the alluvial fill except sulfate, which is released from oxidation of pyrite present in mine wastes. Arsenic, cadmium, copper, lead, manganese, and zinc, which are trace elements associated with mine wastes from historical mining activities, commonly were measured at detectable concentrations in the river. Nutrients in the river were mainly human-derived related to wastewater discharge and agriculture. Statistically significant downward trends detected in dissolved calcium, sulfate, and zinc in the Clark Fork River can be attributed to remediation and restoration efforts during the 1980s and early 1990s. Ground water is a calcium-bicarbonate type with moderately high dissolved solids (213 to 536 milligrams per liter). Nutrient concentrations in ground water were low, indicating minimal effects from agricultural activities in the park. Samples from 4 of the 21 ground-water wells exceeded the human-health standard for arsenic, although none of the wells are used as a water supply. Nutrient input from the sewage irrigation program and trace-element and sediment contamination related to mine tailings and their remediation are the primary water-quality issues for the reach of the Clark Fork River in Grant-Kohrs Ranch National Historic Site.

Great Sand Dunes National Park and Preserve is located along the eastern edge of the broad, flat San Luis Valley in south-central Colorado. Surface water is a calcium-bicarbonate type and dissolved solids primarily are derived from weathering of crystalline bedrock in the Sangre De Cristo Mountains. Visitor use and park facilities likely have a minimal effect on water quality, except perhaps in the lower reaches of Medano Creek. Preliminary data indicate that lakes at high elevations in the park may be in early stages of nitrogen saturation because of atmospheric nitrogen deposition. Sufficient data were available to test for temporal trends in water quality only for field properties at one site, which showed no trends. Water-quality issues for the park include effects of visitor use and atmospheric deposition of pollutants, maintenance of potable water supplies, and attainment of Outstanding Natural Waters designation. The primary threats to water resources in the park are surface- and ground-water withdrawals and long-term climate changes.

The Little Big Horn Battlefield National Monument is located within the Little Bighorn River Valley in south-central Montana near the town of Crow Agency. Surface water is a calcium-bicarbonate-sulfate type, and major constituents primarily are derived from natural weathering processes. Agricultural activities upstream from the park may affect nutrient and sediment concentrations in surface water, particularly during periods of increased streamflow. Because of a lack of long-term monitoring data, it was not possible to identify temporal trends in the water quality of the river. The available water-quality data indicate the river in this reach meets Montana aquatic-life and human-health standards, except perhaps during periods of high sediment transport. The standard comparison, however, is based on relatively few samples and additional data would be needed to characterize water quality conditions during high flow. Ground water is a sodium-bicarbonate-sulfate type with elevated dissolved solid concentrations (more than 800 milligrams per liter). Nutrient concentrations in ground water were low, indicating minimal effects from agricultural activities outside the park. None of the ground-water samples exceeded human-health standards, although several exceeded the secondary standards for manganese and iron. Effects of agricultural activities outside the park on nutrient, bacteria, and sediment concentrations likely are the main water-quality issues for the Little Bighorn River.

Rocky Mountain National Park is located in the Colorado Front Range in north-central Colorado approximately 80 kilometers northeast of Denver. Surface water is a dilute calcium-bicarbonate type and dissolved solids primarily are derived from weathering of plagioclase and trace amounts of calcite in the crystalline bedrock. Nitrogen deposition rates have been increasing in the park during the past two decades, and current levels are estimated to be 15 to 20 times greater than the natural background level. Prolonged nitrogen deposition has caused nitrogen saturation resulting in chronically elevated levels of nitrate in some lakes and streams on the east side of the Continental Divide. Four sites had sufficient data to test for temporal trends in water quality. Upward trends were detected for nitrate and base cations, which were attributed to long-term increases in nitrogen deposition and declines in precipitation amount. Ground-water quality and resources in the park are not well characterized and few water-quality data are available for this resource. The primary water-quality issue in the park is the effect of atmospheric nitrogen deposition on high-elevation lakes and streams. Climate change may have long-term effects on water resources in the park.

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