Questa Baseline and Pre-Mining Ground-Water Quality Investigation. 21. Hydrology and Water Balance of the Red River Basin, New Mexico 1930–2004

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Prepared in cooperation with New Mexico Environment Department

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Conversion Factors and Datums

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)
square foot (ft^2)	0.0929	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon (gal)	3.785	liter (L)
ounce, avoirdupois (oz)	28.3527	gram (g)
ton	0.9072	megagram

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8 \times °C)+32$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C=(°F-32)/1.8$$

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).

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

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Abstract

A study of the hydrology of the Red River Basin of northern New Mexico, including development of a pre-mining water balance, contributes to a greater understanding of processes affecting the flow and chemistry of water in the Red River and its alluvial aquifer. Estimates of mean annual precipitation for the Red River Basin ranged from 22.32 to 25.19 inches. Estimates of evapotranspiration for the Red River Basin ranged from 15.02 to 22.45 inches or 63.23 to 94.49 percent of mean annual precipitation. Mean annual yield from the Red River Basin estimated using regression equations ranged from 45.26 to 51.57 cubic feet per second. Mean annual yield from the Red River Basin estimated by subtracting evapotranspiration from mean annual precipitation ranged from 55.58 to 93.15 cubic feet per second. In comparison, naturalized 1930–2004 mean annual streamflow at the Red River near Questa gage was 48.9 cubic feet per second. Although estimates developed using regression equations appear to be a good representation of yield from the Red River Basin as a whole, the methods that consider evapotranspiration may more accurately represent yield from smaller basins that have a substantial amount of sparsely vegetated scar area.

Hydrograph separation using the HYSEP computer program indicated that subsurface flow for 1930–2004 ranged from 76 to 94 percent of streamflow for individual years with a mean of 87 percent of streamflow. By using a chloride mass-balance method, ground-water recharge was estimated to range from 7 to 17 percent of mean annual precipitation for water samples from wells in Capulin Canyon and the Hansen, Hottentot, La Bobita, and Straight Creek Basins and was 21 percent of mean annual precipitation for water samples from the Red River.

Comparisons of mean annual basin yield and measured streamflow indicate that streamflow does not consistently increase as cumulative estimated mean annual basin yield increases. Comparisons of estimated mean annual yield and measured streamflow profiles indicates that, in general, the river is gaining ground water from the alluvium in the reach from the town of Red River to between Hottentot and Straight Creeks, and from Columbine Creek to near Thunder Bridge. The river is losing water to the alluvium from upstream of the mill area to Columbine Creek. Interpretations of ground- and surface-water interactions based on comparisons of mean annual basin yield and measured streamflow are supported further with water-level data from piezometers, wells, and the Red River.

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 quality at the Molycorp molybdenum mine site in the Red River Basin (fig. 1). This study was prompted by the New Mexico State Water Quality Act (§§74-6-1 and following sections, New Mexico Statutes Annotated 1978), under the jurisdiction of the New Mexico Water Quality Control Commission, which 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 New Mexico Administrative Code) or (2) natural background concentrations.

The Molycorp molybdenum mine has been in operation since the 1920's, and ground-water measurements and chemical analyses were not obtained prior to mining. To infer the pre-mining ground-water chemistry, analogous offsite areas were studied. These analog sites often are disturbed by non-mining, anthropogenic activities, including exploration drilling, road construction, power- and telephone-line construction, forest service construction and maintenance, and residential, commercial, and municipal development. The existing conditions of these analog sites are referred to as "baseline conditions," from which, when combined with data for mined areas, pre-mining conditions of the Molycorp molybdenum mine site (mine site) can be inferred. Straight Creek (fig. 1) and its associated drainage basin were selected as the primary analog site for this study because of the similarity of terrain and geology to the mine site, accessibility, potential for well construction, and minimal anthropogenic activity.

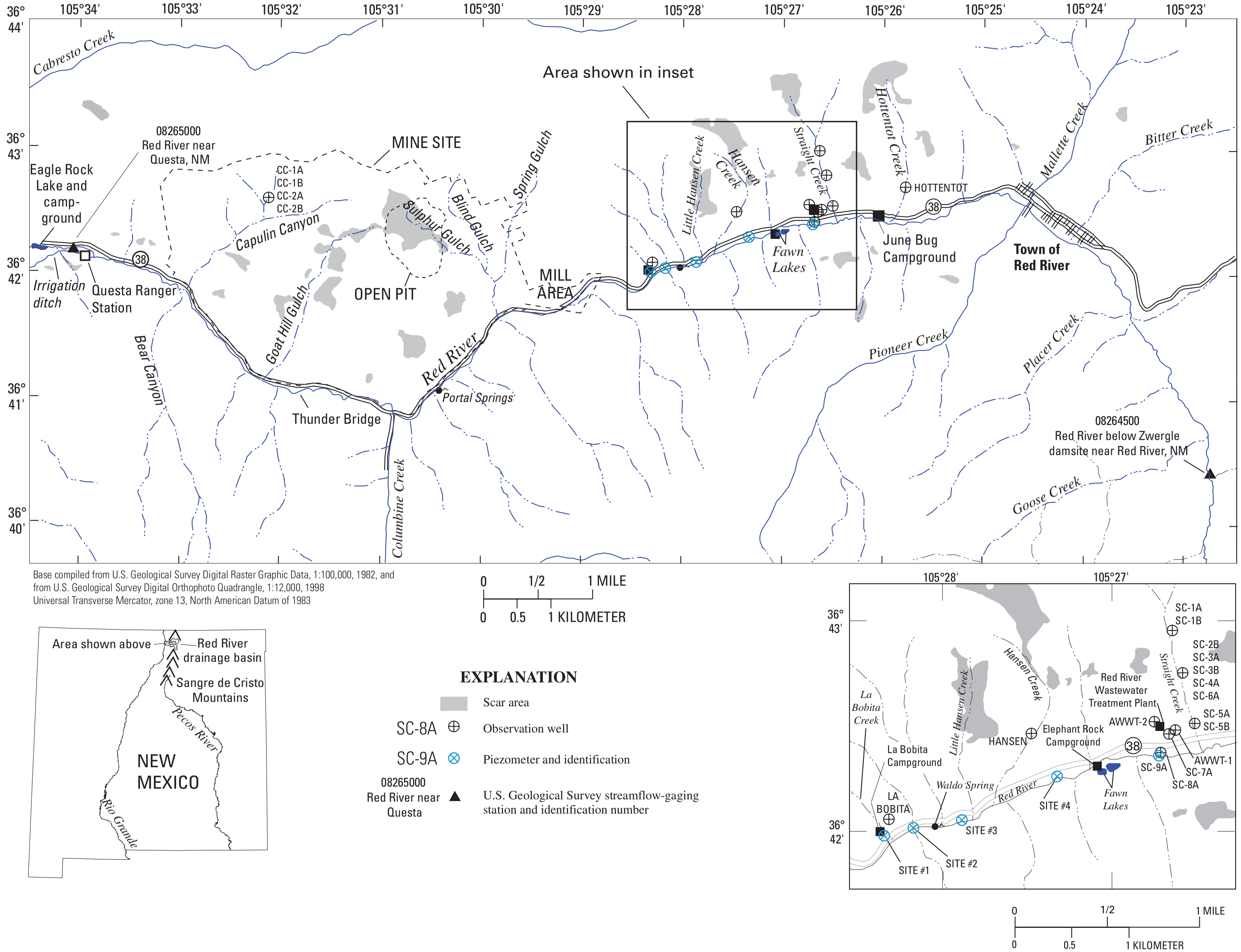

Figure 1 Location of the Molycorp molybdenum mine site and other selected features within the Red River Basin.

Weathering of hydrothermally altered bedrock in the Red River Valley has resulted in steep, isolated areas that are highly erosive and sparsely vegetated. These isolated areas, commonly known as scar areas, or scars, are clearly visible from the ground and in aerial photographs (fig. 1). Acidic surface water and ground water in basins that are tributary to the Red River are generated by oxidation of sulfide minerals in scar-area bedrock. In Straight Creek, for example, pyritized rock in the upper part of the drainage basin is the source of acid rock drainage (pH 2.8 to 3.3) and acidic ground water (pH 3.0 to 4.0) (Naus and others, 2005).

The Red River, a gaining stream along much of the study reach, receives water from tributary drainage basins. Most of the water yield from tributary drainage basins is in the form of ground water, except during extreme runoff. The flow and chemistry of water in the Red River and its alluvial aquifer provide information about the chemistry of ground water and the locations at which ground water discharges to the river. To help provide a better understanding of these processes, a study of the hydrology of the Red River Basin was undertaken, including development of a pre-mining water balance, as part of the USGS and NMED cooperative study. The water balance, constructed for the part of the Red River Basin upstream from USGS streamflow-gaging station 08265000, Red River near Questa, N. Mex. (fig. 2), provides estimates of the amount of ground and surface water yielded from tributary drainages (basin yield) for pre-mining conditions. Partitioning of this water between ground water and surface water was estimated to help understand the effect of ground-water inflow from tributary drainage basin aquifers on surface- and ground-water chemistry in the Red River alluvial system.

Purpose and Scope

This report describes the hydrology of the Red River Basin and documents the development of a water balance for pre-mining conditions for the part of the Red River Basin upstream from the USGS streamflow-gaging station Red River near Questa, N. Mex. (hereinafter referred to as the Questa gage). Hydrologic discussions include descriptions of precipitation, surface water, and ground water. Water-balance components include estimates of average annual precipitation, evapotranspiration, basin yield, ground-water recharge, and partitioning of yield into surface- and ground-water components. This report is one in a series of reports that will contribute to the overall USGS study objective: to infer pre-mining ground-water quality at the mine site.

Physical Description of Study Area

The Red River, a tributary to the Rio Grande, is located in north-central New Mexico (fig. 1). The area is a rugged mountainous terrain with steep slopes and V-shaped valleys. The sparsely vegetated to barren, yellow-brown scar areas are one of the most striking natural features in the Red River Basin. The largest scars are located in Capulin Canyon, Goat Hill and Sulphur Gulches, and the Little Hansen, Hansen, Straight, and Hottentot Creek drainages (fig. 1). The contributing area of the Red River Basin upstream from the Questa gage is approximately 108 mi^2 (square miles) and includes approximately 18 mi (miles) of river reach (fig. 2). The mine site, located upstream (east) of the Questa gage and north of State Highway 38 and the Red River (fig. 1), is approximately 6 mi^2 in area (U.S. Forest Service, 2001) and encompasses three drainages that are tributary to the Red River: Capulin Canyon, Goat Hill Gulch, and Sulphur Gulch (fig. 1).

Mining activities produced extensive underground workings and an open pit approximately 3,000 ft (feet) in diameter (covering approximately 162 acres) near or in Sulphur Gulch (URS, 2001). Waste-rock piles cover steep slopes on the north side of the Red River between Capulin Canyon and Spring Gulch (a tributary valley of Sulphur Gulch).

Climate and Vegetation

Although located in the arid southwestern United States, the Red River Basin receives precipitation in various forms throughout the year. Between 1915 and 2004, the annual average temperature at the town of Red River was about 4°C and the annual average precipitation and snowfall were about 21 and 146 in. (inches), respectively (Western Regional Climate Center, 2004). Daily temperatures generally fluctuated by 18°C throughout the year (Western Regional Climate Center, 2004).

Climate and vegetation vary greatly within short distances, primarily because of differences in topography. Topography in the study area is steep, rising rapidly from the basin-floor elevation of approximately 7,450 ft at the Questa gage to ridge-crest elevations exceeding 13,000 ft (fig. 2). Orographic effects of mountainous topography lead to precipitation on the windward slopes and localized storms within the Red River Basin and tributary drainages.

Dominant vegetation associations in the Red River Basin and their general elevation zones are piñon-juniper woodland from 6,000 to 7,500 ft, mixed conifer woodland (primarily ponderosa and limber pine) from 7,500 to 9,000 ft, and spruce-fir woodland (primarily Douglas and white fir) from 9,000 to 12,000 ft (Knight, 1990; and L. Gouh, U.S. Geological Survey, oral commun., 2003). Willows, cottonwoods, shrubs, perennial grasses, and flowering vegetation are common near the banks of the Red River.

Geology

This section describes the generalized geology and geomorphology of the Red River Basin. Previous studies of the geology and mineralogy of the Red River Basin include those by Schilling (1956), Rehrig (1969), Lipman (1981), and Meyer and Leonardson (1990, 1997). Information in this sec-

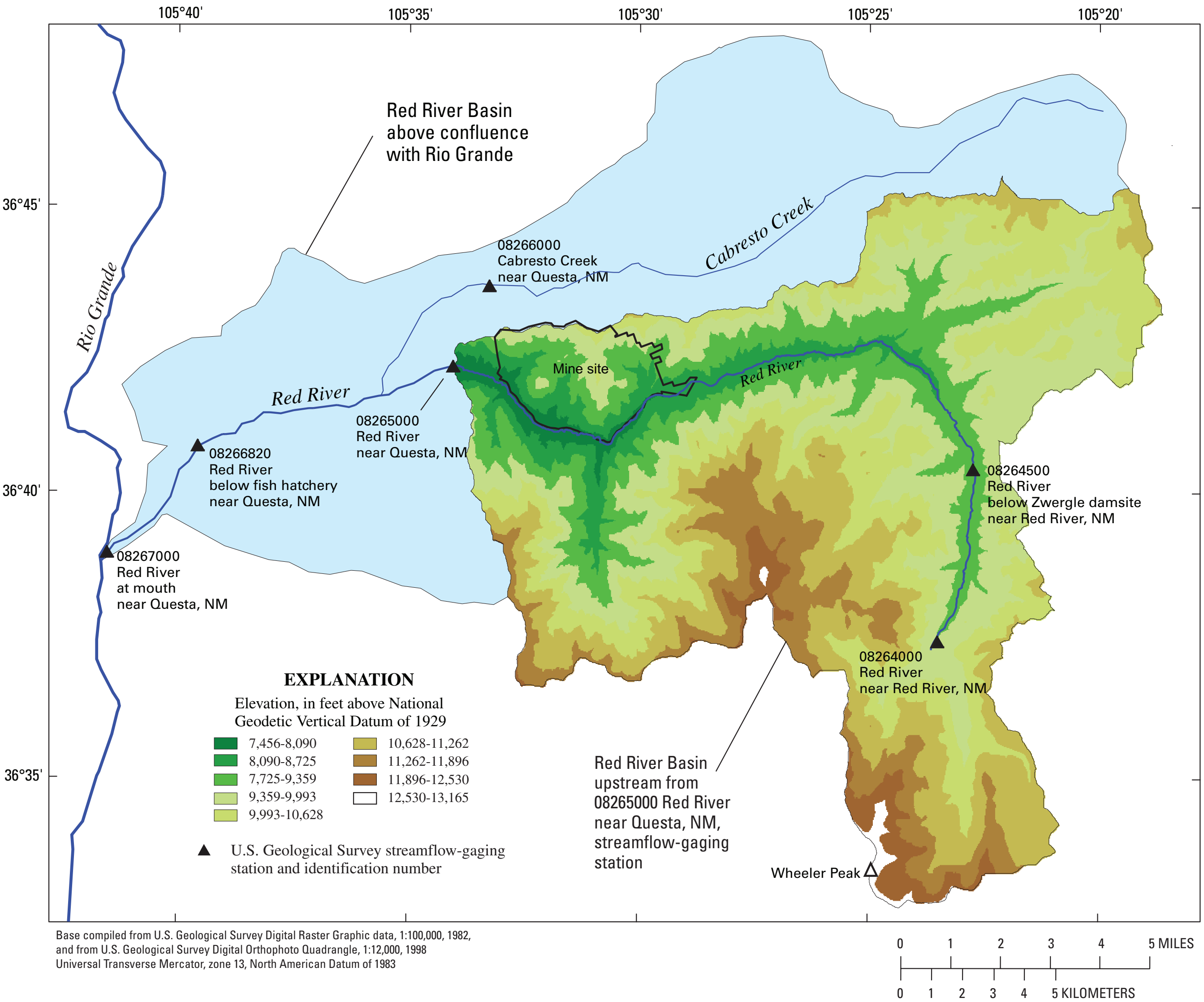

Figure 2. Red River Basin above the confluence of the Red River and the Rio Grande and U.S. Geological Survey streamflow-gaging stations.

tion draws largely from these sources, with additional information from Ludington and others (2004), Kirk Vincent (U.S. Geological Survey, written commun., 2005), and other USGS scientists participating in this study.

The Red River Valley is located along the southern edge of the Questa Caldera and contains complex structural features (Caine, 2003) and extensive zones of hydrothermal alteration. The geology of the Red River Basin consists of volcanic and intrusive rocks of Tertiary age underlain by metamorphic rocks of Precambrian age that were intruded by granitic stocks. The volcanic rocks are primarily intermediate to felsic composition (andesite to rhyolite). Granites and porphyries that intruded the volcanic rocks were the apparent source of the hydrothermal fluids, rock alteration, and subsequent mineralization. The mineral deposits in the Red River Basin are considered Climax-type deposits, which are associated with silica- and fluorine-rich rhyolite porphyry and granitic intrusives.

Ore deposits contain quartz, molybdenite, pyrite, fluorite, calcite, manganiferous calcite, dolomite, and rhodochrosite. Lesser amounts of galena, sphalerite, chalcopyrite, magnetite, and hematite also are present. The hydrothermal alteration that caused mineralization overprints an earlier, regional alteration of rock. In these areas, rocks can contain a mixture of quartz, pyrite, and illite clays replacing feldspar, chlorite, carbonates, and epidote. Minerals in waste rock produced by mining activities include chlorite, gypsum, illite, illite-smectite, jarosite, kaolinite, and muscovite (Gale and Thompson, 2001).

Scar-area bedrock outcrops are composed of andesitic volcanic and volcaniclastic rocks, rhyolitic tuff, quartz latite, and rhyolite porphyry. Most of the andesite and quartz latite have been hydrothermally altered and contain primarily plagioclase feldspar and chlorite. Rhyolite porphyry and rhyolitic tuff do not seem to have been substantially altered.

Runoff from intense summer rainfall over basins tributary to the Red River can transport large quantities of sediment down tributary drainages and form debris fans where these tributaries join the Red River. Where the tributary drainages contain scar areas, the debris fans are large, indicate evidence of active deposition, and contain poorly sorted coarse gravel and cobble to clay-size sediments. The chemistry of debris-flow sediment likely represents the chemistry of sediment eroded from the scar areas. Sediment transported and deposited by the Red River (Red River alluvium), in contrast, generally consists of medium- to well-sorted sand and gravel that is composed of a mix of the bedrock lithologies found in the entire Red River Basin. Large debris fans debouching from tributary drainages have caused aggradation of the Red River streambed in river reaches upstream from debris fans (Kirk Vincent, U.S. Geological Survey, written commun., 2005).

Mining History

Two prospectors first discovered molybdenite in Sulphur Gulch in 1914. Underground mining operations occurred between 1919 and 1958; there were more than 35 mi of underground mine workings by 1954 (Robertson GeoConsultants, 2000b, U.S. Environmental Protection Agency, 2000). Molycorp began removing the rock overburden at Sulphur Gulch in 1964, and the first molybdenite ore was extracted from the open pit in 1965. Overburden and waste rock from open-pit mining was deposited at several locations on the south-facing slopes north of the Red River between Capulin Canyon and Spring Gulch (Robertson GeoConsultants, 2000b, 2000c; URS, 2001). Steffen Robertson & Kirsten (1995), Slifer (1996), and Robertson GeoConsultants, Inc. (2000a, 2000b) estimated that approximately 328 million tons of waste rock were deposited in these drainages between 1964 and 1983. Tailings were transported by pipeline from the mine to the tailings facility near Questa. Water used in the mill operation was obtained from the Red River and from the Red River alluvial aquifer (URS, 2002).

In 1983, Molycorp ceased open-pit mining and initiated a new phase of underground mining in Goat Hill Gulch (fig. 1). As a consequence, waste rock no longer was deposited in the Capulin Canyon and Goat Hill, Sulphur, and Spring Gulch drainages, and the volume of tailings slurry transported by pipeline to the tailings impoundment near Questa increased. Low market values for molybdenum caused the mine to cease operations from 1986 to 1989 and again from 1992 to 1995. While the underground mine was inactive during 1992–95, ground water was not pumped from the underground mine workings, and the workings were allowed to partially reflood. The mine was dewatered and repaired when production resumed in late 1996, and mining of a new ore body began in 1998 (Molycorp, Inc., n.d.).

Previous Studies

Numerous studies of the Red River Basin and Molycorp mine have been conducted, including investigations of water quality and sources of metal load to the river, biological assessments of the river, and characterization of regional and mine site geology and hydrogeology. A detailed summary of investigations undertaken from 1965 to 2001 was presented by consultants to Molycorp (URS, 2001). Most pertinent to the present study are investigations conducted by Vail Engineering Inc. (2000) and Robertson GeoConsultants (2000d, 2001b, 2001c, and 2001d). Vail Engineering Inc. (2000) conducted a water and sulfate load-balance study for the Red River Basin upstream from the Questa gage. Long-term mean annual and mean monthly basin yields were estimated for drainages on the north and south sides of the Red River, and a stream survey on October 13, 1999, provided surface-water flow and sulfate-concentration measurements that were used to construct a flow-and load-balance spreadsheet model for the study reach.

Robertson GeoConsultants developed a water balance for the active mine site (2000d), load balances for the Straight Creek drainage basin (2001b) and the mine site (2001c), and a load-balance model for the Red River Basin upstream from Questa gage (2001d). For the Red River Basin load balance, the Hydrological Simulation Program – Fortran (HSPF) model was used to simulate daily basin yield for the 39-year period from October 1960 to September 1999. Monthly water yields were estimated for physiographic units such as mine waste-rock piles, erosional scars, mineralized rock, and nonmineralized rock, and were partitioned into surface- and ground-water components (Robertson GeoConsultants, 2001d).

Acknowledgments

The authors are grateful to the project advisory committee for their contributions to the design and implementation of the study. Advisory committee members include representatives for Amigos Bravos, Molycorp, and the New Mexico Environment Department. Advice and cooperation from the U.S. Environmental Protection Agency Region 6 and the U.S. Forest Service are gratefully acknowledged.

Hydrology

This section describes the hydrology of the Red River Basin, including the long-term and seasonal variability of precipitation and streamflow and the generalized characteristics of surface and ground water. A brief discussion of general hydrologic processes and a glossary of selected terms (at the back of this report) are presented for the aid of the reader.

A schematic diagram illustrating hydrologic processes is presented in figure 3. Precipitation may be intercepted by vegetation or returned to the atmosphere through evapotranspiration. Precipitation reaching land surface generally infiltrates

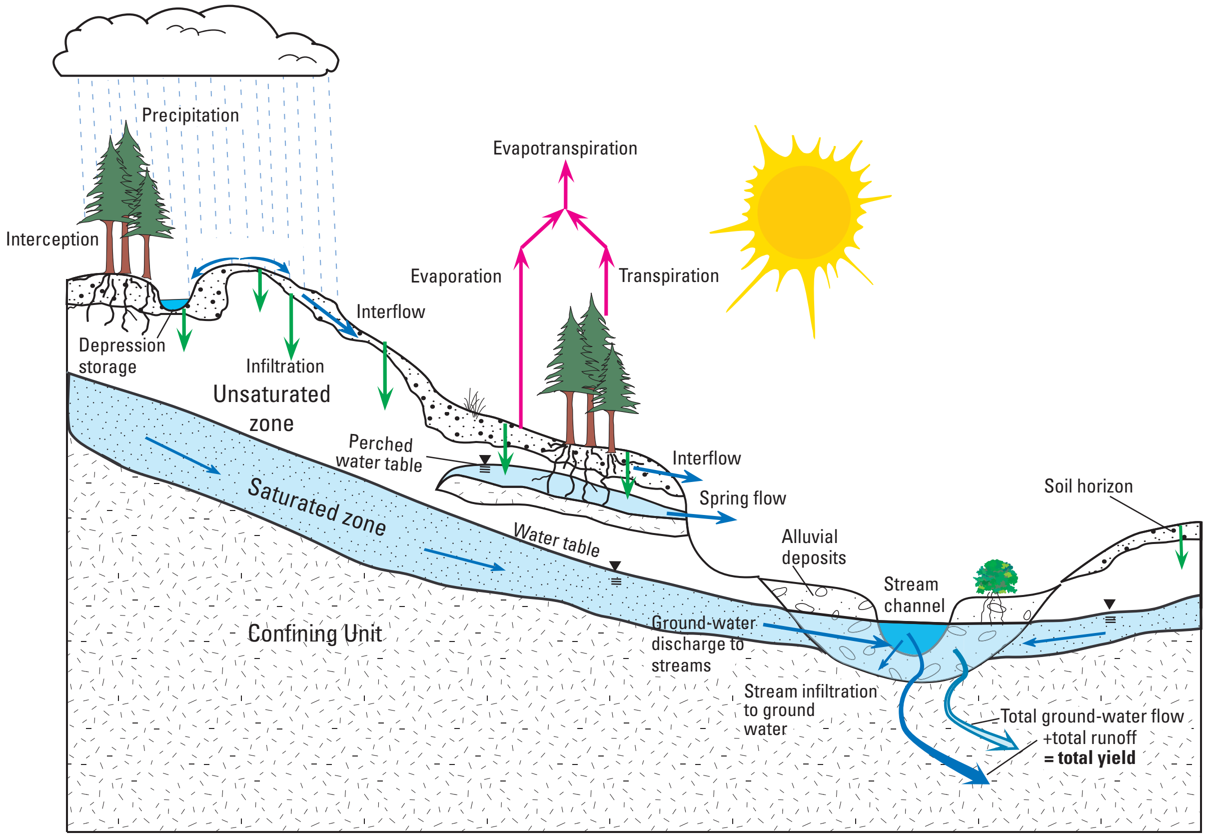

Figure 3. Schematic diagram illustrating hydrologic processes.

into the soil horizon unless the soil is saturated or the infiltration capacity is exceeded, in which case overland flow or runoff will occur. During precipitation, water may be returned from the soil horizon to land surface through interflow, contributing to short-term increases in streamflow. Water infiltrating beyond the root zone in time may recharge ground-water systems. Discharge of subsurface water to streams contributes the base flow of those streams.

Precipitation

In the study area, precipitation has been measured at a long-term climatic station (fig. 4) in the town of Red River (Red River, New Mexico; station 297323) since 1910 (State Engineer Office, 1956; Western Regional Climate Center, 2004). Red River Pass #2, part of the network of automated SNOTEL (SNOwpack TELemetry) stations that collect snowpack and related climatic data in the Western United States (Natural Resources Conservation Service, 2003, 2004), is located on the eastern margin of the Red River Basin (fig. 4). Data also have been collected at other climatic and SNOTEL stations in the Sangre de Cristo Mountains of northern New Mexico and southern Colorado (fig. 4).

Johnson (1998), in her evaluation of precipitation in and near Taos County, determined that a 5-year moving average of total annual precipitation from 1910 to 1995 for the Red River climatic station indicated a period of above-normal precipitation from 1912 through 1932, a period of below-normal precipitation from 1933 through 1979, and a period of above-normal precipitation through 1993. Mean annual precipitation for 1910–95 was 20.70 in. Precipitation data for the Red River climatic station for 1910–2004 (fig. 5A) show the precipitation trends observed by Johnson (1998) and indicate, in addition, the 5-year moving average precipitation continuing to be above normal from 1993 through 2000 but was below normal from 2001 through 2002. The mean annual precipitation for 1910 through 2004 was 20.73 in.

Mean monthly data for the Red River climatic station for 1930-2004 indicate that about 69 percent of total annual precipitation falls during April through October, with about 29 percent falling during July and August (fig. 5B). Mean monthly precipitation in March, April, and May is higher than in fall and winter months. Seasonal trends are similar for climatic stations evaluated by Johnson (1998). However, data collected from 1980 through 2003 for SNOTEL climatic stations at elevations between 9,800 and about 11,000 ft

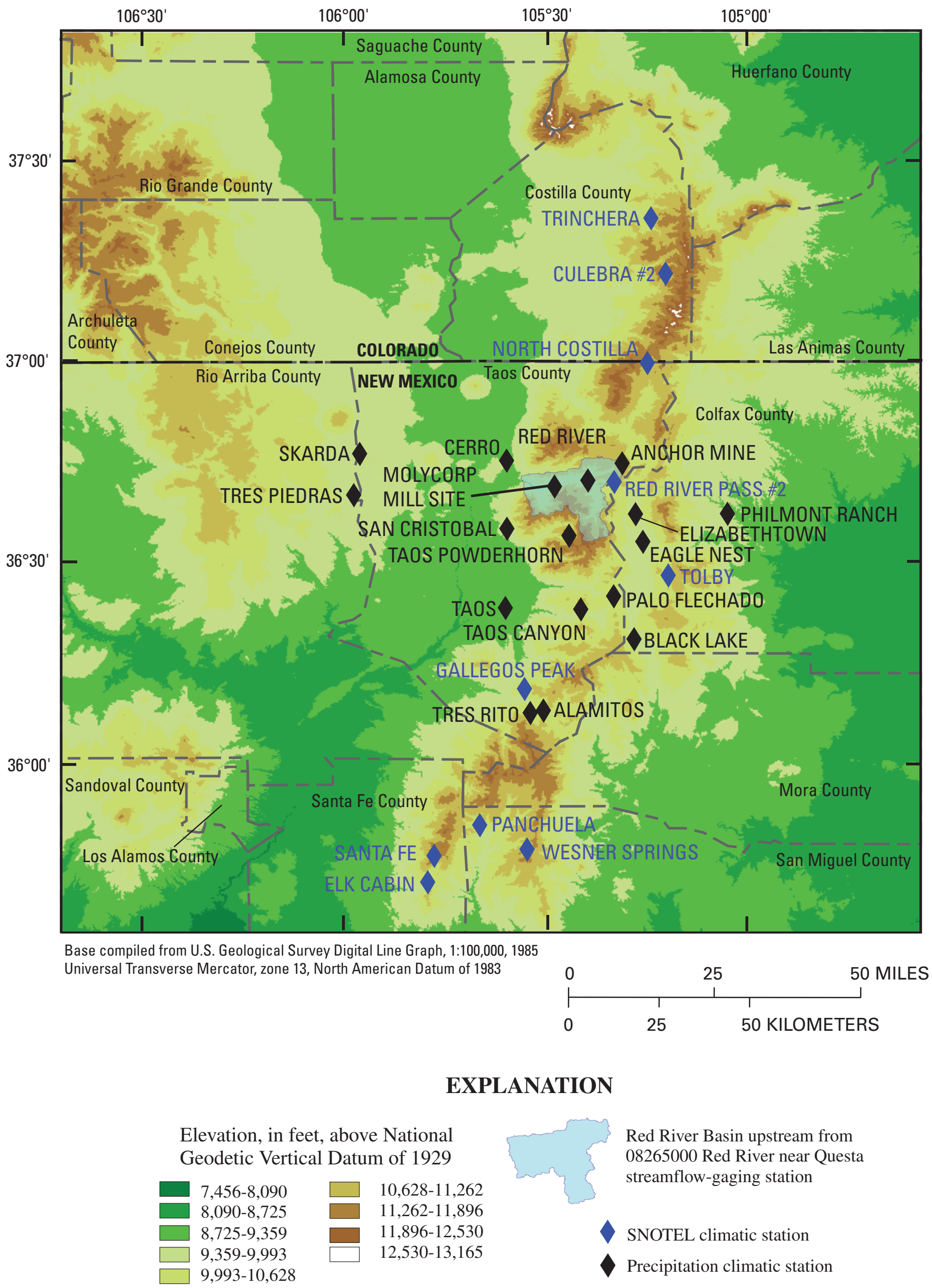

Figure 4. Regional climatic stations in north-central New Mexico and south-central Colorado.

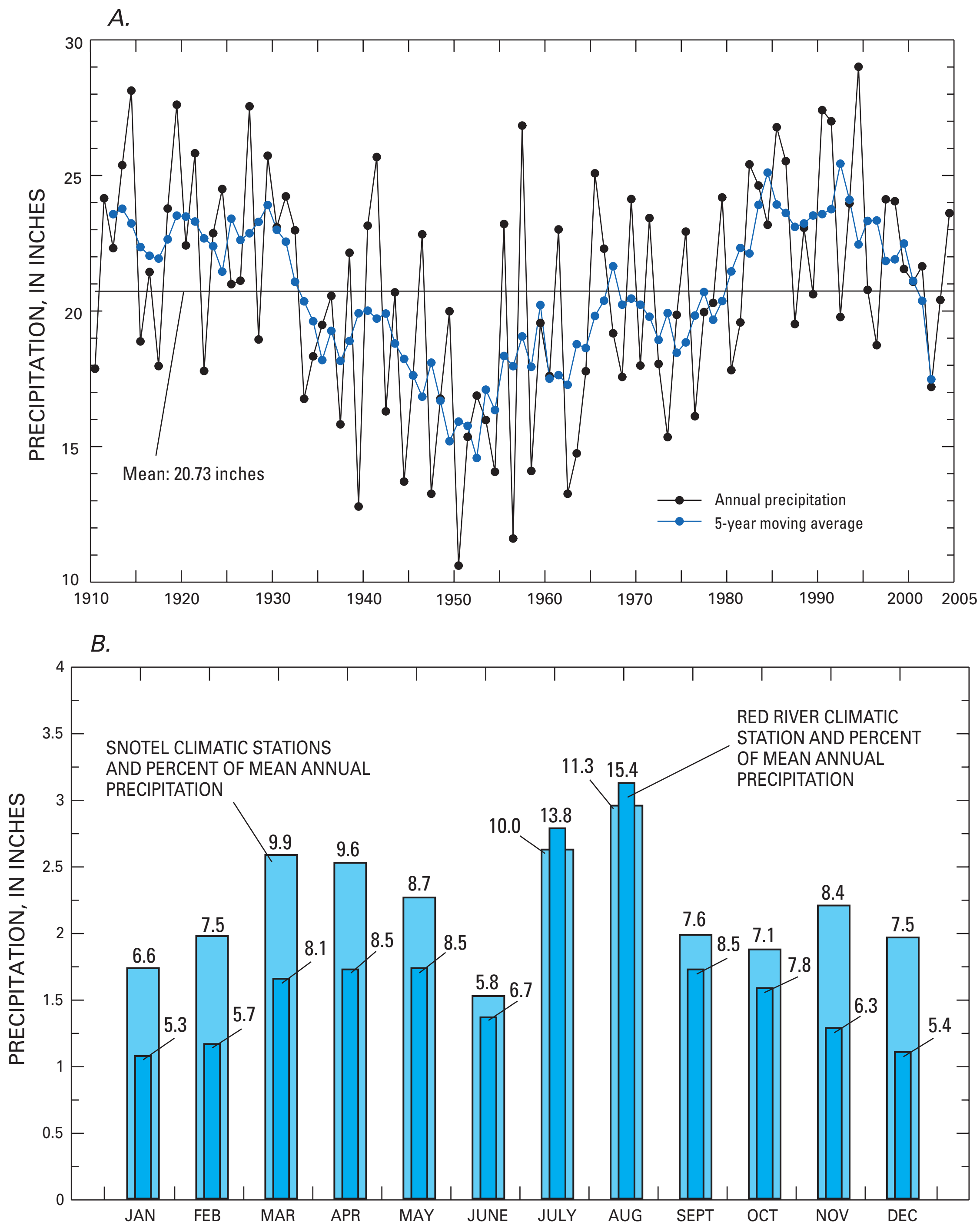

Figure 5. (*A*) Town of Red River climatic station annual, 5-year moving average, and mean precipitation, 1910–2004, and (*B*) town of Red River climatic station mean monthly precipitation, 1930–2004, and the Gallegos Peak, Red River Pass #2, North Costilla, and Culebra #2 SNOTEL climatic stations mean monthly precipitation, 1980–2003.

(Gallegos Peak, Red River Pass #2, North Costilla, and Culebra #2; fig. 4), indicate that the percentage of annual precipitation falling in March and April was almost as high as that falling in July and August (fig. 5B).

Snow water equivalent (SWE), or water content of the existing snowpack, is the amount of water that would result from melting of the snowpack. Johnson (1998) documented that SWE reaches its maximum in March or April at most stations in Taos County. At the Red River Pass #2 SNOTEL station (elevation 9,850 ft), the highest average SWE recorded on April 1 was 7.3 in. (period of record 1971–2000) (Natural Resources Conservation Service, 2004). At other SNOTEL stations at higher elevations in the Sangre de Cristo Mountains, the average April 1 SWE from 1971–2000 was as high as 15.3 in. (Wesner Springs, elevation 11,120 ft; fig. 4). SWE data indicate that snowpack melting generally begins in April (but can begin as early as March) and typically is complete by early July (Natural Resources Conservation Service, 2004).

Surface Water

The Red River originates at an elevation of approximately 12,000 ft near Wheeler Peak (fig. 2) and descends about 5,400 ft as it flows 27 mi to its confluence with the Rio Grande. Total drainage basin area is about 190 mi^2; the area of the drainage basin upstream from the Questa gage (fig. 2) is about 108 mi^2. Red River streamflow, in response to melting of the snowpack, increases from March through May (fig. 6A) and, in contrast to precipitation, generally peaks between mid-May and mid-June (fig. 6A). Based on mean daily streamflow rates for 1930–2004, about 66 percent of annual streamflow occurs by the end of June (fig. 6B). High streamflow events caused by summer thunderstorms occur in July, August, and September but do not produce the same volume or duration of flow as that caused by snowpack melting (figs. 6A and 6B). From 1930 through 2004, annual mean streamflow of the Red River at the Questa gage averaged 46.0 ft^3/s (cubic feet per second) and ranged from 12.8 to 102.7 ft^3/s. Daily mean discharge ranged from 2.5 to 750 ft^3/s with an average of 46.1 ft^3/s. Streamflow at the Questa gage has been directly affected by diversions from the river and indirectly by pumping of wells in the Red River alluvial aquifer. The mean annual volumetric rate of water diverted from the river and pumped from four wells used to supply water for mine operations from 1966 to 2004 was about 5.5 ft^3/s (1966–2003 data obtained from Ralph Vail, Vail Engineering Inc., written commun., 2004; the 2004 diversion amount was assigned to be the average of the 1999–2003 diversion amounts). When annual mean streamflows at the Questa gage are naturalized (fig. 6C) by adding in annual diversion amounts, the 1930–2004 mean annual naturalized streamflow at the Questa gage is 48.9 ft^3/s (fig. 6C). A 5-year moving average of naturalized annual mean streamflow indicates that, in general, streamflow was greater than the 1930-2004 mean annual in the 1930's and 1940's; below normal in the 1950's, 1960's, and 1970's; above normal in the 1980's and most of the 1990's; and below normal after 1997 (fig. 6C). Trends in the 5-year moving average naturalized annual mean streamflow generally correspond to those of the 5-year moving average of annual mean precipitation (fig. 6D).

Streamflow measurement error was estimated based on USGS hydrographers' assessments of measurement accuracy for measurements obtained from October 1983 through December 1994. USGS hydrographers assign a rating code (E, excellent; G, good; F, fair; and P, poor) to each streamflow measurement based on stream conditions and procedural limitations encountered at the time of measurement. The rating codes are used to indicate percent error: E <= 2 percent, G <= 5 percent, F <= 8 percent, and P > 8 percent (Sauer and Meyer, 1992). In an effort to be conservative for this analysis, the rating codes E, G, and F were assigned their maximum possible percent error (E=2, G=5, F=8). Sauer and Meyer (1992) indicated that a measurement rated as "poor" may have an error of as much as 20 percent, so P was assigned a value of 20 percent. The mean error for October 1983 through December 2004 streamflow-measurement data was about ±7.7 percent of measured flow. Assuming that measurements or estimates of diversions also have a 7.7-percent error rate, the error for naturalized mean annual streamflow is ±7.7 percent of 48.9 ft^3/s, or about ±3.8 ft^3/s. Thus, naturalized mean annual streamflow reasonably could be anywhere within the range of 45.1 to 52.7 ft^3/s.

Two other USGS streamflow-gaging stations were located on the Red River (fig. 2). Station 08264500, Red River below Zwergle dam site near Red River, NM (hereinafter referred to as the Zwergle gage), was operated from 1964 to 1973, and station 08264000, Red River near Red River, N.Mex, was operated from 1944 to 1954. Mean annual streamflows at these gages during their respective periods of record were 17.7 and 16.5 ft^3/s. The seasonal pattern of streamflow at these gages is similar to that of the Questa gage (fig. 6A).

The main tributary drainages on the north side of the Red River in the vicinity of the mine site are Capulin Canyon, Goat Hill Gulch, and Sulphur Gulch (fig. 1). Upstream from the mine site, tributary drainages on the north side of Red River that drain scar areas include Little Hansen, Hansen, Straight, and Hottentot Creeks, whereas drainages that drain nonscar areas include Mallette and Bitter Creeks. Bear Canyon and Columbine, Pioneer, Placer, and Goose Creeks drain largely unmineralized nonscar areas on the south and west sides of the river (fig. 1).

In the Red River Basin, most tributary streams flow perennially in the upper reaches and ephemerally and intermittently in the lower reaches. Tributary streamflow typically infiltrates debris fans before reaching the Red River but can discharge directly into the Red River during periods of runoff following intense precipitation. Water discharged from most tributary basins in the lower reaches of the Red River Basin,

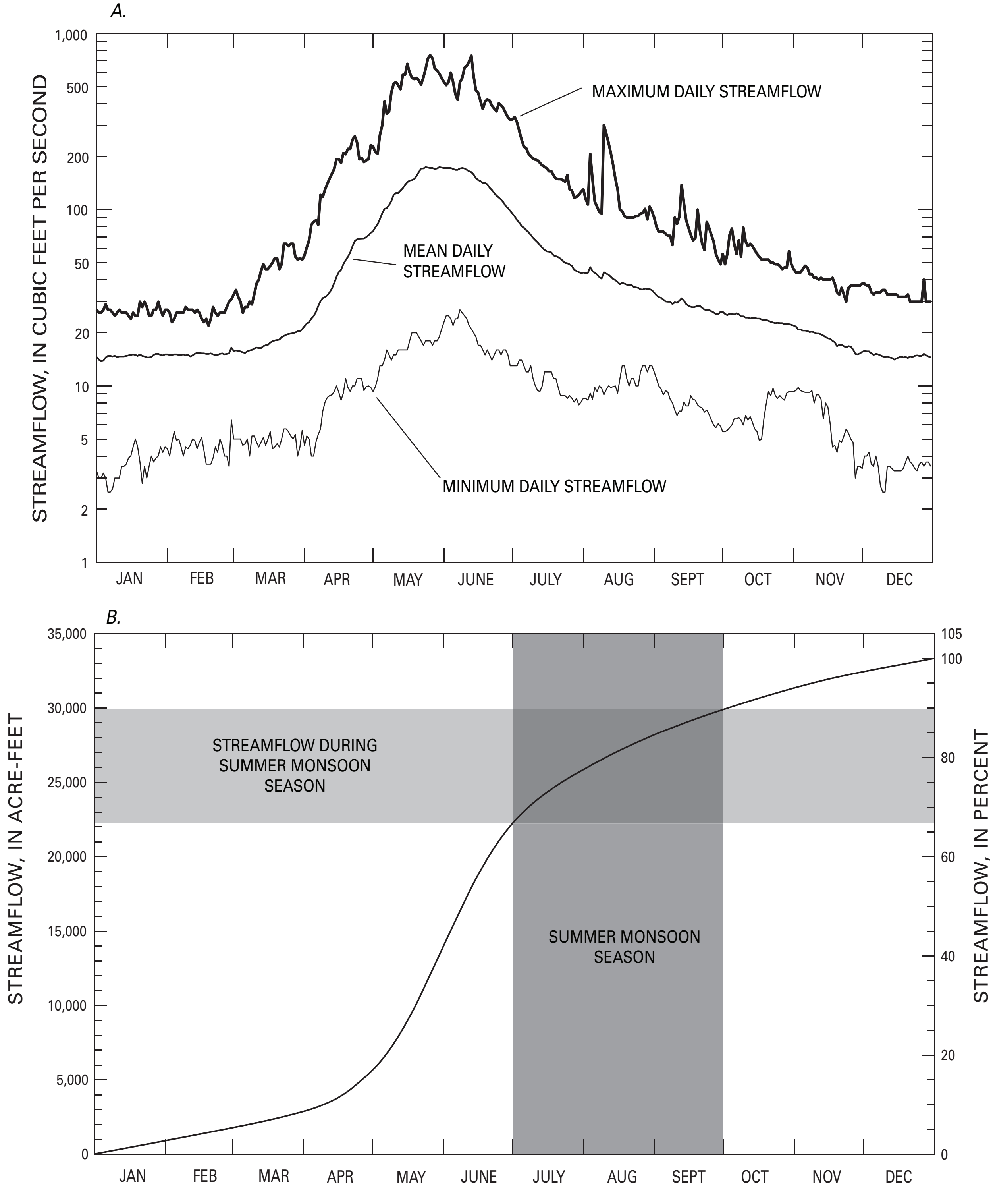

Figure 6. Streamflow at the Red River near Questa gaging station and precipitation at the town of Red River climatic station, 1930–2004. (*A*) Mean daily streamflow, maximum daily streamflow, and minimum daily streamflow; (*B*) cumulative mean daily streamflow; (*C*) annual mean naturalized streamflow, 5-year moving average annual mean naturalized streamflow, and mean annual naturalized streamflow; and (*D*) 5-year moving average annual mean naturalized streamflow and 5-year moving average annual mean precipitation.

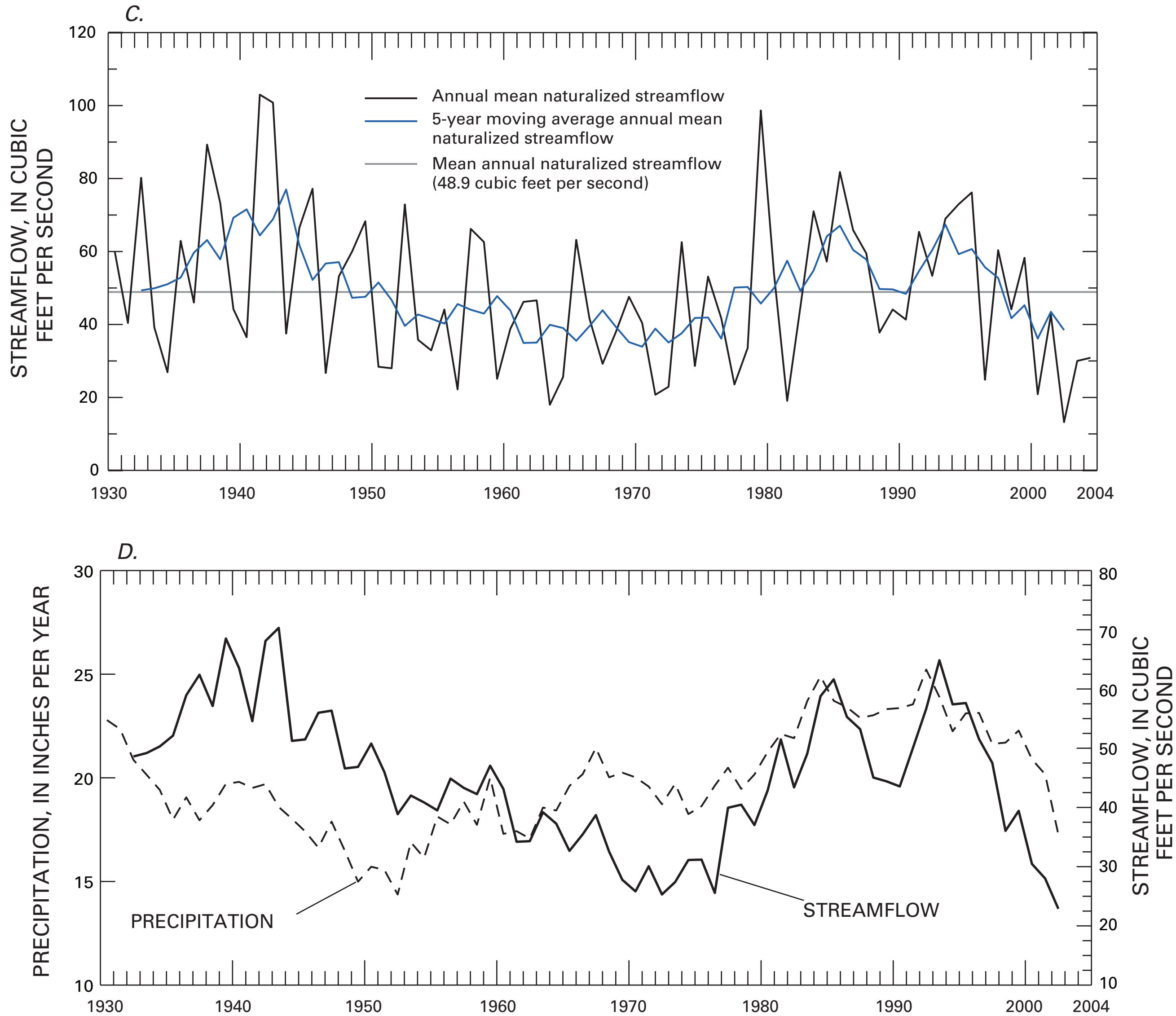

Figure 6. Streamflow at the Red River near Questa gaging station and precipitation at the town of Red River climatic station, 1930–2004. (*A*) Mean daily streamflow, maximum daily streamflow, and minimum daily streamflow; (*B*) cumulative mean daily streamflow; (*C*) annual mean naturalized streamflow, 5-year moving average annual mean naturalized streamflow, and mean annual naturalized streamflow; and (*D*) 5-year moving average annual mean naturalized streamflow and 5-year moving average annual mean precipitation—Continued.

therefore, is primarily ground-water flow from debris-flow material to Red River alluvium.

Between the town of Red River and the Questa gage, there are approximately 25 ephemeral seeps and springs along the banks of the Red River and approximately 20 intermittent seeps and springs in tributary drainages on the north side of the river (South Pass Resources, Inc., 1995; Steffen, Robertson & Kirsten, 1995; Robertson GeoConsultants, Inc., 2001a). The seeps and springs discharge primarily from Red River alluvium. Ground-water seepage to the river and discharge from springs render the Red River a gaining stream over much of its length.

Most seeps and springs discharging from the north side of the river are acidic (pH 2-4) with high specific conductance, dissolved-solids, and metal concentrations (Maest and others, 2004; S. LoVetere, U.S. Geological Survey, written commun., 2005). Aluminum hydroxide often precipitates from springs downgradient from scar and mined areas, affecting the color and turbidity of the river (Vail Engineering Inc., 1989).

Ground Water and Aquifer Properties

Aquifers in the Red River Basin include fractured and weathered bedrock, debris-flow deposits, and Red River alluvium. Bedrock constitutes the largest aquifer in the study area in terms of volume of rock but probably contains only small amounts of ground water because of low porosity and hydraulic conductivity that are controlled by fractures (J.S. Caine, U.S. Geological Survey, written commun., 2005). Although debris-flow deposits and Red River alluvium are restricted in areal extent compared to the bedrock aquifer, the deposits contain most of the ground water in the river valley. Red River alluvium with interfingered debris-flow deposits from tributary drainages is less than 1,000 ft wide and less than 200 ft thick (Kirk Vincent, U.S. Geological Survey, written commun., 2003).

Data from well driller's logs, aquifer pumping and slug tests, and geophysical surveys were used to obtain information about aquifer properties in the study area. For wells completed within bedrock aquifers, hydraulic conductivity estimated from pumping tests ranged from 0.001 to about 6 feet/day (ft/d) (Souder, Miller, and Associates, 2000a; 2000c). Hydraulic conductivity of the bedrock aquifer underlying the debris-flow deposits in Straight Creek was calculated from slug tests to range from less than 0.01 to about 0.8 ft/d.

Hydraulic-conductivity estimates from pumping and slug tests for wells completed within Red River alluvium ranged from 0.04 to 860 ft/d (Hibner and others, 1996; Souder, Miller, and Associates, 2000a, 2000b, 2000c, and 2003). Slug and pumping tests conducted by the USGS in wells in the Straight Creek drainage basin indicate that debris-flow material typically has lower hydraulic conductivity than Red River alluvium, generally ranging from about 0.2 to 1 ft/d (Paul Blanchard, U.S. Geological Survey, written commun., 2005). Coarse-grained, well-sorted channel deposits within the debris-flow deposits probably have higher hydraulic conductivity than more poorly sorted debris-flow material. Channel deposits probably were penetrated in Straight Creek well SC-4A (fig. 1) in which hydraulic conductivity calculated from slug tests was about 20 to 50 ft/d (Paul Blanchard, U.S. Geological Survey, written commun., 2005). Hydraulic conductivity of interfingering debris-flow and alluvial deposits in the Red River Valley near the mouth of Straight Creek was calculated to average about 340 ft/d from an aquifer pumping test (Paul Blanchard, U.S. Geological Survey, written commun., 2005). Hydraulic conductivities of the Red River alluvium in areas nearer the mine site, calculated from aquifer pumping tests, ranged from about 150 to 860 ft/d (Souder, Miller, and Associates, 2000b, 2000c, and 2003).

Water Balance

A water balance was constructed for the part of the Red River Basin upstream from the Questa gage to provide estimates of the volume of ground and surface water discharging from tributary drainages during pre-mining conditions. Water-balance components include estimates of precipitation, evapotranspiration, basin yield, and, by calculation, ground-water recharge. Basin yield also is partitioned into estimates of surface-water and ground-water components.

The Red River Basin upstream from the Questa gage was divided into 79 subbasins on the basis of topography and location north or south of the Red River. Subbasins were delineated using ArcInfo software and gridded land-surface elevation data from USGS 1:24,000-scale Digital Elevation Models (DEM's). Each subbasin was divided further into elevation bands using land-surface elevation contours generated from the DEM's. Each elevation band spanned the width of its subbasin and was bounded vertically at 1,000-ft elevation intervals. Subbasins and corresponding elevation bands then were grouped into 30 incremental basins (table 1; fig. 7) that were defined to facilitate comparisons of water balances for the incremental basins to results from previous studies, such as those of Vail Engineering Inc. (2000). The maximum, minimum, and mean elevations for each of the elevation bands within an incremental basin were averaged to determine average elevation values for each incremental basin.

Precipitation Estimates

Long-term precipitation data are available for only the town of Red River climatic station. Equivalent long-term data from the highest elevations, where precipitation is thought to be greatest, are lacking. Thus, the distribution of precipitation throughout the study area is largely unknown and must be estimated. Two approaches were used to estimate the distribution of mean annual precipitation: (1) the Precipitation-Elevation Regressions on Independent Slopes Model (PRISM)

Table 1. Incremental basin number, area, elevation statistics, and description.

[Max, maximum; Min, minimum; NGVD 29, National Geodetic Vertical Datum of 1929]

Incremental basin number (fig. 7)	Location at which yield, streamflow, and ground-water flow are summed (fig. 7)	Sample-station designation used by Vail Engineering, Inc. (2000)	Incremental basin					Location description
			Area (square feet)	Area (acres)	Elevation, in feet above NGVD 29			
					Min	Max	Mean	
1	A	None	805,220,500	18,485	8,875	13,171	10,880	Above Zwergle gage [north]
2	B	1	227,739,500	5,228	8,667	10,777	9,838	Above town of Red River [north]
3	C	3	405,261,100	9,304	8,625	11,207	9,753	Below town of Red River [north]
4	D	4	38,758,100	890	8,515	10,965	9,276	Hottentot Creek [north]
5	E	5	30,231,400	694	8,439	10,612	9,635	Straight Creek [north]
6	F	6	23,295,900	535	8,301	10,542	9,302	Hansen Creek [north]
7	G	6A	26,373,300	605	8,244	10,537	9,501	Above La Bobita [north]
8	H	7	23,012,700	528	8,112	10,165	9,425	Above mill area [north]
9	I	8	79,129,760	1,817	7,954	10,807	9,099	Mill area to above Portal Springs [north]
10	J	10	9,305,000	214	7,848	9,510	8,444	Above Columbine Creek [north]
11	K	11B	6,726,300	154	7,789	9,291	8,349	Above Thunder Bridge [north]
12	L	12	46,561,400	1,069	7,635	10,030	9,019	Below Goat Hill Gulch [north]
13	M	13	7,055,900	162	7,581	9,664	8,617	Above Capulin Canyon [north]
14	N	15	55,785,700	1,281	7,634	10,337	9,090	Eagle Rock Campground [north]
15	O	16	6,420,000	147	7,457	9,010	8,361	Red River near Questa streamflow-gaging station [north]
16	O	16	5,239,700	120	7,456	9,418	8,456	Red River near Questa streamflow-gaging station [south]
17	N	15	70,968,700	1,629	7,496	11,944	9,179	Eagle Rock Campground [south]
18	M	13	6,101,500	140	7,581	9,243	8,341	Above Capulin Canyon [south]
19	L	12	47,456,400	1,089	7,634	10,949	8,912	Below Goat Hill Gulch [south]
20	K	11B	4,978,000	114	7,789	8,968	8,070	Above Thunder Bridge [south]
21	J	9	465,173,000	10,679	7,847	12,702	10,577	Columbine Creek [south]
22	J	10	49,047,700	1,126	7,847	11,377	9,208	Above Columbine Creek [south]
23	I	8	42,828,900	983	7,996	11,901	9,530	Mill area to above Portal Springs [south]
24	H	7	62,068,300	1,425	7,954	11,900	9,709	Above mill area [south]
25	G	6A	3,371,700	77	8,242	9,583	8,882	Above La Bobita [south]
26	F	6	17,567,800	403	8,299	10,738	9,275	Hansen Creek [south]
27	E	5	29,709,800	682	8,439	11,536	9,909	Straight Creek [south}
28	D	4	25,242,300	579	8,514	10,452	9,251	Hottentot Creek [south}
29	C	3	156,515,900	3,593	8,626	12,675	9,658	Below town of Red River [south]
30	B	1	236,008,900	5,418	8,668	12,702	10,570	Above town of Red River [south]
Red River Basin (fig. 2)			3,013,155,160	69,173				Upstream of Questa streamflow-gaging station (08265000, fig. 2)

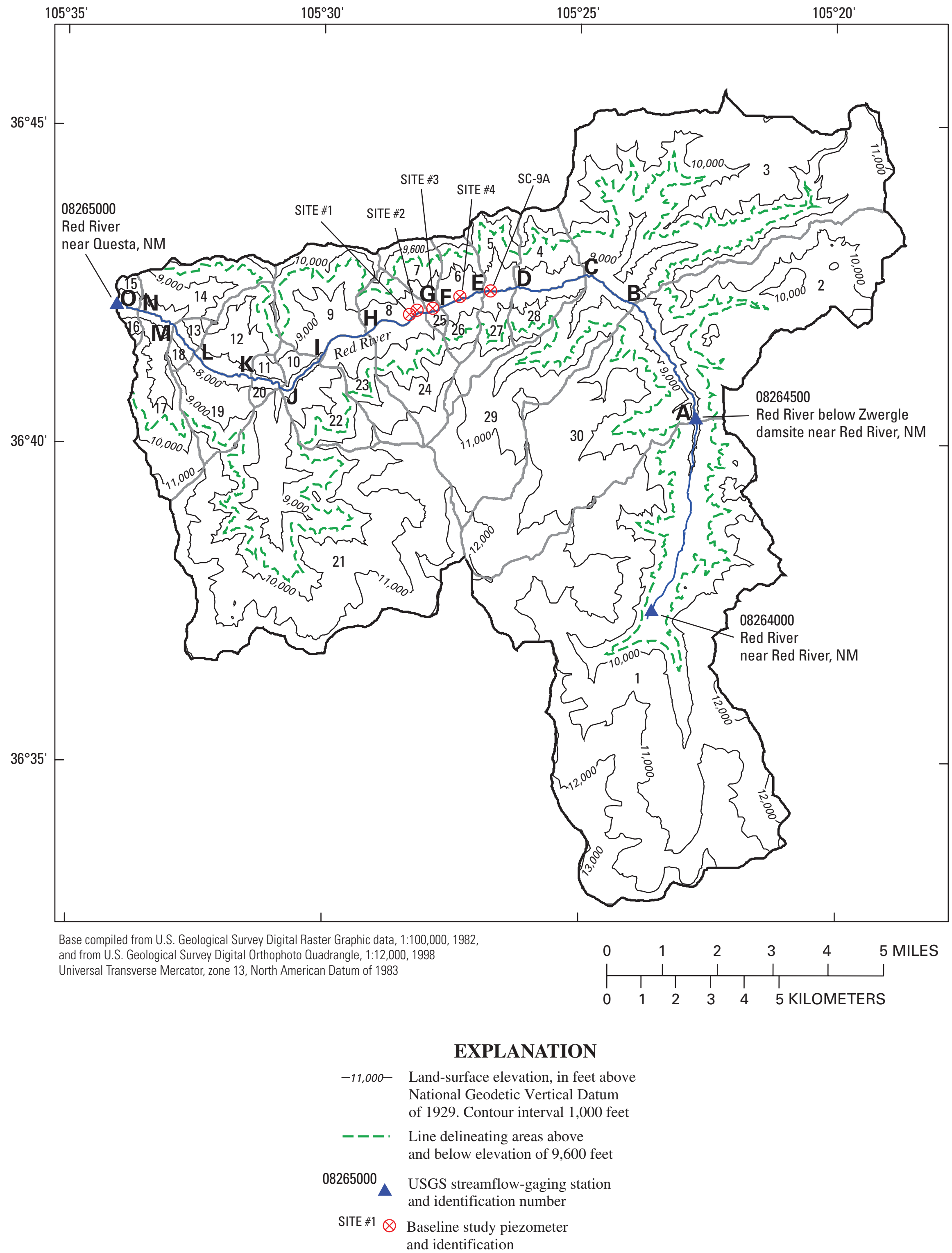

Figure 7. Piezometer sites, incremental basins and corresponding identification numbers, land-surface elevation contours delineating elevation bands, and identification letters for locations on the Red River at which yield, streamflow, and ground-water flow from incremental basins north and south of the river were summed.

developed by Oregon State University (Daly and others, 1994, 1997), and (2) calculation of average annual precipitation using previously developed regional relations between precipitation and elevation.

PRISM is an analytical model that uses point data and a DEM to generate gridded estimates of monthly and annual precipitation (as well as other climatic parameters). PRISM is well suited to mountainous terrain because it incorporates a conceptual framework that addresses the spatial scale and pattern of orographic precipitation (Daly and Taylor, 1998). PRISM has been used to generate mean monthly precipitation estimates for each State in the United States (Daly and others, 1994, 1997). The mean annual PRISM precipitation map for the climatological period 1961–90 for New Mexico, available as an ArcInfo dataset (Spatial Climate Analysis Service, Oregon State University [n.d.]), was used to generate statistics describing the maximum, minimum, and mean annual precipitation, in inches, for each elevation band in the study area. The mean annual precipitation for each incremental basin is tabulated in table 2.

Analysis of data collected at the mine site from August 2000 through April 2003 at three locations at elevations ranging from 8,735 to 9,800 ft did not indicate an increase in precipitation with an increase in elevation (Christoph Wels, Robertson GeoConsultants, Inc., written commun., February 25, 2004). Other investigators using longer term data sets (Pete Stewart, U.S. Forest Service, written commun., 1984 [cited in Wasiolek, 1995, p. 15]; Johnson, 1998, eq. 2; and Robertson GeoConsultants, Inc., 2000d, fig. 6) have developed elevation-precipitation relations that are applicable to the Sangre de Cristo Mountains. Three of these relations were used in this study. Although the individual relations vary somewhat, the analyses support a positive correlation between increasing precipitation with increasing elevation.

The U.S. Forest Service used the following equations for the southern Rocky Mountains of southern Colorado and northern New Mexico (Pete Stewart, U.S. Forest Service, written commun., 1984):

$$MAP = 0.0048(E_r) - 19.16 \qquad (1)$$

where MAP = Mean annual precipitation, in inches;
Er = the representative elevation, in feet:
$= ((E_{max} - E_{min})/3) + E_{min}$ for elevations greater than 9,600 ft (fig. 7) and
$= ((E_{max} - E_{min})/2) + E_{min}$ for elevations less than 9,600 ft;
Emax = the maximum elevation, in feet; and
Emin = the minimum elevation, in feet.

Johnson (1998) investigated the applicability of elevation-precipitation relations for several precipitation stations in Taos County. A regression between mean annual precipitation and elevation (Johnson, 1998, p. 12, eq. 2) was developed using a common period of data (1948–95) for selected stations with similar geographic areas (Taos, Cerro, Black Lake, and Red River; fig. 4). The equation is as follows:

$$MAP = 0.00552 E - 27 \qquad (2)$$

where MAP = Mean annual precipitation, in inches; and
E = Elevation, in feet.

This equation estimates a 5.5-in. precipitation increase per 1,000 ft of elevation increase. As noted by Johnson (1998), this regression specifically applies to the Taos County area of northern New Mexico because of the climatic stations used. None of the four stations used in Johnson's (1998) regression, however, are located at elevations exceeding 9,000 ft, whereas about 87 percent of the terrain elevations within this study area exceed 9,000 ft.

Robertson GeoConsultants, Inc. (2000d), in a water-balance study of the mine site, developed a relation between mean annual precipitation and elevation using data from 12 regional precipitation stations (Skarda, Cerro, Anchor Mine, Tres Piedras, Molycorp mill site, Red River, Red River Pass #2, San Cristobal, Elizabethtown, Philmont Ranch, Eagle Nest, and Taos; fig. 4) with a 1961-1990 common period of record. For stations with no data during that period, Robertson GeoConsultants, Inc. (2000d) adjusted mean annual precipitation values on the basis of correlations with nearby long-term stations (except for Anchor mine). Their relation, which incorporates data from stations with elevations near 10,500 ft, is as follows:

$$MAP = 0.0050 E - 24 \qquad (3)$$

where MAP = Mean annual precipitation, in inches; and
E = Elevation, in feet.

The equation is similar to equation 2 and estimates precipitation increase of about 5 in. per 1,000 ft of elevation increase.

Equations 1-3 were developed for specific elevation ranges, and because the equations are linear they yield unreasonable results (such as negative precipitation amounts) if they are applied to low elevations. However, all the equations appear to result in reasonable precipitation amounts for the range of mean incremental basin elevations in the Red River Basin (8,070 to 10,880 ft; table 2).

Equations 1-3 were used to estimate the amount and distribution of mean annual precipitation in the study area. With the exception of the U.S. Forest Service equation (eq. 1), the mean elevation of each elevation band was substituted for the elevation term in each equation. For the U.S. Forest Service equation the maximum and minimum elevations of each elevation band were used.

Mean annual precipitation estimates using PRISM and equations 1-3 yielded a range of mean annual precipitation values for the Red River Basin (table 2) of 22.32 to

Table 2. Incremental basin mean annual precipitation, mean April snow water equivalent, and seasonal precipitation.

[MAP, mean annual precipitation; Max, maximum; Min, minimum; NGVD 29, National Geodetic Vertical Datum of 1929; PRISM, Precipitation-Elevation Regressions on Independent Slopes Model (Daly and others, 1994, 1997); R^2, coefficient of determination from linear regression; SWE, snow water equivalent; , standard deviation]

Incremental basin number (table 1; fig. 7)	Mean elevation, in feet above NGVD 29	Mean annual precipitation, in inches							Snow water equivalent or precipitation, in inches			
		PRISM	U.S. Forest Service (equation 1; R^2 is unknown),	Johnson (1998) (equation 2; R^2=0.82)	Robertson Geo-Consultants, Inc. (2000d) (equation 3; R^2=0.76)[1]	Average of PRISM and equations 1, 2, and 3	Above-normal (+1σ)	Below-normal (-1σ)	Mean April SWE (equation 4; R^2=0.65)	Spring (March-June) precipitation (R^2=0.40)	Summer and fall (July-September) precipitation (R^2=0.07)	Winter (October-February) precipitation (R^2=0.46)
1	10,880	29.02	31.65	32.15	29.57	30.60	34.98	26.22	15.12	9.52	9.37	11.71
2	9,838	24.15	27.82	27.29	25.17	26.11	30.49	21.73	8.98	8.18	8.41	9.52
3	9,753	26.41	28.44	28.06	25.87	27.19	31.57	22.81	8.60	8.50	8.69	10.00
4	9,276	22.74	25.99	24.96	23.07	24.19	28.57	19.81	6.78	7.60	8.01	8.58
5	9,635	22.52	26.05	25.09	23.18	24.21	28.59	19.83	8.11	7.61	8.00	8.60
6	9,302	22.03	24.71	23.42	21.67	22.96	27.34	18.58	6.87	7.24	7.75	7.97
7	9,501	22.14	26.13	25.33	23.40	24.25	28.63	19.87	7.59	7.62	7.99	8.64
8	9,425	22.62	23.93	22.46	20.80	22.45	26.83	18.07	7.30	7.09	7.68	7.68
9	9,099	22.59	25.31	24.33	22.50	23.68	28.06	19.30	6.21	7.45	7.90	8.33
10	8,444	23.32	21.72	19.84	18.43	20.83	25.21	16.45	4.47	6.61	7.40	6.82
11	8,349	23.14	21.29	19.38	18.01	20.45	24.83	16.07	4.26	6.50	7.32	6.63
12	9,019	22.36	22.92	21.39	19.84	21.63	26.01	17.25	5.96	6.84	7.51	7.28
13	8,617	21.42	20.88	18.74	17.43	19.62	24.00	15.24	4.87	6.24	7.09	6.29
14	9,090	20.29	23.79	22.56	20.89	21.88	26.26	17.50	6.18	6.91	7.47	7.51
15	8,361	16.02	19.93	17.52	16.33	17.45	21.83	13.07	4.29	5.57	6.44	5.44
16	8,456	17.27	20.63	18.68	17.37	18.49	22.87	14.11	4.50	5.88	6.68	5.92
17	9,179	22.36	26.62	26.00	24.00	24.74	29.12	20.36	6.46	7.76	8.07	8.91
18	8,341	21.29	20.62	18.61	17.32	19.46	23.84	15.08	4.25	6.20	7.05	6.22
19	8,912	23.74	23.34	21.88	20.28	22.31	26.69	17.93	5.65	7.05	7.68	7.57
20	8,070	23.48	20.32	18.19	16.93	19.73	24.11	15.35	3.71	6.29	7.19	6.25

Table 2. Incremental basin mean annual precipitation, mean April snow water equivalent, and seasonal precipitation—Continued.

[MAP, mean annual precipitation; Max, maximum; Min, minimum; NGVD 29, National Geodetic Vertical Datum of 1929; PRISM, Precipitation-Elevation Regressions on Independent Slopes Model (Daly and others, 1994, 1997); R^2, coefficient of determination from linear regression; SWE, snow water equivalent; , standard deviation]

		Mean annual precipitation, in inches							Snow water equivalent or precipitation, in inches			
Incremental basin number (table 1; fig. 7)	Mean elevation, in feet above NGVD 29	PRISM	U.S. Forest Service (equation 1; R^2 is unknown),	Johnson (1998) (equation 2; R^2=0.82)	Robertson Geo-Consultants, Inc. (2000d) (equation 3; R^2=0.76)[1]	Average of PRISM and equations 1, 2, and 3	Above-normal (+1σ)	Below-normal (-1σ)	Mean April SWE (equation 4; R^2=0.65)	Spring (March-June) precipitation (R^2=0.40)	Summer and fall (July-September) precipitation (R^2=0.07)	Winter (October-February) precipitation (R^2=0.46)
21	10,577	27.79	30.29	30.50	28.08	29.16	33.54	24.78	12.99	9.09	9.07	11.00
22	9,208	24.48	25.29	24.36	22.52	24.16	28.54	19.78	6.55	7.60	8.05	8.51
23	9,530	25.59	27.51	27.08	24.99	26.29	30.67	21.91	7.70	8.23	8.48	9.58
24	9,709	25.91	27.98	27.60	25.45	26.73	31.11	22.35	8.42	8.37	8.57	9.79
25	8,882	23.30	23.07	21.32	19.77	21.87	26.25	17.49	5.57	6.92	7.60	7.35
26	9,275	23.67	25.60	24.53	22.68	24.12	28.50	19.74	6.77	7.59	8.03	8.51
27	9,909	24.71	27.92	27.55	25.41	26.39	30.77	22.01	9.30	8.26	8.47	9.66
28	9,251	22.57	25.02	23.78	22.00	23.34	27.72	18.96	6.69	7.35	7.85	8.14
29	9,658	27.33	30.68	30.94	28.49	29.36	33.74	24.98	8.21	9.15	9.09	11.12
30	10,570	27.27	30.30	30.43	28.02	29.01	33.39	24.63	12.95	9.04	9.03	10.93
Red River Basin Max	10,880	29.02	31.65	32.15	29.57	30.60	34.98	26.22	15.12	9.52	9.37	11.71
Red River Basin Min	8,070	16.02	19.93	17.52	16.33	17.45	21.83	13.07	3.71	5.57	6.44	5.44
Red River Basin Mean		23.38	25.19	24.13	22.32	23.76	28.14	19.38	7.18	7.48	7.93	8.35
Red River Basin Median		23.22	25.30	24.35	22.51	23.90	28.28	19.52	6.73	7.52	7.95	8.42

[1]Coefficient of determination calculated based on data presented in table 3 of Robertson GeoConsultants, Inc. (2000d).

25.19 in. The average value of these mean annual precipitation estimates for each incremental basin (table 2) was used for water-balance calculations. To evaluate the mean annual precipitation estimates, values were compared with the mean annual precipitation measured at the Red River climatic station (fig. 4). The 1910–2004 mean annual precipitation for the Red River climatic station, located at an elevation of 8,676 ft, is 20.73 in (fig. 5A). For elevation bands with similar mean elevations (8,662–8,683 ft), the estimated mean annual precipitation ranged from 20.8 to 21.6 in. For incremental basin 13, with a mean elevation of 8,617 ft, the average mean annual precipitation was 19.62 in. (table 2).

A range of values representing above-normal and below-normal average mean annual precipitation (table 2) was generated by increasing and decreasing the estimated mean annual precipitation for each incremental basin by +/- one standard deviation of 1910–2004 Red River climatic station precipitation, or +/- 4.38 in. (table 2). All the mean annual precipitation values estimated using PRISM and equations 1-3 are within the range of +/- one standard deviation of the average mean annual precipitation for each incremental basin (table 2).

Johnson (1998) defined an equation relating mean April SWE and elevation using 1978–96 data from the Tres Rito, Gallegos Peak, Palo Flechado, Taos Canyon, Taos Powderhorn, and Alamitos climatic stations (fig. 4). These stations are located at elevations ranging from about 8,600 to 11,200 ft. The equation relating SWE to elevation for these stations estimated an increase of 9.95 in. of SWE per 1,000-ft elevation increase (Johnson, 1998). Data from two SNOTEL stations located near the study area (North Costilla, elevation 10,600 ft; and Red River Pass #2, elevation 9,850 ft; fig. 4) were not within the 95-percent confidence interval for Johnson's (1998) regression, which lead her to conclude that the Red River area has a unique precipitation-to-elevation relation for winter precipitation. A regression of SWE and elevation for the North Costilla and Red River Pass #2 stations resulted in an estimated SWE 6.5-in. increase per 1,000-ft increase in elevation (Johnson, 1998).

Because Johnson's (1998) SWE regression for the Red River area incorporates data from only two stations, additional data were used for the present study to relate mean April SWE to elevation. The 1971-2000 mean April SWE was related to elevation for nine SNOTEL stations (Elk Cabin, Red River Pass #2, Gallegos Peak, Tolby, North Costilla, Culebra #2, Trinchera, Santa Fe, and Wesner Springs; fig. 4) located at elevations ranging from 8,210 to 11,445 ft. Ninety-six percent of land-surface elevation is within this range in the Red River Basin study area. The resulting equation is as follows:

$$SWE = 0.0656\ e^{0.0005\ E} \qquad (4)$$

where SWE = Mean April snow water equivalent, in inches;
e = The base of the natural logarithm; and
E = Elevation, in feet.

Using equation 4, the estimated mean April SWE for incremental basins ranged from 3.71 in. at an 8,070-ft elevation to 15.12 in. at a 10,880-ft elevation (table 2), resulting in an average SWE increase of 4.06 in. per 1,000 ft increase in elevation.

Evapotranspiration Estimates

Evapotranspiration was estimated by three methods: (1) a graphical technique described by Troendle and Leaf (1980) for the Rocky Mountain region that estimates evapotranspiration using seasonal precipitation, (2) a relation between annual precipitation and evapotranspiration based on paired watershed studies conducted in Colorado (MacDonald and Stednick, 2003), and (3) a reference evapotranspiration calculated using the Hargreaves method (Hargreaves and Samani, 1982; Utah Climate Center, 2004) and crop coefficients (New Mexico Climate Center, 2004) for New Mexico climatic stations.

In the first method, Troendle and Leaf (1980) used a graphical technique to relate seasonal precipitation to seasonal evapotranspiration for watersheds with various energy aspects (see figs. EI-24, I11-25, and III-26 in Troendle and Leaf, 1980). The graphical technique was developed using the computer code WATBAL (Subalpine Water Balance Model) calibrated with observed data from representative and experimental drainage basins in the Rocky Mountain area. Separate graphs are used for different seasons and energy aspects. High-energy aspects are low-elevation, south-facing slopes; intermediate-energy aspects are low- to mid-elevation, east-, west-, and north-facing slopes and high-elevation, south-facing slopes; and low-energy aspects are high-elevation, east-, west-, and north-facing slopes (Troendle and Leaf, 1980).

In keeping with the method used by Troendle and Leaf (1980) of dividing the year into seasons, winter is considered to extend from October through February, spring from March through June, and summer/fall from July through September. To estimate evapotranspiration using the Troendle and Leaf (1980) method, the seasonal distribution of precipitation was calculated from mean monthly precipitation data (Natural Resources Conservation Service, 2003) for the nine SNOTEL stations that were used to estimate mean April SWE in the study area (Elk Cabin, Red River Pass #2, Gallegos Peak, Tolby, North Costilla, Culebra #2, Trinchera, Santa Fe, and Wesner Springs; fig. 4). Linear regression relations between precipitation amounts and elevation, developed for each season, were used to calculate seasonal (winter, spring, and summer/fall) and annual precipitation for each elevation band in the study area. Because annual precipitation estimated in this way differed from the average mean annual precipitation, the percentages of precipitation attributed to each season derived by using the linear regression calculations were calculated for each incremental basin and used to partition the average mean annual precipitation estimate into seasonal amounts for each incremental basin (table 2).

The method of Troendle and Leaf (1980) includes reducing the amount of winter precipitation to account for snow evaporation and sublimation of the snowpack. The method relies on the assumption that evaporation and sublimation are most pronounced within large, treeless areas where snow is unprotected by forest canopy and can be redistributed by wind. Winter precipitation was reduced for treeless areas in this study using the graphical relation between diameter of treeless areas and height of surrounding trees developed by Troendle and Leaf (1980). Treeless areas were delineated from USGS 7 ½-minute topographic quadrangle maps (1:24,000 scale); from maps by Meyer and Leonardson (1990), Vail Engineering Inc. (2000), and Robertson GeoConsultants, Inc. (2001a) that depict the location and extent of scar areas; and from the digital National Land Cover Data (NLCD) 1992 dataset developed from multiresolution land characterization data (U.S. Geological Survey, 2004).

Energy aspects for use in the Troendle and Leaf (1980) method were determined using USGS 1:24,000-scale DEM's. The direction that each of the DEM grid cells faced (aspect) was determined on the basis of maximum gradient to adjacent grid cells. Because of the high elevations in the study area, all DEM grid cells were classified as having either intermediate- or low-energy aspects.

For each elevation band, the seasonal evapotranspiration for intermediate-energy and low-energy aspects was determined using the Troendle and Leaf (1980) graphical relation between seasonal precipitation and seasonal evapotranspiration. The percentages of DEM grid cells assigned intermediate- and low-energy aspect within each elevation band were calculated, and mean seasonal evapotranspiration was calculated by weighting seasonal evapotranspiration by the percentages of intermediate- and low-energy aspects. The mean seasonal evapotranspiration of elevation bands was averaged and the seasonal amounts summed to determine the annual evapotranspiration for incremental basins (table 3). This method may underestimate evapotranspiration because sublimation is approximated only by reducing the amount of winter precipitation on treeless areas. Snow interception by trees and subsequent evaporation are not accounted for in this method.

The second method of estimating evapotranspiration used MacDonald and Stednick's (2003, p. 7) relation between annual precipitation and evapotranspiration in the Fraser Experimental Forests of Colorado (modified from units of millimeters to inches):

$$ET = 18 + 0.28(P - 18) \qquad (5)$$

where ET = Evapotranspiration, in inches; and
P = Annual precipitation, in inches.

In this method, MacDonald and Stednick (2003) indicated that annual precipitation of 18 in. or less in mountain watersheds is either transpired by vegetation or evaporated from soil. In addition, about 28 percent of annual precipitation in excess of 18 in. was assumed to be intercepted by and evaporated from vegetation. The remaining 72 percent of annual precipitation in excess of 18 in. becomes water yield from the basin (MacDonald and Stednick, 2003). An assumption of this method is that in barren areas where vegetation does not intercept precipitation, water yield is greater (evapotranspiration is less) than in forested areas by an amount equal to 28 percent of the annual precipitation amount exceeding 18 in. (table 3).

The third method used to estimate evapotranspiration for this study was to calculate reference evapotranspiration. Reference evapotranspiration expresses the evaporating power of the atmosphere for a specific vegetation type at a specific location and time of year. Reference evapotranspiration is commonly estimated either by physically based equations such as an energy-budget approach (Penman, 1948; Monteith, 1965) or by empirical relations between meteorological variables (Blaney and Criddle, 1950; Hargreaves and Samani, 1982).

For this study, reference evapotranspiration was calculated using the method of Hargreaves and Samani (1982), meteorological data for several stations near the study area, and crop coefficients developed by the New Mexico Climate Center (2004). Meteorological data were obtained from the Utah Climate Center for the following climatic stations: Culebra #2, Gallegos Peak, North Costilla, Panchuela, Red River, Red River Pass #2, Trinchera, and Wesner Springs (fig.4) (Utah Climate Center, 2004).

For the Red River Pass #2 climatic station (fig. 4), estimates of annual cumulative growing degree day (GDD) for 1989-94 (Utah Climate Center, 2004) ranged from 2,258 to 3,295 GDD. For this growing degree day range, crop coefficients ranged from approximately 0.50 to 0.58 for Douglas fir and from 0.55 to 0.75 for pine. Mean annual evapotranspiration estimates for climatic stations in the study area were calculated using the mean (0.625) of the range of crop-coefficient values given above and average monthly reference evapotranspiration values for October 1988 to May 1995 (Utah Climate Center, 2004). A regression of estimated annual evapotranspiration and elevation was used to estimate mean annual evapotranspiration for the elevation bands in the study area.

Values of estimated mean annual evapotranspiration for the Red River Basin, calculated using the three methods discussed above, ranged from 15.02 to 22.45 in. per year (table 3) or 63.23 to 94.49 percent of mean annual precipitation. Expressed as a percentage of mean annual precipitation for each incremental basin (table 2), evapotranspiration estimated using the method of Troendle and Leaf (1980) ranged from 54 to 82 percent (table 3). Uncertainties in parameters used to calculate Troendle and Leaf (1980) evapotranspiration include the elevation and seasonal precipitation regressions that explain less than half of the variability in the data (values of R^2 ranged from 0.07 to 0.46) (table 2) and DEM elevation averaging errors over steep terrain. Evapotranspiration estimated using the method of MacDonald and Stednick (2003) ranged from 68 to 98 percent of average mean annual precipitation (table 3), with the uncertainty quantified in terms of an R^2 of 0.69. Evapotranspiration estimated using the reference evapotranspiration method ranged from 59 to

Table 3. Incremental basin estimated mean annual evapotranspiration.

[MAP, mean annual precipitation; Max, maximum; Min, minimum; R^2, coefficient of determination from linear regression]

Incremental basin number (table 1; fig. 7)	Estimated evapotranspiration, in inches					Average MAP, in inches (table 2)	Estimated evapotranspiration, as a percentage of average MAP				
	Troendle and Leaf (1980) method		MacDonald and Stednick (2003) method (equation 5; R^2=0.69)		Reference evapo-transpira-tion method		Troendle and Leaf (1980) method		MacDonald and Stednick (2003) method		Reference evapo-transpiration method
	NLCD[1]	Scar[1]	NLCD[1]	Scar[1]			NLCD[1]	Scar[1]	NLCD[1]	Scar[1]	
1	18.17	16.53	20.87	21.58	18.09	30.60	59	54	68	71	59
2	17.93	15.96	19.74	20.35	20.73	26.11	69	61	76	78	79
3	16.92	16.33	20.40	20.63	20.31	27.19	62	60	75	76	75
4	17.01	15.90	19.10	19.56	22.00	24.19	70	66	79	81	91
5	16.86	15.63	19.29	19.64	21.93	24.21	70	65	80	81	91
6	16.77	15.45	18.70	19.21	22.84	22.96	73	67	81	84	99
7	16.23	15.68	19.49	19.79	21.80	24.25	67	65	80	82	90
8	16.94	15.13	18.59	19.27	23.36	22.45	75	67	83	86	104
9	18.96	15.63	18.74	19.46	22.34	23.68	80	66	79	82	94
10	16.31	14.39	17.99	18.52	24.78	20.83	78	69	86	89	119
11	14.68	14.30	18.34	18.44	25.03	20.45	72	70	90	90	122
12	17.81	14.78	18.13	18.82	23.93	21.63	82	68	84	87	111
13	13.64	13.64	18.01	18.17	25.38	19.62	70	70	92	93	129
14	16.18	14.68	18.61	19.05	23.30	21.88	74	67	85	87	106
15	13.80	12.96	17.10	17.12	26.04	17.45	79	74	98	98	149
16	12.90	12.90	17.52	17.53	25.41	18.49	70	70	95	95	137
17	15.67	15.12	19.79	19.97	21.43	24.74	63	61	80	81	87
18	13.62	13.39	17.90	18.11	25.45	19.46	70	69	92	93	131
19	14.48	14.36	19.03	19.12	23.67	22.31	65	64	85	86	106
20	13.40	13.40	18.22	18.22	25.68	19.73	68	68	92	92	130
21	17.83	16.28	20.56	21.20	18.99	29.16	61	56	71	73	65
22	14.98	14.98	19.72	19.73	22.32	24.16	62	62	82	82	92
23	15.47	15.47	20.38	20.39	20.84	26.29	59	59	78	78	79
24	15.62	15.62	20.51	20.52	20.56	26.73	58	58	77	77	77
25	14.37	14.37	19.10	19.12	23.97	21.87	66	66	87	87	110
26	15.00	15.00	19.74	19.76	22.23	24.12	62	62	82	82	92
27	15.58	15.58	20.40	20.41	20.59	26.39	59	59	77	77	78
28	14.82	14.70	19.28	19.45	22.64	23.34	63	63	83	83	97
29	16.71	16.15	20.90	21.23	18.74	29.36	57	55	71	72	64
30	16.89	16.27	20.80	21.14	19.02	29.01	58	56	72	73	66
Red River Basin Max	18.96	16.53	20.90	21.58	26.04	30.60	82	74	98	98	149
Red River Basin Min	12.90	12.90	17.10	17.12	18.09	17.45	57	54	68	71	59
Red River Basin Mean	15.85	15.02	19.23	19.52	22.45	23.76	66.73	63.23	80.96	82.16	94.49
Red River Basin Median	15.93	15.13	19.19	19.51	22.33	23.90	67.50	65.00	81.50	82.00	93.00

[1]"NLCD" refers to results of estimating evapotranspiration using National Land Cover Data (U.S. Geological Survey, 2004) to define treeless areas, and "Scar" refers to results of estimating evapotranspiration using maps of scar areas to define treeless areas.

149 percent. This range in values, especially the values that exceed 100 percent, shows that this method has the greatest uncertainties in parameters used to estimate evapotranspiration.

Basin Yield

Basin yield, the amount of ground and surface water yielded from basins tributary to the Red River, was estimated using three different equations that relate basin yield to elevation and (or) precipitation and using the difference between estimates of precipitation and evapotranspiration developed for this study.

Robertson GeoConsultants, Inc. (2000d) developed and used the following equation for the Questa mine site that relates basin yield to average basin elevation:

$$MAY = 0.00905\ (10^{\,0.000276\,E}) - 0.9 \tag{6}$$

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

Robertson GeoConsultants, Inc. (2000d) used streamflow data from six gaging stations in and near the study area (08264000, Red River near Red River, N. Mex.; 08264500, the Zwergle gage; 08265000, the Questa gage; 08266000, Cabresto Creek near Questa, N. Mex.; 08266820, Red River below fish hatchery, near Questa, N. Mex.; and 08267000, Red River at mouth, near Questa, N. Mex.) (fig. 2). Drainage areas, used to compute mean annual basin yield as a volume per unit of time, for these six gaging stations range from about 19 to 190 mi^2. Streamflow data for 1961–90 were naturalized to account for diversions upstream from the gages (Robertson GeoConsultants, Inc. 2000d).

Hearne and Dewey (1988, eq. 8) developed an equation relating mean annual basin yield to basin area and mean winter (October through April) 1931–60 precipitation using streamflow data from gaging stations in the Sangre de Cristo Mountains. The equation is as follows:

$$MAY = 7.62 \times 10^{-5}\ (A^{\,0.977})\ (P_w^{\,3.596}) \tag{7}$$

where MAY = mean annual basin yield, in cubic feet per second;
A = basin area, in square miles; and
P_w = mean winter precipitation, in inches.

Hearne and Dewey (1988) selected 16 gaged basins with a period of record of 1950–80 and no unmeasured diversions upstream from the gaging stations. Because thin alluvial deposits overlie crystalline bedrock at all 16 basins, groundwater flow past the gages was considered to be negligible compared to streamflow. Hearne and Dewey (1988) therefore assumed that streamflow measured at the gages was a reasonable measure of total basin yield.

Because of rounding errors, use of equation 7, with the basin area term raised to the 0.977th power, to calculate mean annual yield for each elevation band designated for this study resulted in a total Red River Basin yield, calculated by summation, that did not equal the total Red River Basin yield calculated by application of equation 7 to the entire basin. The Hearne and Dewey (1988) equation therefore was modified as follows:

$$MAY = 7.62 \times 10^{-5}\ A\ (P_w^{\,3.596}) \tag{8}$$

where terms are as defined for equation 7.

A similar equation relating streamflow to basin area and average basin mean winter precipitation was developed by Waltemeyer and Kernodle (1992) using streamflow data for 15 gaging stations in the Sangre de Cristo Mountains and 1931–60 mean October through April precipitation. For the present study, the equation was modified in the same way as equation 8 so that the exponent of the basin area term is one. The equation is:

$$MAY = 7.24 \times 10^{-5}\ A\ (P_w^{\,3.67}) \tag{9}$$

where MAY = mean annual basin yield, in cubic feet per second;
A = basin area, in square miles; and
P_w = mean winter precipitation, in inches.

Estimates for the various methods are shown in figure 8. The mean annual yields at the Questa gage estimated using equations 6, 8, and 9 (table 4) range from 45.26 to 51.57 ft^3/s, which are within the reasonable range of naturalized mean annual streamflow at the Questa gage (45.1 to 52.7 ft^3/s). The equation 8 mean annual yield estimate of 17.61 ft^3/s (table 4) for incremental basin 1 (fig. 7) compares well with the 1964–73 mean annual streamflow of 17.7 ft^3/s at the discontinued Zwergle gage. Streamflow during 1964–73 generally was below normal at the Questa gage (fig. 6C), however, so the long-term mean annual streamflow at the Zwergle gage probably is higher than 17.7 ft^3/s.

Basin yields also were calculated by subtracting estimated evapotranspiration (table 3) from the estimated average mean annual precipitation (tables 2 and 3). At the Questa gage, this method resulted in Red River Basin yield estimates ranging from 55.58 to 93.15 ft^3/s (table 4).

Red River Basin yield calculated using scar areas from maps and evapotranspiration from equation 5 (55.58 ft^3/s) (table 4) is most similar to the 1930-2004 naturalized mean annual streamflow at the Questa gage (48.9 ft^3/s) (fig.6C) but is outside the reasonable range of naturalized mean annual streamflow (45.1 to 52.7 ft^3/s). Therefore, the median annual basin yield estimate obtained from regression equations 6, 8, and 9 (table 4) was used in this study for further analyses.

Although equations 6, 8, and 9 appear to be a good representation of yield from the Red River Basin as a whole,

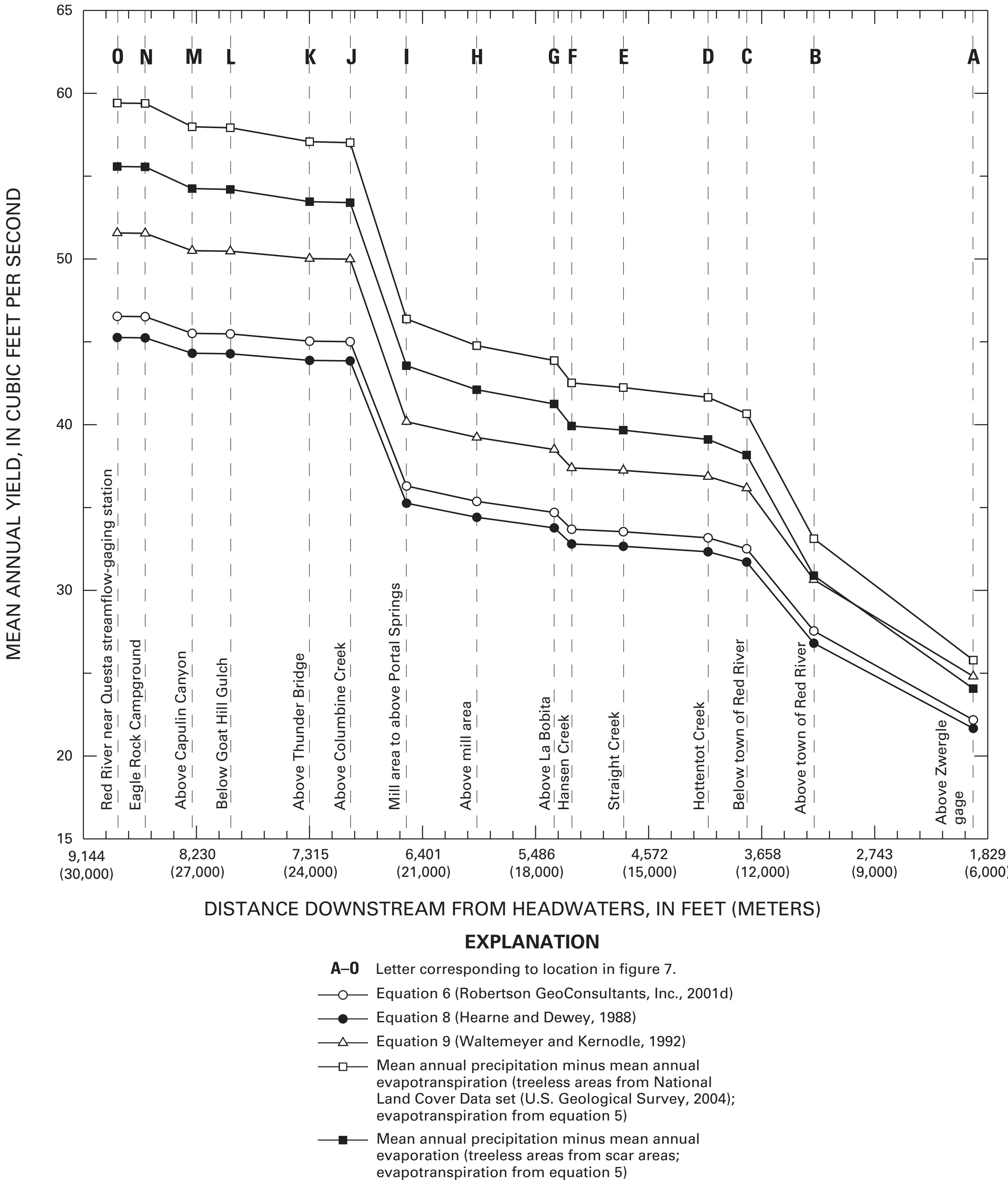

Figure 8. Estimated mean annual basin yield.

Table 4. Mean annual yields for incremental basins and the Red River Basin estimated using regression equations and mean annual precipitation minus mean annual evapotranspiration.

[R^2, coefficient of determination from linear regression]

Incremental basin number (table 1; fig. 7)	Regression equation mean annual yield, in cubic feet per second				Average mean annual precipitation (table 2) minus mean annual evapotranspiration (table 3), in cubic feet per second				
	Robertson GeoConsultants, Inc. (2000d) (equation 6; R^2=0.88)[1]	Hearne and Dewey (1988) (equation 8; R^2 unknown)[2]	Waltemeyer and Kernodle (1992) (equation 9; R^2=0.88)	Median of equations 6, 8, and 9	Troendle and Leaf (1980) method		MacDonald and Stednick (2003) method (equation 5; R^2=0.69)		Reference evapotranspiration method[3]
					NLCD[4]	Scar[4]	NLCD[4]	Scar[4]	
1	18.02	17.61	20.18	18.02	26.42	29.91	20.68	19.17	12.50
2	2.34	2.20	2.47	2.34	4.92	6.10	3.83	3.46	5.38
3	4.80	4.76	5.38	4.80	11.00	11.63	7.27	7.02	6.88
4	0.30	0.28	0.31	0.30	0.73	0.85	0.52	0.47	2.19
5	0.24	0.21	0.24	0.24	0.59	0.68	0.39	0.36	2.28
6	0.14	0.13	0.14	0.14	0.38	0.46	0.26	0.23	0.12
7	0.21	0.19	0.22	0.21	0.56	0.60	0.33	0.31	2.45
8	0.12	0.11	0.12	0.12	0.33	0.44	0.23	0.19	0.00
9	0.56	0.50	0.56	0.56	0.99	1.68	1.03	0.88	1.35
10	0.03	0.03	0.03	0.03	0.11	0.16	0.07	0.06	0.00
11	0.02	0.02	0.02	0.02	0.10	0.11	0.04	0.04	0.00
12	0.20	0.18	0.20	0.20	0.47	0.84	0.43	0.34	0.00
13	0.02	0.02	0.02	0.02	0.11	0.11	0.03	0.03	0.00
14	0.30	0.26	0.29	0.29	0.84	1.06	0.48	0.42	0.00
15	0.01	0.01	0.01	0.01	0.06	0.08	0.01	0.01	0.00
16	0.01	0.01	0.01	0.01	0.08	0.08	0.01	0.01	0.00
17	0.71	0.67	0.76	0.71	1.70	1.80	0.93	0.89	3.31
18	0.01	0.01	0.01	0.01	0.09	0.10	0.03	0.02	0.00
19	0.24	0.22	0.25	0.24	0.98	1.00	0.41	0.40	0.00
20	0.01	0.01	0.01	0.01	0.08	0.08	0.02	0.02	0.00
21	8.68	8.56	9.78	8.68	13.93	15.83	10.57	9.78	10.18
22	0.37	0.35	0.39	0.37	1.19	1.19	0.58	0.57	1.84
23	0.55	0.53	0.61	0.55	1.22	1.22	0.67	0.67	5.45
24	0.80	0.78	0.89	0.80	1.82	1.82	1.02	1.02	6.17
25	0.01	0.01	0.01	0.01	0.07	0.07	0.02	0.02	0.00
26	0.13	0.12	0.13	0.13	0.42	0.42	0.20	0.20	1.89
27	0.36	0.34	0.39	0.36	0.85	0.85	0.47	0.47	5.80
28	0.16	0.14	0.15	0.15	0.57	0.58	0.27	0.26	0.71
29	3.03	2.94	3.36	3.03	5.23	5.46	3.50	3.36	10.62
30	4.16	4.06	4.63	4.16	7.56	7.94	5.11	4.90	9.99
Total for Red River Basin	46.54	45.26	51.57	46.52	83.40	93.15	59.41	55.58	89.11

[1] Coefficient of determination calculated on the basis of data presented in table 3 of Robertson GeoConsultants, Inc. (2000d).

[2] Equation 8 was modified from equation 7. Coefficient of determination of equation 7, 0.91, calculated on the basis of data presented in table 10 of Hearne and Dewey (1988).

[3] Negative values were replaced with zero.

[4] "NLCD" refers to results of estimating evapotranspiration using National Land Cover Data to define treeless areas, and "Scar" refers to results of estimating evapotranspiration using maps of scar areas to define treeless areas.

these equations are not necessarily the best representations of yield from smaller basins that have a substantial amount of sparsely vegetated scar area. Equations 6, 8, and 9 are based on relations between elevation and precipitation or basin area and precipitation and do not account for other hydrologic processes, such as evapotranspiration, that play a substantial role in small basins with sparsely vegetated scar area. The methods of Troendle and Leaf (1980) and MacDonald and Stednick (2003) (table 4) do account for evapotranspiration and may more accurately represent yield from basins with a substantial percentage of scar area. The reference evapotranspiration method (table 4) gives implausible results because it predicts that, for some incremental basins, all annual precipitation would be consumed as evapotranspiration, producing no runoff or infiltration of precipitation to ground water.

Ground-Water and Surface-Water Partitioning and Estimated Recharge

Estimates of the ground-water and surface-water components of watershed yield are important because ground water discharged from drainage basins that are tributary to the Red River can affect the quality of water in the Red River and its alluvial aquifer. Methods used for this analysis include hydrograph separation to estimate the subsurface-water contribution to streamflow, estimation of ground-water recharge using chloride mass balances, and subtraction of streamflow from basin yield. Additional insight into ground-water/surface-water interactions is provided by measured surface-water stages and ground-water levels in piezometers completed in the Red River alluvium.

Hydrograph Separation

Hydrograph separation is a tool used to estimate volumes of water in a stream that originated from different sources. For this study it is important to estimate the separate volumes of water that are derived from surface runoff and from discharge of ground water to the Red River. Surface runoff is water that falls as precipitation and either runs directly off land surface to a stream or is stored as snow or ice until it melts and then runs directly off land surface to a stream. Surface runoff generally cannot occur unless the land surface upon which rain falls or snow and ice melts is saturated with water and the rate of rainfall or melting exceeds the rate at which the soil can absorb the incident moisture. This saturation-excess runoff varies with soil properties; soils that transmit water more readily, such as stony or sandy soils with small amounts of clay-size material, produce less surface runoff than soils with finer-grained material and a larger percentage of clay-size material.

Water that does infiltrate the soil can move downward to the water table and eventually may discharge to a stream as base flow or can move laterally through permeable soil horizons above the water table and discharge to a stream as interflow. Although both base flow and interflow technically can be considered ground water, the term “ground water” often is reserved to indicate water below the water table. Therefore, in this report, base flow and interflow will be collectively termed “subsurface flow.” For this study the importance of including interflow with base flow is that both these components of subsurface water come into close contact with soil and develop an aqueous chemistry that reflects the chemistry of the soil. Although the residence time of interflow water in the soil may be shorter than that of base flow water, the near-surface soil chemistry in Red River Basin scar areas is a substantial contributor to water chemistry in the Red River.

The computer program HYSEP (Sloto and Crouse, 1996) was used to separate streamflow hydrographs for the Questa gage into subsurface-flow and surface-runoff components. The HYSEP program accepts daily-mean streamflow data as input and uses three methods to separate the components of a streamflow hydrograph: (1) fixed interval, (2) sliding interval, and (3) local minimum (Sloto and Crouse, 1996). Hydrographs were separated using all three methods for 1930-2004, which corresponds to the part of the period of record for the Questa gage for which continuous daily streamflow data are available. The different methods produced nearly identical amounts of subsurface flow and runoff. The local-minimum method with 1930-2004 daily streamflow (fig. 9A) was arbitrarily chosen for use in further analyses.

Because hydrograph separation can be affected by surface-water and ground-water diversions, daily mean streamflow measured at the Questa gage was naturalized using measured daily diversions (B. Walker, Molycorp, Inc., written commun., 2004) for January 2000-December 2002. Results of application of the local-minimum method of hydrograph separation to this naturalized data set (fig. 9B) were very similar to those resulting from hydrograph separations using the 1930-2004 data set.

Hydrograph-separation results illustrate that the ground-water contribution to Red River Basin yield is substantial. For the 1930-2004 data set, subsurface flow as a percentage of streamflow for individual years ranged from 76 to 94 percent with a mean of 87 percent or about 42 ft^3/s as an equivalent proportion of the naturalized mean annual streamflow (48.9 ft^3/s) at the Questa gage. These results are consistent with those of Wolock (2003), who calculated that 81 percent of the 1924-99 annual streamflow at the Questa gage is subsurface flow. Mean monthly subsurface flow and runoff for 1930-2004 were highest during May and June and lowest during December, January, and February (fig. 9A). Mean monthly subsurface flow ranged from 81 percent of monthly streamflow in April and May to 94 percent of streamflow in July. These results are consistent with field observations that most of the drainage basins tributary to the Red River produce surface-water runoff primarily during periods of snowmelt or intense precipitation. Surface runoff from scar areas during intense summer storms was observed to flow overland all the way to the Red River. In contrast, surface-water flow from snowmelt in the Straight Creek Basin was observed to infil-

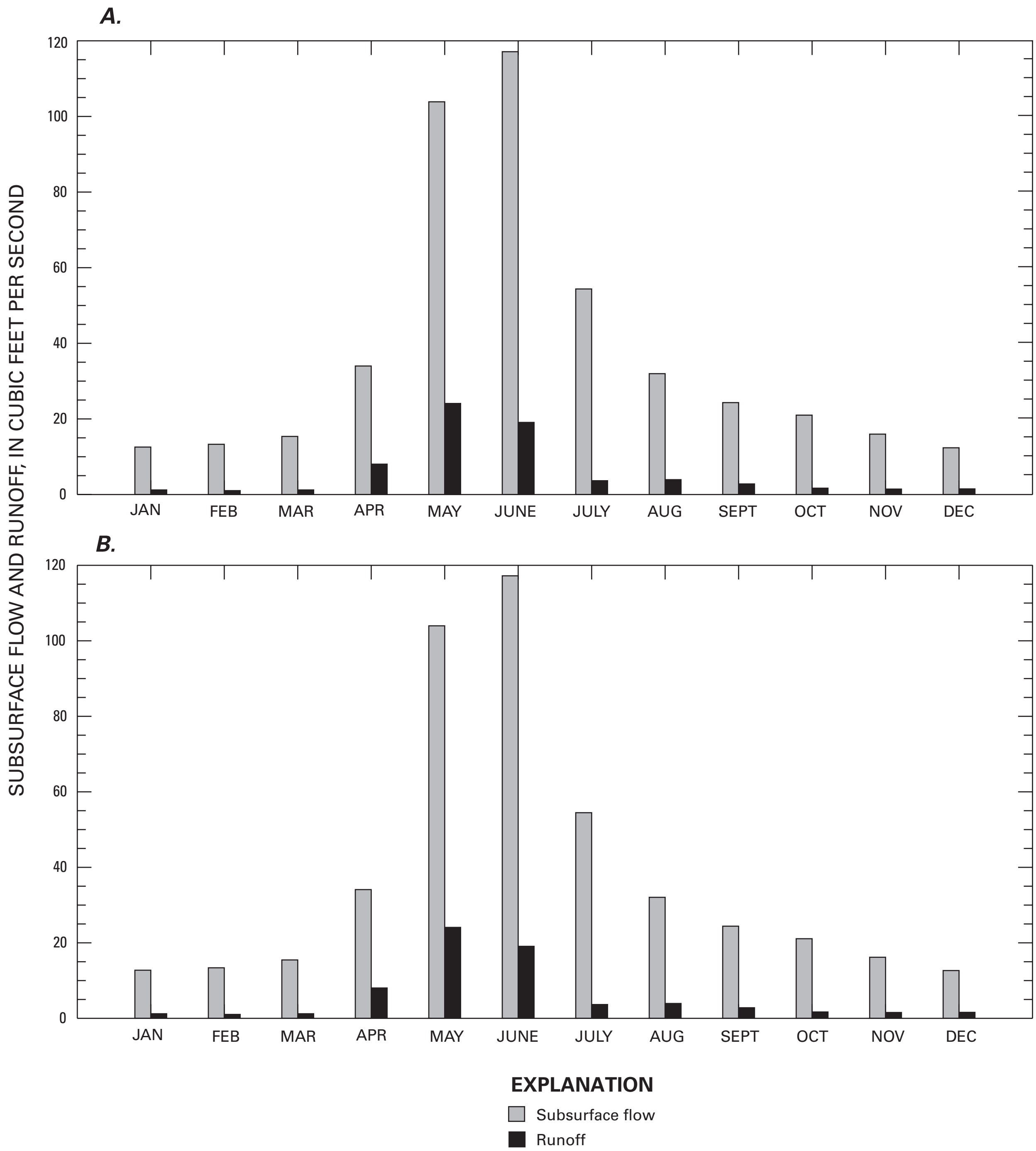

Figure 9. Mean monthly subsurface flow and runoff from hydrograph separation for the Red River near Questa streamflow-gaging station using (*A*) the local-minimum method with 1930–2004 daily streamflow and (*B*) local-minimum method with naturalized January 2000–December 2002 daily streamflow.

trate into debris-flow deposits before reaching the Red River. If this model for snowmelt runoff prevails throughout the Red River Basin, then most of the water yielded from the Red River Basin would be in the form of subsurface flow. The predominance of subsurface flow in tributary basins also is supported by a detailed water budget developed for the Straight Creek drainage basin (Doug McAda, U.S. Geological Survey, written commun., 2005) that indicated that 97 percent of total mean annual yield from this basin is ground-water flow.

Because the HYSEP program does not recognize long-term, gradual streamflow increases such as those that occur during spring snowmelt, the program's estimates of the amount of subsurface flow in the Red River during snowmelt season could be too high. However, Sueker (1995), using sodium concentrations in surface and subsurface water to perform hydrograph separations for three basins in Rocky Mountain National Park, Colorado, indicated that average subsurface-water contributions to streamflow during snowmelt ranged from 47 to 90 percent of streamflow during the snowmelt period. Sueker (1995) attributed these differences in average subsurface-water contribution to geomorphic differences between the basins; principally the greater subsurface contribution occurred in the basins with thicker colluvium. In her study, Sueker (1995) did not differentiate base flow from interflow. The amount of water from below-ground sources estimated by HYSEP is consistent with the interpretation that this water originates both as base flow and interflow (subsurface flow).

Chloride Mass Balance

Recharge to debris-flow aquifers in tributary drainages was estimated using a chloride mass-balance method (Anderholm, 1994, 2001). This method is based on the principle that chloride is concentrated in recently precipitated water or shallow ground water by evapotranspiration. It is applicable to areas where there is no appreciable source of chloride other than that in precipitation. The addition of chloride from non-precipitation sources will decrease estimated recharge, resulting in recharge values that represent minimum possible recharge. The equation used to estimate recharge (Anderholm, 2001; equation 1) is:

$$R = P\ CP / CR \qquad (10)$$

where R = Recharge, in inches;
P = Precipitation, in inches;
CP = Chloride concentration in bulk precipitation, in milligrams per liter; and
CR = Chloride concentration in recharge, in milligrams per liter.

In ratio form the equation can be written as:

$$R / P = CP / CR\ . \qquad (11)$$

Chloride concentrations in ground-water recharge were estimated using (1) chloride concentrations measured in water samples collected from wells in the Capulin Canyon, and the Hansen, Hottentot, La Bobita, and Straight Creek Basins (fig. 1; table 5) (Naus and others, 2005; Nordstrom and others, 2005), and (2) mean chloride concentration measured in Red River water samples collected upstream from the town of Red River wastewater treatment plant and Straight Creek (fig. 1) during an August 2001 low-flow tracer-injection study (McCleskey and others, 2003). The wells are located close to the apex of debris fans or other unconsolidated deposits, and chloride concentrations in water from these wells should be representative of concentrations in recharge over the wells' local basins unless the concentrations were affected by soil or rock chemistry. Red River water samples obtained during the August 2001 low-flow tracer-injection study were collected when there was no overland flow from precipitation; streamflow in the Red River, therefore, should have been representative of ground-water recharge over the Red River Basin upstream from Straight Creek. Chloride concentrations measured in snow samples collected in March 2002 ranged from 0.3 mg/L (milligram per liter) in a sample from the Straight Creek Basin to 0.4 mg/L in the Hansen Creek Basin (R. B. McCleskey, U.S. Geological Survey, written commun., 2003). These chloride concentrations in snow are consistent with chloride concentrations used by Anderholm (2001) to represent chloride in bulk (wet plus dry) precipitation. The average concentration of the two snow samples (0.35 mg/L) was used to represent the chloride concentration in bulk precipitation for the Red River Basin.

Ground-water recharge ranged from 7 to 17 percent of mean annual precipitation for water samples from wells in Capulin Canyon and the Hansen, Hottentot, La Bobita, and Straight Creek Basins and was 21 percent of mean annual precipitation for water samples from the Red River (table 5). Mean annual recharge for the basins ranged from 0.11 to 0.40 ft^3/s for the ground-water samples, exceeding the median of the regression-equation (equations 6, 8, and 9; table 4) yield estimates for the Hansen and Hottentot Creek basins (table 5). Although based on a small set of ground-water samples from one location within the basin, these exceedances may show that the regression equations underestimate the yield from these two basins. For the Red River water samples, the area-weighted mean annual recharge for basins upstream from the Wastewater Treatment Plant and Straight Creek (incremental basins 1-5 and 27-30) was 28.98 ft^3/s or about 87 percent of the median regression-equation yield for these basins (table 5). Extrapolating the Red River results to the entire Red River basin upstream from the Questa gage, the area-weighted mean annual recharge was 39.73 ft^3/s or about 81 percent of the naturalized mean annual streamflow (48.9 ft^3/s) at the Questa gage (table 5). The area-weighted mean annual recharge values obtained from Red River chloride data are consistent with recharge percentages estimated using hydrograph-separation techniques and with the estimate of Wolock (2003).

Table 5. Chloride concentrations in ground- and surface-water samples, ratio of chloride concentration in snow samples to chloride concentration in ground- and surface-water samples, and estimated area-weighted mean annual recharge.

[ft3/s, cubic feet per second; mg/L, milligrams per liter; MAP, mean annual precipitation]

Sampling site and incremental basin number in which site is located (figure 7, table 1)	Basin area, in square feet (table 1)	Mean MAP, in inches (table 2)	Median regression equation yield, in ft^3/s (table 4)	Mean chloride concentration in water samples, in mg/L	Recharge : precipitation ratio calculated using precipitation chloride concentration of 0.35 mg/L, in percent	Area-weighted mean annual recharge calculated on the basis of incremental basin mean MAP and recharge : precipitation ratio		
						Inches	ft^3/s	[3]Percentage of median regression equation yield
Wells CC-1A, and CC-2A; incremental basin 14	55,785,700	21.88	0.29	5.34	7	1.53	0.23	79
Hansen well; incremental basin 6	23,295,900	22.96	0.14	2.01	17	3.90	0.24	171
Hottentot well; incremental basin 4	38,758,100	24.19	0.3	2.23	16	3.87	0.40	133
La Bobita well; incremental basin 8	23,012,700	22.45	0.12	4.55	8	1.80	0.11	92
Well SC-1A; incremental basin 5	30,231,400	24.21	0.24	3.76	9	2.18	0.17	71
Red River above Wastewater Treatment Plant (incremental basins --5 and 27–30)	1,954,687,500	26.71	33.4	1.7	21	5.61	28.98	87
Extrapolation of Red River data to incremental basins 1–30	3,013,155,160	23.76	[1]48.9	1.7	21	4.99	39.73	[2]81

[1]Naturalized mean annual streamflow at Red River near Questa streamflow-gaging station.

[2]As percentage of naturalized mean annual streamflow at Red River near Questa streamflow-gaging station.

[3]Median of results from equations 6, 8, and 9 (table 4).

Basin Yield and Streamflow Comparisons

Comparisons of basin yield and measured streamflow were used to provide qualitative information about ground- and surface-water interaction between the alluvial aquifer and the Red River. Three sets of streamflow measurements made on the Red River between the town of Red River and the Questa gage by Vail Engineering Inc. (2000) (August 19, 1997; October 13, 1999; and March 16, 2000), one set of streamflow measurements reported by Borland and others (1990) (October 25, 1988), and one set of streamflow measurements done during tracer-injection studies (August 17-24, 2001) were selected for this analysis. The data were selected to represent various seasons and a range of streamflow at the Questa gage. In addition, streamflow measurement sets selected from Vail Engineering Inc. (2000) included measured streamflow upstream from the mill and were collected on dates when streamflow was not being diverted for mill operations.

Comparison of estimated mean annual yield to measured streamflow was facilitated by calculating estimated mean annual yield at selected locations along the Red River (fig. 8) as a percentage of estimated mean annual yield at the Questa gage and by calculating measured streamflow as a percentage of total streamflow at the Questa gage (fig. 10).

Comparisons of estimated mean annual basin yield and measured streamflow (fig. 10A-E) indicate that at various locations upstream from the Questa gage, streamflow as a percentage of streamflow at the Questa gage does not consistently increase as cumulative estimated mean annual basin yield increases. Streamflow at the gage was 38.9 ft^3/s on August 19, 1997; 24. 9 ft^3/s on October 13, 1999; and 18.0 ft^3/s on March 16, 2000 (Vail Engineering Inc., 2000). Streamflow was 29.8 ft^3/s on October 25, 1988 (Borland and others, 1990), and averaged 38.6 ft^3/s during the August 2001 tracer-injection study. The relative differences between mean annual basin yield and streamflow percentages on these dates indicate that, in general, ground water is a smaller percentage of total basin yield during higher streamflow conditions (fig. 10).

Care needs to be taken when comparing profiles in figure 10 because streamflow measurement locations are not always coincident for different measurement dates. The profiles generally have similar shapes, however, indicating that geologic constraints, sources of ground and surface water, and hydraulic responses are more or less constant within the study area for nonstorm low-flow conditions. Comparisons of the general shape of the estimated mean annual yield and measured streamflow profiles provide information about where the river may be gaining ground water from or losing surface water to the Red River alluvium. Increases in measured streamflow percentage in the downstream direction without a corresponding increase in estimated mean annual yield percentage indicate a gaining stream reach. Conversely, decreases in streamflow percentage in the downstream direction indicate a losing stream reach.

On all profiles with data from above the town of Red River (figs. 10A, 10B, 10C, and 10D), streamflow percentage increases from above the town of Red River (fig. 7, location B) to approximately the midway point of the river reach between Hottentot and Straight Creeks (fig. 7, locations D and E). The slope of the streamflow profile is steeper than that of the estimated mean annual yield profile in this reach, indicating a gaining stream in this reach. Similarly, a gaining stream generally is evident on all plots in the reach extending from just downstream from Columbine Creek (near location J) to between above Thunder Bridge (location K) and below Goat Hill Gulch (location L). A losing stream is indicated on all profiles in the reach extending from above the mill area (location H) to above Columbine Creek (location J).

In the reach extending from between Hottentot and Straight Creeks (fig. 7, locations D and E) to above the mill area (location H) the August 19, 1997, and March 16, 2000, profiles (fig. 10A and 10C) indicate a gaining stream, whereas the October 13, 1999, (fig. 10B) profile indicates no change in streamflow percentage. The estimated mean annual yield profile shows some gain in this reach, and the lack of corresponding gain in streamflow percentage indicates that streamflow loss or water yielded from tributary basins is going directly to ground water in the Red River alluvium.

The streamflow profile for the USGS seepage investigation conducted on October 25, 1988 (Borland and others, 1990) (fig. 10D), indicates a total streamflow gain of 9.9 ft^3/s between the Zwergle gage and the Questa gage (Borland and others, 1990). Streamflow measurements indicate streamflow gains between the Zwergle gage (fig. 7, location A) and above the mill area (location H) and between Columbine Creek (near location J) and the Questa gage (location O). Streamflow measurements also indicate a streamflow loss between the mill area and Columbine Creek. Locations of streamflow gain and loss (fig. 10D) generally correspond to the other profiles shown in figure 10.

Vail Engineering Inc. (2000) used measured and estimated streamflow and estimated yield to construct a flow balance for the Red River Basin between the town of Red River and the Questa gage for October 13, 1999. Locations of streamflow gain and loss identified by Vail Engineering Inc. (2000), like those identified by Borland (1990), generally were consistent with the profiles shown in figure 10. Vail Engineering Inc. (2000) estimated ground-water flow in the alluvial aquifer above the mill area (location H, figs. 7 and 10) to be about 5.4 ft^3/s (about 22 percent of the October 13, 1999 daily mean streamflow at the Questa gage). Ground-water flow in the alluvial aquifer below Capulin Canyon (approximately location M, figs. 7 and 10) was estimated to be about 0.7 ft^3/s (about 3 percent of the October 13, 1999, daily mean streamflow at the Questa gage). Vail Engineering Inc. (2000) concluded that measured streamflow gains in the reach between the mill area and Capulin Canyon resulted from the seepage of alluvial ground water to the river, and that the magnitude of ground-water inflow to the river was too large to be accounted for by ground-water contributions solely from tributary basins within this reach. The source of much of the ground-water discharge to the river, therefore, was concluded to be tributary

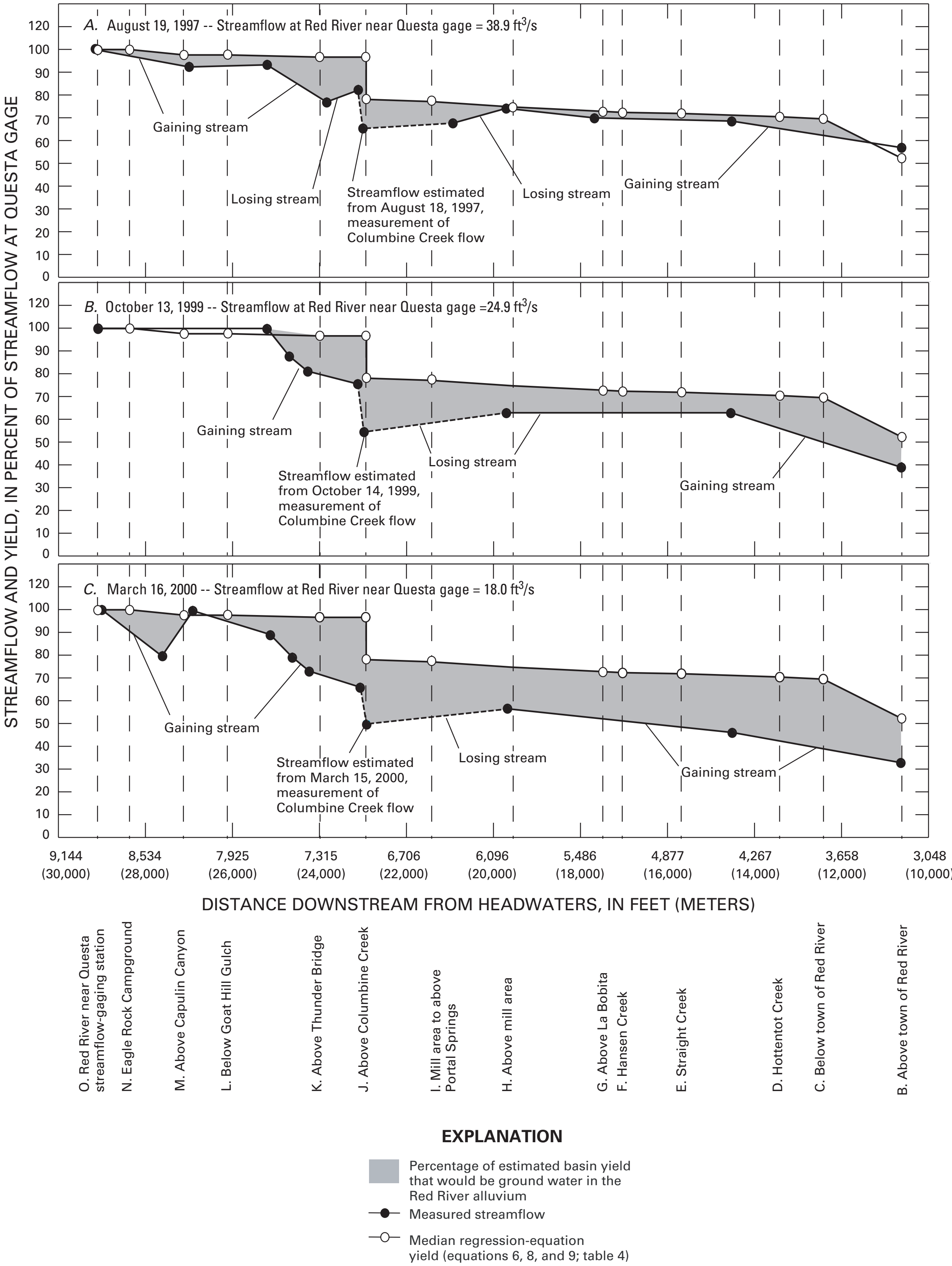

Figure 10. Estimation of ground-water flow using estimated annual basin yield and streamflow measured by Vail Engineering Inc. (2000) on (*A*) August 19, 1997; (*B*) October 13, 1999; and (*C*) March 16, 2000; streamflow measured by Borland and others (1990) on (*D*) October 25, 1988; and streamflow measured during tracer-injection studies by McCleskey and others (2003) on (*E*) August 17–24, 2001.

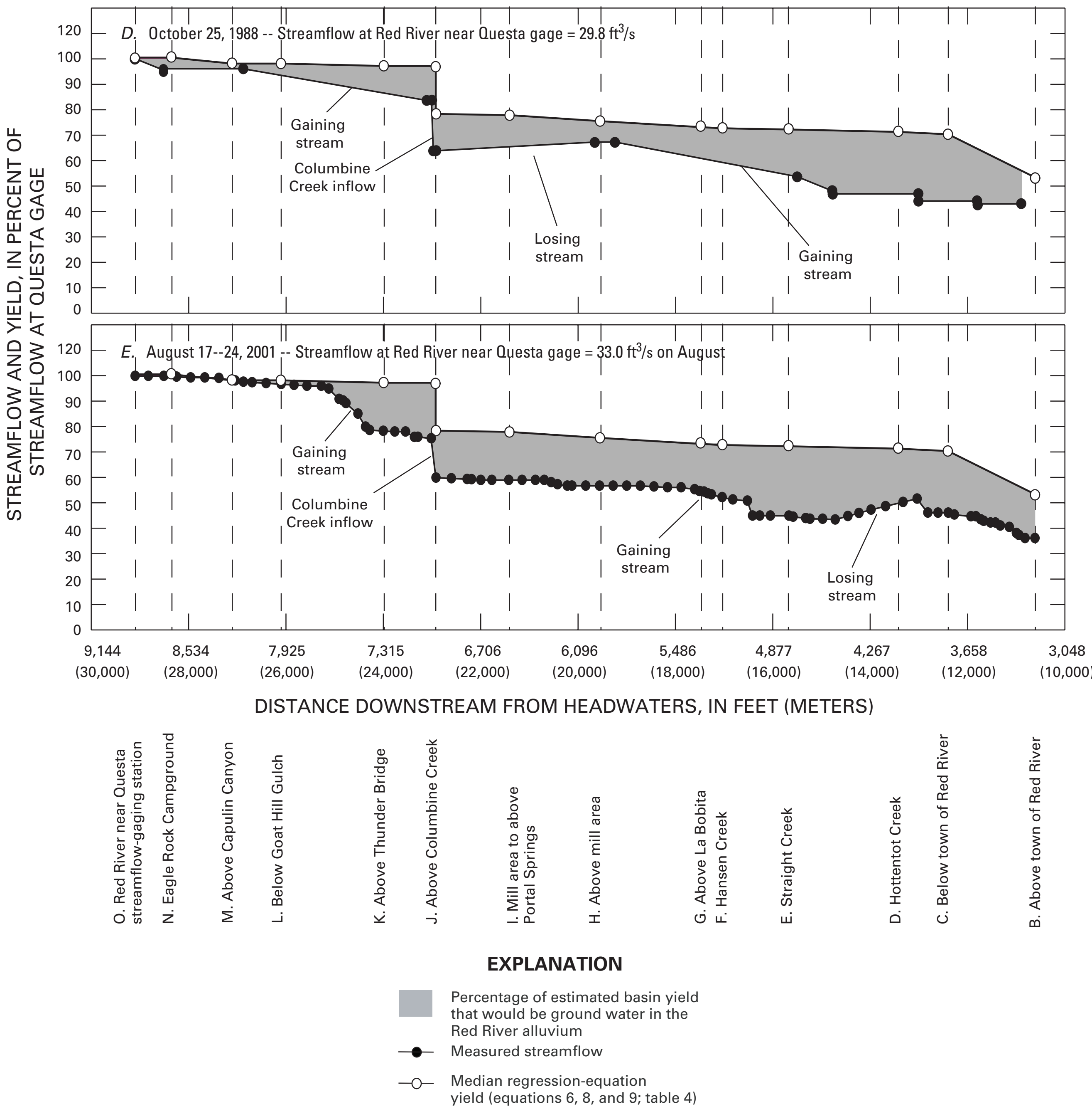

Figure 10. Estimation of ground-water flow using estimated annual basin yield and streamflow measured by Vail Engineering Inc. (2000) on (*A*) August 19, 1997; (*B*) October 13, 1999; and (*C*) March 16, 2000; streamflow measured by Borland and others (1990) on (*D*) October 25, 1988; and streamflow measured during tracer-injection studies by McCleskey and others (2003) on (*E*) August 17–24, 2001—Continued.

basins upstream from the mill area (Vail Engineering Inc., 2000).

As part of the USGS baseline study, detailed tracer-injection studies were conducted August 17–24, 2001, and March 30–April 1, 2002 (Kimball and others, 2006). The August 17–24, 2001, tracer study was the more detailed of the two tracer studies and so is examined further herein. During the August 17–24, 2001, tracer-injection study, the cumulative increase in Red River streamflow between the town of Red River and the Questa gage was 24.6 ft^3/s. Seventy percent of this streamflow increase was attributed to ground-water discharge to the stream. Columbine Creek, Pioneer Creek, and Bear Canyon streamflow contributions made up the remainder of the increase in Red River streamflow. The tracer-injection study indicated that the most substantial increase in streamflow per river-reach length was in the Thunder Bridge area (fig. 10E), which concurs with streamflow measurement data presented by Vail Engineering Inc. (2000) (figs. 10A, 10B, and 10C). The set of streamflow measurements presented by Borland (1990) did not include any measurements in the Thunder Bridge reach.

The locations of springs and seeps documented during the tracer-injection studies correspond to the gaining streamflow reaches indicated in figure 10 between locations B and C, E and G, and J and L. These discharge zones correspond to locations where the geomorphology of the canyon indicates that ground water should discharge to the river (Kirk Vincent, U.S. Geological Survey, written commun., 2005). Kimball and others (2006) noted spatial changes in the chemical character of Red River water over these ground-water discharge zones, and the majority of sulfate load also was contributed in these zones.

The partitioning of ground water and surface water determined in the present study shows that the relative proportions of the surface-water and ground-water components of estimated mean annual yield can vary under differing streamflow conditions (fig. 10). Interpretations of ground-water and surface-water interactions that are based on data for a single measurement date therefore may be different from those based on long-term mean annual conditions. For example, figure 10A shows that the cumulative mean annual yield above the mill area (location H) on August 19, 1997, primarily is in the form of streamflow (the streamflow and mean annual yield percentages are nearly the same), whereas the cumulative mean annual yield at location H may consist of greater proportions of ground water (the streamflow and the mean annual yield percentages are dissimilar) under lower flow conditions encountered on October 13, 1999, and March 16, 2000 (figs. 10B and 10C).

Measured Surface-Water and Ground-Water Elevations

Interpretations of mean annual basin yield and measured streamflow as indicators of surface-water and ground-water interactions along the Red River can further be supported with ground- and surface-water-level data from piezometers, wells, and the Red River. Piezometers were installed during this study at five locations along the north bank of the Red River between La Bobita Campground and Straight Creek (figs. 1 and 7) (Paul Blanchard, U.S. Geological Survey, written commun., 2005). The piezometers were designed to allow comparisons between the elevations of water in piezometers and in the river.

Piezometer SC-9A, located next to the Red River about 100 ft south of well SC-8A (fig. 1), was drilled at an angle under the Red River so that the well screen was about 21 ft directly below the Red River. This piezometer was dry when first completed in November 2002 and did not contain measurable water until spring 2004 (Paul Blanchard, U.S. Geological Survey, written commun., 2005). The water-level elevation in SC-9A on May 12, 2004, was 15.3 ft higher than that in nearby well SC-8A and about 16.2 ft lower than the water-level elevation in the Red River (Paul Blanchard, U.S. Geological Survey, written commun., 2005). The water-level elevation differences between SC-8A, SC-9A, and the river show that the Red River is poorly connected to the underlying ground-water system and may be perched at this location (Paul Blanchard, U.S. Geological Survey, written commun., 2005). This interpretation of surface- and ground-water levels is consistent with August 2001 tracer-injection study results that show that for the reach of the Red River between locations D and E (fig. 7), the river was either losing water to the ground-water system or neither gaining or losing (fig. 10E).

About 3,100 ft downstream from piezometer SC-9A, the difference between water-level elevations in the site #4 piezometers (fig. 1) and the water-level elevation of the Red River was small, indicating that the river and ground water are hydraulically connected at this location (Paul Blanchard, U.S. Geological Survey, written commun., 2005). About 3,000 ft downstream from piezometer site #4, the difference between water-level elevations in the piezometer at site #3 (fig. 1) and the water-level elevation of the river also was small (Paul Blanchard, U.S. Geological Survey, written commun., 2005). The August 2001 tracer-injection study results indicate that for the reach of the river from midway between locations E and F to location G (fig. 7) corresponding to the site #3 and #4 piezometer locations, the Red River was gaining water from the ground-water system (fig. 10E).

At the piezometer site #2 location (fig. 1), water-level elevations in the piezometers were similar to the water-level elevation of the river. At this location, however, the shallow ground-water system and the river appear to be perched on a semiconsolidated rock layer, possibly ferricrete, at about 15 ft below land surface (Paul Blanchard, U.S. Geological Survey, written commun., 2005) because water-level elevations in the nearby site #1 piezometer, located about 800 ft west of site #2 (fig. 1), were about 30 to 35 ft lower than those in site #2 piezometers (Paul Blanchard, U.S. Geological Survey, written commun., 2005). The August 2001 tracer-injection study indicated little or no gain in the river reach between locations G and H (fig. 7), which correspond to the site #1 and #2 piezometer locations.

Summary

In April 2001, the U.S. Geological Survey (USGS) and the New Mexico Environment Department began a cooperative study to infer the pre-mining ground-water quality at the Molycorp molybdenum mine site in the Red River Basin by studying analogous offsite areas. Straight Creek and its associated drainage basin were selected as the primary analog site for this study because of the similarity of its terrain and geology to the mine site, accessibility, potential for well construction, and minimal anthropogenic activity.

A pre-mining water balance for the part of the Red River Basin upstream from USGS streamflow-gaging station Red River near Questa, N. Mex. was developed to provide estimates of the amount of ground and surface water yielded from tributary drainages for pre-mining conditions. The water balance and partitioning of this water between ground and surface water help in understanding the effect of ground-water inflow from tributary drainage basin aquifers on surface- and ground-water chemistry in the Red River alluvial system.

The Red River, a tributary to the Rio Grande, is located in north-central New Mexico in rugged mountainous terrain. Sparsely vegetated to barren yellow-brown scar areas are one of the most striking natural features in the Red River Basin. The contributing area of the Red River Basin upstream from the Questa gage is approximately 108 mi^2 and includes approximately 18 mi of river reach. The area of the mine site is about 6 mi^2; mining activities have produced extensive underground workings and an open pit that is about 162 acres in area. The topography of the area is steep, rising rapidly from the basin-floor elevation of approximately 7,450 ft at the Questa gage to ridge-crest elevations exceeding 13,000 ft. Orographic effects of the mountainous topography lead to precipitation on windward slopes and localized storms within the Red River Basin and tributary drainages.

The Red River Valley is located along the southern edge of the Questa Caldera and contains complex structural features and extensive zones of hydrothermal alteration. Volcanic and intrusive rocks of Tertiary age are underlain by metamorphic rocks of Precambrian age that were intruded by granitic stocks. Hydrothermal fluids associated with the intrusions altered and mineralized the existing rock. Ore deposits primarily contain quartz, molybdenite, pyrite, fluorite, calcite, manganiferous calcite, dolomite, and rhodochrosite.

Runoff from intense summer rainfall can transport large quantities of poorly sorted sediment down tributary drainages and form debris fans where the tributaries join the Red River. Sediment transported and deposited by the Red River, in contrast, generally consists of medium- to well-sorted sand and gravel. Large debris fans debouch from tributary drainages and cause aggradation of the Red River streambed in river reaches upstream from debris fans.

Although located in the arid southwestern United States, the Red River Basin receives precipitation in various forms. Between 1915 and 2004, the annual average temperature at the town of Red River was about 4°C, and the annual average precipitation and snowfall were about 21 and 146 in., respectively. In the study area, precipitation has been measured in the town of Red River and at other climatic stations located throughout the Sangre de Cristo Mountains of northern New Mexico and southern Colorado. Mean annual precipitation at the town of Red River was 20.73 in. for 1910 through 2004. About 69 percent of total annual precipitation falls during the months of April through October, with about 29 percent falling in July and August. Mean monthly precipitation in March, April, and May is relatively higher than in fall and winter months. The maximum snow water equivalent (SWE) occurs in March or April at most stations in Taos County. SWE data show that snowpack melting generally begins as early as March and typically is complete by early July.

The Red River originates at an elevation of approximately 12,000 ft near Wheeler Peak, descending about 5,400 ft as it flows 27 mi to its confluence with the Rio Grande. Streamflow increases from March through May in response to snowpack melting, peaking between mid-May and mid-June. About 66 percent of annual streamflow occurs by the end of June. High streamflow events caused by summer thunderstorms occur in July, August, and September but do not produce the same volume or duration of flow as that caused by snowpack melting. Between 1930 and 2004, annual mean streamflow of the Red River at the Questa gage averaged 46.0 ft^3/s. Addition of the amount of water diverted upstream from the Questa gage results in a naturalized mean annual streamflow of 48.9 ft^3/s. Trends in the 5-year moving average of naturalized annual mean streamflow generally correspond to those of the 5-year moving average of annual mean precipitation. Streamflow measurement error was estimated to be about ±7.7 percent of naturalized mean annual streamflow (48.9 ft^3/s) or about ±3.8 ft^3/s. The 1964 to 1973 mean annual streamflow at the Zwergle gage was 17.7 ft^3/s.

In the Red River Basin, most tributary streams flow perennially in the upper reaches and ephemerally and intermittently in the lower reaches. Tributary streamflow typically infiltrates debris fans before reaching the Red River but can discharge directly into the Red River during periods of runoff following intense precipitation. Water discharged from most tributary basins in the lower reaches of the Red River Basin, therefore, is primarily by ground-water flow from debris-flow material to Red River alluvium.

Aquifers in the Red River Basin include fractured and weathered bedrock, debris-flow deposits, and Red River alluvium. Although the bedrock aquifer is probably the largest in terms of volume of rock, the debris-flow deposits and Red River alluvium contain most of the ground water in the river valley. Hydraulic-conductivity estimates for the bedrock aquifer ranged from 0.001 to about 6 ft/d; for the Red River alluvium they ranged from 0.04 to 860 ft/d; and for the Straight Creek debris-flow material they ranged from about 0.2 to 1 ft/d. The hydraulic conductivity of interfingering debris-flow and alluvial deposits in the Red River Valley near the mouth of Straight Creek was calculated to average about 340 ft/d.

The Red River Basin upstream from the Questa gage was divided into 79 subbasins and elevation bands. These subbasins then were grouped into 30 incremental basins that were defined to facilitate comparisons of water balances for the incremental basins to results from previous studies.

Because long-term precipitation data were available for only the town of Red River climatic station, two approaches were used to estimate the distribution of mean annual precipitation, including the Precipitation-Elevation regressions on Independent Slopes Model (PRISM) and calculation of average annual precipitation using previously developed regional relations between precipitation and elevation. The three precipitation-elevation regression relations used in this study were one developed by the U.S. Forest Service for the southern Rocky Mountains, one developed for a 1998 water-balance study for Taos County, New Mexico, and one developed for a 2000 water-balance study of the mine site. The equations were developed for specific elevation ranges and can yield unreasonable results, such as negative precipitation amounts, if they are applied to low elevations. However, all the equations appear to give reasonable precipitation amounts for the range of elevations within the Red River Basin. Mean annual precipitation estimates using PRISM and the three regression equations yielded a range of mean annual precipitation for the Red River Basin of 22.32 to 25.19 in. The 1910–2004 mean annual precipitation for the town of Red River climatic station compared well with mean annual precipitation estimated for elevation bands with similar mean elevations.

Evapotranspiration was estimated using three methods including the Troendle and Leaf method, the MacDonald and Stednick method, and the Hargreaves reference evapotranspiration method. Using the three methods, estimated mean annual evapotranspiration for the Red River Basin ranged from 15.02 to 22.45 inch per year or 63.23 to 94.49 percent of mean annual precipitation. For each incremental basin, evapotranspiration estimates using the Troendle and Leaf method ranged from about 54 to 82 percent, using the MacDonald and Stednick method they ranged from 68 to 98 percent; and using the Hargreaves reference evapotranspiration method they ranged from 59 to 149 percent.

Basin yield, the amount of ground and surface water yielded from basins tributary to the Red River, was estimated using three regression equations that relate watershed yield to elevation and (or) precipitation and the differences between estimates of precipitation and evapotranspiration developed for this study. The mean annual Red River Basin-yield estimates determined with the regression equations ranged from 45.26 to 51.57 ft^3/s and were similar to the naturalized mean annual streamflow at the Questa gage (48.9 ft^3/s). Basin yields calculated by subtracting estimated evapotranspiration from estimated mean annual precipitation ranged from 55.58 to 93.15 ft^3/s. Although the regression equations appear to be good representations of yield from the Red River Basin as a whole, the evapotranspiration methods may more accurately represent yield from small basins with a substantial percentage of scar area.

The ground- and surface-water components of watershed yield were estimated by hydrograph separation, by chloride mass-balance calculations, and by subtraction of streamflow from basin yield. Hydrograph-separation results showed that the subsurface flow contribution to streamflow ranged from 76 to 94 percent of streamflow and averaged 87 percent of streamflow for 1930–2004. Mean monthly subsurface flow for 1930–2004 ranged from 81 percent of monthly streamflow in April and May to 94 percent of streamflow in July. Chloride mass balance was calculated using chloride concentrations in water samples from wells in the Capulin Canyon and the Hansen, Hottentot, La Bobita, and Straight Creek Basins, from the Red River upstream from the wastewater treatment plant, and from chloride concentrations measured in snow samples from the Straight Creek and Hansen Creek Basins. Chloride mass-balance calculations indicate that ground-water recharge ranged from 7 to 17 percent of mean annual precipitation in Capulin Canyon and the Hansen, Hottentot, La Bobita, and Straight Creek Basins, and was 21 percent of mean annual precipitation for water samples from the Red River.

Comparisons of mean annual basin yield and measured streamflow indicate that streamflow does not consistently increase as cumulative estimated mean annual basin yield increases. The relative differences between mean annual basin yield and streamflow indicate that, in general, ground water is a smaller percentage of total basin yield during higher streamflow conditions. Comparisons of estimated mean annual yield and measured streamflow profiles indicate that, in general, the river is gaining ground water from the alluvium in the reach from the town of Red River to between Hottentot and Straight Creeks, and from Columbine Creek to near Thunder Bridge. The river is a losing stream from upstream from the mill area to Columbine Creek. The locations of springs and seeps documented during tracer-injection studies correspond to the gaining streamflow reaches. Interpretations drawn from the comparison of estimated mean annual yield and measured streamflow profiles also are supported by ground- and surface-water-level data from piezometers, wells, and the Red River.

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Glossary

A

Annual Mean: The average of values for 1 year. For example, annual mean streamflow would be the sum of all daily mean streamflow values obtained during 1 year divided by the number of daily mean streamflow values.

B

Base flow: The volume of flow in a stream that is derived from ground-water discharge to a stream.

Basin yield: The amount of surface- and ground-water outflow from a basin. Basin yield is calculated as precipitation over the basin minus evapotranspiration over the basin.

D

Daily mean: The average of values for 1 day. For example, daily mean streamflow would be the sum of all streamflow values obtained during 1 day divided by the number of streamflow values.

E

Energy aspect: A combination of slope-face compass direction and elevation. A south-facing slope at low elevation would have a higher energy aspect than a north-facing slope at high elevation.

Evapotranspiration: The sum of evaporation plus transpiration. It includes evaporation of surface water, shallow soil moisture, and precipitation intercepted by vegetation, and the transpiration of soil moisture and ground water by plants.

G

Growing degree day: A measure of thermal time or the daily accumulation of heat relative to a threshold temperature (degrees Fahrenheit in this report). Calculated as the departure of the daily mean temperature from a threshold temperature. Threshold temperatures are defined for specific vegetation types, such as corn or pine forest. One growing-degree day is accumulated for each degree that the daily mean temperature exceeds the threshold temperature.

I

Interflow: The part of precipitation or snowmelt that infiltrates into soil, but not to the water table, and moves laterally through soil horizons toward a stream channel.

N

Naturalized Streamflow: Streamflow measured at a stream-flow-gaging station that has been increased to account for upstream diversions that are not included in the total streamflow at the streamflow-gaging station.

M

Mean annual: The average of a series of annual values. For example, mean annual streamflow would be the sum of annual mean streamflow for a number of years divided by that number of years.

Mean monthly: The average of a series of monthly values segregated by month. For example, mean monthly streamflow would be the sum of streamflow values obtained for a month for a number of years divided by that number of years. Values for each January would be calculated separately from values for February, and so on.

O

Overland flow: Water derived from precipitation that flows over the land surface toward stream channels.

P

Potential evapotranspiration: Water loss that will occur through evaporation from soil and transpiration by plants if at no time there is a deficiency of water in the soil for use by vegetation.

R

Reference evapotranspiration: The evaporating power of the atmosphere for a specific vegetation type at a specific location and time of year.

S

Snow water equivalent: The amount of liquid water obtained by melting a column of snow.

Surface runoff: The water derived from overland flow that enters stream channels most immediately after rainfall or snowmelt.

Spring flow: Ground-water discharge that occurs in more or less discrete and identifiable locations.

Subsurface flow: The flow of water below land surface. As used in this report, subsurface flow includes ground water from below the water table that may be discharged to streams as base flow and water flowing in shallow soil layers above the water table that may be discharged to streams as interflow.