

GEOHYDROLOGY AND POTENTIAL HYDROLOGIC EFFECTS OF  
UNDERGROUND COAL MINING IN THE RAPID CREEK BASIN,  
MESA COUNTY, COLORADO

By Tom Brooks

---

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 86-4172

Prepared in cooperation with the  
U.S. BUREAU OF LAND MANAGEMENT

Denver, Colorado

1986



DEPARTMENT OF THE INTERIOR  
DONALD PAUL HODEL, Secretary  
U.S. GEOLOGICAL SURVEY  
Dallas L. Peck, Director

---

For additional information  
write to:

District Chief  
U.S. Geological Survey  
Water Resources Division  
Box 25046, Mail Stop 415  
Denver Federal Center  
Denver, Colorado 80225

Copies of this report can  
be purchased from:

U.S. Geological Survey  
Books and Open-File Reports  
Building 41, Box 25425  
Denver Federal Center  
Denver, CO 80225  
[Telephone: (303) 236-7476]

## CONTENTS

	Page
Abstract-----	1
Introduction-----	1
Purpose and scope-----	3
Acknowledgments-----	3
Location and background information-----	3
Geohydrology-----	4
Surface-water characteristics-----	12
Ground-water characteristics-----	17
Water balance-----	19
Potential effects of underground mining-----	21
Need for additional studies-----	24
Summary and conclusions-----	25
References cited-----	27

## PLATE

Plate 1. Map showing location of stream, reservoir, spring, and well sites in the Rapid Creek basin, Mesa County, Colorado-----	In pocket
---	-----------

## FIGURES

	Page
Figure 1. Map showing location of the Rapid Creek basin-----	2
2. Diagram showing system of numbering stream, spring, and well-measurement sites using township, range, and section-----	5
3. Map showing surficial geology-----	7
4. Diagram showing generalized geologic section-----	8
5. Diagrammatic geohydrologic section through unconsolidated deposits-----	11
6. Map showing overburden thickness above the Cameo coal zone of the Mesaverde Group-----	22

## TABLES

	Page
Table 1. Stream data and overburden thickness-----	13
2. Chemical analyses of water samples-----	15
3. Reservoir data and overburden thickness-----	16
4. Spring data and overburden thickness-----	18
5. Well data-----	20

## CONVERSION FACTORS

Inch-pound units used in this report may be converted to International System of Units (SI) by using the following conversion factors:

<i>Multiply inch-pound units</i>	<i>By</i>	<i>To obtain SI units</i>
inch (in.)	25.40	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square mile (mi <sup>2</sup> )	2.590	square kilometer
acre	0.4047	hectare
acre-foot (acre-ft)	1,233	cubic meter
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometers per year
foot per mile (ft/mi)	0.1894	meter per kilometer
inch per year (in./yr)	25.40	millimeter per year
foot per day (ft/d)	0.3048	meter per day
cubic foot per second (ft <sup>3</sup> /s)	0.02832	cubic meter per second
gallon per minute (gal/min)	0.06308	liter per second

To convert degree Fahrenheit (°F) to degree Celsius (°C), use the following formula:  $^{\circ}\text{C}=(^{\circ}\text{F}-32)\times 5/9$ . To convert degree Celsius (°C) to degree Fahrenheit (°F), use the following formula:  $^{\circ}\text{F}=(^{\circ}\text{C}\times 9/5)+32$ .

The following terms and abbreviations also are used in this report: microsiemens per centimeter at 25° Celsius ( $\mu\text{S}/\text{cm}$ ); and milligrams per liter (mg/L).

Altitudes discussed in the report are referenced to the National Geodetic Vertical Datum of 1929 (NGVD of 1929) which is defined as follows:

A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "Mean Sea Level."

GEOHYDROLOGY AND POTENTIAL HYDROLOGIC EFFECTS  
OF UNDERGROUND COAL MINING IN THE  
RAPID CREEK BASIN, MESA COUNTY, COLORADO

---

By Tom Brooks

---

ABSTRACT

The U.S. Bureau of Land Management may lease additional coal tracts in the Rapid Creek basin. Springs in this basin are used as a water supply for the town of Palisade. This report describes the geohydrology of the basin and summarizes the potential hydrologic effects of underground coal mining in the basin.

Geologic formations in the basin consist of Cretaceous sandstone and shale, Tertiary sandstone, shale, and basalt, and unconsolidated deposits of Quaternary age. Some sandstone and coal beds are permeable, although bedrock in the basin typically is a confining bed. Unconsolidated deposits contain aquifers that are the source of spring discharge.

Stream discharge was measured on Rapid and Cottonwood Creeks, and inventories were made of 7 reservoirs, 25 springs, and 12 wells. Specific conductance of streams ranged from 320 to 1,050 microsiemens per centimeter at 25° Celsius; pH ranged from 7.8 to 8.6. Specific conductance of springs ranged from 95 to 1,050 microsiemens per centimeter at 25° Celsius; pH ranged from 6.8 to 8.3.

Discharge from the basin includes about 18,800 acre-feet per year as evapotranspiration, 1,300 acre-feet per year as springflow, 1,280 acre-feet per year as streamflow, and negligible ground-water flow in bedrock. With appropriate mining methods, underground mining would not decrease flow in basin streams or from springs. The potential effects of mining-caused subsidence might include water-pipeline damage and temporary dewatering of bedrock adjacent to coal mining.

INTRODUCTION

Coal has been mined underground at the Roadside Mine (pl. 1) near Palisade (fig. 1) since 1907 (Schwochow, 1978), and production was accelerated beginning in 1974. The Powderhorn Coal Co. currently (1985) mines from Federal leases in the northern one-half of the Rapid Creek basin.

The U.S. Bureau of Land Management may consider leasing additional coal-mining tracts in the Rapid Creek basin (fig. 1). Springs in the basin are a supply of water for the town of Palisade, and consequently the effects of underground coal mining on the supply and quality of surface and ground

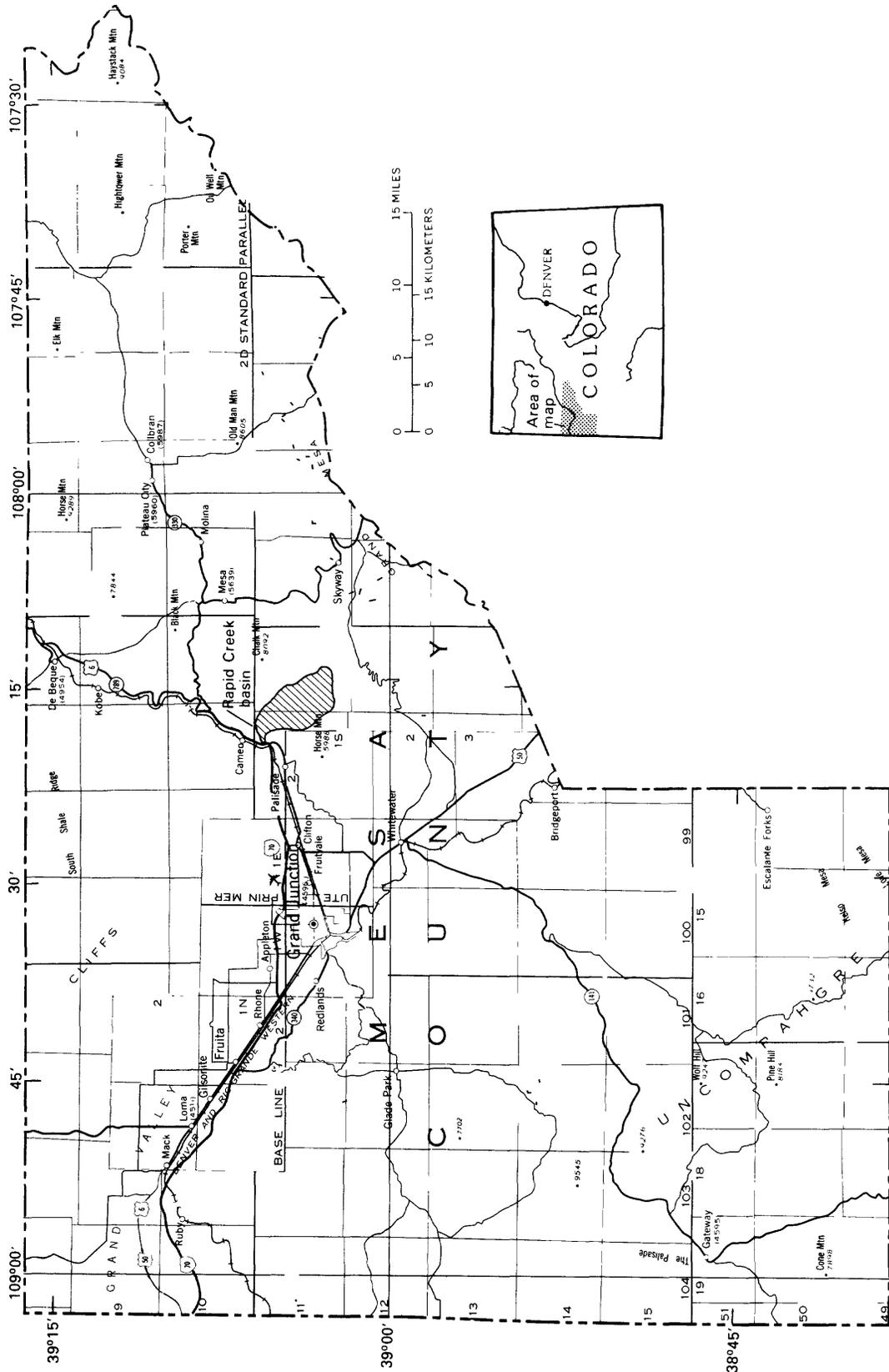


Figure 1.--Location of the Rapid Creek basin.

water in the basin need to be evaluated. The purpose of the study was to describe the geohydrology of the basin and summarize the potential hydrologic effects of underground coal mining in the basin.

Spring discharge in the Rapid Creek basin, and from Kruzen Springs outside the southern border of the basin, are the primary water sources for the town of Palisade, population 1,551 (U.S. Bureau of the Census, 1981). Because the study area is a municipal watershed, the U.S. Bureau of Land Management, in cooperation with the town of Palisade, would determine leasing suitability. These resources need to be protected from mining effects to insure a continued water supply. A better understanding of local geohydrology will help assess the suitability of additional coal leasing in the basin.

### Purpose and Scope

The purpose of this report is to provide data to describe the geohydrology of the Rapid Creek basin and to evaluate the potential effects of underground coal mining on the hydrology of the basin. Stream discharge was measured at six sites in the basin. In addition, 7 reservoirs, 25 springs, and 12 wells were inventoried. Water temperature, pH, and specific conductance (an indirect measure of dissolved-solids concentration) were measured at 10 stream sites, 6 reservoirs, and 24 springs. Stream discharge measurements were made using methods described by Rantz and others (1982). Chemical analyses were done for samples collected from two stream sites. Water-sampling and analysis were done using methods described by Skougstad and others (1979).

Data presented in this report were collected by the U.S. Geological Survey between May 1985 and September 1985. Additional data were provided by the Powderhorn Coal Co. and the town of Palisade.

### Acknowledgments

The Powderhorn Coal Co. provided stream-discharge data and well-log descriptions. Russell Goddard, Town Manager for Palisade, provided background information about streams, reservoirs, and springs in the basin.

Richard Dunrud of the U.S. Geological Survey, John Abel of the Colorado School of Mines, Allan Fejes of the U.S. Bureau of Mines, and Steven Renner of the Colorado Department of Natural Resources, Mined Land Reclamation Division, provided background information on subsidence.

## LOCATION AND BACKGROUND INFORMATION

The Rapid Creek basin (fig. 1), an area of about 21 mi<sup>2</sup>, is about 15 mi east of Grand Junction in western Colorado. Altitudes in the basin range from about 10,040 ft at the northern escarpment of Grand Mesa to 4,700 ft at the confluence of Rapid Creek and the Colorado River (pl. 1). The Rapid Creek basin contains streams, springs, reservoirs, and water pipelines that connect these sources to the town of Palisade.

Because of differences in altitude within the basin, precipitation ranges from about 10 to 30 in./yr (Colorado Climate Center, 1984). About two-thirds of the annual precipitation occurs as snowfall from October through April. Average monthly air temperatures at the town of Palisade, about 3 mi west of the Rapid Creek basin on the Colorado River, range from 28.3°F in January to 79.4°F in July for years 1951 through 1980 (National Climatic Data Center, 1984). Air temperature data are not available for higher altitudes in the basin.

Sagebrush and juniper are the most common vegetation in the lower part of the basin; scrub oak is common in mid-basin; aspen and spruce are common at higher altitudes. Some cottonwood trees grow along Rapid and Cottonwood Creeks.

Data-collection sites are shown on plate 1. On plate 1, stream sites are shown with letters, and springs and wells are shown with numbers. These letters and numbers are used throughout this report. The local identifier used in the tables in this report can be used to access additional data in WATSTORE, the U.S. Geological Survey's computer file of water-resources data. The local identifier is explained in figure 2.

## GEOHYDROLOGY

The surficial geology of the Rapid Creek basin is shown in figure 3; a generalized geologic section, from the top of Grand Mesa to near the Colorado River, is shown in figure 4. Rapid Creek basin is in the southwestern part of the Piceance Creek structural basin. Sedimentary rocks in the Rapid Creek basin dip about 3° to the northeast (Grancia and Johnson, 1980) and the geologic data in figure 4 indicate no structural gradient of the bedrock to induce much ground-water flow along the length of the basin, from A' to A in figure 3. Faults have not been encountered in the Roadside Mine (H. A. Barbe, Powderhorn Coal Co., oral commun., 1985) or mapped in the basin.

Stratigraphic units referred to in this report include (from oldest to youngest) the Mesaverde Group of Late Cretaceous age; Wasatch Formation, Green River Formation, an unnamed formation, and basalt of Tertiary age; and deposits of Quaternary age. Lithologic descriptions used in this report are from Fisher and others (1960), Yeend (1969), and Whitney (1981). Formation thicknesses are determined from data from two oil and gas wells drilled near the southern border of the basin at sites 36 and 37 (pl. 1).

Interpretations of the water-bearing characteristics of bedrock and unconsolidated deposits are based on lithologic and structural conditions in the basin and data for similar rocks near the study area. Geohydrologic data and characteristics are summarized in the explanation for figure 3.

The Mesaverde Group, which is about 2,900-ft thick in the Rapid Creek basin, includes the Mount Garfield Formation in the lower part of the Mesaverde Group and the Hunter Canyon Formation in the upper part of the upper Mesaverde Group. The Mount Garfield and Hunter Canyon Formations are undifferentiated in this report because the formations are transitional and the division between them is arbitrary (Erdmann, 1934). The Mesaverde Group

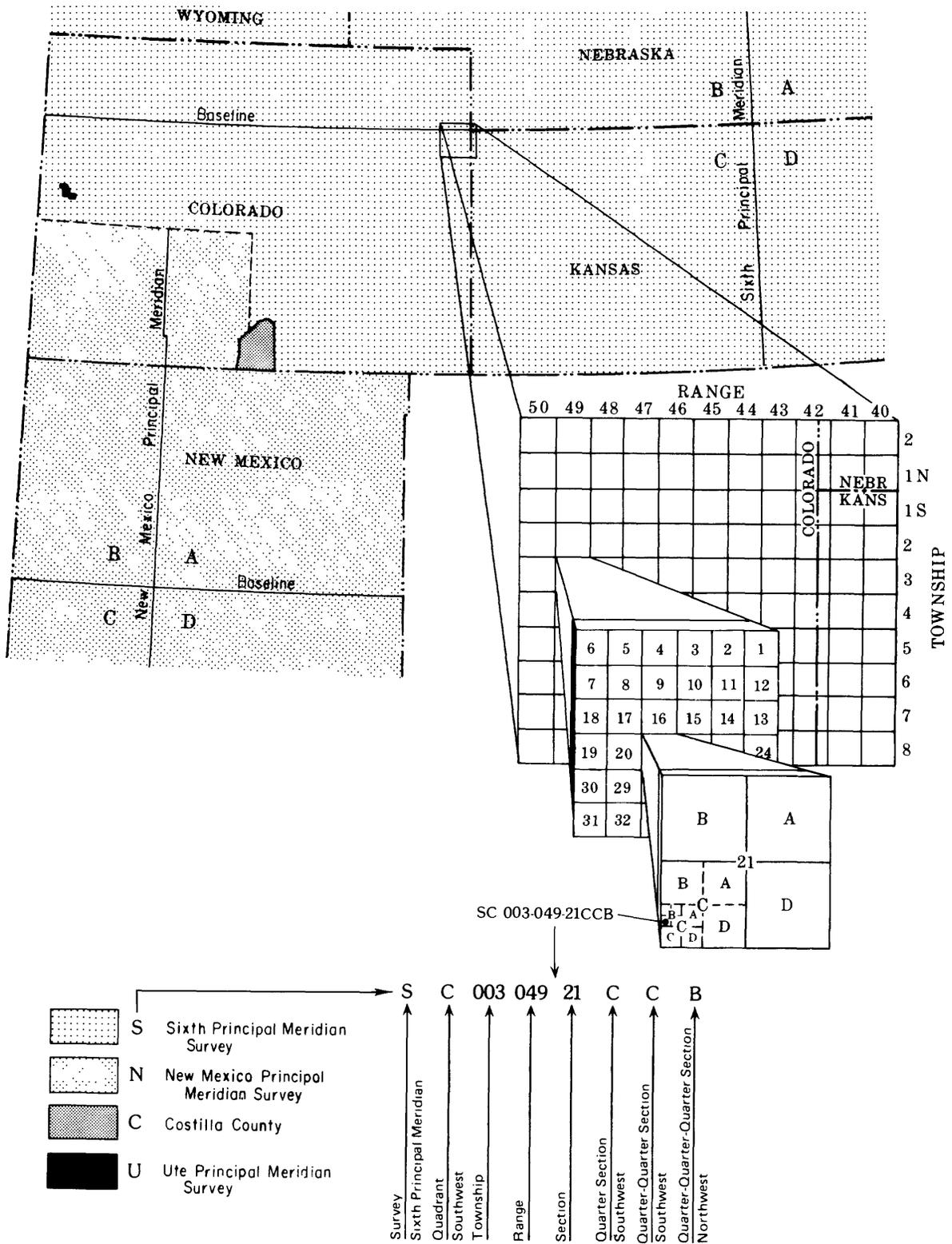


Figure 2.--System of numbering stream, spring, and well-measurement sites using township, range, and section.

EXPLANATION FOR FIGURE 3

Erathem	System and series	Geologic unit (map symbol in figure 3)	Maximum thickness (feet)	Lithology	Geohydrologic characteristics		
CENOZOIC	QUATERNARY	Alluvium (Qa)	10	Clay, silt, sand, and gravel; typically poorly sorted.	Hydraulic conductivity ranges from 20 to 450 feet per day.		
		Gravel (Qg)	40	Well-sorted pebbles, cobbles, and boulders in a sandy matrix.	Hydraulic conductivity is similar to alluvium and perhaps larger, dependent on sorting and compaction.		
		Landslide deposits (Ql)	?	Slumped deposits, debris flows, earthflows, rock-falls, and rock-topple deposits.	Hydraulic conductivity is expected to be as much as 1,000 feet per day but greatly variable.		
		Till (Qt)	10	Unsorted deposits from clay to boulder size.	Hydraulic conductivity is least of unconsolidated deposits.		
	TERTIARY	Basalt	230	Ranges from dense basalt-flow centers to weathered surfaces between flows.	Most ground-water flow would be between basalt flows.		
		Unnamed formation	400	Gravel, shale, and clay.	Most ground water would be in gravel.		
		Green River Formation (Tg)	1,400	Sandstone, freshwater marlstone, and shale. Grain size ranges from fine silt to medium sand.	Generally a confining bed with larger permeability in sandstone. Hydraulic conductivity ranges from 0.01 to 1 foot per day for sandstone and much less for marlstone and shale.		
		Wasatch Formation (Tw)	1,000	Fluvial and lacustrine clay with some sandstone and marine limestone. Grain size ranges from from clay to coarse silt.	Generally a confining bed although hydraulic conductivity for sandstone ranges from 1-10 feet per day.		
		MESOZOIC	UPPER CRETACEOUS	Mesaverde Group; undifferentiated includes Hunter Canyon and Mount Garfield Formations (Kmv)	2,900	Lenticular sandstone, marine claystone, mudstone, and coal; proportionally more sandstone and thinner coal in upper part of formation.	Generally a confining bed except for lenticular sandstone, coal, or fractured rock. Average hydraulic conductivity was 0.11 foot per day for coal, 0.007 foot per day for shale and sandstone above the coal, and 16.63 feet per day for fractured sandstone. Vertical hydraulic conductivity through the rock above the coal was 0.00007 foot per day. These values were from tests, 30 miles west of the Rapid Creek basin.

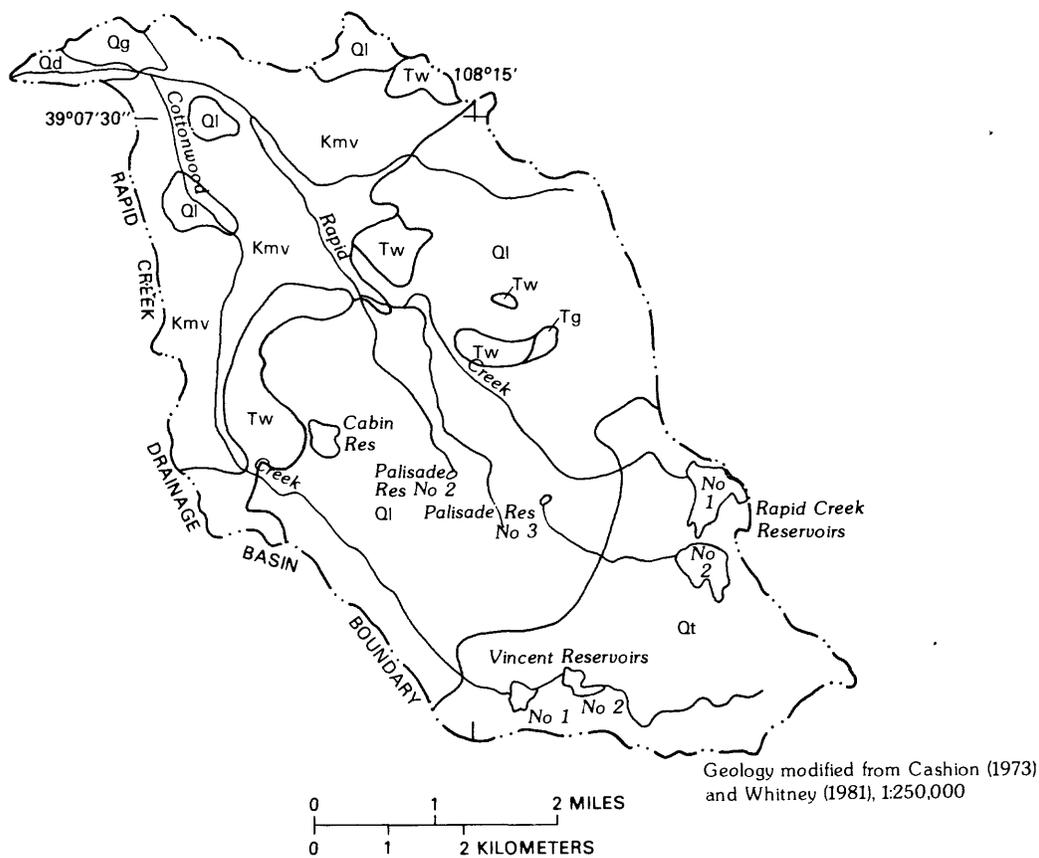


Figure 3.--Surficial geology.

includes sandstone, marine claystone, mudstone, and coal. The Mount Garfield Formation contains major coal seams and forms slopes where it is exposed, whereas, the Hunter Canyon Formation contains fewer and thinner coal seams and forms cliffs where it is exposed because it contains proportionally more sandstone.

Coal zones and associated members of the Mount Garfield Formation are in the lower 700 ft of the Mesaverde Group and include (in ascending order) the Corcoran Sandstone Member, Cozzette Sandstone Member, Palisade coal zone, Rollins Sandstone Member, Cameo coal zone, and Carbonera coal zone. The greatest reserves in the Palisade coal zone are west of the Colorado River; they likely are too thin to mine in the Rapid Creek basin. Coal currently (1985) is mined in the Rapid Creek basin from the 6- to 10-ft thick Cameo coal zone.

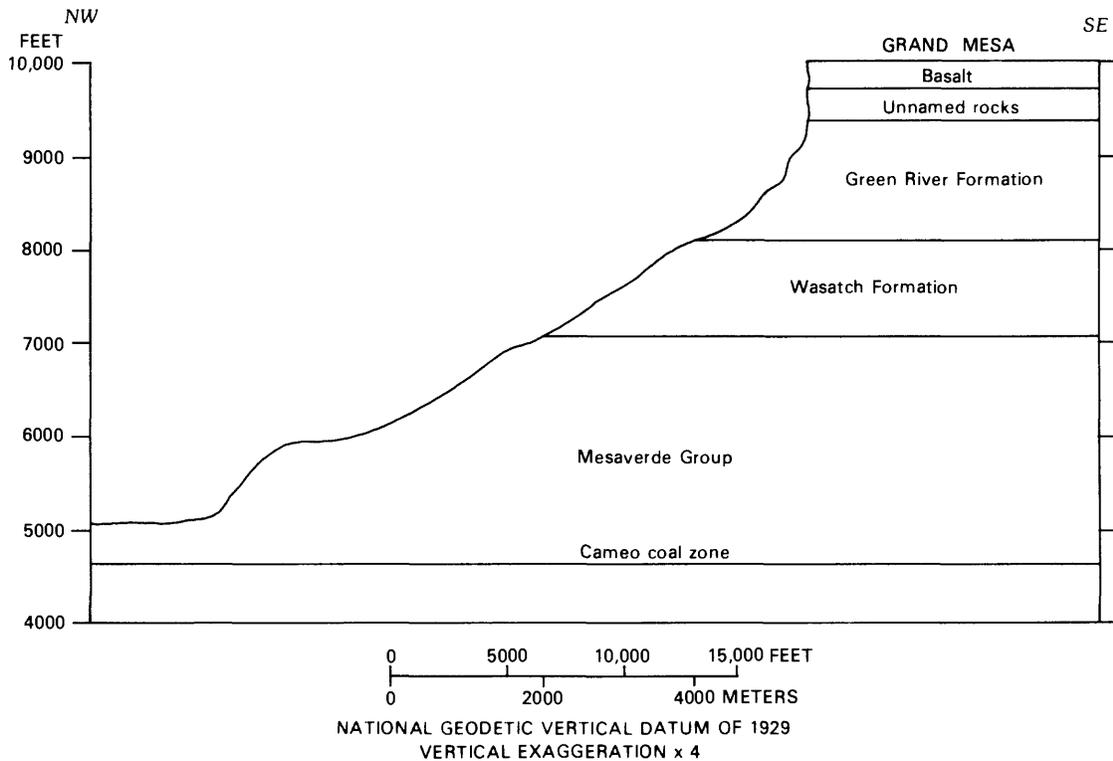


Figure 4.--Generalized geologic section.

The Carbonera coal zone is 40 to 100 ft above the Cameo coal zone. During 1985, the Powderhorn Coal Co. drilled wells (sites 26 through 35 on pl. 1) that penetrated about 16 ft of the Carbonera coal zone. It includes shale and coal with a 5-in. thick bentonitic clay zone, which swells when saturated. The Carbonera coal zone is in the Grand Mesa coal field east of the Colorado River and the zone has not been mined because drill-hole data indicate that the Carbonera coal zone splits into thinner coal seams.

Most precipitation falling on bedrock becomes runoff because the rock is dense and the slopes are steep, allowing little opportunity for infiltration. This is especially true for the steep sandstone canyons formed by the Mesaverde Group. Although the Mesaverde Group and other bedrock is considered to have minimal hydraulic conductivity, some infiltration and storage certainly has occurred in these 10- to 80-million-year-old rocks over geologic time. Small inflow into the Roadside Mine is from above, in, and beneath the Cameo coal zone. Water was measured in the coal-exploration holes drilled by the Powderhorn Coal Co. in 1985; wells completed in these rocks would yield little water. No springs discharge from the Mesaverde Group in the sandstone canyons, indicating little ground-water movement into these canyons.

J.F. Sato and Associates, Inc. (1983) did slug-type aquifer tests about 30 mi west of the Rapid Creek basin in the Bookcliffs coal field, and they reported that the average hydraulic conductivity of the Mesaverde Group was

0.11 ft/d for coal, 0.007 ft/d for shale and sandstone above the coal, and 16.63 ft/d for fractured sandstone. The reported vertical hydraulic conductivity of shale and sandstone above the coal was 0.00007 ft/d.

The Wasatch Formation is about 1,000-ft thick in the Rapid Creek basin and includes stream- and lake-deposited clay with some sandstone and marine limestone. The dominant range of grain size is from clay to coarse silt (Johnson and May, 1978). There are sandstone zones near the middle of the Wasatch Formation which are more permeable; however, thick claystone and mudstone above and below the zones retard recharge to the sandstone. Based on its lithology, the Wasatch Formation is a confining bed. No wells are completed in the formation in or near the study area. Hydraulic conductivity for sandstone in the Wasatch Formation ranges from 1 to 10 ft/d (R.T. Hurr, U.S. Geological Survey, oral commun., 1985) and much less for the more common claystone and fine-grained rock.

The Green River Formation in the Rapid Creek basin is about 1,400-ft thick; it includes sandstone, freshwater marlstone, and shale. The dominant range of grain size is from fine silt to medium sand (Johnson and May, 1978). The Green River Formation typically is a confining bed. Hydraulic conductivity is greater for sandstone and may range from 0.01 to 1 ft/d and much less for marlstone and shale (R.T. Hurr, U.S. Geological Survey, oral commun., 1985). The driller's log for site 36 reports circulation losses while drilling through the Green River Formation, likely in sandstone.

The unnamed formation above the Green River Formation may be as much as 400-ft thick; it includes gravel, shale, and clay. J.R. Donnell (U.S. Geological Survey, oral commun., 1985) measured about 100 ft of this formation at Lands End, 2 mi south of the southeastern limit of the Rapid Creek basin, and about 400 ft at Mesa Lakes, about 5 mi east of the southeastern limit of the Rapid Creek basin. Donnell's lithologic description included river gravel, possibly from the ancestral Gunnison River, and red shale. The ability of the unnamed formation to transmit water is a function of lithology, which is variable. Significant ground-water movement and storage are much more likely in gravel and sandstone than in shale and other fine-grained zones in this rock.

The sedimentary rocks underlying Grand Mesa have been protected from erosion by a 230-ft thick series of basalt flows in the headwaters of the Rapid Creek basin. Each basalt flow typically has: (1) An erosional surface at the bottom of the flow; (2) more dense basalt toward the center of the flow; and (3) another erosional surface at the top of the flow. The erosional surfaces, referred to as interflow zones, are more permeable than the dense basalt toward the center of the flow and are the principal ground-water flow paths in the basalt.

Wells at sites 36 and 37 (pl. 1) were drilled through basalt in the southern part of the Rapid Creek basin, although they were cased through the basalt and do not provide water-level data. The basalt that caps Grand Mesa contains water. Recharge to basalt is through the poorly sorted glacial till mantle and the dense basalt at the center of each flow. Lateral ground-water movement occurs in interflow zones.

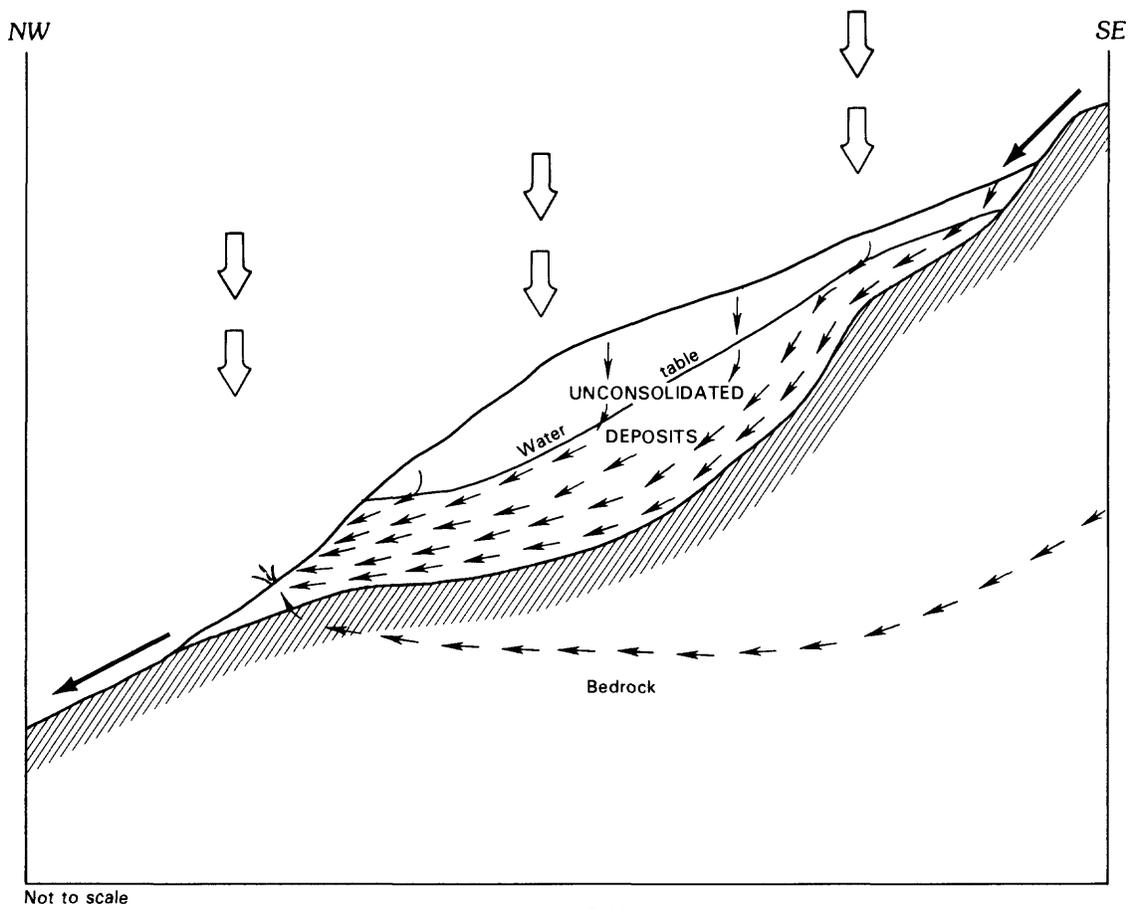
Deposits of Quaternary age are unconsolidated and include: (1) Glacial till overlying basalt at the highest part of the basin; (2) landslide deposits high in the basin; (3) gravel in the lower part of the basin; and (4) alluvium in Rapid and Cottonwood Creeks and at the junction of Rapid Creek and the Colorado River (Whitney, 1981). Till includes unsorted glacial-derived material ranging from clay to boulder-sized rock; the upper 6 ft usually is weathered. Landslide deposits are formed by slumping, debris flow, earthflow, rockfall, and rock toppling. Slumping is caused by slope failure, mostly in the shaly Green River Formation, and in weak sandstone, siltstone, and shale of the Wasatch Formation. Gravel typically underlies stream terraces; it includes well-sorted pebbles, cobbles, and boulders in a sandy matrix. Gravel may underlie alluvium and windblown sand. Alluvium includes clay, silt, sand, and gravel underlying modern flood plains. Alluvium in Rapid Creek, Cottonwood Creek, and tributary canyons typically is thin and is poorly sorted.

Unconsolidated deposits transmit most of the ground water in the Rapid Creek basin; ground-water flow within these deposits is limited by the extent of the deposits. Unconsolidated-deposit slopes are less steep than bedrock slopes and have a much better potential for recharge. Most precipitation that infiltrates into and through unconsolidated deposits on the flanks of Grand Mesa discharges to streams or springs near or above the top of the Mesaverde Group. All springs diverted by the town of Palisade are above 6,820 ft and are recharged at higher altitudes. There is some ground-water flow in alluvium and landslide deposits in the lower sandstone canyons. The hydraulic conductivity of unconsolidated deposits is dependent on grain size, sorting, and compaction. The hydraulic conductivity of unconsolidated deposits may be as much as four orders of magnitude larger than that of bedrock, indicating little water movement between unconsolidated deposits and bedrock. Generalized ground-water flow paths in unconsolidated deposits in the Rapid Creek basin are shown in figure 5. Most ground water in the Rapid Creek basin flows in shallow, short flow paths rather than deep, regional flow paths. Deeper ground water in the bedrock formations has larger concentrations of dissolved solids and it primarily discharges to the Colorado River or beyond.

Glacial till overlying basalt on Grand Mesa is poorly sorted and supports shallow ponds and reservoirs that usually are dry by late summer. The hydraulic conductivity of till is small because of poor sorting. The hydraulic conductivity of landslide deposits may be as large as 1,000 ft/d. No data are available for hydraulic conductivity of gravel deposits in the study area, but they are likely similar or larger than that of the Colorado River deposits. Hydraulic conductivity of Colorado River alluvium ranges from 20 to 450 ft/d (W.A. Phillips, U.S. Bureau of Reclamation, oral commun., 1985).

The general ground-water flow system in the Rapid Creek basin is summarized as follows:

1. Precipitation falls on the rubble bedrock in the upper part of Rapid Creek basin;
2. Water infiltrates into the rubble;
3. Ground water moves down valley within the rubble;
4. Infiltrated water mixes with smaller quantities of ground water contributed by the Wasatch and Green River Formations that contain larger concentrations of dissolved solids; and
5. Ground water discharges near bedrock contacts such as sites C and I (pl. 1).



Not to scale

EXPLANATION

-  PRECIPITATION
-  SURFACE-WATER FLOW
-  GROUND-WATER FLOW

Figure 5.--Geohydrologic section through unconsolidated deposits.

## SURFACE-WATER CHARACTERISTICS

Cottonwood Creek is a major tributary of Rapid Creek. Oak Springs Creek is tributary to Rapid Creek, joining it at site F (pl. 1). Oak Springs Creek typically is dry by September. It was flowing during October 1985 because of greater than normal precipitation from 1983 to 1985. Stream sites where stream discharge, pH, specific conductance, and water temperatures were measured are shown on plate 1.

Stream channels in the basin contain cobbles, gravel, silt, and sand. The stream gradient from the Rapid Creek Reservoir No. 1 outlet, on the top of Grand Mesa, near the basalt escarpment, to the confluence with the Colorado River is 750 ft/mi. The gradient of the headwaters of Rapid Creek on top of the basalt-capped mesa is much less, about 20 ft/mi.

About three-quarters of the annual runoff occurs during the snowmelt period from April through July; peak flow generally occurs from late May through early June. Stream discharge in Rapid Creek near its junction with the Colorado River is measured by gages operated by the Powderhorn Coal Co. Their records are incomplete but stream discharge was estimated to be about 1,280 acre-ft for the 1981 water year.

Gain-and-loss measurements of stream discharge were made at three sites on Rapid Creek, one site on Oak Springs Creek, and two sites on Cottonwood Creek (table 1). Data indicate slight downstream gains of flow in all reaches. The accuracy of the stream-discharge measurements was rated fair to poor because calcite cementation and cobbles and boulders caused the streambed to be irregular, making it difficult to find good measurement sections. Therefore, stream-discharge variation of less than 10 percent between measurements was considered not significant. Stream discharge in Rapid Creek downstream from its junction with Cottonwood Creek totaled 1.15 ft<sup>3</sup>/s, the sum of Rapid Creek and Cottonwood Creek discharges upstream from the junction.

The slope of the land surface from the Mesaverde Group contact, near sites C and I, to the Grand Mesa basalt escarpment is less in the Rapid Creek drainage than in the Cottonwood Creek drainage. Landslides have undercut more of the basalt-capped Grand Mesa at the upper part of the Rapid Creek drainage than in the upper part of the Cottonwood Creek drainage. Thus, more rubbled bedrock is present from landslides and slope failures in the upper part of the Rapid Creek drainage than in the upper part of the Cottonwood Creek drainage. This lesser gradient allows more precipitation to infiltrate and, as a result, more recharge occurs to deposits in the upper Rapid Creek drainage than in the upper Cottonwood Creek drainage. Therefore, ground water likely constitutes a larger part of the flow in Rapid Creek than in Cottonwood Creek, as indicated by larger concentrations of dissolved solids in Rapid Creek than in Cottonwood Creek.

Water temperature, pH, and specific conductance were measured at stream sites. Specific conductance was larger in Rapid Creek than in Cottonwood Creek. Specific conductance in Rapid Creek ranged from 400 to 760  $\mu$ S/cm, increasing downstream with an anomalous measurement of 1,050  $\mu$ S/cm at site C. The greater specific conductance at site C probably is caused by the discharge of several springs in the streambed that precipitate calcite. Water in

Table 1.--Stream data and overburden thickness

[--, no data]

Letter on plate 1	Local identifier (see figure 2)	Stream name	Discharge (cubic feet per second)	Water temperature (degrees Celsius)	pH	Specific conductance (microsiemens per centimeter at 25° Celsius)	Date measured	Overburden thickness above Cameo coal zone (feet)
A	SC01109721AAD1	Rapid Creek at uppermost Palisade diversion.	--	--	--	--	--	3,400
B	SC01109716CCB1	Rapid Creek at middle Palisade diversion.	--	12.0	8.1	400	07-17-85	2,500
C	SC01109708CDB1	Rapid Creek at lowest Palisade diversion.	--	17.0 11.5	8.0 7.9	1,050 1,000	07-18-85 09-04-85	1,800
D	SC01109707ABB1	Rapid Creek at Powderhorn Coal Co. stream gage.	0.25	6.0	8.5	530	09-24-85	1,200
E	SC01109706BBC1	Rapid Creek upstream from junction with Oak Springs Creek.	0.33	7.5	8.5	540	09-24-85	800
F	SC01109706BBC2	Oak Springs Creek at mouth.	0.39	8.5	8.6	925	09-24-85	800
G	SC01109801BBA1	Rapid Creek upstream from junction with Cottonwood Creek.	0.79	9.0	8.6	760	09-24-85	300
H	SC01109719DBA1	Cottonwood Creek at uppermost Palisade diversion.	--	11.5	8.4	320	07-17-85	1,800
I	SC01109819BDA1	Cottonwood Creek at middle Palisade diversion.	--	10.5 8.0	7.8 8.0	445 440	09-04-85 09-24-85	1,600
J	SC01109824ADA1	Cottonwood Creek at lowest Palisade diversion.	--	12.5	8.1	340	07-18-85	1,400
K	SC01109801BBA2	Cottonwood Creek upstream from junction with Rapid Creek.	0.36	11.5	8.5	640	09-24-85	300

landslide deposits typically discharges to the streams near where the landslide deposits overlie the Mesaverde Group. This is most evident at site C where springs discharge to the streambed. The ground water flows less than 4 mi through landslide deposits from the basalt escarpment to the head of the sandstone canyons formed by the Mesaverde Group. In these 4 mi, the water dissolves soluble minerals from the unconsolidated Green River and Wasatch Formations and transmits them in solution. The specific-conductance measurement at site C represents mineralized ground water entering the stream that is still in inequilibrium. Chemical equilibrium returns by the time streamflow reaches site D. Specific conductance in Cottonwood Creek increased downstream, and ranged from 320 to 640  $\mu\text{S}/\text{cm}$ .

There was no stream discharge about 100 ft upstream from site C in October 1985. Calcite has precipitated where water from the rubbled Green River and Wasatch Formations enters Rapid Creek at site C. The calcite precipitate has cemented the streambed, creating small waterfalls near and downstream from site C. This sudden and localized increase of stream discharge and specific conductance near the upper contact of the Mesaverde Group indicates that this location is a principal ground-water discharge site.

The town of Palisade has three water-system intakes on Cottonwood Creek at sites H, I, and J. Specific-conductance measurements of 320  $\mu\text{S}/\text{cm}$  at site H and 340  $\mu\text{S}/\text{cm}$  at site J in July 1985 indicate that water quality did not change across the Mesaverde Group contact in the Cottonwood Creek drainage. This lack of change is likely the result of less rubble and landslide deposits in the upper drainage of Cottonwood Creek compared to Rapid Creek. The Wasatch and Green River Formations may contribute more flow to Rapid Creek. Specific conductance at site I was 440  $\mu\text{S}/\text{cm}$  and specific conductance at site K was 640  $\mu\text{S}/\text{cm}$  when these sites were measured in September 1985.

Water-quality samples were collected at sites C and I and analyzed by the U.S. Geological Survey central laboratory in Lakewood, Colorado (table 2). Sites C and I were chosen because these are the primary stream intakes for the town of Palisade. The analyses indicated that water at site I in Cottonwood Creek was of suitable quality for domestic use, although surface water generally requires more treatment for biota and turbidity than does spring water. The dominant ions in water from Cottonwood Creek were calcium and bicarbonate. The dominant ions from site C in water from Rapid Creek were calcium, sodium, bicarbonate, and sulfate. Concentrations of dissolved solids in Rapid Creek at site C exceeded U.S. Environmental Protection Agency's proposed (1983) standards for secondary maximum contaminant levels of public drinking waters.

Reservoirs store water in the Rapid Creek basin and sustain stream and spring discharge. Reservoir water infiltrates through permeable soils, rubbled bedrock, and fractured rock underlying the reservoirs, and discharges at lower altitudes to streams and springs. The location of each reservoir is shown on plate 1 and reservoir data are given in table 3.

Rapid Creek Reservoirs No. 1 and 2 are used for irrigation. Rapid Creek Reservoir No. 2 drains into Palisade Reservoir No. 3 during the spring. Vincent Reservoirs No. 1 and 2 typically are dry by late summer. Palisade Reservoir No. 2 is used for water storage without pipeline outlets; it

Table 2.--*Chemical analyses of water samples*

[Dissolved concentrations in milligrams per liter unless otherwise noted]

Characteristic	Site C (see plate 1)	Site I (see plate 1)
Sample source	Rapid Creek	Cottonwood Creek
Date of sample	Sept. 4, 1985	Sept. 4, 1985
Water temperature (degrees Celsius)	11.5	10.5
pH (units)	7.9	7.8
Specific conductance (microsiemens per centimeter at 25° Celsius)	1,000	445
Dissolved solids	651	286
Hardness'	430	240
Potassium	3.6	2.6
Calcium	99	60
Magnesium	45	22
Sodium	71	13
Chloride	15	6.1
Fluoride	0.4	0.3
Alkalinity	388	210
Nitrogen (nitrite plus nitrate)	0.43	Less than 0.1
Sulfate	150	29
Arsenic	0.004	0.002
Boron	0.06	0.02
Cadmium	Less than 0.001	Less than 0.001
Chromium	Less than 0.01	Less than 0.01
Copper	0.006	0.002
Iron	0.004	0.021
Lead	0.002	0.001
Manganese	0.006	0.013
Selenium	0.001	Less than 0.001
Silica	32	27
Zinc	0.029	0.008
Sodium-adsorption ratio	1.6	0.4
Percent sodium	26	10.

typically is dry by late summer. Palisade Reservoir No. 3 has not held water since 1983 because of damage to the headgate, but prior to this held water through the year.

Cabin Reservoir is the primary water storage for the town of Palisade; water pipelines connect it to springs, streams, and water-treatment facilities lower in the basin. This reservoir has a surface area of about 25 acres and can hold as much as 1,000 acre-ft of water. Inflow is from streams and springs in the upper part of the Rapid Creek basin, and from Kruzen Springs outside the basin.

Conditions associated with reservoir location affect the quality of reservoir water. Reservoir water overlying glacial till and basalt on Grand

Table 3.--Reservoir data and overburden thickness

[--, no data]

Reservoir name	Ownership and description	Maximum water-surface altitude (feet)	Water temperature (degrees Celsius)	pH	Specific conductance (microsiemens per centimeter at 25° Celsius)	Date water quality measured	Overburden thickness above coal zone (feet)
Rapid Creek No. 1	Owned by Richard Lloyd	9,940	19.5	6.8	30	07-01-85	4,400
Rapid Creek No. 2	Owned by Richard Lloyd	9,940	17.0	8.1	30	07-01-85	4,400
Vincent No. 1	Owned by the town of Palisade; dam removed and reservoir drained in 1985.	9,900	22.0	6.4	55	06-28-85	4,000
Vincent No. 2	Owned by the town of Palisade; dam removed and reservoir drained in 1985.	9,910	18.0	6.3	60	06-28-85	4,200
Palisade No. 2	Owned by the town of Palisade.	7,990	21.0	8.4	170	07-02-85	2,500
Palisade No. 3	Owned by the town of Palisade; dry in 1985.	8,310	--	--	--	--	3,000
Cabin	Owned by the town of Palisade; controlled inflow and outflow.	7,500	17.0	8.2	240	07-02-85	1,800

Mesa generally was slightly acidic (pH values of 6.3, 6.4, and 6.8); reservoir water below the basalt escarpment and underlain by rubble bedrock was slightly basic (pH values of 8.2 and 8.4). Snowmelt and rain have pH values of about 5, and water from these sources fills the reservoirs on the top of Grand Mesa. Reservoir water on the mesa top also has less chemical-reaction time with the less-alkaline basalt and glacial till, so there is less opportunity for buffering and for mineral solution. Reservoir water lower in the basin has traveled longer distances overland and, therefore, it has had a longer effective contact time with rock and soils. Runoff entering the lower reservoirs flows over weathered and more basic or alkaline rock of the Green River and Wasatch Formations, which increases the pH of surface water.

The specific conductance of reservoir water was less for reservoirs on Grand Mesa than for reservoirs on the flanks of the Mesa. Reservoir water on the top of Grand Mesa had specific-conductance values of less than 100  $\mu\text{S}/\text{cm}$ . Reservoir water on the flanks of the mesa had specific-conductance values of 170 and 240  $\mu\text{S}/\text{cm}$ . These reservoirs contain water that has traveled over or through the rubble Green River and Wasatch Formations, with greater opportunity for mineral dissolution.

#### GROUND-WATER CHARACTERISTICS

Springs in the Rapid Creek basin and Kruzen Springs (sites 23, 24, and 25) near the basin (pl. 1), supply nearly all the water required by the town of Palisade and supply the Roadside Mine with water for drinking and showers. Palisade's water system is described in a report by Henningson, Durham, and Richardson, Inc. (1979).

During 1984, the town of Palisade diverted about 1,520 acre-ft of discharge from springs in the Rapid Creek basin, and about 220 acre-ft of discharge from Kruzen Springs, adjacent to the basin (W.R. Goddard, Town Manager, Palisade, Colorado, oral commun., 1985). Discharge from 25 springs (table 4) flow through pipelines to Cabin Reservoir or directly to the Palisade water-treatment plant. Excess spring discharge is diverted to Cabin Reservoir and used in late summer and fall to augment decreased spring discharge.

All inventoried springs (table 4) in the Rapid Creek basin are above 6,800 ft; they discharge from landslide, land-creep, and alluvium deposits and nearly all are perennial. No springs have been enlarged by excavating bedrock (W.R. Goddard, Town Manager, Palisade, Colorado, oral commun., 1985). Big Spring (site 9), Crystal Spring (site 12), and Kruzen Springs have the largest observed discharge in the Palisade watershed. Concrete shells encase the springs and the springs discharge into water pipes, buried at shallow depth or lying on the land surface. The construction design of the spring enclosures prevented spring-discharge measurements from being made.

The range of pH measurements for spring water in the watershed was 6.8 to 8.3 and the median was 7.4. The range of specific-conductance measurements was 95 to 1,050  $\mu\text{S}/\text{cm}$  and averaged about 420  $\mu\text{S}/\text{cm}$ . The specific conductance of spring water generally increased at lower altitudes in the basin because of longer flow paths and increased contact time of ground water with minerals.

Table 4.--Spring data and overburden thickness  
[--, no data]

Number on plate 1	Local identifier (see figure 2)	Land surface altitude, approx- imate (feet)	Water temper- ature (degrees Celsius)	pH	Specific conductance (microsie- mens per centimeter at 25° Celsius)	Date measured	Overburden thickness above Cameo coal zone (feet)
1	SC09701121DDA1	8,690	4.5	7.9	190	07-16-85	3,200
2	SC09701121ADC1	8,590	5.0	7.3	460	07-16-85	3,200
3	SC09701121ACA1	8,430	5.5	7.4	540	07-16-85	3,100
4	SC09701121BDD1	8,365	6.5	8.1	370	07-16-85	3,000
5	SC09701121BDD2	8,365	4.0	7.5	280	07-16-85	3,000
6	SC09701121BDD3	8,365	4.5	7.5	280	07-16-85	3,000
7	SC09701121BCA1	8,165	7.0	7.8	340	07-17-85	2,700
8	SC09701121BCB1	8,080	4.5	7.8	400	07-17-85	2,700
9	SC09701120DAA1	8,280	4.0	7.6	130	07-17-85	2,700
10	SC09701120AAB1	7,960	15.5	8.3	235	07-17-85	2,500
11	SC09701120AAB2	7,960	--	--	--	--	2,500
12	SC09701117DDA1	7,790	6.5	7.1	410	07-17-85	2,400
13	SC09701117DDC1	7,760	7.0	7.2	380	07-17-85	2,400
14	SC09701117DDC2	7,760	7.0	7.2	330	07-17-85	2,400
15	SC09701117DDC3	7,780	7.0	7.4	410	07-17-85	2,400
16	SC09701117DCA1	7,675	12.5	7.9	435	07-17-85	2,300
17	SC09701119BDA1	7,200	7.0	6.9	390	07-18-85	1,600
18	SC09701119BDA2	7,240	7.0	6.8	380	07-18-85	1,600
19	SC09701108CCA1	6,920	8.0	7.2	1,050	07-18-85	1,700
20	SC09701108CCA2	6,920	8.5	7.4	800	07-18-85	1,700
21	SC09701108CCA3	6,900	8.5	7.2	1,050	07-18-85	1,700
22	SC09701108CCA4	6,820	9.0	7.5	750	07-18-85	1,600
23	SC09701132ABB1	9,120	5.0	7.3	95	07-19-85	3,600
24	SC09701129CDD1	9,030	3.5	7.2	150	07-19-85	3,200
25	SC09701129CDD2	9,030	3.5	7.2	150	07-19-85	3,200

Specific conductance of 19 springs in the Rapid Creek drainage averaged 465  $\mu\text{S}/\text{cm}$ ; specific conductance of 5 springs in the Cottonwood Creek drainage averaged 233  $\mu\text{S}/\text{cm}$ .

The water-level altitudes were too irregular to be contoured, although the range from 5,510 to 5,820 ft above sea level does indicate a general northeast direction of water movement in the Mesaverde Group. The well data also indicate that any water in the Rollins Sandstone Member of the Mount Garfield Formation of the Mesaverde Group, likely is not under large pressure in the basin. This indicates that the direction of ground-water movement in the Mesaverde Group is primarily controlled by the structure of the formation, to the northeast and the Colorado River.

The town of Palisade may develop additional water sources by 1995, probably in areas on Grand Mesa adjacent to the Rapid Creek basin (Henningson, Durham, and Richardson, Inc., 1979).

The Powderhorn Coal Co. drilled 10 observation holes in June, July, and August 1985. Each hole was drilled into the Mesaverde Group to the Rollins Sandstone Member. These holes were drilled to aid in mine design as mining progresses into these areas. Water levels were measured in the uncased holes (table 5) before the holes were sealed. The location of each hole is shown on plate 1.

Drilling logs for exploration holes typically indicated that the holes penetrated sandstone and shale, with proportionally more sandstone toward the upper part of the Mesaverde Group. About 4 in. of bentonitic clay consistently was penetrated by drilling through the upper Carbonera coal zone above the Cameo coal zone. This clay swelled and sealed one hole after drilling was completed, preventing a water-level measurement. Drilling in shale was difficult, because fractures caused hole failure. Coal zones typically were between shale layers.

Depth to water in the exploration holes was measured using a resistivity geophysical tool, usually within 3 days of drilling completion. These measured water levels may not be the true potentiometric surface because the hydraulic-head potential may not have reached equilibrium during the 3 days because of the minimal hydraulic conductivity of the rocks. Saturated zones were noted during drilling but completed holes were dry, indicating that these zones produced little water.

#### WATER BALANCE

Most water derived from precipitation is evaporated from moist soils, ponds, and streams, and is transpired by plants. Some water percolates downward through unconsolidated deposits and discharges from these deposits at the bedrock contact. Some water may travel across the contact of unconsolidated deposits and bedrock. A small part of the water in unconsolidated deposits percolates into the underlying bedrock and discharges further down basin and northeastward.

Sources of recharge to the Rapid Creek basin include:

1. Precipitation.
2. Ground-water inflow.

Sources of discharge from the Rapid Creek basin include:

1. Evapotranspiration.
2. Stream discharge.
3. Spring diversions to the town of Palisade.
4. Ground-water outflow.

Table 5.--Well data

[--, no data]

Number on plate 1	Local identifier (see figure 2)	Land surface altitude (feet)	Hole depth (feet)	Water level (feet)	Date water level measured	Remarks
26	SC01109811AAB1	5,434	191	Dry	06-17-85	
27	SC01109811DBD1	5,720	520	Dry	06-13-85	Yields of as much as 5 gallons per minute between 270-280 feet, although completed well was dry.
28	SC01109811DCD1	5,913	283	5,733	06-20-85	
29	SC01109812BDD1	5,940	650	5,510	06-20-85	
30	SC01109812CAA1	6,016	710	5,584	06-20-85	Yields of as much as 7 gallons per minute; first water at about 560 feet.
31	SC01109812CDB1	6,931	1,483	5,576	07-15-85	Fractured shale.
32	SC01109812DCB1	7,021	1,585	--	07-20-85	Clay in Carbonera coal zone sealed hole after drilling completed.
33	SC01109813BAA1	6,908	1,544	5,530	07-27-85	
34	SC01109813BCD1	7,218	1,595	5,714	08-10-85	
35	SC01109813CDC1	7,284	1,524	5,820	08-14-85	
36	SC01109726CDB1	9,994	2,755	--	--	Oil and gas well used for stratigraphic thickness.
37	SC01109726DBA1	9,991	10,064	--	--	Oil and gas well used for stratigraphic thickness.

The minimal hydraulic conductivity of bedrock in the basin indicates that any ground-water recharge from an adjacent basin to the Rapid Creek basin, or ground-water discharge from the Rapid Creek basin would be insignificant to the total water balance of the basin. Therefore, evapotranspiration is assumed to be equal to precipitation minus stream discharge and spring diversions.

Precipitation on the Rapid Creek basin was about 21,300 acre-ft/yr, calculated using the Colorado Climate Center (1984) map of precipitation and the area of the Rapid Creek basin. Stream discharge was calculated from the Powderhorn Coal Co. records obtained at a streamflow-gaging station near the mouth of Rapid Creek. Spring-diversion records were provided by the town of Palisade.

Discharges from Rapid Creek basin include:

1. About 1,300 acre-ft/yr as spring discharge (excluding discharge from Kruzen Springs outside the basin) diverted by the town of Palisade or 6 percent of the total discharge.
2. About 1,280 acre-ft/yr as stream discharge or 6 percent of the total discharge.
3. Negligible ground water.
4. About 18,800 acre-ft/yr as evapotranspiration, or 88 percent of the total discharge.

#### POTENTIAL EFFECTS OF UNDERGROUND MINING

Subsidence occurs as coal is removed during or after underground mining. The effects vary from fracturing and rubbing of bedrock adjacent to the underground mine, to cracks and subsidence at land surface overlying the mine. The effects are dependent on mining method, depth of mining, mine dimensions, mining rate, topography, and lithology and structure of overburden rock.

Several reports describe the general effects of subsidence caused by underground mining. Turney (1985) describes subsidence for a nontechnical audience; Lee and Abel (1983) describe subsidence and underground mining; Dunrud (1984) describes subsidence in the western United States.

The possible effects of subsidence on surface water in the Rapid Creek basin include:

1. Subsidence cracks in streambeds that could increase leakage of water from streams.
2. Subsidence cracks that could increase leakage of water from reservoirs.

The possible effects of subsidence on ground water in the basin include:

1. Subsidence cracks near a spring that could decrease spring discharge.
2. Subsidence-caused fracturing of rock near the underground mine that could increase permeability in the mine vicinity, causing increased leakage from overlying rock and mine inflow.
3. Depth to water in wells could become deeper because of the increased storage coefficient of the fractured bedrock.

Other effects could include:

1. Damage to dams.
2. Damage to water pipelines.

The effects of subsidence will only be considered in this report where overburden thicknesses are less than 3,000 ft (fig. 6). This is the maximum thickness that the U.S. Bureau of Land Management considers economical for mining and would, therefore, consider for leasing. The following hydrologic features considered in this report would, therefore, be unaffected:

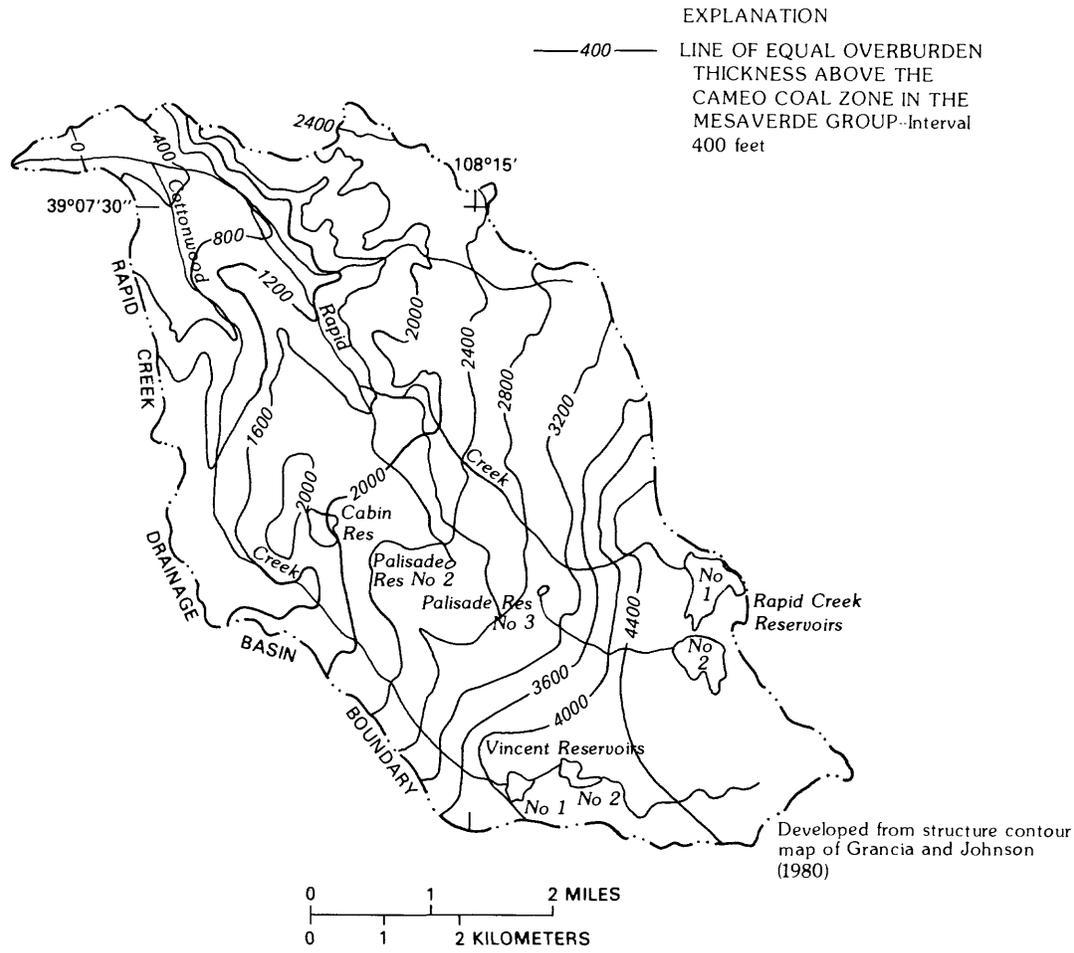


Figure 6.--Overburden thickness above the Cameo coal zone of the Mesaverde Group.

1. Rapid Creek Reservoirs No. 1 and 2.
2. Vincent Reservoirs No. 1 and 2.
3. Palisade Reservoir No. 3.
4. Headwaters of Rapid and Cottonwood Creeks.
5. Nine of the 25 springs supplying water to the town of Palisade.

Most of the land between the existing leases and the limit of the 3,000-ft overburden might be considered for leasing. Buffer zones would be designed to surround streams, springs, reservoirs, and pipelines.

A surface feature can be protected by decreased extraction or non-extraction of coal beneath the feature, leaving a buffer zone between the surface feature and the underlying coal. This zone is defined by a limit

angle (Lee and Abel, 1983), a function of geology. The limit angle used by the U.S. Bureau of Land Management in the northwestern part of the Rapid Creek basin is 21°. The limit angle has not been determined for areas at higher altitudes in the Rapid Creek basin.

The Powderhorn Coal Co. currently (1985) mines coal in the Rapid Creek basin using room-and-pillar methods. Longwall mining may be used in the future. Mining will be completed in current leases (pl. 1) by about 1995 (James Stover, Powderhorn Coal Co., oral commun., 1985). Overburden thickness for current lease areas ranges from 100 to 2,200 feet and increases to the southeast.

The mine extracts about 75 percent of the coal from room-and-pillar panels where subsidence's effects do not cause damage. A study by the U.S. Bureau of Mines (Allan Fejes, Bureau of Mines, oral commun., 1985) determined that with about 400 ft of overburden and 75-percent extraction, the magnitude of subsidence was 54 percent of the thickness of the coal seam mined. That is, if 75 percent of an 8-ft coal seam (the maximum coal thickness reported from well logs in Rapid Creek basin) were mined, the land surface would subside about 4 ft. Subsidence would decrease with thicker overburden. The mined area was subcritical and, therefore, these values may not be a maximum. The U.S. Bureau of Mines study detected no subsidence 1 year after mining completion where about 50 percent of the coal was extracted beneath about 400 ft of overburden thickness.

Mining coal in the Mesaverde Group temporarily will dewater the rock adjacent to the underground mine. The adjacent rock, especially above the mine, will become rubble and fractured because of subsidence during mining advancement. These subsidence effects will increase the permeability of rock in the mining vicinity and increase inflow of ground water to the mine.

The potentiometric surface (water level) will decline near underground mines because the increase in the permeability of the rock from fracturing and rubble also increases the storage capacity of the rock. The dewatering is temporary and water levels should return to near premining levels after the underground mine is sealed. All pore spaces and fractures would become saturated after mining completion; saturation would occur after several years.

Inflow of ground water to the mine will increase as additional surface area in the mine is exposed to the water in coal and sandstone. Inflow probably would be small with decreased or no extraction of coal beneath streams, springs, and Cabin Reservoir and because the Mesaverde Group generally is a confining bed.

No critical aquifers would be dewatered by underground mining in the northwestern part of the Rapid Creek basin. Water in bedrock is the smallest part of the water balance for the basin and it is unused by the town of Palisade. Most unconsolidated deposits containing water are underlain by at least 1,800 ft of overburden and are above the sandstone canyons formed by the Mesaverde Group.

Most of the pipelines transmitting water in the basin are sand-cast iron and were installed by the town of Palisade in the 1930's. The pipe sections are 10 and 18 ft long and 4, 6, and 8 in. in diameter. The joints are sealed with lead, and they are inflexible and require occasional resealing and repair. This includes pipelines that follow Cottonwood and Rapid Creeks, overlie less than 1,800 ft of overburden, and typically are buried under less than 1 ft of soil.

A pipeline connecting springs above Cabin Reservoir with Rapid Creek near site C overlies about 1,600 to 1,800 ft of overburden. This pipeline is made of 21-ft pipe, is 6 in. in diameter, and is ductile iron with rubber seals.

Damage to older cast-iron pipes is unlikely where they are adjacent to Cottonwood and Rapid Creeks and can be protected by limited coal extraction beneath these creeks. Because newer, ductile iron pipe is more flexible, damage is less likely in the pipeline from near Cabin Reservoir to Rapid Creek.

#### NEED FOR ADDITIONAL STUDIES

This report describes present (1985) surface-water characteristics. Future surface-water monitoring would describe any changes to the system as underground mining progresses beneath the basin.

Such a monitoring network could include continuous water-stage recorders, and bimonthly stream-discharge measurements on Rapid and Cottonwood Creeks. Streamflow-gaging stations at sites G and K could measure stream discharge from Rapid and Cottonwood Creeks and a streamflow-gaging station upstream from the junction of Rapid Creek with the Colorado River could measure total discharge from the basin. Any diversions from or to the streams would need to be monitored so that correct adjustments could be made to stream-discharge records. The data collected would provide baseline surface-water data for a better water-balance interpretation.

Additional ground-water data would better describe premining ground-water flow systems in the basin. No current or past records of spring discharge in the Rapid Creek basin exist, therefore, no data are yet available to determine any future changes in spring discharge caused by underground mining. Modifications to spring housings could allow discharge measurements to be made.

Because the effects of subsidence are a function of geologic conditions, geologic mapping is needed in the Rapid Creek basin. Geologic maps at 1:24,000 scale and geologic sections would require additional drilling and could be used for better interpretations of the effects of subsidence as well as aiding in coal leasing.

Drilling additional coal-exploration holes could better define where additional tracts might be leased. Overburden-thickness data were developed from a structural map that did not include well-log data in the Rapid Creek basin. Exploration-hole data are needed east and southeast of the 2,000-ft thickness line in figure 6 to more accurately define the thickness lines and, therefore, determine whether overburden thicknesses would permit additional

leasing. Drilling also could provide ground-water data for higher-altitude areas in the basin; these data would be useful in planning for any mine dewatering. Any drilled holes could be used for monitoring ground-water levels by installing piezometers completed above, in, and below the Cameo coal zone.

Subsidence surveys need to be done over past, current (1985), and future mining areas as mining progresses southeastward in the basin. These data could be used to determine values for limit angles at higher altitudes in the Rapid Creek basin. Accurate limit angles are needed to protect springs and reservoirs during mining. A long-term benefit of these surveys would be to provide onsite data for empirical applications of subsidence research that could be used later to predict subsidence effects in areas of similar geology and where similar mining methods are used.

### SUMMARY AND CONCLUSIONS

The U.S. Bureau of Land Management may consider leasing additional coal tracts in the Rapid Creek basin in cooperation with the town of Palisade. The Bureau cannot offer additional lease tracts if underground mining would adversely affect streams, reservoirs, or springs in this basin. The Rapid Creek basin contains 7 reservoirs, 25 springs, and stream diversions from Cottonwood and Rapid Creeks that are the water supply for the town of Palisade. The Roadside Mine is mining on Federal leases beneath the Rapid Creek basin.

Data were collected in the basin from streams, reservoirs, springs, and wells to describe present geohydrologic conditions. Geologic and subsidence information was used to interpret potential effects of underground mining on these water resources.

Sedimentary bedrock dips about  $3^{\circ}$  to the northeast. No faults have been detected in the Roadside Mine or mapped in the study area. The local stratigraphy includes (in ascending order) the Mesaverde Group of Late Cretaceous age; Wasatch Formation, Green River Formation, an unnamed formation, and basalt of Tertiary age; and unconsolidated deposits of Quaternary age. The coal is removed from the Cameo coal zone in the lower part of the Mesaverde Group. Coal overburden includes sandstone, claystone, and mudstone in the Mesaverde Group; claystone and some sandstone in the Wasatch Formation; and sandstone, marlstone, and shale in the Green River Formation. Overlying the unnamed rocks are series of basalt flows.

Deposits of Quaternary age contain the most productive aquifers in the Rapid Creek basin and are limited by deposit boundaries. Bedrock units are confining beds except where they consist of sandstone or where they are fractured.

Rapid and Cottonwood Creeks are perennial streams in the Rapid Creek basin. Tributaries typically are dry by September. Oak Springs Creek was flowing in October 1985 because of greater than normal precipitation in recent years. The town of Palisade can divert streamflow from Rapid and Cottonwood Creeks but seldom does; spring discharge is of better quality.

Spring discharge is the primary source of water for the town of Palisade. Spring water flows by pipeline from 25 springs to the water-treatment plant near Palisade with any excess water diverted to Cabin Reservoir. The range of pH measurements for springs was 6.8 to 8.3 and the median was 7.4. The range of specific conductance measurements was 95 to 1,050  $\mu\text{S}/\text{cm}$  and averaged about 420  $\mu\text{S}/\text{cm}$ .

The Powderhorn Coal Co. drilled 10 coal-exploration holes in 1985. Geophysical and water-level data from these holes and interpretation of the ground-water flow systems based on lithologic and structural conditions are used to describe ground-water flow in the basin.

Precipitation is the primary source of recharge to the basin. Recharge to the Rapid Creek basin is about 21,300 acre-ft/yr. Most recharge occurs at high altitudes and most discharge occurs at low altitudes in the basin. Flow systems range from short flow paths in areally-limited unconsolidated deposits to possible regional flow paths in the Piceance Creek structural basin. The greatest proportion of ground water in Rapid Creek basin flows in shallow flow systems. Evapotranspiration accounts for 88 percent of the discharge from the basin. Other discharges in decreasing order are springs, streamflow, and ground water.

Underground mining causes subsidence. It can affect streams, reservoirs, springs, wells, ground-water flow systems, mine inflow, and water pipelines. The following effects of underground mining are possible, based on current (1985) mine plans in the Rapid Creek basin:

1. Stream-, reservoir-, and spring-water losses could occur during and after mining unless protected by appropriate mining methods and restricted mining areas.
2. Temporary dewatering of the Mesaverde Group could occur adjacent to the mining area.
3. It is unlikely that aquifers would be dewatered.
4. Some damage could occur to water pipelines unless the land surface is protected by decreased coal extraction beneath the pipeline.

Additional data collection would improve the description of surface- and ground-water flow systems in the Rapid Creek basin. To determine if there are any stream or spring losses or pipeline damage, the following could be done:

1. Measure stream discharge regularly at sites G and K on Rapid and Cottonwood Creeks, and at the mouth of Rapid Creek.
2. Measure spring discharge several times each year or as frequently as possible.

Other data collection to determine the effects of subsidence could include:

1. Water-level measurements in any wells drilled for observation.
2. Subsidence surveys to monitor subsidence.

## REFERENCES CITED

- Cashion, W.B., 1973, Geologic and structure map of the Grand Junction quadrangle, Colorado and Utah: U.S. Geological Survey Miscellaneous Investigations Series Map I-736, scale 1:250,000.
- Colorado Climate Center, 1984, Colorado average annual precipitation 1951-1980: Ft. Collins, Colorado State University, 1 sheet.
- Dunrud, C.R., 1984, Coal mine subsidence--western United States, in Holzer, T.L., Man-induced land subsidence: Geological Society of America Reviews in Engineering Geology, v. 6, p. 151-194.
- Erdmann, C.E., 1934 [1935], The Book Cliffs coal field in Garfield and Mesa Counties, Colorado: U.S. Geological Survey Bulletin 851, pl. 1.
- Fisher, D.J., Erdmann, C.E., and Reeside, J.B., Jr., 1960, Cretaceous and Tertiary formations of the Book Cliffs, Carbon, Emery, and Grand Counties, Utah, and Garfield and Mesa Counties, Colorado: U.S. Geological Survey Professional Paper 332, 80 p.
- Grancia, M.P., and Johnson, R.C., 1980, Structure contour and isochore map of the nonmarine part of the Mesaverde Formation Group, Piceance Creek Basin, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-1189, scale 1:250,000.
- Henningson, Durham, and Richardson, Inc., 1979, Palisade [Colorado] water system: Denver, unpublished report, 118 p.
- J.F. Sato and Associates, Inc., 1983, Impact of longwall mining on the hydrologic balance--preliminary data collection: U.S. Bureau of Mines Open-file Report 187-83, 141 p.
- Johnson, R.C., and May, Fred, 1978, Preliminary stratigraphic studies of the upper part of the Mesaverde Group, the Wasatch Formation, and the lower part of the Green River Formation, DeBeque area, Colorado: U.S. Geological Survey Miscellaneous-Field Investigations Studies Map MF-1050, 2 sheets, no scale.
- Lee, F.T., and Abel, J.F., 1983, Subsidence from underground mining--environmental analysis and planning considerations: U.S. Geological Survey Circular 876, 28 p.
- Rantz, S.E., and others, 1982, Measurement and computation of streamflow, volume 1. Measurement of stage and discharge: U.S. Geological Survey Water-Supply Paper 2175, 284 p.
- Schwochow, S.D., 1978, Mineral resources survey of Mesa County: Colorado Geological Survey Resource Series 2, 110 p.
- Skougstad, M.W., Fishman, M.J., Friedman, L.C., Erdmann, D.E., and Duncan, S.S., eds., 1979, Methods for determination of inorganic substances in water and fluvial sediments: U.S. Geological Survey Techniques of Water-Resources Investigations, book 5, chapter A1, 626 p.
- Turney, J.E., 1985, Subsidence above inactive coal mines: Colorado Geological Survey Special Publications 26, 32 p.
- U.S. Bureau of the Census, 1981, 1980 census of population, number of inhabitants, Colorado: U.S. Bureau of the Census Report PC (1)-A 7, 30 p.
- U.S. Environmental Protection Agency, 1983, National secondary drinking water regulations (proposed): Federal Register, v. 42, no. 62, pt. I, p. 17143-17147.
- U.S. National Climatic Data Center, 1984, Climatological data, Annual summary, Colorado, Palisade station: Asheville, N.C., v. 89, no. 13, 36 p.

Whitney, J.W., 1981, Surficial geologic map of the Grand Junction 1°X 2°  
Quadrangle, Colorado and Utah: U.S. Geological Survey Miscellaneous  
Investigations Map I-1289, scale 1:250,000.

Yeend, W.E., 1969, Quaternary geology of the Grand and Battlement Mesas area:  
U.S. Geological Survey Professional Paper 617, 49 p.