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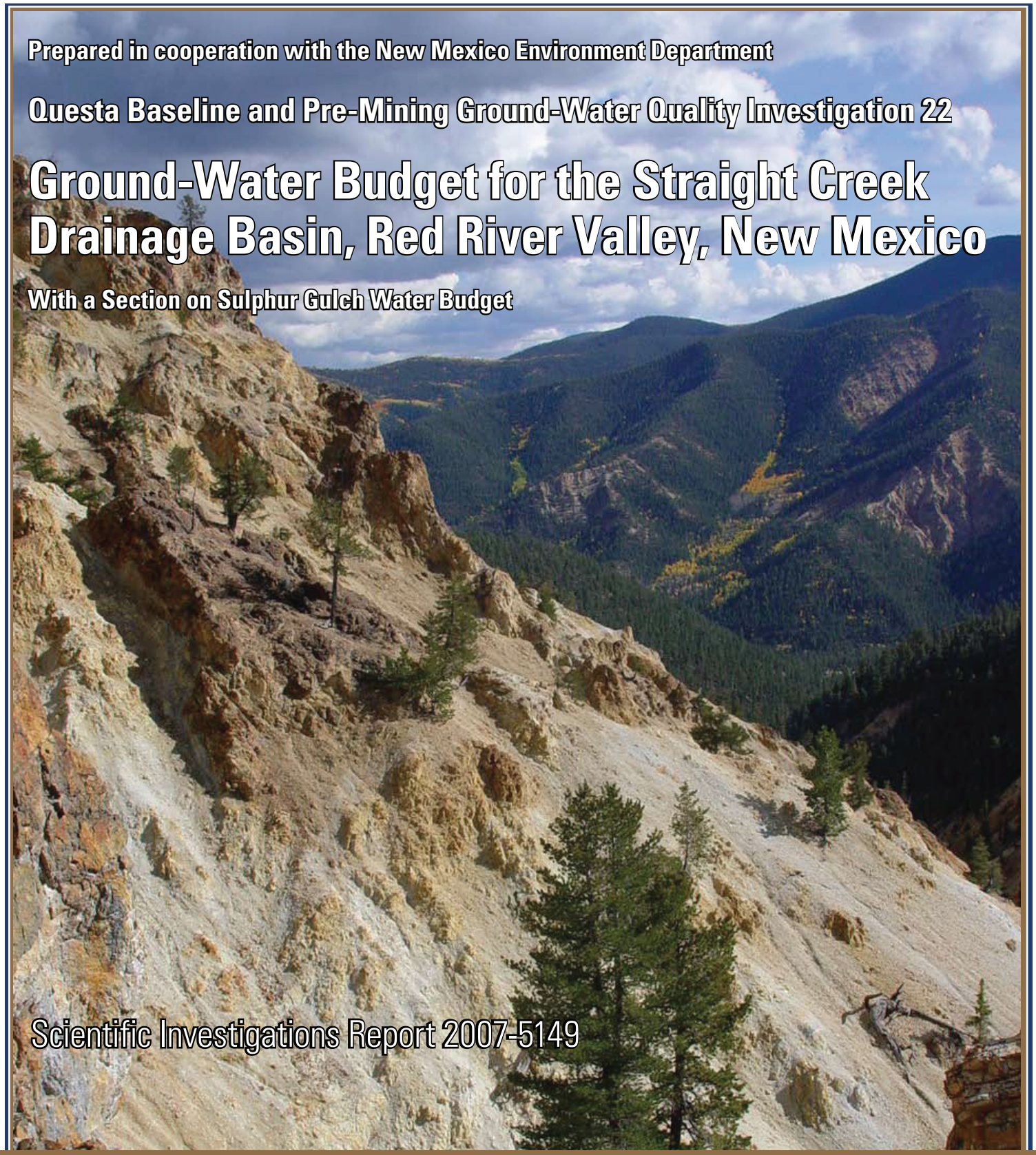

Prepared in cooperation with the New Mexico Environment Department

Questa Baseline and Pre-Mining Ground-Water Quality Investigation 22

Ground-Water Budget for the Straight Creek Drainage Basin, Red River Valley, New Mexico

With a Section on Sulphur Gulch Water Budget

Scientific Investigations Report 2007-5149

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

Front cover: View southwest across Straight Creek scar (photograph by Nathan Myers).

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U.S. Department of the Interior
DIRK KEMPTHORNE, Secretary

U.S. Geological Survey
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Conversion Factors and Datum

Multiply	By	To obtain
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
foot per day (ft/d)	0.3048	meter per day (m/d)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06309	liter per second (L/s)

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

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

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

Questa Baseline and Pre-Mining Ground-Water-Quality Investigation 22 — Ground-Water Budget for the Straight Creek Drainage Basin, Red River Valley, New Mexico

By Douglas P. McAda and Cheryl A. Naus

With a Section on Sulphur Gulch Water Budget by Kirk R. Vincent

Abstract

In April 2001, the U.S. Geological Survey (USGS) and the New Mexico Environment Department (NMED) began a cooperative study to infer the pre-mining ground-water chemistry at the Molycorp molybdenum mine site in the Red River Valley. The Molycorp mine has been in operation since the 1920s. Because ground-water conditions prior to mining are not available, sites analogous to the pre-mining conditions at the mine site must be studied to infer those pre-mining conditions. The Straight Creek drainage basin (watershed) was selected as the primary analog site for this study because of its similar terrain and geology to the mine site, accessibility, potential for well construction, and minimal anthropogenic activity. The purpose of this report is to present results of a water-budget analysis of the debris-flow aquifer in the Straight Creek watershed. The water budget is based on mean annual conditions and is assumed to be steady state.

For this study, the Straight Creek watershed was divided into subwatersheds on the basis of locations of seismic lines, which were used to calculate cross-section area through the Straight Creek debris-flow deposits and underlying fractured and weathered bedrock (regolith). Water-budget components were calculated for areas upstream from and between the seismic lines. Components of the water budget were precipitation, evapotranspiration, surface-water flow, and ground-water flow under a steady-state mean annual condition. Watershed yield, defined as precipitation minus evapotranspiration, was separated into surface-water flow, ground-water flow through the debris-flow deposits and regolith, and ground-water flow through fractured bedrock. The approach to this calculation was to use Darcy's Law to calculate the flow through the cross-section area of the saturated debris-flow deposits and underlying regolith as defined by the interpreted seismic data. The amount of watershed yield unaccounted for through this section then was attributed to either surface-water flow or the component of ground-water flow through fractured bedrock.

The inflow to the watershed, calculated to be 701 gallons per minute, is from precipitation. The calculated outflow from the watershed at or upstream from seismic-line 5 (the downstream-most line in Straight Creek prior to entering the Red River Valley) is 540 gallons per minute of evapotranspiration in the watershed upstream from line 5 (77.0 percent of precipitation), 5 gallons per minute of surface-water flow (0.7 percent of precipitation), 122 gallons per minute of ground-water flow through the debris-flow deposits and underlying regolith defined by the seismic data (17.4 percent of precipitation), and 34 gallons per minute of ground-water flow through fractured bedrock below the defined seismic line (4.9 percent of precipitation).

The ground-water flow through the alluvium and intertonguing debris-flow deposits of the Red River Valley was calculated to be 5,227 gallons per minute at seismic-line 7, the first seismic line in the Red River Valley downstream from Straight Creek. The water budget indicates the amount of ground-water flow that enters the Red River alluvium from the debris-flow deposits and regolith in Straight Creek is small (about 2.3 percent; 122 gallons per minute) compared to the volume of flow that moves through the Red River alluvium. The total amount of ground-water flow from Straight Creek (156 gallons per minute; 122 gallons per minute from debris-flow deposits and regolith plus 34 gallons per minute through fractured bedrock) is about 3.0 percent of the ground-water flow calculated at line 7 for the Red River alluvium.

Introduction

In April 2001, the U.S. Geological Survey (USGS) and the New Mexico Environment Department (NMED) began a cooperative study to infer the pre-mining ground-water chemistry at the Molycorp molybdenum (Questa) mine site in the Red River Valley (mine site, fig. 1). This study was prompted by the Water Quality Act, under the jurisdiction of the New Mexico Water Quality Control Commission, which

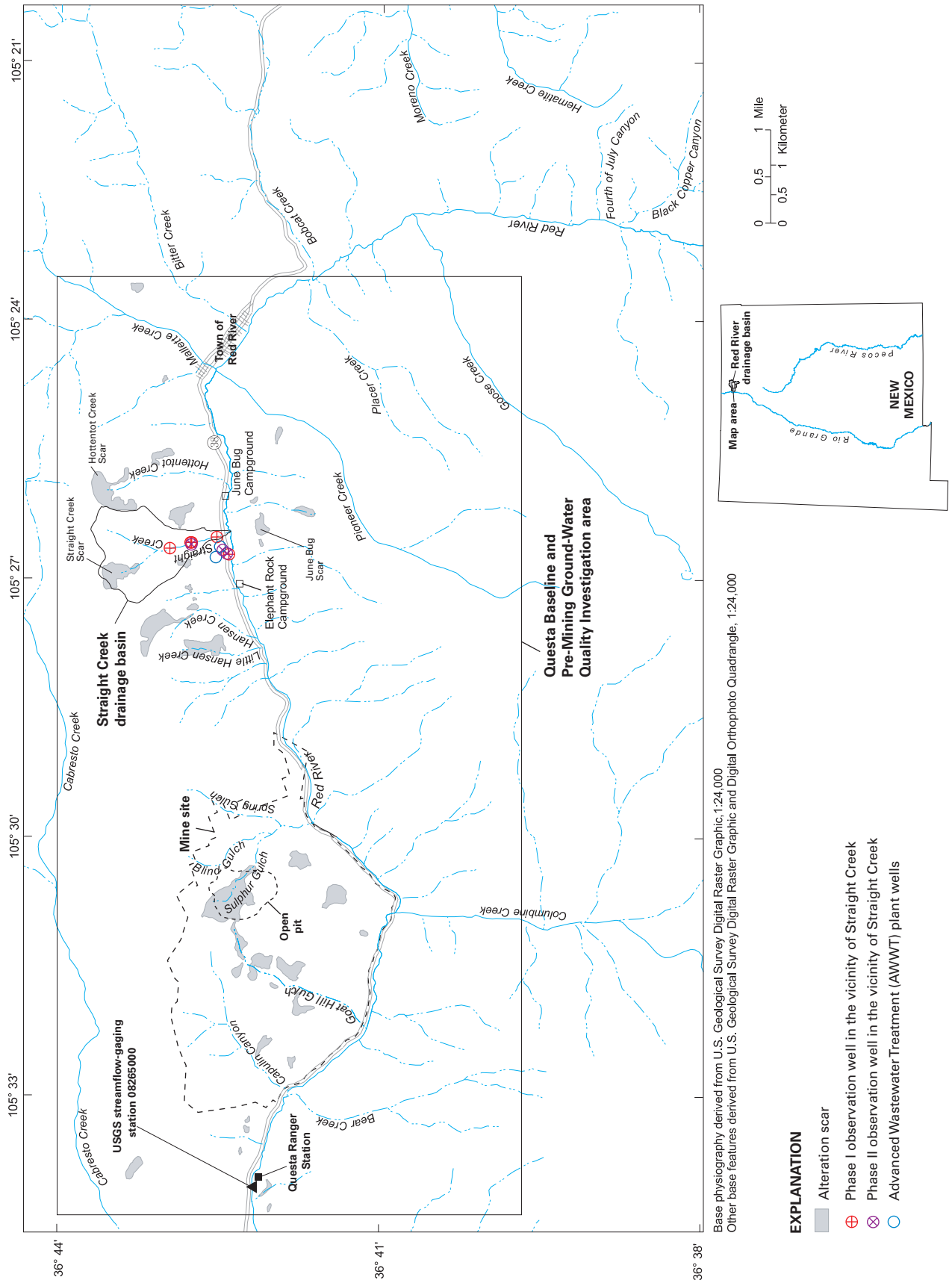


Figure 1. Location of Straight Creek drainage basin within Questa baseline and pre-mining ground-water-quality investigation area (modified from Naus and others, 2005, fig. 1).

requires an operator to develop and complete an approved closure plan that prevents the exceedence of (1) standards set forth in New Mexico Water Quality Control Commission Regulations (§20.6.2.3103 NMAC) or (2) natural background concentrations.

The Molycorp mine has been in operation since the 1920s. Records of ground-water conditions prior to mining, including ground-water levels and ground-water chemical analyses, are not available to evaluate pre-mining conditions. Therefore, sites analogous to the pre-mining conditions at the mine site must be studied to infer pre-mining conditions.

The Straight Creek drainage basin (watershed) (fig. 1) was selected as the primary analog site for this study because of its similar terrain and geology to the mine site, accessibility, potential for well construction, and minimal anthropogenic activity.

Purpose and Scope

The purpose of this report is to present results of a water-budget analysis of the debris-flow aquifer in the Straight Creek drainage basin (watershed). This report is one in a series of reports that describe conditions in Straight Creek and comparisons with pre-mining conditions at the mine site.

The authors were asked to develop a water budget to calculate watershed yield for three subwatersheds within Sulphur Gulch as this report was nearing completion. The resulting water budget is documented in the "Supplementary Information" section of this report.

Physical Setting

A description of the Red River, of which Straight Creek is tributary, and the Red River Valley (fig. 1) is given in a report by Naus and others (2005). That description includes physical, climate, vegetation, hydrogeology, surface-water, and mining-history discussions. The following paragraph is summarized from that report.

In general, the entire area under study to infer pre-mining conditions at the mine site includes about 63 square miles of the Red River drainage (fig. 1) from the town of Red River to the USGS streamflow-gaging station near Questa (08265000, Red River near Questa). The area is mountainous with steep V-shaped valleys. Elevations range from about 7,450 feet above NGVD 29 at the gaging station to more than 10,500 feet above NGVD 29 at the mountain ridges. Vegetation ranges from piñon-juniper woodland near the Questa gaging station to mixed conifer woodlands at elevations between about 7,500 and 9,000 feet above NGVD 29. Spruce-fir woodland occurs at the highest elevations (Knight, 1990). Altered bedrock on the steep mountain slopes is highly erosive, resulting in sparsely vegetated scars on the landscape (fig. 1). Debris flows, resulting from intense precipitation that caused erosion of the altered bedrock, have filled several of the tributary valleys of the Red River with debris-flow deposits, and have created debris fans extending into the Red River Valley.

Description of the Straight Creek Drainage Basin

The study described in this report focuses on the Straight Creek drainage basin (watershed). A diagram of the basin, including all the area included in the water-budget analysis, is shown in figure 2. The total area (about 660 acres) considered in the water-budget analysis includes the subwatershed areas tributary to Straight Creek and the Red River Valley upstream from seismic-line 8 and downstream from seismic-line 9 (fig. 2) and the watershed of Straight Creek upstream from the Red River Valley at seismic-line 5 (about 520 acres).

The area for this study (fig. 2) extends from an elevation of about 8,450 feet above NGVD 29 along the Red River at seismic-line 8 to about 10,600 feet above NGVD 29 at the upper end of the watershed (from USGS 1:24,000 Digital Elevation Models [DEMs]). The vegetation type along the Red River channel and the side slopes bordering the Straight Creek debris fan is mixed conifer woodlands. The south-facing slopes of the debris fan that leads from the Red River to the wastewater treatment plant facilities (fig. 3) consist primarily of ponderosa pine woodlands. The lower part of the south-facing debris fan in Straight Creek consists of ponderosa pine woodlands, and the upper part of the debris fan consists of mixed conifer woodlands. The slopes of the Straight Creek watershed transition from mixed conifer in the lower elevations to spruce-fir woodland in the upper elevations.

The geology in the Straight Creek watershed is described by Naus and others (2005). The debris-flow deposits and Red River alluvium in the valley areas (fig. 2) are of Quaternary age. The side slopes and upper parts of the watershed consist of andesite, Amalia Tuff, and granite of Tertiary age (Lipman and Reed, 1979; Naus and others, 2005). The major portions of the scars are cut into the andesite and Amalia Tuff.

In preparation for the water-budget analysis, the Straight Creek watershed was divided into subwatersheds (fig. 2). The subwatersheds were based primarily on the locations of seismic lines, described by Powers and Burton (2004) and by Michael Powers (U.S. Geological Survey, written commun., January 2004), so water-budget components could be calculated for areas upstream from and between the seismic lines. The subwatersheds were further divided on the basis of the potential need to calculate water-budget components. The further divisions included the separation of subwatersheds by valley bottom and by which side of the valley the subwatershed enters; the separation of scar areas from non-scar areas; and the separation of subwatersheds upstream from the 9,600-foot elevation contour from those downstream from that contour. The separation of valley bottom from valley sides was done to help facilitate estimation of subwatershed aspect although the principal aspects ultimately were not calculated in the anticipated manner. The separation of scar and non-scar areas was done to facilitate calculation of evapotranspiration and watershed yields. The separation of upstream and downstream subwatersheds was done to facilitate estimation of mean annual precipitation by one of the methods described in the "Precipitation" section.

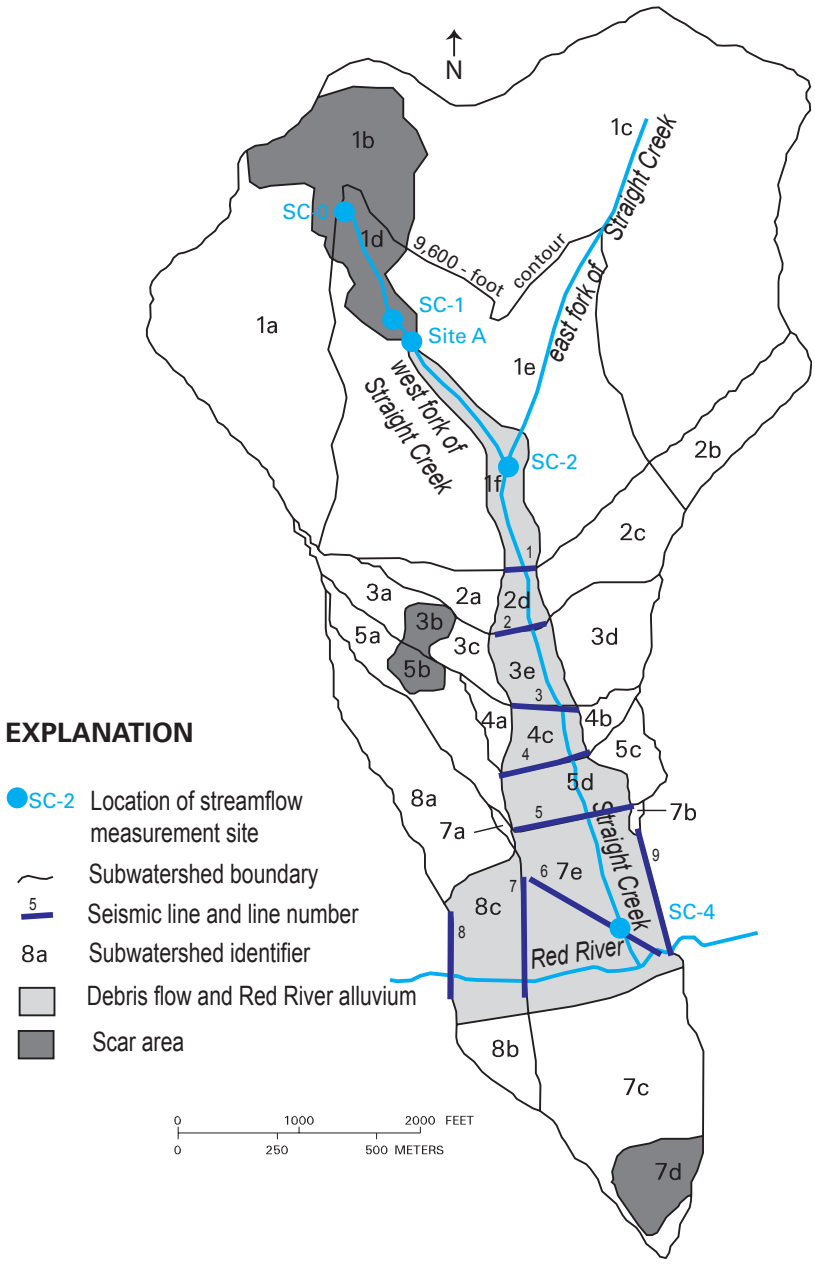


Figure 2. Straight Creek drainage basin subwatersheds used for water-budget analysis.

Acknowledgments

The authors wish to thank the project advisory committee, representing Amigos Bravos; Molycorp and its consultants; the NMED; and the USGS for their guidance on this study. The authors would specifically like to thank Christoph Wels (Robertson GeoConsultants, Inc.), Tom Myers (Amigos Bravos), Richard Bell (USGS), and Chuck Heywood (USGS) for their reviews of this report.

Hydrology of the Straight Creek Drainage Basin

Precipitation

There are no long-term records of precipitation within the Straight Creek drainage basin (watershed). The nearest long-term precipitation station is in the town of Red River, approximately 2 miles from the watershed. Precipitation in the town of Red River may be representative of precipitation in the Red River Valley in the vicinity of Straight Creek; however, considering that the topography and elevation of the watershed varies considerably, it is necessary to estimate the precipitation in the watershed.

Precipitation at the mine site (fig. 1) was measured from August 2000 through April 2003 (2-year 9-month period) at three locations with elevations that range from 8,735 to 9,800 feet above NGVD 29. Analysis of daily precipitation data from these locations did not indicate an increase in daily precipitation with an increase in elevation (Cristoph Wels, Robertson GeoConsultants, Inc., written commun., Feb. 24, 2004). However, as Wels noted, the short duration of precipitation-data collection at these locations and the dry years in which the data were collected makes the applicability of these data to Straight Creek unclear. Additionally, the short timeframe throughout which the data were collected does not allow for an analysis of mean annual precipitation. A comparison between the precipitation data collected at the mine site (Cristoph Wels, Robertson GeoConsultants, Inc., written commun., Feb. 24, 2004) and precipitation data collected at the National Oceanic and Atmospheric Administration's (NOAA) Red River weather station (at an elevation of 8,676 feet above

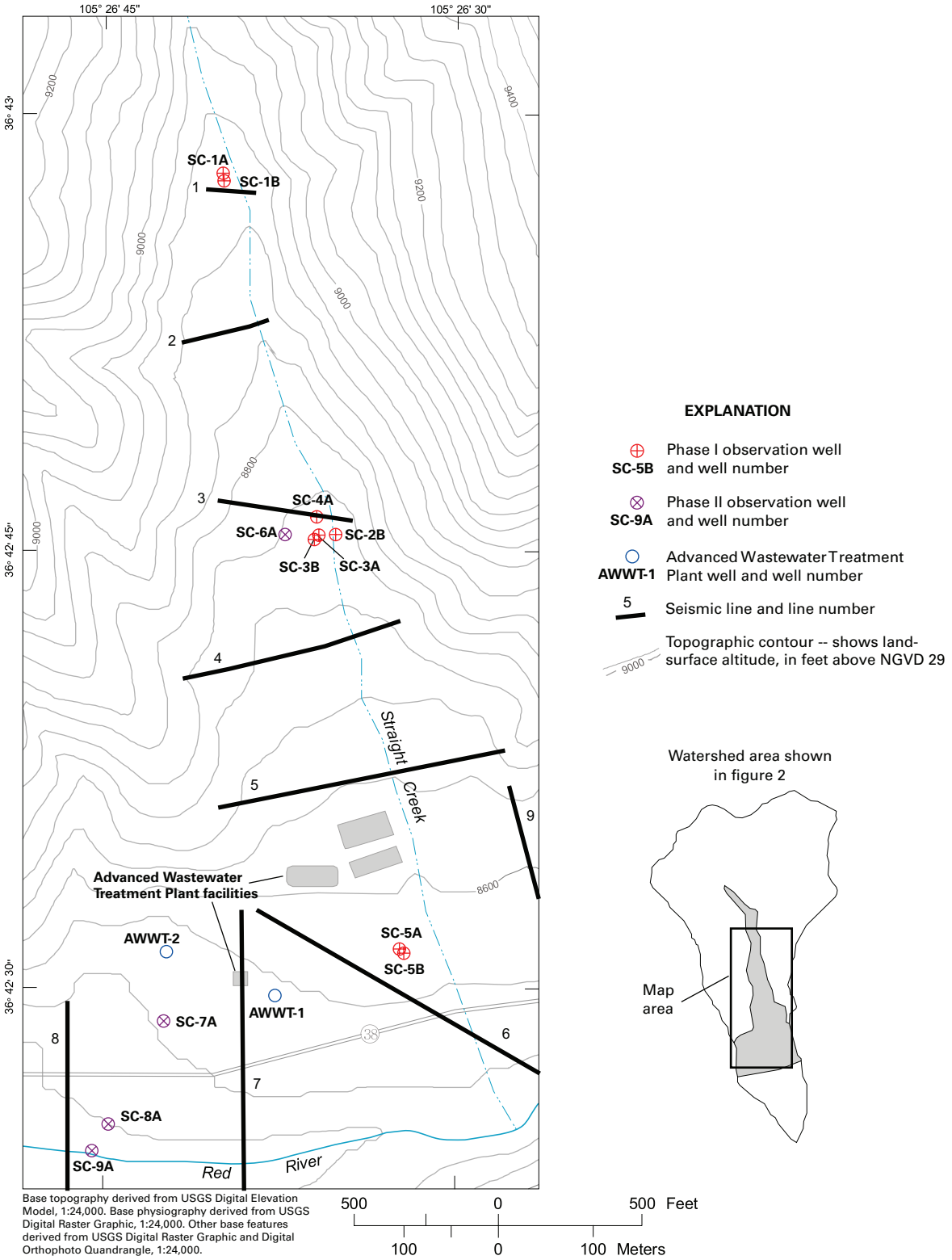


Figure 3. Observation wells in the vicinity of Straight Creek (modified from Naus and others, 2005, fig. 3).

NGVD 29; Western Regional Climate Center, 2003) indicates more annual precipitation was recorded at the Red River weather station than at any of the precipitation data-collection locations at the mine site. The elevation at the Red River weather station is comparable to the lowest elevation of the data-collection locations at the mine site (8,676 compared to 8,735 feet above NGVD 29). Although the 2001 May through October precipitation at the mine site (between 10.14 and 10.46 inches) is relatively consistent with that in the town of Red River (10.98 inches), the 2001 November through April precipitation at the mine site (between 3.49 and 6.47 inches) is substantially less than that recorded at Red River (10.67 inches). Only one of the mine-site locations (at 9,250 feet above NGVD 29) had a complete record for 2002. The 2002 May through October precipitation at that location (11.03 inches) was again relatively consistent with that at Red River (12.05 inches); however, the 2002 November through April precipitation (2.3 inches) was substantially less than that in Red River (5.15 inches). Because of its proximity to Straight Creek, conditions at the NOAA Red River weather station are considered to be representative of conditions in the lower elevations of Straight Creek.

Evidence indicates mean annual precipitation increases with an increase in elevation. The ponderosa pine vegetation type predominates in the lower elevations of the watershed, whereas the mixed conifer vegetation type transitioning to spruce-fir woodland, which requires a greater average amount of precipitation to establish and survive (U.S. Forest Service Rocky Mountain Research Station and University of Arizona, 2004), predominates in the higher elevations of the watershed.

Several investigators have developed elevation-precipitation relations using long-term precipitation data that are applicable to the Sangre de Cristo Mountains in northern New Mexico. Three of these relations (Johnson, 1998, eq. 2; Robertson GeoConsultants, Inc., 2001b, fig. 3; and Pete Stewart, U.S. Forest Service, written commun., 1984 [cited in Wasiolek, 1995, p. 15]) are used for this study. Although the individual relations vary somewhat, these analyses show the relation between long-term precipitation and elevation.

Johnson (1998, eq. 2) developed an elevation-precipitation relation for the mountainous areas of eastern Taos County, New Mexico. The equation is as follows:

$$MAP = 0.00552(E) - 27 \qquad (1)$$

Where:

MAP = mean annual precipitation, in inches; and
E = elevation above NGVD 29, in feet.

Robertson GeoConsultants, Inc. (2001b, fig. 3) developed a precipitation-elevation relation similar to that shown by equation 1 for the mine site. Because some different precipitation stations were used to develop the two equations, the two equations have slightly different slopes and intercepts. The Robertson GeoConsultants, Inc. equation is as follows:

$$MAP = 0.0050(E) - 24 \qquad (2)$$

Where:

MAP = mean annual precipitation, in inches; and
E = elevation above NGVD 29, in feet.

The U.S. Forest Service has used equations for the Rocky Mountains of southern Colorado and northern New Mexico (Pete Stewart, U.S. Forest Service, written commun., 1984, cited in Wasiolek, 1995, p. 15). The equations are as follows:

$$MAP = 0.0048(E_r) - 19.16 \qquad (3)$$

Where:

MAP = mean annual precipitation, in inches;
E_r = representative elevation above NGVD 29, in feet: $((E_{max} - E_{min})/3) + E_{min}$ for elevations greater than 9,600 feet above NGVD 29; and $((E_{max} - E_{min})/2) + E_{min}$ for elevations less than 9,600 feet above NGVD 29;
E_{max} = maximum elevation above NGVD 29, in feet; and
E_{min} = minimum elevation above NGVD 29, in feet.

Mean annual precipitation for the subwatersheds shown in figure 2 was estimated using equations 1, 2, and 3 (table 1). The elevation terms used in the equations were determined from USGS 1:24,000-scale DEMs. The mean elevation of each subwatershed was used for the elevation term in equations 1 and 2. The minimum and maximum elevations of each subwatershed were used in equation 3. Table 1 shows the mean, minimum, and maximum elevations and the estimated precipitation for each subwatershed. Estimated mean annual precipitation is consistently largest using equation 3 and is consistently smallest using equation 2. The largest range in mean annual precipitation estimates occurs in subwatershed 7c (20.10 to 24.11 inches; table 1, fig. 2) and the smallest range in estimates occurs in subwatershed 2b (25.80 to 28.11 inches). The best agreements between the estimates occur for the higher-elevation subwatersheds and the poorest agreements occur for the lower-elevation subwatersheds. The range in the estimates for the subwatersheds listed in table 1 likely represents a plausible range in the values of mean annual precipitation for the subwatersheds.

Evapotranspiration

Evapotranspiration in the subwatersheds was estimated using two methods. The first method was described by Troendle and Leaf (1980) for the Rocky Mountain/Inland Intermountain region and involves a graphical technique using seasonal precipitation. The second was a relation described by MacDonald and Stednick (2003) based on paired watershed plot studies conducted in Colorado and discussed by Troendle and Reuss (1997).

The Troendle and Leaf (1980) method uses graphs of seasonal precipitation in relation to seasonal evapotranspiration for watersheds with various energy aspects. The aspect of a watershed slope is the direction in which the

Table 1. Areas, elevations, and mean annual precipitation estimates for Straight Creek drainage basin subwatersheds.

[NGVD 29, National Geodetic Vertical Datum of 1929]

Subwatershed (figure 2)	Area (acres)	Elevation (in feet above NGVD 29)			Mean annual precipitation (inches)		
		Mean	Minimum	Maximum	Equation 1 (Johnson, 1998)	Equation 2 (Robertson, 2001b)	[1]Equation 3
1a	66.49	9,936	9,600	10,410	27.85	25.68	28.22
1b	25.84	9,820	9,600	10,080	27.21	25.10	27.69
1c	169.15	10,024	9,600	10,612	28.33	26.12	28.54
1d	11.04	9,441	9,220	9,598	25.11	23.21	26.00
1e	108.73	9,363	8,916	9,600	24.68	22.82	25.28
1f	12.22	9,030	8,895	9,211	22.85	21.15	24.29
Area-weighted mean		9,766			26.91	24.83	27.32
Subtotal	393.47						
2a	7.37	9,137	8,903	9,461	23.44	21.68	24.91
2b	14.30	9,960	9,600	10,345	27.98	25.80	28.11
2c	16.41	9,295	8,917	9,600	24.31	22.48	25.28
2d	4.23	8,883	8,847	8,923	22.03	20.42	23.49
Area-weighted mean		9,451			25.17	23.26	25.99
Subtotal	42.31						
3a	7.12	9,395	9,195	9,675	24.86	22.98	26.13
3b	3.06	9,133	9,023	9,234	23.41	21.67	24.66
3c	4.78	8,990	8,843	9,093	22.62	20.95	23.89
3d	15.67	9,108	8,786	9,389	23.28	21.54	24.46
3e	7.88	8,830	8,756	8,922	21.74	20.15	23.27
Area-weighted mean		9,092			23.19	21.46	24.47
Subtotal	38.51						
4a	3.19	8,868	8,770	9,044	21.95	20.34	23.59
4b	3.15	8,905	8,724	9,128	22.16	20.53	23.68
4c	7.09	8,743	8,704	8,818	21.26	19.72	22.89
Area-weighted mean		8,811			21.64	20.05	23.25
Subtotal	13.43						
5a	14.32	9,073	8,718	9,533	23.08	21.37	24.64
5b	2.97	9,085	8,972	9,191	23.15	21.43	24.43
5c	5.92	8,821	8,690	9,076	21.69	20.11	23.48
5d	10.59	8,688	8,638	8,770	20.96	19.44	22.62
Area-weighted mean		8,909			22.18	20.55	23.79
Subtotal	33.80						
7a	0.53	8,733	8,679	8,786	21.21	19.67	22.76
7b	0.55	8,663	8,629	8,718	20.82	19.32	22.47
7c	41.38	8,819	8,529	9,499	21.68	20.10	24.11
7d	9.24	9,076	8,819	9,374	23.10	21.38	24.50
7e	37.87	8,556	8,468	8,697	20.23	18.78	22.04
Area-weighted mean		8,733			21.21	19.66	23.25
Subtotal	89.57						

Table 1. Areas, elevations, and mean annual precipitation estimates for Straight Creek drainage basin subwatersheds.—Continued

[NGVD 29, National Geodetic Vertical Datum of 1929]

Subwatershed (figure 2)	Area (acres)	Elevation (in feet above NGVD 29)			Mean annual precipitation (inches)		
		Mean	Minimum	Maximum	Equation 1 (Johnson, 1998)	Equation 2 (Robertson, 2001b)	[1]Equation 3
8a	27.96	8,921	8,542	9,498	22.24	20.61	24.14
8b	7.64	8,702	8,533	8,974	21.04	19.51	22.86
8c	16.87	8,511	8,454	8,654	19.98	18.56	21.90
Area-weighted mean		8,757			21.34	19.79	23.23
Subtotal	52.47						

[1]Pete Stewart (U.S. Forest Service, written commun., 1984), cited in Wasiolek (1995, p. 15).

slope faces and is relevant to the intensity of the sun's energy on the slope. The seasons are December through February for winter, March through May for spring, June through August for summer, and September through November for fall. The mean annual precipitation calculated for the subwatersheds was divided into seasonal precipitation by assuming the same proportionate distribution as the 1961-90 normal precipitation for the Red River weather station. This resulted in 16.9 percent of mean annual precipitation in winter, 24.0 percent in spring, and 59.1 percent in summer and fall (table 2). The graphical technique uses separate graphs for different energy aspects (high-, intermediate-, or low-energy aspects) and seasons. Because of the altitude of Straight Creek, none of the subwatersheds have high-energy aspects. South-facing slopes are considered to have an intermediate energy aspect, and east-, west-, and north-facing slopes are considered to have low-energy aspects. The aspect of each of the 10-meter DEM grid cells in the Straight Creek watershed was determined on the basis of the maximum gradient to adjacent grid cells. The percentages of each subwatershed with an intermediate-energy aspect (south-facing slopes) and a low-energy aspect (east-, west-, and north-facing slopes) then were calculated. The mean seasonal evapotranspiration for the subwatershed then was calculated by weighting the seasonal evapotranspiration by energy aspect with those percentages. The resulting seasonal and annual evapotranspiration for each subwatershed is listed in table 2. Evapotranspiration for the subwatersheds as estimated by the Troendle and Leaf (1980) method, ranges from about 57 percent (subwatershed 1a) to about 76 percent (subwatersheds 7e and 8c) of mean annual precipitation.

MacDonald and Stednick (2003) defined the relation between annual precipitation and evapotranspiration in the mixed conifer forest of the Fraser Experimental Forests of Colorado. The relation is based on comparisons by Troendle and Reuss (1997, p. 331) between water outflow from forested and clearcut plots at an elevation of about 9,500 feet. MacDonald and Stednick (2003) estimated that the point of zero discharge, where evapotranspiration equals precipitation, to be 18.2 inches and that 28 percent of precipitation above that amount contributes to increased evapotranspiration rather than outflow. The equation given by MacDonald and Stednick [2003, p. 7; ET = 460 mm + 0.28 (P – 460 mm)] is converted to units of inches as follows:

$$ET = 18 + 0.28(P - 18) \quad (4)$$

Where:

ET = evapotranspiration, in inches; and
P = annual precipitation, in inches.

MacDonald and Stednick (2003) explained that annual precipitation of as much as 18 inches is used for evapotranspiration, either transpiration by vegetation or evaporation from soil. About 28 percent of the annual precipitation greater than 18 inches is intercepted by vegetation and is lost to evaporation. The remainder is watershed yield from the basin. Absence of vegetation to intercept precipitation would allow a decrease in evapotranspiration of the 28 percent of the annual precipitation greater than 18 inches. MacDonald and Stednick (2003, p. 8) stated that the consistency between equation 4 (their equation 2) and the paired watershed studies in the Rocky Mountains indicates the threshold of 18 to 19 inches of annual precipitation before watershed yield (and, therefore, evapotranspiration) can be affected by forest thinning. Additionally, they indicated this result is consistent with the threshold (18 to 20 inches) suggested by Bosch and Hewlett (1982) in their analyses of a wide range of conifer forests. Bosch and Hewlett (1982, p. 4) stated that different relations exist between watershed yield, forest cover, and precipitation for different vegetation types (such as conifer, deciduous hardwood, or scrub). Therefore, equation 4 is applicable only to conifer vegetation. Because the Straight Creek watershed consists of conifer vegetation (ponderosa pine, mixed conifer, and spruce-fir), the average watershed elevation is consistent with the study sites for which equation 4 was developed (the area-weighted average elevation is 9,400 feet compared to 9,500 feet above NGVD 29 for the study sites), and the watershed is within the Rocky Mountain region, equation 4 is applicable to the Straight Creek watershed.

Table 2. Evapotranspiration estimated by the Troendle and Leaf (1980) method.

Subwatershed (figure 2)	Area (acres)	Mean annual precipitation (inches) (Johnson, 1998)	Mean winter precipitation (inches)	Mean spring precipitation (inches)	Mean summer and fall precipitation (inches)	Percent area with inter-mediate energy aspect	Percent area with low-energy aspect	Mean winter evapo-transpiration (inches)	Mean spring evapo-transpiration (inches)	Mean summer and fall evapo-transpiration (inches)	Mean annual evapo-transpiration (inches)	Mean annual evapo-transpiration (percent precipitation)
1a	66.49	27.85	4.71	6.67	16.46	9	91	1.44	5.26	9.30	16.00	57.46
1b	25.84	27.21	4.60	6.52	16.08	40	60	1.56	5.34	9.30	16.20	59.55
1c	169.15	28.33	4.79	6.79	16.75	43	57	1.57	5.48	9.30	16.35	57.71
1d	11.04	25.11	4.25	6.02	14.85	38	62	1.55	5.08	9.30	15.93	63.43
1e	108.73	24.68	4.17	5.92	14.59	31	69	1.52	5.00	9.30	15.82	64.09
1f	12.22	22.85	3.86	5.48	13.51	44	56	1.57	4.78	9.30	15.65	68.53
Area-weighted mean		26.91									16.10	59.84
Subtotal	393.47											
2a	7.37	23.44	3.96	5.62	13.86	17	83	1.47	4.78	9.30	15.55	66.34
2b	14.30	27.98	4.73	6.71	16.54	51	49	1.60	5.47	9.30	16.37	58.54
2c	16.41	24.31	4.11	5.83	14.37	31	69	1.52	4.94	9.30	15.76	64.87
2d	4.23	22.03	3.73	5.28	13.03	42	58	1.57	4.65	9.30	15.52	70.43
Area-weighted mean		25.17									15.91	63.21
Subtotal	42.31											
3a	7.12	24.86	4.20	5.96	14.70	37	63	1.55	5.04	9.30	15.89	63.92
3b	3.06	23.41	3.96	5.61	13.84	44	56	1.58	4.87	9.30	15.75	67.24
3c	4.78	22.62	3.83	5.42	13.38	16	84	1.47	4.67	9.30	15.44	68.21
3d	15.67	23.28	3.94	5.58	13.76	40	60	1.56	4.83	9.30	15.69	67.43
3e	7.88	21.74	3.68	5.21	12.85	41	59	1.57	4.61	9.30	15.48	71.16
Area-weighted mean		23.19									15.66	67.53
Subtotal	38.51											
4a	3.19	21.95	3.71	5.26	12.98	33	67	1.53	4.62	9.30	15.45	70.38
4b	3.15	22.16	3.75	5.31	13.10	42	58	1.57	4.67	9.30	15.54	70.14
4c	7.09	21.26	3.60	5.10	12.57	53	47	1.61	4.56	9.30	15.47	72.76
Area-weighted mean		21.64									15.48	71.56
Subtotal	13.43											

Table 2. Evapotranspiration estimated by the Troendle and Leaf (1980) method.—Continued

Subwatershed (figure 2)	Area (acres)	Mean annual precipitation (inches) (Johnson, 1998)	Mean winter precipitation (inches)	Mean spring precipitation (inches)	Mean summer and fall precipitation (inches)	Percent area with inter-mediate energy aspect	Percent area with low-energy aspect	Mean winter evapo-transpiration (inches)	Mean spring evapo-transpiration (inches)	Mean summer and fall evapo-transpiration (inches)	Mean annual evapo-transpiration (inches)	Mean annual evapo-transpiration (percent precipitation)
5a	14.32	23.08	3.90	5.53	13.65	38	62	1.55	4.80	9.30	15.65	67.80
5b	2.97	23.15	3.91	5.55	13.69	50	50	1.60	4.85	9.30	15.75	68.02
5c	5.92	21.69	3.67	5.20	12.82	58	42	1.63	4.65	9.30	15.58	71.82
5d	10.59	20.96	3.54	5.02	12.39	58	42	1.63	4.52	9.30	15.45	73.74
Area-weighted mean		22.18									15.58	70.27
Subtotal	33.80											
7a	0.53	21.21	3.59	5.08	12.54	50	50	1.60	4.54	9.30	15.44	72.83
7b	0.55	20.82	3.52	4.99	12.31	68	32	1.67	4.52	9.30	15.49	74.42
7c	41.38	21.68	3.67	5.20	12.82	0	100	1.40	4.48	9.30	15.18	70.02
7d	9.24	23.10	3.91	5.54	13.66	0	100	1.40	4.68	9.30	15.38	66.58
7e	37.87	20.23	3.42	4.85	11.96	67	34	1.67	4.42	9.30	15.39	76.05
Area-weighted mean		21.21									15.29	72.11
Subtotal	89.57											
8a	27.96	22.24	3.76	5.33	13.15	54	46	1.62	4.72	9.30	15.64	70.31
8b	7.64	21.04	3.56	5.04	12.44	0	100	1.40	4.39	9.30	15.09	71.72
8c	16.87	19.98	3.38	4.79	11.81	50	50	1.60	4.33	9.30	15.23	76.24
Area-weighted mean		21.34									15.43	72.30
Subtotal	52.47											

The lack of vegetation in the scar areas results in the absence of vegetation to intercept precipitation and allows evaporation as described previously. Therefore, evapotranspiration in the scar areas is reduced compared with evapotranspiration in the non-scar areas. The estimated mean annual evapotranspiration for each subwatershed is listed in table 3. Evapotranspiration for the subwatersheds, as estimated by the MacDonald and Stednick (2003) method (eq. 4), ranges from about 66 percent (subwatershed 1b, a scar area) to about 93 percent (subwatershed 8c) of mean annual precipitation.

The two methods used to estimate evapotranspiration result in a wide range of estimated values for all subwatersheds—from a low of about 15 inches per year (table 2) to a high of almost 21 inches per year (table 3). The values estimated for each subwatershed using the MacDonald and Stednick (2003) method (eq. 4) range from about 11 to 30 percent larger and average about 22 percent larger than those estimated using the Troendle and Leaf (1980) method. This range in values illustrates the uncertainty involved in estimating evapotranspiration. The MacDonald and Stednick (2003) method (eq. 4) is considered to be the most reasonable method of estimation for this study because (1) equation 4 was developed by comparison of watersheds that have differing amounts of vegetation removal, thus allowing better understanding of vegetation-watershed yield-precipitation relations, and (2) the effects of vegetation removal on evapotranspiration and watershed yield are applicable to the scar areas in the Straight Creek watershed.

Watershed Yield

For the purpose of this study, watershed yield is defined as the total surface-water and ground-water discharge produced by the watershed. It is equivalent to precipitation minus evapotranspiration.

Empirical equations that relate watershed yield to elevation and precipitation have been developed and used for areas in the Sangre de Cristo Mountains in northern New Mexico and southern Colorado. Robertson GeoConsultants, Inc. (2001b, fig. 4) developed and used the following equation for the mine site:

$$MAY = 0.00905\ (10^{0.000276\,E}) - 0.9 \qquad (5)$$

Where:

MAY = mean annual watershed yield, in inches; and
E = average basin elevation, in feet.

The mean annual watershed yield estimated for each subwatershed using equation 5 is listed in table 4. The watershed yield estimated for the subwatersheds using this method ranges from about 6 (subwatersheds 5d, 7b, 7e, and 8c) to 15 (subwatersheds 1a, 1c, and 2b) percent of mean annual precipitation.

Hearne and Dewey (1988, eq. 8) developed an empirical equation that relates mean annual watershed yield to basin area and mean winter precipitation using streamflow-gaging stations in the Sangre de Cristo Mountains. The equation is as follows:

$$Q = 7.62 \times 10^{-5}\ (A^{0.977})\ (P^{3.596}) \qquad (6)$$

Where:

Q = mean annual watershed yield, in cubic feet per second;
A = basin area, in square miles; and
P = mean winter precipitation, in inches.

The mean winter precipitation variable (P) is, as defined by the U.S. Weather Service, October through April precipitation. The basin-area variable (A) raised to the 0.977 power has the effect of increasing calculated yield for basins of less than 1 square mile and decreasing yield for basins of greater than 1 square mile but has no effect for basins of 1 square mile. The watershed area considered in the water-budget analysis for Straight Creek is about 1 square mile (about 660 acres or 1.03 square miles). Therefore, the area term has an insignificant effect on the estimated watershed yield for the entire watershed. Because the use of equation 6 in this study is to simply divide the watershed yield into components from each subwatershed (all subwatersheds are substantially less than 1 square mile in area), use of the area term raised to the 0.977 power would artificially increase the total watershed yield estimated from the sum of the yield for each subwatershed. Therefore, equation 6 was modified for use in this study as follows:

$$Q = 7.62 \times 10^{-5}\ A\ (P^{3.596}). \qquad (7)$$

Equation 7 then was modified to calculate mean annual watershed yield, in inches as follows:

$$MAY = 8.694 \times 10^{3}\ (Q / SA) \qquad (8)$$

Where:

Q = mean annual watershed yield, in cubic feet per second;
MAY = mean annual watershed yield, in inches; and
SA = subwatershed area, in acres.

The mean annual watershed yield estimated for each subwatershed using equation 8 is listed in table 4. The watershed yield estimated for the subwatersheds using this method ranges from about 16 (subwatershed 8c) to 40 (subwatershed 1c) percent of mean annual precipitation.

The two methods used to estimate watershed yield result in a wide range of estimated values for the subwatersheds. Watershed yield estimated using equation 8 is about 2.6 to 2.9 times greater than that estimated using equation 5. That range illustrates the range in plausible values for mean annual watershed yield from the Straight Creek watershed.

A third method used to estimate watershed yield is to subtract evapotranspiration from precipitation. The watershed yield estimated using this method falls within

Table 3. Evapotranspiration estimated by the MacDonald and Stednick (2003) method.

Subwatershed (figure 2)	Area (acres)	Mean annual precipitation (inches) (Johnson, 1998)	Mean annual evapo-transpiration (inches) (MacDonald and Stednick, 2003)	Mean annual evapo-transpiration (percent precipitation)
1a	66.49	27.85	20.76	75
1b	25.84	27.21	18.00	66
1c	169.15	28.33	20.89	74
1d	11.04	25.11	18.00	72
1e	108.73	24.68	19.87	81
1f	12.22	22.85	19.36	85
Area-weighed mean		26.91	20.27	75
Subtotal	393.47			
2a	7.37	23.44	19.52	83
2b	14.30	27.98	20.79	74
2c	16.41	24.31	19.77	81
2d	4.23	22.03	19.13	87
Area-weighted mean		25.17	20.01	79
Subtotal	42.31			
3a	7.12	24.86	19.92	80
3b	3.06	23.41	18.00	77
3c	4.78	22.62	19.29	85
3d	15.67	23.28	19.48	84
3e	7.88	21.74	19.05	88
Area-weighted mean		23.19	19.33	83
Subtotal	38.51			
4a	3.19	21.95	19.11	87
4b	3.15	22.16	19.16	86
4c	7.09	21.26	18.91	89
Area-weighted mean		21.64	19.02	88
Subtotal	13.43			
5a	14.32	23.08	19.42	84
5b	2.97	23.15	18.00	78
5c	5.92	21.69	19.03	88
5d	10.59	20.96	18.83	90
Area-weighted mean		22.18	19.04	86
Subtotal	33.80			
7a	0.53	21.21	18.90	89
7b	0.55	20.82	18.79	90
7c	41.38	21.68	19.03	88
7d	9.24	23.10	18.00	78
7e	37.87	20.23	18.62	92
Area-weighted mean		21.21	18.75	88
Subtotal	89.57			
8a	27.96	22.24	19.19	86
8b	7.64	21.04	18.85	90
8c	16.87	19.98	18.55	93
Area-weighted mean		21.34	18.94	89
Subtotal	52.47			

the range estimated by the previous two methods (table 4). The estimates for the subwatersheds of the scar areas (subwatersheds 1b, 1d, 3b, 5b, and 7d), accounting for lack of vegetation in the scars, are nearly as large as the estimates from equation 8, whereas the estimates for the non-scar subwatersheds are near the mid-range of the estimates from equations 5 and 8. The watershed yields estimated from equation 4 are considered to be the most appropriate estimates for this study for the same reasons stated previously, in the "Evapotranspiration" section of this report.

Surface Water

Straight Creek has perennial flow through the scar area and onto the debris fan at the upper end of the west fork (fig. 2). The stream becomes intermittent on the upper part of the debris fan and is ephemeral through the middle and lower parts of the debris fan. The east fork of Straight Creek has rarely been observed to flow. However, a trickle of water was observed in October 2003. No continuous records of Straight Creek discharge are available; therefore, the volume of runoff during any time period cannot be determined.

Discharge of Straight Creek at site A on the west fork (fig. 2) was measured 18 times from May 2001 to December 2004 (table 7 in "Supplemental Information" section). Those measurements were made at irregular intervals; therefore, the average likely is not representative of any particular condition in the watershed. The discharge measurements ranged from 3.7 gallons per minute on August 20, 2002, to 91 gallons per minute on September 19, 2002, and averaged about 16 gallons per minute.

Robertson GeoConsultants, Inc. (2001a) conducted multiple measurements of Straight Creek discharge at four sites during 2000 (sites SC-0, SC-1, SC-2, and SC-4; fig. 2). The measurements indicated most of the discharge is from the upper scar areas (subwatersheds 1b and 1d; Robertson GeoConsultants, Inc. 2001a, p. 9). Robertson GeoConsultants, Inc. (2001a) used those measurements to calibrate rainfall-runoff and snowmelt models and estimated average annual discharge for water year 2000 at sites SC-1, SC-2, and SC-4 as 11, 5, and 2 gallons per minute, respectively. Their analysis of total runoff adjusted for diversions at the Red River streamflow-gaging station near Questa indicated runoff for water year 2000 was about 51 percent of the 30-year average. Applying this factor to the estimated 2000 discharges result in estimated mean annual discharges at sites SC-1, SC-2, and SC-4 to be about 22, 10, and 4 gallons per minute, respectively.

Ground-Water Flow

The ground-water system in the Straight Creek watershed (fig. 4) consists of (1) the debris-flow aquifer along Straight Creek, (2) the shallow fractured and weathered bedrock (regolith) in the upper areas of the watershed and underlying the debris-flow deposits, and (3) a deep bedrock system underlying the entire watershed. At the mouth of Straight Creek, the debris-flow aquifer interfingers with the Red River alluvium, which is underlain by the regolith (fig. 4). The primary focus of this study is the debris-flow aquifer underlying Straight Creek. However, the regolith below the debris-flow deposits is hydraulically well connected to the debris-flow aquifer as evidenced by the tracking of water levels in the Straight Creek well nests (lower Straight Creek aquifer test archive, files of the USGS New Mexico

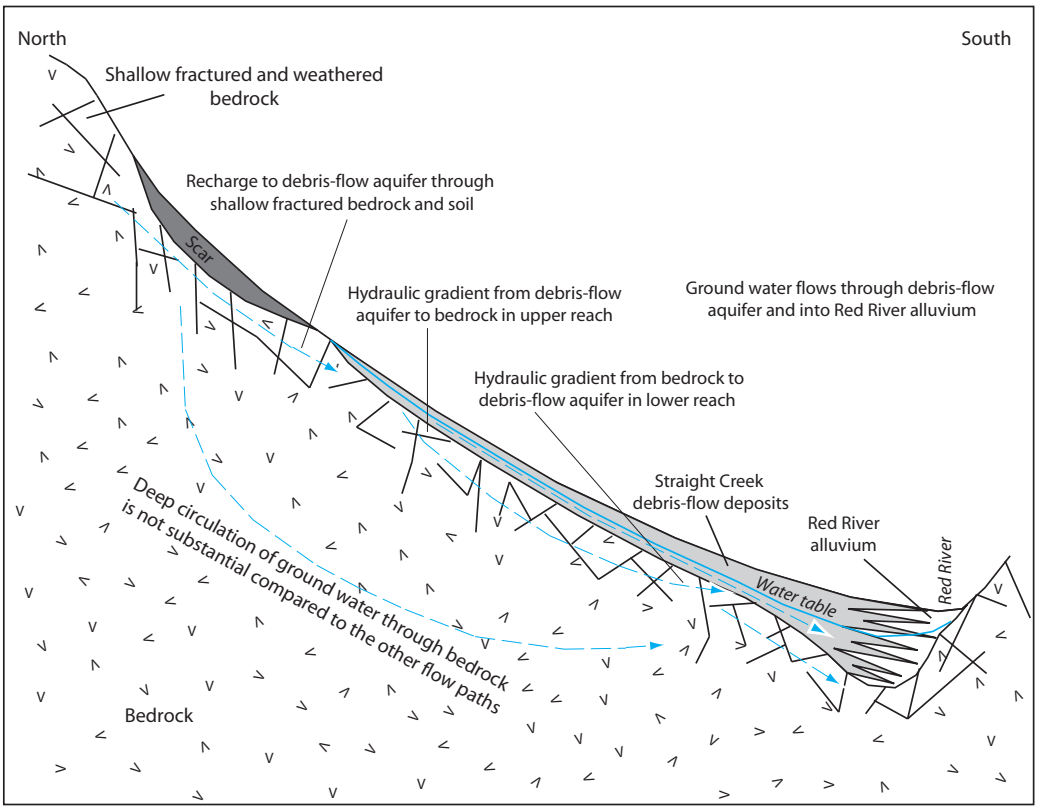


Figure 4. Conceptualized ground-water flow paths along section of Straight Creek.

Table 4. Mean annual watershed yield estimated using various methods.

[NGVD 29, National Vertical Datum of 1929]

Subwatershed (figure 2)	Area (acres)	Mean elevation (in feet above NGVD 29)	Mean annual precipitation (inches) (Johnson, 1998)	Mean annual watershed yield calculated using equation 5 (inches)	Mean annual watershed yield calculated using equation 8 (inches)	Mean annual watershed yield calculated as precipitation minus evapo-transpiration (equation 4) (inches)	Mean annual watershed yield calculated using equation 5 (percent precipitation)	Mean annual watershed yield calculated using equation 8 (percent precipitation)	Mean annual watershed yield calculated as precipitation minus evapo-transpiration (percent precipitation)
1a	66.49	9,936	27.85	4.10	10.75	7.09	15	39	25
1b	25.84	9,820	27.21	3.74	9.88	9.21	14	36	34
1c	169.15	10,024	28.33	4.39	11.44	7.44	15	40	26
1d	11.04	9,441	25.11	2.75	7.41	7.11	11	30	28
1e	108.73	9,363	24.68	2.57	6.97	4.81	10	28	19
1f	12.22	9,030	22.85	1.91	5.27	3.49	8	23	15
Area-weighted mean		9,766	26.91	3.67	9.68	6.64	13	36	24
Subtotal	393.47								
2a	7.37	9,137	23.44	2.11	5.78	3.91	9	25	17
2b	14.30	9,960	27.98	4.18	10.93	7.19	15	39	26
2c	16.41	9,295	24.31	2.43	6.59	4.54	10	27	19
2d	4.23	8,883	22.03	1.66	4.63	2.90	8	21	13
Area-weighted mean		9,451	25.17	2.89	7.72	5.16	11	30	20
Subtotal	42.31								
3a	7.12	9,395	24.86	2.65	7.15	4.94	11	29	20
3b	3.06	9,133	23.41	2.10	5.76	5.41	9	25	23
3c	4.78	8,990	22.62	1.84	5.09	3.33	8	23	15
3d	15.67	9,108	23.28	2.05	5.64	3.80	9	24	16
3e	7.88	8,830	21.74	1.58	4.41	2.69	7	20	12
Area-weighted mean		9,092	23.19	2.04	5.61	3.85	9	24	17
Subtotal	38.51								

Table 4. Mean annual watershed yield estimated using various methods.—Continued

[NGVD 29, National Vertical Datum of 1929]

Subwatershed (figure 2)	Area (acres)	Mean elevation (in feet above NGVD 29)	Mean annual precipitation (inches) (Johnson, 1998)	Mean annual watershed yield calculated using equation 5 (inches)	Mean annual watershed yield calculated using equation 8 (inches)	Mean annual watershed yield calculated as precipitation minus evapo-transpiration (equation 4) (inches)	Mean annual watershed yield calculated using equation 5 (percent precipitation)	Mean annual watershed yield calculated using equation 8 (percent precipitation)	Mean annual watershed yield calculated as precipitation minus evapo-transpiration (percent precipitation)
4a	3.19	8,868	21.95	1.64	4.57	2.84	7	21	13
4b	3.15	8,905	22.16	1.70	4.72	2.99	8	21	14
4c	7.09	8,743	21.26	1.44	4.07	2.35	7	19	11
Area-weighted mean		8,811	21.64	1.55	4.34	2.62	7	20	12
Subtotal	13.43								
5a	14.32	9,073	23.08	1.99	5.47	3.66	9	24	16
5b	2.97	9,085	23.15	2.01	5.53	5.15	9	24	22
5c	5.92	8,821	21.69	1.56	4.38	2.66	7	20	12
5d	10.59	8,688	20.96	1.36	3.87	2.13	6	18	10
Area-weighted mean		8,909	22.18	1.72	4.78	3.14	8	21	14
Subtotal	33.80								
7a	0.53	8,733	21.21	1.43	4.03	2.31	7	19	11
7b	0.55	8,663	20.82	1.33	3.78	2.03	6	18	10
7c	41.38	8,819	21.68	1.56	4.37	2.65	7	20	12
7d	9.24	9,076	23.10	1.99	5.49	5.10	9	24	22
7e	37.87	8,556	20.23	1.18	3.41	1.60	6	17	8
Area-weighted mean		8,733	21.21	1.44	4.07	2.46	7	19	11
Subtotal	89.57								
8a	27.96	8,921	22.24	1.72	4.79	3.06	8	22	14
8b	7.64	8,702	21.04	1.38	3.92	2.19	7	19	10
8c	16.87	8,511	19.98	1.12	3.26	1.43	6	16	7
Area-weighted mean		8,757	21.34	1.48	4.17	2.40	7	19	11
Subtotal	52.47								

Water Science Center, Albuquerque) and therefore, must be considered as part of the aquifer system that transmits water into the alluvial-regolith aquifer system along the Red River. Circulation of ground water through the deep bedrock along Straight Creek may exist but it is likely small in comparison to the amount of water transmitted through the debris-flow aquifer, regolith, and shallow fractured bedrock. Robertson GeoConsultants, Inc. (2001a) estimated the amount of flow through deep bedrock to be less than 1 percent of the overall water budget of Straight Creek. No additional information is available to further refine estimates of this amount. For the purposes of this report, the quantity of water transmitted through the deep bedrock of Straight Creek is considered unsubstantial compared to the amount transmitted through the debris-flow aquifer, underlying regolith, and shallow fractured bedrock.

The debris-flow aquifer in Straight Creek consists of poorly sorted debris-flow deposits that range in size from clay to large boulders. Surface-water flow on top of the debris-flow deposits washes out the fine-grained sediment, leaving coarse-grained sand and gravel. Coarse-sediment channels are buried throughout the debris-flow aquifer and may provide preferential pathways for ground water to flow; however, the distribution of these channels is unknown. Because of the reduced width of the upstream debris fan compared to that of the downstream debris fan along Straight Creek, the surface-water channels upstream likely are a larger percentage of the width of the debris fan. Therefore, it is reasonable to assume the volume of the coarse sediment within the debris fan relative to the debris fan itself increases in the upstream direction in the debris-flow aquifer.

Recharge to the ground-water system in the Straight Creek watershed originates as precipitation over the watershed. Water that does not run off as surface water and is not evapotranspired becomes ground water. In the upper parts of Straight Creek watershed, ground water moves through the soil and shallow fractured bedrock (fig. 4). This shallow ground water either evapotranspires, returns to surface flow, recharges the debris-flow aquifer, continues to move through the regolith, or recharges the shallow fractured bedrock below the debris-flow deposits.

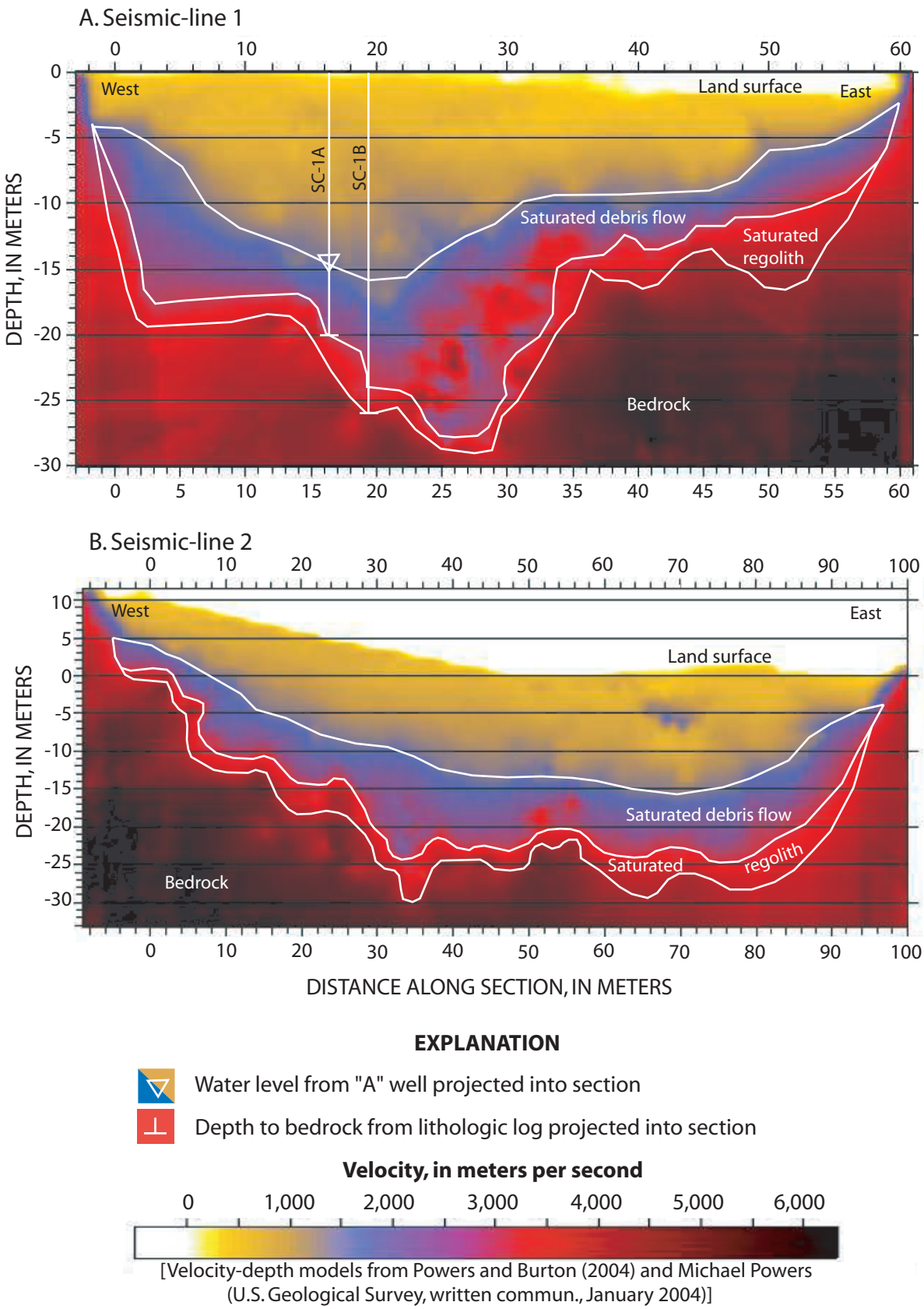
Some of the ground water in the soils and shallow fractured bedrock discharges as surface water in the upper parts of the watershed. The perennial flow of the west fork of Straight Creek is a result of this type of discharge. As the surface water in the west fork flows over the debris fan, surface water readily infiltrates into and recharges the debris-flow aquifer. Except for runoff during thunderstorms, surface water from the west fork of Straight Creek was observed over the duration of this study to completely infiltrate into the debris-flow aquifer upstream from the confluence with the east fork.

Some ground water in the shallow fractured bedrock also continues to flow through the bedrock, presumably in the downslope direction. Part of this water recharges the debris-flow aquifer along the margins of the Straight Creek Valley. A portion of the water likely continues to flow into the regolith beneath the debris-flow aquifer and continues toward the Red River Valley. A component of the ground water in the regolith may flow into a shallow fractured bedrock system (fig. 4), which presumably would discharge to the regolith and alluvium along the Red River. Ground water interacts between the debris-flow aquifer and the underlying regolith as it moves toward the Red River Valley.

Ground water in the debris-flow aquifer continues to flow through the debris-flow deposits toward the Red River Valley. A component of this flow moves from the debris-flow deposits and into the underlying shallow bedrock in the upper part of the Straight Creek Valley. This is evidenced by the downward gradient from the debris-flow aquifer to the underlying bedrock in wells SC-1A and B and SC-3A and B (fig. 3). In the lower reaches of the Straight Creek Valley, the hydraulic gradient is upward and water moves from the shallow bedrock to the debris-flow aquifer as evidenced by hydraulic gradients in wells SC-5A and B. The downward movement of water in the upper part of Straight Creek and the upward movement of water in the lower reaches of Straight Creek also is evidenced by the chemistry of water sampled in the SC wells (Naus and others, 2005). The part of the bedrock that transmits water below the debris-flow deposits is considered to be the highly fractured upper part of the bedrock rather than the deep bedrock system.

The water table is substantially below land surface in the debris-flow aquifer except in the upper end of the debris-flow deposits in the west fork. Water levels measured in wells range from about 50 feet (SC-1A) to about 150 feet (SC-5A) below land surface. Although no wells were drilled in the debris-flow aquifer in the west fork of Straight Creek, the water table likely is very near land surface in the upper reaches of the debris-flow aquifer in that area. This is evidenced by the perennial nature of Straight Creek on the upper west fork debris fan and the observation that the stream often disappears and then reappears near the lowest reach of perennial surface-water flow.

Powers and Burton (2004) and Michael Powers (U.S. Geological Survey, written commun., January 2004) interpreted seismic data along sections across the Straight Creek debris flow and the Red River Valley near the mouth of Straight Creek (fig. 2). These interpreted seismic profiles (fig. 5) provide a means by which the cross-section areas of saturated ground-water flow can be calculated. Seismic-lines 1-5 and 7-9 were used. Seismic-line 6 was not used in the water-budget analysis because it extended at an angle from the north end of line 7 to the south end of line 9 and does not fit the requirement of being substantially orthogonal to the valley. The descriptive interpretations of the color interfaces for the water table, debris-flow depost/bedrock contact, and the consolidated bedrock contact by Powers and Burton (2004) were used as a guide to digitize the cross-section areas of the saturated debris-flow deposits and saturated regolith. Water levels (of the time closest to the time of the seismic surveys) from the Straight Creek wells and picks of geologic contacts



[Velocity-depth models from Powers and Burton (2004) and Michael Powers (U.S. Geological Survey, written commun., January 2004)]

Figure 5. Velocity-depth models from seismic data collected near Straight Creek.

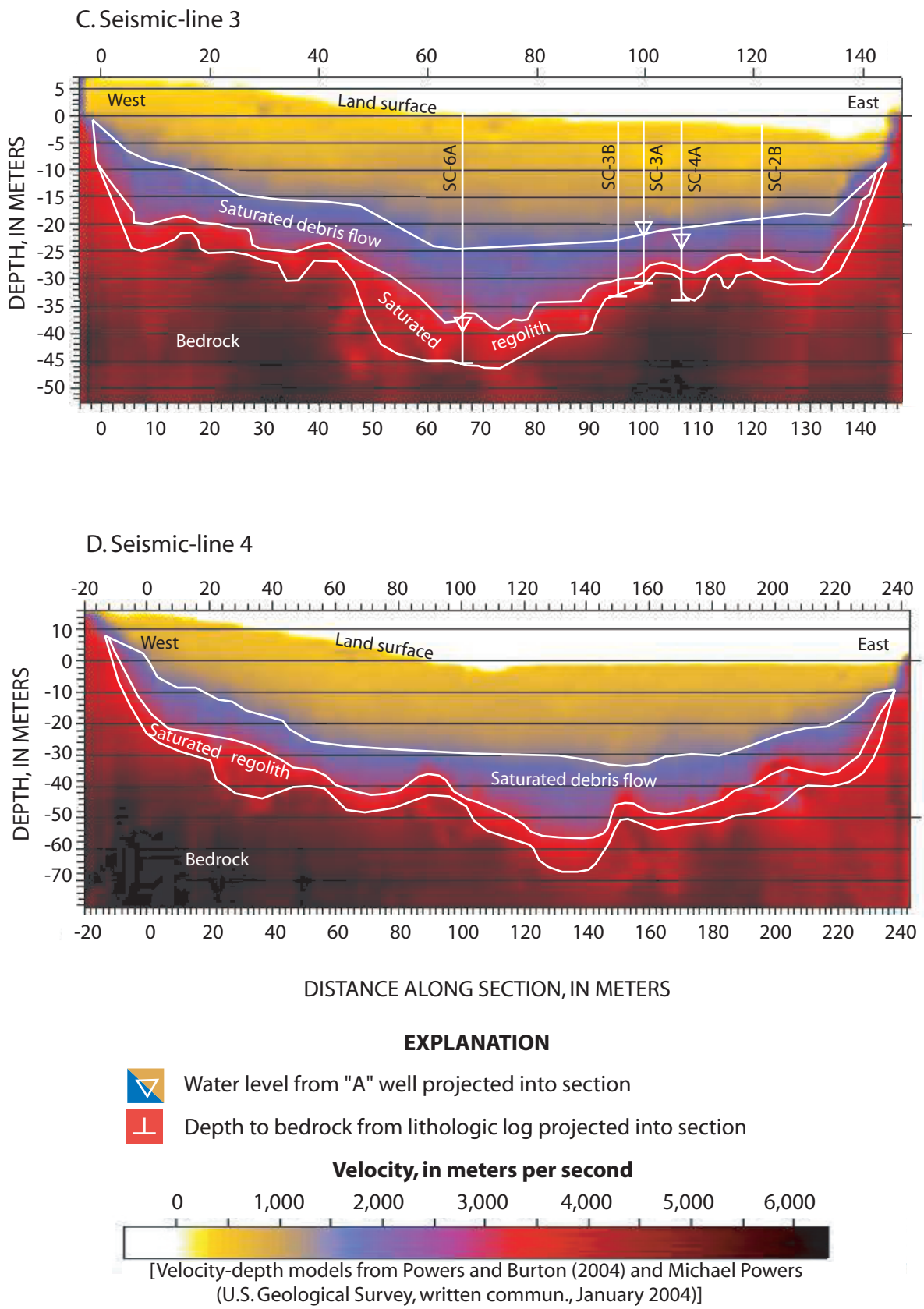
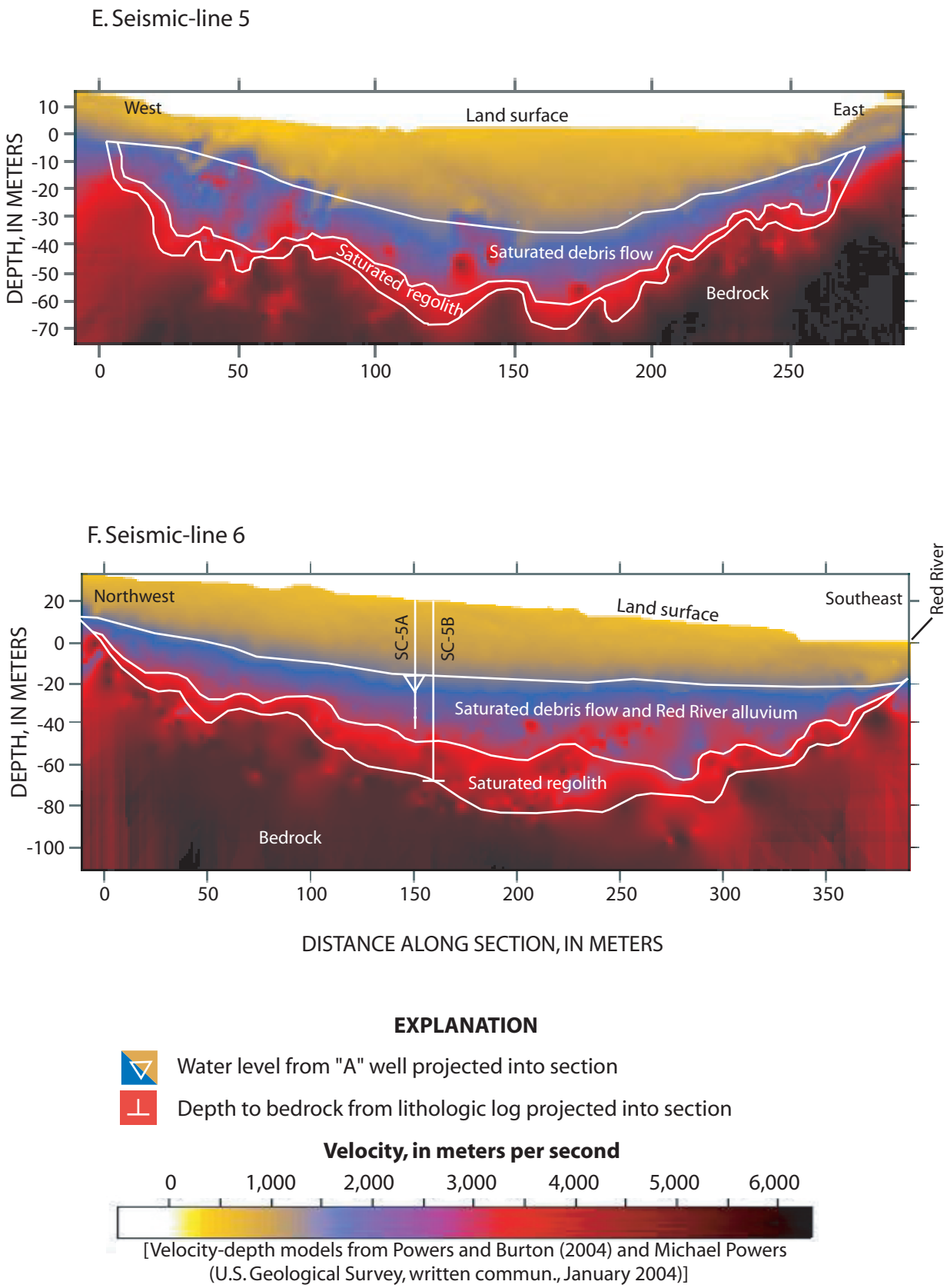


Figure 5. Velocity-depth models from seismic data collected near Straight Creek—Continued.



[Velocity-depth models from Powers and Burton (2004) and Michael Powers (U.S. Geological Survey, written commun., January 2004)]

Figure 5. Velocity-depth models from seismic data collected near Straight Creek—Continued.

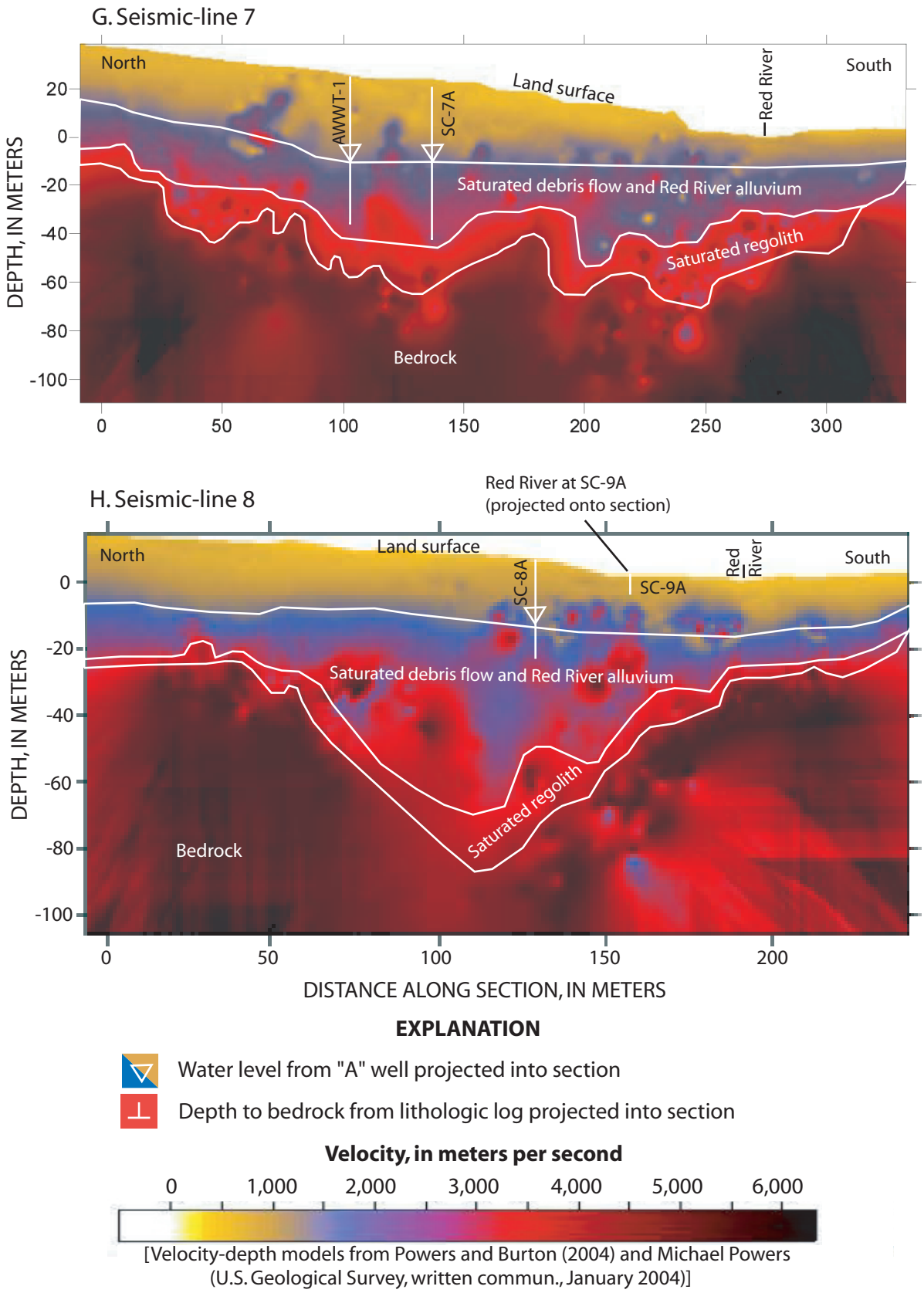


Figure 5. Velocity-depth models from seismic data collected near Straight Creek—Continued.

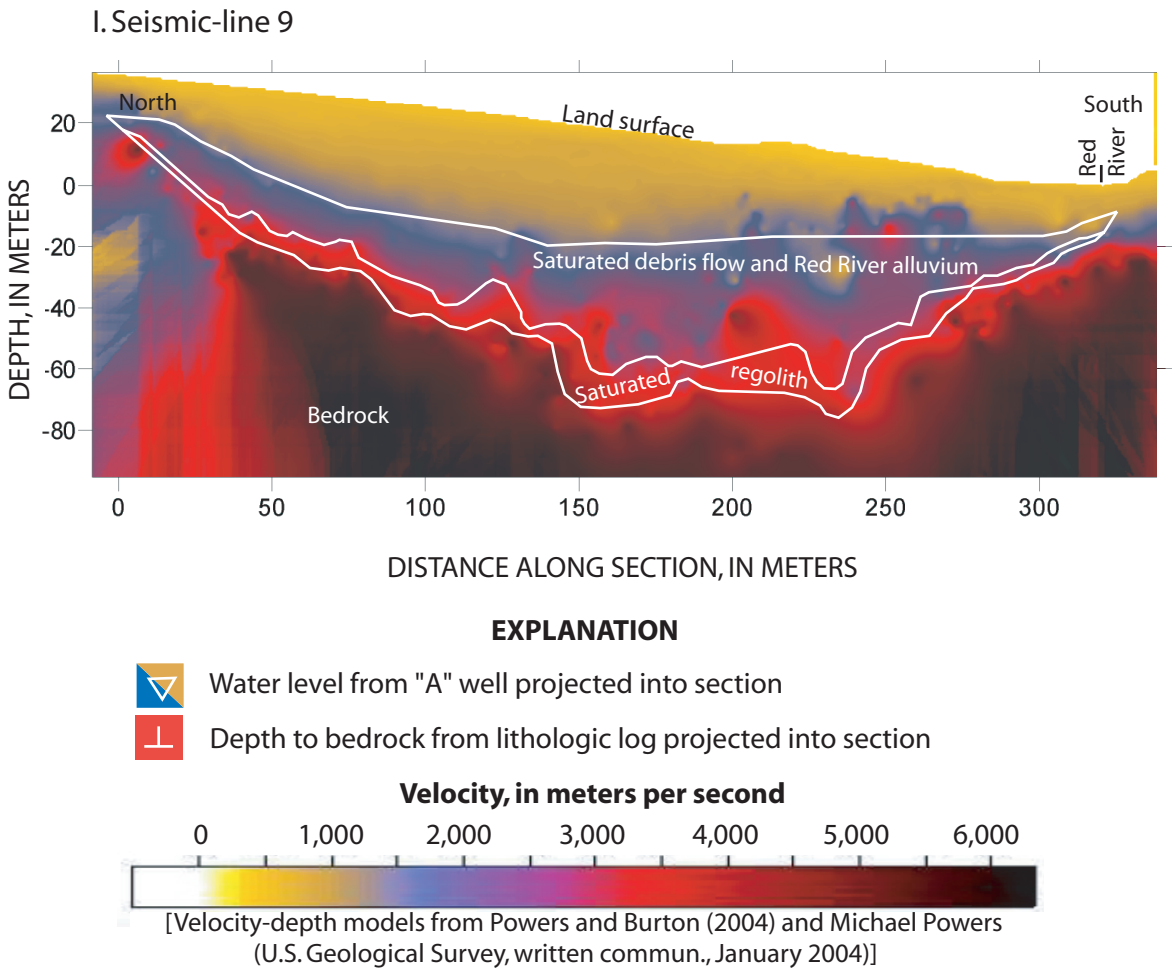


Figure 5. Velocity-depth models from seismic data collected near Straight Creek—Continued.

from the lithologic logs of the wells were superimposed on the interpreted seismic sections to help guide the digitizing (fig. 5). The cross-section areas estimated for the debris-flow deposits and the underlying regolith along the seismic lines are listed in table 8 of the "Supplemental Information" section of this report. For use in the water-budget analysis, the cross-section areas were adjusted to correspond with a section line that would be orthogonal across the valley, the orientation assumed to be perpendicular to the major component of ground-water flow. The correction factors ranged from 0.948 times the digitized areas for line 3 to 1.000 (no correction) for lines 5 and 9 (table 8). The cross-section areas of these seismic sections provide a basis to evaluate ground-water flow as it moves toward and down the Red River Valley.

There is a substantial unsaturated zone below the Red River alluvium that extends beyond the area surveyed by the seismic lines (fig. 2); therefore, the Red River does not have direct saturated hydraulic connection to the alluvium and debris-flow aquifer at the mouth of Straight Creek. The unsaturated zone is identified by well SC-9A, which was drilled directly below the Red River. The well has been dry except for one water-level measurement, which was greater than 15 feet below river level. The unsaturated zone also is identified in all of the seismic lines that cross the Red River (lines 6-9; fig. 5 F-I).

Aquifer Characteristics

The primary focus of this study is the debris-flow aquifer in Straight Creek. The debris-flow deposits have low hydraulic conductivity, calculated to be about 0.3 foot per day in well SC-3A and 0.7 foot per day in well SC-1A (Straight Creek slug test archive, files of USGS New Mexico Water Science Center, Albuquerque). Both wells were completed in primarily debris-flow deposits. Coarse-grained channels within the debris-flow deposits have substantially higher hydraulic conductivity than the debris-flow deposits. Such channels likely were encountered in well SC-4A (middle well cluster, fig. 3). The hydraulic conductivity of the sediment encountered in that well was calculated from slug tests to be

about 30 feet per day (Straight Creek slug test archive, files of USGS New Mexico Water Science Center, Albuquerque). The calculated hydraulic conductivity for well SC-4A likely is a composite value that is representative of alternating intervals of debris-flow deposits and coarse channels. An isolated interval of only coarse-grained channel deposits likely would have substantially higher hydraulic conductivity than 30 feet per day.

The debris-flow aquifer interfingers with the Red River alluvial aquifer at the lower end of Straight Creek. Hydraulic conductivity of the Red River alluvium at the lower end of Straight Creek was calculated to average about 340 feet per day from an aquifer test conducted in the lower well cluster (wells including and south of SC-5A) shown in figure 3 (lower Straight Creek aquifer test archive, files of the USGS New Mexico Water Science Center, Albuquerque). Hydraulic conductivities of the alluvium along other reaches of the Red River compiled from consulting reports ranges from about 150 to 860 feet per day (Cheryl Naus, U.S. Geological Survey, written commun., 2003).

Hydraulic conductivity of the bedrock underlying the debris-flow aquifer in Straight Creek was calculated to range from 0.005 to 0.3 foot per day from slug tests conducted in the bedrock wells (Straight Creek slug test archive, files of USGS New Mexico Water Science Center, Albuquerque). These values are representative of the number and characteristics of the fractures encountered at the open interval of the wells. Larger values of hydraulic conductivity possibly may exist within fracture systems missed by the well openings.

With the exception of well SC-5B (lower well cluster), the bedrock wells (including AWWT-2) show significant response to barometric pressure changes, indicating the bedrock aquifer underlying the debris-flow aquifer is semi-confined (lower Straight Creek aquifer test archive, files of the USGS New Mexico Water Science Center, Albuquerque). Wells completed in the debris-flow deposits at the upper and middle well clusters also respond to barometric pressure changes, indicating that parts of the debris-flow aquifer also are semi-confined. The semi-confined nature of the aquifer is not surprising, given that zones within the debris-flow aquifer would be confined by the fairly impermeable debris-flow deposits. Water levels in wells that penetrate the debris-flow deposits and Red River alluvium at the lower well cluster (including AWWT-1) show no response to barometric pressure changes, indicating these wells are completed in or are hydraulically well connected to the unconfined Red River alluvial aquifer. Well AWWT-1 is reported to be completed in fractures at the base of the alluvial aquifer (lower Straight Creek aquifer test archive, files of the USGS New Mexico Water Science Center, Albuquerque). However, water levels in this well respond quickly to changes in alluvium water levels. The response of water levels in wells SC-5B and AWWT-1 (both completed in bedrock) indicate there likely is a permeable fractured and weathered zone of bedrock beneath the Red River alluvium.

Ground-Water Budget for the Straight Creek Drainage Basin

The approach to the water budget of Straight Creek assumes steady-state and mean annual conditions. The water-budget components are evaluated for the cross sections defined by the seismic lines (fig. 2). The emphasis of the water budget is ground-water flow in the debris-flow aquifer and underlying regolith and the comparison of ground-water flow in the alluvium along the Red River. The components of the water budget are precipitation, evapotranspiration, surface-water flow, and ground-water flow. Watershed yield is defined as mean annual precipitation minus evapotranspiration and is equivalent to the total surface-water and ground-water discharge.

The water budget for Straight Creek evaluated sequentially in the downstream direction at each of the seismic sections (fig. 2) is listed in table 5. The basis for the calculation of the ground-water component of the water budget at each cross section is Darcy's Law (Freeze and Cherry, 1979, p. 15) using the cross-section areas, hydraulic gradients, and hydraulic conductivities for the debris-flow aquifer and regolith. The calculated watershed yield upgradient from each section is divided into surface-water and ground-water components. The surface-water component is estimated on the basis of the available information. The ground-water flow through the defined section of debris-flow aquifer and regolith underlying the debris flow is calculated. The watershed yield not attributed to surface water or to ground-water flow through the defined section is considered to be flow through the fractured bedrock below the depth that could be defined by the seismic soundings and is not considered to be ground-water flow through deep bedrock.

The cross-section area of saturated debris-flow deposits, a combination of saturated debris-flow deposits and alluvium along Straight Creek, and the regolith were estimated for each of the seismic lines (fig. 5). Corrections to the cross-section areas, ranging from 0.948 to 1.00 (no correction), were made so the areas represent an orthogonal section across the valley. The calculated areas and the correction factors applied to each section are listed in table 8 in the "Supplemental Information" section of this report.

Wells were not associated with all seismic lines and, therefore, water levels measured from the wells could not be used consistently to determine hydraulic gradients to calculate ground-water flow at the sections. The seismic sections were determined to be the most consistent way to determine hydraulic gradient for all sections. The water-level depth below land surface measured from the seismic sections and the land-surface elevations from 10-meter DEMs were used to determine hydraulic head at about 5-meter intervals along the sections. These head determinations were used to calculate mean head at each cross section and then mean hydraulic gradient between the cross sections. The mean, maximum,

Table 5. Water budget for Straight Creek.

[A, area; ft^2, square feet; L, distance from previous line; ft, feet; H, head; H_1, head in the upstream direction; H_2, head in the downstream direction; Q, discharge; K, hydraulic conductivity; gal/min, gallons per minute]

Seismic line number (figure 2)	Debris-flow cross-section area, A (ft^2)	Regolith cross-section area, A (ft^2)	Distance from previous line, L (ft)	Head at line, H (ft)	Head gradient (H_1-H_2)/L (ft/ft)	Discharge, Q=KA(H_1-H_2)/L (gal/min)	Increase in Q from previous line (gal/min)	Contributing watershed area between lines (acres)	Scar area between lines (acres)	Watershed yield from non-scar areas between lines (gal/min)	Watershed yield from scar areas between lines (gal/min)	Total incremental watershed yield (gal/min)	Mean surface-water flow (gal/min)	Ground-water component below defined section (gal/min)	Total ground-water component (gal/min)
Line 1	4,311	1,709		8,867.4	0.092	12.8	12.8	393.4	36.9	118.5	16.3	134.9	10.0	112.0	124.9
			492												
Line 2	8,671	3,534		8,821.9	0.135	27.6	14.8	42.3	0	11.3	0	11.3	8.9	109.7	137.3
			661												
Line 3	13,293	7,602		8,711.2	0.160	45.5	17.9	38.5	3.1	6.8	0.9	7.7	7.3	101.0	146.5
			495												
Line 4	38,579	19,616		8,636.8	0.142	100.2	54.7	13.4	0	1.8	0	1.8	6.2	49.2	149.4
			496												
Line 5	56,012	21,167		8,570.6	0.133	121.7	21.5	33.8	3.0	4.7	0.8	5.5	5.0	34.4	156.1
Total yield										143.1	18.0	161.1			

and minimum hydraulic heads along each of the eight sections are listed in table 9.

As described previously in this report (discussed in the "Aquifer Characteristics" section), average hydraulic conductivity in the debris-flow aquifer likely decreases in the downstream direction. The debris-flow aquifer was estimated to have an average hydraulic conductivity of 5.0 feet per day at seismic-line 1. Seismic lines 2–5 were estimated to have an average hydraulic conductivity of 3.3, 2.4, 2.0, and 2.0, respectively. The hydraulic-conductivity values estimated for bedrock in Straight Creek (discussed "Aquifer Characteristics" section) likely are more representative of hard bedrock than the fractured and weathered bedrock of the regolith at the bottom of the debris-flow aquifer. Therefore, the average hydraulic conductivity of the regolith likely is larger than that estimated from the slug tests cited in this report. The average hydraulic conductivity of the regolith was estimated to be about 3 feet per day for the ground-water discharge components of the water budget (table 5).

The total watershed yield available for either surface or ground water in Straight Creek was estimated on the basis of the calculation of mean annual precipitation using the Johnson (1998) equation (eq. 1) and evapotranspiration using the MacDonald and Stednick (2003) method (tables 3, 4). The calculated mean annual precipitation upstream from seismic-line 5, weighted by area, is 26.05 inches, resulting in a rate of 701 gallons per minute. The calculated weighted evapotranspiration is 20.07 inches, resulting in a rate of 540 gallons per minute. The estimated mean annual watershed yields from both scar and non-scar areas are shown in table 5.

The watershed yield available at each section can be either ground-water flow through the debris-flow aquifer and regolith, a component of ground-water flow below the defined section through fractured bedrock, or surface-water discharge. Evapotranspiration already is accounted for in the watershed-yield equation. As described previously, no measurements are available for direct calculation of surface-water discharge. The mean annual discharges at site SC-2 (near seismic-line 1) and site SC-4 at the lower part of Straight Creek (fig. 2) estimated from Robertson GeoConsultants, Inc. (2001a) were assumed to be the surface-water components of the water budget at line 1 and line 5, respectively. The surface-water components at the intervening lines were estimated by linearly interpolating between line 1 and line 5. The resulting estimates for each line are shown in table 5. The amount of watershed yield from contributing areas upstream from each line that is not accounted for by estimated ground-water discharge or surface-water discharge at each line is estimated to be ground-water discharge below the defined section (table 5).

The largest component of discharge at seismic-line 1 is the fractured bedrock component below the defined section (112 gallons per minute) (table 5). The debris-flow aquifer gains water from fractured bedrock between each subsequent line. At seismic-line 5, where ground-water from Straight Creek enters the Red River Valley, the largest component of ground-water flow is estimated to be in the defined section of debris-flow aquifer and regolith rather than in the underlying fractured bedrock. At line 5, about 78 percent of the ground-water component is estimated to be in the debris-flow aquifer and regolith defined by the seismic section.

The inflow to the watershed, calculated to be 701 gallons per minute, is from precipitation. The calculated outflow from the watershed at or upstream from seismic-line 5 (the downstream-most line in Straight Creek prior to entering the Red River Valley) is 540 gallons per minute of evapotranspiration in the watershed upstream from line 5 (77.0 percent of precipitation), 5 gallons per minute of surface-water flow (0.7 percent of precipitation), 122 gallons per minute of ground-water flow through the debris-flow aquifer and underlying regolith defined by the seismic data (17.4 percent of precipitation), and 34 gallons per minute of ground-water flow through fractured bedrock below the defined seismic line (4.9 percent of precipitation).

The ground-water component of the Red River Valley alluvium compared to the ground water discharging from Straight Creek is listed in table 6. Seismic-line 6 (fig. 2) is not used because it is non-orthogonal to the valley. The ground-water discharge at each line is calculated in the same manner as that described for the Straight Creek lines. The hydraulic conductivity of the regolith beneath the Red River alluvium was assumed to be the same as described earlier in this section (3 feet per day). As described in the "Aquifer Characteristics" section of this report, the combined Red River alluvium and the interfingering debris-flow deposits are estimated to have an average hydraulic conductivity of about 340 feet per day. That value was used to calculate the ground-water discharge in the alluvium. Because the Red River is hydraulically disconnected from the ground water in the alluvium, the ground water calculated for seismic-line 9 is used as the input to the alluvium. The estimated increase in ground-water flow from line 9 to seismic-line 7 is about 242 gallons per minute. The total ground-water component estimated to enter the Red River Valley from Straight Creek at seismic-line 5 (about 156 gallons per minute; table 6) plus the total watershed yield of the intervening contributing area (about 11 gallons per minute [table 6]; a total of about 167 gallons per minute) is similar to the estimated difference between lines 7 and 9 when compared to the magnitude of total calculated flow in the alluvium (5,227 gallons per minute at line 7). The difference (about 75 gallons per minute) is 1.4 percent of the estimated flow at line 7. Minor adjustments in either the estimated hydraulic conductivity of the alluvium or the estimated cross-section area of flow at either line 7 or line 9 could compensate for this difference. The effects of adjusting these values to make the budget estimates more precise are considered in the "Ground-Water Budget Sensitivity" section of this report. The estimated ground-water flow at seismic-line 8 (5,821 gallons per minute) is 594 gallons per minute greater than the estimated flow at line 7. The small contributing area of watershed yield between lines 7 and 8 (fig. 2) relative to the contributing area between lines 7 and 9, results in an estimated

Table 6. Estimated ground-water flow at selected Red River Valley cross sections.

[A, area; ft^2, square feet; L, distance from previous line; ft, feet; H, head; H_1, head in the upstream direction; H_2, head in the downstream direction; ft/d, feet per day; Q, discharge; K, hydraulic conductivity; gal/min, gallons per minute; N/A, not applicable]

Seismic-line number (figure 2)	Red River alluvium and debris-flow deposit cross-section area, A (ft^2)	Regolith cross-section area, A (ft^2)	Distance from previous line, L (ft)	Head at line, H (ft)	Head gradient $(H_1-H_2)/L$ (ft/ft)	Hydraulic conductivity of Red River alluvium (ft/d)	Hydraulic conductivity of regolith (ft/d)	Discharge, $Q=KA(H_1-H_2)$ (gal/min)	Increase in Q (gal/min)	Ground-water discharge from Straight Creek at line 5 (gal/min)	Contributing watershed area between lines (acres)	Scar area between lines (acres)	Watershed yield from non-scar areas between lines (gal/min)	Watershed yield from scar areas between lines (gal/min)	Total incremental watershed yield (gal/min)
Line 9	87,572	29,608		8,477.5	0.032	340	3.0	4,985	4,985		N/A	N/A	N/A	N/A	N/A
			1,136												
Line 7	88,672	55,087		8,441.0	0.033	340	3.0	5,227	242	156.1	89.6	9.2	8.9	2.4	11.4
			635.6												
Line 8	93,742	21,449		8,418.7	0.035	340	3.0	5,821	594		52.5	0	6.5	0	6.5

yield of about 6.5 gallons per minute at line 8 (table 6). The difference (about 588 gallons per minute) is about 10 percent of the flow at line 8. Adjustments to reduce this difference in the budget calculations also were not done and are considered in the "Ground-Water Budget Sensitivity" section of this report. The 10-percent error calculated between lines 7 and 8 likely is a more realistic error associated with the water budget than the 1.4 percent error calculated between lines 7 and 9, but still may be an underestimate of the error.

The water budget indicates the amount of ground-water flow entering the Red River alluvium from the debris-flow aquifer and regolith in Straight Creek is small (about 2.3 percent) compared to the volume of flow moving through the Red River alluvium. About 122 gallons per minute is calculated to enter the alluvium from the Straight Creek debris-flow aquifer and regolith defined by seismic-line 5 (table 5) compared to about 5,227 gallons per minute calculated to move through the inter-fingering alluvium, debris-flow deposits, and regolith along the Red River at seismic-line 7 (table 6). Including the ground-water component below the defined section calculated at line 5, the 156 gallons per minute of total ground-water flow is about 3.0 percent of the ground-water flow calculated at line 7 for the Red River alluvium.

Uncertainty exists in all components of the Straight Creek water budget. Components of the budget are either estimated on the basis of relations developed from areas similar to Straight Creek and deemed to be the most applicable on the basis of available information or calculated on the basis of limited data. Precipitation, evapotranspiration, and watershed yield were estimated from empirical relations deemed to be applicable to the Straight Creek watershed; however, potential error exists in their application. Surface runoff in Straight Creek was estimated on the basis of streamflow measurements collected at irregular time intervals at four locations, but the measurements cannot be extended to mean annual streamflow with certainty. Ground-water flow was calculated on the basis of an estimated distribution of hydraulic conductivity using results of site-specific aquifer tests. Considering the anisotropic nature of the debris-flow deposits and the underlying fractured bedrock, the representative hydraulic conductivity values of the material between the seismic lines contain potential error. Additionally, ground-water flow is calculated assuming flow is perpendicular to seismic lines. Although conceptually this seems to be primarily the case, some parallel component of flow is likely to exist. If the parallel component of flow is substantial compared to the perpendicular component of flow, error in the flow calculation would result.

The ground-water flow components shown in table 5 indicate there may be a significant component of flow below the defined sections in Straight Creek shown in figure 5. However, as described previously (in the "Ground-Water Flow" section), this is not considered to be ground-water flow through deep bedrock. Powers and Burton (2004) indicated the red coloring on the sections indicates bedrock, interpreted, for the purpose of calculating ground-water flow for the budget, as the upper highly fractured part of the bedrock, or regolith. Michael Powers (U.S. Geological Survey, oral commun., January 2004) noted that after seismic velocities representing bedrock are encountered in the subsurface, materials below that cannot be distinguished. Therefore, it is likely that the depth of regolith or fractured bedrock defined in the sections shown in figure 5 is arbitrary and that fractured bedrock may extend deeper than can be shown in the seismic sections. As indicated by results of the slug tests described in the "Aquifer Characteristics" section of this report, the hydraulic conductivity of consolidated bedrock is not sufficient to transport substantial quantities of water compared to the hydraulic conductivity of fractured bedrock. Therefore, the fractured bedrock below the reach of seismic imaging would account for the amount of ground-water flow calculated below the defined section at seismic-line 5. As described in the "Ground-Water Flow" section, the hydraulic gradient is downward from debris-flow aquifer to bedrock at seismic-line 1 (wells SC-1A and B) and at seismic-line 3 (wells SC-3A and B), whereas the gradient is upward from bedrock to debris-flow deposits at line 5. This indicates the fractured bedrock is extensive in the vicinity of the upper seismic lines, allowing water to move freely and, thus, creating the downward gradient. The greater component of ground-water flow calculated below the defined section at lines 1 through 3 is consistent with this observation. At line 5, the fractured bedrock may be more limited in extent or less transmissive, forcing an upward gradient into the overlying debris-flow aquifer. Most of the ground-water flow calculated to flow through the defined section at line 5 is consistent with that observation. It should be noted that the component of flow attributed to the fractured bedrock below the defined section at line 5 is 28 percent of the flow calculated for the defined debris-flow aquifer and regolith. Therefore, a 28-percent increase in the combined effective hydraulic conductivity of the section would account for all of the available ground-water flow at the section. That increase likely is within the potential error of estimated hydraulic conductivity. The sensitivity of the calculated flow to variations in hydraulic conductivity is addressed in the "Water-Budget Sensitivity" section.

Water-Budget Sensitivity

Components of the water budget, whether calculated or measured, are not known with certainty. The sensitivity of the water budget to variations in cross-section area of the sections, hydraulic gradient, hydraulic conductivity of the aquifer materials, watershed yield, and mean surface-water flow were tested to evaluate the effect of each component on the water budget. Changes in the water budget as a result of changes in these components are compared for the ground-water flow components at seismic-line 5, the line just upstream from where the Straight Creek debris flow enters the Red River

Valley. Precipitation is not directly evaluated in the water budget shown in table 5 but is reflected in the relation between precipitation and watershed yield. A discussion of how a long-term change in precipitation could affect the water budget of Straight Creek follows the evaluation of the individual components.

The sensitivity analysis is approached in the same way the water budget was calculated—that is, the ground-water flow at a cross section is calculated on the basis of Darcy's Law and the remainder of watershed yield must be either surface-water runoff or a component of ground-water flow through fractured bedrock below the defined section. Because surface-water flow was calculated and fixed in the water budget, the component of ground-water flow in the fractured bedrock below the defined section is calculated as the remainder in this sensitivity analysis.

The sensitivity of the calculated ground-water flow for the debris-flow aquifer and regolith at seismic-line 5 is shown in figure 6. Because ground-water flow through the debris-flow aquifer and regolith is calculated on the basis of Darcy's Law, this component of the water budget is sensitive only to the components of Darcy's Law. The components of Darcy's Law are cross-section area, hydraulic gradient, and hydraulic conductivity. Each of these components has a direct one-to-one relation with ground-water flow as shown in figure 6 for cross-section area and hydraulic gradient—that is, a percentage increase or decrease in any one of these components has an equal percentage change in calculated flow. Changing the components of either the debris-flow aquifer or regolith separately while keeping the other constant, such as is illustrated by the sensitivity of the hydraulic conductivity of the debris-flow deposits and regolith (fig. 6), has the effect of reduced flow. The reduced flow is proportional to the relative cross-section areas of the two geologic units. Changing areas or hydraulic gradients within the units separately would have the same proportionate effect to area as illustrated in figure 6. Therefore, although the sensitivity of ground-water flow to cross-section area, hydraulic gradient, and hydraulic conductivity is equal when changed uniformly, the flow is more sensitive to characteristics of the debris-flow deposits than to characteristics of the regolith because the debris-flow deposits comprise more area.

The sensitivity of the calculated component of ground-water flow in the fractured bedrock below the defined section of seismic-line 5 is shown in figure 7. As described earlier in this section, this component of ground-water flow is calculated as the residual of all other water-budget components. Because this component of the Straight Creek water budget is small (about 34 gallons per minute) relative to all but the calculated surface-water flow, percentage changes to the large components of the water budget have a dramatic effect on this component. A 20-percent change in the largest component of the water budget, watershed yield (fig. 7), has a 94-percent change in the ground-water flow component below the defined section. However, because of the small value of this ground-water flow component, that 94 percent is only about 32 gallons per minute. Changes that affect the calculation of flow through the debris-flow aquifer and regolith (fig. 6) have the opposite effect on the ground-water flow component below the defined section (fig. 7) – that is, a positive increase in flow through the debris-flow deposits and regolith results in a reduction in the ground-water flow component below the defined section. The absolute values of the changes are the same; however, it is a larger percentage of the ground-water

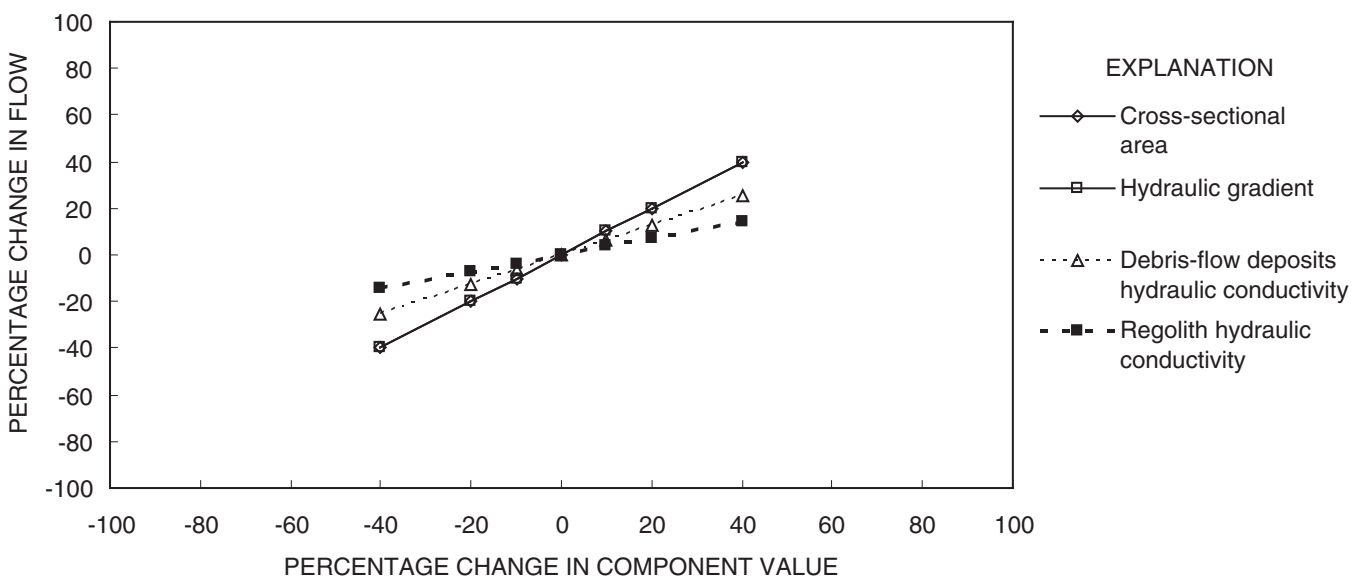


Figure 6. Sensitivity of calculated ground-water flow through the debris-flow deposits and regolith to changes in components describing aquifer characteristics of Straight Creek.

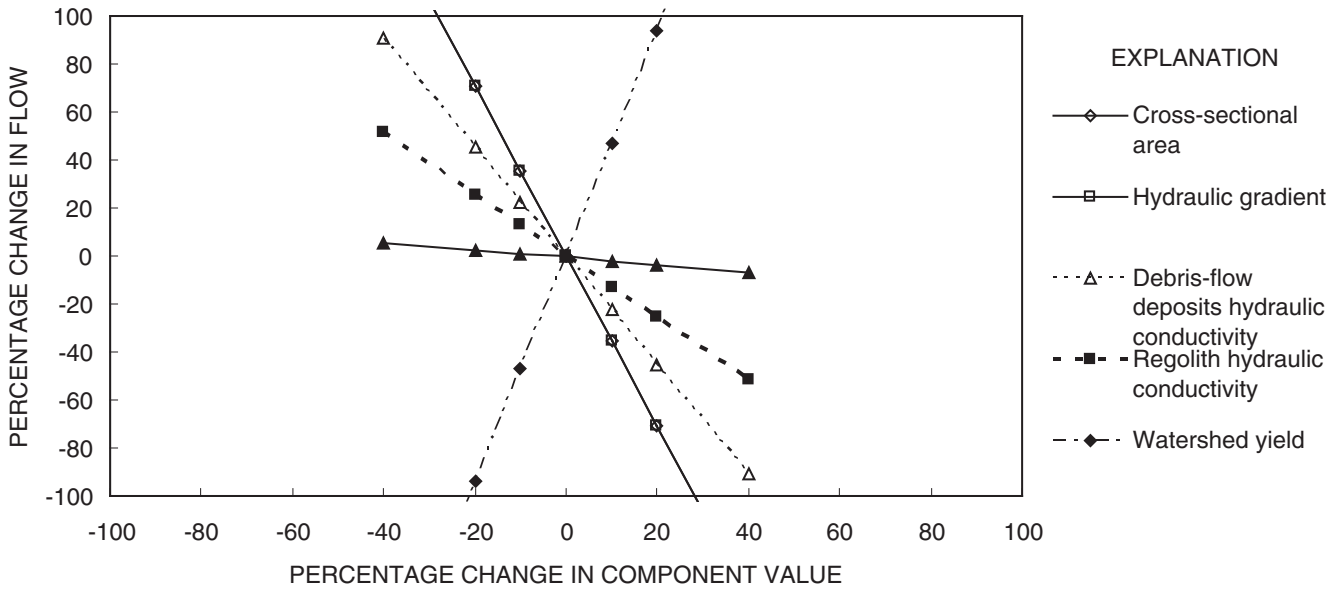


Figure 7. Sensitivity of calculated ground-water flow below the defined seismic section to changes in aquifer-characteristics and water-budget components for Straight Creek.

flow component below the section. The sensitivity of the ground-water flow component below the section is least for surface-water flow because surface-water flow is the smallest component (5.0 gallons per minute) relative to the others.

Sensitivity of ground-water flow calculated through the Red River alluvium and regolith is the same as that calculated through the debris-flow aquifer and regolith at seismic-line 5 because Darcy's Law is used for both. A uniform change in the components of Darcy's Law results in a one-to-one sensitivity—that is, a percentage change in the component results in the same percentage change in flow. As described earlier in this section, a change in a component related to just one of the geologic units results in a change in flow, and the change in flow is relative to the proportionate area the unit represents.

The sensitivity of the water budget to precipitation was evaluated on the basis of the standard deviation of annual precipitation for Red River for the period of record. The mean annual precipitation for years with complete records between 1915 and 2002 is 20.55 inches (Western Regional Climate Center, 2003) and the standard deviation is 4.00 inches (19.5 percent). The mean annual precipitation calculated for Straight Creek watershed using the Johnson (1998) equation was increased by 19.5 percent and reduced by 19.5 percent to evaluate sensitivity on the water budget. Precipitation has a nonlinear influence on the watershed yield for the basin. As in the water budget, the MacDonald and Stednick (2003) equation is used. Using the MacDonald and Stednick (2003) equation, a 19.5-percent reduction in precipitation would reduce watershed yield from 161 gallons per minute (table 5) to 60.4 gallons per minute, a 62-percent reduction. A 19.5-percent increase in precipitation would increase watershed yield from 161 gallons per minute (table 5) to 263 gallons per minute, a 63-percent increase. With the assumed steady-state conditions for this water-budget analysis, a change in long-term precipitation would not be distributed to ground-water and surface-water flow proportionally. Because of the relatively small estimated values of mean surface-water flow compared to ground-water flow in table 5, the percentage reduction in watershed yield because of reduced precipitation would be a reasonable approximation to the reduction in ground-water flow from Straight Creek. However, with an increase in precipitation, a greater proportionate volume of the increase in watershed yield would reasonably be applied to surface-water flow and a less proportionate volume of water applied to ground-water flow. With this reasoning, the ground-water flow in Straight Creek likely would increase less than the 63-percent increase calculated for watershed yield.

The volume of water flowing through the Red River alluvium also would change with a change in long-term precipitation. However, the relative proportions of ground-water flow from Straight Creek compared to Red River alluvium can be calculated if the variation in precipitation and resulting changes in ground-water flow out of Straight Creek were considered to represent potential error, the proportionate changes in watershed yield were applied to ground-water flow, and ground-water flow in the Red River alluvium were not changed. The ground-water flow calculated at seismic-line 5 would represent a range of 0.9 percent (46.2 compared to 5,227 gallons per minute) under reduced precipitation to 3.8 percent (198 compared to 5,227 gallons per minute) under increased precipitation compared to the flow calculated at seismic-line 7. Using the total ground-water flow component, the range would be 1.1 percent (59.3 compared to 5,227 gallons per minute) to 4.9 percent (254.4 compared to 5,227 gallons per minute) of the flow calculated at line 7.

Summary and Conclusions

In April 2001, the U.S. Geological Survey (USGS) and the New Mexico Environment Department (NMED) began a cooperative study to infer the pre-mining ground-water chemistry at the Molycorp molybdenum mine site in the Red River Valley. The Molycorp mine has been in operation since the 1920s. Because records of ground-water conditions prior to mining are not available, sites analogous to the pre-mining conditions at the mine site must be studied to infer those pre-mining conditions.

The Straight Creek drainage basin (watershed) was selected as the primary analog site for this study because of its similar terrain and geology to the mine site, accessibility, potential for well construction, and minimal anthropogenic activity. The purpose of this report is to present results of a water-budget analysis of the debris-flow aquifer in the Straight Creek watershed. This report is one in a series of reports that describes conditions in Straight Creek and comparisons with pre-mining conditions at the mine site.

The total area considered in the water-budget analysis includes the subwatershed areas tributary to Straight Creek and part of the Red River Valley, about 660 acres. The watershed of Straight Creek upstream from the Red River Valley encompasses about 520 acres. Elevations of the watershed range from about 8,450 feet above NGVD 29 along the Red River to about 10,600 feet above NGVD 29 at the upper end of the watershed.

The Straight Creek watershed was divided into subwatersheds for this study on the basis of locations of seismic lines. Water-budget components were calculated for areas upstream from and between the seismic lines. Components of the water budget considered in this analysis were precipitation, evapotranspiration, surface-water flow, and ground-water flow under a steady-state mean annual condition. Each of these water-budget components was estimated at each of the seismic lines. Watershed yield, defined as precipitation minus evapotranspiration (equivalent to ground-water plus surface-water discharge), was separated into surface-water flow, ground-water flow through the debris-flow aquifer and regolith, and ground-water flow through fractured bedrock below the depth of seismic imaging. The approach to this calculation was to use Darcy's Law to calculate the flow through the cross section of the saturated debris-flow deposits and underlying regolith defined by the interpreted seismic data. The amount of watershed yield unaccounted for through this section then is attributed to either surface-water flow or to ground-water flow through fractured bedrock below the defined seismic section. Surface-water flow was estimated based on previous analysis; therefore, the component of ground-water flow below the defined section was calculated as the remainder.

The water budget calculated at or upstream from seismic-line 5 in Straight Creek is listed in terms of mean annual flow expressed in gallons per minute:

Mean annual precipitation in the watershed upstream from seismic-line 5: 701 gallons per minute

Weighted evapotranspiration in the watershed upstream from line 5: 540 gallons per minute

Surface-water flow at line 5: 5 gallons per minute

Ground-water flow through debris-flow aquifer and regolith at line 5: 122 gallons per minute

Ground-water flow though fractured bedrock below the defined section at line 5: 34 gallons per minute

Total precipitation in the watershed upstream from seismic-line 5 is the sum of evapotranspiration (77.0 percent of precipitation), surface-water flow (0.7 percent of precipitation), ground-water flow through the debris-flow deposits and underlying regolith (17.4 percent of precipitation), and ground-water flow through the fractured bedrock below the defined seismic section (4.9 percent of precipitation).

The calculated ground-water flow component downstream from the defined sections in Straight Creek likely is a component of flow through fractured bedrock below the depth at which seismic imaging could penetrate and is not considered to represent a substantial component of flow through deep consolidated bedrock. It should be noted that the component of flow calculated downstream from the defined section at seismic-line 5 is 28 percent of the flow calculated for the defined debris-flow aquifer and regolith. Therefore, a 28-percent increase in the combined effective hydraulic conductivity of the section would account for all of the available ground-water flow at the section. It is possible that calculated flow below the defined section represents a combination of both error in the calculation of flow and flow through fractured bedrock below the defined seismic sections.

The ground-water flow through the alluvium and inter-fingering debris-flow deposits of the Red River valley was calculated to be 5,227 gallons per minute at seismic-line 7, the first seismic line in the Red River Valley below Straight Creek. The water budget indicates the amount of ground-water flow entering the Red River alluvium from the debris-flow aquifer and regolith in Straight Creek is small (about 2.3 percent; 122 gallons per minute) compared to the volume of flow moving through the Red River alluvium. The total ground-water component exiting Straight Creek (156 gallons per minute; 122 gallons per minute through debris-flow deposits and regolith plus 34 gallons per minute through fractured bedrock) is about 3.0 percent of the ground-water flow calculated at line 7 for the Red River alluvium.

Uncertainty exists in all components of the Straight Creek water budget. Components of the budget are either estimated on the basis of relations developed from areas similar to Straight Creek and deemed to be the most applicable on the basis of available information or calculated on the basis of

limited data. Precipitation, evapotranspiration, and watershed yield were estimated from empirical relations deemed to be applicable to the Straight Creek watershed; however, potential error exists in their application. Surface runoff in Straight Creek was estimated on the basis of streamflow measurements collected at irregular time intervals at four locations, but the measurements cannot be extended to mean annual streamflow with certainty. Ground-water flow was calculated on the basis of estimated distribution of hydraulic conductivity using results of site-specific aquifer tests. Considering the anisotropic nature of the debris-flow deposits and the underlying fractured bedrock, the representative hydraulic conductivity values of the material between the seismic lines contain potential error. Additionally, ground-water flow is calculated assuming flow is perpendicular to seismic lines. Although conceptually this seems to be primarily the case, some parallel component of flow is likely to exist. If the parallel component of flow is substantial compared to the perpendicular component of flow, error in the flow calculation would result.

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Supplemental Information

Supplemental Tables

Table 7. Straight Creek discharge measurements.

[Measurement site (site A) shown in figure 2. F indicates flume; B indicates bucket and stop watch method, and number of measurements indicates the number of repetitions of measurements using method B (discharge is calculated as the average); --, not applicable.]

Measurement date	Discharge (gallons per minute)	Measurement method	Number of measurements
05/22/01	9.4	F	--
06/06/01	11.	F	--
08/24/01	9.4	F	--
10/23/01	3.8	B	3
08/20/02	3.7	B	9
09/19/02	91.	B	6
10/15/02	5.7	B	2
02/01/03	7.	B	--[1]
04/16/03	69.	B	6
05/11/03	6.5	B	5
06/04/03	5.5	B	4
07/09/03	4.9	B	6
08/22/03	8.3	B	5
09/18/03	9.4	B	2
10/07/03	8.7	B	2
12/05/03	5.7	B	3
03/26/04	17.	B	7
05/12/04	9.4	B	4

[1]Notes misplaced—discharge estimated from memory of time to fill bucket.

Table 8. Cross-section areas at seismic lines and corrections applied to represent areas orthogonal to valleys.

Seismic-line number (see figure 2 for locations and figure 5 for cross sections)	Cross-section area of saturated debris-flow deposit (square feet)	Cross-section area of saturated debris-flow deposit and Red River alluvium (square feet)	Cross-section area of regolith (square feet)	Correction factor for area orthogonal to valleys	Corrected debris-flow deposit and (or) alluvium cross-section area (square feet)	Corrected regolith cross-section area (square feet)
Seismic lines across Straight Creek Valley						
Line 1	4,323		1,714	0.997	4,311	1,709
Line 2	8,790		3,583	0.986	8,671	3,534
Line 3	14,027		8,022	0.948	13,293	7,602
Line 4	38,776		19,716	0.995	38,579	19,616
Line 5	56,012		21,167	1.000	56,012	21,167
Seismic lines across Red River Valley						
Line 6		114,076	62,448	not used	not used	not used
Line 7		90,244	56,063	0.983	88,672	55,087
Line 8		94,968	21,730	0.987	93,742	21,449
Line 9		87,572	29,608	1.000	87,572	29,608

Table 9. Calculated hydraulic head along sections.

Seismic line number (figure 2)	Mean hydraulic head (in feet above NVGD 29)	Maximum hydraulic head (in feet above NVGD 29)	Minimum hydraulic head (in feet above NVGD 29)
Line 1	8,867.4	8,894.5	8,846.0
Line 2	8,821.9	8,859.9	8,794.8
Line 3	8,711.2	8,798.2	8,681.1
Line 4	8,636.8	8,721.6	8,600.3
Line 5	8,570.6	8,640.5	8,515.0
Line 7	8,441.0	8,516.0	8,415.4
Line 8	8,418.7	8,454.3	8,395.9
Line 9	8,477.5	8,607.2	8,441.1

Sulphur Gulch Water Budget

By Kirk R. Vincent

The authors were asked to develop a water budget to estimate watershed yield of three subwatersheds within Sulphur Gulch as this report was nearing completion. The purpose of the Sulphur Gulch water budget is to provide background data for use in geochemical studies. The methods and results for the Sulphur Gulch water budget are discussed as supplemental information in this report.

Prior to mining, Sulphur Gulch was a southeast and a south-flowing tributary of the Red River located approximately halfway between the towns of Questa (about 1.5 miles east of the Questa Ranger Station; fig. 1) and Red River (fig. 1). Starting in 1965, operation of the Molycorp Questa mine modified the topography of the Sulphur Gulch watershed with excavation of the open pit and emplacement of waste rock in the Gulch, but the Sulphur Gulch water budget is intended to approximate the conditions prior to mining. Thus, topography on the USGS Questa and Red River 1:24,000-scale Quadrangle maps (fig. 8), which was based on aerial photographs taken in 1962, was used for calculation of mean elevation and area of the subwatersheds. These maps subsequently were released in digital raster graphic (DRG) and digital elevation model (DEM) form. The 10-meter DEM was used to calculated mean elevations for the subwatersheds.

The three subwatersheds selected for analysis are illustrated in figure 8. The Blind Gulch and Spring Gulch subwatersheds are self-explanatory. The upper Sulphur Gulch subwatershed is herein defined as the headwater portion of the area labeled on USGS maps as Sulphur Gulch and extends downstream to the point of confluence with the stream that drains Blind Gulch. Vegetated and unvegetated areas likely have differing water yields as discussed in the main body of this report. Thus, the upper Sulphur Gulch subwatershed was further subdivided into the portion that consisted of unvegetated alteration scar and the portion that did not contain scars.

As in the Straight Creek water budget, mean annual precipitation values for the Sulphur Gulch water budget were estimated using equation 1, developed for the Taos Range by Johnson (1998). This relation requires estimation of the mean elevations (above NGVD 29) of the subwatersheds. Appropriate portions of the DEMs, with 10-meter elevation grids, were imported into a Geographic Information System (GIS) within which mean elevations were calculated (table 10). The GIS program gave results in meters, which were converted to feet (1.0 meter = 3.2808 feet) and then rounded to three significant digits (table 10). The mean annual precipitation estimates are listed in table 10.

As in the Straight Creek water budget, mean annual evapotranspiration values for the Sulphur Gulch water budget were estimated using equation 4, developed by MacDonald and Stednick (2003). This equation contains a term that accounts for transpiration by vegetation and evaporation from soil and a separate term that accounts for evaporative loss of water intercepted by vegetation foliage. As in the Straight Creek water budget, the term for evaporative loss of intercepted water is omitted in the calculation of evapotranspiration for the scar in upper Sulphur Gulch (see ‘Evapotranspiration’ section). The mean annual evapotranspiration estimates are listed in table 10.

The annual yields from the subwatersheds were calculated as precipitation minus evapotranspiration (table 10). As mentioned in the main body of the text, yield is considered the total surface-water plus ground-water discharge produced by the subwatershed. Unlike the water budget for Straight Creek, the yield from Sulphur Gulch subwatersheds could not be subdivided into surface-water and ground-water components because the geometry and hydraulic properties of alluvium and underlying regolith within the Sulphur Gulch prior to mining are unknown. Thus, a ground-water flow model cannot be constructed and used to subdivide watershed yield.

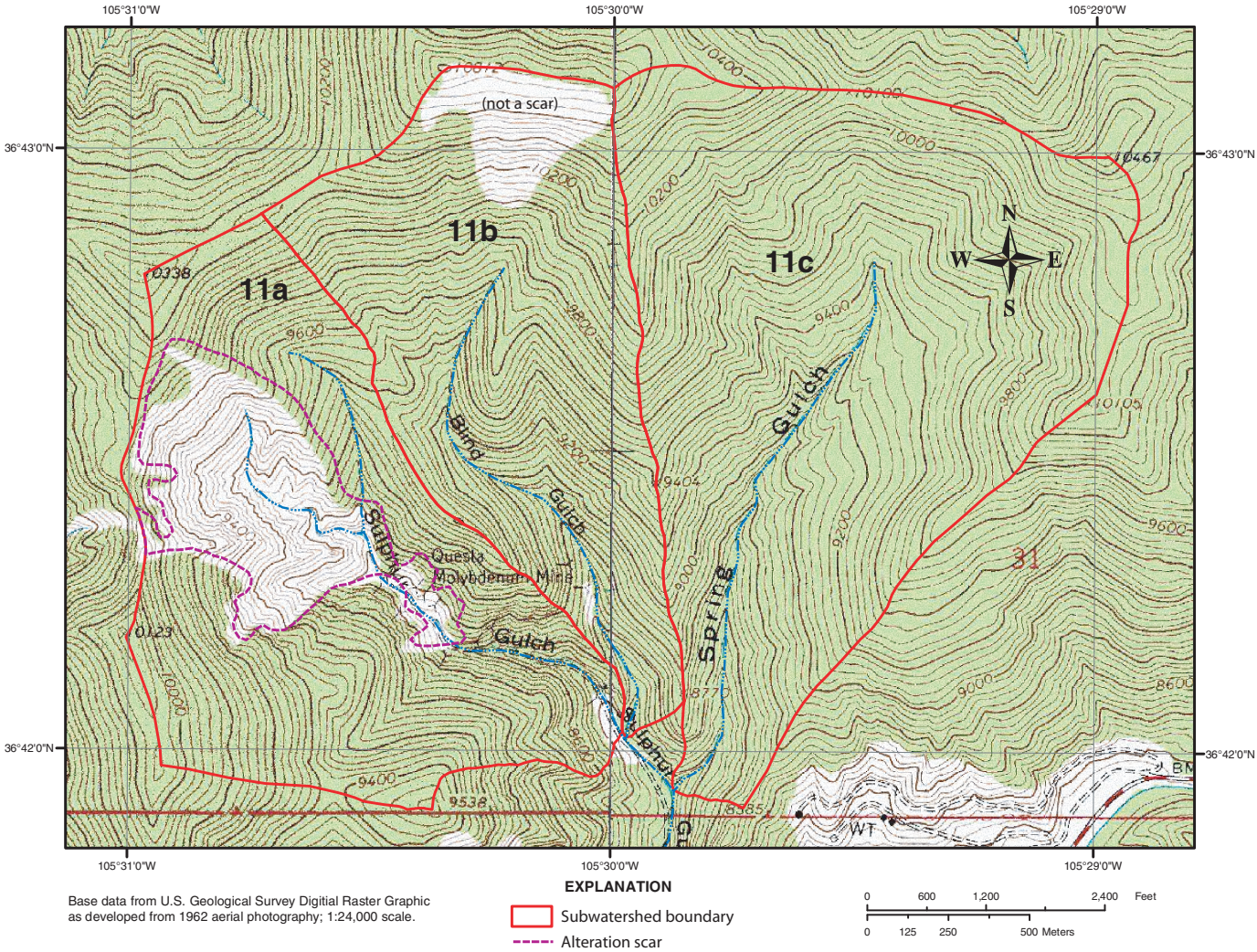

Figure 8. Subwatersheds within the Sulphur Gulch watershed.

Table 10. Data for annual water budgets of subwatersheds within Sulphur Gulch.

Subwatershed (figure 8)	Mean elevation of subwatershed (in feet above NGVD 29)	Mean annual precipitation (inches) (Johnson, 1998)	Mean annual evapo-transpiration (inches) (MacDonald and Stednick, 2003)	Mean annual watershed yield, as precipitation minus evapo-transpiration (inches)	Area of subwatershed (square feet)	Mean annual watershed yield (gallons per minute)
Upper Sulphur Gulch						
scar portion	9,340	24.56	18.00	6.56	4,810,000	37.4
non-scar portion	9,380	24.78	19.90	4.88	13,300,000	77.0
total						114.4
Blind Gulch	9,650	26.27	20.32	5.95	14,500,000	102.4
Spring Gulch	9,560	25.77	20.18	[1]5.60	24,400,000	161.9

[1] Numbers rounded after calculation.

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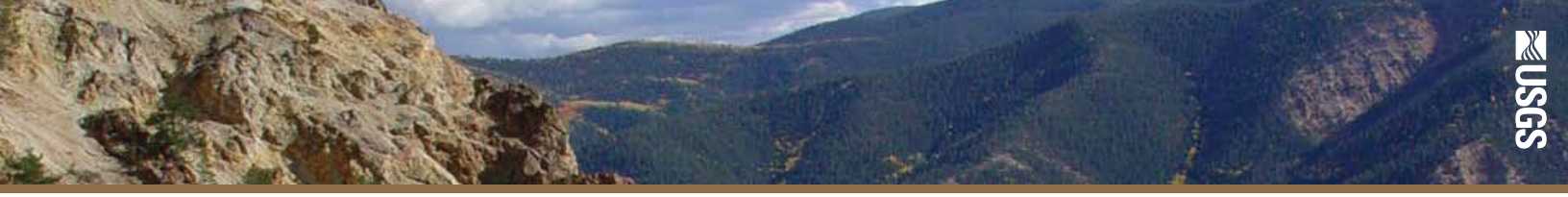

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