

Snowpack Chemistry at Selected Sites in Northwestern Colorado During Spring 1995

by George P. Ingersoll

U.S. GEOLOGICAL SURVEY

Open-File Report 96-411

Prepared in cooperation with
ROUTT COUNTY, COLORADO, and the
COLORADO DEPARTMENT OF PUBLIC HEALTH AND ENVIRONMENT

Denver, Colorado
1996



U.S. DEPARTMENT OF THE INTERIOR
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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATIONS

Multiply	By	To obtain
centimeter (cm)	0.3937	inch
kilometer (km)	0.6214	mile
liter (L)	0.2643	gallon
meter (m)	3.281	foot

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

Degree Celsius (°C) may be converted to degree Fahrenheit (°F) by using the following equation:

$$^{\circ}\text{F} = 9/5 (^{\circ}\text{C}) + 32.$$

Abbreviations used for water-quality terminology:

microequivalent per liter (μeq/L)

micrometer (μm)

milligram per liter (mg/L)

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Abstract

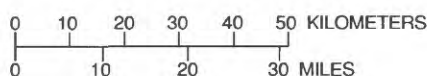
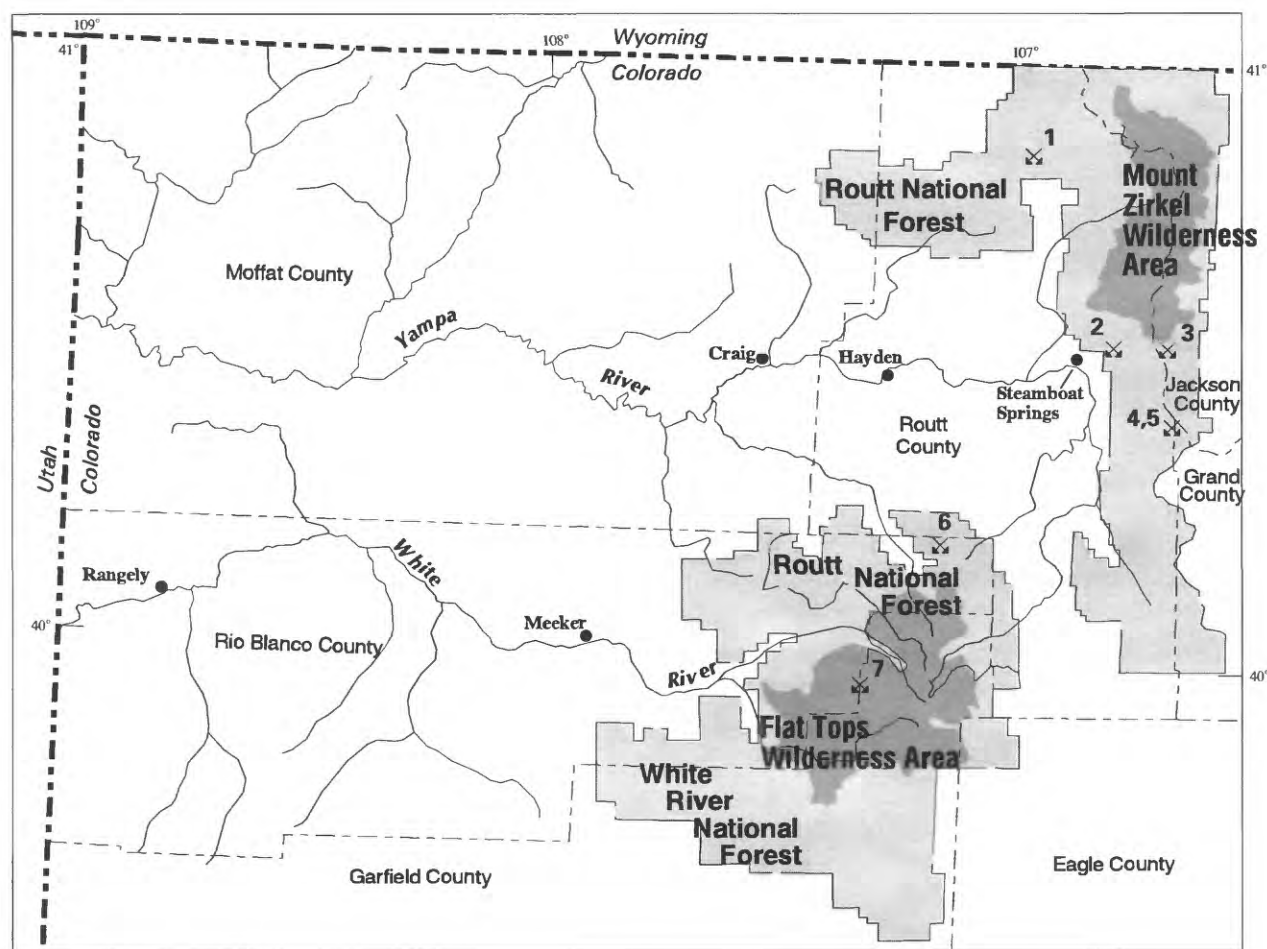
Samples of the alpine and subalpine snowpack were collected in and near the headwater basins of the Yampa River in northwestern Colorado during maximum annual accumulation of snowpack in spring 1995. Sampling protocol at seven selected sites at more than 2,500 meters above sea level divided the snowpack into two distinct strata to enable separate chemical analyses of upper and lower layers of the annual snow cover. These two layers correspond to the early snow season beginning in September until December 12, 1994, and the remainder of the season from January 1 until the sampling date in spring 1995. At one site these two strata were resampled at closely spaced intervals defining substrata to observe variance within the two strata dividing the snow season. Analytical results of snowpack chemistry are presented in support of investigations of seasonal effects on ion concentrations in the snowpack. Chemical concentrations of major anions and cations, dissolved organic carbon, and alkalinity; measured pH; calculated charge balance between anions and cations; the stable-sulfur isotope ratio ($^{34}\text{S}/^{32}\text{S}$); and summary statistics of chemical concentrations are tabulated. Sampling sites are plotted on a map of the area. Spatial distributions of the concentrations of the hydrogen, nitrate, and sulfate ions and stable-sulfur isotope ratios also are mapped.

Several unusual, late-season, snowfall events occurred during April and May of 1995 after the snowpack was sampled at most of the seven sites in the study area. Consequently, a considerable fraction of the total annual snowpack was not sampled. At one site, the full snowpack was sampled again in June, after the late-spring storms, for comparison to the chemistry of the snowpack sampled earlier in April. Precipitation chemistry from a National Atmospheric Deposition Program (NADP) collector located near the site is presented for comparison of the chemistry of the late-season snow to that of the typical annual snowpack season.

INTRODUCTION

The U.S. Geological Survey (USGS) has established sites in northwestern Colorado for long-term monitoring of snow and lake chemistry. During spring 1995, the USGS, in cooperation with Public Service Company of Colorado and Routt County, Colorado, collected data on concentrations of major chemical species in the snowpack at seven sites in northwestern Colorado (fig. 1). This report summarizes information related to the spring 1995 snowpack sampling and includes snowpit site selection, sample timing, sampling protocol, laboratory analytical methods, concentrations of major chemical constituents, relative amounts of the stable-sulfur isotope ratio, and summary statistics. The spatial distributions of these chemical concentrations in the annual snowpack are shown on maps.

Snow samples were collected at most sites during March and April 1995, when annual snow accumulations typically are maximum. However, the spring of 1995 was unusual. Several late-season snowstorms occurred during April and May after most snow samples were obtained in the study area. Snowpack water content at Rabbit Ears Pass (2,940 m above sea level) was twice the 30-year average for mid-May; the higher Buffalo Pass snowpack (3,140 m above sea level) doubled the 30-year norm for mid-June. As a result of the late-season accumulation, a considerable fraction of the total annual snowpack was not sampled at most sites. A second sampling was performed at the Buffalo Pass site in June, 7 weeks after the initial sampling in April. The chemistry of these two samples from the same site before and after the storms of April and May is listed for comparison. Additional snow-melt chemistry from a National Atmospheric Deposition Program (NADP) precipitation collector located near the Buffalo Pass site is shown for comparison of concentrations of major ions in the late-season snow and that of the typical snowfall season.



EXPLANATION

7 SNOWPIT SITE—Number refers to site numbers listed below. Location of snowpit sites is approximate.

- 1 Elk River
- 2 Dry Lake
- 3 Buffalo Pass
- 4 Rabbit Ears Pit 1
- 5 Rabbit Ears Pit 2
- 6 Dunckley Pass
- 7 Ned Wilson



COLORADO

Figure 1. General location of selected snowpit sampling sites in northwestern Colorado.

Background

Chemical concentrations in surface waters and snow have been monitored at sites in the alpine and subalpine areas of northwestern Colorado since the mid-1980's (Turk and others, 1992, 1993). Synoptic snow sampling of the maximum-accumulation snowpack was performed at these sites for water years 1991–94. The snow-chemistry data for 1995 presented here provide a reference for past, current, and future concentrations of chemical constituents in snow in alpine and subalpine regions of northwestern Colorado and support long-term monitoring studies of the surface-water quality in the study area.

In water years prior to 1993 in northwestern Colorado, snowpack chemistry was assessed using samples of the full snowpack column. The sampling method used at the sites presented in this report involves dividing the snowpack into two strata (upper and lower) to document chemistry of the annual snow cover in the two layers separately. Details of the sample-collection procedures are presented in the “Data-collection methods and sampling protocol” section.

Sampling by upper and lower snow strata first was done in the area in and around the Mount Zirkel Wilderness Area in the spring of 1993 (John Turk, U.S. Geological Survey, written commun., 1993). The upper and lower strata of the 1994 and 1995 snowpacks also were sampled during spring to examine the seasonal changes in the snowpack chemistry and to assess changes in ionic concentrations in the annual snowpack. Data from 1994 are presented in Ingersoll (1995).

Study Area Description

The seven sampling sites are located near Steamboat Springs in northwestern Colorado near the headwaters of the Yampa River (fig. 1). Public lands in the Routt and White River National Forests surround the sampling sites. Bedrock, tundra grasses, aspen, and conifers dominate the landscape, and sites are at least 50 m from roadways to minimize contamination from vehicular traffic. The seven sites are at elevations of more than 2,500 m above sea level where the seasonal snowpack is maintained throughout the winter, and substantial melt does not occur until spring runoff. Winter and spring temperatures typically drop below freezing nightly and preserve a cold snowpack until late March to early May, depending on elevation. Snowpack at the lowest site, Dry Lake, at 2,530 m above sea level, begins to melt in the latter part of March or early April; the highest site, Ned Wilson, at 3,400 m elevation, is snow-covered well into May most years. Snow cover remained into July 1995 due to the heavy, late-spring snows. Accessibility to sampling locations required various methods of transportation during the maximum-snowpack timeframe; helicopters and over-snow vehicles were necessary to reach the remote sampling sites. Distances from plowed roadways ranged from about 50 m to 12 km.

Acknowledgments

Cooperation from many sources including the Colorado Department of Public Health and Environment; Public Service Company of Colorado; Routt County, Colorado; Tri-State Generation and Transmission Association; and the U.S. Forest Service made these analyses possible.

DATA-COLLECTION METHODS AND SAMPLING PROTOCOL

Snowpit Site Selection

Sampling site locations were chosen to represent the alpine and subalpine terrain surrounding the headwaters of the Yampa River (fig. 1) at the same locations as in previous years (Ingersoll, 1995). Snowpits were positioned in reasonably level clearings in forests where trees provided windbreaks and facilitated uniform snow accumulation. Snow cover free of onsite anthropogenic effects or other disturbances such as excessive tree litter or animal activity was chosen for sampling. Scoured or drifted areas were avoided because such areas would not best represent a cumulative seasonal snowpack that contained layers from all snowfall events. When possible, sites were collocated with Natural Resources Conservation Service snow-telemetry (SnoTel) instrument sites where

measurements of snow-water equivalence (SWE) were reported daily. These SWE values from SnoTel sites in turn were used to define the boundary between the separate snow strata sampled.

Sample Timing

The timing of maximum seasonal snowpack accumulation for water year 1995 (WY95, October 1994–September 1995) snowfall events was estimated from 30-year-averaged, maximum-SWE values reported from SnoTel sites near the sampling sites. Where SnoTel instrumentation was not collocated with a sampling site, the nearest SnoTel site at a similar elevation was used to estimate daily amounts of SWE. Biweekly SWE values for the 30-year period 1961–90 were used to forecast timeframes when snowmelt might begin. Sampling dates were scheduled 2 or 3 weeks before the forecasted maximum SWE timeframe to collect samples before episodes of earlier-than-usual melting, thereby reducing the chance of loss of chemical solutes held in the snowpack throughout the winter and spring. Because the late-spring snows of 1995 extended the time of maximum annual snowpack accumulation by several weeks, sampling at most sites was from 45 to 58 days before the actual dates of maximum accumulations at the reference SnoTel sites. An exception was the Ned Wilson site, which was sampled on June 2, 1995, several weeks later than the other six sites. Unsuitable weather during the succession of late-season storms in April and May of 1995 prevented earlier helicopter access. Other means of access to this remote site by skis or over-snow vehicles were either infeasible or restricted. Thus, the snowpack was sampled at Ned Wilson two days after the annual maximum snow accumulation reported at the nearest SnoTel site at a comparable elevation.

Sampling Protocol

The total depth of the seasonal snowpack for WY95 was divided into upper and lower layers corresponding to the annual snow cover accumulated during two time periods: The beginning of the season in September until December 12, 1994, and the remainder of the season from January 1 until the sampling date in spring 1995. A buffer zone of the snowpack between the upper and lower layers of snow corresponding to the time interval December 12, 1994, to January 1, 1995, was not sampled in order to reduce the possibility of overlap of the upper and lower layers. Thicknesses of these buffer zones not sampled at the seven sampling sites ranged from 10 to 30 cm; total snow depths ranged from 122 to 385 cm.

Approximating the location of this buffer zone defining the boundary between upper and lower strata was done by locating sample snowpits near SnoTel sites, if possible, and using cumulative SWE values measured daily at the SnoTel sites for the time interval bounding the buffer zone. SnoTel SWE values from three dates were used to approximate the buffer zone delimiting the upper and lower strata: (1) The date used as the final day of accumulation of the lower strata, December 12, 1994; (2) the date marking the beginning of the upper strata, January 1, 1995; and (3) a date close to the actual sampling date. Density measurements were made in each of the snowpits at the seven sites where snow samples were collected, and SWE was computed at 10- or 20-cm intervals vertically throughout the snowpack. The percentage of SWE reported at a nearby SnoTel site was calculated for the dates December 12, 1994, and January 1, 1995, relative to a recent day before the sampling date.

These percentages of accumulated SWE at the SnoTel sites prior to the dates December 12, 1994, and January 1, 1995, were applied to the total SWE measured in the sample snowpits to estimate the amount of SWE at the boundaries of the buffer zone between the upper and lower strata. For example, the Buffalo Pass snowpit was prepared and sampled on April 5, 1995. A record of the measured SWE at the nearest SnoTel site was available for the entire season up to April 3, 1995. The SWE reported from the SnoTel site for April 3, 1995 (representing cumulative SWE to date for WY95), was used to calculate the percentage of total SWE on December 12, 1994, and January 1, 1995. Reported values of SWE for December 12, 1994, January 1, 1995, and April 3, 1995, were 33.0, 41.9, and 116 cm, respectively. Dividing the SWE for each date defining the buffer zone timeframe by the cumulative SWE on the last reported day before sampling (April 3, 1995) gives $33.0/116 = 0.28$ or 28 percent, corresponding to December 12, 1994, and $41.9/116 = 0.36$ or 36 percent, corresponding to January 1, 1995. By December 12, 1994, 28 percent of the SWE reported for the whole snow season as of April 3, 1995, was present at the SnoTel site; by January 1, 1995, 36 percent of the SWE for the period was reported. Measured SWE values were summed at 10- or 20-cm intervals in a vertical profile from the bottom

to the top of the snowpack in the sample snowpits. SWE values at positions on the cumulative SWE profile corresponding to the percentage (as in the example above) of cumulative SWE reported at SnoTel sites were cross-referenced to depth and identified the buffer-zone boundaries. In the previous example, 28 percent of the measured SWE in the Buffalo Pass pit was taken as the upper limit of the lower stratum, and 36 percent of the measured SWE was taken as the lower limit of the upper stratum.

At one of the seven sites sampled in 1995, Rabbit Ears Pit 1, the two distinct strata were sampled in the same manner as at the other sites, but the upper and lower strata were resampled at closely spaced intervals to observe variance within the two main strata dividing the snow season. These substrata of the upper and lower strata were sampled to determine whether seasonal differences in chemistry between the upper and lower strata were more significant than differences between substrata within the upper or lower strata. Snow collected from the substrata represents fractions of the snow season and more nearly corresponds to individual storm events.

Snowpits were prepared with a smooth, freshly cut, vertical face extending from the ground surface upward throughout the entire depth of the snowpack. Separate samples were collected for each of the upper and lower layers. The bottom 10 cm of the snowpack was not sampled to avoid inclusion of forest litter and soils in the samples. Accordingly, the top 5 cm of snowpack was discarded to exclude snow contaminated by activities resulting from transport to and preparation of the snowpit. Latex laboratory gloves were worn, and clean plastic shovels and scoops were used to collect a vertical snow column for each sample representative of the entire stratum to be analyzed. The snow columns were cut and placed in prerinsed 8-L Teflon bags and 60-L plastic carboys. These containers were sealed against contamination and transported to the USGS Regional Research Laboratory in Boulder, Colorado, for analysis.

ANALYTICAL METHODS

Snow samples were melted in the Teflon collection bags and were processed within 12 hours by using a variety of analytical procedures. Samples were maintained below 4°C during melting and analysis. Major cation concentrations were determined on filtered (0.45 µm), acidified aliquots using two emission-spectroscopy techniques—inductively coupled plasma [for species: calcium (Ca^{2+}), magnesium (Mg^{2+}), and sodium (Na^+)] and atomic absorption [for potassium (K^+) only]. Chloride (Cl^-) and sulfate (SO_4^{2-}) concentrations were determined on filtered (0.45 µm) aliquots by ion chromatography. Nitrate (NO_3^-) and ammonium (NH_4^+) ion concentrations were analyzed on filtered (0.45 µm), frozen subsamples by air-segmented, continuous-flow colorimetry. Detection limits were 0.5, 0.5, 1.0, 0.3, 0.5, 0.4, 0.2, 0.5 µeq/L for Ca^{2+} , Mg^{2+} , Na^+ , K^+ , Cl^- , SO_4^{2-} , NO_3^- , and NH_4^+ , respectively. Analysis of the stable-sulfur isotope ratio ($^{34}\text{S}/^{32}\text{S}$) used mass spectrometry to determine the $\delta^{34}\text{S}$ values in parts per mil relative to the $\delta^{34}\text{S}$ value for the standard reference Canyon Diablo Troilite (Faure, 1986). Specific conductance was measured with a platinum electrode; pH was determined with a combination glass electrode designed for low ionic-strength waters. Alkalinity was determined using a Gran titration method. Dissolved organic carbon (DOC) levels were obtained using infrared detection.

Quality control involved systematically analyzing deionized-water (DI) blanks, an internal reference sample, and USGS standard reference water samples. Water from Chaos Creek in Rocky Mountain National Park, Colorado, was selected as the internal reference sample to monitor instrument precision because of its similarity of ionic strength compared to snowmelt from the sites reported here. Approximately 40 percent of sample batch run time for the analytical instrumentation was dedicated to analyzing blanks, duplicates, reference samples, and standards. Calibration verifications were made with standards at the beginning and end of each batch of sample analyses. Processing blanks were analyzed to detect possible contamination from DI rinse water, filtering apparatus, and the Teflon collection bags. A duplicate snowpit (Rabbit Ears Pit 2) was sampled at Rabbit Ears Pass as quality control of field methods. Charge balance was calculated between anions and cations to check the quality of the analyses.

SNOWPACK CHEMICAL CONCENTRATIONS

Snowpack water equivalent and chemical concentrations are presented in tables 1, 3, 5, and 7, and a table summarizing basic statistics of the chemical concentrations (means, standard deviations, number of samples, minimum value, and maximum value) follows each data table (tables 2, 4, 6, and 8). Relative values for concentrations of H^+ , SO_4^{2-} , NO_3^- , and $\delta\text{-}^{34}\text{S}$ in upper and lower strata are shown geographically for each sample location in figures 2 through 5.

The late-season snowstorms in the spring of 1995 resulted in a considerable fraction of the seasonal snowpack that was not sampled. To compensate for this, the Buffalo Pass site was resampled after the April and May 1995 snowstorms to define the difference between chemical levels in the snow sampled on April 5, relative to those of snow sampled at the site on June 1, 1995. Chemical concentrations in the second Buffalo Pass snowpack sample represent the entire snowpack accumulated from October 1994, until June 1, 1995, and are listed in tables 1 and 3 as Buffalo Pass II. The Buffalo Pass site was chosen among the others in the study area to be sampled a second time for two main reasons. First, the high elevation (3,140 m) preserved the seasonal snowpack against melting throughout the unusual, late-spring snowstorms until about the time of the annual maximum accumulation. Second, accessibility to the site by snowmobile in cloudy weather conditions (that would restrict helicopter access) made the second sampling effort at the Buffalo Pass site independent of the weather.

Further comparisons of the snow chemistry before and after the late-season snowstorms can be made with the NADP chemical concentrations from a precipitation collector located near the Buffalo Pass snowpit site. Monthly volume-weighted mean concentrations of major ions from the NADP collector are listed (table 9) for comparison of the chemistry of the late-season snow to that of the typical snow-accumulation season (tables 1, 3, 5, and 7).

A comparison of snow chemistries from different timeframes of the annual snowfall season can be made with data from the Ned Wilson site (tables 1 and 3). There, the snowpack was sampled from three distinct strata: lower, middle, and upper. SWE reported at the nearest SnoTel site of a similar elevation was used to define the three strata in the Ned Wilson snowpit in the same manner as with the other sites in the study area. The upper strata at the Ned Wilson site represents the snowfall deposited from April 5 to June 2, 1995, and corresponds to the late-season snowfall that accumulated after the Buffalo Pass site was initially sampled. This comparison between the Ned Wilson and Buffalo Pass sites was made because they are the two highest sites in the study area and have similar deep, cold snowpacks and because both were sampled after the unusual late-spring snows. Thus, additional comparisons can be made of snowpack chemical concentrations before and after the late-season snowfall that was not sampled at the other five sites.

Table 1. Snow-water equivalent (SWE), concentrations of dissolved organic carbon (DOC), pH, and cations [hydrogen (H⁺), ammonium (NH₄⁺), calcium (Ca²⁺), magnesium (Mg²⁺), sodium (Na⁺), and potassium (K⁺)] for all sites and strata

[(u), upper strata; (m), middle strata; (l), lower strata; (f) full snowpack; SWE in centimeters; DOC in milligrams per liter; pH in standard units; cations in microequivalents per liter; <, less than]

Sampling site name	Sampling date	SWE	DOC	pH	H ⁺	NH ₄ ⁺	Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺
Buffalo Pass (u)	04-05-95	69.0	0.6	4.81	15.5	6.2	5.0	0.8	<1.0	<0.3
Buffalo Pass (l)	04-05-95	33.3	0.5	4.98	10.5	5.0	5.0	0.8	1.3	<0.3
Buffalo Pass II (f)	06-01-95	166	0.9	4.89	12.9	7.6	8.5	1.6	<1.0	0.5
Dry Lake (u)	03-13-95	22.6	0.6	4.67	21.4	8.2	6.5	1.6	1.7	0.5
Dry Lake (l)	03-13-95	15.1	0.7	4.71	19.5	4.8	5.5	0.8	1.3	<0.3
Dunkley Pass (u)	03-30-95	20.3	2.2	5.37	4.3	4.9	19.0	3.3	2.2	3.8
Dunkley Pass (l)	03-30-95	16.6	2.0	5.48	3.3	3.9	12.0	2.5	<1.0	5.4
Elk River (u)	03-13-95	25.4	0.7	4.92	12.0	6.1	7.0	1.6	1.3	<0.3
Elk River (l)	03-13-95	16.0	0.8	5.03	9.3	4.7	10.0	0.8	<1.0	0.8
Ned Wilson (u)	06-02-95	26.5	0.4	5.75	1.8	2.9	5.5	0.8	<1.0	<0.3
Ned Wilson (m)	06-02-95	57.0	1.2	5.60	2.5	5.0	14.0	1.6	1.7	0.8
Ned Wilson (l)	06-02-95	25.1	0.8	5.31	4.9	2.5	4.7	0.9	<1.0	<0.3
Rabbit Ears Pit 1 (u)	03-30-95	46.9	0.6	4.81	15.5	5.7	4.7	0.9	1.6	<0.3
Rabbit Ears Pit 1 (l)	03-30-95	16.8	1.5	5.08	8.3	6.7	6.3	1.7	1.8	3.8
Rabbit Ears Pit 2 (u)	03-30-95	43.7	0.7	4.85	14.1	6.9	5.4	1.0	<1.0	0.5
Rabbit Ears Pit 2 (l)	03-30-95	13.7	1.0	4.95	11.2	4.6	5.5	1.4	1.1	1.0

Table 2. Summary statistics of snow-water equivalent (SWE), dissolved organic carbon (DOC), pH, and cations listed in table 1

[SWE in centimeters; DOC in milligrams per liter; for pH statistics, the *median* is listed in place of the mean; cations in microequivalents per liter; values below detection limits were set to zero in calculations]

	SWE	DOC	pH	H ⁺	NH ₄ ⁺	Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺
Mean	38.4	0.95	4.965	10.4	5.36	7.79	1.38	0.88	1.07
Standard deviation	37.7	0.53	Not calculated	5.99	1.57	4.07	0.71	0.83	1.69
Number of samples	16	16	16	16	16	16	16	16	16
Maximum	166	2.20	5.75	21.4	8.20	19.0	3.30	2.20	5.40
Minimum	13.7	0.40	4.67	1.80	2.50	4.70	0.80	0.00	0.00

Table 3. Concentrations of anions [chloride (Cl^-), sulfate (SO_4^{2-}), and nitrate (NO_3^-)], alkalinity, $\delta^{34}\text{S}$, and percent charge balance for all sites and strata

[(u), upper strata; (m), middle strata; (l), lower strata; (f) full snowpack; anions and alkalinity in microequivalents per liter; $\delta^{34}\text{S}$ in parts per mil]

Sampling site name	Sampling date	Cl^-	SO_4^{2-}	NO_3^-	Alkalinity	$^1\delta^{34}\text{S}$	Sum cations ² (table 1)	Sum anions	Percent charge balance ³
Buffalo Pass (u)	04-05-95	1.7	12.9	11.8	-15.4	7.5	27.5	26.4	2.0
Buffalo Pass (l)	04-05-95	0.6	10.4	8.8	-10.2	6.6	22.6	19.8	6.6
Buffalo Pass II (f)	06-01-95	1.1	15.2	12.3	-12.3	6.6	31.1	28.6	4.2
Dry Lake (u)	03-13-95	1.4	14.6	18.4	-21.7	8.1	39.9	34.4	7.4
Dry Lake (l)	03-13-95	0.9	10.4	19.5	-19.9	7.2	31.9	30.8	1.8
Dunkley Pass (u)	03-30-95	1.4	9.0	12.6	0.1	5.3	37.5	23.0	24.0
Dunkley Pass (l)	03-30-95	0.9	6.9	10.6	-0.3	6.2	27.1	18.4	19.1
Elk River (u)	03-13-95	2.0	10.0	14.3	-13.3	7.0	28.0	26.3	3.1
Elk River (l)	03-13-95	0.6	9.4	13.4	-10.7	5.4	25.6	23.4	4.5
Ned Wilson (u)	06-02-95	0.9	3.1	2.5	1.1	5.2	11.0	6.5	25.7
Ned Wilson (m)	06-02-95	1.1	7.7	9.0	-0.2	5.0	25.6	17.8	18.0
Ned Wilson (l)	06-02-95	0.9	4.2	7.9	-4.4	4.5	13.0	13.0	0.0
Rabbit Ears Pit 1 (u)	03-30-95	1.1	12.7	9.9	-15.7	7.5	28.4	23.7	9.0
Rabbit Ears Pit 1 (l)	03-30-95	1.1	10.2	10.7	-7.3	6.4	28.7	22.0	13.2
Rabbit Ears Pit 2 (u)	03-30-95	0.9	13.1	12.3	-14.4	7.3	28.0	26.3	3.1
Rabbit Ears Pit 2 (l)	03-30-95	0.9	10.2	10.1	-10.4	6.6	24.9	21.2	8.0

¹ $\delta^{34}\text{S}$ values expressed as parts per mil relative to Canyon Diablo Troilite.

²Sum of cations and sum of anions based on unrounded values.

³Charge balance for all anions and cations is calculated as: $100 \times (\text{sum of cations} - \text{sum of anions}) / (\text{sum of cations} + \text{sum of anions})$.

Table 4. Summary statistics of anions, alkalinity, and $\delta^{34}\text{S}$ listed in table 3

[Anions and alkalinity, in microequivalents per liter; $\delta^{34}\text{S}$ in parts per mil]

	Cl^-	SO_4^{2-}	NO_3^-	Alkalinity	$^1\delta^{34}\text{S}$
Mean	1.09	10.0	11.5	-9.6	6.4
Standard deviation	0.37	3.38	3.99	7.2	1.05
Number of samples	16	16	16	16	16
Maximum	2.0	15.2	19.5	1.1	8.1
Minimum	0.6	3.1	2.5	-21.7	4.5

¹ $\delta^{34}\text{S}$ values expressed as parts per mil relative to Canyon Diablo Troilite.

Table 5. Snow-water equivalent (SWE), concentrations of dissolved organic carbon (DOC), pH, and cations [hydrogen (H⁺), ammonium (NH₄⁺), calcium (Ca²⁺), magnesium (Mg²⁺), sodium (Na⁺), and potassium (K⁺)] at sampling site Rabbit Ears Pit 1 for upper and lower strata and substrata within each strata

[cm, centimeters; SWE in centimeters; DOC in milligrams per liter; cations in microequivalents per liter; <, less than]

Sampled snow strata and range of snow depth at Rabbit Ears Pit 1 (cm)	Sampling date	SWE	DOC	pH	H ⁺	NH ₄ ⁺	Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺
Upper stratum, 60–200	03-30-95	45.1	0.6	4.81	15.5	5.7	4.7	0.9	1.6	<0.3
Upper substratum, 180–200	03-30-95	4.06	2.0	5.22	6.0	1.1	27.9	4.1	1.9	1.8
Upper substratum, 160–180	03-30-95	5.37	0.8	5.01	9.8	5.1	7.0	0.8	3.4	0.8
Upper substratum, 140–160	03-30-95	6.09	1.1	4.67	21.4	7.6	7.5	1.6	1.8	1.8
Upper substratum, 120–140	03-30-95	6.85	0.7	4.60	25.1	10.4	3.0	0.8	<1.0	<0.3
Upper substratum, 100–120	03-30-95	7.24	0.9	4.65	22.4	6.4	2.5	0.8	<1.0	0.5
Upper substratum, 80–100	03-30-95	7.83	0.9	4.78	16.6	6.3	3.0	0.8	<1.0	<0.3
Upper substratum, 60–80	03-30-95	7.70	0.5	4.76	17.4	3.9	2.5	0.8	<1.0	<0.3
Lower stratum, 10–50	03-30-95	14.1	1.5	5.08	8.3	6.7	6.3	1.7	1.8	3.8
Lower substratum, 40–50	03-30-95	3.79	0.7	4.86	13.8	2.9	2.0	0.8	1.6	<0.3
Lower substratum, 30–40	03-30-95	3.60	0.8	4.85	14.1	2.9	4.0	0.8	<1.0	0.5
Lower substratum, 20–30	03-30-95	3.41	1.5	4.99	10.2	7.8	6.9	1.9	1.1	3.8
Lower substratum, 10–20	03-30-95	3.25	2.5	5.17	6.8	9.3	11.3	3.0	2.5	6.4

Table 6. Summary statistics of snow-water equivalent (SWE), dissolved organic carbon (DOC), pH, and cations listed in table 5

[SWE in centimeters; DOC in milligrams per liter; for pH statistics, the *median* is listed in place of the mean; cations in microequivalents per liter; values below detection limits were set to zero in calculation of these summary statistics]

	SWE	DOC	pH	H ⁺	NH ₄ ⁺	Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺
Mean	5.38	1.1	4.85	14.9	5.8	7.0	1.5	1.1	1.4
Standard deviation	1.83	0.6	Not calculated	6.4	2.9	7.5	1.1	1.2	2.0
Number of samples ¹	11	11	11	11	11	11	11	11	11
Maximum	7.83	2.5	5.22	25.1	10.4	27.9	4.1	3.4	6.4
Minimum	3.25	0.5	4.60	6.0	1.1	2.0	0.8	0.0	0.0

¹Eleven substrata are summarized in these statistics; upper (60–200 cm) and lower strata (0–50 cm) were not included in the calculations for this table.

Table 7. Concentrations of anions [chloride (Cl^-), sulfate (SO_4^{2-}), and nitrate (NO_3^-)], alkalinity, and percent charge balance at sampling site Rabbit Ears Pit 1 for upper and lower strata and substrata within each strata

[cm, centimeter; anions and alkalinity in microequivalents per liter]

Sampled snow strata and range of snow depth at Rabbit Ears Pit 1 (cm)	Sampling date	Cl^-	SO_4^{2-}	NO_3^-	Alkalinity	Sum cations ¹ (table 5)	Sum anions	Percent charge balance ²
Upper stratum, 60–200	03-30-95	1.1	12.7	9.9	–15.7	28.4	23.7	9.0
Upper substratum, 180–200	03-30-95	1.4	11.3	21.9	–3.3	42.9	34.6	10.7
Upper substratum, 160–180	03-30-95	0.9	9.6	7.8	–7.5	26.8	18.3	18.8
Upper substratum, 140–160	03-30-95	1.4	14.4	18.5	–20.0	41.6	34.3	9.6
Upper substratum, 120–140	03-30-95	3.7	14.4	15.9	–23.4	39.3	34.0	7.2
Upper substratum, 100–120	03-30-95	0.6	15.8	12.3	–22.3	32.6	28.7	6.4
Upper substratum, 80–100	03-30-95	0.9	10.8	10.2	–15.0	26.7	21.9	9.9
Upper substratum, 60–80	03-30-95	0.6	10.2	9.8	–17.2	24.6	20.6	8.8
Lower stratum, 10–50	03-30-95	1.1	10.2	10.7	–7.3	28.7	22.0	13.2
Lower substratum, 40–50	03-30-95	0.6	7.5	8.4	–14.0	21.1	16.5	12.2
Lower substratum, 30–40	03-30-95	0.9	5.4	12.9	–12.5	22.3	19.2	7.5
Lower substratum, 20–30	03-30-95	1.4	12.7	10.4	–8.4	31.8	24.5	13.0
Lower substratum, 10–20	03-30-95	1.4	15.0	11.6	–3.1	39.3	28.0	16.8

¹Sum of cations and sum of anions based on unrounded values.

²Charge balance for all anions and cations is calculated as: $100 \times (\text{sum of cations} - \text{sum of anions}) / (\text{sum of cations} + \text{sum of anions})$.

Table 8. Summary statistics of anions and alkalinity listed in table 7

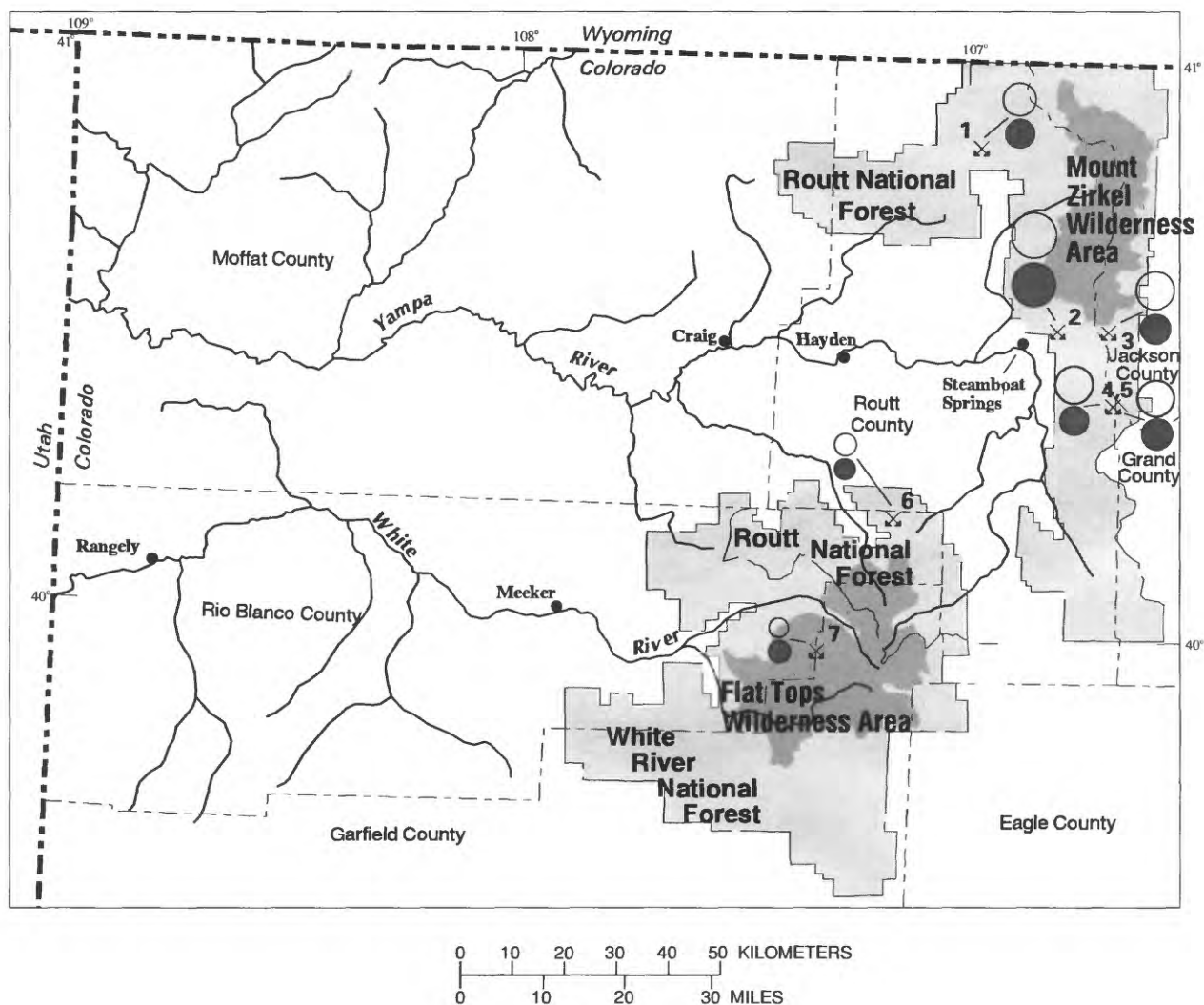
[Anions and alkalinity in microequivalents per liter]

	Cl^-	SO_4^{2-}	NO_3^-	Alkalinity
Mean	1.2	11.6	12.7	–13.3
Standard deviation	0.9	3.29	4.4	7.1
Number of samples ¹	11	11	11	11
Maximum	3.7	15.8	21.9	–3.1
Minimum	0.6	5.40	7.8	–23.4

¹Eleven substrata are summarized in these statistics; upper (60–200 cm) and lower strata (0–50 cm) were not included in the calculations for this table.

Table 9. Volume-weighted mean concentrations of cations [hydrogen (H^+), ammonium (NH_4^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), and potassium (K^+)] and anions [chloride (Cl^-), sulfate, (SO_4^{2-}), and nitrate (NO_3^-)] at the Buffalo Pass National Atmospheric Deposition Program site

Month	Year	pH	H^+	NH_4^+	Ca^{2+}	Mg^{2+}	Na^+	K^+	Cl^-	SO_4^{2-}	NO_3^-
October	1994	4.77	16.9	3.8	2.1	0.3	1.4	0.1	1.6	15.3	7.2
November	1994	4.95	11.2	3.9	4.1	0.5	1.4	0.1	1.3	9.9	9.1
December	1994	4.76	17.3	2.3	0.5	0.2	0.7	0.1	0.8	10.3	8.7
January	1995	4.65	22.2	4.8	0.0	0.2	0.7	0.1	0.9	19.1	8.9
February	1995	4.78	16.7	7.3	2.5	0.6	1.4	0.1	2.5	13.7	11.9
March	1995	4.91	12.2	8.7	8.9	1.2	2.6	0.3	1.8	16.1	13.3
April	1995	5.21	6.1	9.2	8.6	1.7	3.2	0.2	1.8	12.3	9.2
May	1995	4.89	12.9	5.4	5.5	1.1	1.6	0.2	1.4	13.9	9.4



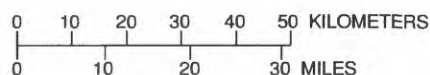
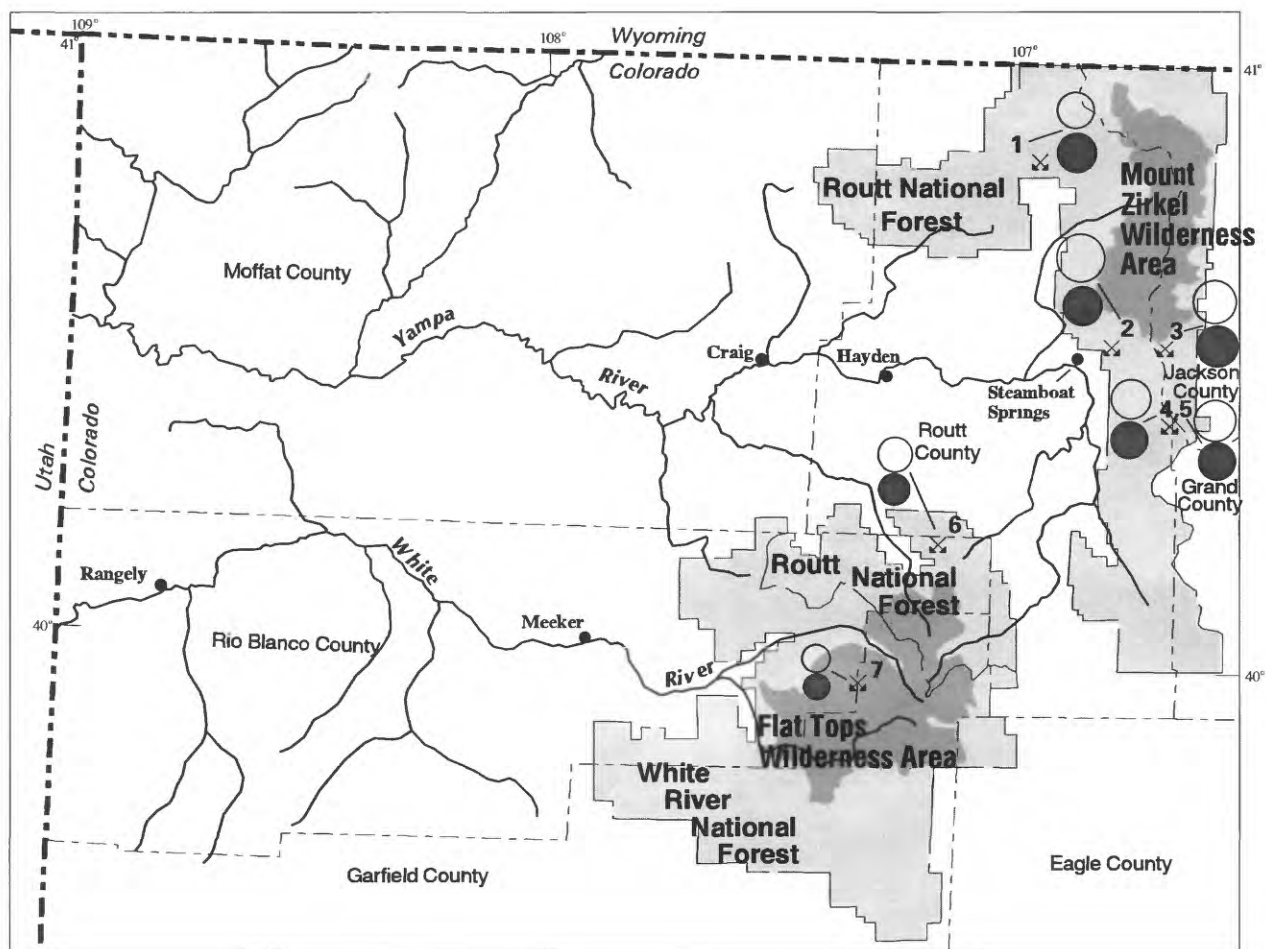
EXPLANATION



SNOWPIT SITE—Number refers to site numbers listed below. Circles indicate hydrogen-ion concentration, in microequivalents per liter (range 1.8 to 21.4). Diameter of circle indicates relative concentration. Open circle indicates upper strata; shaded circle indicates lower strata. Location of snowpit sites is approximate.

- 1 Elk River
- 2 Dry Lake
- 3 Buffalo Pass
- 4 Rabbit Ears Pit 1
- 5 Rabbit Ears Pit 2
- 6 Dunckley Pass
- 7 Ned Wilson

Figure 2. Hydrogen-ion concentrations by snowpack strata.



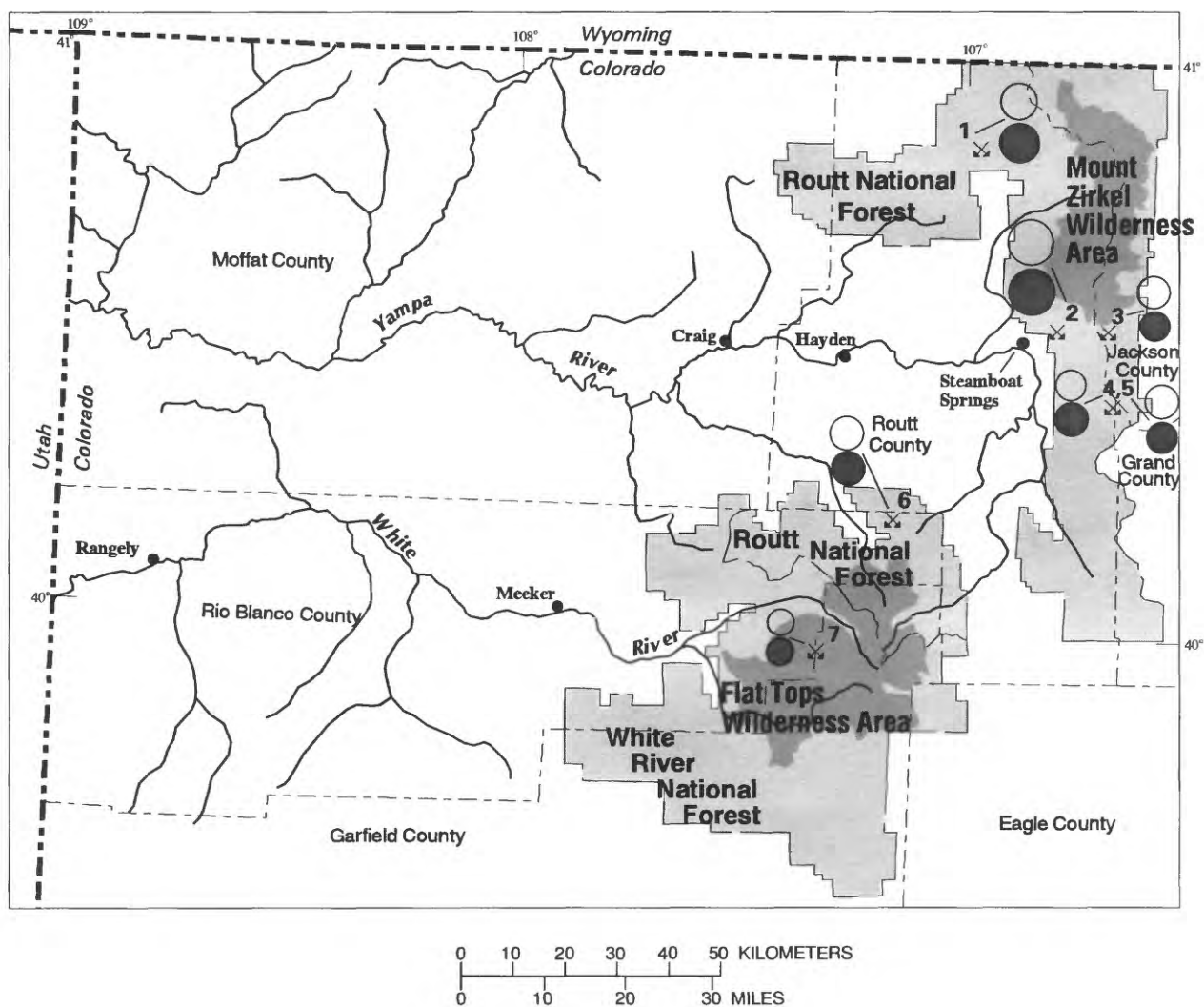
EXPLANATION



SNOWPIT SITE—Number refers to site numbers listed below. Circles indicate sulfate-ion concentration, in microequivalents per liter (range 3.1 to 15.2). Diameter of circle indicates relative concentration. Open circle indicates upper strata; shaded circle indicates lower strata. Location of snowpit sites is approximate.

- 1 Elk River
- 2 Dry Lake
- 3 Buffalo Pass
- 4 Rabbit Ears Pit 1
- 5 Rabbit Ears Pit 2
- 6 Dunckley Pass
- 7 Ned Wilson

Figure 3. Sulfate-ion concentrations by snowpack strata.



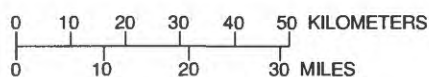
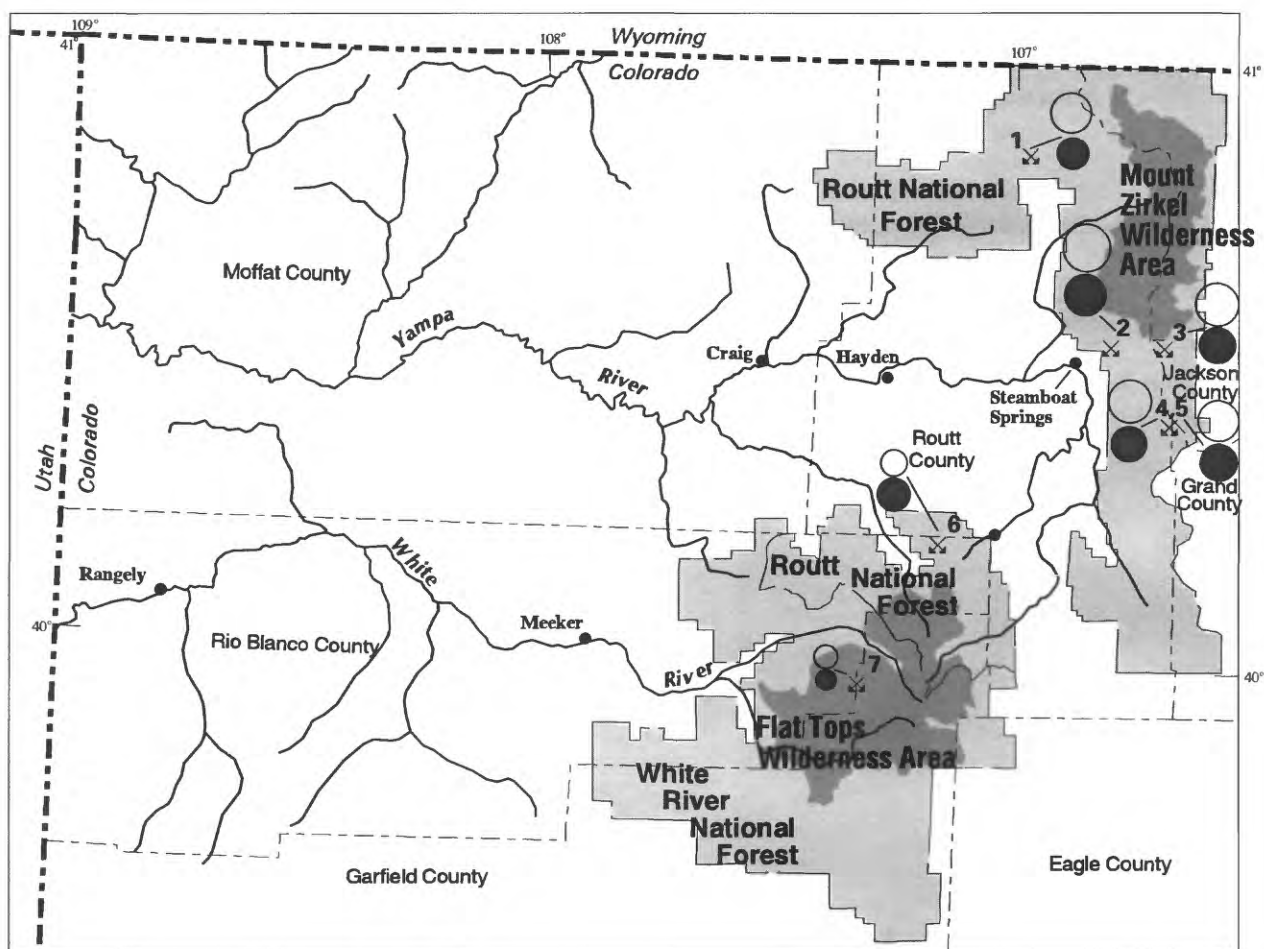
EXPLANATION



SNOWPIT SITE—Number refers to site numbers listed below. Circles indicate nitrate-ion concentration, in microequivalents per liter (range 2.5 to 19.5). Diameter of circle indicates relative concentration. Open circle indicates upper strata; shaded circle indicates lower strata. Location of snowpit sites is approximate.

- 1 Elk River
- 2 Dry Lake
- 3 Buffalo Pass
- 4 Rabbit Ears Pit 1
- 5 Rabbit Ears Pit 2
- 6 Dunckley Pass
- 7 Ned Wilson

Figure 4. Nitrate-ion concentrations by snowpack strata.



EXPLANATION



SNOWPIT SITE—Number refers to site numbers listed below. Circles indicate $\text{del-}^{34}\text{S}$ concentration, in parts per mil (range 4.5 to 8.1) relative to Canyon Diablo Troilite. Diameter of circle indicates relative concentration. Open circle indicates upper strata; shaded circle indicates lower strata. Location of snowpit sites is approximate.

- 1 Elk River
- 2 Dry Lake
- 3 Buffalo Pass
- 4 Rabbit Ears Pit 1
- 5 Rabbit Ears Pit 2
- 6 Dunckley Pass
- 7 Ned Wilson

Figure 5. $\text{del-}^{34}\text{S}$ levels by snowpack strata.

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