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Contents

Figures

Tables

Metric Conversion Factors

Multiply	By	To obtain
Foot (ft)	1.609	Meter (m)
Inch (in.)	0.3048	Millimeters (mm)
Mile (mi)	2.54	Kilometer (km)

Temperature in degrees Celcius (°C) can be converted to degrees Farenheit (°F) as follows: $°F = (1.8 \times °C) + 32$

Influence of Rock Composition on the Geochemistry of Stream and Spring Waters from Mountainous Watersheds in the Gunnison, Uncompahgre, and Grand Mesa National Forests, Colorado

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Abstract

The ranges of geochemical baselines for stream and spring waters were determined and maps were constructed showing acid-neutralizing capacity and potential release of total dissolved solids for streams and spring waters for watersheds underlain by each of ten different rock composition types in the Gunnison, Uncompahgre, and Grand Mesa National Forests, Colorado (GMUG). Water samples were collected in mountainous headwater watersheds that have comparatively high precipitation and low evapotranspiration rates and that generally lack extensive ground-water reservoirs. Mountainous headwaters react quickly to changes in input of water from rain and melting snow and they are vulnerable to anthropogenic impact. Processes responsible for the control and mobility of elements in the watersheds were investigated. The geochemistry of water from the sampled watersheds in the GMUG, which are underlain by rocks that are relatively unmineralized, is compared to the geochemistry of water from the mineralized Redcloud Peak area.

The water with the highest potential for release of total dissolved solids is from watersheds that are underlain by Paleozoic sedimentary rocks; that high potential is caused primarily by gypsum in those rocks. Water that has the highest acid-neutralizing capacity is from watersheds that are underlain by Paleozoic sedimentary rocks. The water from watersheds underlain by the Mancos Shale has the next highest acid-neutralizing capacity. Water that has the lowest acid-neutralizing capacity is from watersheds that are underlain by Tertiary ash-flow tuff. Tertiary sedimentary rocks containing oil shale, the Mesavede Formation containing coal, and the Mancos Shale all contain pyrite with elevated metal contents. In these mountainous headwater areas, water from watersheds underlain by these rock types is only slightly impacted by oxidation of pyrite, and overall it is of good chemical quality. These geochemical baselines demonstrate the importance of rock composition in determining the types of waters that are in the headwater areas. The comparison of these geochemical baselines to later geochemical baselines will allow recognition of any significant changes in water quality that may occur in the future.

Introduction

In a mountainous watershed, precipitated water comes into contact with rock minerals and chemical weathering is initiated. Chemical weathering involves the congruent dissolution of minerals such as calcite, or the incongruent dissolution and transformation of minerals such as plagioclase to clay minerals. These chemical weathering processes release elements to the natural waters of a watershed. Therefore, the chemical compositions of natural waters in a watershed, in the absence anthropogenic input, are determined mostly by the chemical compositions of rocks in the drainage basin. In addition, minor input of dissolved species can come from atmospheric precipitation or dry fall. Biota activity in the soil concentrates CO_2, and biota may concentrate or consume species. Other factors such as rates of mechanical erosion, the grain size and crystallinity of the rock minerals, the amount and distribution of precipitation, temperature, and type and amount of vegetation influence the rates of water-rock chemical interaction. However, the chemical composition of the rocks is the fundamental factor that determines the type of water that evolves in a headwater watershed. The major element compositions of most rock types are generally known from geologic maps, giving insight into the expected major element compositions of natural water in the drainage basin in question. Estimates for trace elements cannot be made from knowing the rock composition. Trace elements can vary two or more orders of magnitude within similar rock composition types.

The background geochemistry of natural water in a basin can be modified by input from anthropogenic processes such as nuclear fallout, atmospheric emission, or mining waste. There probably is no place in the world where the natural background composition of water has not been modified to some extent by anthropogenic processes; the effects of these processes always are superimposed on the natural background geochemistry. However, there are mountainous headwater areas that are only minimally affected by anthropogenic input. Headwater areas are the highest and the most remote regions of a watershed. There the water is imprinted by the chemical compositions of the rocks that underlie the watershed. Many of the headwater areas are critical to water resource development. Those areas have comparatively high precipitation and low evapotranspiration rates, and generally they lack extensive ground-water reservoirs because they are characterized by shallow soils and extensive outcrops of bedrock. The distribution of water in streams in the mountainous headwater areas is uneven throughout the year—high flows occur during the spring runoff and after summer thunderstorms. In the winter, water levels in streams and springs are a minimal; element concentrations are high but mass flux is low. At that time, runoff is maintained mainly by recession of the ground-water reservoir. Mountainous headwaters react quickly to changes in input of dissolved species and are especially vulnerable to anthropogenic impact.

Geochemical baselines, at a specific time and year for stream and spring waters, can be determined in these mountainous headwaters. These geochemical baselines can be used to understand processes responsible for the chemical compositions of water in a watershed. In addition, because water geochemistry is sensitive to changes in the environment, by monitoring water geochemistry in these mountainous headwater areas and comparing the results to earlier baseline data, changes in the environment within the basin can be determined. This geochemical baseline is an approximation of the natural background and if remediation is needed in the future because of anthropogenic contamination, this baseline is the ideal goal.

The purpose of this study is to determine, for different rock composition types, the range of chemical species and other geochemical parameters and to characterize the baseline geochemistry of stream and spring waters in mountainous watersheds in three national forests in western Colorado. The ranges of species and other parameters were determined for each of the major rock composition types in the Gunnison, Uncompahgre, and Grand Mesa National Forests (GMUG), and maps of mean pH values, potential release of total dissolved solids, and acid-neutralizing capacity were constructed for each of the national forests. In addition, processes responsible for the control and mobility of the elements in the natural waters were investigated.

Study Area

The study area, in Western Colorado, includes the Gunnison, Uncompahgre, and Grand Mesa National Forests (fig. 1). The eastern part of the study area is in the Southern Rocky Mountains and the western part is in the Colorado Plateau physiographic province (Hunt, 1974). The mountain ranges and intermountain basins generally trend north-northwest. Dendritic drainage patterns are well developed, and most of the area is of moderate to high relief. Uncompahgre Peak, at 14,390 feet altitude, is the highest elevation in the study area. The lowest elevation is along the west flank of Battlement Mesa, at approximately 6000 feet altitude. The main river systems that drain the study area are the Uncompahgre, Gunnison, San Miguel, and Dolores Rivers. The river systems drain to the Colorado River beyond the limits of the study area. Annual precipitation ranges from approximately 20 in. in the northwestern part of the study area to more than 50 in. at the higher elevations (Colorado Climate Center, 1984). The higher elevations receive the highest precipitation, mainly as snow during the winter. Winter weather is influenced by storm systems originating over the Pacific Ocean. Snow pack above 10,000 feet begins to accumulate in late October, and the maximum is in mid-April (Benedict, 1991). In summer, particularly in July, August, and early September, an influx of moist air from the Gulf of Mexico causes afternoon thunderstorms and storm runoff. Snowmelt runoff usually is from April through July, and it peaks in May and June (Apodaca and others, 1996).

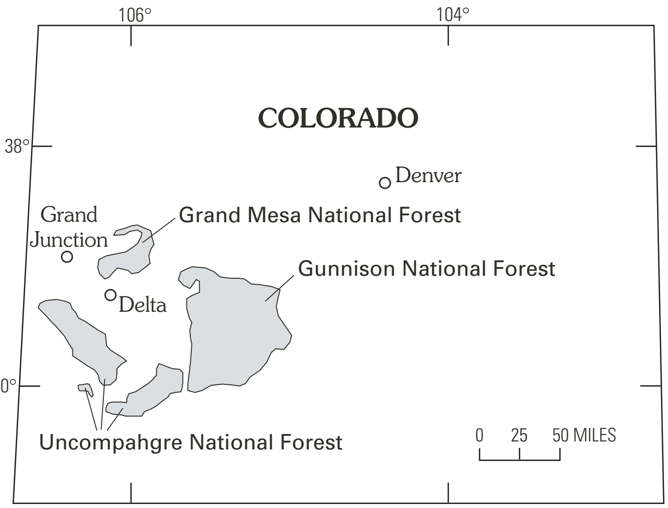

Figure 1. Map showing localities of the Gunnison, Umcompahre, and Grand Mesa National Forests, Colorado.

Because of the large differences in altitude, the climate in the study area varies from cool-humid in the higher mountains to semi-arid at lower elevations. Mean annual temperature varies from approximately 32°F at the highest elevations to higher than 50°F at lower elevations (Benci and McKee, 1977). The natural vegetation in the study area is strongly zoned by altitude; it is divided into six general groups, based on the classification of the U.S. Department of Agriculture (1972). Except for grasslands, which are at both high and low elevations, the groups, from the highest to the lowest elevation, are 1, alpine tundra; 2, subalpine forest; 3, pinyon pine-juniper forest; 4, oak scrubland; 5, sagebrush scrubland; and 6, grassland. Timberline is approximately 11,000 feet; its altitude varies in relation to of slope orientation to sun, rock-to- soil cover, and other surface phenomena.

Geology

Geologic materials in the three national forests vary, from Proterozoic granite, quartz monzonite, schist, and gneiss to Quaternary unconsolidated sediments (table 1). The major bedrock types in the Grand Mesa National Forest (fig. 2) are, from youngest to oldest: 1, Pliocene and Miocene basalt flows and associated tuff, breccia, and conglomerate; 2, sandstone and siltstone of the Eocene Uinta Formation; 3, marlstone, sandstone, and oil shale of the Eocene Green River Formation; 4, claystone, mudstone, and conglomerate of the Eocene Wasatch Formation and the Upper Cretaceous Ohio Creek Member of

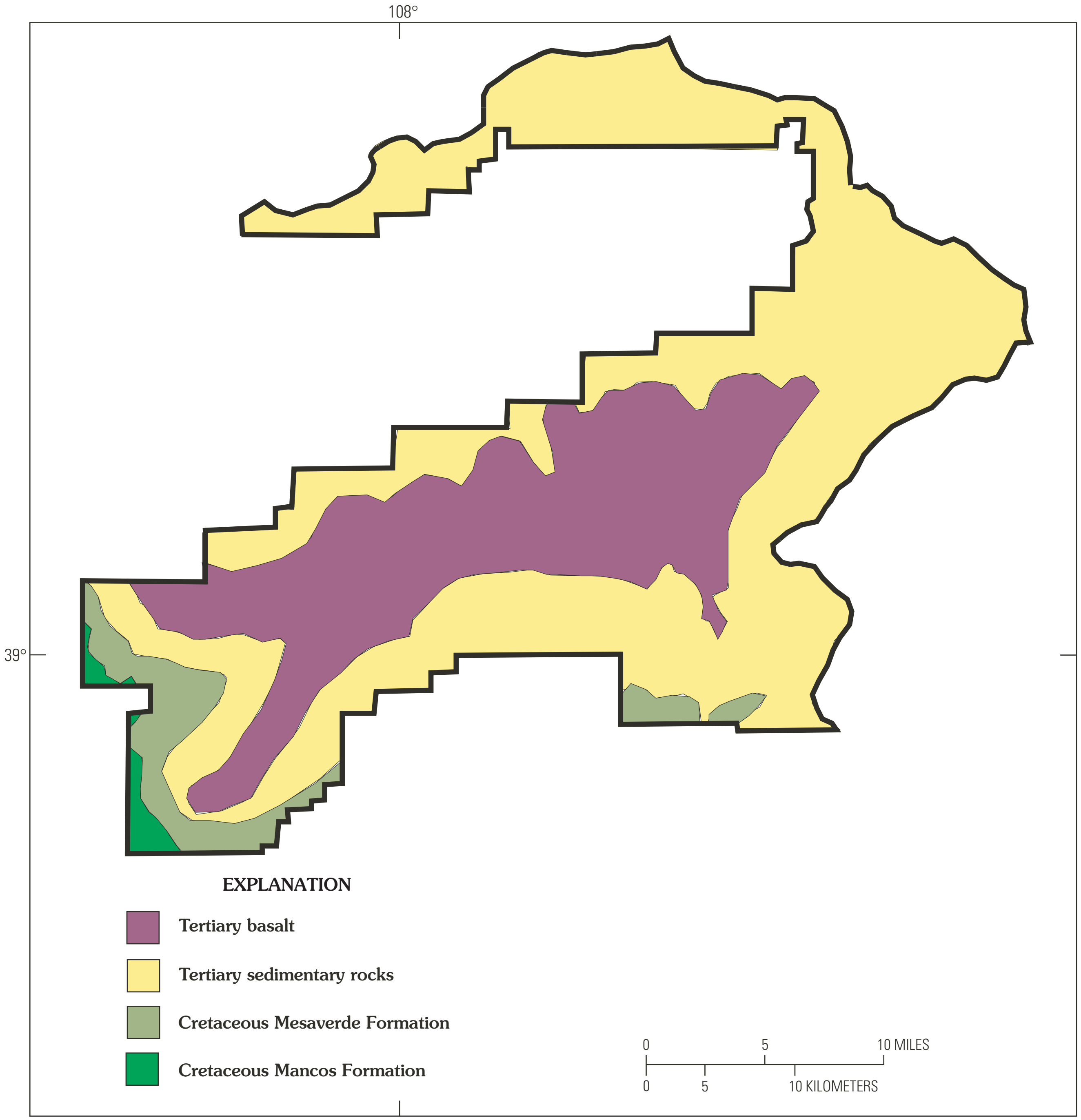

Figure 2. Generalized geologic map of the Grand Mesa National Forest, Colorado. Modified from Tweto (1979).

the Mesaverde Formation. The volcanic rocks and related sedimentary rocks cap Grand Mesa; the Eocene and Cretaceous sedimentary rocks crop out on the flanks of Grand Mesa and on the summit and flanks of Battlement Mesa.

The major rock types in the Uncompahgre National Forest (fig. 3) are, from youngest to oldest: 1, Pliocene and Miocene basalt flows and associated tuff, breccia, and conglomerate; 2, Oligocene ash-flow tuff; 3, Oligocene inter-ash-flow quartz latitic lava and breccia; 4, Oligocene andesitic lava and breccia; 5, sandstone, shale, claystone, and conglomerate of the Cretaceous Mancos Shale Formation and Dakota Sandstone; 6, claystone, sandstone, mudstone, shale, siltstone, and limestone of the Jurassic Morrison and Summerville Formations and Entrada Sandstone; 7, sandstone, siltstone, and conglomerate of the Triassic Wingate, Chinle and Dolores Formations; 8, arkosic sandstone, siltstone, and conglomerate of Permian Cutler Formation; 9, arkosic sandstone, conglomerate, shale, and limestone of Pennsylvanian Hermosa Formation; 10, limestone, dolomite, arkosic sandstone, conglomerate, and shale of Mississippian Leadville Limestone, Devonian Ouray Limestone, and Devonian Elbert Formation; and 11, Tertiary granodiorite, quartz monzonite, and granite and Proterozoic granite.

The major rock types in the Gunnison National Forest (fig. 4) are, from youngest to oldest: 1, Pliocene and Miocene basalt

Table 1. Generalized stratigraphic column of dominant rock types in the Grand Mesa, Uncompahgre, and Gunnison National Forests, Colorado.

[Fm, Formation; Gp, Group; Mbr, Member; Ss, Sandstone; Ls, Limestone]

Period	Epoch	Rock Unit or Type	Dominant Lithology
Quaternary	Holocene and Pleistocene	Alluvium, colluvium, glacial, and landslide deposits	Silt, sand, clay, gravel, boulders
Tertiary	Pliocene and Miocene	Basalt flows and associated rocks	Lava flows, tuff, breccia, and conglomerate
Tertiary	Oligocene	Ash-flow tuff	Rhyolitic ash-flow tuff
Tertiary	Oligocene	Quartz latitic lava and breccia	Latitic lava and breccia
Tertiary	Oligocene	Andesitic lava and associated rock	Andesitic lava, breccia, tuff, and conglomerate
Tertiary	Oligocene and Eocene	Intrusive stocks and dikes	Granite, granodiorite, and quartz monzonite
Tertiary	Eocene	Uinta Fm	Sandstone and siltstone
Tertiary	Eocene	Green River Fm	Marlstone, sandstone, siltstone, and oil shale
Tertiary	Eocene	Wasatch Fm	Claystone, mudstone, sandstone, and conglomerate
Cretaceous	Late	Ohio Creek Mbr of Mesaverde Fm	Claystone, mudstone, sandstone, and conglomerate
Cretaceous	Late	Mesavede Gp or Fm	Mudstone, shale, coal, and sandstone
Cretaceous	Late	Mancos Shale	Shale and calcareous shale with sandstone
Cretaceous	Early	Dakota Ss, Burro Canyon Fm	Sandstone, shale, conglomerate, and thin coal beds
Jurassic	Late	Morrison Fm	Siltstone and mudstone with lens of sandstone and limestone
Jurassic	Middle	Entrada Ss, Summerville Fm	Sandstone
Jurassic	Early	Wingate Ss	Sandstone
Triassic	Late	Chinle Fm, Dolores Fm	Siltstone, sandstone,and limestone
Permian and Pennsyvanian		Cutler Fm, Maroon Fm, Minturn Fm, Belden Fm, Hermosa Fm	Arkosic sandstone, siltstone, conglomerate, local limestone
Mississipian through Cambrian		Leadville Ls, Ouray Ls, Elbert Fm, Chaffee Gp, Fremont Ls, Harding Sandstone, Manitou Dolomite, Sawatch Quartzite	Limestone, dolomite, sandstone, chert
Precambrian		Igneous and metamorphic rocks	Granite, grandiorite, quartz monzonite, diorite, gneiss, and gabbro

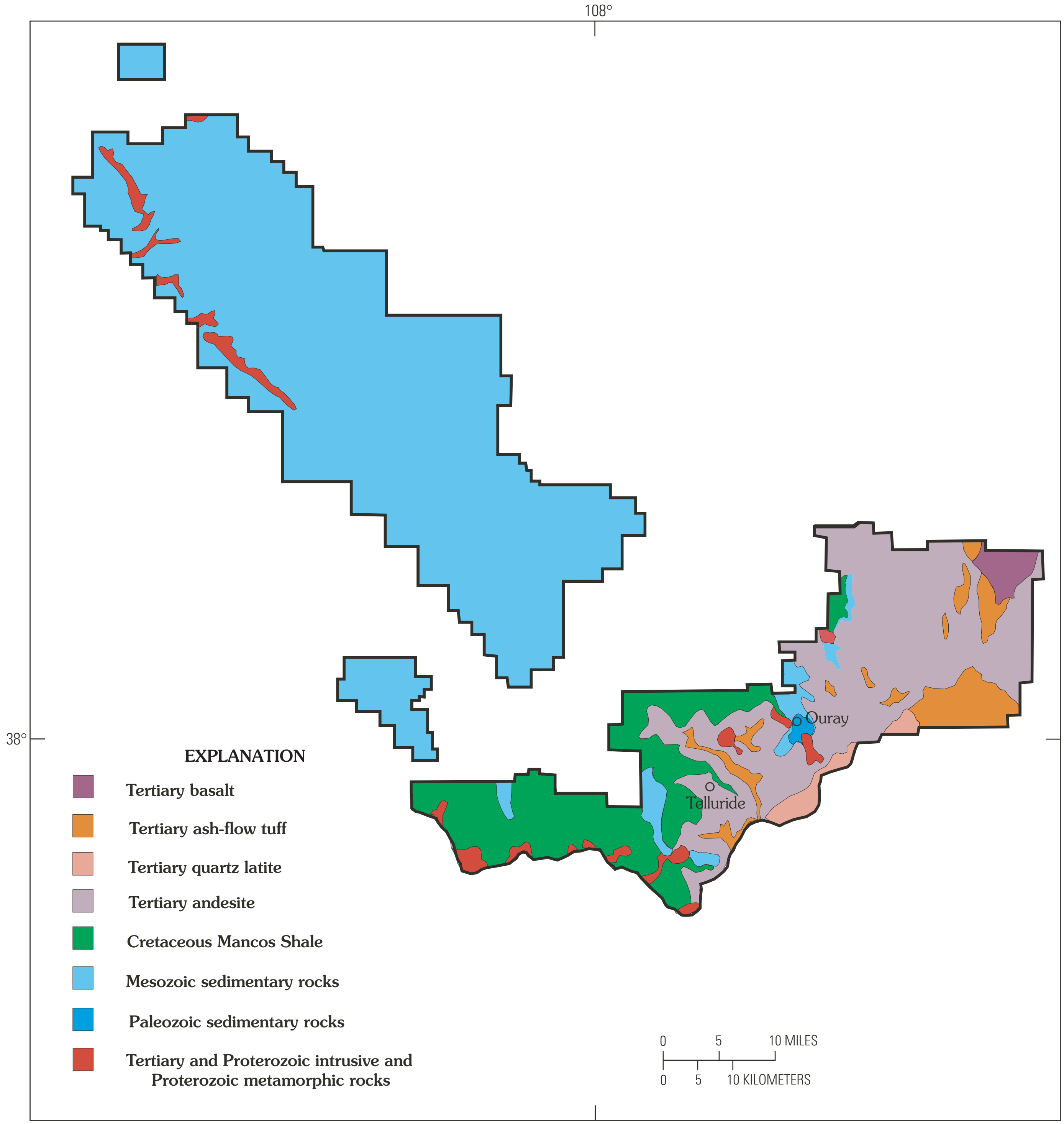

Figure 3. Generalized geologic map of the Uncompahgre National Forest, Colorado. Modified from Tweto (1979).

flows and associated tuff, breccia, and conglomerate; 2, Oligocene ash-flow tuff; 3, Oligocene inter-ash-flow quartz latitic lava and breccia; 4, Oligocene andesitic lava and breccia; 5, sandstone and shale of the Oligocene Duchesne River Formation; 6, claystone, mudstone, sandstone, and conglomerate of the Eocene Wasatch Formation and Upper Cretaceous Ohio Creek Member of Mesaverde Formation; 7, sandstone and shale with coal beds of the Cretaceous Mesaverde Formation; 8, sandstone, shale, and conglomerate of the Cretaceous Mancos Shale; 9, arkosic sandstone, siltstone, conglomerate, and limestone of the Permian and Pennsylvanian Maroon Formation; 10, arkosic sandstone, shale, conglomerate, and limestone of the Pennsylvanian Minturn and Belden Formations; 11, limestone, dolomite, arkosic sandstone, shale, limestone, dolomite, arkosic sandstone, conglomerate and conglomerate of the Mississippian Leadville Limestone, Mississippian and Devonian Chaffee Group, Ordovician Fremont Limestone, Ordovician Harding Sandstone and Ordovician Manitou Limestone, and Cambrian

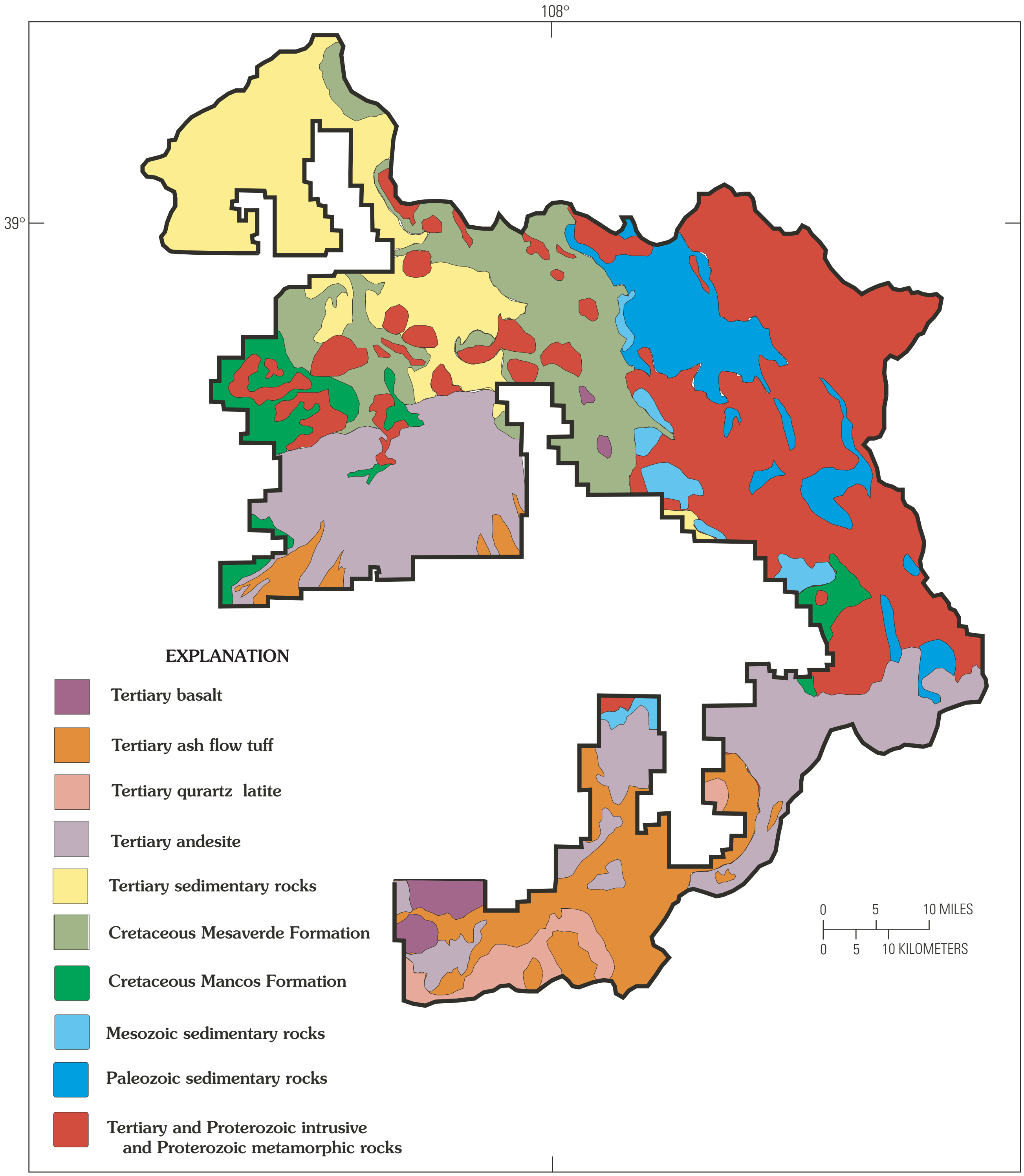

Figure 4. Generalized geologic map of the Gunnison National Forest, Colorado. Modified from Tweto (1979).

Sawatch Quartzite and Peerless Formation; and 12, Tertiary granodiorite, quartz monzonite, and granite and Proterozoic granite, granodiorite, quartz monzonite, diorites, gneiss, and gabbro.

The major rock types in the three national forests are divided into ten dominant rock composition types. Some of the composition types are represented by a single formation such as the Mesavede Formation. Others are represented by rocks of different ages, such as Cretaceous, Jurassic, and Triassic sedimentary rocks of similar composition. In some cases, the designation of a rock composition type such as felsic ash-flow tuff, adesitic lavas and breccia, and basalts flows and associated rocks is straightforward. In other cases, such as the Mancos Shale type and the Mesaverde Formation type, the rock type is predominantly a single lithology. In other cases, such as Tertiary, Mesozoic, and Paleozoic sedimentary rocks, the composition type is selected partly for practical reasons. Some water in

Table 2. The ten dominant rock compositon types in the Grand Mesa, Uncompahgre, and Gunnison National Forests, Colorado.

Age	Rock Composition Type	Setting
Tertiary	Basalt flows and associated rocks	Grand Mesa
Tertiary	Felsic ash-flow tuff	San Juan volcanic field
Tertiary	Quartz latitic lava and breccia	San Juan volcanic field
Tertiary	Andesitic lava and breccia	West Elk volcanic field
Tertiary	Sedimentary rocks: shale, oil shale, sandstone, marlstone, Claystone, and lignite	Battlement and Grand Mesa
Cretaceous	Mesaverde Formation: sandstone, shale, coal, minor intrusive rock, and claystone	Piceance Basin, Elk Mountains
Cretaceous	Mancos Shale: marine shale, sandstone, and calcareous sandstone	San Juan volcanic field, Paradox Basin
Mesozoic	Sedimentary rocks: sandstone, siltstone, shale, limestone, conglomerate, and mudstone	Uncompahgre uplift
Paleozoic	Sedimentary rocks: sandstone, conglomerate, carbonate, quartzite, shale, mudstone,and grit	West flank of Sawatch Range
Tertiary and Proterozoic	Granite, granodiorite, quartz monzonite, diorite, gneiss, and gabbro	Sawatch Range; scattered throughout remaining area

areas underlain by composition types of small aerial extent would be difficult or impossible to sample. Also, the rock types must represent major spatial distributions of rock composition types. It would not be practical to sample a rock type that comprises only 1 percent of the total distribution of the rock types in the three national forests.

The dominant rock types selected (table 2) are 1, Tertiary basalt flows and associated rocks; 2, Tertiary felsic ash-flow tuff; 3, Tertiary quartz latitic lava and breccia; 4, Tertiary andesitic lavas and associated rocks; 5, Tertiary sedimentary rocks; 6, Cretaceous Mesavede Formation; 7, Cretaceous Mancos Shale; 8, Mesozoic sedimentary rocks consisting of Cretaceous, Jurassic, and Triassic sedimentary rocks that are predominantly sandstone; 9, Paleozoic sedimentary rocks; and 10, Tertiary granodiorite, quartz monzonite, and granite and Proterozoic granite, granodiorite, quartz monzonite, diorites, gabbro, and gneiss. The ten dominant rock composition types represent more than 95 percent of the rocks at the surface in the three national forests.

Methods

Generally, small streams were sampled. Usually the streams had watershed areas of several square miles, although some watersheds were larger. Springs within a watershed also were sampled. The sample sites were selected to provide coverage to each of the ten major rock composition types within the three national forests.

Samples of water were collected from stream and spring sites in the study area during July and August of 1998 and during August of 1999. The samples were collected after runoff had occurred but prior to the streams reaching base flow. Samples from areas underlain by each major rock composition type usually were collected during an interval of one or two days. Samples from lower elevations were collected earlier in the season than were those in high alpine areas. During sampling, the weather was stable and no precipitation occurred. Samples were collected by width and depth integration (Edwards and Glysson, 1988) or, for springs from a point source. Temperature, pH, and conductivity were measured at each site. An Orion model 250 pH meter was used with an Orion Ross Sure-Flow electrode. Conductivity was measured using an Orion model 120 conductivity meter. Samples were collected in high-density polyethylene bottles. For dissolved cation analyses, a sample was filtered at the site through a 0.45 µm-membrane filter and acidified with ultrapure reagent-grade Ultrex nitric acid to pH <2. Another sample was filtered, but not acidified, for anion analyses, and an unfiltered, unacidified sample was collected for alkalinity measurement. The samples initially were stored in an ice chest and later in a refrigerator; they were kept cool until analyzed in the laboratory.

In the laboratory, alkalinity, as HCO_3^-, was determined by titration with H_2SO_4 using Gran's plot technique (Orion Research, Incorporated, 1978). Sulfate, chloride, nitrate, and fluoride concentrations were determined by ion chromatography (IC) (Fishman and Pyen, 1979). Cations were analyzed by inductively coupled plasma-atomic emission spectromentry (ICP-AES) or inductively coupled plasma-mass spectromentry (ICP-MS). IC and alkalinity analyses were performed by Murdock Environmental Laboratory, University of Montana, Missoula, Montana. The ICP-MS analyses for samples collected in 1998 were determined by ACTLABS, Wheat Ridge, Colorado. The samples collected in 1999 were determined by USGS laboratory, under the direction of Paul Lamothe. The ICP-AES analyses for samples collected in 1998 were determined by Murdock Environmental Laboratory. The samples collected in 1999 were determined by USGS laboratory, under the direction of Paul Briggs. Duplicate water samples, blank samples, and USGS Water Resource Division standard reference waters were analyzed with each data set. The chemical analyses are in appendix 1.

Results

Water samples were collected from small streams or springs in watersheds that were in or mainly in the three national forests. The watersheds are mountainous headwaters that were not impacted by historic mining. Grazing of cattle in some of the watersheds possibly affects the water quality. The sample sites were selected so that, as closely as possible, the geochemical baseline chemistry approximates the natural background geochemistry for each of the ten rock composition types (table 2) that are dominant in the three national forests. The ranges and means of chemical species and other parameters were determined for water from areas that are underlain by each of the dominant rock composition types. The means of chemical species in water of the ten rock composition types can be compared to average fresh water (table 3).

Tertiary Basalt Flows and Associated Rocks

Water samples were collected from four small streams in areas underlain by Pliocene and Miocene basaltic lava, tuff, breccia, and conglomerate on the summit of Grand Mesa in the Grand Mesa National Forest (fig. 5). The ranges and means of selected chemical species in the waters are listed in table 4. The chemical analyses of samples from these sites and other sites are in appendix 1. The summit of Grand Mesa is more than a mile higher than the surrounding valley floors. The basaltic rocks that cap the mesa overlie the Tertiary Green River and Wasatch Formations and the Cretaceous Ohio Creek Member of the Mesaverde Formation. The relief on the surface of Grand Mesa is low. The area receives 30 to 45 in. of annual precipitation (Colorado Climate Center, 1984), and snow pack ranges from 5 to 10 feet each year. The vegetation is mainly sub-alpine forest and grassland.

The water samples are dilute Ca^{2+}- HCO_3^- type water with slightly alkaline pH values and moderate to low alkalinity values. The mean pH is 7.41 and mean conductivity is 63 µS/cm. The mean Cl concentration is 0.29 mg/L, indicating that much of the water is snow melt with minimal duration of contact with the rocks. The Cl does not normally react and precipitate with other species until highly concentrated; therefore it is a good indicator of evaporation effects. All specie concentrations are low, except for Al. The mean Al concentration is 54 µg/L, probably because the initial low pH values of the melting snow are favorable for mobility of Al. Generally, water in contact with basaltic rocks is well buffered, with moderate values of alkalinity. Because of the short duration of contact of melting snow with the basaltic rocks on Grand Mesa, the water has moderately low alkalinity values. The alkalinity ranges from 24 to 30 mg/L as HCO_3^-, with a mean of 28 mg/L. This low mean value indicates that the summit of Grand Mesa is moderately susceptible to introduced acidification. Introduced acidity from sources such as acid rain in the future possibly could neutralize the alkalinity in water, causing the streams and lakes on Grand Mesa to become acidic. Except for moderate amounts of Al, the water from Grand Mesa is excellent in water quality.

Table 3. Background of trace metals in fresh water and chemical analyses of mean river water.

Background of trace metals (in µg/L) in fresh water	
Element	Data from Forstner and Wittmann (1979)
Al	<30
Fe	<30
Mn	<5
Cu	1.8
Zn	10
As	2
Mo	1
Pb	0.2
Sb	0.1
Cd	0.07
Cr	0.5
Ni	0.3
Co	0.05
V	0.9
Ba	10
Be	0.01
Li	1
Se	0.1
Sr	50
U	0.5
Chemical analyses (in mg/L) of mean river water	
Element	Data from Livingstone (1963)
Ca	15
Mg	4.1
Na	6.3
K	2.3
SiO_2	13.1
SO_4^{2-}	11.2
HCO_3^-	58.4
Cl^-	7.8

Tertiary Ash-Flow Tuff

Water samples were collected from three streams and two springs in the Los Pinos Creek and Pauline Creek watersheds, in the Gunnison National Forest in areas underlain by Oligocene rhyolitic ash-flow tuff (fig. 6). The source of the tuff is calderas in the San Juan Mountains to the south. The relief in the area is high, and the dominant vegetation is subalpine forest. Annual precipitation ranges from 16 to 30 in. (Colorado Climate Center, 1984). The ranges and means of selected chemical species in the water are listed in table 5. The water samples are Ca^{2+}-HCO_3^- type water with slightly acidic to slightly alkaline pH values and moderately low conductivity values. The mean pH is 7.43 and the mean conductivity is 100 µS/cm. The mean Zn and Cu concentrations are very low, at 0.24 µg/L and <0.1 µg/L, respectively. The SiO_2 concentrations ranged from 19 to 41 mg/L with a mean of 29 µg/L. The higher concentrations of SiO_2 probably are caused by the felsic composition of the bedrock; because of the fine grain size of the minerals that compose the rock, the felsic rocks are particularly susceptible to silicate

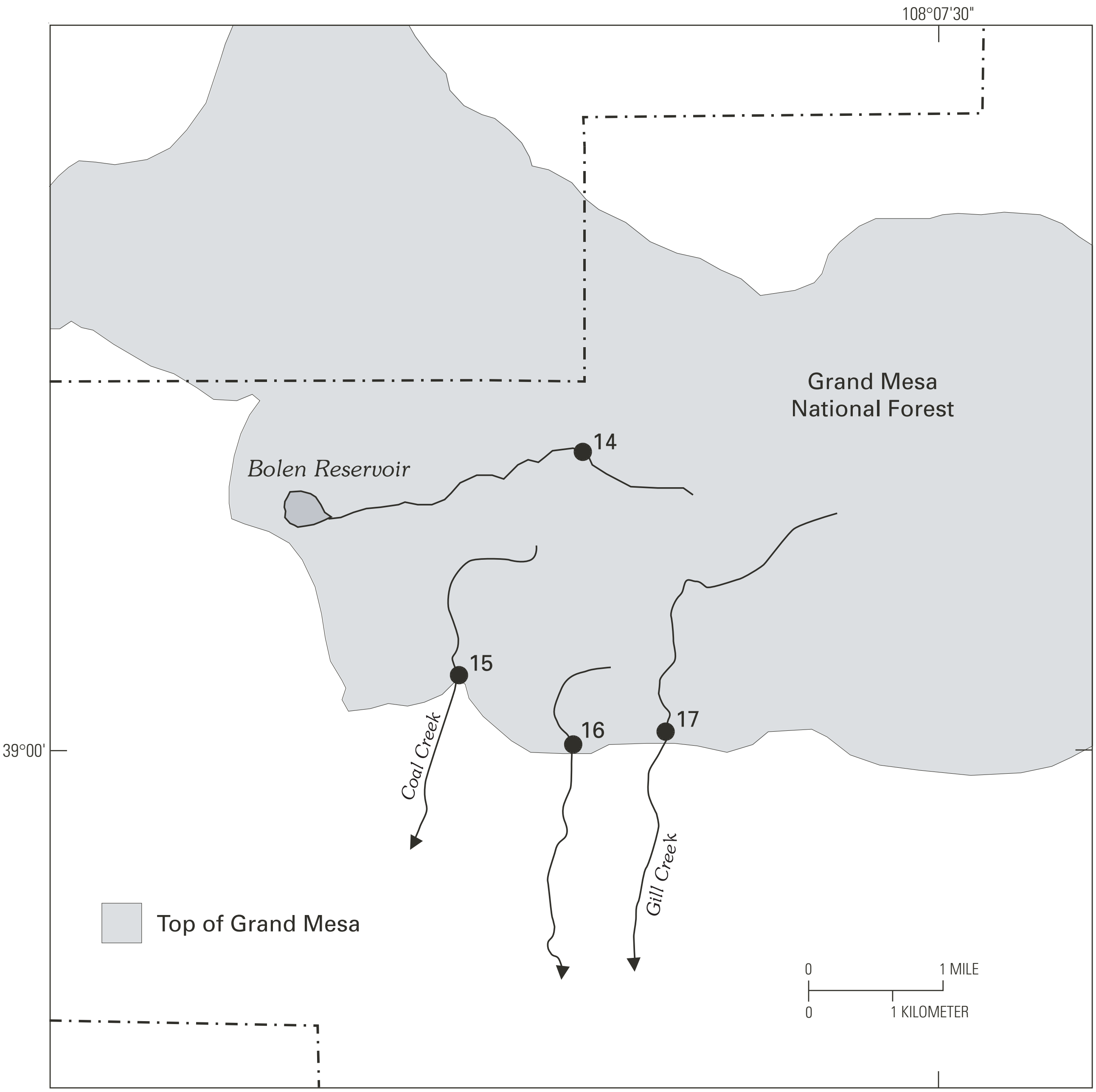

Figure 5. Site localities of stream water samples from areas underlain by Tertiary basalt flows and associated rocks, Grand Mesa National Forest (patterned), Colorado.

dissolution. The alkalinity values ranged from 32 to 70 mg/L as HCO_3^-, with a mean of 46 mg/L. This moderately low value reflects the fact that felsic rocks do not weather as rapidly as do more mafic rocks. The mean Cl content is 0.88 mg/L, which is low; it reflects the short residence time of the melting snow and storm runoff in contact with the rocks and also a lack of significant evaporation. The Fe concentrations in two stream samples were high, with 255 and 640 µg/L (app. 1). Both sites were contaminated by cattle waste, and the samples were yellowish brown in color. The wastes probably cause more reducing conditions, which favor mobility of Fe. It is also possible that the Fe mobility is caused by Fe complexing with organic matter. Other water samples from watersheds underlain by the Tertiary ash-flow tuff are of good chemical quality. The felsic rock type and the short duration of contact of the water and rock both favor moderately low alkalinity. Because of the moderately low alkalinity, the area is moderately susceptible to introduced acidification. Moderate acidification from mining or atmospheric precipitation in the future possibly could neutralize alkalinity and cause the stream waters to become acidic.

Tertiary Quartz Latitic Lava and Breccia

Water samples were collected from four streams in the Mineral Creek drainage in the northern part of the San Juan volcanic field in the La Garita Wilderness, Gunnison National Forest (fig. 7). The area is underlain by Oligocene inter-ash-flow

Table 4. Summary of the chemistry of four stream water samples from watersheds underlain by Tertiary basalt flows and associated rocks, Grand Mesa National Forest, Colorado.

Measurement[1]	Range		Mean[2]
	Minimum	Maximum	
Conductivity	59	66	63
pH	7.09	7.67	7.41
Ca	4	6.1	5.4
Mg	1.8	2.3	2.1
Na	1.5	2	1.8
K	0.24	0.45	0.37
SiO_2	11	19	14
Alkalinity	24	30	28
SO_4	0.38	1.6	0.65
Cl	<0.25	0.6	0.29
F	<0.1	<0.1	<0.1
Al	38	107	54
Fe	44	151	91
Mn	4.2	27	15
Cu	<1	<1	<1
Zn	0.32	0.52	0.4
Pb	<0.1	1.4	0.15
Mo	<0.5	0.53	<0.5
Sb	<0.01	0.22	0.017
As	<0.03	0.67	0.048
Th	0.069	0.1	0.083
U	0.036	0.15	0.069
Li	<0.5	<0.5	<0.5
Ba	10	17	14
Sr	29	39	36
V	<0.5	0.57	<0.5
Sc	17	26	21
Rb	0.29	1.3	0.5
Y	0.31	0.53	0.41
Zr	0.28	1	0.43
La	0.17	0.31	0.25
Br	<3	<3	<3
I	<0.2	20	0.98

[1] Conductivity in µS/cm; Ca, Mg, Na, K, SiO_2, SO_4, Cl, and F in mg/L; alkalinity in mg/L HCO_3^-; remaining elements in µg/L

[2] All variables are geometric means except for pH, which is arithmetic mean

Table 5. Summary of the chemistry of three stream water samples and two spring water samples from watersheds underlain by Tertiary felsic ash-flow tuff, Gunnison National Forest, Colorado.

Measurement[1]	Range		Mean[2]
	Minimum	Maximum	
Conductivity	57	139	100
pH	6.89	8.02	7.43
Ca	5.3	16.5	11
Mg	0.83	2.8	1.7
Na	3.1	7.9	4.4
K	0.87	2.3	1.3
SiO_2	19	41	29
Alkalinity	32	70	46
SO_4	1.4	6	2.7
Cl	0.37	1.9	0.88
F	<0.1	0.14	0.1
Al	6.7	34	16
Fe	9.5	640	65
Mn	<0.3	32	2.9
Cu	<1	<1	<1
Zn	<0.2	0.32	0.24
Pb	<0.1	1.1	0.12
Mo	<0.5	0.6	<0.5
Sb	<0.01	0.13	0.021
As	0.79	2.2	1.2
Th	0.07	0.57	0.19
U	0.012	0.2	0.058
Li	0.86	2.8	1.5
Ba	10	32	18
Sr	47	109	79
V	<0.5	3.4	1.2
Sc	22	51	35
Rb	0.3	3.1	1.2
Y	0.047	0.18	0.1
Zr	0.12	19	0.51
La	<0.005	0.17	0.024
Br	<3	33	3.5
I	<0.2	7.8	2.2

[1] Conductivity in µS/cm; Ca, Mg, Na, K, SiO_2, SO_4, Cl, and F in mg/L; alkalinity in mg/L HCO_3^-; remaining elements in µg/L

[2] All variables are geometric means except for pH, which is arithmetic mean

quartz latitic lava and breccia (Tweto, 1976). The relief is high and the dominant vegetation is subalpine forest. The annual precipitation ranges from 16 to 25 in. (Colorado Climate Center, 1984). The ranges and means of selected chemical species in the water samples are listed in table 6. The sites produced three Ca^{2+}- HCO_3^- type samples and one Na^+- HCO_3^- type sample with slightly alkaline pH values and moderately low conductivity values. The mean pH is 7.48 and mean conductivity is 124 µS/cm. Trace metal concentrations are low. The mean Zn, Cu, Mo, and As concentrations are 0.5, 0.56 , 0.54, and <3 µg/L, respectively. The range of SiO_2 concentrations is 20 to 56 mg/L, with a mean of 31 mg/L. The higher values probably are caused by the felsic composition of the rocks and by the fine grain size of the rock minerals with high surface areas available for chemical reactions, which favor chemical dissolution of the silicates. The mean concentrations of Al and Fe are moderately high, 60 and 55 µg/L, respectively. The concentration of Mn is low, with a mean of 2.7 µg/L. The low mean Cl concentration, 0.56 mg/L, reflects the short residence time of the water from melting snow and rain in contact with the rocks and also the lack of significant evaporation. The alkalinity as HCO_3^- ranged from 29 to 44 mg/L, with a mean of 36 mg/L, indicating weak acid-neutralizing capacity. The felsic rock lithology and the short duration of time of the water and rock favor moderately low alkalinity values. Because of the moderately low alkalinity values, the areas underlain by quartz latitic rocks are

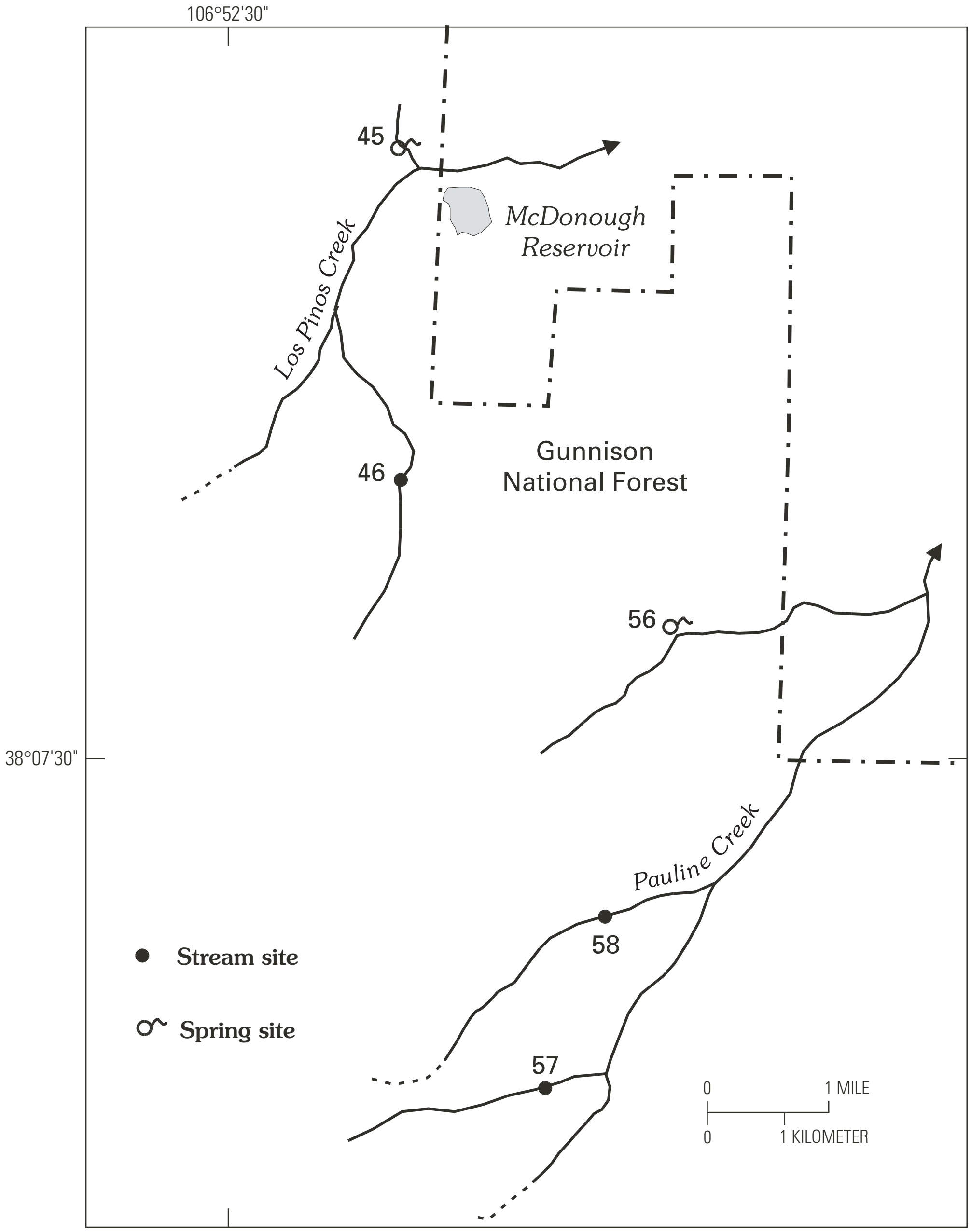

Figure 6. Site localities of stream and spring water samples from areas underlain by Tertiary ash-flow tuff in Los Pinos and Pauline Creek watersheds, Gunnison National Forest, Colorado.

moderately susceptible to introduced acidification. Moderate acidification in the future possibly could neutralize the alkalinity and cause the stream waters to become acidic. The chemical quality of the waters from watersheds underlain by Tertiary quartz latitic rocks is good.

Tertiary Andesitic Lava and Breccia

Water samples were collected from eight streams in the Soap Creek area of the West Elk Mountains, Gunnison National Forest (fig. 8). The area is underlain by Oligocene andesitic lava flows, breccia, tuff, and conglomerate. The andesitic rocks originated from the nearby West Elk volcanic centers (Hansen, 1965; Gaskill and others, 1981). The relief is high and the dominant vegetation is subalpine forest. The annual precipitation ranges from 20 to 40 in. (Colorado Climate Center, 1984). The ranges and means of selected chemical species in the samples are listed in table 7. The samples are Ca^{2+}- HCO_3^- type water with alkaline pH values and moderate conductivity values. The mean pH is 7.99 and the mean conductivity is 158 µS/cm. The trace element concentrations are low to very low. The mean Zn, Cu, Mo, and As concentrations are 0.22 µg/L, <1 µg/L, <0.5 µg/L, and 0.7 µg/L, respectively. The range of SiO_2 concentrations is 22 to 48 mg/L, with a mean of 35 mg/L. The higher values probably are caused by the fine grain size of the rock minerals with high surface areas available for chemical reactions, which favors dissolution of silicates. The mean concentrations of Al,

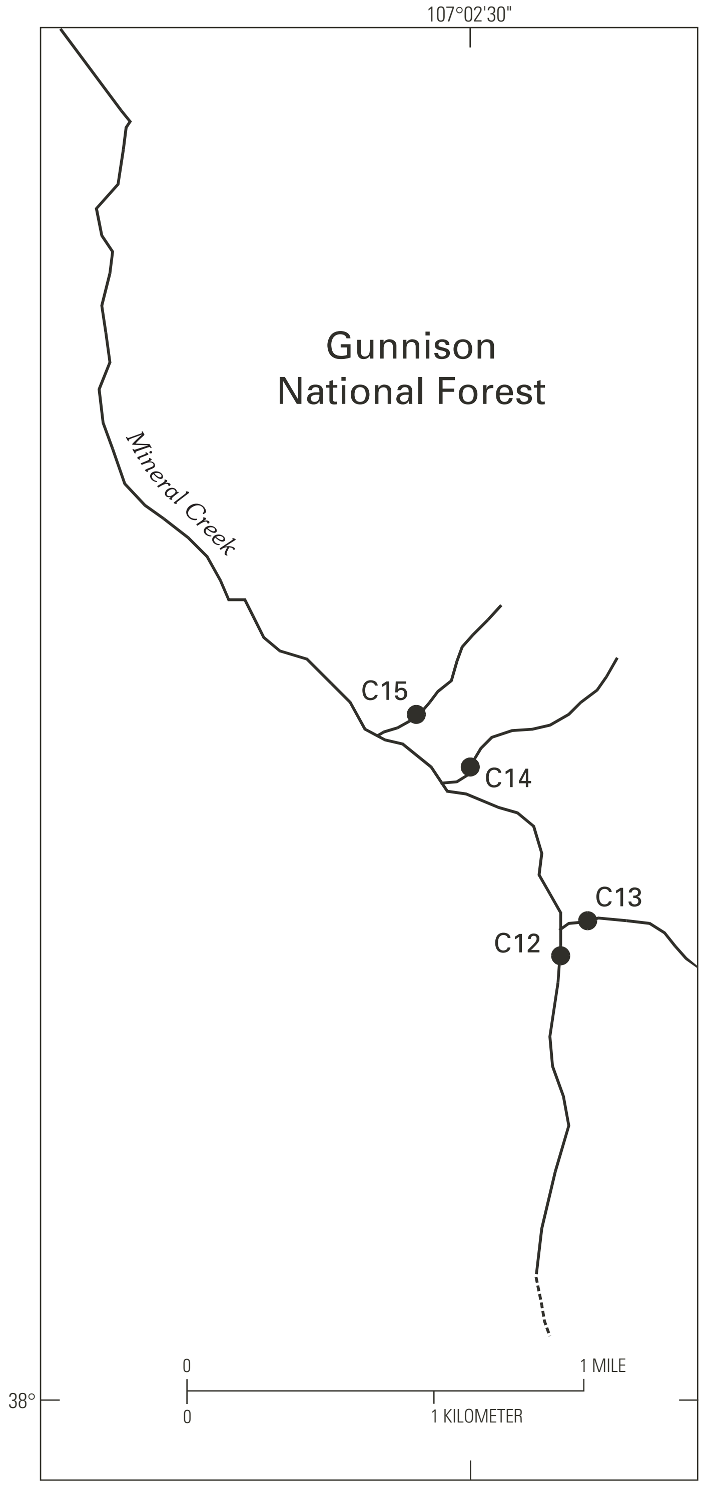

Figure 7. Site localities of stream water samples from areas underlain by Tertiary quartz latitic lava and breccia in the Mineral Creek watershed, Gunnison National Forest, Colorado.

Table 6. Summary of the chemistry of four stream water samples from watersheds underlain by Tertiary quartz latitic lava and breccia, Gunnison National Forest, Colorado.

Measurement[1]	Range		Mean[2]
	Minimum	Maximum	
Conductivity	108	140	124
pH	7.35	7.75	7.48
Ca	8.7	16	12.6
Mg	0.78	2.9	1.8
Na	3.7	13	6.9
K	0.69	2.2	1.1
SiO_2	20	56	30.8
Alkalinity	29	44	36
SO_4	10	28	16.6
Cl	<0.25	1.5	0.56
F	<0.1	<0.1	<0.1
Al	7.9	356	55
Fe	33	159	60
Mn	1	21	2.7
Cu	<0.5	0.8	0.56
Zn	<0.5	1	0.5
Pb	<0.05	<0.05	<0.05
Mo	0.3	1	0.54
Sb	<0.1	0.2	<0.1
As	<3	<3	<3
Th	<0.005	0.15	0.03
U	0.08	0.32	0.14
Li	1.7	10	3.6
Ba	2.6	13	4.6
Sr	58	171	115
V	0.8	1.6	1.1
Sc	1.9	5.3	2.9
Rb	0.9	3	1.4
Y	0.1	1.5	0.32
Zr	0.08	1.4	0.32
La	0.05	0.5	0.13

[1] Conductivity in μS/cm; Ca, Mg, Na, K, SiO_2, SO_4, Cl, and F in mg/L; alkalinity in mg/L HCO_3^-; remaining elements in μg/L

[2] All variables are geometric means except for pH, which is arithmetic mean

Fe, and Mn are moderately low, 13, 16, and 0.48 μg/L, respectively. The low mean Cl concentration, 0.7 mg/L, reflects the short residence time of the water from melting snow and storm runoff in contact with the rocks and also the lack of significant evaporation. The alkalinity as HCO_3^- ranges from 32 to 102 mg/L, with a mean of 72 mg/L, indicating moderate acid-neutralizing capacity for introduced acidification. Although the residence time of water in contact with rock is short, the fine-grained minerals and the intermediate composition of the rocks ensure that the rate of chemical weathering is rapid. Therefore, the water in this area underlain by Tertiary andesitic rocks, has moderate acid-neutralizing capacity for introduced acidification. The chemical quality of the water from watersheds underlain by Tertiary andesitic rocks is good.

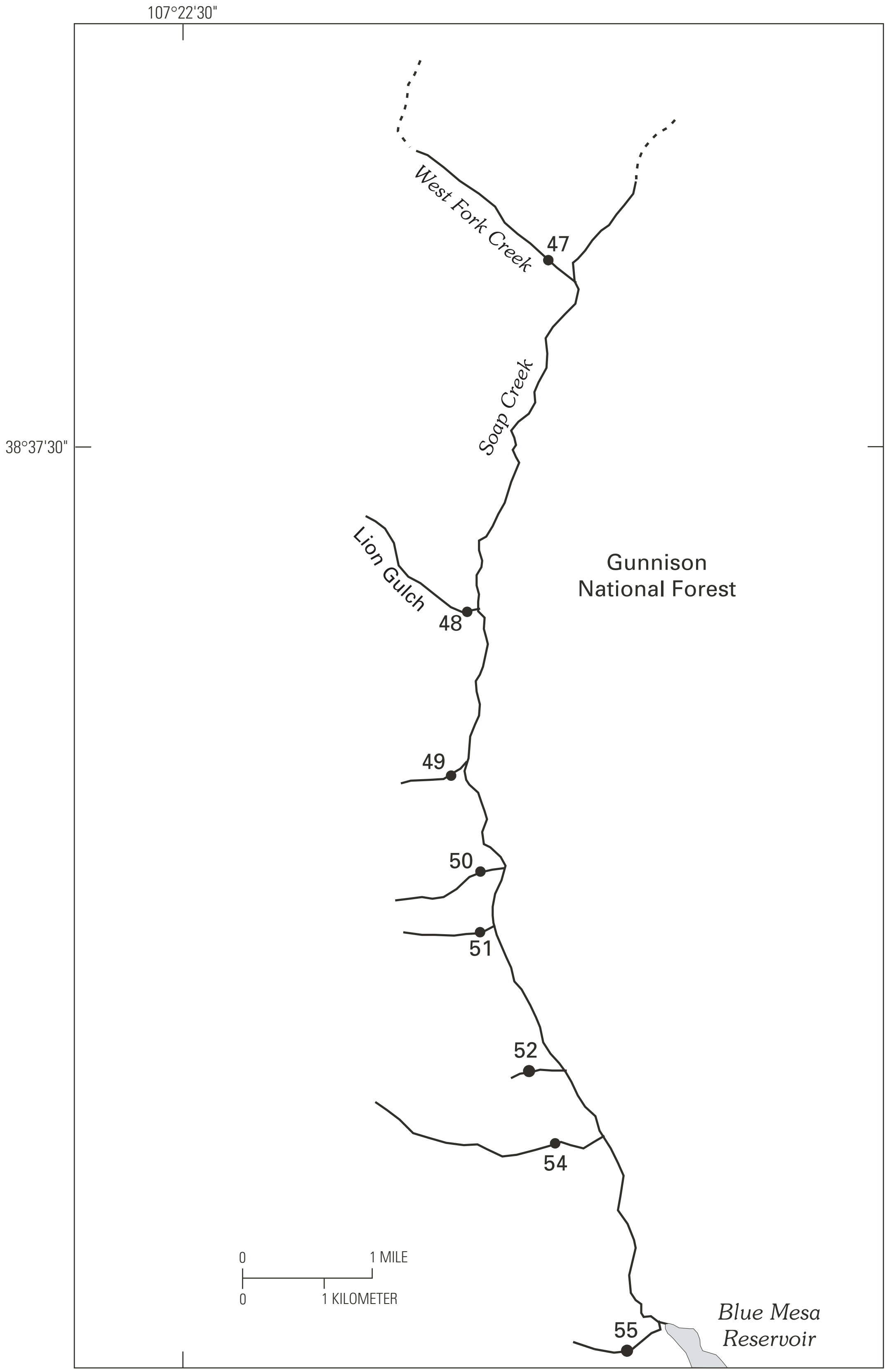

Figure 8. Site localities of stream water samples from areas underlain by Tertiary andesitic lava and breccia in the Soap Creek watershed, Gunnison National Forest, Colorado.

Table 7. Eight stream water samples from watersheds underlain by Tertiary andesitic lava and breccia, Gunnison National Forest, Colorado.

Measurement[1]	Range		Mean[2]
	Minimum	Maximum	
Conductivity	104	242	158
pH	7.49	8.53	7.99
Ca	10	22	16
Mg	1.6	7.7	3
Na	4.8	15	7.7
K	0.81	2.4	1.7
SiO_2	22	48	35
Alkalinity	32	102	72
SO_4	0.76	23	3.5
Cl	0.34	1	0.7
F	<0.1	0.14	<0.1
Al	8.9	21	13
Fe	8.6	31	16
Mn	<0.3	4	0.48
Cu	<1	<1	<1
Zn	<0.2	0.38	0.22
Pb	<0.1	<0.1	<0.1
Mo	<0.5	0.59	<0.5
Sb	<0.01	0.074	0.012
As	0.4	1.3	0.7
Th	0.12	0.37	0.2
U	<0.001	0.28	0.092
Li	0.79	2.9	1.3
Ba	1.5	9.2	5
Sr	60	149	95
V	0.8	2.9	2.2
Sc	26	54	41
Rb	1.4	3.7	2.4
Y	0.05	0.11	0.071
Zr	0.15	0.45	0.27
La	<0.005	<0.005	<0.005
Br	<3	<3	<3
I	<0.2	2.2	0.21

[1] Conductivity in µS/cm; Ca, Mg, Na, K, SiO_2, SO_4, Cl, and F in mg/L; alkalinity in mg/L HCO_3^-; remaining elements in µg/L

[2] All variables are geometric means except for pH, which is arithmetic mean

Tertiary Sedimentary Rocks

Samples of water were collected from seven streams draining headwater watersheds underlain by the Eocene Green River and Wasatch Formations and by the Cretaceous Ohio Creek Member of the Mesaverde Formation in Grand Mesa National Forest (fig. 9). Most of the rocks are Tertiary in age, and here they all are referred to as Tertiary sedimentary rocks. The Wasatch Formation and the Ohio Creek Member were formed from detritus shed from the rising Rocky Mountains onto vast river flood plains and deltas that flanked an immense freshwater lake (Bradley, 1964; Roehler, 1974). The Green River sediments were deposited in the lake; accumulation of plant and animal detritus resulted in formation of oil shale (Bradley, 1964; Roehler, 1974). The sample sites were mainly selected because of the presence of outcrops of the Parachute Creek Member of the Green River Formation, which contains oil shale.

The watersheds are along the flanks of Battlement Mesa and Grand Mesa. The relief is moderate to high. The area receives 20 to 35 in. of annual precipitation (Colorado Climate Center, 1984); the higher elevations receive the most precipitation. Vegetation in the higher areas is mainly oak scrubland and subalpine forest. Grazing of cattle physically impacts some of the watersheds; an increase in sediments in the streams and deterioration of wetlands are caused by erosion by the hooves of cattle and by accumulation of cattle wastes.

The ranges and means of selected chemical species in water samples are listed in table 8. The samples all are Ca^{2+}-HCO_3^- type water with alkaline pH values and moderately high conductivity values. The mean pH is 8.50 and the mean conductivity is 365 µS/cm. The water is well buffered, with mean alkalinity of 191 mg/L as HCO_3^-. The mean Cl concentration is 1.4 mg/L. The background Cl for this area probably is less than 0.5 mg/L, in the absence of input of Cl from weathering of rocks. Possibly there is some addition of Cl from the rocks. Halite is present in oil shale in the subsurface (Tuttle, 1992). But it is likely that some of the water may have undergone some evaporation and consequent increase in dissolved species, particularly Cl. The mean concentration of SiO_2 is 17.5 mg/L, is slightly above the average background concentration for fresh water (table 3). The concentrations of Cu, Zn, and other trace metals present as cations are very low (<1 µg/L), although the oil shale in the Green River Formation contains anomalous concentrations of trace metals (Harrison and others, 1992). The high pH ensures that hydrolysis reactions keep the concentrations of trace metal cations low. The concentrations of some of the trace species, present as anions, are slightly elevated compared to average concentrations in fresh water (table 3). The mean concentrations of Mo, As, and U are 1.9, 1.9, and 1.4 µg/L, respectively. The concentrations of I, Br, Li, and Sr are elevated, compared to those in fresh water (table 3). Although these element concentrations are elevated, particularly for headwater watersheds, no element poses a problem for water quality.

Five of the streams that were sampled drain watersheds that contain outcrops of the Parachute Creek Member of the Green River Formation, which contains oil shale (app. 1). Pyrite in the oil shale oxidizes when exposed to the atmosphere; it releases sulfate, trace metals contained in the pyrite, and acidity to the water. The well-buffered water with high alkalinity values reacts with and neutralizes acidity released during oxidation of pyrite, and high pH hydrolyzes trace metals carried as cations and reduces their mobility. Sulfate values as high as 25 mg/L (app. 1) indicate that pyrite is being weathered and sulfate is being released. If gypsum is present in the rocks, sulfate can also be released from the dissolution of gypsum. Some As values, as high as 5.8 µg/L (app. 1), are elevated.

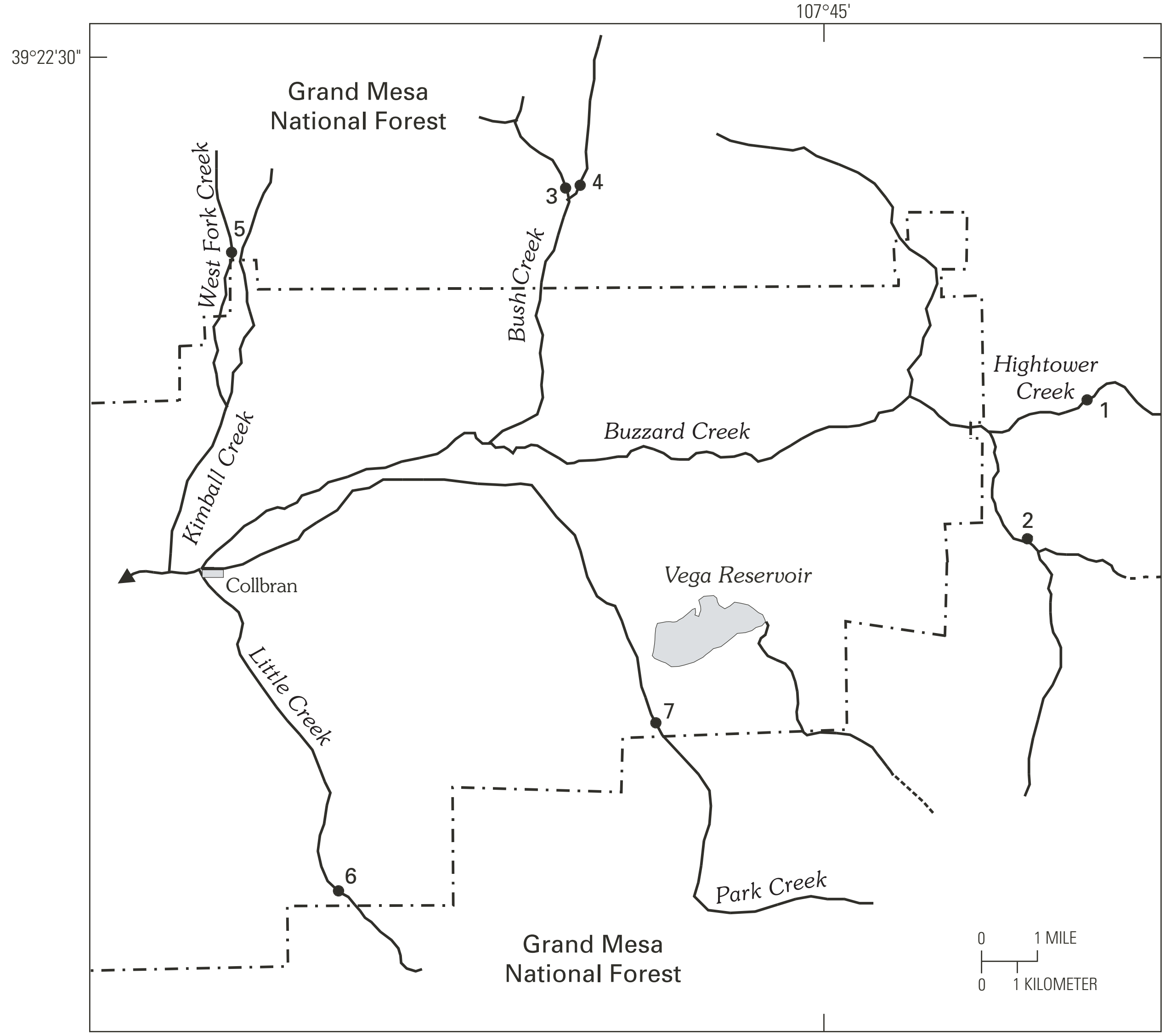

Figure 9. Site localities of stream water samples from areas underlain by Eocene Green River and Wasatch Formations and Upper Cretaceous Ohio Creek Member of Mesaverde Formation in the Buzzard Creek watershed, Grand Mesa National Forest, Colorado.

Weathering of pyrite probably causes the elevated values. However, overall there is no significant impact to the water quality of these headwater streams. The high alkalinity of the water probably is due to the presence of marlstone. The marlstone is fine grained; the calcite reacts rapidly, releasing carbonate species, mostly bicarbonate, to the water. Because of the high alkalinity, the watersheds underlain by these rock are not susceptible to introduced acidification from processes such as acid rain or acid-mine drainage. The water in the watersheds underlain by the Green River Formation, Wasatch Formation, and Ohio Creek Member are moderately high in dissolved solids, for headwater streams, but they pose no human health risk in terms of chemical water quality.

Cretaceous Mesaverde Formation

Water samples were collected from seven streams and one spring in the Coal Creek and Snowshoe Creek areas on the northern flank of the West Elk Mountains in the Gunnison National Forest (fig. 10). The ranges and means of selected chemical species in the samples are listed in table 9. Rocks of the Upper Cretaceous Mesaverde Formation underlie the area containing the sample sites. Smaller areas of Oligocene intermediate-composition intrusive rocks also are present in some watersheds. The Mesaverde Formation is mostly sandstone with some shale and coal beds. The sediments were deposited in beach, river delta, and swamp environments. The economically important low-sulfur bituminous coal beds are products of accumulation of organic material in marshes and lagoons behind sand barrier islands (Benedict, 1991). The relief in the area is high, and the annual precipitation ranges from 20 to 35 in. (Colorado Climate Center, 1984). The dominant vegetation is subalpine forest. The samples are Ca^{2+}- HCO_3^- type water with alkaline pH values and moderate conductivity values. The pH values ranged from 8.00 to 8.57, with a mean of 8.31. Conductivity values ranged from 76 to 268 µS/cm, with a mean of 126 µS/cm. The mean Cl content is 0.49 mg/L, indicating that no

Table 8. Seven stream water samples from areas underlain by Tertiary sedimentary rocks, Grand Mesa National Forest, Colorado.

Measurement[1]	Range		Mean[2]
	Minimum	Maximum	
Conductivity	195	652	365
pH	8.16	8.69	8.50
Ca	18	62	39
Mg	6.6	37	12
Na	5.2	45	15
K	0.65	3.8	1.4
SiO_2	6.5	27	18
Alkalinity	92	352	191
SO_4	3.4	25	8.1
Cl	0.63	8.3	1.4
F	<0.1	0.51	0.16
Al	<3	24	12
Fe	<5	36	13
Mn	<0.3	171	4.7
Cu	<1	1.7	<1
Zn	<0.2	0.53	0.22
Pb	<0.1	2.9	0.18
Mo	0.53	7.5	1.9
Sb	<0.01	0.29	0.12
As	0.62	5.8	1.9
Th	0.18	1.5	0.36
U	0.39	8.8	1.4
Li	1.3	25	7.2
Ba	32	208	62
Sr	114	718	311
V	1.3	5.5	2.8
Sc	11	36	25
Rb	0.4	0.84	0.6
Y	0.05	0.17	0.083
Zr	0.14	1.3	0.42
La	<0.005	0.072	0.017
Br	<3	182	6.6
I	<0.2	36	1.5

[1] Conductivity in µS/cm; Ca, Mg, Na, K, SiO_2, SO_4, Cl, and F in mg/L; alkalinity in mg/L HCO_3^-; remaining elements in µg/L

[2] All variables are geometric means except for pH, which is arithmetic mean

Table 9. Summary of the chemistry of seven stream water samples and one spring from areas underlain by the Cretaceous Mesaverde Formation water sample, Gunnison National Forest, Colorado.

Measurement[1]	Range		Mean[2]
	Minimum	Maximum	
Conductivity	76	268	126
pH	8	8.57	8.31
Ca	7.7	31	13
Mg	1.3	8.3	3
Na	3.8	13.4	5.4
K	0.32	0.81	0.49
SiO_2	11	15	13
Alkalinity	34	122	54
SO_2	1.5	19	5.3
Cl	0.25	1	0.49
F	<0.1	0.75	0.11
Al	9	27	12
Fe	<5	30	14
Mn	1.4	7	2
Cu	<1	<1	<1
Zn	<0.2	0.36	0.24
Pb	<0.1	<0.1	<0.1
Mo	<0.5	0.63	<0.5
Sb	<0.01	<0.01	<0.01
As	<0.03	2.4	0.08
Th	<0.002	0.023	0.003
U	0.077	0.51	0.13
Li	0.72	4.7	1.4
Ba	11	49	18
Sr	52	364	189
V	<0.5	0.74	<0.5
Sc	16	21	18
Rb	0.14	0.45	0.32
Y	<0.03	0.12	0.042
Zr	<0.05	0.62	0.15
La	<0.005	0.089	<0.005
Br	<3	<3	<3
I	<0.2	<0.2	<0.2

[1] Conductivity in µS/cm; Ca, Mg, Na, K, SiO_2, SO_4, Cl, and F in mg/L; alkalinity in mg/L HCO_3^-; remaining elements in µg/L

[2] All variables are geometric means except for pH, which is arithmetic mean

significant evaporation and no long-term contact of the water with the rocks occurred. A significant portion of the stream water probably is snowmelt. The range of concentrations of SiO_2 is 11 to 15 mg/L, with a mean of 13 mg/L, about average for fresh water (table 3). Waters from areas underlain by sandstone contain less SiO_2 than do waters from areas underlain by ash-flow tuff and andesitic rocks; this probably reflects the coarse grain size and well crystallized nature of the silica minerals. The concentrations of trace elements Zn, Cu, Mo, and As are very low, with means of 0.24, <1, <0.5, and <0.08 µg/L, respectively. Concentrations of Al, Fe, and Mn also are low with means of 12, 14, and 2 µg/L, respectively. Alkalinity values range from 34 to 122 mg/L as HCO_3^- with a mean of 54 mg/L. This wide range in alkalinity values possibly is due to the local presence of pyrite associated with the coal beds. Sulfate concentrations range up to 19 mg/L with a mean of 5.3 mg/L.

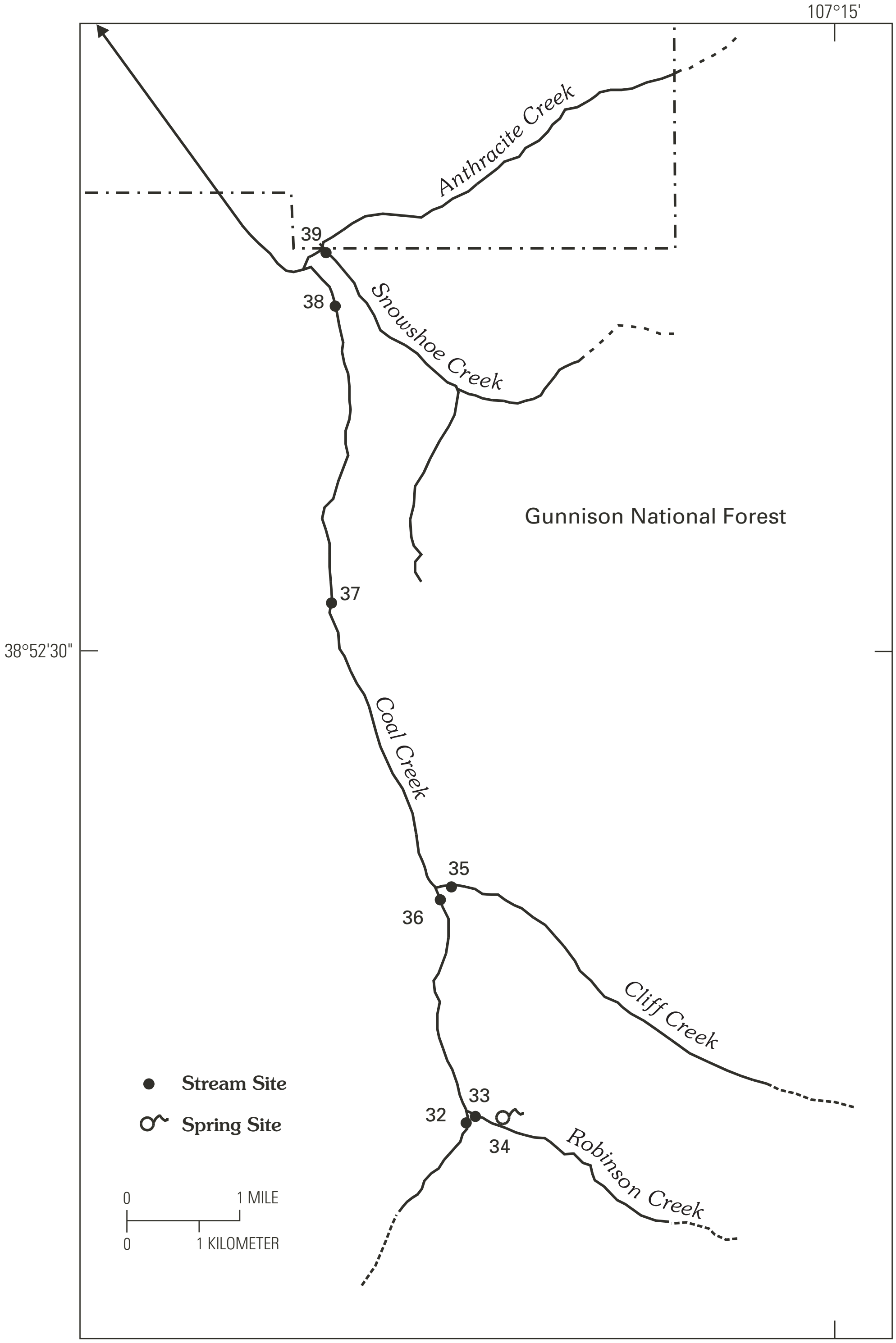

Figure 10. Site localities of stream and spring water samples from areas underlain by Cretaceous Mesaverde Formation in the Coal Creek and Snowshoe Creek watersheds, Gunnison National Forest, Colorado.

Weathering of pyrite releases sulfate and acid to the waters, and the acid consumes some of the alkalinity. The moderately low mean alkalinity indicates a low to moderate acid-neutralizing capacity of the watershed to introduced acidification. Overall, the water quality is good.

Cretaceous Mancos Shale

Water samples were collected from two areas underlain by Mancos Shale. Six streams were sampled in the southwestern part of the Uncompahgre National Forest, in the Beaver and Goat Creek watersheds (fig. 11). Two springs were sampled along the northwest flank of the West Elk Mountains, in the area of Bell Creek in the Gunnison National Forest (fig. 12). The ranges and means of selected chemical species in the samples are listed in table 10. The Cretaceous Mancos Shale consists of silty and sandy shale and thin-bedded sandstone with calcareous zones; it was deposited in a marine setting. Relief in the two areas is high and the annual precipitation ranges from 16 to 40 in. (Colorado Climate Center, 1984). The dominant vegetation in both areas is subalpine forest; in lower areas outside the national forest, badland topography with sparse scrub vegetation is present. The samples all are Ca^{2+}- HCO_3^- type water with alkaline pH values and moderately high conductivity values. The pH values range from 7.46 to 8.58, with a mean of 8.20. The conductivity values range from 107 to 401 µS/cm, with a mean of 258 µS/cm. The mean Cl content is 0.6 mg/L, indication that evaporation and duration of contact of the water with rock and soil were not significant. It is possible that some of the Cl is a product of rock weathering, but the low concentration of Cl indicates that this process is insignificant. Note that these sites are at higher elevations and chemical processes at these sites are not necessarily the same as those at lower elevations in less-vegetated areas underlain by the Mancos Shale outside the national forests. The mean concentration of SiO_2 is 13 mg/L, about average for fresh water (table 3). Concentrations of trace elements generally are low, with mean Zn, Cu, Mo, and As values of 0.21, <1, 0.71, and 0.12 µg/L, respectively. High Se concentrations in samples from the lower parts of valleys are a problem. One possible cause is high Se concentrations in the Mancos Shale (Wright and Butler, 1993). In the headwater watersheds underlain by the Mancos Shale, Se concentrations in all of the water samples are <0.2 µg/L. The high Se concentrations in the lower parts of valleys probably are a result of evaporation effects from natural processes and irrigation. Se, similar to Cl, is concentrated as a result of evaporation. The concentrations of Al, Fe, and Mn are low, at 10, 15, and 2.2 µg/L, respectively. The alkalinity values are moderately high; they range from 30 to 180 mg/L as HCO_3^-, with a mean of 101 mg/L. The moderately high alkalinity probably is due to the presence of calcareous zones in the bedrock. These values of alkalinity indicate that the water in mountainous headwater areas

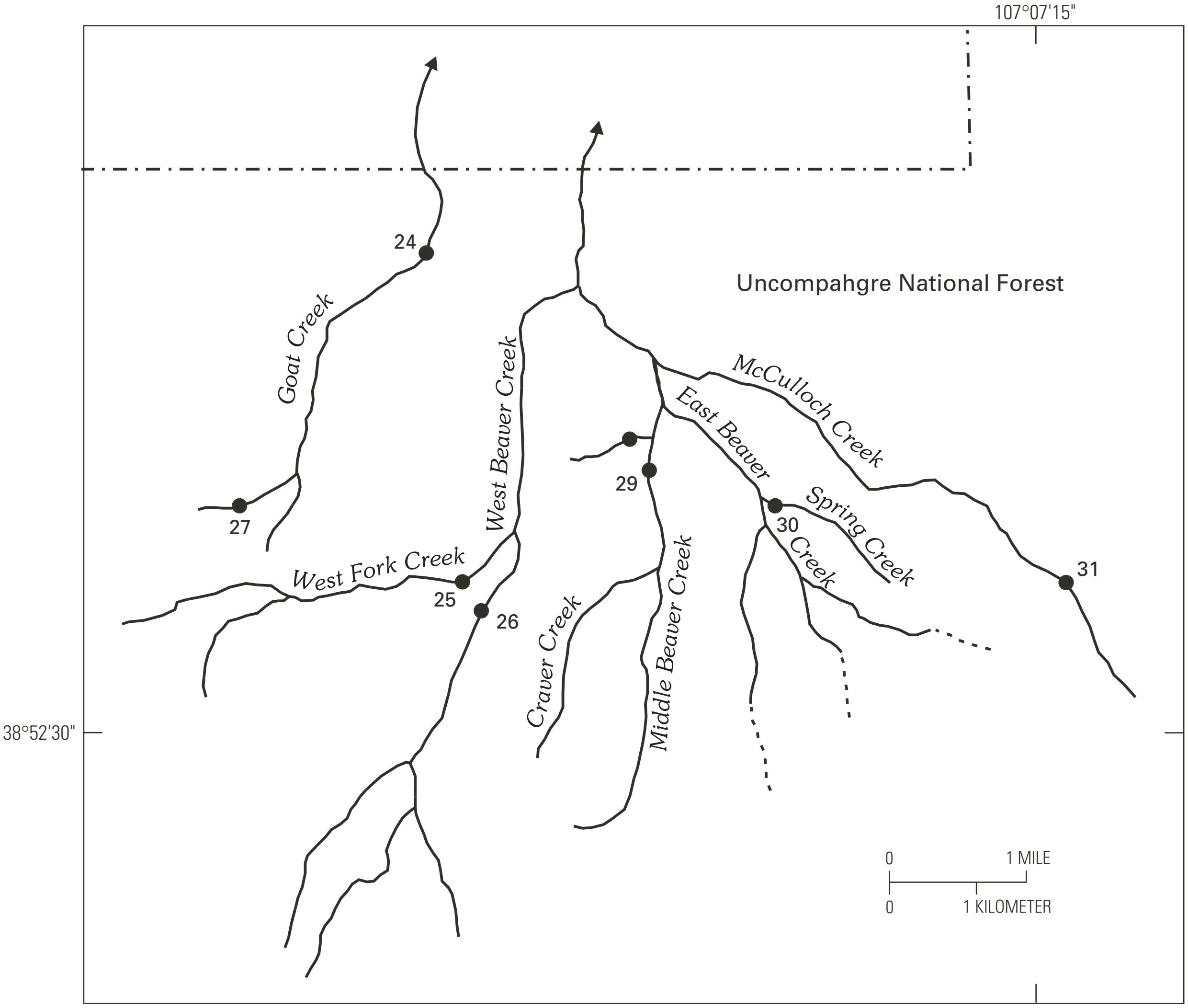

Figure 11. Site localities of stream water samples from areas underlain by Cretaceous Mancos Shale in the Beaver and Goat Creek watersheds, Uncompahgre National Forest, Colorado.

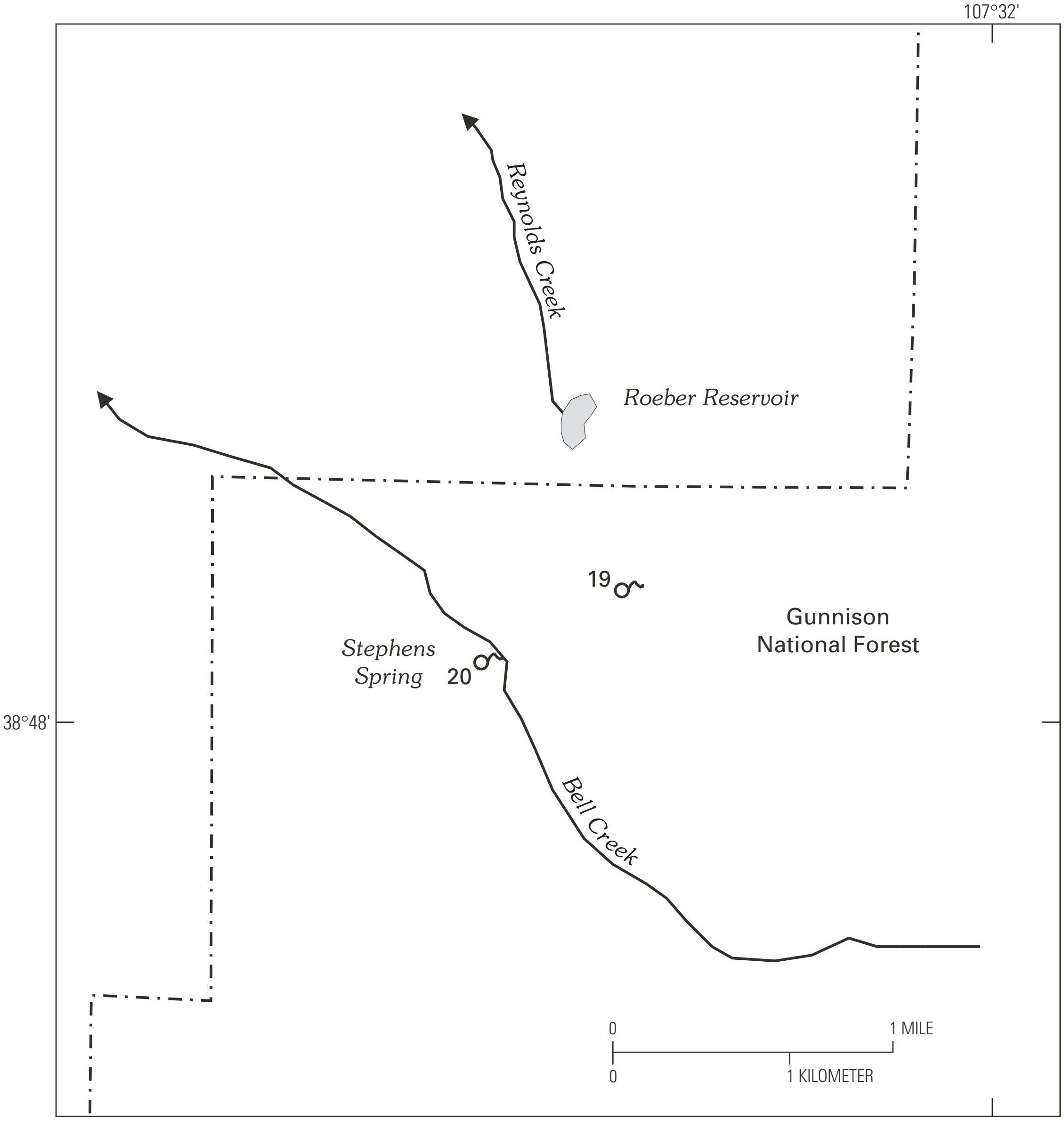

Figure 12. Site localities of spring water samples from areas underlain by Cretaceous Mancos Shale in the Bell Creek area, Gunnison National Forest, Colorado.

underlain by the Mancos Shale has moderate acid-neutralizing capacity to introduced acidification. Except for the moderately high dissolved solid content, the water quality is good.

Mesozoic Sedimentary Rocks

Water samples were collected from one stream and four springs on the summit and east flank of the Uncompahgre Plateau in the Uncompahgre National Forest (fig. 13). The ranges and means of selected chemical species in the samples are listed in table 11. Cretaceous, Jurassic, and Triassic sedimentary rocks underlie the area. Dominant units include the Cretaceous Dakota Sandstone and Burro Canyon Formation; the Jurassic Morrison Formation, Summerville Formation, Entrada Sandstone, and Wingate Sandstone, and the Triassic Chinle Formation (Tweto, 1979). The rocks are mostly sandstone, siltstone, mudstone, and conglomerate. They are dominantly terrestrial in origin and most are fluvial; however dune, flood-plain, and lacustrine deposits also are present. Many of the rocks were deposited in a warm, dry environment. Rocks of marine origin that are included consist of shale and limestone. Several of the units, particularly the Morrison, Entrada, and Chinle Formations, contain uranium and vanadium deposits along the west flank of the Uncompahgre Plateau outside the Uncompahgre National Forest boundaries. Impure coal beds are present in the Dakota Sandstone. The relief ranges from moderate, along the top, to high, along the flanks of the plateau. The annual precipitation ranges from 16 to 25 in. (Colorado Climate Center, 1984). The dominant vegetation is mainly subalpine forest, although scrublands are present along the lower slopes.

The stream and spring samples are Ca^{2+}- HCO_3^- type water with alkaline pH values and moderately high conductivity values. The range in pH values is 7.48 to 8.53, with a mean

Table 10. Summary of the chemistry of eight stream water samples and two spring water samples from areas underlain by the Cretaceous Mancos Shale, Gunnison and Uncompahgre National Forest, Colorado.

Measurement[1]	Range		Mean[2]
	Minimum	Maximum	
Conductivity	107	401	258
pH	7.46	8.58	8.20
Ca	12	50	32
Mg	2.3	13	7.5
Na	2.5	13	4.7
K	0.15	1	0.36
SiO_2	8.6	27	13
Alkalinity	30	180	101
SO_4	6.1	37	18
Cl	0.26	1.9	0.6
F	<0.1	0.19	0.12
Al	4.5	16	10
Fe	<5	60	15
Mn	<0.3	29	2.2
Cu	<1	<1	<1
Zn	<0.2	0.47	0.21
Pb	<0.1	<0.1	<0.1
Mo	<0.5	1.7	0.71
Sb	<0.01	0.14	0.015
As	<0.03	0.48	0.12
Th	0.02	0.062	0.032
U	0.12	0.58	0.27
Li	<0.5	5.9	1.6
Ba	4.8	35	18
Sr	39	581	169
V	<0.5	1.7	0.43
Sc	14	35	19
Rb	0.052	0.65	0.16
Y	0.034	0.13	0.053
Zr	<0.05	0.42	0.067
La	<0.005	<0.005	<0.005
Br	<3	<3	<3
I	<0.2	3.9	0.51

[1] Conductivity in µS/cm; Ca, Mg, Na, K, SiO_2, SO_4, Cl, and F in mg/L; alkalinity in mg/L HCO_3^-; remaining elements in µg/L

[2] All variables are geometric means except for pH, which is arithmetic mean

Table 11. Summary of the chemistry of one stream water sample and four spring water samples from areas underlain by Mesozoic sedimentary rocks, Uncompahgre National Forest, Colorado.

Measurement[1]	Range		Mean[2]
	Minimum	Maximum	
Conductivity	299	527	413
pH	7.48	8.53	7.94
Ca	43	84	59
Mg	7.4	14	10
Na	2	15	5.2
K	1.3	2.8	1.8
SiO_2	6.9	19	10.9
Alkalinity	152	262	205
SO_4	2.5	7.9	4.7
Cl	1.6	6.1	3.5
F	<0.1	0.15	0.12
Al	<3	18	6.7
Fe	<5	25	4.6
Mn	<0.3	3.9	0.68
Cu	<1	1	<1
Zn	<0.2	0.29	0.23
Pb	<0.1	1.7	0.13
Mo	<0.5	0.65	<0.5
Sb	<0.01	0.086	0.019
As	0.33	2.8	1.2
Th	0.045	0.094	0.07
U	1.4	5.8	2.7
Li	7.9	20	12
Ba	227	439	286
Sr	161	535	241
V	<0.5	2.7	0.68
Sc	11	25	15
Rb	1.5	4	2.4
Y	<0.03	0.2	0.035
Zr	<0.05	0.44	0.14
La	<0.005	0.064	0.005
Br	<3	78	8
I	<0.2	5.5	0.98

[1] Conductivity in µS/cm; Ca, Mg, Na, K, SiO_2, SO_4, Cl, and F in mg/L; alkalinity in mg/L HCO_3^-; remaining elements in µg/L

[2] All variables are geometric means except for pH, which is arithmetic mean

of 7.94. The range in conductivity values is 299 to 527 µS/cm, with a mean of 413 µS/cm. The mean Cl concentration is 3.5 mg/L, indicating that the water was in longer contact with rocks than surface water and that there was evaporation and concentration. Four of the samples are ground water from springs (fig. 13). The mean SiO_2 concentration is 10.9 mg/L, which is low compared to average fresh water (table 3). The low SiO_2 concentration probably reflects the large grain size and well-crystallized mineral grains in the sandstone. The mean concentrations of trace elements Zn, Cu, Mo, and As are low, at 0.23, <1, <0.5, and 1.2 µg/L, respectively, but the mean concentrations of U and As are elevated, at 2.7 and 1.2 µg/L, respectively, compared to average fresh water (table 3). The mean concentrations of Al, Fe, and Mn are low, at 6.7, 4.6, and 0.68 µg/L, respectively. The alkalinity values are high, from 152 to 262 mg/L as HCO_3^-, with a mean of 205 mg/L. The

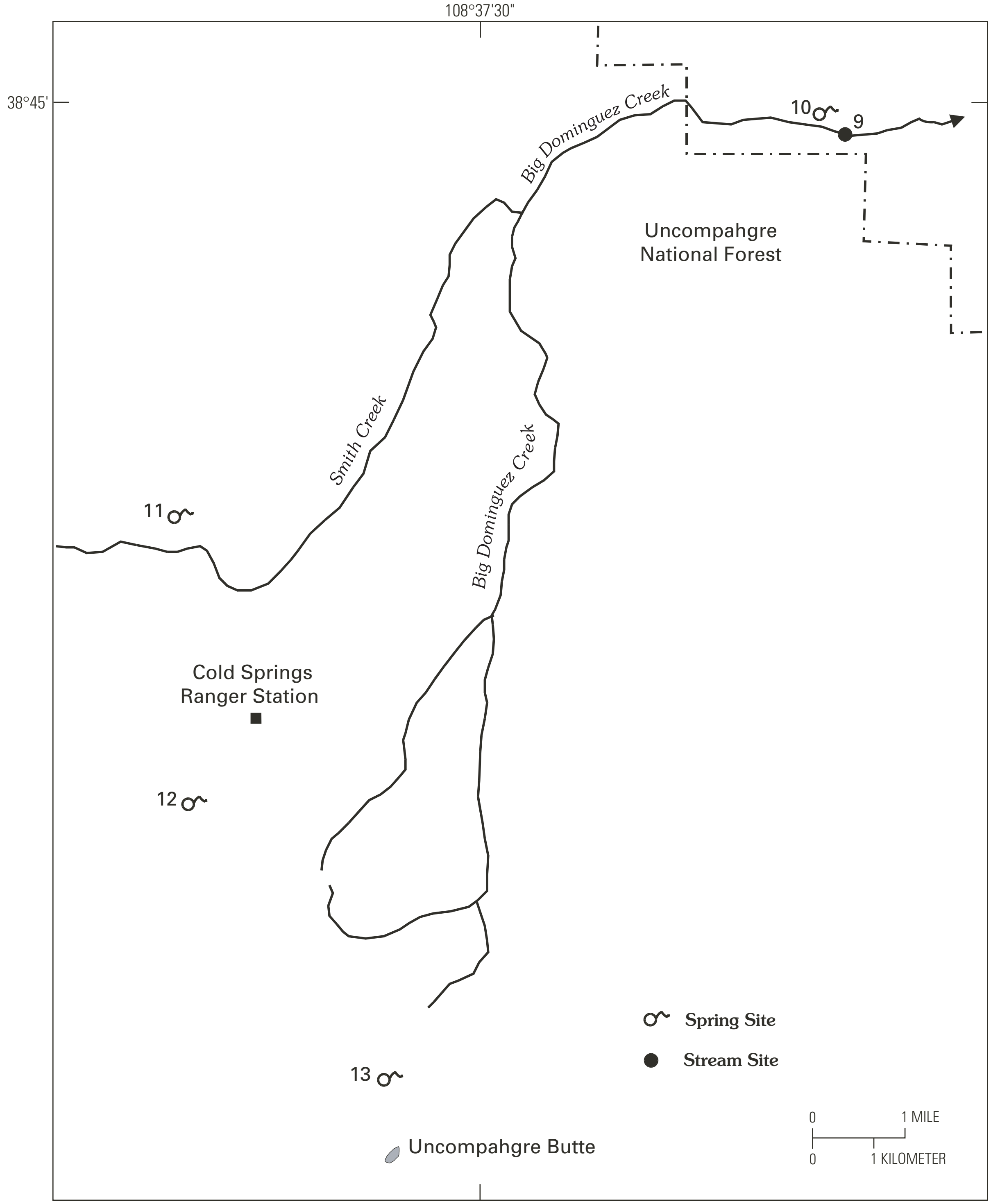

Figure 13. Site localities of stream and spring water samples from areas underlain by Mesozoic sedimentary rocks along the top and east flank of the Uncompahgre Plateau, Uncompahgre National Forest, Colorado.

high alkalinity values probably are a result of the presence of fine-grained, poorly crystallized calcite in marlstones and lacustrine deposits and as cement in sandstone. The high alkalinity ensures that the water from this area has good acid-neutralizing capacities to introduced acidification. The water is moderately high in total dissolved solids, compared to values from headwater areas; otherwise it is of good chemical quality.

Paleozoic Sedimentary Rocks

Water samples were collected from 14 streams and one spring in the Cement Creek and Spring Creek drainages along the west flank of the Sawatch Range in Gunnison National Forest (fig. 14). The ranges and means of selected chemical species in the samples are listed in table 12. Paleozoic sedimentary

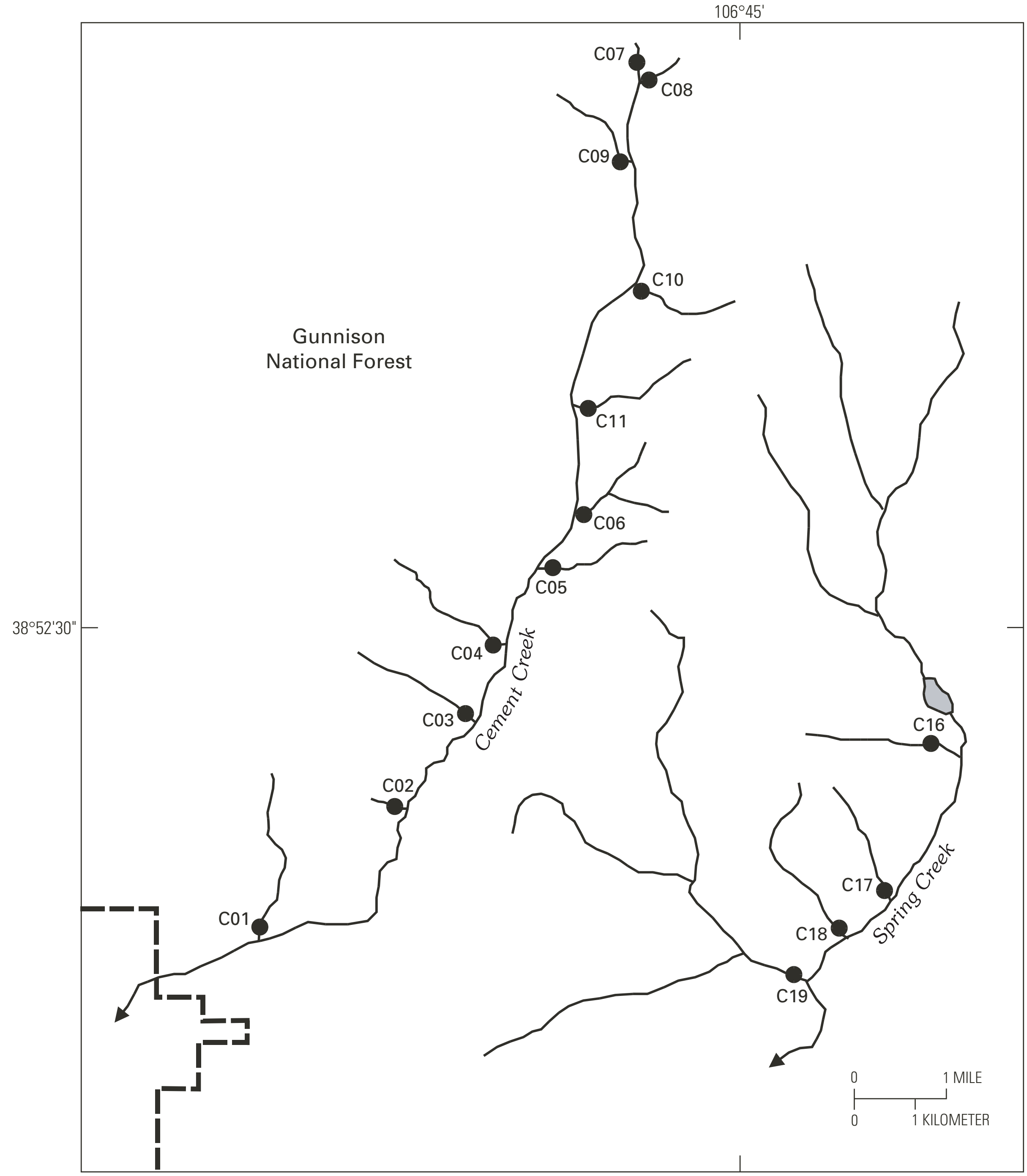

Figure 14. Site localities of stream and spring water samples from areas underlain by Paleozoic sedimentary rocks, in the Cement Creek watershed, Gunnison National Forest, Colorado.

rocks underlie the area. The dominant rock units include the Permian and Pennsylvanian Maroon Formation; the Pennsylvanian Minturn and Belden Formations; the Mississippian Leadville Limestone; the Ordovician Manitou Dolomite; and the Cambrian Sawatch quartzite (Tweto, 1976). The rocks are mostly limestone, dolomite, arkosic sandstone, conglomerate, and shale. The relief is high, and annual precipitation ranges from 25 to 40 in. (Colorado Climate Center, 1984). The dominant vegetation is mainly subalpine forest.

Fourteen samples are Ca^{2+}- HCO_3^- type water and one sample is Ca^{2+}- SO_4^{2-} type water. The pH values are alkaline and the conductivity values are high. The range in pH is 7.97 to 8.59, with a mean of 8.30. The range in conductivity values is 225 to 659 µS/cm, with a mean of 356 µS/cm. The mean Cl concentration is <0.25 mg/L, which is low. It reflects the short residence time of the water from melting snow and storm runoff in contact with the rocks and also a lack of significant evaporation. The mean SiO_2 concentration is 6.3 mg/L, which is low compared to average fresh water (table 3). The low concentration probably reflects the large grain size and well-crystallized grains of the silicate minerals and the abundance of carbonate minerals. The sulfate concentrations range from 0.85 to 204

Table 12. Summary of fourteen stream water samples and one spring water sample from watersheds underlain by Paleozoic sedimentary rocks, Gunnison National Forest, Colorado.

Measurement[1]	Range		Mean[2]
	Minimum	Maximum	
Conductivity	225	659	356
pH	7.97	8.59	8.30
Ca	40.6	101	52.6
Mg	2.94	25	11
Na	0.61	5.4	1.3
K	0.11	1.3	0.47
SiO_2	3.7	12	6.31
Alkalinity	110	194	143
SO_4	0.85	204	13.5
Cl	<0.25	1.7	<0.25
F	<0.1	0.2	<0.1
Al	0.77	7.7	0.34
Fe	<20	61	<20
Mn	0.1	29	0.6
Cu	<0.5	0.7	<0.5
Zn	<0.5	4.7	0.6
Pb	<0.05	<0.05	<0.05
Mo	<0.25	1.5	0.41
Sb	<0.01	0.2	<0.1
As	<3	<3	<3
Th	<0.005	0.02	0.01
U	<0.001	1.2	0.56
Li	0.6	15	2.1
Ba	54	264	88.5
Sr	26	107	107
V	0.7	1.8	0.9
Sc	0.6	1.3	0.9
Rb	0.5	3.1	0.47
Y	<0.01	0.1	0.03
Zr	<0.05	<0.05	<0.05
La	<0.01	0.02	<0.01

[1] Conductivity in µS/cm; Ca, Mg, Na, K, SiO_2, SO_4, Cl, and F in mg/L; alkalinity in mg/L HCO_3^-; remaining elements in µg/L

[2] All variables are geometric means except for pH, which is arithmetic mean

mg/L, with a mean of 13.5 mg/L. At seven sites sulfate concentrations were >30 mg/L, and at two sites they were >100 mg/L (app. 1). The high sulfate concentrations probably are due to dissolution of gypsum that is present in the Permian and Pennsylvanian rocks. The Eagle Valley Evaporite and the Eagle Valley Formation north of Gunnison National Forest contain gypsum, and intertongue with the Minturn and Belden Formations and the lower part of the Maroon Formation (Tweto, 1976). The samples with sulfate concentrations of >100 mg/L are from drainages underlain by the Maroon Formation and the Minturn and Belden Formations. The mean concentrations of trace elements Zn, Cu, Mo, and As are low, at 0.6, <0.5, <0.41, and <3 µg/L, respectively. The mean concentrations of Al, Fe, and Mn are low, at 0.34, <20, and 0.6 µg/L, respectively. The alkalinity values are moderately high; they range from 110 to 194 mg/L as HCO_3^-, with a mean of 143 mg/L. The moderately high alkalinity values probably are a result of the presence of abundant carbonate rocks and the carbonate cement in some of the clastic rocks. The moderately high alkalinity ensures that water in this area has a good capacity to neutralize effects from introduced acidification. The waters are moderately high in total dissolved solids; otherwise they are of good chemical quality.

Tertiary and Proterozoic Intrusive Rocks and Proterozoic Metamorphic Rocks

Water samples were collected from seven streams and one spring along the west flank of the Sawatch Range, in the Quartz Creek area (fig. 15) and Tomichi Creek area (fig. 16) in the Gunnison National Forest. The ranges and means of selected chemical species in water samples are listed in table 13. The areas are underlain by Proterozoic granite, granodiorite, quartz monzonite, diorites, gneiss, and gabbro, and by Tertiary granodiorite, quartz monzonite, and granite. The Proterozoic rocks are a basement complex, mainly metamorphic gneiss that was intruded by granite. The rocks are mostly felsic in composition, and here all are grouped as one rock type. The areas are of high relief, and annual rainfall ranges from 16 to 35 in. (Colorado Climate Center, 1984). The vegetation is mainly subalpine forest. The samples all are dilute Ca^{2+}- HCO_3^- type water with slightly acidic to alkaline pH values. The pH values range from 6.89 to 8.18, with a mean of 7.82. The conductivity values are low; they range from 47 to 126 µS/cm, with a mean of 83 µS/cm. The mean Cl concentration is 0.39 mg/L. This indicates that the water, which contains significant snow melt, is in short-duration contact with the rocks, as is expected in areas underlain by dominantly crystalline rocks and characterized by poorly developed soil zones and poor reserves of ground water. In addition, the mainly felsic rock composition ensures that chemical weathering is slow. The mean SiO_2 concentration is 14 mg/L, and it is about average for fresh water (table 3). Sulfate concentrations range from 1 to 15 mg/L, with a mean of 3.5 mg/L. The higher sulfate values of some samples (app. 1) probably are a result of oxidation of pyrite that is present in some of the rocks. Abandoned mines are present in the area, but disturbance in the sampled watersheds is insignificant. The mean concentrations of Cu and As are low, at <1 and <0.03 µg/L, respectively. The mean concentrations of Zn, Mo, and U, at 0.64, 0.83, and 0.78 µg/L, respectively, are slightly elevated compared to those in water from areas underlain by other rock types in this study. This probably is due to the presence of minor pyrite present in rocks in some of the watersheds. The mean concentrations of Al, Fe, and Mn are low, at 14, 13, and 0.3 µg/L, respectively. The alkalinity values range from 20 to 50 mg/L as HCO_3^-, with a mean of 34 mg/L. The low mean alkalinity indicates that the water in areas underlain by these rocks has a low capacity to neutralize introduced acidity. Therefore, the area is moderately susceptible to introduced acidification. The chemical quality of the waters is excellent.

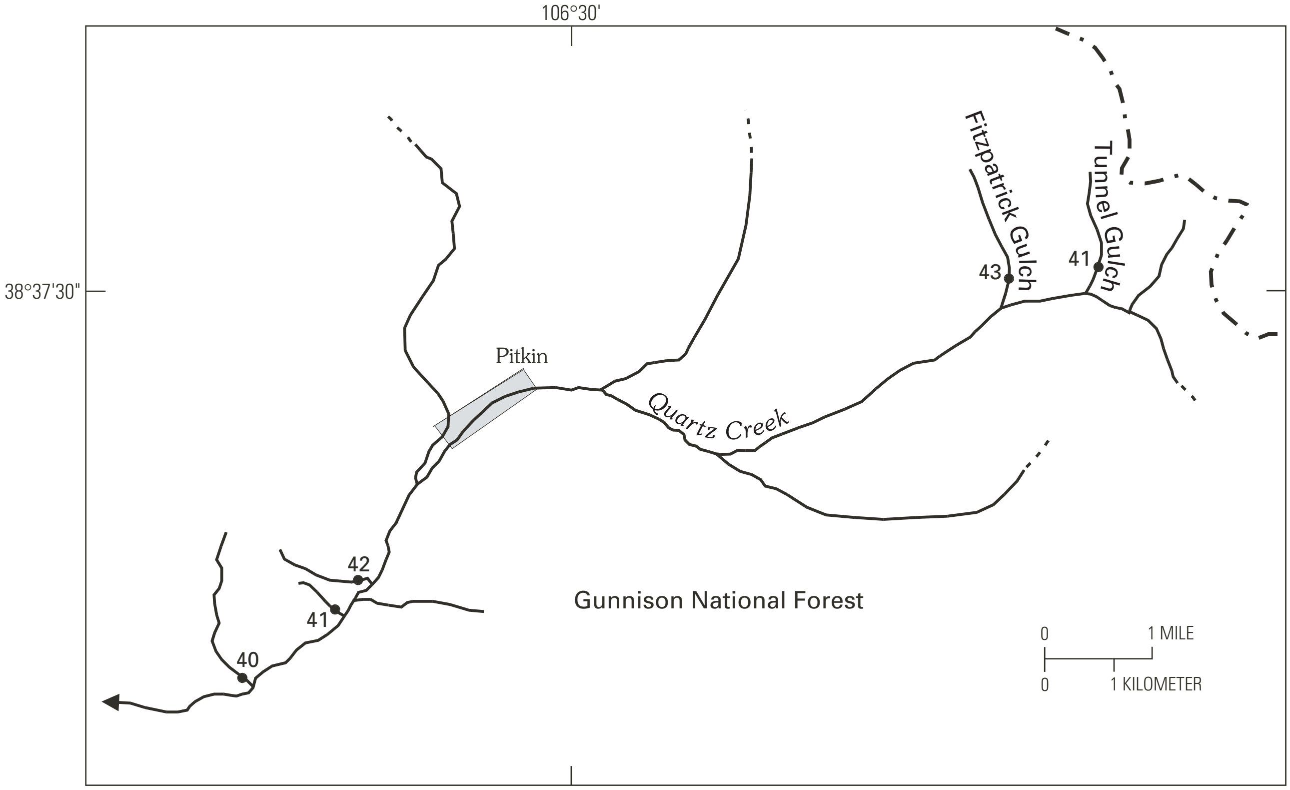

Figure 15. Site localities of stream water samples from areas underlain by Tertiary and Proterozoic intrusive rocks and Proterozoic metamorphic rocks in the Quartz Creek area, Gunnison National Forest, Colorado.

Comparison of the Chemistry of Water Samples from Areas Underlain by the Ten Rock Types

The chemistry of water in mountainous headwater areas depends on the chemical composition of the underlying bedrock. A unique range of water chemistry is associated with each rock type. For the ten rock composition types in this study, the means of selected chemical species and other parameters are listed in table 14.

The value of total dissolved solids (TDS) can be used to compute the rates at which rivers transport chemical weathering products to the ocean and can be used to calculate rates of chemical weathering. The TDS values also can be used to compare waters from different geologic terrains, as a means of comparing chemical weathering rates. A TDS value is the total amount of solids (mg/L) remaining when a water sample is evaporated. In calculations on the basis of analytical chemical data, a TDS value is the sum of all of the dissolved constituents, with bicarbonate converted to equivalent carbonate in the solid phase. This assumes that half of the bicarbonate is volatilized (Hem, 1992). The TDS value calculated for the water sample from each site is listed in appendix 1. The mean TDS values for water samples from the ten rock types are listed in table 14. Water with the highest mean TDS values is in areas underlain by Mesozoic sedimentary rocks; next highest values are in areas underlain by Tertiary sedimentary rocks. Type and amounts of dissolved solids in the water are related primarily to the rock composition types, but also to the duration of contact of the water and the rocks and also to evaporation effects.

One way to minimize the duration of contact and the evaporation effects is to normalize TDS values by dividing The TDS value by the Cl content. This assumes that the Cl content is conservative and does not readily react with other ions and precipitate and that there was no addition of Cl to the water by dissolution of minerals (such as halite) containing Cl. This normalization is done for the samples at each site, and the mean then is calculated for all the sites for a specific rock type to obtain a mean TDS/Cl value for that rock composition type. The highest normalized TDS values are from areas underlain by Paleozoic sedimentary rocks. The next highest values are from areas underlain by Mancos Shale, Tertiary sedimentary rocks, and Mesaverde Formation (table 15). The lowest normalized TDS values are from areas underlain by Mesozoic sedimentary rocks and Tertiary ash-flow tuff.

Chemical weathering rates are dependent on the amount of atmospheric precipitation; the greater the precipitation, the higher the chemical weathering rate. By normalizing TDS values, precipitation dependency is eliminated and the normalized TDS values reflect potential chemical weathering. The actual weathering rate is dependent on amounts of precipitation. Another way to look at potential weathering rate is that this would be the rate if all the rock types received the same amounts of precipitation.

Paleozoic sedimentary rocks are undergoing the most rapid potential rate of chemical weathering. Gypsum in the Paleozoic

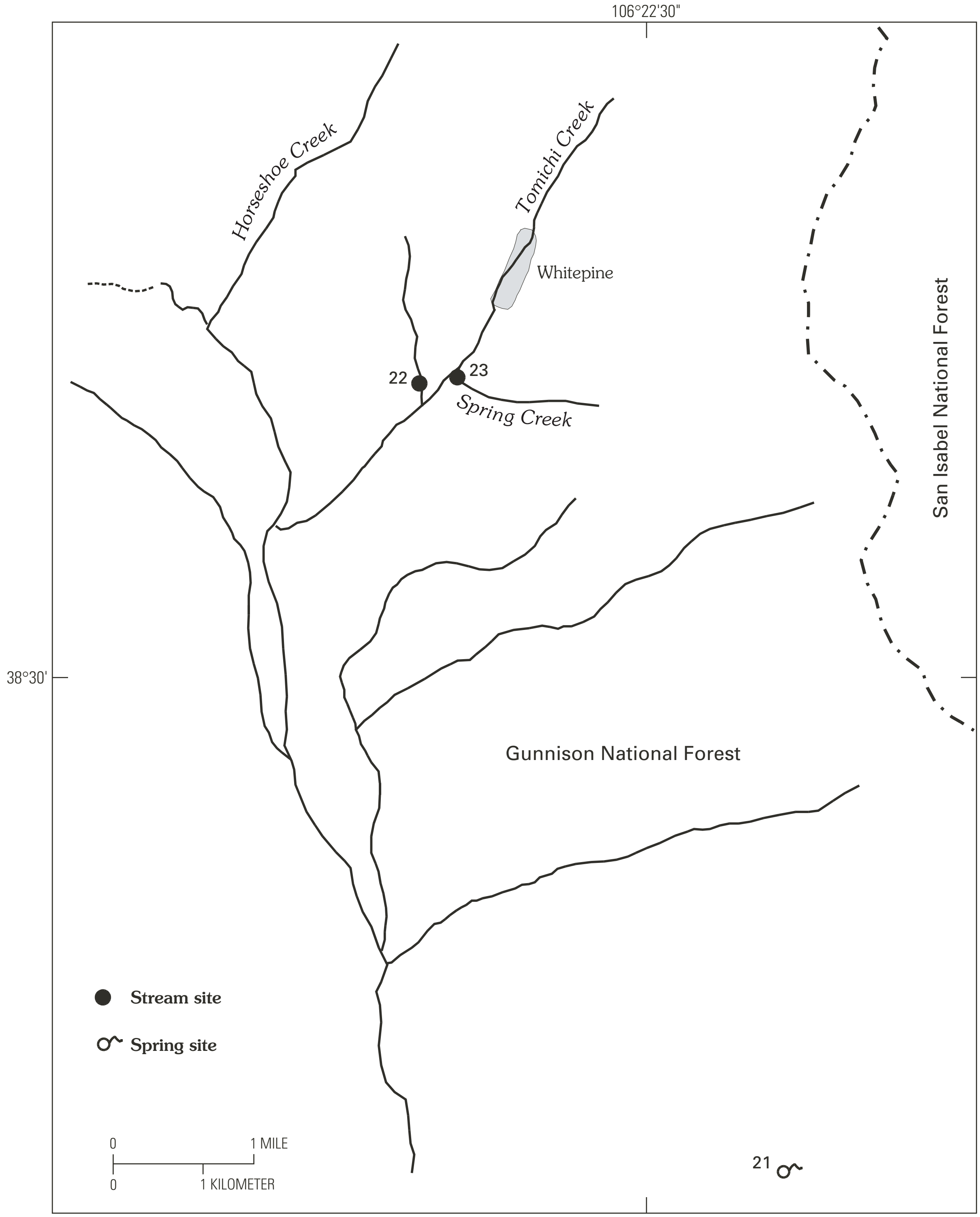

Figure 16. Site localities of stream and spring water samples from areas underlain by Proterozoic intrusive and metamorphic rocks along the western flank of the Sawatch Range, Gunnison National Forest, Colorado.

sedimentary rocks probably is a major contributor to the TDS of water in areas underlain by these rocks. The Mesozoic sedimentary rocks and the Tertiary ash-flow tuff are undergoing the slowest potential rate of chemical weathering, and they are supplying the lowest amounts of dissolved solids to the water. The Mesozoic sedimentary rocks contain abundant, well-crystallized silica minerals that are resistant to weathering. The felsic Tertiary ash-flow tuff is more resistant to weathering than are more mafic rocks.

Maps were constructed showing the potential release of TDS, as normalized TDS values that are recalculated so that all values were between 0 and 1. The highest mean normalized TDS value (table 15) is from Paleozoic sedimentary rocks, and it therefore was assigned a value of one. The recalculated mean

Table 13. Summary of the chemistry of seven stream water samples and one spring water sample from areas underlain by Tertiary and Proterozoic intrusive rocks and Proterozoic metamorphic rocks, Gunnison National Forest, Colorado.

Measurement[1]	Range		Mean[2]
	Minimum	Maximum	
Conductivity	47	126	83
pH	6.89	8.18	7.82
Ca	5.8	12	8
Mg	0.51	4.1	1.7
Na	1.2	5.3	3.1
K	0.24	0.84	0.55
SiO_2	6.1	22	14
Alkalinity	20	50	34
SO_4	11	5	3.5
Cl	<0.25	0.9	0.39
F	<0.1	2.2	0.21
Al	5.1	47	14
Fe	<5	35	13
Mn	<0.3	0.49	<0.3
Cu	<1	1	<1
Zn	0.22	5.1	0.64
Pb	<0.1	1.3	0.2
Mo	<0.5	2.9	0.83
Sb	<0.01	0.15	0.015
As	<0.03	<0.03	<0.03
Th	0.023	0.37	0.077
U	0.17	7.3	0.78
Li	0.68	5.7	1.7
Ba	2.6	29	8.7
Sr	28	48	37
V	<0.5	0.57	<0.5
Sc	<10	30	20
Rb	0.12	1.5	0.35
Y	<0.3	0.77	0.17
Zr	0.084	12.5	0.35
La	<0.005	0.57	0.036
Br	<3	<3	<3
I	<0.2	3.2	0.22

[1] Conductivity in µS/cm; Ca, Mg, Na, K, SiO_2, SO_4, Cl, and F in mg/L; alkalinity in mg/L HCO_3^-; remaining elements in µg/L

[2] All variables are geometric means except for pH, which is arithmetic mean

normalized TDS values for the other rock composition types were calculated by dividing the mean normalized TDS value for that rock type by the highest mean normalized TDS value. Ranks of the potential release of TDS are listed in table 16. Maps showing the potential release of TDS were constructed for each of the three national forests, by plotting the recalculated mean normalized TDS values from table 16 in relation to the rock composition types. The maps of potential release of TDS for the three national forests are figures 17–19.

The mean values for pH of water from areas underlain by the ten rock composition types range from 7.41, for Tertiary basaltic rocks, to 8.50 for Tertiary sedimentary rocks. The pH values in these headwater streams are affected by the amount of snow and storm runoff as a component of the total flow, and by the duration of contact of water and rock. Because the pH of atmospheric precipitation is buffered by CO_2 to approximately 5.7 (Carroll, 1962), snow and storm runoff generally lower the pH. The pH of water in contact with rock minerals such as silicates and carbonates generally increases with duration of contact of the water and rock. Because the pH values of the water samples are important for assessment of acidity of the watersheds, maps were made showing the mean pH. The mean pH values were plotted in relation to each of the rock composition types for each of the three national forests (figs. 20-22).

The alkalinity of a solution is the capacity for solutes it contains to react with and neutralize acid (Hem, 1992). Alkalinity is determined by titration with a strong acid. Several different chemical species may contribute to alkalinity. However, for almost all natural fresh water, the alkalinity is produced by the dissolved carbon dioxide species bicarbonate and carbonate (Hem, 1992). In this study alkalinity is reported as equivalent amounts of bicarbonate. If an area is affected by acid mine drainage or acid rain, the alkalinity will react with and consume the introduced acid until all the alkalinity is used up. After this, if acid is still introduced, the acidity of the water increases. Therefore, the alkalinity is a measure of the capacity of a watershed to resist the introduction of acid. The higher the alkalinity value, the greater the capacity of the water to neutralize and consume acid.

The mean alkalinity values of water from areas underlain by the ten rock types range from 28 to 205 mg/L as HCO_3^-. The water samples with the highest alkalinity values are from areas underlain by Mesozoic sedimentary rocks and the samples with the lowest alkalinity values are from areas underlain by Tertiary basaltic rocks (table 14). Alkalinity depends primarily on the rock composition type, but it also is related to the duration of contact of the rocks and water and to evaporation effects. To decrease the effect of the duration of contact and effects of evaporation, alkalinity is normalized using the Cl content, in a manner similar to the procedure used to normalize TDS. This assumes that the Cl content is conservative, and that there is no addition of dissolved solids to the water by dissolution of soluble salts containing Cl. Note that this procedure is carried out for the sample from each site, and then the mean is calculated for all of the samples associated with a specific rock type, to obtain the mean alkalinity/Cl value. The highest mean normalized alkalinity value is from areas underlain by Paleozoic sedimentary rocks, followed by areas underlain by the Mancos Shale and Tertiary sedimentary rocks (table 15). The lowest mean normalized alkalinity value is from areas underlain by Tertiary ash flow tuff. The normalized alkalinity value is a measure of the ability of the watershed to neutralize introduced acidity.

Maps showing acid-neutralizing capacity were constructed by recalculating the mean normalized alkalinity values in a manner similar to the procedure for normalization of TDS values, so that all values were between 0 and 1. The highest mean normalized alkalinity value, of water from areas underlain by Paleozoic sedimentary rocks, was assigned a value of one. The recalculated mean normalized alkalinity values water associated

Table 14. Summary of the chemical analyses and other parameters of water samples from areas underlain by various rock composition types, Grand Mesa, Uncompahgre, and Gunnison National Forests, Colorado.

[Complete data shown in app. 1]

Dominant rock compositon type	Setting	Relief	Precipitation annual, in in.	Dominant vegetation	Number samples	Dominant water type	TDS mg/L	pH	Conductivity µS/cm	Ca mg/L	Mg mg/L	Na mg/L	K mg/L	SiO_2 mg/L	Alkalinity mg/L HCO_3^-	SO_4 mg/L	Cl mg/L	F mg/L	Al µg/L	Fe µg/L	Mn µg/L
Tertiary basalt flows and associated rocks	Grand Mesa	low	30 to 45	subalpine forest, grassland	4	Ca^{2+}, HCO_3^-	39.3	7.41	63	5.4	2.1	1.8	0.37	14	28	0.65	0.29	<0.10	54	91	15
Tertiary felsic ash-flow tuff	San Juan volcanic field	high	16 to 30	subalpine forest	5	Ca^{2+}, HCO_3^-	74.5	7.43	100	11	1.7	4.4	1.3	29	46	2.7	0.88	0.10	16	65	2.9
Tertiary quartz latitic lava and breccia	San Juan volcanic field	high	16 to 25	subalpine forest	4	Ca^{2+}, HCO_3^-	93	7.48	124	12.6	1.8	6.9	1.1	30.8	36	16.6	0.56	<0.1	55	60	2.7
Tertiary andesitic lava and breccia	West Elk volcanic field	high	20 to 40	subalpine forest	8	Ca^{2+}, HCO_3^-	109	7.99	158	16	3	7.7	1.7	35	72	3.5	0.7	<0.10	13	16	0.48
Tertiary sedimentary rocks	Battlement and Grand Mesa	moderate	20 to 35	subalpine forest, oak scrublands	7	Ca^{2+}, HCO_3^-	196	8.50	365	39	12	15	1.4	18	191	8.1	1.4	0.16	12	13	4.7
Cretaceous Mesaverde Formation	Piceance Basin and Elk Mountains	high	20 to 35	subalpine forest	8	Ca^{2+}, HCO_3^-	69.5	8.31	126	13	3	5.4	0.49	13	54	5.3	0.49	0.11	12	14	2.0
Cretaceous Mancos Shale	San Juan volcanic field and Paradox Basin	high	16 to 40	subalpine forest	10	Ca^{2+}, HCO_3^-	134	8.20	258	32	7.5	4.7	0.36	14	101	18	0.60	0.12	10	15	2.2
Mesozoic sedimentary rocks	Uncompahgre uplift	high	16 to 25	subalpine forest	5	Ca^{2+}, HCO_3^-	200	7.94	413	59	10	5.2	1.8	11	205	4.7	3.5	0.12	6.7	<5	0.68
Paleozoic sedimentary rocks	West flank Sawatch Range	high	25 to 40	subalpine forest	15	Ca^{2+}, HCO_3^-	174	8.30	356	52.6	11.0	1.3	0.47	6.3	143	13.5	<0.25	<0.1	0.34	<20	0.57
Tertiary and Proterozoic intrusive rocks and Proterozoic metamorphic rocks	Sawatch Range	high	16 to 35	subalpine forest	8	Ca^{2+}, HCO_3^-	50.9	7.82	83	8	1.7	3.1	0.55	14	34	3.5	0.39	0.21	14	13	<0.3

Dominant rock compositon type	Cu µg/L	Zn µg/L	Co µg/L	Mo µg/L	Ni µg/L	Cr µg/L	As µg/L	Sb µg/L	W µg/L	Pb µg/L	U µg/L	Th µg/L	Li µg/L	Be µg/L	Ba µg/L	Ti µg/L	Sc µg/L	V µg/L	Se µg/L	Br µg/L	I µg/L	Sr µg/L	Rb µg/L	Y µg/L	Zr µg/L	Cs µg/L	La µg/L	Ce µg/L
Tertiary basalt flows and associated rocks	<1	0.40	<0.5	<0.5	<2	<0.1	0.048	0.017	0.20	0.15	0.069	0.083	<0.5	<0.05	14	2.1	21	<0.5	<0.2	<3	0.98	36	0.50	0.41	0.43	<0.002	0.25	0.43
Tertiary felsic ash-flow tuff	<1	0.24	<0.5	<0.5	<2	<0.1	1.2	0.021	<0.01	0.12	0.058	0.19	1.5	<0.05	18	<2	35	1.2	<0.2	3.5	2.2	79	1.2	0.10	0.51	<0.002	0.024	0.035
Tertiary quartz latitic lava and breccia	0.56	0.5	0.06	0.41	0.4	<1	<3	<0.1	<0.02	<0.05	0.140	0.03	3.6	<0.05	4.6	1.8	2.9	1.1	<5	n.d.	n.d.	115	1.4	0.32	0.3	0.03	0.13	0.17
Tertiary andesitic lava and breccia	<1	0.22	<0.5	<0.5	<2	<0.1	0.7	0.012	<0.01	<0.10	0.092	0.2	1.3	<0.05	5	<2	41	2.2	<0.2	<3	0.21	95	2.4	0.071	0.28	<0.002	<0.005	0.016
Tertiary sedimentary rocks	<1	0.22	<0.5	1.9	<2	<0.1	1.9	0.12	0.018	0.18	1.4	0.36	7.2	<0.05	62	<2	25	2.8	<0.2	6.6	1.5	311	0.60	0.083	0.42	<0.002	0.017	0.071
Cretaceous Mesaverde Formation	<1	0.24	<0.5	<0.5	<2	<0.1	0.08	<0.010	0.01	<0.10	0.13	0.038	1.4	<0.05	18	<2	18	<0.5	<0.2	<3	<0.2	102	0.32	0.042	0.15	<0.002	<0.005	0.006
Cretaceous Mancos Shale	<1	0.21	<0.5	0.71	<2	<0.1	0.12	0.015	<0.01	<0.10	0.27	0.032	1.6	<0.05	18	<2	19	0.43	<0.2	<3	0.51	169	0.16	0.053	0.067	<0.002	<0.005	<0.005
Mesozoic sedimentary rocks	<1	0.23	<0.5	<0.5	<2	<0.1	1.2	0.019	<0.01	0.13	2.7	0.07	12	<0.05	286	<2	15	0.68	0.27	8	0.98	241	2.4	0.035	0.14	0.056	0.005	<0.005
Paleozoic sedimentary rocks	<0.5	0.6	0.06	0.41	1.2	2.6	<3	<0.1	0.02	<0.05	0.56	0.01	2.1	<0.05	88.5	0.3	0.9	0.9	<5	n.d.	n.d.	107	0.47	0.03	<0.05	0.01	<0.01	<0.01
Tertiary and Proterozoic intrusive rocks and Proterozoic metamorphic rocks	<1	0.64	<0.5	0.83	<2	<0.1	<0.03	0.015	0.03	0.2	0.78	0.077	1.7	<0.05	8.7	<2	20	<0.5	<0.2	<3	0.22	37	0.35	0.17	0.35	0.002	0.036	0.033

Table 15. Mean normalized values for selected parameters and species for water samples from Grand Mesa, Uncompahgre, and Gunnison National Forests and the Redcloud Peak area, Colorado.

[Complete data shown in app. 1, 2]

	Mean Chloride	Mean TDS	Mean TDS/Cl	Mean Alkalinity	Mean Alkalinity/Cl	Mean Sulfate	Mean Sulfate/Cl	Mean F	Mean F/Cl	Mean U	Mean U/Cl	Mean Li	Mean Li/Cl
GMUG Area													
Tertiary basalt flows and associated rock	0.29	39.3	134	28	97	0.65	2.24	0.07	0.24	0.069	0.24	0.3	1.03
Tertiary felsic ash-flow tuff	0.88	74.5	84.7	46	52	2.7	3.07	0.1	0.11	0.058	0.07	1.5	1.7
Tertiary quartz latitic lava and breccia	0.56	93	166	36	64	16.6	30	<0.1	0.125	0.14	0.25	3.6	6.4
Tertiary andesitic lava and breccia	0.65	109	156	72	103	3.5	5	0.07	0.1	0.092	0.13	1.3	1.86
Tertiary sedimentary rocks	1.4	196	145	191	136	8.1	5.79	0.16	0.11	1.4	1	7.2	5.14
Cretaceous Mesaverde Formation	0.49	69.5	142	54	110	5.3	10.8	0.11	0.22	0.13	0.27	1.4	2.86
Cretaceous Mancos Shale	0.6	134	222	101	168	18	30	0.12	0.2	0.27	0.45	1.6	2.67
Mesozoic sedimentary rocks	3.4	200	58.1	205	59	4.7	1.34	0.12	0.03	2.7	0.77	12	3.43
Paleozoic sedimentary rocks	<0.25	174	715	143	572	13.5	54	<0.1	0.28	0.56	2.24	2.1	8.4
Tertiary and Proterozoic intrusive and Proterozoic metamorphic rocks	0.39	50.9	132	34	87	3.5	8.97	0.21	0.54	0.78	2	1.7	4.36
Redcloud Peak Area													
Sunshine Peak Tuff	0.12	66.4	552	3.9	33	30	252	0.17	1.41	0.66	5.49	3.7	31

Total dissolved solids (TDS) in mg/L; chloride, sulfate, and fluoride in mg/L; alkalinity in mg/L HCO_3^-; remaining elements in µg/L; TDS/Cl, Alkalinity/Cl, F/Cl, U/Cl and Li/Cl are unitless.

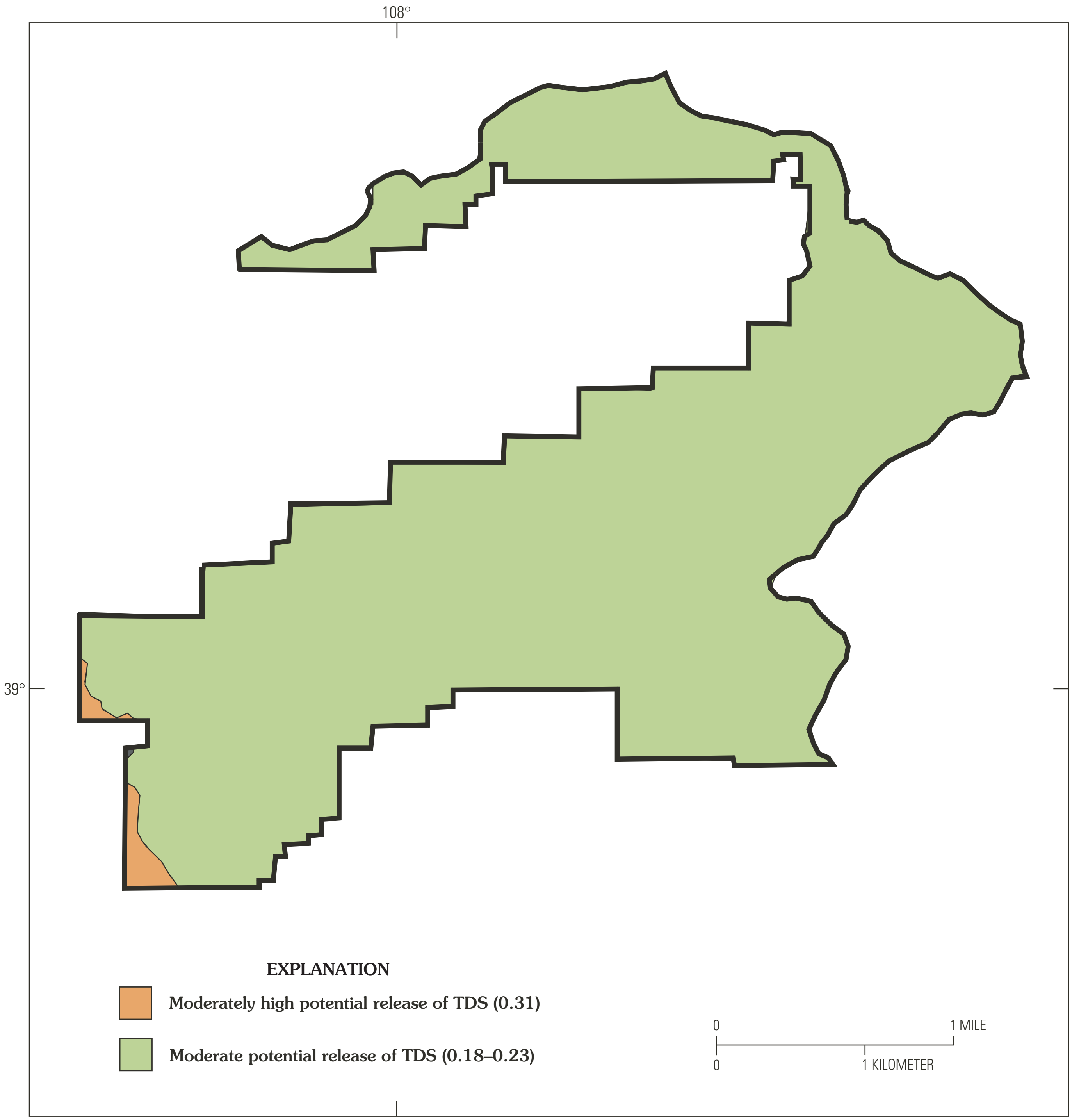

Figure 17. Potential release of total dissolved solids (TDS) in stream and spring waters in the Grand Mesa National Forest, Colorado.

with other rock composition types were calculated by dividing the mean normalized alkalinity value of the specific rock type by the highest mean normalized alkalinity value. The ranks of acid-neutralizing capacities to introduced acidity are listed in table 16. Maps showing acid-neutralizing capacities to introduced acidity for each of the three national forests were constructed by plotting the recalculated mean normalized alkalinity values from table 16 in relation to the rock composition types. The maps of the three national forests are figs. 23–25.

The mean concentrations of silica in water from areas underlain by the ten composition rock types range from 11 mg/L, for Mesozoic sedimentary rocks, to 35 mg/L, for Tertiary andesitic rocks (table 14). Other high mean silica concentrations are from areas underlain by Tertiary quartz latitic lava and breccia (31 mg/L) and ash flow tuff (29 mg/L). The high mean silica values probably are related to the fact that these rocks contain fine-grained silicate minerals with large surface areas, and therefore they are particularly susceptible to dissolution of

Table 16. Ranking of rock composition types with respect to potential release of total dissolved solids (TDS) and neutralizing capacity to introduced acidity in the Grand Mesa, Uncompahgre, and Gunnison National Forests, Colorado.

	Potential Release of TDS		
Rock Composition	Mean TDS[1]	Mean Normalized TDS/Cl	Recalculated Mean TDS/Cl
Tertiary basalt flows and associated rock	39.3	134	0.19
Tertiary felsic ash flow tuff	74.5	84.7	0.12
Tertiary latitic lava and breccia	93	166	0.23
Tertiary andesitic lava and breccia	109	156	0.22
Tertiary sedimentary rock	196	145	0.20
Cretaceous Mesaverde Formation	69.5	142	0.20
Cretaceous Mancos Shale	133.8	222	0.31
Mesozoic sedimentary rock	200	58.1	0.08
Paleozoic sedimentary rock	174	715	1.00
Tertiary and Proterozoic intrusive and Proterozoic metamorphic rocks	50.9	132	0.18
	Acid-Neutralizing Capacity		
Rock Composition	Mean Alkalinity[2]	Mean Normalized Alkalinity (Alkalinity/Cl)	Recalculated Mean Normalized Alkalinity
Tertiary basalts	28	97	0.17
Tertiary felsic ash flow tuff	46	52	0.09
Tertiary latitic lava and breccia	36	64	0.11
Tertiary andisites	72	103	0.18
Tertiary sedimentary rock	191	136	0.24
Cretaceous Mesaverde Formation	54	110	0.19
Cretaceous Mancos Shale	101	168	0.29
Mesozoic sedimentary rock	205	59	0.1
Paleozoic sedimentary rock	143	572	1
Tertiary and Proterozoic intrusive and metamorphic rocks	34	87	0.15

[1] TDS in mg/L

[2] Alkalinity as mg/L HCO_3^-

silica. Conversely, the Mesozoic sedimentary rocks contain sandstone that is composed of large-sized and well-crystallized mineral grains that have smaller surface areas. The latter grains are more resistant to silica dissolution.

The mean concentrations of Cu, Zn, Co, Ni, Cr, Sb, Pb, and Be in water samples from watersheds underlain by the ten rock types all are low (table 14). In addition, the mean values for Se all are <0.2 µg/L, except for samples from areas underlain by Mesozoic sedimentary rocks, for which the mean is 0.27 µg/L. Thus, the contribution of Se in these mountainous headwater watersheds is very low. The Mancos Shale is a source of Se concentrations in water in the lower parts of valleys, particularly in areas of irrigation (Wright and Butler, 1993). In these mountainous headwater streams, in areas underlain by the Mancos Shale, evaporation effects are minimal and Se concentrations are low.

The mean concentrations of Mo are low, except for a slightly elevated mean value (1.9 µg/L) in water from areas underlain by Tertiary sedimentary rocks. The mean concentrations of U are low, except for slightly elevated mean values in water from areas underlain by Mesozoic sedimentary rocks (2.7 µg/L) and Tertiary sedimentary rocks (1.4 µg/L). The mean concentrations of As are low for water from the three national forests, except for slightly elevated mean values in water from areas underlain by Tertiary sedimentary rocks (1.9 µg/L), Tertiary ash-flow tuff (1.2 µg/L), and Mesozoic sedimentary rocks (1.2 µg/L) (table 14).

The mean values for Al of all rock types are low compared to average fresh water (table 3), except for elevated mean values (54 and 55 µg/L) in water from areas underlain by Tertiary basalt and Tertiary quartz latitic lava and breccia. The mean values for Fe of all rock types are low, except for elevated mean values (91, 65, and 60 µg/L) in water from areas underlain by Tertiary basalt, Tertiary quartz latitic lava and breccia, and Tertiary ash flow tuff. The mean values for Mn of all rock types are low, except for elevated mean value (15 µg/L) in water from areas underlain Tertiary basalt (table 14).

Sulfate, F, and U are mobile as anion species in alkaline water. The degree to which these elements are concentrated in water depends on the duration of contact of the water and rock, and also on evaporation effects. The highest mean sulfate concentration (18 mg/L) is in water from areas underlain by the Mesaverde Formation (table 14). The Mesaverde Formation

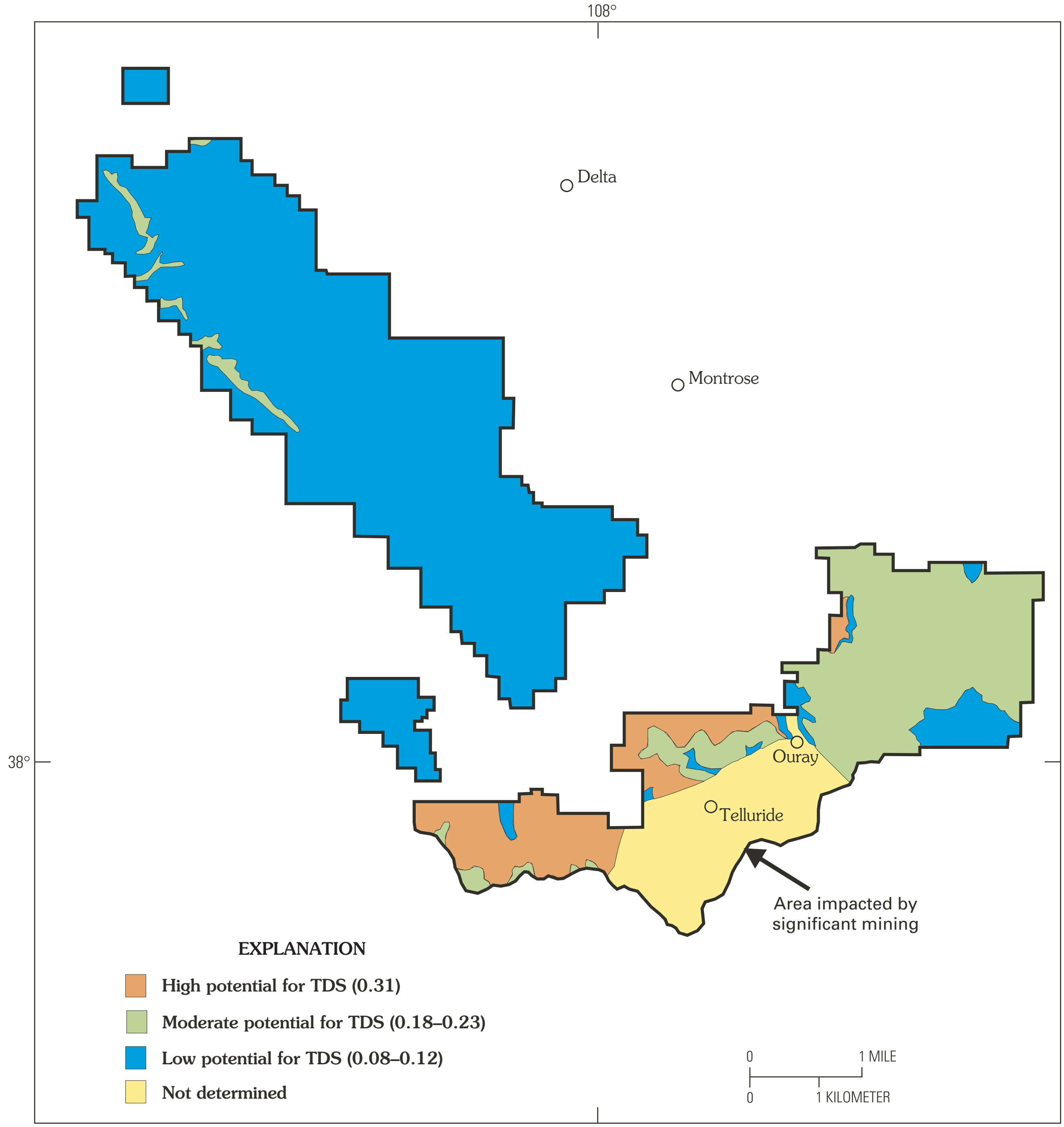

Figure 18. Potential release of total dissolved solids (TDS) in stream and spring waters in the Uncompahgre National Forest, Colorado.

contains coal with associated pyrite. Weathering of the pyrite probably is the source of the sulfate. To reduce the effects of evaporation and the duration of contact of water and rock, sulfate values were normalized by dividing the sulfate concentration by the Cl concentration for each sample, and the mean was calculated for all sites associated with a specific rock type to produce the mean sulfate/Cl value. The highest mean normalized values for sulfate are from water from areas underlain by Paleozoic sedimentary rocks and the Mancos Shale, followed by water from areas underlain by Tertiary sedimentary rocks and the Mesaverde Formation (table 15). This highest mean normalized sulfate value, from areas underlain by Paleozoic sedimentary rocks, probably is due to dissolution of gypsum in the rocks. The high values in water associated with other rock composition types probably are due to the weathering of pyrite in the sedimentary rocks.

The highest mean F concentration (0.21 mg/L) is in water from areas underlain by Tertiary and Proterozoic intrusive and Proterozoic metamorphic rocks (table 14). The high concentration of F probably is a result of the high F content of the Tertiary and Proterozoic intrusive and Proterozoic metamorphic rocks. When F is normalized in a manner similar to the procedure used

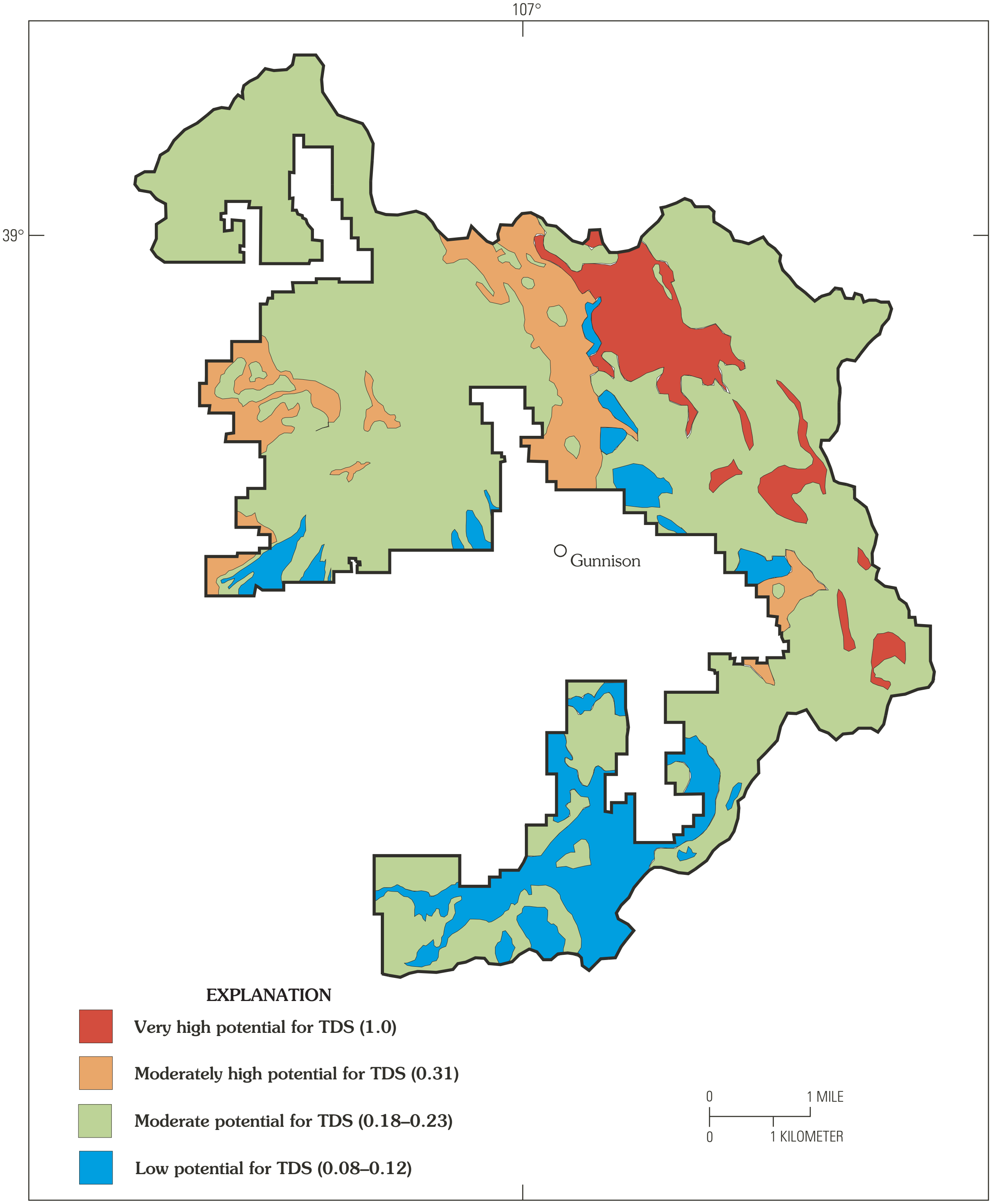

Figure 19. Potential release of total dissolved solids (TDS) in stream and spring waters in the Gunnison National Forest, Colorado.

to produce mean normalized values for sulfate, these rocks are even more anomalous, compared to the other major rock composition types (table 15). The Tertiary basaltic rocks are next highest in normalized F, indicating that the basaltic rocks are elevated in F.

The highest mean U concentrations (table 14) are in water from areas underlain by Mesozoic sedimentary rocks (2.7 µg/L), Tertiary sedimentary rocks (1.4 µg/L), and Tertiary and Proterozoic intrusive and Proterozoic metamorphic rocks (0.78 µg/L). When U is normalized, in a manner similar to the procedure used for sulfate, the highest values (table 15) are in water from areas underlain by Paleozoic sedimentary rocks (2.2), Tertiary and Proterozoic intrusive and Proterozoic metamorphic rocks (2.0), Tertiary sedimentary rocks (1.0), and Mesozoic sedimentary rocks (0.77). These values indicate that these rock composition types are elevated in leachable U.

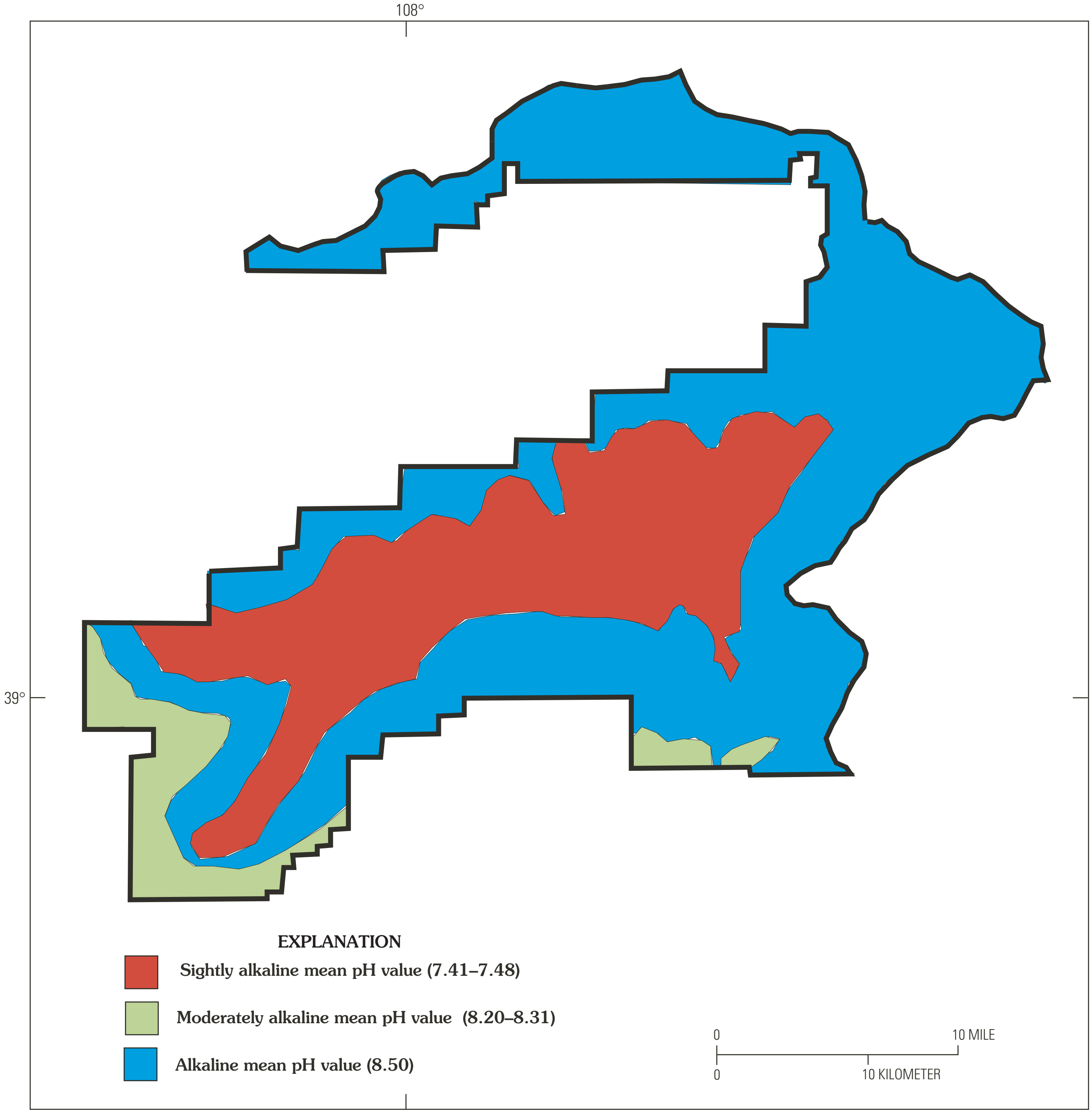

Figure 20. Mean pH values of stream and spring waters in the Grand Mesa National Forest, Colorado.

The highest mean Li value (12 µg/L) is in water from areas underlain by Mesozoic sedimentary rocks. This value is high, compared to values from samples associated with the other rock composition types (table 14). Much of the high mean Li concentration is the result of a longer duration of contact of water and rock and to the evaporation effects associated with the spring water. If Li is normalized in a manner similar to that described previously, the water samples with the highest mean normalized Li values are associated with Tertiary sedimentary rocks (5.14), followed by Tertiary and Proterozoic intrusive and Proterozoic metamorphic rocks (4.36), and Mesozoic sedimentary rocks (3.43) (table 15).

To gain an understanding of processes such as chemical speciation of elements and the identification of the saturation state of minerals that possibly control the concentration, mobility, and attenuation of elements in the stream water, chemical modeling of the stream water was carried out using PHREEQC (Parkhurst, 1995). The modeling program assumes that there is mineral-solution equilibrium. For some chemical reactions, particularly with slow kinetics, this possibly is not the case.

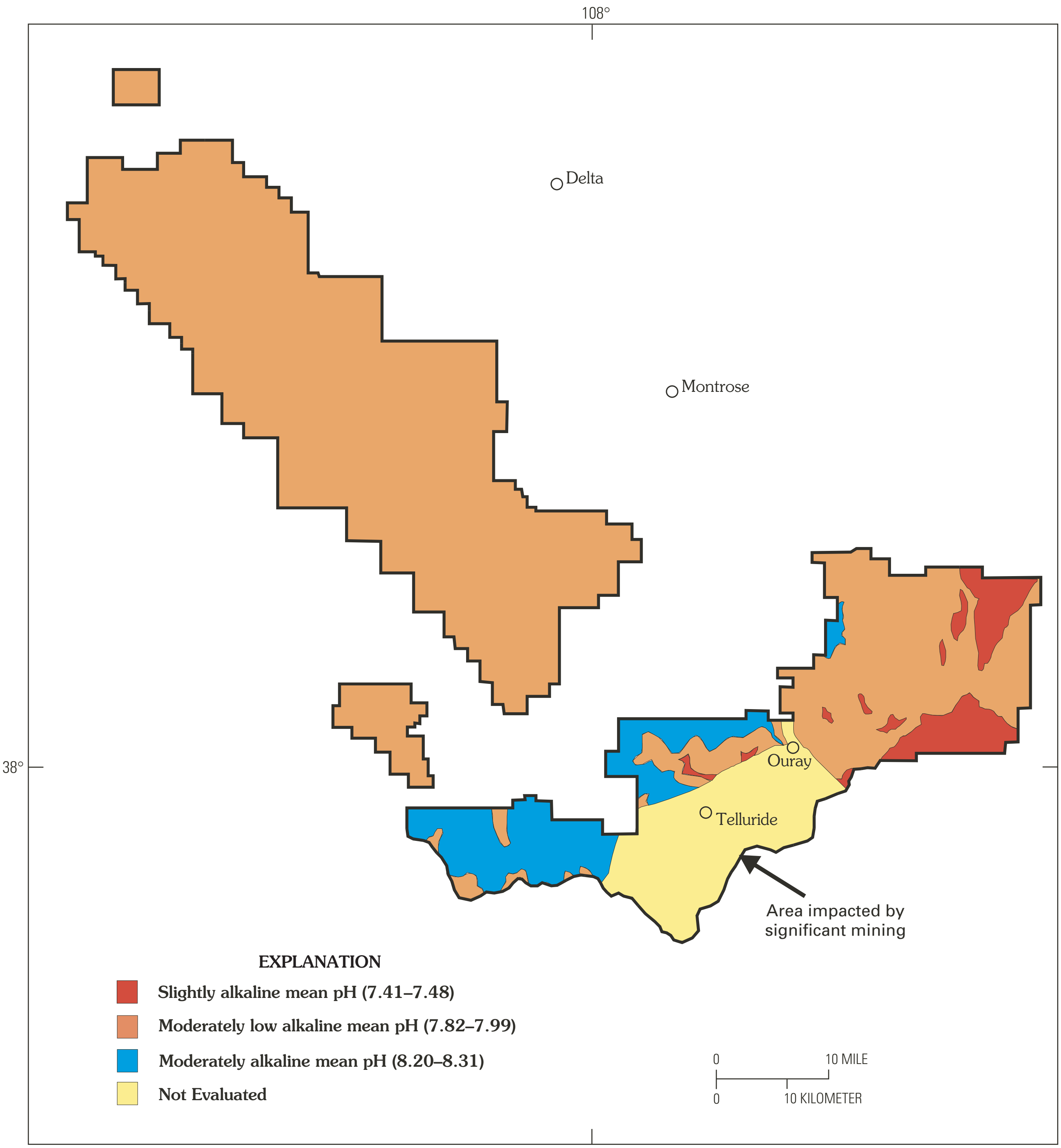

Figure 21. Mean pH values of stream and spring waters in the Uncompahgre National Forest, Colorado.

Except for Al, the cations in the stream water samples are present mostly as simple cations, and the anions are present as chloride, sulfate, carbonate, and bicarbonate complexes (table 17). In addition, the state of saturation of the water with mineral phases was calculated. Saturation indices were calculated for a suite of minerals, to determine if concentrations of species in the water were controlled by mineral phases. The saturation index is a convenient way to express saturation states of minerals (Barnes and Clark, 1969) where:

$$SI=\log_{10} IAP/K_T.$$

In the expression, SI is the saturation index, IAP is the ion activity product, and K_T is the equilibrium constant of the dissolution reaction at the temperature of the sample. Mineral phases are supersaturated at $SI>0$, saturated at $SI=0$, and undersaturated at $SI<0$.

The input for the modeling was the mean values for each rock composition type listed in table 14. The water from areas

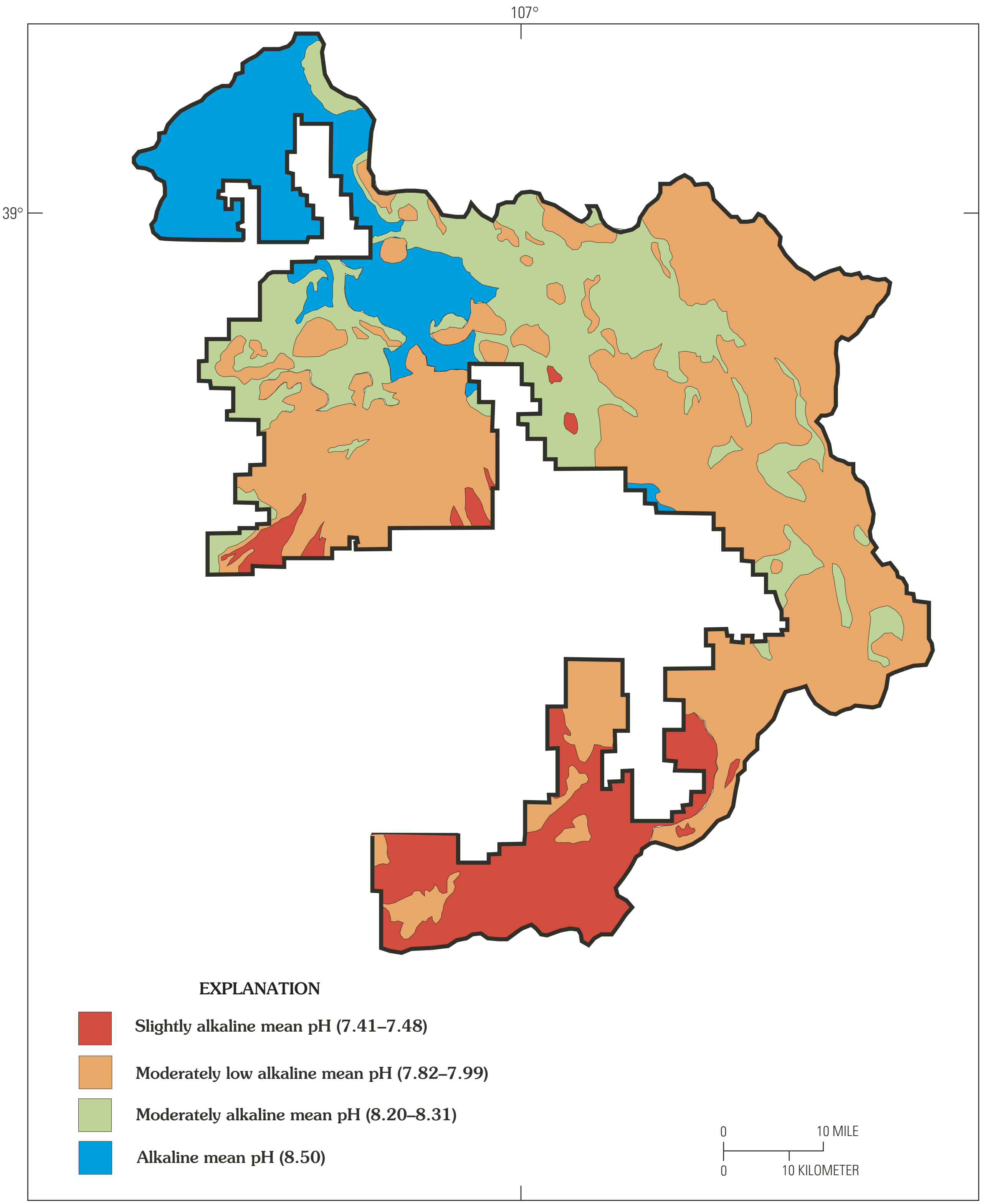

Figure 22. Mean pH values of stream and spring waters in the Gunnison National Forest, Colorado.

underlain by Tertiary sedimentary rocks, the Mancos Shale, Mesozoic sedimentary rocks, and Paleozoic sedimentary rocks is supersaturated with respect to calcite and dolomite (table 18). These are headwater streams, not streams in the lower parts of valleys where secondary calcite is abundant. Therefore, the water is in contact with dissolving carbonate minerals, such as calcite and dolomite that are present in the bedrock. Another mineral, which influences chemical species in water, is chalcedony. Most of the water associated with each of the rock composition types is saturated or slightly oversaturated with respect to chalcedony (table 18). Chalcedony appears to control the amount of dissolved silica in the water. Water associated with

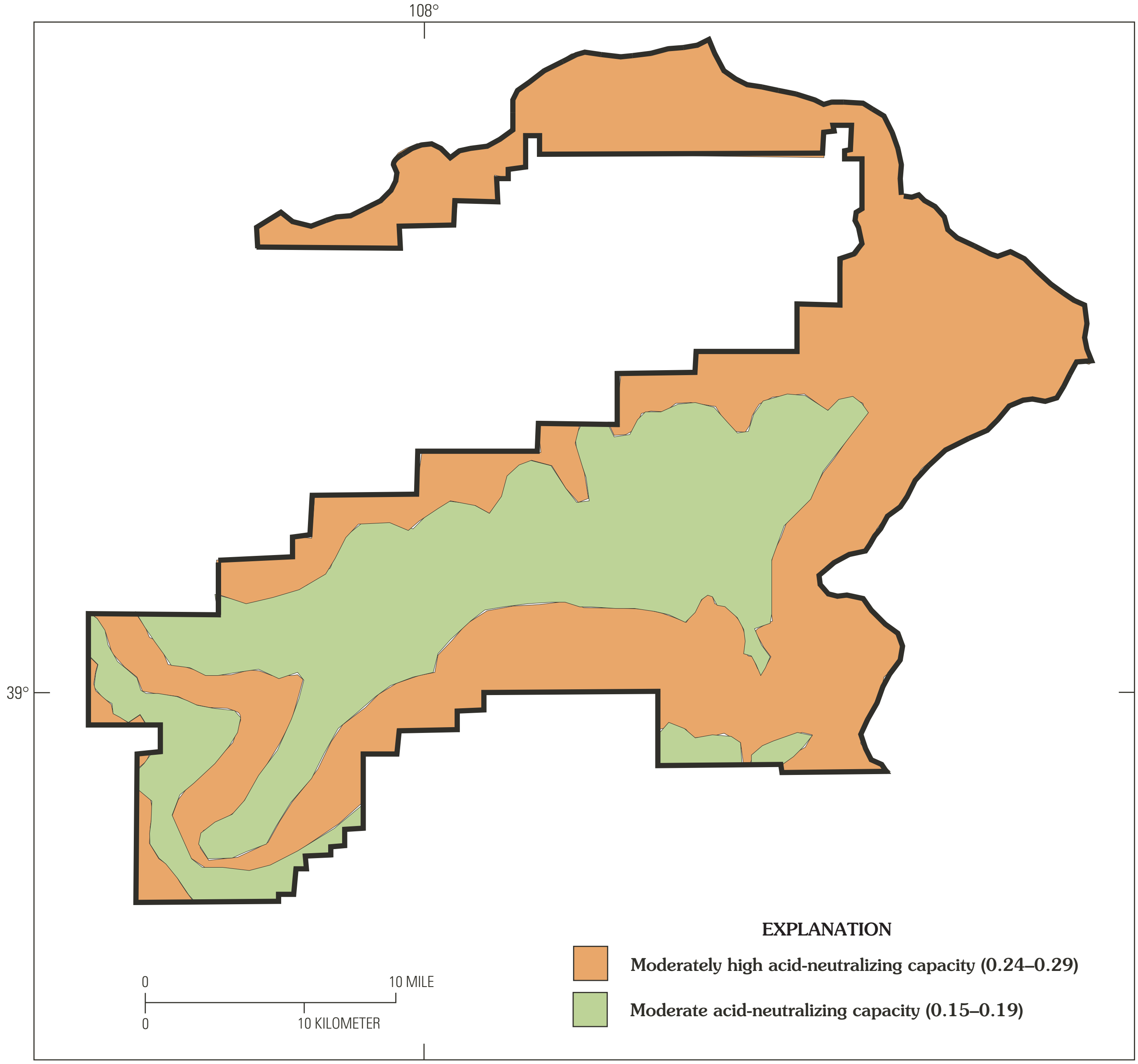

Figure 23. Acid-neutralizing capacity to introduced acidity in the Grand Mesa National Forest, Colorado.

Tertiary sedimentary rocks is oversaturated with respect to sepiolite (table 18). Sepiolite appears to control Mg mobility. Mg is probably the product of weathering of dolomite.

Comparison of Water Samples from Areas Underlain by the Ten Rock Composition Types and Water Samples from an Area Underlain by Mineralized Rocks

No significant mineralization has been identified in the watersheds sampled in the three National Forests. Significant mineralization is present in other watersheds in the three national forests, particularly in upper parts of the Uncompahgre and San Miguel River basins and in the Crested Butte area. Contamination from mining has altered the natural baselines of water in watersheds where mining has taken place; therefore, natural baselines for these areas cannot be determined directly.

The Redcloud Peak area near Lake City, Colo., is administered by the Bureau of Land Management (BLM) and is adjacent to the Gunnison and Uncompahgre National Forests. The area contains significant mineralization, but no large-scale mining has taken place. Water samples from streams in the Redcloud Peak area were collected in a previous study (Miller and McHugh, 1998). The water chemistry of this mineralized area here is compared to the water chemistry in areas underlain by

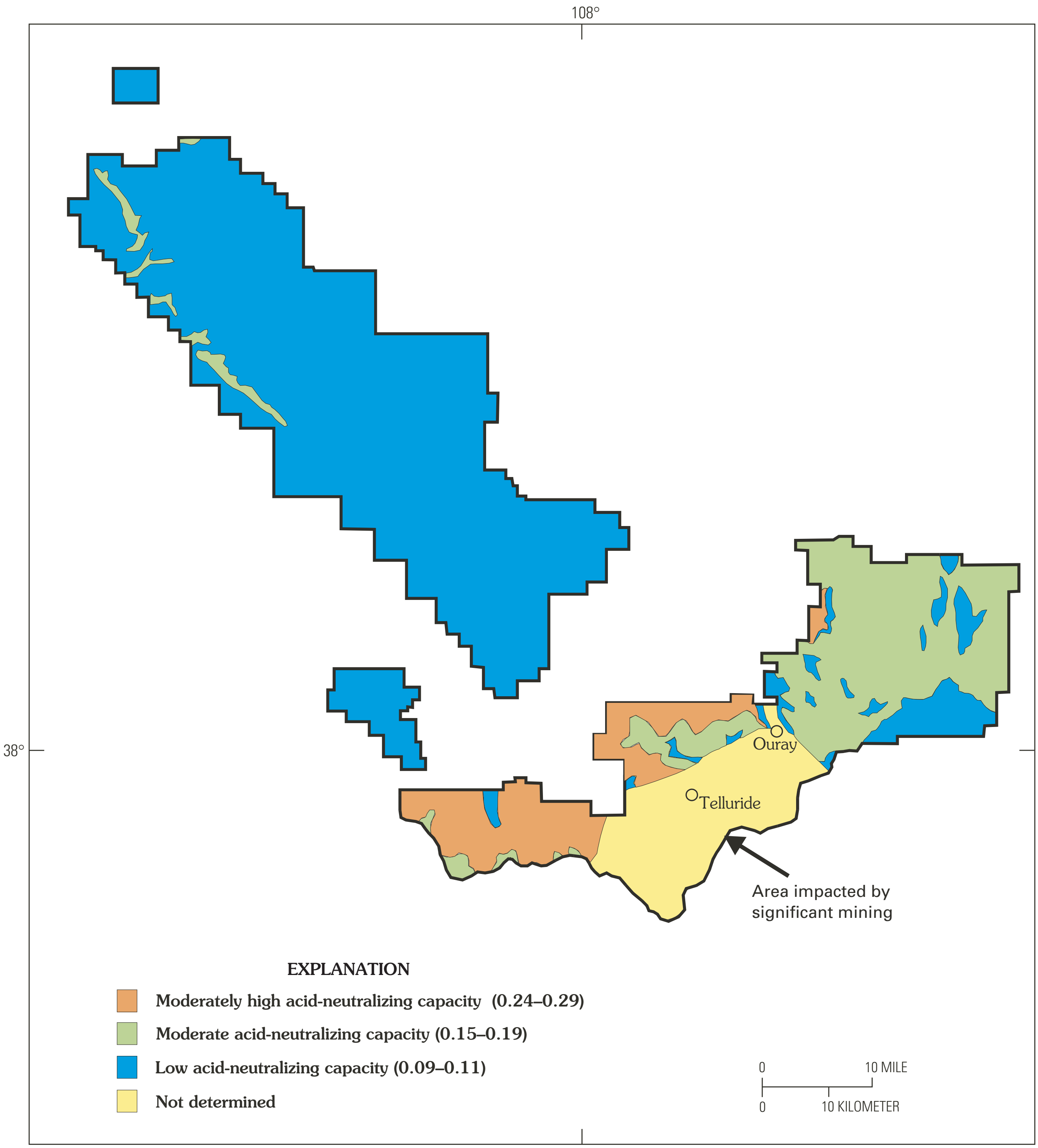

Figure 24. Acid-neutralizing capacity to introduced acidity in the Uncompahgre National Forest, Colorado.

the ten rock composition types in the GMUG area, in order to evaluate effects of mineralization on water chemistry. The chemistry of water from the Redcloud Peak area is similar to, in a qualitative manner only, the natural baselines of water from watersheds in the mined areas in the GMUG areas. This comparison is presented only to show trends of effect of mineralization on water chemistry in watersheds that overlie significantly mineralized rocks; it does not determine the pre-mining natural geochemical baselines of water from mined watersheds in the GMUG area.

The Redcloud Peak area is within the Lake City caldera. Samples of water were collected in July of 1994 from 19 headwater streams in watersheds underlain by the Sunshine Peak silicic alkalic rhyolite tuff. The multiple-flow tuff is more than 1 km thick. The tuff was densely welded and propylitically altered about 22.5 m.y. ago (Lipman, 1976). The chemical

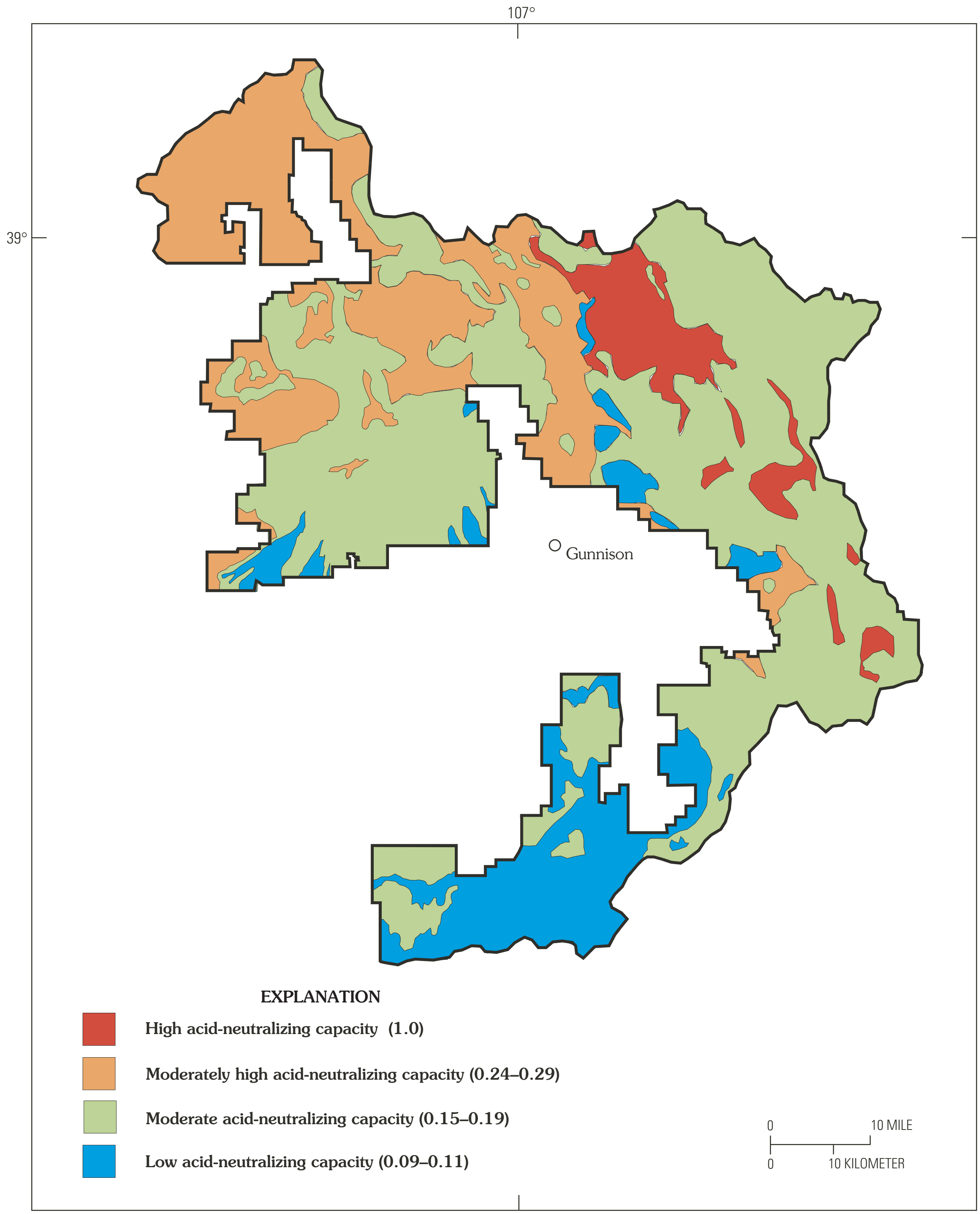

Figure 25. Acid-neutralizing capacity to introduced acidity in the Gunnison National Forest, Colorado.

analyses of the 19 stream water samples are listed in appendix 2. The ranges and means of selected chemical species in stream water samples from the Redcloud Peak area are listed in table 19.

The relief in the Redcloud Peak area is high, and the dominant vegetation is alpine tundra and subalpine forest. The annual precipitation ranges from 25 to 40 in. (Colorado Climate Center, 1984). The 19 samples are mostly Ca^{2+}- SO_4^{2-} type

Table 17. Chemical speciation of selected elements for water samples from the Grand Mesa, Uncompahgre, and Gunnison National Forests, Colorado.

Element	Specie
Ca	Ca^{2+}
Mg	Mg^{2+}
Na	Na^{+}
K	K^{+}
S	SO_4^{2-}
C	HCO_3^{-}
Cl	Cl^{-}
F	F^{-}
Si	$H_4SiO_4^0$
Al	$Al(OH)_4^{-}$
Fe	Fe^{2+}
Mn	Mn^{2+}, except Tertiary sediments as $MnCO_3^0$

water, in contrast to the GMUG samples that are mostly Ca^{2+}-HCO_3^- type water. The samples are acidic to slightly alkaline, and conductivity values are moderately low. Natural acid-drainage waters are present in the upper portions of several of the watersheds. Abundant Al hydroxides precipitate in and along several streams and at junctions with tributaries. Fe hydroxides also precipitate, but they are not as widespread as the Al hydroxides. The mineralized rocks contain disseminated pyrite, and oxidation and dissolution of the pyrite releases acidity and sulfate to the waters (see Miller and McHugh (1998) for details about natural acid-drainage processes in this area). The Al is mobilized because of the low pH values. The values for pH range from 3.58 to 7.6, with a mean of 6.09 (table 19). The mean pH value of water from areas underlain by the mineralized Sunshine Peak Tuff is much lower than that in water from areas underlain by the ten predominantly unmineralized rock types from the GMUG (table 20). Because of the low pH, most of the alkalinity generated in the Redcloud Peak area is neutralized and consumed by the acidity released by the weathering of pyrite. The alkalinity values range from 0 to 94 mg/L as HCO_3^-, with a mean of 3.9 mg/L. This mean is much lower than the mean alkalinity values of water from the GMUG. If the mean alkalinity values are normalized in a manner similar to the procedure outlined previously for water samples from the GMUG, the mean normalized alkalinity also is much lower than that for water from the GMUG (table 15).

The values for conductivity for water samples from the Redcloud Peak area range from 44 to 320 µS/cm, with a mean of 110 µS/cm. These moderately low values reflect the large input of runoff from melting snow, the short duration of contact of the water with rocks, and the poor ground-water reservoir in this mountainous headwater area. The concentrations of Cl are very low, with a mean of 0.12 mg/L, again indication of large runoff from melting snow. The mean TDS value of samples from areas underlain by the Sunshine Peak Tuff is 66.4 mg/L (table 15). That mean is lower than the means of samples associated with eight of the ten rock composition types from the GMUG. If TDS is normalized in a manner similar to the procedure outlined previously for water from the GMUG, the mean normalized TDS (TDS/Cl) is 552 (table 15). In the GMUG, only the mean normalized TDS value of water from areas underlain by Paleozoic sedimentary rocks is higher than the mean normalized TDS value from the Redcloud Peak area. Therefore the potential release of TDS from areas underlain by the mineralized Sunshine Peak Tuff is higher than that for nine of the ten areas underlain by predominantly unmineralized rocks in the sampled watersheds in the GMUG.

The sulfate concentrations in water samples from areas underlain by the Sunshine Peak Tuff range from 6.9 to 106 mg/L, with a mean of 30 mg/L (table 19). This mean is much higher than the means of samples from the GMUG watersheds, mainly because larger amounts of pyrite, the likely source of the sulfate, are present in the Sunshine Peak Tuff than in the rocks underlying the watersheds in the GMUG. If the sulfate concentrations are normalized by dividing the sulfate concentrations by Cl concentrations, to reduce the effect of duration of contact of water and rock and effects of evaporation, the differences are even

Table 18. Saturation indices of selected minerals for water samples from the Grand Mesa, Uncompahgre, and Gunnison National Forests, Colorado.

[Bold type indicates saturation or supersaturation of the water with respect to the mineral phase]

Rock composition type	Calcite	Dolomite	Siderite	Rhodochrosite	Chalcedony	Gypsum	Fluorite	Sepiolite	$Al(OH)_3$
Tertiary basalt flows and associated rock	-1.92	-4.09	-1.47	-1.97	**0.08**	-4.57	-4.06	-5.58	-0.75
Tertiary felsic ash flow tuff	-1.42	-3.54	-1.45	-2.51	**0.43**	-3.68	-3.43	-4.82	-1.2
Tertiary latitic lava and breccia	-1.49	-3.76	-1.6	-2.66	**0.48**	-2.84	-3.65	-4.64	-0.58
Tertiary andesitic lava and breccia	-0.57	-1.73	-1.42	-2.65	**0.45**	-3.38	-3.64	-2.14	-1.91
Tertiary sedimentary rock	**0.78**	**1.28**	-0.69	-1.08	**0.11**	-2.85	-2.69	**0.44**	-2.65
Cretaceous Mesaverde Formation	-0.36	-1.15	-1.16	-1.8	**0**	-3.34	-3.75	-1.83	-2.39
Cretaceous Mancos Shale	**0.23**	**0.04**	-0.95	-1.53	**0.04**	-2.37	-2.93	-1.18	-2.4
Mesozoic sedimentary rock	**0.35**	**0.02**	-1.67	-2.27	**0.01**	-2.89	-2.65	-2.74	-2.04
Paleozoic sedimentary rock	**0.51**	**0.45**	-0.89	-2.18	-0.24	-2.47	-3.17	-1.92	-3.72
Tertiary and Proterozoic intrusive and Proterozoic metamorphic rocks	-1.34	-3.28	-1.93	-3.46	**0.14**	-3.68	-2.87	-4.29	-1.52

Table 19. Summary of the chemistry of 19 steam water samples from areas underlain by the mineralized Sunshine Peak Tuff, a rhyolitic ash-flow tuff, Redcloud Peak area, Colorado.

Measurement[1]	Range		Mean[2]
	Minimum	Maximum	
Conductivity	44	320	110
TDS	31.3	166.7	66.4
pH	3.58	7.6	6.09
Ca	6.3	33	12
Mg	0.5	4.5	1.6
Na	0.4	4.4	1
K	0.3	4.5	1
SiO_2	32	9	8.4
Alkalinity	<1	94	3.9
SO_4	6.9	106	30
Cl	<0.1	0.18	0.12
F	<0.5	0.96	0.17
Al	<100	4400	420
Fe	<10	450	30
Mn	<10	2000	40
Cu	<1	6	1.2
Zn	<5	280	11
Mo	<1	9	1
As	<1	1	<1
U	<0.1	8.1	0.66
Li	<1	21	3.7
Ba	0.9	32	7.7
Sr	29	320	72
Sc	2	8.9	5.1
Rb	0.8	21	3.3
Y	<0.1	13	0.43
La	<0.1	66	0.58

[1] TDS, Ca, Mg, Na, K, SiO_2, SO_4, Cl, and F in mg/L; alkalinity in mg/L HCO_3^-; conductivity in µS/cm; remaining elements in µg/L

[2] All variables are geometric means except for pH, which is arithmetic mean

more striking (table 15). The mean value of F of water from areas underlain by the Sunshine Peak Tuff is 0.17 mg/L (table 19). Only water from areas underlain by Tertiary and Proterozoic intrusive and Proterozoic metamorphic rocks in GMUG has a higher mean F concentration, 0.21 mg/L. If the F concentration is normalized in a manner similar to the procedure used to normalize sulfate concentrations from GMUG, the mean value of water from areas underlain by the Sunshine Peak Tuff area, 1.41 is higher than any of the mean normalized values from GMUG (table 15). The mean U concentration, 0.66 µg/L, in water samples from areas underlain by the Sunshine Peak Tuff, is elevated. The high concentration probably is related to the felsic rock composition. However, it is not as high as the concentration in water in areas underlain by Mesozoic and Tertiary sedimentary rocks and Tertiary and Proterozoic intrusive and Proterozoic metamorphic rocks (table 20). If U is normalized in a manner similar to the procedure used for sulfate concentrations from GMUG, the mean normalized value is 5.49. That value is higher than any of the mean normalized values from GMUG (table 15). This indicates that the sulfate, F, and U contents of the Sunshine Peak Tuff are higher than those in rocks in the GMUG study areas.

The mean concentrations of Cu, Mo, and As are low in samples from areas underlain by the Sunshine Peak Tuff; they are similar to the concentrations in samples from the GMUG watersheds. The mean Zn concentration, 11 µg/L, is high compared to concentrations in samples from GMUG watersheds. The highest mean concentration of Zn in GMUG, from the Trtiary and Proterozoic intrusive and Proterozoic metamorphic rocks, is 0.64 µg/L (table 20). The mean concentrations of Al and Mn are higher in samples from areas underlain by the Sunshine Peak Tuff, with mean concentrations of 420 and 40 µg/L, respectively, compared to concentrations in GMUG samples (table 20). Within GMUG, water from areas underlain by Tertiary basaltic rocks contained the highest mean Al concentration, 54 µg/L, nearly an order of magnitude lower than the concentrations in water from areas underlain by the Sunshine Peak Tuff. Weathering of pyrite, present in the Sunshine Peak Tuff, releases acidity and the acidity mobilizes the Al in the waters. Within GMUG, water from areas underlain by Tertiary sedimentary rocks contained the highest mean Mn concentration, 4.7 µg/L, nearly an order of magnitude lower than mean concentrations in water from areas underlain by the Sunshine Peak Tuff (table 20). The mean Fe concentration in samples from areas underlain by the Sunshine Peak Tuff area is 30 µg/L, an elevated concentration compared to those from the GMUG watersheds. However, water from areas overlying Tertiary basaltic rocks (91 µg/L) and Tertiary ash-flow tuff (65 µg/L) contained higher mean concentrations of Fe.

Summary and Conclusions

This study determines, for mountainous headwater areas, the range of baseline geochemistry of stream and spring water in areas that are underlain by each of ten major rock composition types in the Gunnison, Uncompahgre, and Grand Mesa National Forests, Colorado. Chemical processes responsible for the control and mobility of chemical species in water were investigated. By comparing the geochemistry of the water associated with each of the dominant rock composition types, the rock types are characterized with respect to their acid-neutralizing capacities and also to potential release of TDS or chemical weathering. For each of the three national forests, maps were constructed to show potential release of TDS, mean pH values, and acid-neutralizing capacities, in relation to the distribution of each of the ten major rock composition types. In addition, the geochemistry of water samples from the watersheds in the GMUG, which are underlain by rocks that are relatively unmineralized, is compared to the geochemistry of samples from the Redcloud Peak area, an adjacent area that has been mineralized and probably contains significant mineral deposits. The following are the most significant conclusions of this study:

Table 20. Comparison of the geochemistry of water samples from watersheds underlain by relatively unmineralized rocks in the Grand Mesa, Uncompahgre, and Gunnison National Forests and water samples from watersheds underlain by the mineralized Sunshine Peak tuff, Redcloud Peak area, Colorado

Rock composition type	Number	Water Type	Temp. °C	pH	Conductivity µS/cm	TDS mg/L	Ca mg/L	Mg mg/L	Na mg/L	K mg/L	SiO_2 mg/L	Alkalinity mg/L	SO_4 mg/L	Cl mg/L	F mg/L	Al µg/L
							GMUG area									
Tertiary basalt flows and associated rock	4	Ca^{2+}-HCO_3^-	12.2	7.41	63	39.3	5.4	2.1	1.8	0.37	14.3	28	0.65	0.29	<0.10	54
Tertiary felsic ash-flow tuff	5	Ca^{2+}-HCO_3^-	9.9	7.43	100	74.5	11	1.7	4.3	1.3	29.9	46	2.7	0.88	0.10	16
Tertiary quartz latitic lava and breccia	4	Ca^{2+}-HCO_3^-	7.0	7.48	124	93	12.6	1.8	6.9	1.1	30.8	36	16.6	0.56	<0.10	55
Tertiary andesitic lava and breccia	9	Ca^{2+}-HCO_3^-	12.6	7.94	151	109.4	16	2.8	7.3	1.6	34.2	67	4.1	0.65	<0.10	13
Tertiary sedimentary rocks	7	Ca^{2+}-HCO_3^-	15.9	8.50	365	196	39	12.0	15	1.4	17.5	191	8	1.4	0.16	12
Cretaceous Mesaverde Formation	8	Ca^{2+}-HCO_3^-	14.4	8.31	126	69.5	13	3	5.4	0.49	12.8	54	5.3	0.49	<0.10	12
Cretaceous Mancos Shale	11	Ca^{2+}-HCO_3^-	14.4	8.24	294	133.8	35	8.6	6.1	0.45	13.9	104	24	0.80	0.12	10
Mesozoic sedimentary rocks	5	Ca^{2+}-HCO_3^-	8.8	7.94	413	200.3	59	10	5.2	1.8	10.9	205	4.7	3.4	0.12	6.7
Paleozoic sedimentary rocks	15	Ca^{2+}-HCO_3^-	9.4	8.30	356	174	52.6	11.0	1.3	0.47	6.3	143	13.5	<0.25	<0.1	0.34
Tertiary and Proterozoic intrusive and Proterozoic metamorphic rocks	8	Ca^{2+}-HCO_3^-	7.3	7.82	83	50.9	8	1.7	3.1	0.55	14.3	34	3.5	0.39	0.21	14
							Redcloud Peak Area									
Sunshine Peak Tuff	19	Ca^{2+}, SO_4^-	9.7	6.09	110	66.4	12	1.6	1	1	8.4	3.9	30	0.12	0.17	420

Rock composition type	Fe µg/L	Mn µg/L	Cu µg/L	Zn µg/L	Co µg/L	Mo µg/L	Ni µg/L	Cr µg/L	As µg/L	U µg/L	Li µg/L	Be µg/L	Ba µg/L	Sc µg/L	Rb µg/L	Y µg/L	La µg/L
								GMUG area									
Tertiary basalt flows and associated rock	91	15	<1	0.40	<0.5	<0.5	<2	<0.1	0.05	0.07	<0.5	<0.05	14	21	0.50	0.41	0.25
Tertiary felsic ash-flow tuff	65	2.9	<1	0.24	<0.5	<0.5	<2	<0.1	1.2	0.06	1.5	<0.05	18	34	1.2	0.10	0.024
Tertiary quartz latitic lava and breccia	60	2.7	0.56	0.5	0.06	0.41	0.4	<1	<3	0.14	3.6	<0.05	4.6	2.9	1.4	0.32	0.13
Tertiary andesitic lava and breccia	15	0.5	<1	0.21	<0.5	<0.5	<2	<0.1	0.47	0.08	1.2	<0.05	4.6	39	2.3	0.07	<0.005
Tertiary sedimentary rocks	13	4.7	<1	0.22	<0.5	1.9	<2	<0.1	1.9	1.4	7.2	<0.05	62	25	0.60	0.083	0.017
Cretaceous Mesaverde Formation	14	2.0	<1	0.24	<0.5	<0.5	<2	<0.1	0.08	0.14	1.4	<0.05	18	18	0.32	0.04	0.005
Cretaceous Mancos Shale	17	3.0	<1	0.22	<0.5	0.77	<2	<0.1	0.16	0.35	2.0	<0.05	19	20	0.20	0.06	<0.005
Mesozoic sedimentary rocks	4.6	0.68	<1	0.23	<0.5	<0.5	<2	<0.1	1.2	2.7	12	<0.05	286	15	2.4	0.03	0.006
Paleozoic sedimentary rocks	<20	0.57	<0.5	0.6	0.06	0.41	1.2	2.6	<3	0.56	2.1	<0.05	88.5	0.9	0.47	0.03	<0.01
Tertiary and Proterozoic intrusive and Proterozoic metamorphic rocks	13	<0.3	<1	0.64	<0.5	0.83	<2	<0.1	<0.03	0.78	1.7	<0.05	8.6	19	0.35	0.17	0.036
								Redcloud Peak Area									
Sunshine Peak Tuff	30	40	1.2	11	1.1	1	1.1	<0.2	<1	0.66	3.7	0.48	7.7	5.1	3.3	0.43	0.58

1. The baseline geochemistry of stream and spring water in the mountainous headwater areas is controlled primarily by the chemical composition of the underlying bedrock. Each rock composition type produces a unique range of water compositions. Other factors, such as annual precipitation, temperature, topographic setting, the physical character of minerals, such as grain size and crystallinity, and biotic activity are important, but they mainly influence the rates of chemical reactions but not which elements are present in the water.
2. The water in the headwater areas in GMUG generally is Ca^{2+}-HCO_3^- type water, with alkaline pH values and low to moderate total dissolved solids. The water generally is of good chemical quality, with low concentrations of elements such as Cu, Zn, Mo, As, U, Al, Fe, and Mn. Slightly elevated concentrations of some of these elements in some areas are caused by the presence and dissolution of pyrite and other minerals. The dominant chemical species in most of the water samples are Ca^{2+}, Mg^{2+}, Na^+, K^+, SO_4^{2-}, HCO_3^-, Cl^-, F^-, $H_4SiO_4^0$, $Al(OH)_4^-$, Fe^{2+}, and Mn^{2+}.
3. The chloride concentrations in most of the samples from the three national forests are generally low, indicating that there is a significant snow and storm runoff component in stream water. Shallow soil zones and minimal ground-water reservoirs characterize the mountainous headwater areas. Therefore, except for water in areas underlain by Mesozoic and Tertiary sedimentary rocks, the duration of contact of water with the rocks is short and evaporation processes are minimal.
4. The TDS values, which are measures of chemical weathering rates, are highest for watersheds underlain by Mesozoic and Tertiary sedimentary rocks. The lowest TDS values are from samples from watersheds that are underlain by Tertiary basalt and by Tertiary and Proterozoic intrusive and Proterozoic metamorphic rocks, which consist of granodiorite, quartz monzonite, granite, diorite, gneiss, and gabbro. If TDS values are normalized by dividing the TDS value by Cl concentration to reduce the effects of duration of contact of water and rock and the effects of evaporation processes, the highest potential release of TDS is from Paleozoic sedimentary rocks, followed by the Mancos Shale, Tertiary sedimentary rocks, and the Mesaverde Formation. The calculated potential release of TDS does not take into account the amount of precipitation in an area.
5. Sulfate concentrations in water samples from areas underlain by Paleozoic sedimentary rocks are as high as several hundred mg/L. The high concentration probably is due to dissolution of gypsum in the Minturn and Belden Formations and the lower part of the Maroon Formation.
6. Alkalinity is a measure of the acid-neutralizing capacity of waters to introduced acidification. Water from Mesozoic and Tertiary sedimentary rocks has the highest mean alkalinity values. The water that has the lowest mean alkalinity values and that is most susceptible to introduced acidity is from the top of Grand Mesa. Grand Mesa is composed of basaltic rocks. When alkalinity values are normalized by dividing TDS value by Cl to reduce the effects of evaporation and the duration of contact of water and rocks, the water samples with the highest mean normalized alkalinity are from watersheds underlain by Paleozoic sedimentary rocks, followed by the Mancos Shale and Tertiary sedimentary rocks. The higher normalized alkalinity values of water from watersheds underlain by these rocks probably are caused by carbonate rocks and local calcareous zones present within the bedrock units. The waters in watersheds underlain by these sedimentary rocks have the greatest acid-neutralizing capacity and are most resistant to introduced acidification from processes such as acid-mine drainage or dry fallout from coal-burning power plants. The water with the lowest mean normalized alkalinity values is from watersheds that are underlain by Tertiary ash-flow tuff and Tertiary and Proterozoic intrusive and Proterozoic metamorphic rocks; these watersheds are the most susceptible to introduced acidification.
7. The Tertiary sedimentary rocks contain oil shale. The shale outcrops in some of the sampled watersheds. These rocks contain pyrite, generally with elevated trace metal concentrations. Sulfate concentration as high as 25 mg/L, in samples from these watersheds, probably indicates weathering of pyrite. However, enough calcareous material is present to generate sufficient alkalinity to neutralize the acidity. The higher pH values ensure that trace metals that are present as cations form hydroxides or are adsorbed, and thus their concentrations are low. The concentration of arsenic, present as an anion, is slightly elevated (as high as 5.8 µg/L). Overall, there is only a slight impact of the oil shale on the chemical quality of water in these mountainous headwater areas.
8. The Mesaverde Formation contains extensive coal deposits that contain pyrite. The sulfate concentration in water samples from watersheds in areas underlain by Mesaverde Formation (as high as 19 mg/L) probably reflects weathering of pyrite. However, the pH values are alkaline, indicating that generated acidity is buffered by the alkalinity. The mean alkalinity value is moderately low, at 54 mg/L as HCO_3^-, probably because the acidity generated from weathering pyrite neutralizes and lowers the alkalinity. In addition, the lower alkalinity may also be due to less calcareous material in the Mesaverde Formation. Overall, the chemical quality of the water from areas underlain by the Mesaverde Formation is good, but water in areas underlain by Mesaverde Formation is more susceptible to introduced acidification than is water associated with the other sedimentary rock units in GMUG.
9. The Mancos Shale is marine in origin. It contains black shale and associated pyrite and it has elevated trace metal concentrations. Calcareous-rich zones locally are present, and high alkalinity is produced in water from areas underlain by these rocks. The high alkalinity buffers acidity produced by the oxidizing pyrite and, because of the higher pH values, it reduces the mobility of trace metal cations. Se from the Mancos Shale is in elevated concentrations in water in the lower parts of the valleys downstream from the headwater areas. Se concentrations in water are low (mean Se <0.2 µg/L) in the sampled mountainous headwater watersheds that are underlain by Mancos Shale. The high

Se concentrations in topographically lower, more arid areas underlain by the Mancos Formation outside the GMUG area probably are concentrated by evaporation effects. The water from these mountainous headwater areas is well buffered, and overall chemical quality is good.

10. The Mesozoic sedimentary rocks contain uranium concentrations that were mined adjacent to the GMUG area, along the west flank of the Uncompahgre plateau. Water from these rocks in GMUG contains only slightly elevated concentrations of uranium (as high as 5.8 μg/L) and the uranium is not a problem to water quality.
11. Parts of the GMUG area are heavily grazed by cattle. The cattle tend to concentrate in wetlands, where their hoofs muddy and disturb the surface. This physical disturbance, along with the cattle waste, decreases the oxygen content of the water leading to more reducing conditions. One impact on water quality appears to be increased mobility of Fe due to the more reducing conditions. Overall, the chemical quality of the water is not significantly impacted.

The unique geochemical baselines for water samples from areas underlain by the ten rock composition types demonstrate the importance of the composition of the bedrock in determining the geochemistry of water in these mountainous headwater areas. The geochemical baselines provide values that approximate the natural background geochemistry of the stream and spring water in these watersheds for each of the ten major rock composition types. Comparison of these geochemical baselines with future baselines will allow recognition of any significant changes in water quality.

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Appendix 1. Chemical analyses of stream and spring water samples from watersheds underlain by the ten dominant rock composition types in the Grand Mesa, Uncompahgre, and Gunnison National Forests, Colorado.

[Leader indicates (_) not determined]

Sample no.	Latitude			Longitude			Dominant rock type
	Degree	Minute	Second	Degree	Minute	Second	
Tertiary basalt (table 3)							
G14	39	1	58	108	10	34	Basaltic flows, tuff, breccia, conglomerate
G15	39	0	34	108	11	29	Basaltic flows, tuff, breccia, conglomerate
G16	39	0	3	108	10	36	Basaltic flows, tuff, breccia, conglomerate
G17	38	0	7	108	9	41	Basaltic flows, tuff, breccia, conglomerate
Tertiary ash flow tuff							
G45	38	12	6	106	50	53	Ash flow tuff, felsic
G46	38	10	20	106	51	15	Ash flow tuff, felsic
G56	38	8	29	106	48	23	Ash flow tuff, felsic
G57	38	4	56	106	50	2	Ash flow tuff, felsic
G58	38	6	12	106	49	30	Ash flow tuff, felsic
Tertiary quartz latite							
C12	38	03	1	107	21	3	Quartz latitic lavas and breccias
C13	38	03	8	107	22	3	Quartz latitic lavas and breccias
C14	38	11	5	107	21	8	Quartz latitic lavas and breccias
C15	38	12	0	107	22	3	Quartz latitic lavas and breccias
Tertiary andesite							
G47	38	38	49	106?	19	17	Andesitic lava, breccia, tuff, conglomerate
G48	38	36	23	107	19	58	Andesitic lava, breccia, tuff, conglomerate
G49	38	35	11	107	20	14	Andesitic lava, breccia, tuff, conglomerate
G50	38	34	39	107	19	59	Andesitic lava, breccia, tuff, conglomerate
G51	38	34	25	107	20	1	Andesitic lava, breccia, tuff, conglomerate
G52	38	33	35	107	19	43	Andesitic lava, breccia, tuff, conglomerate
G54	38	32	45	107	19	19	Andesitic lava, breccia, tuff, conglomerate
G55	38	30	42	107	18	53	Andesitic lava, breccia, tuff, conglomerate
Tertiary sedimentary rock							
G01	39	17	1	107	34	50	Claystone, carbonate. shale, lignite
G02	39	14	46	107	41	1	Claystone, carbonate. shale, lignite
G03	39	20	26	107	50	33	Shale, sandstone, marlstone, oil shale
G04	39	20	19	107	50	6	Shale, sandstone, marlstone, oil shale
G05	39	19	12	107	57	10	Shale, oil shale, siltstone, sandstone, marl
G06	39	91	7	107	55	5	Oil shale, siltstone, sandstone, marl
G07	39	12	18	107	48	46	Shale, sandstone, marlstone, oil shale
Cretaceous Mesaverde Formation							
G32	38	48	45	107	18	45	Sandstone, shale, coal
G33	38	48	49	107	18	44	Sandstone, shale, coal
G34	38	48	43	108	18	20	Sandstone, shale, coal
G35	38	50	37	107	19	7	Sandstone, shale, coal
G36	38	50	36	107	19	8	Sandstone, shale, coal
G37	38	52	38	107	20	4	Sandstone, shale, coal
G38	38	55	17	107	20	7	Sandstone, shale, coal
G39	38	55	44	107	20	18	Sandstone, shale, coal
Cretaceous Mancos Shale							
G19	38	48	17	107	33	29	Marine shale
G20	38	48	8	107	33	56	Marine shale
G24	37	55	41	108	12	20	Marine shale
G25	37	53	31	108	12	0	Marine shale
G26	37	53	17	108	11	52	Marine shale
G27	37	54	8	108	14	0	Marine shale
G28	37	54	32	108	10	45	Marine shale
G29	37	54	10	108	10	30	Marine shale
G30	37	54	3	108	93	1	Marine shale
G31	37	53	29	108	70	0	Marine shale
Mesozoic sedimentary rock							
G09	38	44	41	108	32	59	Sandstone, siltstone, shale, limestone, conglomerate
G10	38	44	48	108	33	23	Sandstone, siltstone, shale, limestone, conglomerate
G11	38	40	59	108	41	25	Sandstone, sandy shale, mudstone, limestone
G12	38	38	8	108	41	22	Sandstone, mudstone, limestone
G13	38	35	25	108	38	56	Sandstone, mudstone, limestone
Paleozoic sedimentary rock							
C01	38	49	31	106	50	54	Carbonate, quartzite
C02	38	50	44	106	49	13	Sandstone, grit, conglomerate, shale, limestone
C03	38	51	32	106	48	19	Sandstone, conglomerate, mudstone, shale, grit, limestone, shale
C04	38	52	17	106	47	52	Sandstone, conglomerate, mudstone
C05	38	53	5	106	47	25	Sandstone, conglomerate, mudstone
C06	38	53	38	106	46	55	Sandstone, conglomerate, mudstone
C07	38	57	55	106	46	11	Sandstone, grit, conglomerate, shale, carbonate
C08	38	57	37	106	46	13	Sandstone, grit, conglomerate, shale, carbonate
C09	38	56	58	106	46	18	Sandstone, grit, conglomerate, shale, carbonate
C10	38	55	50	106	46	10	Sandstone, conglomerate, mudstone
C11	38	54	37	106	46	56	Sandstone, conglomerate, mudstone
C16	38	51	23	106	42	42	Sandstone, grit, conglomerate, shale, carbonate, mudstone
C17	38	49	54	106	43	10	Sandstone, grit, conglomerate, shale, carbonate, mudstone
C18	38	49	32	106	43	42	Sandstone, grit, conglomerate, shale, carbonate, mudstone
C19	38	49	10	106	44	17	Carbonate, sandstone, quartzite, grit, conglomerate, shale
Tertiary and Proterozoic rock							
G21	38	26	31	106	21	47	Granite, quartz monzonite, granodiorite
G22	38	31	46	106	24	19	Granite, intermediate to felsic intrusive rock
G23	38	31	57	106	24	9	Granite, intermediate to felsic intrusive rock
G40	38	34	10	106	33	35	Felsic and hornblende gneiss
G41	38	34	46	106	32	32	Granite, quartz monzonite, granodiorite
G42	38	35	6	106	32	18	Granite, quartz monzonite, granodiorite
G43	38	37	36	106	25	19	Felsic intrusive rock
G44	38	37	42	106	24	22	Felsic intrusive rock

Appendix 1—*Continued*. Chemical analyses of stream and spring water samples from watersheds underlain by the ten dominant rock composition types in the Grand Mesa, Uncompahgre, and Gunnison National Forests, Colorado.

[Leader indicates (_) not determined]

Sample no.	Water type	Estimated flow, gallons per minute	Comments	Temperature in °C	pH	Conductivity in μS/cm
Tertiary basalt						
G14	unnamed stream	0.004	nearly dry	13.6	7.09	59
G15	Coal Creek	0.5	cattle signs	13.1	7.37	66
G16	unnamed stream	15 - 20	yellow color, from wetlands	9.5	7.67	66
G17	unnamed stream	2 - 4	from wetlands	12.7	7.49	62
Tertiary ash flow tuff						
G45	spring	0.125 - 0.25	clear	8.7	7.40	139
G46	Blue Creek	1 - 2	hard to filter, wetlands, some sediments	13.1	8.02	132
G56	spring	0.062 - 0.125	water from steel pipe, clear	6	6.89	117
G57	Perfecto Creek	7 - 15	yellow color, hard to filter, old cattle signs	10.6	7.37	57
G58	Pauline Creek	40 - 50	yellow color, hard to filter	10.9	7.46	81
Tertiary quartz latite						
C12	Mineral Creek	100	some sediments in water, hard to filter	7.4	7.4	136
C13	small stream	0.25	sediments, hard to filter, rain	7	7.35	108
C14	small stream	4	silt, hard to filter, rain	5.7	7.4	140
C15	small stream	4	silty from raising stream, rain	7.7	7.75	116
Tertiary andesite						
G47	West Soap Creek	15 - 30	clear	12.4	7.49	104
G48	Lion Gulch	0.125	clear	12.3	8.20	242
G49	unnamed stream	0.125	intermittent flow in bed	16.2	8.53	185
G50	unnamed stream	1	clear	11.8	7.93	160
G51	unnamed stream	0.125 - 0.25	clear, hard to filter	10.9	7.97	144
G52	unnamed stream	0.25	clear	12.4	8.06	170
G54	Oregon Gulch	5 - 10	clear	11.4	7.90	142
G55	Chance Gulch	1	hard to filter, orange color	13.5	7.86	150
Tertiary sedimentary rock						
G01	Hightower Creek	0.25 - 0.5	hard to filter, cattle signs	21.6	8.46	467
G02	unnamed stream	0.25 - 0.5	some sediments, cattle signs	23.5	8.69	652
G03	West Bush Creek	15	some sediments, cattle signs	16	8.51	247
G04	East Bush Creek	22 - 30	clear	14.8	8.65	365
G05	Kimball Creek	0.5 - 1	clear	9.1	8.47	523
G06	unnamed stream	15	clear	12.9	8.16	195
G07	Park Creek	22 - 30	hard to filter	13.4	8.55	310
Cretaceous Mesaverde Formation						
G32	Coal Creek	40 - 75	murky, some sediments	11.1	8.36	117
G33	Robenson Creek	7.5 - 15	murky, some sediments	15.7	8.57	268
G34	spring	0.125	clear	11.3	8.00	257
G35	Cliff Creek	75	clear	11.9	8.10	76
G36	Coal Creek	75 - 112	some sediments, hard to filter	13.3	8.30	124
G37	Coal Creek	187	slightly murky	14	8.36	98
G38	Coal Creek	187 - 225	clear	17.7	8.26	103
G39		60 - 75	clear	20	8.54	85
Cretaceous Mancos Shale						
G19	spring	0.25	series of springs, cattle signs	11.4	7.46	219
G20	springs	0.5 - 0.75	series of springs, cattle signs	9.7	8.17	401
G24	unnamed stream	15	hard to filter, some sediments	13.5	8.14	345
G25	West Beaver Creek	7.5 - 15	clear	13.4	8.26	294
G26	East Beaver Creek	15 - 22	clear	7.6	8.26	107
G27	unnamed stream	1 - 2	clear	8.6	8.16	286
G28	unnamed stream	0.5 - 1	drainage from wetlands, cattle signs	20.2	8.22	245
G29	Beaver Creek	1	cattle impacted, meadows	22	8.48	272
G30	Spring Creek	0.5 - 1	clear	16.1	8.58	338
G31	McCullach Creek	2	clear	11.8	8.29	210
Mesozoic sedimentary rock						
G09	Big Dominguez Creek	22	clear	13.7	8.53	299
G10	spring	.062 - 0.125	galvanized pipe coated with carbonate	11.4	8.25	454
G11	spring	1 - 2	clear	7.2	7.74	527
G12	spring	0.25	clear	6.6	7.48	460
G13	California Spring	0.25	water from plastic pipe	4.9	7.71	363
Paleozoic sedimentary rock						
C01	Walrod Gulch	5	some silt	8.6	8.33	442
C02	small stream	2	abundant cream colored coatings	12.4	8.23	429
C03	small stream	4	some silt	8.8	8.36	331
C04	small stream	10	clear	7.6	8.13	225
C05	small stream	7	clear	7.2	8.25	252
C06	small stream	7	clear	8.1	8.4	272
C07	Upper Cement Creek	1	small mine above	11.2	8.14	424
C08	small stream	0.75	coming from wetland	11.5	8.17	403
C09	small stream	10	clear	9.4	8.44	659
C10	small stream	5	clear	7.3	8.38	491
C11	small stream	8	clear	9	8.39	300
C16	small stream	10	clear	5.7	8.2	263
C17	spring	1	coming from wetland	10.7	7.97	452
C18	small stream	2	clear	11.5	8.47	327
C19	Deadman Gulch	25	clear	11.5	8.59	298
Tertiary and Proterozoic rock						
G21	spring	2 - 4	water from steel pipe	7.7	6.89	74
G22	unnamed stream	2	clear	11.2	7.63	71
G23	Spring Creek	1	clear	9	7.79	126
G40	unnamed stream	0.25	clear	12.1	8.14	97
G41	unnamed stream	0.125	clear	10.3	8.18	118
G42	unnamed stream	0.25	clear	10.8	8.18	123
G43	Fitzpatrick Gulch	7.5 - 15	clear	6.5	8.00	47
G44	Tunnel Gulch	7.5	clear	7.3	7.75	53

Appendix 1—*Continued*. Chemical analyses of stream and spring water samples from watersheds underlain by the ten dominant rock composition types in the Grand Mesa, Uncompahgre, and Gunnison National Forests, Colorado.

[Leader indicates (_) not determined]

Sample no.	TDS mg/L	Ca mg/L	Mg mg/L	Na mg/L	K mg/L	SiO_2 mg/L	Alkalinity mg/L HCO_3^-	SO_4 mg/L	Cl mg/L	F mg/L	N (nitrate) mg/L	Al µg/L
Tertiary basalt												
G14	32	4.05	1.77	1.5	0.2	10.9	24	1.60	0.31	<0.10	<0.125	107
G15	40	5.89	2.24	1.92	0.4	13.7	30	0.378	0.60	<0.10	<0.125	54
G16	46	6.10	2.29	2.02	0.5	19.0	30	0.638	<0.25	<0.10	<0.125	38
G17	41	5.65	2.13	1.92	0.4	14.9	30	0.453	<0.25	<0.10	<0.125	40
Tertiary ash flow tuff												
G45	106	16.5	2.80	5.12	1	39.6	70	3.85	1.9	0.14	0.172	8
G46	99	13.3	1.71	7.86	2	41.2	52	5.96	1.3	0.13	<0.125	32
G56	84	14.4	2.03	3.7	1	32.6	54	2.13	1.1	0.11	<0.125	7
G57	49	5.30	0.826	3.47	1	20.8	32	1.37	0.55	<0.10	<0.125	34
G58	53	8.44	1.63	3.1	0.9	19.2	34	2.07	0.37	<0.10	<0.125	17
Tertiary quartz latite												
C12	75	15.7	2.58	3.67	1.17	9.49	29	27.9	<0.25	<0.1	<0.1	7.90
C13	80	8.74	0.78	13	2.19	26.1	35	10.4	1.50	<0.1	<0.1	356
C14	78	14.5	2.94	7.94	0.688	12.3	44	17.1	0.56	<0.1	<0.1	58.9
C15	69	12.7	1.92	6.14	0.878	14.2	36	15.2	0.58	<0.1	<0.1	55.4
Tertiary andesite												
G47	101	19.3	3.32	7.28	2	39.4	32	14.0	0.34	<0.10	<0.125	12
G48	133	9.95	1.74	14.8	1	31.6	102	22.5	0.82	<0.10	<0.125	9
G49	88	11.4	1.66	4.91	0.8	21.9	84	5.16	0.70	0.11	<0.125	10
G50	121	22.2	7.72	12.4	2	34.7	80	1.88	0.70	<0.10	<0.125	16
G51	100	21.5	4.20	5.68	2	29.5	68	2.74	0.76	0.14	0.136	12
G52	109	14.8	2.84	11.1	2	35.0	82	2.58	0.71	<0.10	<0.125	21
G54	113	16.5	3.03	5.55	2	47.4	72	1.36	0.81	0.10	<0.125	14
G55	117	18.9	2.33	5.54	2	48.1	78	0.757	0.99	<0.10	<0.125	14
Tertiary sedimentary rock												
G01	250	62.3	11.4	20.5	4	6.5	250	14.0	8.3	0.51	<0.125	24
G02	330	42.7	36.9	45.1	3	19.6	352	5.34	3.4	0.17	<0.125	11
G03	152	31.4	6.61	9.31	0.7	17.2	160	7.39	0.63	0.11	<0.125	16
G04	191	44.5	11.5	14.1	0.6	19.8	182	10.3	0.69	0.14	<0.125	21
G05	274	56.1	12.6	32.2	0.8	26.8	242	25.4	1.3	0.21	<0.125	<3
G06	108	18.2	7.84	5.21	2	26.1	92	3.36	0.75	0.07	<0.125	14
G07	157	37.0	10.2	7.25	1	16.9	160	4.82	0.72	0.15	<0.125	16
Cretaceous Mesaverde Formation												
G32	65	12.9	2.86	4.43	0.5	13.8	44	8.71	0.33	<0.10	<0.125	10
G33	139	30.5	7.85	8.41	0.8	10.7	122	19.2	1.0	0.16	<0.125	13
G34	123	23.8	8.29	13.4	0.3	13.1	112	7.81	0.99	0.11	<0.125	15
G35	47	7.67	1.31	4.25	0.4	14.5	34	1.48	0.25	<0.10	<0.125	9
G36	68	13.5	3.06	4.22	0.5	11.9	52	8.46	0.40	<0.10	<0.125	12
G37	55	10.6	2.16	4.39	0.4	12.8	40	4.65	0.37	<0.10	<0.125	10
G38	57	10.8	2.22	4.88	0.4	12.7	42	4.81	0.49	<0.10	<0.125	9
G39	50	8.83	1.67	3.8	0.6	12.6	40	1.67	0.57	<0.10	<0.125	27
Cretaceous Mancos Shale												
G19	124	27.4	6.42	6.61	0.2	21.6	88	17.5	0.97	0.10	<0.125	8
G20	212	50.3	13.3	12.8	0.2	27.1	162	27.2	1.9	0.14	<0.125	16
G24	175	48.2	10.6	3.99	0.7	12.0	168	16.1	0.59	0.15	<0.125	8
G25	147	41.9	7.64	3.46	0.5	8.6	120	25.9	0.40	0.16	<0.125	11
G26	56	12.0	2.26	2.71	0.2	9.5	30	13.9	0.26	<0.10	<0.125	15
G27	140	32.3	11.1	3.01	0.2	12.1	106	29.0	0.45	<0.10	<0.125	4
G28	129	32.4	5.23	4.87	1	9.5	84	34.7	0.38	0.19	<0.125	10
G29	143	33.6	8.32	6.97	0.5	15.7	144	6.06	1.0	0.13	<0.125	13
G30	176	47.0	10.6	5.91	0.5	16.2	180	6.16	1.0	0.14	<0.125	10
G31	107	22.0	7.18	2.53	0.4	9.5	58	36.5	0.31	<0.10	<0.125	12
Mesozoic sedimentary rock												
G09	143	43.5	7.43	3.38	2	6.9	152	2.50	2.5	0.12	<0.125	7
G10	222	60.6	13.5	10.3	2	16.9	214	7.94	6.1	0.13	<0.125	12
G11	248	83.8	10.8	3.51	1	9.1	262	5.16	5.8	0.15	0.316	4
G12	222	73.1	11.3	2.02	2	7.8	246	3.17	1.6	0.15	0.153	<3
G13	185	43.6	9.14	14.9	3	19.0	172	7.05	3.5	<0.10	0.445	18
Paleozoic sedimentary rock												
C01	213	55.3	20.4	5.38	1.33	6.29	180	33.5	1.69	0.2	0.2	1.96
C02	213	51.2	25	1.21	0.79	6.89	194	32.4	0.44	<0.1	0.2	<0.1
C03	149	44.2	14.2	1.66	0.574	7.02	148	8.0	<0.25	<0.1	<0.1	0.39
C04	105	40.6	2.94	0.945	0.201	4.88	110	0.8	<0.25	<0.1	<0.1	4.32
C05	118	44.1	3.29	1.59	0.288	7.23	120	1.6	<0.25	<0.1	<0.1	<0.1
C06	130	47.2	4.17	1.73	0.496	7.27	138	1.1	<0.25	<0.1	<0.1	<0.1
C07	225	63.4	16.3	0.609	0.231	4.71	178	52.0	<0.25	<0.1	<0.1	0.75
C08	201	57.4	17	0.61	0.108	4.41	165	40.4	<0.25	<0.1	<0.1	<0.1
C09	387	101	19.5	0.742	0.598	3.72	118	203.6	<0.25	<0.1	<0.1	0.71
C10	260	63.7	20.1	0.773	0.723	4.86	138	102.2	<0.25	<0.1	<0.1	<0.1
C11	138	44.5	10.6	1.18	0.451	5.99	139	6.1	<0.25	<0.1	<0.1	0.98
C16	120	44.3	4.83	1.49	0.603	9.60	112	3.8	<0.25	0.1	<0.1	<0.1
C17	224	64.3	17.6	2.07	0.626	8.62	169	47.4	<0.25	0.1	<0.1	7.67
C18	160	47	12.9	1.68	1.13	11.64	138	17.2	<0.25	<0.1	<0.1	<0.1
C19	137	44.4	11.3	0.977	0.371	5.88	135	7.8	<0.25	<0.1	<0.1	0.77
Tertiary and Proterozoic rock												
G21	54	5.89	1.24	5.01	0.6	22.3	28	4.09	0.90	<0.10	<0.125	47
G22	47	6.41	1.13	3.23	0.8	15.9	20	9.83	0.27	<0.10	<0.125	18
G23	77	11.8	4.09	3.59	0.6	21.3	42	14.7	0.36	<0.10	<0.125	9
G40	58	9.38	2.86	3.03	0.7	13.2	50	3.58	0.49	0.69	<0.125	13
G41	67	10.3	3.93	5.27	0.6	19.4	50	2.38	0.55	1.8	<0.125	25
G42	63	9.70	4.03	5.05	0.6	16.9	48	2.70	0.54	2.2	<0.125	17
G43	31	5.81	0.555	1.58	0.4	9.0	26	1.03	<0.25	<0.10	<0.125	5
G44	30	7.05	0.507	1.15	0.2	6.1	26	1.56	<0.25	<0.10	<0.125	9

Appendix 1—*Continued.* Chemical analyses of stream and spring water samples from watersheds underlain by the ten dominant rock composition types in the Grand Mesa, Uncompahgre, and Gunnison National Forests, Colorado.

[Leader indicates (_) not determined]

Sample no.	Fe µg/L	Mn µg/L	Ba µg/L	Be µg/L	Cd µg/L	Co µg/L	Cu µg/L	Li µg/L	Ni µg/L	Sr µg/L	Ti µg/L	Zn µg/L	V µg/L
Tertiary basalt													
G14	44	4	17	<0.05	<0.5	<0.5	<1	<0.5	<2	29	4	0.4	<0.5
G15	125	27	14	<0.05	<0.5	<0.5	<1	<0.5	<2	39	2	0.5	<0.5
G16	151	21	10	<0.05	<0.5	<0.5	<1	<0.5	<2	38	<2	0.4	0.57
G17	81	19	15	<0.05	<0.5	<0.5	<1	<0.5	<2	37	<2	0.3	<0.5
Tertiary ash flow tuff													
G45	12	22	5	<0.05	<0.5	<0.5	<1	2	<2	107	<2	0.3	<0.5
G46	61	22	19	<0.05	<0.5	<0.5	<1	3	<2	109	<2	0.2	3.38
G56	9	<0.3	32	<0.05	<0.5	<0.5	<1	2	<2	79	<2	<.2	2.31
G57	255	11	0	<0.05	<0.5	<0.5	<1	0.9	<2	47	<2	0.3	0.79
G58	640	32	12	0.06	<0.5	<0.5	<1	0.9	<2	72	<2	0.3	1.26
Tertiary quartz latite													
C12	0.0724	21.4	13.2	<0.05	<0.5	0.07	0.76	1.7	0.4	171	0.5	0.6	0.8
C13	0.159	2.2	3.54	0.1	<0.5	0.09	0.74	10.0	0.4	57.6	7.6	1	1.6
C14	0.0331	1.0	2.59	<0.05	<0.5	0.04	<0.5	3.0	0.3	163	1.9	0.5	1.0
C15	0.0338	1.1	3.81	<0.05	<0.5	0.05	0.60	3.4	0.4	109	1.4	<0.5	1.2
Tertiary andesite													
G47	14	<0.3	6	<0.05	<0.5	<0.5	<1	1	<2	112	<2	<.2	0.80
G48	16	3	1	<0.05	<0.5	<0.5	<1	1	<2	60	<2	<.2	2.07
G49	9	0.6	3	<0.05	<0.5	<0.5	<1	0.8	<2	62	<2	0.2	2.63
G50	11	<0.3	5	<0.05	<0.5	<0.5	<1	3	<2	97	<2	0.3	2.32
G51	14	0.3	9	<0.05	<0.5	<0.5	<1	1	<2	149	<2	0.4	2.92
G52	16	<0.3	6	<0.05	<0.5	<0.5	<1	0.9	<2	121	<2	0.3	2.69
G54	24	<0.3	8	<0.05	<0.5	<0.5	<1	1	<2	100	<2	<.2	2.67
G55	31	4	8	<0.05	<0.5	<0.5	<1	2	<2	92	<2	0.2	2.67
Tertiary sedimentary rock													
G01	36	171	208	<0.05	<0.5	<0.5	2	3	<2	348	<2	0.5	1.56
G02	17	6	118	<0.05	<0.5	<0.5	1	25	<2	718	<2	0.3	4.18
G03	9	9	42	<0.05	<0.5	<0.5	<1	5	<2	202	<2	<.2	3.13
G04	7	2	36	<0.05	<0.5	<0.5	<1	9	<2	326	<2	<.2	4.40
G05	<5	<0.3	44	<0.05	<0.5	<0.5	<1	17	<2	452	<2	<.2	5.51
G06	16	23	2	<0.05	<0.5	<0.5	<1	1	<2	114	<2	0.2	2.10
G07	26	76	9	<0.05	<0.5	<0.5	<1	12	<2	337	<2	0.3	1.28
Cretaceous Mesaverde Formation													
G32	13	21	1	<0.05	<0.5	<0.5	<1	1	<2	82	<2	0.3	<0.5
G33	18	74	9	<0.05	<0.5	<0.5	<1	5	<2	226	<2	0.3	<0.5
G34	<5	23	5	<0.05	<0.5	<0.5	<1	2	<2	364	<2	<.2	<0.5
G35	25	11	1	<0.05	<0.5	<0.5	<1	0.7	<2	52	<2	0.2	0.71
G36	14	21	4	<0.05	<0.5	<0.5	<1	2	<2	89	<2	0.2	<0.5
G37	13	11	2	<0.05	<0.5	<0.5	<1	1	<2	70	<2	0.3	<0.5
G38	12	21	4	<0.05	<0.5	<0.5	<1	1	<2	74	<2	0.2	<0.5
G39	30	22	9	<0.05	<0.5	<0.5	<1	0.8	<2	75	<2	0.4	0.74
Cretaceous Mancos Shale													
G19	15	51	4	<0.05	<0.5	<0.5	<1	2	<2	241	<2	0.5	0.74
G20	15	13	5	<0.05	<0.5	<0.5	<1	2	<2	581	<2	0.2	0.73
G24	39	29	35	<0.05	<0.5	<0.5	<1	2	<2	192	<2	0.2	<0.5
G25	22	19	20	<0.05	<0.5	<0.5	<1	2	<2	141	<2	0.2	<0.5
G26	15	0.9	7	<0.05	<0.5	<0.5	<1	0.9	<2	39	<2	<.2	<0.5
G27	<5	<0.3	5	<0.05	<0.5	<0.5	<1	<0.5	<2	190	<2	<.2	<0.5
G28	14	32	6	<0.05	<0.5	<0.5	<1	6	<2	174	<2	0.4	<0.5
G29	60	92	1	<0.05	<0.5	<0.5	<1	1	<2	176	<2	<.2	<0.5
G30	8	0.5	29	<0.05	<0.5	<0.5	<1	2	<2	194	<2	<.2	1.71
G31	9	0.4	16	<0.05	<0.5	<0.5	<1	1	<2	111	<2	<.2	<0.5
Mesozoic sedimentary rock													
G09	25	4	257	<0.05	<0.5	<0.5	1	8	<2	161	<2	0.3	0.57
G10	<5	0.4	227	<0.05	<0.5	<0.5	<1	11	<2	241	<2	0.2	2.71
G11	<5	<0.3	439	<0.05	<0.5	<0.5	<1	20	<2	192	<2	0.3	1.02
G12	<5	2	274	<0.05	<0.5	<0.5	<1	15	<2	205	<2	<.2	<0.5
G13	<5	<0.3	274	<0.05	<0.5	<0.5	<1	11	<2	535	<2	0.3	<0.5
Paleozoic sedimentary rock													
C01	<20	0.4	108	<0.05	_	0.06	0.63	14.5	1.2	142	0.7	1	1.0
C02	<20	0.1	61.3	<0.05	_	0.05	<0.5	4.5	1.2	129	0.6	0.5	0.8
C03	<20	0.4	72.9	<0.05	_	0.06	<0.5	2.6	0.9	56.2	0.1	0.5	0.9
C04	<20	0.1	99.0	<0.05	_	0.05	<0.5	0.6	1.0	25.5	<0.1	<0.5	0.9
C05	<20	0.2	169	<0.05	_	0.05	<0.5	1.0	1.0	47.0	<0.1	<0.5	1.6
C06	<20	0.3	264	<0.05	_	0.06	<0.5	1.6	1.1	94.5	<0.1	0.6	1.8
C07	<20	0.3	64.0	<0.05	_	0.07	<0.5	1.2	1.5	123	0.8	0.9	0.9
C08	<20	3.5	55.7	<0.05	_	0.07	<0.5	1.5	1.4	143	0.7	0.7	0.8
C09	<20	0.2	54.6	<0.05	_	0.10	0.72	1.8	2.3	793	3.1	0.7	0.7
C10	<20	0.1	53.5	<0.05	_	0.06	0.52	2.0	1.6	419	1.6	0.8	0.7
C11	<20	0.3	134	<0.05	_	0.06	<0.5	1.6	1.1	70.0	0.1	0.6	1.3
C16	<20	0.8	84.5	<0.05	_	0.04	<0.5	2.3	0.9	38.0	<0.1	<0.5	0.9
C17	61	28.8	73.7	<0.05	_	0.12	<0.5	3.5	1.6	246	1.1	4.7	0.9
C18	35	3.9	85.3	<0.05	_	0.06	<0.5	3.4	1.1	133	0.2	<0.5	0.7
C19	<20	3.6	102	<0.05	_	0.06	<0.5	1.2	1.0	47.5	<0.1	<0.5	0.7
Tertiary and Proterozoic rock													
G21	35	<0.3	5	<0.05	<0.5	<0.5	<1	6	<2	36	<2	0.6	<0.5
G22	14	<0.3	13	<0.05	<0.5	<0.5	<1	2	<2	48	<2	4	<0.5
G23	10	0.5	9	<0.05	<0.5	<0.5	<1	2	<2	36	<2	5	<0.5
G40	14	0.4	11	<0.05	<0.5	<0.5	<1	0.7	<2	36	<2	0.4	<0.5
G41	30	<0.3	29	<0.05	<0.5	<0.5	<1	2	<2	31	<2	0.3	0.51
G42	13	<0.3	20	<0.05	<0.5	<0.5	<1	1	<2	28	<2	0.2	<0.5
G43	<5	<0.3	3	<0.05	<0.5	<0.5	1	1	<2	37	<2	0.3	0.57
G44	13	<0.3	3	<0.05	<0.5	<0.5	<1	1	<2	45	<2	0.3	<0.5

Appendix 1—*Continued*. Chemical analyses of stream and spring water samples from watersheds underlain by the ten dominant rock composition types in the Grand Mesa, Uncompahgre, and Gunnison National Forests, Colorado.

[Leader indicates (_) not determined]

Sample no.	Sc µg/L	Cr µg/L	Ga µg/L	As µg/L	Se µg/L	Br µg/L	Rb µg/L	Y µg/L	Zr µg/L	Mo µg/L	Sn µg/L	Sb µg/L	I µg/L
Tertiary basalt													
G14	17	<0.1	<0.01	<0.03	<0.2	<3	0.294	0.31	0.282	0.53	<0.05	<0.01	<0.2
G15	21	<0.1	<0.01	0.7	<0.2	<3	0.350	0.44	0.431	<0.5	1.913	0.22	19.64
G16	26	<0.1	<0.01	<0.03	<0.2	<3	1.340	0.53	1.027	<0.5	<0.05	<0.01	2.05
G17	22	<0.1	<0.01	<0.03	<0.2	<3	0.438	0.38	0.277	<0.5	<0.05	<0.01	<0.2
Tertiary ash flow tuff													
G45	48	<0.1	<0.01	0.9	<0.2	33	0.764	0.08	0.220	<0.5	<0.05	0.09	7.82
G46	51	<0.1	<0.01	2.2	<0.2	<3	2.248	0.08	0.843	0.60	<0.05	0.13	5.17
G56	35	<0.1	<0.01	1.5	<0.2	<3	0.327	0.05	8.512	<0.5	<0.05	<0.01	3.51
G57	25	<0.1	<0.01	0.9	<0.2	<3	3.118	0.14	0.124	<0.5	<0.05	<0.01	<0.2
G58	22	<0.1	<0.01	0.8	<0.2	<3	1.609	0.18	0.178	<0.5	<0.05	<0.01	2.51
Tertiary quartz latite													
C12	1.9	<1	<0.02	–	–	–	3.05	0.10	0.08	0.26	–	<0.1	–
C13	5.3	<1	0.1	–	–	–	1.51	1.49	1.4	0.82	–	<0.1	–
C14	2.5	<1	0.02	–	–	–	0.85	0.28	0.3	1.08	–	<0.1	–
C15	2.8	<1	<0.02	–	–	–	1.07	0.24	0.3	0.37	–	<0.1	–
Tertiary andesite													
G47	26	<0.1	<0.01	0.4	<0.2	<3	1.420	0.07	0.171	<0.5	<0.05	<0.01	<0.2
G48	42	<0.1	<0.01	0.7	<0.2	<3	1.712	0.07	0.426	<0.5	<0.05	<0.01	<0.2
G49	37	<0.1	<0.01	0.6	<0.2	<3	2.122	0.10	0.277	<0.5	<0.05	0.07	<0.2
G50	41	<0.1	<0.01	0.6	<0.2	<3	3.165	0.11	0.153	<0.5	<0.05	0.06	<0.2
G51	37	<0.1	<0.01	1.3	<0.2	<3	2.032	0.07	0.256	0.53	<0.05	<0.01	<0.2
G52	48	<0.1	<0.01	0.8	<0.2	<3	2.759	0.06	0.374	0.59	<0.05	<0.01	<0.2
G54	54	<0.1	<0.01	0.5	<0.2	<3	3.717	0.05	0.227	<0.5	<0.05	<0.01	<0.2
G55	51	<0.1	<0.01	1.0	<0.2	<3	3.705	0.05	0.449	<0.5	<0.05	<0.01	2.16
Tertiary sedimentary rock													
G01	11	<0.1	<0.01	1.3	<0.2	90	0.658	0.17	1.256	0.53	<0.05	0.17	35.69
G02	27	<0.1	<0.01	1.4	<0.2	182	0.840	0.06	0.762	2.10	<0.05	0.26	24.76
G03	25	<0.1	<0.01	2.4	<0.2	<3	0.569	0.07	0.182	3.28	<0.05	0.13	2.45
G04	27	<0.1	<0.01	4.1	<0.2	<3	0.490	0.06	0.685	2.51	<0.05	0.26	<0.2
G05	35	<0.1	<0.01	5.8	<0.2	<3	0.600	0.05	0.220	7.48	<0.05	0.29	<0.2
G06	36	<0.1	<0.01	0.6	<0.2	<3	0.733	0.10	0.139	1.54	<0.05	0.09	<0.2
G07	24	<0.1	<0.01	1.3	<0.2	<3	0.403	0.12	0.628	0.82	<0.05	<0.01	2.27
Cretaceous Mesaverde Formation													
G32	19	<0.1	<0.01	<0.03	<0.2	<3	0.398	0.04	0.623	<0.5	<0.05	<0.01	<0.2
G33	16	<0.1	<0.01	0.3	<0.2	<3	0.306	0.04	0.116	<0.5	<0.05	<0.01	<0.2
G34	17	<0.1	<0.01	<0.03	<0.2	<3	0.136	<0.03	0.241	<0.5	<0.05	<0.01	<0.2
G35	21	<0.1	<0.01	<0.03	<0.2	<3	0.350	0.03	0.485	<0.5	<0.05	<0.01	<0.2
G36	17	<0.1	<0.01	2.4	<0.2	<3	0.447	0.04	<0.05	<0.5	<0.05	<0.01	<0.2
G37	19	<0.1	<0.01	<0.03	<0.2	<3	0.429	0.04	<0.05	<0.5	<0.05	<0.01	<0.2
G38	18	<0.1	<0.01	0.6	<0.2	<3	0.365	0.06	0.057	0.63	<0.05	<0.01	<0.2
G39	18	<0.1	<0.01	<0.03	<0.2	<3	0.279	0.12	0.500	<0.5	<0.05	<0.01	<0.2
Cretaceous Mancos Shale													
G19	28	<0.1	<0.01	0.4	<0.2	<3	0.071	0.04	0.415	0.80	<0.05	-0.01	2.32
G20	35	<0.1	<0.01	0.3	<0.2	<3	0.078	0.04	<0.05	0.72	<0.05	0.01	3.63
G24	17	<0.1	<0.01	0.5	<0.2	<3	0.227	0.04	0.141	0.80	<0.05	0.07	3.85
G25	14	<0.1	<0.01	0.4	<0.2	<3	0.249	0.09	<0.05	0.81	<0.05	0.14	<0.2
G26	15	<0.1	0.013	<0.03	<0.2	<3	0.153	0.06	0.069	<0.5	<0.05	0.06	<0.2
G27	17	<0.1	<0.01	<0.03	<0.2	<3	0.052	0.03	0.070	<0.5	<0.05	<0.01	<0.2
G28	15	<0.1	<0.01	<0.03	<0.2	<3	0.653	0.13	0.064	1.35	<0.05	0.01	<0.2
G29	23	<0.1	<0.01	0.5	<0.2	<3	0.230	0.05	0.073	1.28	<0.05	<0.01	3.24
G30	24	<0.1	<0.01	0.3	<0.2	<3	0.238	0.05	0.055	1.74	<0.05	<0.01	<0.2
G31	15	<0.1	<0.01	<0.03	<0.2	<3	0.163	0.06	<0.05	<0.5	<0.05	<0.01	<0.2
Mesozoic sedimentary rock													
G09	11	<0.1	<0.01	2.8	<0.2	<3	1.508	0.03	0.241	0.65	<0.05	0.01	2.67
G10	21	<0.1	<0.01	2.0	<0.2	78	2.741	<0.03	0.083	<0.5	<0.05	<0.01	5.53
G11	12	<0.1	<0.01	1.8	2.71	51	4.048	<0.03	0.440	<0.5	<0.05	0.09	2.78
G12	12	<0.1	<0.01	0.3	<0.2	<3	3.455	<0.03	0.232	<0.5	<0.05	<0.01	<0.2
G13	25	<0.1	<0.01	0.6	<0.2	<3	1.466	0.20	<0.05	<0.5	<0.05	0.06	<0.2
Paleozoic sedimentary rock													
C01	0.9	3.2	<0.02	–	–	–	3.05	0.02	<0.05	0.68	–	0.20	–
C02	1.0	3.4	<0.02	–	–	–	0.88	<0.01	<0.05	0.91	–	<0.1	–
C03	0.9	2.7	<0.02	–	–	–	0.53	0.02	<0.05	0.48	–	<0.1	–
C04	0.7	2.2	<0.02	–	–	–	0.18	0.08	<0.05	<0.2	–	<0.1	–
C05	1.0	2.1	<0.02	–	–	–	0.16	0.04	<0.05	<0.2	–	<0.1	–
C06	0.9	2.3	<0.02	–	–	–	0.32	0.05	<0.05	<0.2	–	<0.1	–
C07	0.8	3.2	<0.02	–	–	–	0.05	0.03	<0.05	0.73	–	<0.1	–
C08	0.6	2.7	<0.02	–	–	–	0.11	0.02	<0.05	0.66	–	<0.1	–
C09	0.6	2.3	<0.02	–	–	–	0.49	0.10	<0.05	0.84	–	<0.1	–
C10	0.7	2.7	<0.02	–	–	–	0.61	0.03	<0.05	1.46	–	<0.1	–
C11	0.8	2.6	<0.02	–	–	–	0.21	0.04	<0.05	0.26	–	<0.1	–
C16	1.1	2.1	<0.02	–	–	–	3.13	0.05	<0.05	<0.2	–	<0.1	–
C17	1.1	3.1	<0.02	–	–	–	1.02	0.04	<0.05	0.45	–	<0.1	–
C18	1.3	2.3	<0.02	–	–	–	2.10	0.03	<0.05	0.51	–	<0.1	–
C19	0.7	2.1	<0.02	–	–	–	0.39	0.04	<0.05	0.25	–	<0.1	–
Tertiary and Proterozoic rock													
G21	30	<0.1	<0.01	<0.03	<0.2	<3	0.121	0.77	0.571	<0.5	<0.05	<0.01	3.16
G22	22	<0.1	<0.01	<0.03	<0.2	<3	1.489	0.17	0.084	<0.5	<0.05	<0.01	<0.2
G23	28	<0.1	<0.01	<0.03	<0.2	<3	0.720	<0.03	0.175	0.72	<0.05	<0.01	<0.2
G40	20	<0.1	<0.01	<0.03	<0.2	<3	0.187	0.65	0.366	1.26	<0.05	<0.01	<0.2
G41	26	<0.1	<0.01	<0.03	<0.2	<3	0.247	0.37	0.110	1.40	1.475	0.13	<0.2
G42	24	<0.1	<0.01	<0.03	<0.2	<3	0.182	0.77	0.085	2.90	<0.05	<0.01	<0.2
G43	13	<0.1	0.011	<0.03	<0.2	<3	0.336	0.03	12.503	<0.5	<0.05	<0.01	<0.2
G44	-10	<0.1	<0.01	<0.03	<0.2	<3	0.636	0.04	0.678	2.21	<0.05	0.15	<0.2

Appendix 1—*Continued.* Chemical analyses of stream and spring water samples from watersheds underlain by the ten dominant rock composition types in the Grand Mesa, Uncompahgre, and Gunnison National Forests, Colorado.

[Leader indicates (_) not determined]

Sample no.	Cs µg/L	La µg/L	Ce µg/L	Pr µg/L	Nd µg/L	Sm µg/L	Eu µg/L	Gd µg/L	Tb µg/L	Dy µg/L	Ho µg/L	Er µg/L	Tm µg/L
Tertiary basalt													
G14	<0.002	0.262	0.563	0.076	0.331	0.053	0.025	0.132	<0.001	0.048	<0.001	0.036	<0.001
G15	<0.002	0.313	0.500	0.103	0.425	0.063	0.037	0.105	0.014	0.088	<0.001	0.057	<0.001
G16	<0.002	0.264	0.379	0.067	0.314	0.040	0.031	0.136	0.021	0.078	0.019	0.043	<0.001
G17	<0.002	0.174	0.321	0.050	0.335	0.053	0.017	0.060	<0.001	0.037	<0.001	0.029	<0.001
Tertiary ash flow tuff													
G45	<0.002	<0.005	<0.005	<0.002	0.054	-0.001	<0.001	0.020	0.001	0.011	<0.001	<0.001	0.001
G46	<0.002	0.068	0.142	<0.002	<0.004	-0.001	<0.001	0.026	<0.001	<0.001	<0.001	<0.001	<0.001
G56	<0.002	<0.005	<0.005	<0.002	<0.004	0.012	<0.001	0.027	<0.001	<0.001	<0.001	<0.001	<0.001
G57	<0.002	0.075	0.143	0.026	0.143	<0.001	<0.001	0.038	<0.001	0.011	<0.001	0.011	<0.001
G58	<0.002	0.165	0.304	0.034	0.123	<0.001	<0.001	0.038	<0.001	0.022	<0.001	0.014	<0.001
Tertiary quartz latite													
C12	0.01	0.05	0.06	0.01	0.06	0.01	0.005	0.009	<0.005	0.02	<0.005	0.01	<0.005
C13	0.05	0.49	0.55	0.14	0.67	0.13	0.03	0.19	0.03	0.17	0.04	0.16	0.02
C14	0.01	0.12	0.16	0.04	0.14	0.02	<0.005	0.04	0.006	0.04	0.009	0.03	<0.005
C15	0.13	0.11	0.17	0.03	0.17	0.03	0.006	0.04	<0.005	0.03	0.008	0.02	<0.005
Tertiary andesite													
G47	<0.002	<0.005	<0.005	<0.002	0.054	<0.001	<0.001	0.020	<0.001	<0.001	<0.001	<0.001	<0.001
G48	<0.002	<0.005	0.055	<0.002	<0.004	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.027	<0.001
G49	<0.002	<0.005	0.069	<0.002	0.074	<0.001	<0.001	0.026	<0.001	<0.001	<0.001	0.011	<0.001
G50	<0.002	<0.005	0.063	<0.002	0.087	0.018	<0.001	<0.001	<0.001	<0.001	<0.001	0.030	<0.001
G51	<0.002	<0.005	0.052	<0.002	<0.004	0.011	<0.001	0.026	<0.001	<0.001	<0.001	0.014	<0.001
G52	<0.002	<0.005	<0.005	<0.002	<0.004	<0.001	<0.001	0.044	<0.001	<0.001	<0.001	<0.001	<0.001
G54	<0.002	<0.005	<0.005	<0.002	0.043	0.012	<0.001	0.033	<0.001	0.023	<0.001	<0.001	<0.001
G55	<0.002	<0.005	0.053	<0.002	<0.004	<0.001	<0.001	0.039	<0.001	<0.001	<0.001	<0.001	<0.001
Tertiary sedimentary rock													
G01	0.002	0.072	0.128	0.050	0.138	0.028	0.153	0.054	0.041	0.040	0.027	0.038	0.026
G02	<0.002	<0.005	0.283	0.037	0.153	0.027	0.071	0.088	0.019	0.024	0.018	<0.001	0.018
G03	<0.002	0.051	0.108	0.002	0.064	<0.001	0.025	<0.001	<0.001	0.032	<0.001	0.013	<0.001
G04	<0.002	0.071	0.052	0.023	0.082	0.022	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
G05	<0.002	<0.005	<0.005	<0.002	0.040	0.016	0.030	0.037	<0.001	<0.001	<0.001	0.011	<0.001
G06	<0.002	<0.005	0.134	<0.002	0.083	0.016	0.015	<0.001	<0.001	0.025	<0.001	0.021	<0.001
G07	<0.002	<0.005	0.110	<0.002	0.059	<0.001	0.048	0.025	<0.001	0.025	<0.001	0.016	<0.001
Cretaceous Mesaverde Formation													
G32	<0.002	<0.005	<0.005	<0.002	0.047	<0.001	<0.001	0.014	<0.001	<0.001	<0.001	<0.001	<0.001
G33	<0.002	<0.005	<0.005	<0.002	<0.004	<0.001	<0.001	<0.001	<0.001	0.020	<0.001	<0.001	<0.001
G34	<0.002	<0.005	<0.005	<0.002	<0.004	<0.001	0.010	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
G35	<0.002	<0.005	<0.005	<0.002	0.044	<0.001	<0.001	0.021	<0.001	<0.001	<0.001	<0.001	<0.001
G36	<0.002	<0.005	0.051	<0.002	<0.004	<0.001	0.012	0.021	<0.001	<0.001	<0.001	<0.001	<0.001
G37	<0.002	<0.005	<0.005	<0.002	<0.004	<0.001	<0.001	0.022	<0.001	<0.001	<0.001	<0.001	<0.001
G38	<0.002	<0.005	<0.005	<0.002	0.058	<0.001	<0.001	0.029	<0.001	<0.001	<0.001	<0.001	<0.001
G39	<0.002	0.089	0.086	<0.002	0.145	0.013	<0.001	0.016	<0.001	0.020	<0.001	<0.001	<0.001
Cretaceous Mancos Shale													
G19	<0.002	<0.005	<0.005	<0.002	0.055	<0.001	<0.001	0.014	<0.001	<0.001	<0.001	<0.001	<0.001
G20	<0.002	<0.005	<0.005	<0.002	<0.004	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
G24	<0.002	<0.005	<0.005	<0.002	0.063	0.025	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
G25	<0.002	<0.005	<0.005	<0.002	<0.004	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
G26	<0.002	<0.005	<0.005	<0.002	0.042	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
G27	<0.002	<0.005	<0.005	<0.002	<0.004	<0.001	<0.001	0.014	<0.001	<0.001	<0.001	<0.001	<0.001
G28	<0.002	<0.005	<0.005	<0.002	<0.004	0.012	<0.001	0.034	<0.001	<0.001	<0.001	<0.001	<0.001
G29	<0.002	<0.005	<0.005	<0.002	<0.004	0.012	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
G30	<0.002	<0.005	<0.005	<0.002	0.063	<0.001	<0.001	0.015	<0.001	<0.001	<0.001	<0.001	<0.001
G31	<0.002	<0.005	<0.005	<0.002	0.081	<0.001	<0.001	0.021	<0.001	0.011	<0.001	<0.001	<0.001
Mesozoic sedimentary rock													
G09	<0.002	<0.005	<0.005	<0.002	0.052	<0.001	0.142	0.013	<0.001	<0.001	<0.001	0.011	<0.001
G10	0.297	<0.005	<0.005	<0.002	<0.004	<0.001	0.109	0.025	<0.001	<0.001	<0.001	<0.001	<0.001
G11	0.311	<0.005	<0.005	<0.002	<0.004	<0.001	0.258	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
G12	0.107	<0.005	<0.005	<0.002	<0.004	<0.001	0.116	0.031	<0.001	<0.001	<0.001	<0.001	<0.001
G13	0.037	0.064	<0.005	<0.002	0.072	0.023	0.110	0.032	<0.001	0.010	<0.001	<0.001	<0.001
Paleozoic sedimentary rock													
C01	0.12	0.01	0.02	<0.01	<0.01	<0.01	0.007	<0.005	<0.005	0.006	<0.005	<0.005	<0.005
C02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
C03	<0.01	<0.01	0.01	<0.01	<0.01	<0.01	0.008	0.005	< 0.005	<0.005	<0.005	<0.005	<0.005
C04	<0.01	0.02	<0.01	<0.01	0.02	0.01	0.01	0.006	< 0.005	0.01	<0.005	<0.005	<0.005
C05	<0.01	0.02	<0.01	<0.01	0.02	<0.01	0.02	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
C06	<0.01	0.02	<0.01	<0.01	0.02	<0.01	0.02	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
C07	<0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
C08	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
C09	<0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
C10	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
C11	<0.01	<0.01	<0.01	<0.01	0.01	<0.01	0.01	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
C16	0.06	<0.01	<0.01	<0.01	<0.01	<0.01	0.006	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
C17	<0.01	<0.01	0.02	<0.01	0.01	<0.01	0.007	<0.005	<0.005	0.005	<0.005	<0.005	<0.005
C18	<0.01	<0.01	<0.01	<0.01	0.01	<0.01	0.009	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
C19	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.008	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Tertiary and Proterozoic rock													
G21	<0.002	0.571	0.384	0.160	0.658	0.170	0.029	0.186	0.018	0.170	0.031	0.098	<0.001
G22	<0.002	0.083	0.067	0.032	0.163	0.011	0.014	0.026	<0.001	0.027	<0.001	0.027	<0.001
G23	<0.002	0.003	<0.005	<0.002	0.043	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.012	<0.001
G40	<0.002	0.093	0.097	0.022	0.236	0.087	<0.001	0.101	<0.001	0.072	0.015	0.027	<0.001
G41	<0.002	0.109	0.136	0.037	0.209	0.027	0.015	0.081	<0.001	0.059	<0.001	0.035	<0.001
G42	<0.002	0.202	0.167	0.060	0.332	0.081	<0.001	0.127	<0.001	0.088	0.014	0.054	<0.001
G43	<0.002	<0.005	<0.005	<0.002	<0.004	0.029	0.015	0.037	0.001	<0.001	0.011	0.021	<0.001
G44	0.030	<0.005	<0.005	0.024	<0.004	-0.001	<0.001	0.026	<0.001	<0.001	<0.001	0.014	<0.001

Appendix 1—*Continued.* Chemical analyses of stream and spring water samples from watersheds underlain by the ten dominant rock composition types in the Grand Mesa, Uncompahgre, and Gunnison National Forests, Colorado.

[Leader indicates (_) not determined]

Sample no.	Yb µg/L	Lu µg/L	Hf µg/L	W µg/L	Re µg/L	Tl µg/L	Pb µg/L	Bi µg/L	Th µg/L	U µg/L
Tertiary basalt										
G14	0.027	<0.001	<0.002	<0.01	<0.001	<0.005	<0.1	<0.005	0.069	0.15
G15	0.033	<0.001	<0.002	3.775	<0.001	<0.005	1.42	<0.005	0.100	0.07
G16	0.041	<0.001	0.033	0.551	<0.001	<0.005	<0.1	<0.005	0.092	0.06
G17	<0.001	<0.001	<0.002	0.112	<0.001	<0.005	<0.1	<0.005	0.073	0.04
Tertiary ash flow tuff										
G45	<0.001	<0.001	0.068	<0.01	<0.001	0.054	<0.1	<0.005	0.567	0.19
G46	<0.001	0.013	0.077	<0.01	<0.001	0.059	1.10	<0.005	0.501	0.20
G56	0.014	<0.001	0.112	<0.01	<0.001	<0.005	<0.1	<0.005	0.072	0.06
G57	0.021	<0.001	<0.002	<0.01	<0.001	<0.005	<0.1	<0.005	0.097	0.02
G58	0.024	<0.001	<0.002	<0.01	<0.001	<0.005	<0.1	<0.005	0.130	0.01
Tertiary quartz latite										
C12	0.01	–	–	<0.02	–	–	<0.05	<0.005	0.007	0.08
C13	0.17	–	–	<0.02	–	–	0.06	0.007	0.15	0.32
C14	0.03	–	–	<0.02	–	–	<0.05	<0.005	0.04	0.17
C15	0.02	–	–	<0.02	–	–	<0.05	<0.005	0.02	0.09
Tertiary andesite										
G47	<0.001	<0.001	0.034	<0.01	<0.001	<0.005	<0.1	<0.005	0.297	<0.001
G48	<0.001	<0.001	0.047	<0.01	<0.001	<0.005	<0.1	<0.005	0.365	0.10
G49	<0.001	<0.001	0.047	<0.01	<0.001	<0.005	<0.1	<0.005	0.280	0.28
G50	0.014	<0.001	0.020	<0.01	<0.001	<0.005	<0.1	<0.005	0.160	0.19
G51	<0.001	<0.001	<0.002	<0.01	<0.001	<0.005	<0.1	<0.005	0.176	0.24
G52	<0.001	<0.001	<0.002	<0.01	<0.001	<0.005	<0.1	<0.005	0.124	0.13
G54	0.021	<0.001	<0.002	<0.01	<0.001	<0.005	<0.1	<0.005	0.122	0.20
G55	<0.001	<0.001	0.030	<0.01	<0.001	<0.005	<0.1	<0.005	0.172	0.23
Tertiary sedimentary rock										
G01	0.045	0.035	0.217	0.175	<0.001	0.062	<0.1	1.028	1.517	2.29
G02	0.026	0.022	0.192	0.192	0.016	<0.005	1.19	<0.005	0.841	8.84
G03	<0.001	<0.001	0.048	<0.01	<0.001	<0.005	2.87	<0.005	0.301	1.22
G04	0.023	<0.001	0.026	<0.01	<0.001	<0.005	<0.1	<0.005	0.225	0.95
G05	<0.001	<0.001	0.062	<0.01	<0.001	<0.005	<0.1	<0.005	0.248	1.70
G06	<0.001	<0.001	0.054	<0.01	<0.001	<0.005	<0.1	<0.005	0.204	0.39
G07	0.017	<0.001	0.032	<0.01	<0.001	<0.005	<0.1	<0.005	0.183	0.68
Cretaceous Mesaverde Formation										
G32	<0.001	<0.001	<0.002	<0.01	<0.001	<0.005	<0.1	<0.005	0.0015	0.09
G33	<0.001	<0.001	<0.002	<0.01	<0.001	<0.005	<0.1	<0.005	0.023	0.27
G34	<0.001	<0.001	<0.002	<0.01	<0.001	<0.005	<0.1	<0.005	0.0015	0.51
G35	<0.001	<0.001	<0.002	<0.01	<0.001	<0.005	<0.1	<0.005	0.0015	0.08
G36	<0.001	<0.001	<0.002	0.149	<0.001	<0.005	<0.1	<0.005	0.0015	0.12
G37	0.001	<0.001	<0.002	<0.01	<0.001	<0.005	<0.1	<0.005	0.0015	0.08
G38	<0.001	<0.001	<0.002	<0.01	<0.001	<0.005	<0.1	<0.005	0.0015	0.09
G39	<0.001	<0.001	<0.002	<0.01	<0.001	0.054	<0.1	<0.005	0.021	0.13
Cretaceous Mancos Shale										
G19	0.021	<0.001	<0.002	<0.01	<0.001	<0.005	<0.1	<0.005	0.040	0.35
G20	<0.001	<0.001	<0.002	<0.01	0.001	<0.005	<0.1	<0.005	0.041	0.58
G24	<0.001	<0.001	<0.002	<0.01	<0.001	<0.005	<0.1	<0.005	0.037	0.45
G25	<0.001	<0.001	<0.002	<0.01	<0.001	<0.005	<0.1	<0.005	0.031	0.22
G26	<0.001	<0.001	<0.002	<0.01	<0.001	<0.005	<0.1	<0.005	0.062	0.12
G27	0.014	<0.001	<0.002	<0.01	<0.001	<0.005	<0.1	<0.005	0.020	0.27
G28	<0.001	<0.001	<0.002	<0.01	0.026	0.055	<0.1	<0.005	0.049	0.14
G29	<0.001	<0.001	<0.002	<0.01	<0.001	<0.005	<0.1	<0.005	0.021	0.34
G30	<0.001	<0.001	<0.002	<0.01	0.011	<0.005	<0.1	<0.005	0.022	0.52
G31	<0.001	<0.001	<0.002	<0.01	<0.001	<0.005	<0.1	<0.005	0.022	0.12
Mesozoic sedimentary rock										
G09	<0.001	<0.001	<0.002	<0.01	0.010	<0.005	<0.1	<0.005	0.094	1.43
G10	<0.001	<0.001	<0.002	<0.01	<0.001	<0.005	1.66	<0.005	0.077	2.33
G11	<0.001	<0.001	<0.002	<0.01	0.026	<0.005	<0.1	<0.005	0.065	5.78
G12	<0.001	<0.001	<0.002	<0.01	0.010	<0.005	<0.1	<0.005	0.079	2.12
G13	0.031	<0.001	<0.002	<0.01	0.019	<0.005	<0.1	<0.005	0.045	3.70
Paleozoic sedimentary rock										
C01	<0.005	–	–	0.07	–	–	<0.05	0.005	0.02	0.84
C02	<0.005	–	–	0.05	–	–	<0.05	<0.005	0.007	1.22
C03	<0.005	–	–	0.05	–	–	<0.05	<0.005	0.006	0.69
C04	0.01	–	–	0.03	–	–	<0.05	<0.005	<0.005	0.13
C05	<0.005	–	–	<0.02	–	–	<0.05	<0.005	0.005	0.26
C06	<0.005	–	–	0.03	–	–	<0.05	<0.005	<0.005	0.49
C07	<0.005	–	–	<0.02	–	–	<0.05	<0.005	0.006	1.08
C08	<0.005	–	–	0.03	–	–	<0.05	<0.005	0.006	0.76
C09	<0.005	–	–	0.05	–	–	<0.05	<0.005	0.01	0.54
C10	<0.005	–	–	0.02	–	–	<0.05	<0.005	0.01	0.70
C11	<0.005	–	–	<0.02	–	–	<0.05	<0.005	0.005	0.28
C16	0.006	–	–	<0.02	–	–	<0.05	<0.005	0.005	0.70
C17	<0.005	–	–	<0.02	–	–	<0.05	<0.005	0.008	0.74
C18	<0.005	–	–	<0.02	–	–	<0.05	<0.005	0.006	0.61
C19	<0.005	–	–	<0.02	–	–	<0.05	<0.005	<0.005	0.48
Tertiary and Proterozoic rock										
G21	0.087	0.016	<0.002	<0.01	<0.001	<0.005	1.31	<0.005	0.079	7.27
G22	0.017	<0.001	<0.002	<0.01	<0.001	<0.005	1.07	<0.005	0.046	0.62
G23	<0.001	<0.001	<0.002	<0.01	0.017	<0.005	<0.1	<0.005	0.023	0.59
G40	0.015	<0.001	0.002	<0.01	<0.001	<0.005	<0.1	<0.005	0.033	0.17
G41	0.027	<0.001	<0.002	1.430	<0.001	<0.005	1.02	<0.005	0.071	0.98
G42	0.027	0.013	0.043	0.107	<0.001	<0.005	<0.1	<0.005	0.050	1.36
G43	<0.001	0.017	0.206	0.261	<0.001	0.052	<0.1	<0.005	0.375	0.37
G44	<0.001	0.019	0.045	<0.01	<0.001	0.068	<0.1	<0.005	0.333	0.63

Appendix 2. Chemical analyses of stream water samples from watersheds underlain by the Sunshine Peak Tuff, Redcloud Peak area, Colorado.

[Summarized in table 19]

Site	Latitude			Longitude			Water Type	Flow, gallons per minute	Comments	Temperature °C	pH
	Degree	Minute	Second	Degree	Minute	Second					
RW02	37	58	59	107	29	7	Unnamed stream	15	No precipitates	8	7.09
RW10	37	56	40	107	28	42	Rock Creek	5	Slight staining	9	6.73
RW11	37	56	37	107	28	9	Cooper Creek	10	Al oxide coatings on float	10	5.17
RW12	37	56	54	107	26	19	South Fork Silver Creek	20	Al oxide coatings on float	8	4.92
RW14	37	56	56	107	26	25	Unnamed stream	1	Abundant recent Fe oxide precipitates	13	3.58
RW15	37	56	46	107	26	39	Unnamed stream	0.25	Slight Fe staining	5	6.08
RW16	37	56	28	107	27	13	Unnamed stream	0.75	Slight Fe staining	9	4.17
RW17	38	0	12	107	21	45	Alpine Gulch	18	Slightly murky; Fe staining	10	7
RW21	37	54	29	107	22	31	Unnamed stream	1	None	12	6.91
RW22	37	54	26	107	22	49	Bent Creek	2	None	12	7
RW23	37	54	24	107	25	55	Unnamed stream	1	None	11	7.42
RW24	37	54	44	107	26	27	Unnamed stream	1	None	11	7.6
RW25	37	55	5	107	26	51	Unnamed stream	1	None	8	7.57
RW26	37	56	9	107	27	30	Silver Creek	2	None	14	6.06
RW27	37	54	20	107	24	33	Unnamed stream	1	None	11	7.05
RW30	37	58	22	107	26	33	Unnamed stream	1	None	10	4.42
RW31	37	58	24	107	26	36	Upper Cooper Creek	1	None	8	6.4
RW32	37	57	53	107	27	4	Unnamed stream	1	None	6	3.9
RW33	37	57	19	107	27	50	Unnamed stream	1	None	10	6.6

Site	Conductivity µS/cm	Ca mg/L	Mg mg/L	Na mg/L	K mg/L	SiO_2 mg/L	Alkalinity mg/L HCO_3^-	SO_4 mg/L	Cl mg/L	F mg/L	NO_3 mg/L	Al mg/L	Mn mg/L	Fe mg/L	Cu µg/L
RW02	110	15	1.7	0.7	0.5	3	29	32	0.15	0.12	2	0.005	0.007	0.02	0.7
RW10	117	14	2.5	0.4	0.9	6	12	42	0.07	0.09	0.15	0.005	0.007	0.01	0.7
RW11	117	12	1.5	1	1.2	10	15	45	0.07	0.27	0.32	1.2	0.5	0.04	1
RW12	127	12	2	0.6	1.9	9	0.1	49	0.15	0.19	1.1	1.6	0.52	0.007	4
RW14	320	22	4.5	2.2	4.5	29	0.1	106	0.14	0.96	0.15	2.62	2	0.45	3
RW15	70	7.8	1.2	0.6	1.7	16	13	23	0.14	0.15	0.15	0.005	0.007	0.02	0.7
RW16	148	11	2	0.5	3.6	25	0.1	53	0.15	0.33	0.15	1.7	1.2	0.07	3
RW17	128	15	2.4	2	0.9	10	18	43	0.1	0.18	0.15	0.005	0.02	0.27	0.7
RW21	93	12	1.4	1.2	0.7	6	29	23	0.13	0.07	0.15	0.005	0.007	0.01	0.7
RW22	94	12	1.4	1.2	0.7	6	15	23	0.11	0.08	0.15	0.005	0.007	0.03	0.7
RW23	121	18	1.6	2.3	0.3	7	45	16	0.15	0.32	0.15	0.005	0.007	0.02	0.7
RW24	210	33	2	4.4	1.2	8	94	24	0.17	0.28	0.15	0.005	0.007	0.02	0.7
RW25	87	11	1.2	1.1	1	8	13	24	0.11	0.09	0.15	0.005	0.007	0.01	0.7
RW26	129	14	2.4	1.1	1.7	10	0.1	50	0.13	0.2	0.59	0.3	0.26	0.03	3
RW27	44	6.3	0.5	0.9	0.5	6	23	6.9	0.13	0.08	0.15	0.005	0.007	0.04	0.7
RW30	140	12	1.4	1.2	1.2	10	0.1	52	0.07	0.26	0.37	2.1	0.67	0.07	2
RW31	55	7.6	0.7	0.4	0.4	3	15	13	0.18	0.12	0.15	0.005	0.007	0.01	0.7
RW32	194	14	2.3	1.1	2.3	17	0.1	74	0.17	0.69	0.15	4.4	0.53	0.04	6
RW33	47	6.7	0.7	0.4	0.5	4	20	10	0.07	0.03	0.15	0.005	0.007	0.02	0.7

Appendix 2—*Continued.* Chemical analyses of stream water samples from watersheds underlain by the Sunshine Peak Tuff, Redcloud Peak area, Colorado.

[Summarized in table 19]

Site	Zn µg/L	Co µg/L	Ni µg/L	Mo µg/L	As µg/L	U µg/L	Li µg/L	Be µg/L	Sc µg/L	Cr µg/L	Rb µg/L	Sr µg/L	Y µg/L	Cs µg/L	Ba µg/L
RW02	2	0.7	0.7	1	0.7	0.1	3	0.15	2	0.3	1.5	120	0.07	0.2	3.4
RW10	7	0.7	0.7	0.7	0.7	0.07	3	0.2	3	0.15	4.1	55	0.07	0.15	4.9
RW11	90	1	2	0.7	0.7	2.6	3	1.7	2	0.15	3.6	54	8.8	0.15	14
RW12	110	0.7	2	0.7	0.7	6.6	5	2.9	3	0.15	6.8	39	9.2	0.15	8.9
RW14	280	12	7	0.7	0.7	3.4	16	6.9	7.1	0.15	21	56	9.2	1.8	6.5
RW15	10	0.7	0.7	0.7	0.7	0.2	2	0.6	4.7	0.15	6.2	29	0.2	0.15	7.5
RW16	83	4	3	0.7	0.7	3.5	8.7	4.3	6.1	0.15	18	35	3.5	2.5	26
RW17	5	2	1	1	0.7	0.07	2	0.15	5	0.15	1.9	160	0.07	0.15	18
RW21	2	0.7	0.7	0.7	0.7	0.3	4	0.15	4.8	0.15	1.9	140	0.07	0.15	4.3
RW22	2	0.7	0.7	0.7	0.7	0.2	3	0.15	4.3	0.15	1.8	140	0.07	0.15	4.1
RW23	2	0.7	0.7	6	0.7	2.1	11	0.15	5.4	0.2	1.2	190	0.07	0.2	2.4
RW24	2	0.7	0.7	9	0.7	8.1	21	0.15	5.2	0.5	2.4	320	0.07	0.4	32
RW25	2	0.7	0.7	1	0.7	0.1	2	0.15	6.9	0.15	2.1	38	0.07	0.15	5.1
RW26	100	1	2	0.7	0.7	2.6	4	2.5	6.6	0.3	6.6	110	4	0.2	14
RW27	2	0.7	0.7	2	0.7	0.6	4.7	0.15	7	0.2	1.8	39	0.1	0.7	0.9
RW30	130	3	2	0.7	0.7	5.2	3	3.3	8.9	0.15	4	49	13	0.15	14
RW31	2	0.7	0.7	0.7	0.7	0.07	0.7	0.15	8.2	0.15	0.8	42	0.07	0.15	13
RW32	93	3	0.7	0.7	1	4.6	5.7	1	8.2	0.2	9.5	44	13	1.1	7.2
RW33	2	0.7	0.7	0.7	0.7	0.07	0.7	0.15	8.1	0.15	1.1	79	0.07	0.2	14

Site	La µg/L	Ce µg/L	Pr µg/L	Nd µg/L	Sm µg/L	Eu µg/L	Gd µg/L	Dy µg/L	Yb µg/L
RW02	66	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
RW10	0.2	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
RW11	7	14	2.2	8.7	1.8	0.2	2	1.6	0.6
RW12	5.8	10	1.7	5.8	1.4	0.2	1.8	1.5	0.7
RW14	2.9	6.7	1	4.7	1.2	0.2	1.6	1.3	0.6
RW15	0.2	0.07	0.07	0.1	0.07	0.07	0.07	0.07	0.07
RW16	1	2.1	0.4	1.6	0.3	0.07	0.4	0.4	0.2
RW17	0.2	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
RW21	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
RW22	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
RW23	0.1	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
RW24	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
RW25	0.2	0.1	0.07	0.1	0.07	0.07	0.07	0.07	0.07
RW26	2.2	3.5	0.6	2.4	0.5	0.07	0.7	0.5	0.2
RW27	0.07	0.1	0.07	0.07	0.07	0.07	0.07	0.07	0.07
RW30	9.8	21	2.8	10	2.2	0.2	2.4	2	0.9
RW31	0.2	0.07	0.07	0.2	0.07	0.07	0.07	0.07	0.07
RW32	4.1	13	2	9	2.1	0.3	2.9	2.2	0.8
RW33	0.07	0.1	0.07	0.07	0.07	0.07	0.07	0.07	0.07