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Hydrogeologic Setting and Simulation of Groundwater Flow near the Canterbury and Leadville Mine Drainage Tunnels, Leadville, Colorado

Scientific Investigations Report 2011–5085

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

Cover. Left photo: Miners at Carbonate Hill, 1881. (Photograph used with permission of Mark L. Evans and Ted Kierscey.)
Right photo: Remediating mine-waste piles, Leadville Mining District, Colorado, 2008. (Photograph by Tristan Wellman, U.S. Geological Survey.)

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U.S. Geological Survey
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Conversion Factors and Datums

SI to Inch/Pound

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6215	mile (mi)
	Area	
square centimeter (cm^2)	0.001076	square foot (ft^2)
square meter (m^2)	10.76	square foot (ft^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic meter (m^3)	264.2	gallon (gal)
cubic meter (m^3)	35.31	cubic foot (ft^3)
	Flow rate	
cubic meter per year (m^3/yr)	264.2	gallon per year (gal/yr)
cubic meter per second (m^3/s)		cubic foot per second (ft^3/s)

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

$$°F=(1.8×°C)+32$$

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

$$°C=(°F–32)/1.8$$

Vertical coordinate information was referenced to the North American Vertical Datum of 1988 (NAVD 88).

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

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

Abbreviations and Acronyms

°C	degree Celsius
‰	per mil
µ	micrometer
µg/L	microgram per liter
gal/min	gallon per minute
km	kilometer
m	meter
m^3/yr	cubic meter per year
mg/L	milligram per liter
m.y.	million years (duration or interval)
BOR	Bureau of Reclamation
CFC	chlorofluorocarbon
DC	direct current
DOC	dissolved organic carbon
ET	evapotranspiration
ICP–AES	inductively coupled plasma–atomic emission spectroscopy
NPL	National Priorities List (of U.S. Environmental Protection Agency)
OU	operable unit
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
UTM	Universal Transverse Mercator

Hydrogeologic Setting and Simulation of Groundwater Flow near the Canterbury and Leadville Mine Drainage Tunnels, Leadville, Colorado

By Tristan P. Wellman, Suzanne S. Paschke, Burke Minsley, and Jean A. Dupree

Abstract

The Leadville mining district is historically one of the most heavily mined regions in the world producing large quantities of gold, silver, lead, zinc, copper, and manganese since the 1860s. A multidisciplinary investigation was conducted by the U.S. Geological Survey, in cooperation with the Colorado Department of Public Health and Environment, to characterize large-scale groundwater flow in a 13 square-kilometer region encompassing the Canterbury Tunnel and the Leadville Mine Drainage Tunnel near Leadville, Colorado. The primary objective of the investigation was to evaluate whether a substantial hydraulic connection is present between the Canterbury Tunnel and Leadville Mine Drainage Tunnel for current (2008) hydrologic conditions.

Altitude in the Leadville area ranges from about 3,018 m (9,900 ft) along the Arkansas River valley to about 4,270 m (14,000 ft) along the Continental Divide east of Leadville, and the high altitude of the area results in a moderate subpolar climate. Winter precipitation as snow was about three times greater than summer precipitation as rain, and in general, both winter and summer precipitation were greatest at higher altitudes. Winter and summer precipitation have increased since 2002 coinciding with the observed water-level rise near the Leadville Mine Drainage Tunnel that began in 2003. The weather patterns and hydrology exhibit strong seasonality with an annual cycle of cold winters with large snowfall, followed by spring snowmelt, runoff, and recharge (high-flow) conditions, and then base-flow (low-flow) conditions in the fall prior to the next winter. Groundwater occurs in the Paleozoic and Precambrian fractured-rock aquifers and in a Quaternary alluvial aquifer along the East Fork Arkansas River, and groundwater levels also exhibit seasonal, although delayed, patterns in response to the annual hydrologic cycle.

A three-dimensional digital representation of the extensively faulted bedrock was developed and a geophysical direct-current resistivity field survey was performed to evaluate the geologic structure of the study area. The results show that the Canterbury Tunnel is located in a downthrown structural block that is not in direct physical connection with the Leadville Mine Drainage Tunnel. The presence of this structural discontinuity implies there is no direct groundwater pathway between the tunnels along a laterally continuous bedrock unit.

Water-quality results for pH and major-ion concentrations near the Canterbury Tunnel showed that acid mine drainage has not affected groundwater quality. Stable-isotope ratios of hydrogen and oxygen in water indicate that snowmelt is the primary source of groundwater recharge. On the basis of chlorofluorocarbon and tritium concentrations and mixing ratios for groundwater samples, young groundwater (groundwater recharged after 1953) was indicated at well locations upgradient from and in a fault block separate from the Canterbury Tunnel. Samples from sites downgradient from the Canterbury Tunnel were mixtures of young and old (pre-1953) groundwater and likely represent snowmelt recharge mixed with older regional groundwater that discharges from the bedrock units to the Arkansas River valley. Discharge from the Canterbury Tunnel contained the greatest percentage of old (pre-1953) groundwater with a mixture of about 25 percent young water and about 75 percent old water.

A calibrated three-dimensional groundwater model representing high-flow conditions was used to evaluate large-scale flow characteristics of the groundwater and to assess whether a substantial hydraulic connection was present between the Canterbury Tunnel and Leadville Mine Drainage Tunnel. As simulated, the faults restrict local flow in many areas, but the fracture-damage zones adjacent to the faults allow groundwater to move along faults. Water-budget results indicate that groundwater flow across the lateral edges of the model controlled the majority of flow in and out of the aquifer (79 percent and 63 percent of the total water budget, respectively). The largest contributions to the water budget were groundwater entering from the upper reaches of the watershed and the hydrologic interaction of the groundwater with the East Fork Arkansas River. Potentiometric surface maps of the simulated model results were generated for depths of 50, 100, and 250 m. The surfaces revealed a positive trend in hydraulic head with land-surface altitude and evidence of increased control on fluid movement by the fault network structure at progressively greater depths in the aquifer.

Results of advective particle-tracking simulations indicate that the sets of simulated flow paths for the Canterbury Tunnel and the Leadville Mine Drainage Tunnel were mutually exclusive of one another, which also suggested that no major hydraulic connection was present between the tunnels. Particle-tracking simulations also revealed that although the fault network generally restricted groundwater movement locally, hydrologic conditions were such that groundwater did cross the fault network at many locations. This cross-fault movement indicates that the fault network controls regional groundwater flow to some degree but is not a complete barrier to flow. The cumulative distributions of adjusted age results for the watershed indicate that approximately 30 percent of the flow pathways transmit groundwater that was younger than 68 years old (post-1941) and that about 70 percent of the flow pathways transmit old groundwater. The particle-tracking results are consistent with the apparent ages and mixing ratios developed from the chlorofluorocarbon and tritium results. The model simulations also indicate that approximately 50 percent of the groundwater flowing through the study area was less than 200 years old and about 50 percent of the groundwater flowing through the study area is old water stored in low-permeability geologic units and fault blocks. As a final examination of model response, the conductance parameters of the Canterbury Tunnel and Leadville Mine Drainage Tunnel were manually adjusted from the calibrated values to determine if altering the flow discharge in one tunnel affects the hydraulic behavior in the other tunnel. The examination showed no substantial hydraulic connection.

The multidisciplinary investigation yielded an improved understanding of groundwater characteristics near the Canterbury Tunnel and the Leadville Mine Drainage Tunnel. Movement of groundwater between the Canterbury Tunnel and Leadville Mine Drainage Tunnel that was central to this investigation could not be evaluated with strong certainty owing to the structural complexity of the region, study simplifications, and the absence of observation data within the upper sections of the Canterbury Tunnel and between the Canterbury Tunnel and the Leadville Mine Drainage Tunnel. There was, however, collaborative agreement between all of the analyses performed during this investigation that a substantial hydraulic connection did not exist between the Canterbury Tunnel and the Leadville Mine Drainage Tunnel under natural flow conditions near the time of this investigation.

Introduction

Leadville, Colorado, is located within the headwaters of the Arkansas River watershed approximately 120 kilometers (km) southwest of Denver, Colorado, and is the highest incorporated city in the United States at an altitude of 3,020 meters (m) or about 10,000 feet (ft). The Leadville mining district was historically one of the most extensively mined districts in the world producing gold, silver, lead, zinc, copper, and manganese from the 1860s through the 1990s (Wallace, 1993). Mining artifacts such as extensive underground workings, shafts, adits, tunnels as well as surficial waste-rock, slag, and tailings piles remain in the area and highlight the historical significance of the region, which is designated as a National landmark (National Park Service, 2009). Three major tunnels—the Yak Tunnel, the Leadville Mine Drainage Tunnel, and the Canterbury Tunnel—were constructed in the area to facilitate mineral exploration and drain water from the mines (fig. 1). In 1983, to address the effects of mining waste and acid mine drainage, an area of about 46 square kilometers (km^2) within the Leadville mining district was included on the U.S. Environmental Protection Agency (USEPA) National Priority List (NPL) and became known as the California Gulch NPL site. Water-treatment plants are operated at the portals of the Yak and Leadville Mine Drainage Tunnels to remove metals and raise the pH of water affected by acid mine drainage from the Leadville mining district. In contrast, the Canterbury Tunnel drains an area outside the mining district, and water from the tunnel has been used as a drinking-water supply for Leadville since 1961. Additional information on the California Gulch NPL site and the construction history of the tunnels is provided in the *Background* section of this report.

Near the Leadville Mine Drainage Tunnel, groundwater levels have risen and portal discharge has decreased since 2005 (Bureau of Reclamation, 2008). In 2007 and 2008, the USEPA and the Lake County Commissioners expressed concern for the rising groundwater levels in the Leadville Mine Drainage Tunnel, and in 2008, the USEPA implemented an emergency response program to lower water levels in the tunnel. Coincident with rising water levels in the Leadville Mine Drainage Tunnel, flow from the Canterbury Tunnel decreased substantially after 2005, raising questions as to whether there was a hydraulic connection between the Canterbury Tunnel and the Leadville Mine Drainage Tunnel. In response to local concerns, in 2008, the Colorado State Legislature directed the Colorado Department of Public Health and Environment (CDPHE) to investigate whether a possible groundwater connection exists between the Canterbury Tunnel and the Leadville Mine Drainage Tunnel. The U.S. Geological Survey (USGS) performed a multidisciplinary investigation, in cooperation with CDPHE, to address groundwater conditions near the Canterbury Tunnel and the Leadville Mine Drainage Tunnel.

Purpose and Scope

This report describes the hydrogeologic setting and simulation of groundwater flow near the Canterbury Tunnel and the Leadville Mine Drainage Tunnel. The primary objective is to evaluate whether a substantial hydraulic connection likely exists between the Canterbury Tunnel and the Leadville Mine Drainage Tunnel. The following tasks provide multiple lines of evidence to evaluate the hydrogeology and water quality near the drainage tunnels:

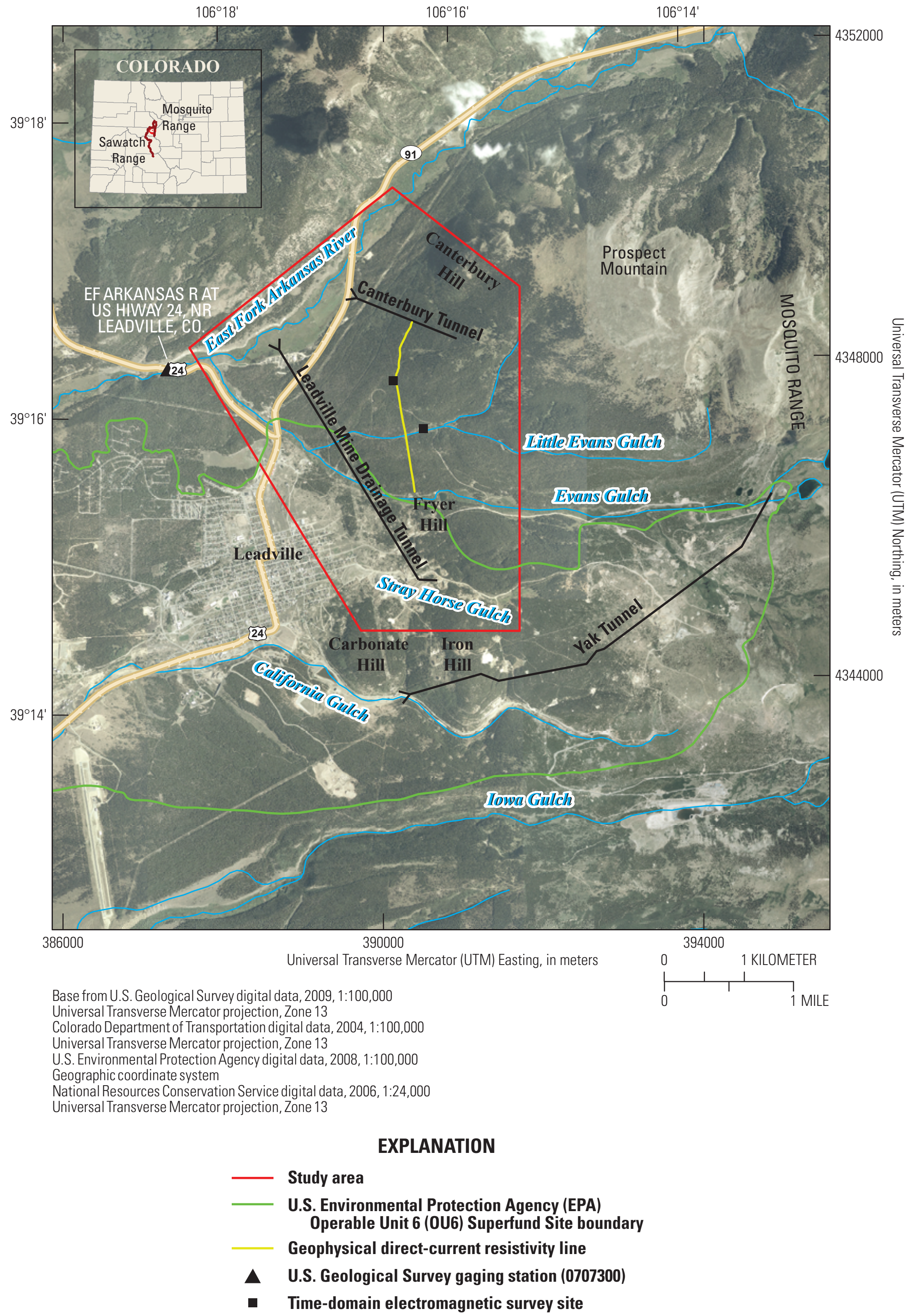


Figure 1. Location of the study area, California Gulch National Priority List site, Operable Unit 6, Yak Tunnel, Leadville Mine Drainage Tunnel, Canterbury Tunnel, geophysical resistivity line, and U.S. Geological Survey gaging station 07079300, Leadville, Colorado.

1. Compilation and analysis of existing hydrologic data;
2. Site reconnaissance near the Canterbury Tunnel to locate groundwater and surface-water sampling locations and surficial expressions of the tunnel;
3. Compilation of existing geologic maps and data into an electronic format for manipulation and display of the geologic framework;
4. A geophysical survey between the Canterbury Tunnel and the Leadville Mine Drainage Tunnel to evaluate subsurface conditions;
5. Water-quality sampling of seven sites (surface water, seeps, and wells) near the Canterbury Tunnel to evaluate whether mining has affected water quality of the tunnel discharge; and
6. Simulation of steady-state groundwater flow in a study area encompassing the Canterbury Tunnel and the Leadville Mine Drainage Tunnel.

Background

The Leadville mining district is historically one of the most productive mining areas in the world, producing gold, silver, lead, zinc, copper, and manganese from the 1860s through the 1990s (Wallace, 1993). Prospectors working along the Arkansas River drainage in the 1860s first discovered gold in alluvial placer deposits. The discovery of silver and lead-zinc ores followed in the 1880s and early 1900s, and underground mining of precious metals through shafts and adits continued through the 1990s (Wallace, 1993). Decades of productive mining resulted in extensive underground mine workings and surficial waste-rock, slag, and tailings piles throughout the mining district. As mining progressed to greater depths, groundwater flooded the mines and became an operational problem. Three tunnels—the Yak Tunnel, Leadville Mine Drainage Tunnel, and Canterbury Tunnel—were constructed to facilitate mineral exploration and drain groundwater from the mine workings (fig. 1). The Canterbury Tunnel and the Leadville Mine Drainage Tunnel are the focus of this report.

In 1983, an area of about 46 km^2 within the Leadville mining district was included on the U.S. Environmental Protection Agency (USEPA) National Priority List and became known as the California Gulch NPL site (U.S. Environmental Protection Agency, 1988). The California Gulch NPL site includes Leadville, the Yak Tunnel, the confluence of California Gulch and the Arkansas River, Stray Horse Gulch, and an 18-kilometer (11-mile) reach of the Arkansas River downstream from California Gulch. In 1994, the California Gulch NPL site was divided into 12 geographical areas called operable units. The Yak Tunnel and associated water-treatment facilities were designated as Operable Unit 1 (OU1). Mine waste dumps and Stray Horse Gulch were included in Operable Unit 6 (OU6), and the southern part of the Leadville Mine Drainage Tunnel lies beneath OU6 (fig. 1). The Canterbury Tunnel is located outside of the California Gulch NPL site boundary (fig. 1) in an area that is not extensively mineralized.

The Yak Tunnel extends approximately 6.5 km east and northeast from its portal in upper California Gulch into the most productive parts of the Leadville mining district (fig. 1). Prior to remediation efforts, concentrations of cadmium, copper, lead, and zinc in the minewater draining from the Yak Tunnel affected surface-water and groundwater quality in lower California Gulch and the upper Arkansas River (U.S. Environmental Protection Agency, 1988). In 1985, a surge of metal-laden water and sludge from the Yak Tunnel released an estimated 3,800 m^3 (about one million gallons) of mine drainage to the Arkansas River within 24 hours (U.S. Environmental Protection Agency, 1988). In 1988, the USEPA issued a Record of Decision for OU1 (U.S. Environmental Protection Agency, 1988). Subsequent remedial actions for OU1 included installation of a bulkhead in the Yak Tunnel to control tunnel discharge; construction, operation, and maintenance of a water-treatment plant and surge pond at the tunnel portal; and monitoring of surface water and groundwater quality. A recent report of monitoring activities at the California Gulch NPL site indicated that the Yak Tunnel bulkhead and monitoring network were operating as intended (HDR Engineering, 2007). However, rising hydraulic head noted in the upper reaches of the tunnel suggested that a blockage was present within the tunnel (HDR Engineering, 2007). Blockage in the Yak tunnel was more recently confirmed, and hydraulic heads have risen substantially in a number of bedrock wells adjacent to the Yak tunnel (Mike Wireman, U.S. Environmental Protection Agency, oral commun., 2010). Presently (2010), water is being pumped from behind the blockage and water levels are being monitored (Mike Wireman, U.S. Environmental Protection Agency, oral commun., 2010).

Operable Unit 6 encompasses about 8.8 km^2 in the northeastern part of the California Gulch NPL site (fig. 1). The USEPA and mining companies performed a series of response actions in 1990 to systematically remediate mine wastes in OU6 (U.S. Environmental Protection Agency, 2003). A complete list of investigative reports on OU6 is available in the OU6 Focused Feasibility Study (U.S. Environmental Protection Agency, 2002). Major response actions in OU6 included (1) limited consolidation and capping of selected mine waste piles; (2) collection and treatment of acid mine drainage from the mine waste piles; (3) diversion of clean surface water around mine waste piles; and (4) rehabilitation of Stray Horse Gulch. Waste rock piles in upper Stray Horse Gulch near Carbonate Hill were not capped as part of the remediation and rain and snowmelt on the waste rock piles generated acidic runoff containing large concentrations of zinc and cadmium (Wireman and others, 2005). The acidic and metal-laden leachate generated from waste rock piles flowed downhill in Stray Horse Gulch, infiltrated into the subsurface and mine workings, and contributed acid mine drainage to the Leadville Mine Drainage Tunnel (Mike Wireman, U.S. Environmental Protection Agency, oral commun., 2010).

The USEPA constructed ponds to capture the leachate as part of the Stray Horse Gulch rehabilitation (U.S. Environmental Protection Agency, 2003); however, the volume of runoff exceeded the capacity of the ponds. Since 2003, the leachate has been collected by a series of constructed channels and routed into a former mine shaft (the Marion shaft) that is connected to the Leadville Mine Drainage Tunnel (Mike Wireman, U.S. Environmental Protection Agency, oral commun., 2010). From the Marion shaft, the acid mine drainage flows through the Leadville Mine Drainage Tunnel and is treated at the tunnel water-treatment plant (Wireman and others, 2005). Three areas of flooded underground mine workings, referred to as “mine pools,” were identified beneath OU6 (Wireman and others, 2005). The mine pools were created when the extensive mine workings beneath downtown Leadville, Fryer Hill, and Carbonate Hill filled with groundwater after mining activities ceased (Wireman and others, 2005). Mine workings likely connect groundwater flow between the mine pools and to some extent between the mine pools and the Leadville Mine Drainage Tunnel (Wireman and others, 2005).

The portal of the Leadville Mine Drainage Tunnel is located in lower Evans Gulch near the East Fork Arkansas River about 2 km north of the Leadville town center. The tunnel extends about 3.4 km southeast from the portal. Construction of the Leadville Mine Drainage Tunnel began in 1943 in response to shortages of lead, zinc and manganese during World War II (U.S. Department of the Interior, 1979). Construction ceased in 1945 after tunneling about 2 km because the unconsolidated glacial deposits encountered in the first kilometer of the tunnel caused unstable conditions and construction complications (U.S. Department of the Interior, 1979). Construction of the Leadville Mine Drainage Tunnel resumed in 1950 because of metal shortages during the Korean War, and construction was completed in 1952. Ownership of the Leadville Mine Drainage Tunnel was transferred from the Bureau of Mines to the Bureau of Reclamation (BOR) in 1959. Because the quality of water discharged from the Leadville Mine Drainage Tunnel is affected by acid mine drainage, a water-treatment plant at the tunnel portal has been operated by the BOR since 2005 to treat discharge from the Leadville Mine Drainage Tunnel before it is released to the East Fork Arkansas River. Before 2005, discharge from the Leadville Mine Drainage Tunnel typically was more than 3.8 m^3/min (1,000 gal/min) and as much as 5.7 m^3/min (1,500 gal/min) (Wireman and others, 2005). The BOR reported a flow of about 4.2 m^3/min (1,120 gal/min) from the Leadville Mine Drainage Tunnel in March 2008 (Bureau of Reclamation, written commun., 2009).

Monitoring of hydraulic heads in the tunnel and in upgradient mine pools began in 2003 as part of the USEPA hydrogeologic characterization. The results indicate that seasonal high water levels have increased since 2003 (Source Water Consulting, 2008). In November 2007, the USEPA expressed concern about the rising hydraulic head and the potential for an uncontrolled surge of water and sediment to discharge from the Leadville Mine Drainage Tunnel. In February 2008, Lake County Commissioners declared a state of emergency in Leadville, and the USEPA began an emergency response program to lower the hydraulic head in the tunnel, associated mine pools, and bedrock groundwater. Emergency response actions undertaken in Leadville since February 2008 have included pumping from a mine shaft in California Gulch (the Gaw shaft), drilling of a relief well completed in the Leadville Mine Drainage Tunnel, and installation of a pipeline from the relief well to the water-treatment plant located at the portal of the Leadville Mine Drainage Tunnel. A drawdown test of the relief well was completed in early June 2008 and the USEPA began pumping from the relief well and delivering pumped groundwater through the pipeline to the Leadville Mine Drainage Tunnel water-treatment plant on June 24, 2008. On June 30, 2008, the BOR released a final draft risk assessment of the Leadville Mine Drainage Tunnel that evaluated existing conditions in the tunnel and the results of geotechnical and structural engineering analyses (Bureau of Reclamation, 2008). The report concluded that there was no immediate threat of uncontrolled discharge from the tunnel (Bureau of Reclamation, 2008). A complete history of events and list of previous work associated with the tunnel can be found in the report, Leadville Mine Drainage Tunnel Risk Assessment (Bureau of Reclamation, 2008).

The Canterbury Tunnel was established as a mine-prospecting tunnel in the 1920s about 3.2 km north of Leadville and about 2 km north of the Leadville Mine Drainage Tunnel on the southwesterly slope of Canterbury Hill, a spur of Prospect Mountain. The Canterbury Tunnel was excavated southeastward from the eastern side of the East Fork Arkansas River valley (fig. 2) about 1.3 km to its terminus under Canterbury Hill at a depth of about 260 m below land surface (Bureau of Reclamation, 1976). Little mineralization

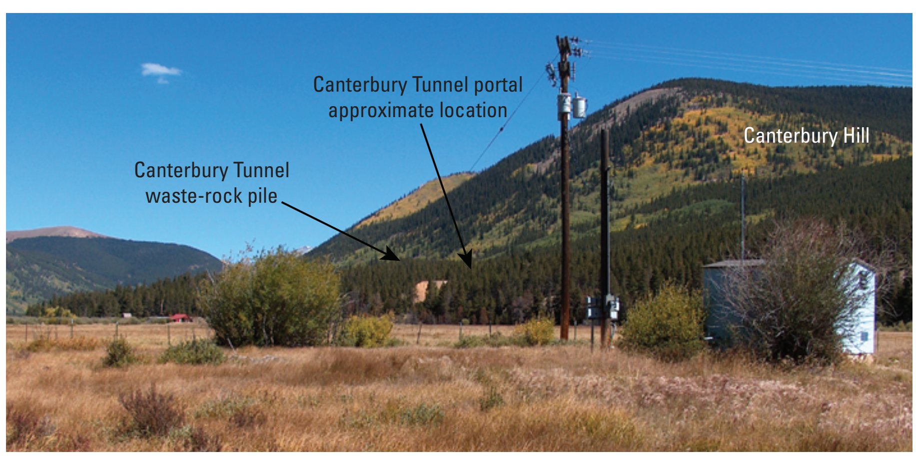


Figure 2. North from well PW2 in the East Fork Arkansas River valley toward Canterbury Hill and Canterbury Tunnel portal, September 2008. Photograph by Suzanne S. Paschke, U.S. Geological Survey.

was encountered by the Canterbury Tunnel, and in 1928, the Leadville Mine Development Company obtained water rights to use the tunnel discharge for irrigating about 5 km^2 (1,240 acres) of land (Behre, 1953). In 1960, the Leadville Water Company, the predecessor to the Parkville Water District (Parkville), changed its Stevens & Leiter Ditch water right to allow water diversion at the tunnel portal (well permit documents obtained from Colorado Division of Water Resources, written commun., 1989). At that time, a wet well, pump stations, and pipeline were constructed at the tunnel portal to collect the discharge and pump it into the existing distribution system for Leadville. From 1961 to 2005, groundwater discharged from the portal at a generally constant rate of at least 2.4 m^3/min (625 gal/min) and almost all of this flow was used in the Leadville municipal water system (Greg Teter, Parkville Water District, oral commun., July 2008). Flow from the Canterbury Tunnel portal (fig. 3) has decreased since 2005 (Source Water Consulting, 2008), likely owing to collapses and resulting blockages in the tunnel. In 2008, flow from the Canterbury Tunnel portal was too small to support operation of pumps in the chlorination plant located at the tunnel portal (Greg Teter, Parkville Water District, oral commun., July 2008). A spring located about 3 m southeast of the portal (fig. 4) and ponded water about 3 m upstream from the portal indicates collapse at the portal. Numerous surface expressions of subsidence exist southeast of the portal along the tunnel alignment (fig. 5). Active and inactive sinkholes (figs. 5, 6) indicate tunnel collapse where the tunnel extends through unconsolidated Quaternary glacial moraine deposits.

Figure 3. Canterbury Tunnel portal pit, which is approximately 2 meters wide by 2 meters deep, September 2008. Photograph by Suzanne S. Paschke, U.S. Geological Survey.

Methods

The investigative tools used in this work included hydrological, geological, geophysical, and geochemical analyses and numerical simulations of groundwater flow with particle tracking.

Several existing data sets were compiled and synthesized to develop conceptual and numerical models of groundwater flow. Climate, streamflow, and groundwater hydraulic-head data are used to describe the hydrologic setting of the study area and were used to define recharge and discharge

Figure 4. *A*, covered portal and *B*, portal spring of Canterbury Tunnel, September 2008. Photograph by Suzanne S. Paschke, U.S. Geological Survey.

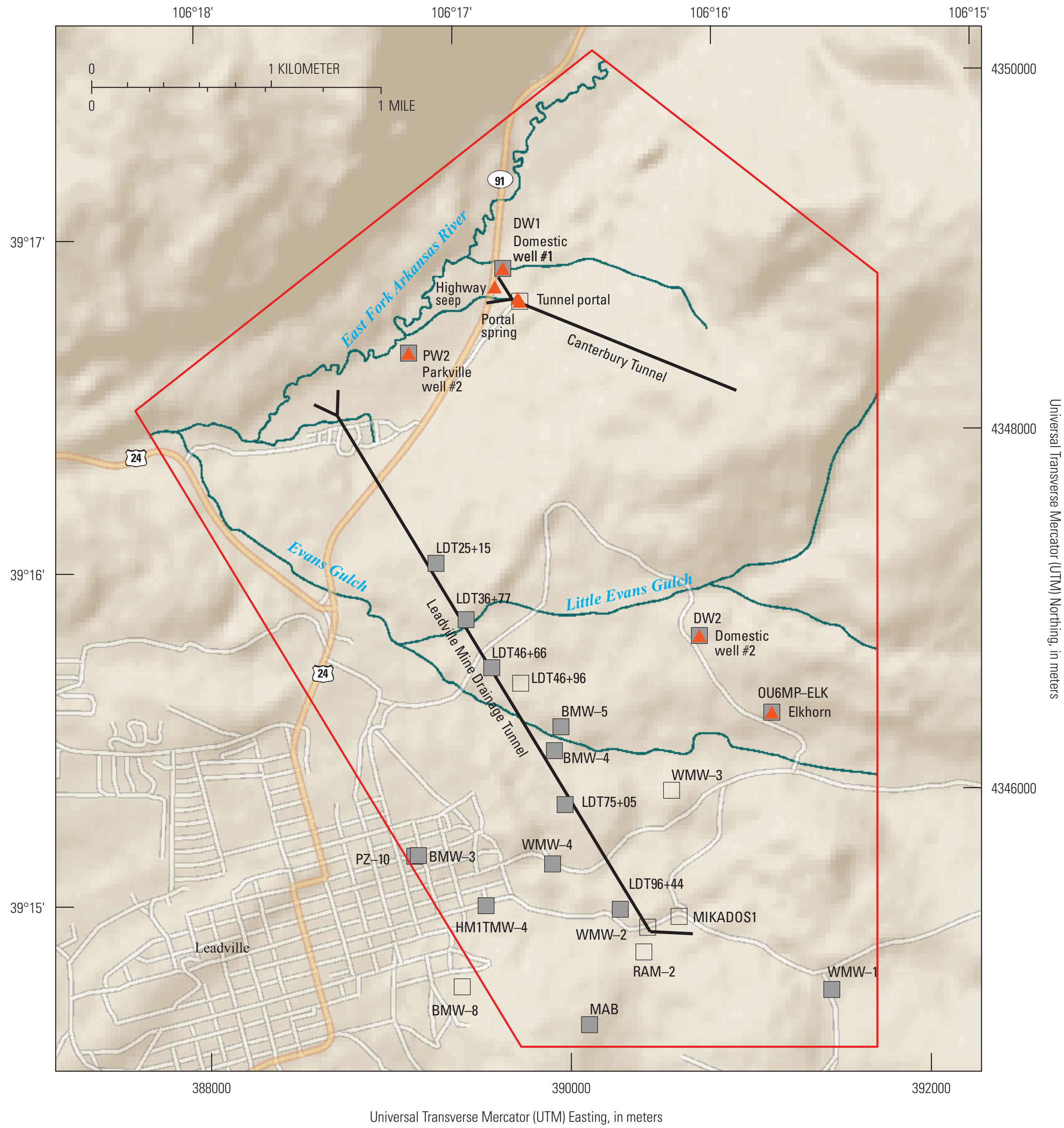
Figure 5. Inactive subsidence east of Canterbury Tunnel portal and along tunnel alignment, September 2008. Photograph by Suzanne S. Paschke, U.S. Geological Survey.

boundaries for the groundwater-flow model. An electronic database was developed to represent the geologic structure and was used to define the geologic framework for the groundwater-flow model. The model was calibrated to existing streamflow and hydraulic-head data. Results from the groundwater-flow model provide water-budget estimates and were used to track advective groundwater flow through the modeled area. Study results provide a groundwater-modeling tool for further quantitative analysis and advance the understanding of groundwater flow and quality in the unique setting of high-altitude fractured-rock aquifers affected by historical mining. Methods for each of the project tasks are provided.

Data Compilation and Analysis

Available data concerning climate, surface water, and groundwater for sites near the Canterbury Tunnel and the Leadville Mine Drainage Tunnel were compiled from various sources as described below. The data were used to develop interpretations of the hydrologic and geologic setting for the area between the Canterbury Tunnel and the Leadville Mine Drainage Tunnel. Hydrologic data available from the USEPA (Mike Wireman, U.S. Environmental Protection Agency, written commun., 2008) and CDPHE (Doug Jamison, Colorado Department of Public Health and Education, written commun., 2008) California Gulch Superfund databases and previous studies (see *Background* section of this report) included surface-water flow, groundwater levels, and water-quality data for the Leadville Mine Drainage Tunnel, the Yak Tunnel, and the surrounding area. From the BOR, historical and recent reports and data related to the geology and operation of the Leadville Mine Drainage Tunnel were compiled. Historic and geologic reference materials related to construction of the Canterbury Tunnel and the Leadville Mine Drainage Tunnel and geology of the study area were obtained from the USGS library in Denver, Colorado, including original field notes, draft maps, and cross sections from Ogden Tweto. Hydrologic data included observations of hydraulic head in wells taken from USEPA and CDPHE databases, well permits, and measured for this study. Water-level data from 23 sites (21 wells, 1 mine shaft, and 1 tunnel portal) were selected as hydraulic-head observations for the groundwater-flow model (fig. 7). Daily values of precipitation, temperature, and snowfall were examined for four National Weather Service sites near Leadville: Climax (station 051660; altitude 3,450 m; period of record 1949–present); Leadville at Lake County Airport (station Leadville AP; altitude 3,029 m; continuous

Figure 6. Active sinkhole along Canterbury Tunnel alignment, September 2008. Photograph by Suzanne S. Paschke, U.S. Geological Survey.



Base from U.S. Geological Survey digital data, 2009, 1:100,000
Universal Transverse Mercator projection, Zone 13
Colorado Department of Transportation digital data, 2008, 1:100,000
Universal Transverse Mercator projection, Zone 13
U.S. Environmental Protection Agency digital data, 2008, 1:100,000
Geographic coordinate system

EXPLANATION

- **Study area**
- **Water-quality sample site**
- **Water-level measurement site**
  - Used for model calibrattion
  - Not used for model calibration

Figure 7. Locations of water-level measurement sites used for model calibration and water-quality sampling sites, September 2008.

record 1983–present); Sugarloaf Reservoir (station 058064; altitude 2,969 m; period of record 1948–1968 and 1971–present); and Twin Lakes Reservoir (station 058501; altitude 2,804 m; period of record 1949–present) (*http://www.ncdc.noaa.gov/oa/climate/stationlocator.html*, accessed October 15, 2008). Streamflow measurements for the East Fork Arkansas River at Leadville (site 07079300) were obtained from the USGS National Water Information System database (*http://waterdata.usgs.gov/co/nwis/*). Other sources of information used to identify locations for field investigations included well permits and geologic logs for wells identified near the Canterbury Tunnel from the Colorado Division of Water Resources well-permit database (*http://www.dwr.state.co.us/WellPermitSearch/default.aspx*, accessed September 3, 2008) and land-ownership records for the area surrounding the Canterbury Tunnel from the Lake County Assessor office.

Site Reconnaissance

Field reconnaissance of the area surrounding the Canterbury Tunnel was conducted during July through September 2008 to locate groundwater and surface-water sampling locations and to explore surficial expression of the tunnel. Sampling locations were identified and locations were recorded with a handheld Global Positioning System (GPS) unit. Locations of active and inactive sinkholes and open shafts also were recorded using the handheld GPS unit. The upslope edge of each collapse feature was recorded with the GPS unit, and results were used to define the alignment of the Canterbury Tunnel for groundwater-flow simulations (fig. 1).

Geologic Digital Database

Geology of the study area was digitally reconstructed in a geodatabase using the ARC Geographic Information System (ArcGIS) Version 9.3 (Environmental Systems Research Institute, Inc., 1999–2010). The extent of geologic units and faults at the land surface was assigned by digitizing geologic maps of the area. Interpretations of mapped bedrock units, the fault network, and lateral displacement of fault blocks were incorporated into the geodatabase. Vertical characteristics of the geologic structure were estimated from mapped cross sections and information regarding vertical block displacement, geologic unit sequences, and unit thicknesses was included. The products created from the analysis included a spatial description of the faults, fracture-damage zones, thickness for the primary bedrock units, Quaternary sediment unit thickness, and land-surface altitude.

Quaternary alluvial and glacial deposits were mapped as a single geologic layer. Layer thickness for the Quaternary deposits was estimated by manually assigning a thickness value to data points selected from geologic cross sections (Tweto, 1974). The thickness values were interpolated across the study area in using an ordinary kriging method available in ArcGIS (Environmental Systems Research Institute, Inc., 1999–2010) to produce a map of estimated Quaternary sediment thickness. Initial attempts at constructing a map of sediment thicknesses used a natural-neighbor interpolative procedure, or Sibson interpolator (Sibson, 1981), but the method created artificial thickness undulations between the data control points, and the interpolation technique was ultimately abandoned.

Digital reconstruction of the faults and primary bedrock units that underlie the Quaternary sediment was prepared primarily from plan-view maps and geologic-unit contacts inferred from cross sections and geologic interpretations of the Leadville mining district (Tweto, 1951, 1974). Previous work of direct observations from within the mines and tunnels (for example, Emmons, 1886; Chapman and Stevens, 1927; Emmons and others, 1927; and Behre, 1953) was used in the digital reconstruction as were unpublished original field notes, map sketches, exploration mine-shaft datasets, and other documents written by Ogden Tweto that were stored in the USGS library in Denver, Colo. These additional resources allowed for the extension of mapped features in the southern part of the study area for which published spatial interpretations of the geology were not available. The mapped geologic interpretations of the bedrock units and fault-network structure were georeferenced to digital raster graphic topographic maps by using a second-order polynomial transformation. The second-order transformation avoided most of the nonlinear distortion introduced during the digital conversion of scanned paper maps. The raster data layers were masked to the extent of the active model boundary, merged, vectorized, and simplified, which allowed for a spatial delineation of the primary bedrock units.

Geophysical Resistivity Survey

A geophysical direct-current (DC) resistivity survey was conducted between Evans Gulch and the Canterbury Tunnel in September 2008 to substantiate the geologic interpretations. The geophysical survey measured subsurface resistivity of the rocks, which was used to delineate lateral changes in lithology of subsurface materials. Areas of low resistivity (high conductivity) indicate subsurface materials with greater water content than the surrounding materials, or possibly greater porosity if the materials are saturated with similar fluids. Areas of high resistivity (low conductivity) indicate subsurface materials with lower water content than the surrounding materials, or possibly lower porosity.

The one-mile DC resistivity survey was conducted along a former power-line easement and dirt trail that extends from Evans Gulch to the Canterbury Tunnel. The southern two-thirds of the line follow a former power-line easement; the line then bends northwards towards the Canterbury tunnel along a dirt trail (fig. 1). Resistivity data were acquired with a SuperSting® R8/IP resistivity meter in conjunction with 108 dual-mode electrodes (*http://www.agiusa.com*). Electrode stakes were placed in the ground at 5-m intervals along the line, and stations were surveyed using a Leica 1200 differential GPS system. Direct-current resistivity data were acquired by injecting current between one pair of electrodes, and measuring the resulting potential difference across a second pair of electrodes. The ratio of the measured voltage to the injected current and the geometry of the transmitting and receiving electrodes were used to input data in an inversion code to recover the subsurface resistivity structure. An inverse Schlumberger acquisition geometry was used for this survey, which reverses the role of transmitting and receiving electrodes. Additionally, many different combinations of transmitting dipole sizes are used (from separations of 1–7 stations) as well as receiving dipole sizes (from 1 station outside the transmitting pair to more than 20 stations). In general, smaller dipoles are sensitive to shallower subsurface structures, while larger dipoles are sensitive to deeper structures. With the SuperSting system, a pre-loaded schedule file automatically switches between many combinations of transmitting and receiving dipoles on the electrode array. The data were downloaded to ensure quality once the schedule was completed. The line was then rolled along by moving 20 electrodes from the beginning of the array to the end and the process was repeated, enabling acquisition of information for the relatively long geophysical survey lines. A total of 424 electrode stations were utilized for this survey.

Resistivity data commonly are reported as the ratio of measured voltage (V) to injected current (I) for each transmitting and receiving dipole pair. Multiplication of this ratio by a geometric factor, K (meters), which has to do with the electrode geometry, results in the apparent resistivity, ρ_a (ohms × meters) (Telford and others, 1990)

$$\rho_a = K\frac{\Delta V}{I}. \tag{1}$$

The apparent resistivity value for a given transmitting and receiving dipole pair represents the resistivity of a homogeneous Earth that would produce a measured response for a given electrode configuration. Apparent resistivity values typically are displayed as a pseudosection, whereby the apparent resistivity value is plotted vertically below the center of the transmitting and receiving dipole at a depth that is proportional to the outer dipole size. This plot provides a useful way to look at data quality and general trends because it conveys approximate variations in resistivity structure along the line and with depth. The top image in figure 8 illustrates the measured apparent resistivity pseudosection for this survey, where each black point in the figure represents one of 9,960 unique transmitting and receiving electrode dipole pairs. Of these data, approximately 10 percent were removed owing to poor data quality and were excluded from further analysis.

In order to recover a model of the subsurface resistivity structure, the data were inverted in conjunction with the acquisition geometry, which included local topography. Inversion of the resistivity data attempted to produce a model of subsurface resistivity values that reproduce the measured data under a simulated survey. The resistivity data were inverted to recover a model of subsurface bulk resistivity (Dahlin, 2001) by using the EarthImager2D® software package (*http://www-agiusa-com.netsolads.com/earthimager3d.shtml?keywords=earthimager%203D&creative=4977932166&adGroup=37786*, accessed June 10, 2011). Starting from an already devised resistivity model, the inversion seeks, by iterative adjustment of model-resistivity values, to minimize the difference between the measured data (apparent resistivity) and predicted data for the current model estimate. These model adjustments were calculated from sensitivity information and differences between the measured and predicted data. Model regularization was utilized to stabilize the inverse problem and promote lateral smoothness of the resistivity structure. A finite-element mesh was used for the computational grid, which readily allowed for the incorporation of topography and thus greatly reduced topographic-related artifacts in the model.

The vertical exaggeration on the inverted resistivity model (fig. 8*C*) is approximately 1.5. The calculated apparent resistivity pseudosection (fig. 8*B*) matches the measured pseudosection, indicating that the recovered model was consistent with the measured data. Because of the inherent nonuniqueness of the DC resistivity inversion, the effect of various inversion parameters and starting models on the final inversion result was explored through sensitivity analysis. Generally, model parameters near the electrode locations were better constrained than deeper ones because of the high sensitivity of these parameters to the data. Analyses showed that sensitivity decreased substantially with depth, but that it was also influenced by topography and model resistivity. One of the most limiting factors in this study was the use of two-dimensional resistivity-survey geometry in an inherently three-dimensional geologic structure.

Water-Quality Sampling

Groundwater and surface-water samples were collected from 7 sites near the Canterbury Tunnel on September 15 and 16, 2008, to evaluate whether mining activities had affected water quality (fig. 7; table 1). No groundwater wells were completed in the Canterbury Tunnel at the time of this investigation and few wells existed in the vicinity, which limited the number of sites available for water-quality characterization.

Sampling Locations in Relation to the Hydrologic System

Water samples were collected from the following accessible sample sites with their abbreviated name conventions shown in parentheses: (1) Canterbury Tunnel portal (tunnel portal); (2) Canterbury Tunnel portal spring (portal spring); (3) standing water and seepage at the base of the Canterbury waste pile along Highway 91 (highway seep); (4) Domestic well #1 (DW1) located near the base of the Canterbury waste-rock pile; (5) Parkville well #2 (PW2) located west of the Canterbury Tunnel, (6) Parkville Elkhorn shaft well (Elkhorn shaft) located southeast of the Canterbury Tunnel; and (7) Domestic well #2 (DW2) located near the Elkhorn shaft (fig. 7; table 1). The Canterbury Tunnel portal and portal

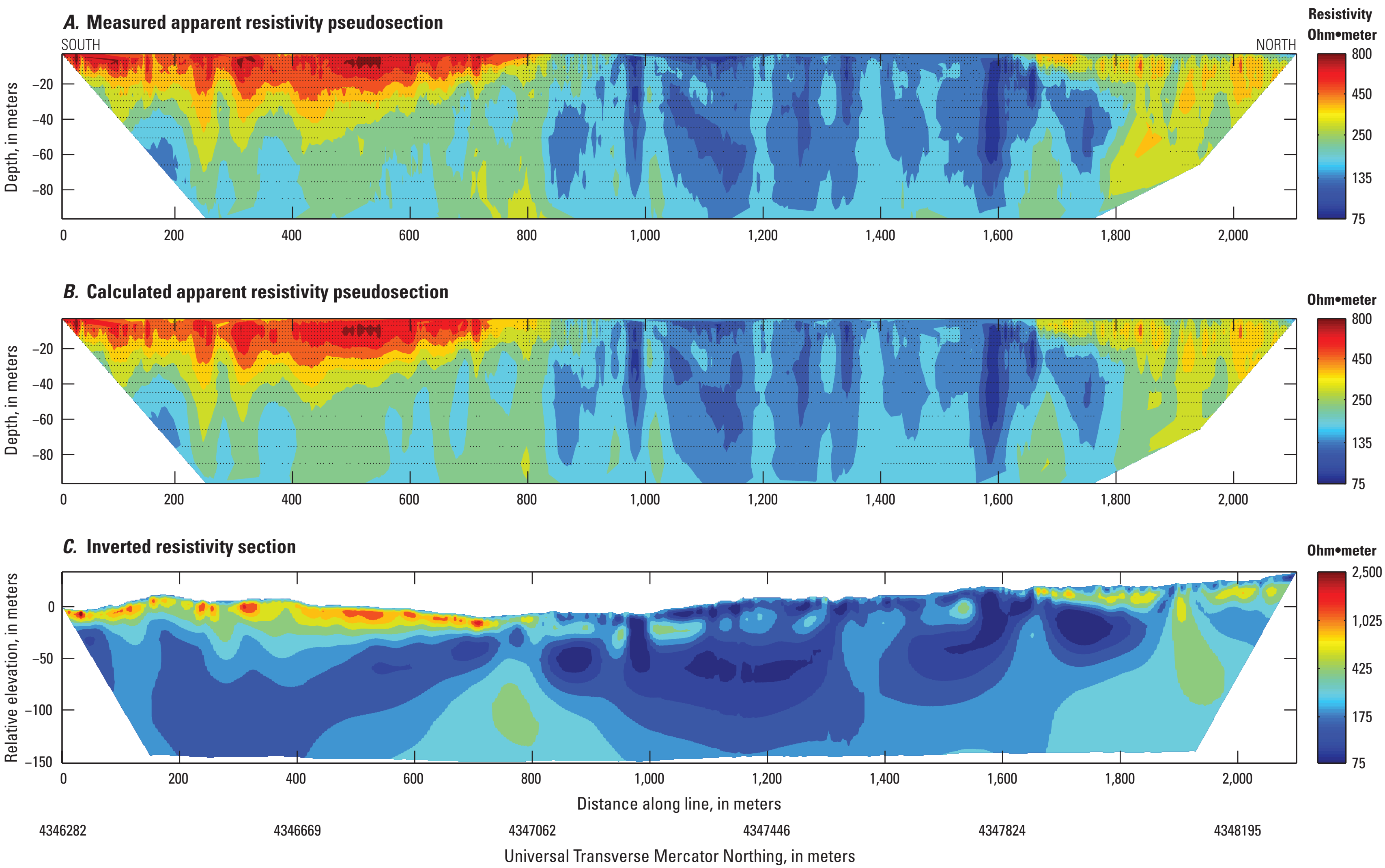


Figure 8. Geophysical survey results: *A*, measured apparent resistivity pseudosection, *B*, calculated apparent resistivity pseudosection, and *C*, inverted bulk resistivity model.

Table 1. Water-quality sampling sites near the Canterbury Tunnel, Leadville, Colorado, September 2008.

[USGS site ID, U.S. Geological Survey site identification number; ddmmss.s, decimal degrees, minutes, seconds; NAD 83, North American Datum of 1983; m, meters; NAVD 88, North American Vertical Datum of 1988; bls, below land surface]

Site name	USGS site ID	Sample date	Latitiude, ddmmss, NAD 83	Longitude, ddmmss.s, NAD 83	Land surface altitude, in m above NAVD 88	Depth to water, in m bls	Well total depth, in m bls	Sample type	Geology of completion interval
Tunnel portal	391651106164301	9/16/2008	391651	1061643	3,069	0	0	Flow from portal	Regional groundwater flow
Portal spring	391650106164301	9/15/2008	391650	1061643	3,072	0	1	Well point	Regional groundwater flow
Highway seep	391653106164901	9/15/2008	391653	1061649	3,048	0	1	Well point	Regional groundwater flow, waste-rock pile
Domestic well #1	391656106164701	9/15/2008	391656	1061647	3,048	10	20	Domestic well	Arkansas River alluvial aquifer
Parkville well #2	391640106170801	9/16/2008	391640	1061708	3,036	3	46	Municipal well	Arkansas River alluvial aquifer
Elkhorn shaft	391537106154301	9/16/2008	391537	1061543	3,241	41	119	Timber-lined open shaft	Manitou Dolomite
Domestic well #2	391550106160001	9/16/2008	391550	1061600	3,240	134	162	Domestic well	St. Kevin Granite

spring samples were collected at the portal and represent regional groundwater flow from the area drained by the tunnel. The portal spring is an upwelling of water within 3 m of the portal possibly caused by blockage at the portal. The highway seep at the base of the Canterbury waste-rock pile is likely a mixture of surface-water flow from the Canterbury Tunnel portal and groundwater discharge from Canterbury Hill. At the time of sampling in 2008, flow from the Canterbury Tunnel portal was too small to support operation of the drinking-water treatment plant. Instead, tunnel discharge flowed in a channel along the south side of the Canterbury Tunnel waste rock pile (fig. 9) and then ponded upstream from a culvert beneath Highway 91 (fig. 10). Groundwater seepage also was evident on the east side of Highway 91 at the break in slope between Canterbury Hill and the valley bottom, and the water-quality sample from this location was collected from an area considered representative of groundwater discharge. The source of groundwater could be regional groundwater flow from beneath Canterbury Hill, or it could be local groundwater discharge of surface water flowing from the Canterbury Tunnel and beneath the Canterbury Tunnel waste rock pile. Domestic well #1 is completed in the alluvial aquifer along the East Fork Arkansas River valley, and well PW2 is a 39-m-deep municipal supply well also completed in the alluvial aquifer. The Elkhorn shaft is a 260-m-deep abandoned mine shaft completed in Paleozoic rock near Evans Gulch that has been used by the Parkville Water District to pump water for municipal supply. The shaft is timber lined and the main source of water to the shaft is lower Paleozoic Manitou Dolomite. Domestic well #2 is 150-m-deep and completed in the St. Kevin Granite of Precambrian age near Evans Gulch. The Elkhorn shaft and Domestic well #2 are completed in a fault block separate from wells near the Canterbury Tunnel, and the quality of water from the Elkhorn shaft and Domestic well #2 is considered representative of the bedrock groundwater upgradient and separate from acid-mine drainage associated with the Leadville mining district.

Sampling and Analytical Methods

Water samples were collected through Teflon®, nylon, or copper connections and tubing, depending on the required sampling procedure for the analyte of interest, connected to existing sampling ports or spigots. Samples from springs and the Canterbury Tunnel portal were collected by attaching the connectors and tubing to a steel well point with a 0.305-m (1-ft) screened interval driven into the source of water. Well purging, sample collection, and equipment cleaning methods followed standard USGS protocols (Koterba and others, 1995; Lapham and others, 1995; Wilde and others, 2002; Wilde, 2004). Following standard USGS protocols, pH, temperature, specific conductance, and dissolved oxygen were measured in the field in a flow-through cell (to prevent contact with the atmosphere) at the time of sample collection (Wilde and others, 2002). Turbidity and alkalinity by titration also were measured in the field at the time of sample collection following standard procedures (Wilde and others, 2002).

Figure 9. Looking east of surface-water flow along the south side of the Canterbury Tunnel waste-rock pile, September 2008. Photograph by Suzanne S. Paschke, U.S. Geological Survey.

Laboratory analyses of water samples included major ions, metals, total dissolved solids, dissolved organic carbon (DOC), and nutrients as indicators of general water quality, and, tritium, dissolved gases, chlorofluorocarbons (CFC), and stable isotopes of hydrogen and oxygen in water as indicators of groundwater origin and age. Samples for major ions, metals, total dissolved solids, DOC, and alkalinity analyses were filtered through a 0.45-micron capsule filter, and samples for cation analyses were preserved in the field to a pH of 2 by using ultrapure nitric acid. Samples for major ions, metals, DOC, and nutrients were analyzed at the USGS National Water-Quality Laboratory in Lakewood, Colo. Anion analytes included bromide, chloride, fluoride, silica, and sulfate. Bromide, chloride, and sulfate were determined using ion-exchange chromatography; fluoride was determined using an ion-selective electrode; and silica (as milligrams SiO_2 per liter) was determined using colorimetry after a reaction with a molybdate reagent in acid (Fishman and Friedman, 1989). Cation and metals analysis included dissolved concentrations of a standard suite of metals including aluminum, antimony, arsenic, barium, beryllium, boron, cadmium, calcium, chromium, cobalt, copper, iron, lead, lithium, magnesium, manganese, molybdenum, nickel, potassium, selenium, silver, sodium, strontium, thallium, uranium, vanadium, and zinc. Dissolved concentrations of selenium and zinc were determined using collision/reaction cell inductively coupled plasma–mass spectrometry (Garbarino and others, 2006). Dissolved concentrations of the remaining cations were measured from filtered and acidified samples by using inductively coupled plasma atomic emissions spectroscopy (ICP–AES) (Fishman, 1993). Samples for analysis of DOC were filtered, acidified, and chilled in amber glass bottles. At the National Water Quality Laboratory, samples were oxidized to carbon dioxide using persulfate in the presence of ultraviolet light. Carbon dioxide was then measured using nondispersive infrared spectrometry (Brenton and Arnett, 1993).

Dissolved gas analytes included oxygen (O_2), carbon dioxide (CO_2), nitrogen (N_2), and argon (Ar) as indicators of recharge temperature, and CFCs were measured to estimate groundwater age. Dissolved gases were analyzed using gas chromatography (Plummer and Busenberg, 2008a), and CFCs were analyzed using purge-and-trap gas chromatography with an electron-capture detector (Plummer and Busenberg, 2008b). Dissolved gas and CFC analyses were performed at the USGS CFC Laboratory in Reston, Va. Procedures for collecting samples for dissolved gas and CFC sample analyses are described by Plummer and Busenberg (2008a, 2008b). Unfiltered samples for tritium analyses were collected and stored in high-density polyethylene

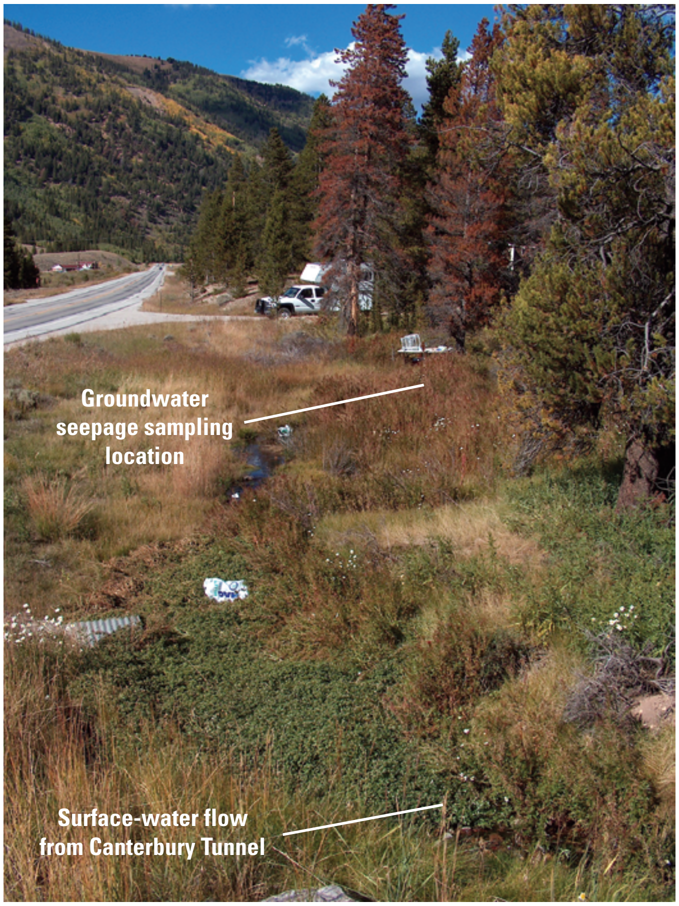


Figure 10. Looking north of surface-water flow and seepage along the east side of Highway 91, September 2008. Photograph by Suzanne S. Paschke, U.S. Geological Survey.

bottles and analyzed by the USGS Isotope Tracers Laboratory in Menlo Park, Calif., using electrolytic enrichment and analysis by liquid scintillation counting (Thatcher and others, 1977). Analysis for stable-isotope ratios of hydrogen ($^2H/^1H$) and oxygen ($^{18}O/^{16}O$) were performed on unfiltered water collected in a clear glass bottle; the water was analyzed at the USGS Reston Stable Isotope Laboratory in Reston, Va. Hydrogen-isotope ratios were analyzed using the gaseous hydrogen equilibration procedure of Coplen and others (1991). Oxygen-isotope ratios were determined from the carbon dioxide-water equilibration technique of Epstein and Mayeda (1953).

Groundwater Flow Simulations

Steady-state groundwater flow in the study area was simulated for the high-flow summer (June–August) condition using the USGS finite-difference code MODFLOW–2000 (Harbaugh and others, 2000). Climate and streamflow data were used to define recharge and discharge boundaries for the groundwater-flow model, and the electronic database of geologic structure was used to define the geologic framework of the groundwater-flow model. The model was calibrated to existing hydraulic-head and streamflow data. Results from the groundwater-flow model were used to identify the major inflow and outflow components to the system and variations in aquifer characteristics and hydraulic response with depth from the land surface. The calibrated flow model also was used to conduct particle-tracking simulations to estimate the source of recharge and water-age distributions for groundwater entering the Canterbury Tunnel and Leadville Mine Drainage Tunnel. Details of the groundwater-flow model setup, calibration, and results are presented in section *Simulation of Groundwater Flow* of this report.

Hydrogeologic Setting

The area of investigation for this study consists of a 13-km^2 region about 3 km northeast of Leadville, Colo. The study area includes the Canterbury Tunnel, the Leadville Mine Drainage Tunnel, parts of Evans Gulch, Little Evans Gulch, and Stray Horse Gulch watersheds, and a 3-km segment of the East Fork Arkansas River (figs. 1, 7). The study area is situated in the headwaters of the upper Arkansas River on the western flank of the Mosquito Range.

Physiography and Climate

Altitude in the Leadville area ranges from about 3,018 m (9,900 ft) along the Arkansas River valley to about 4,270 m (14,000 ft) along the Continental Divide in the Mosquito range east of Leadville. The high altitude of the area results in a moderate subpolar climate (Zogg, 1977). Daily values of precipitation, temperature, and snowfall were examined for four National Weather Service sites near Leadville. The Climax site (station 051660, period of record 1949–present) is located about 17 km northeast of Leadville at an altitude of 3,450 m; the Leadville at Lake County Airport site (station Leadville AP, period of record 1983–present) is located about 3 km southwest of Leadville at an altitude of 3,029 m; the Sugarloaf Reservoir site (station 058064, period of record 1948–1968 and 1971–present) is located about 7 km west of Leadville at an altitude of 2,969 m; and the Twin Lakes Reservoir site (station 058501, period of record 1949–present) is located about 18 km southwest of Leadville at an altitude of 2,804 m (*http://www.ncdc.noaa.gov/oa/climate/stationlocator.html*, accessed October 15, 2008). Average daily recorded temperatures are less than 0°C for several months of each year, and winter temperatures commonly fall below −18°C.

Monthly and annual precipitation data from 1990 to 2007 were examined for temporal and spatial trends and used to develop recharge estimates for the groundwater system. Precipitation fell primarily as snow from September through May of each year (defined herein as winter precipitation, and precipitation fell primarily as rain during the months of June through August (defined herein as summer precipitation). Total winter precipitation from 1990 to 2007 ranged from a minimum of 90 millimeters (mm) in 2006 at Twin Lakes to a maximum of 740 mm in 1996 at Climax (fig. 11*A*), whereas

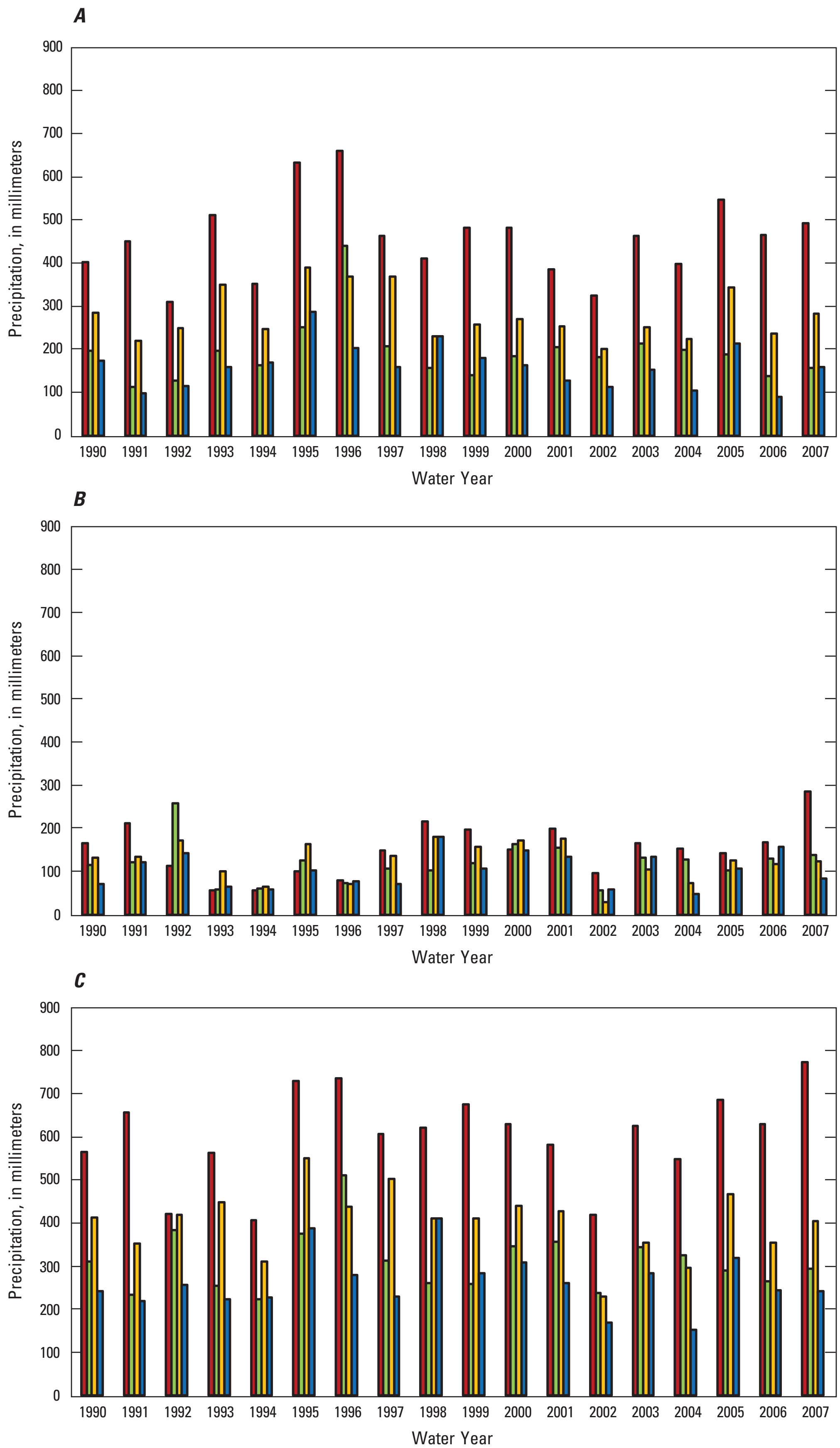


Figure 11. Temporal distribution of *A*, winter precipitation, *B*, summer precipitation, and *C*, total annual precipitation for four National Weather Service stations near Leadville, Colorado, 1990–2007.

summer precipitation ranged from a minimum of 30 mm in 2002 at Sugarloaf Reservoir to a maximum of 290 mm in 2007 at Climax (fig. 11*B*). These results indicate that for the period of record, winter precipitation was about three times greater than summer precipitation. Comparing precipitation data between sites indicates that, in general, both winter and summer precipitation were greatest at higher altitudes, and a linear relation between precipitation and altitude was developed for winter and summer conditions (fig. 12). The effect of a regional drought that began in 1999 was most pronounced in the summer precipitation record of 2002 (fig. 11*B*), as indicated by a decrease in summer precipitation at all four weather stations, although winter precipitation also decreased at these sites in 2002 (fig. 11*A*). Maximum winter precipitation was recorded during 1995–1997 at all sites, and maximum summer precipitation was recorded during 1995 at all sites. In general, both winter and summer precipitation have increased since 2002, and in 2007 total precipitation at the Climax weather station (highest altitude station) exceeded that of 1995 (fig. 11*C*). The increase in total annual precipitation since 2002 coincides with the observed water-level rise near the Leadville Mine Drainage Tunnel that began in 2003.

Surface-Water Hydrology

The weather patterns and hydrology exhibit strong seasonality with an annual cycle of cold winters with large snowfall, followed by spring snowmelt, runoff, and recharge (high-flow) conditions, and then base-flow (low-flow) conditions in the fall prior to the next winter. Streamflow data for the East Fork Arkansas River (USGS gaging station 07079300) from 1991 to 2007 were examined to evaluate discharge variability and estimate base-flow conditions (fig. 13). The discharge record from 1991 to 2007 shows annual peak runoff near the end of May and beginning of June during spring snowmelt, although discharge varied seasonally and annually. The minimum annual peak discharge for the period (0.62×10^8 m^3/yr) occurred in May 2002 during the drought, and the maximum peak discharge for the period (7.2×10^8 m^3/yr) occurred in June 1997. Streamflow generally increased after the 2002 drought year (fig. 13). Base flow for the watershed was estimated at between 3.9×10^6 m^3/yr and 4.1×10^8 m^3/yr using the hydrograph separation method of Boughton (1993) as described by Eckhardt (2005). The proportion of base flow for the watershed contributed by the study area was estimated by subtracting the observed discharge of the Leadville Mine Drainage Tunnel from the estimated base flow and then multiplying the remainder by 0.10 to account for the percentage of the total upstream watershed that occupies the study area.

Groundwater Hydrology

Groundwater flow in the study area is controlled by topography, the locations and quantity of recharge, the locations and orientations of geologic and mining features, and the locations of streams and tunnels. On a basinwide scale, melting snow and rain at higher altitudes in the Mosquito Range east of the study area recharges a bedrock groundwater system, which flows generally southwestward following topography toward the Arkansas River valley at the base of the watershed. Bedrock groundwater discharges to surface water and to alluvial sand and gravel deposits along the Arkansas River valley. The valley-fill deposits form an unconfined alluvial aquifer at the base of the mountains. Stratigraphy, geologic structure, fracture and fault networks, karst features, mine workings, and tunnels affect groundwater flow directions on a local scale.

Recharge

Recharge to groundwater in the study area is from incident precipitation and snowmelt and was estimated as a percentage of annual precipitation for fall low-flow and spring high-flow conditions. Previous studies indicate groundwater

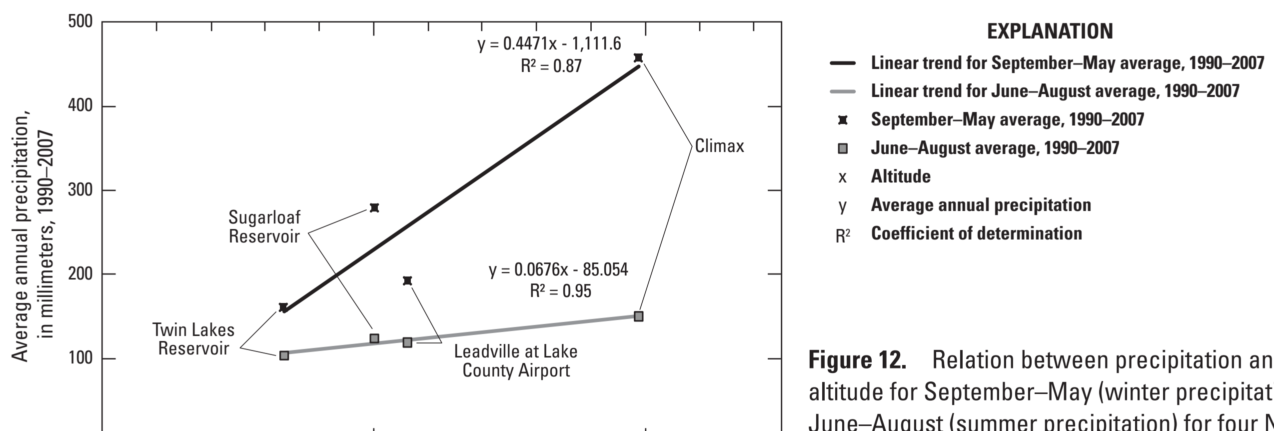


Figure 12. Relation between precipitation and altitude for September–May (winter precipitation) and June–August (summer precipitation) for four National Weather Service stations near Leadville, Colorado, 1990–2007.

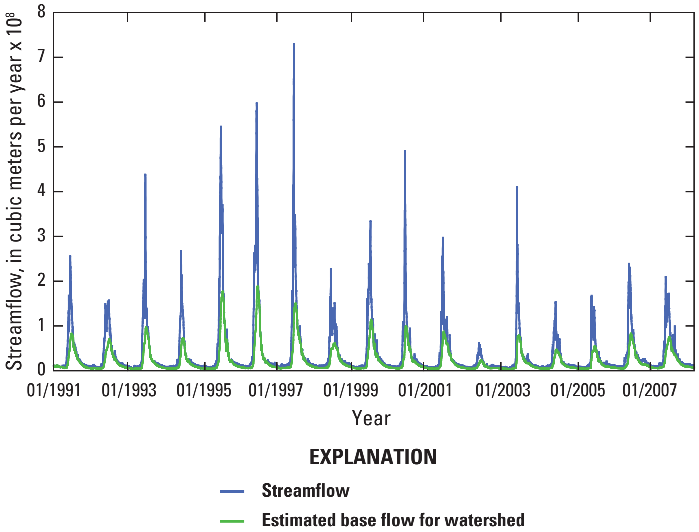


Figure 13. Streamflow data and estimated base flow for the East Fork Arkansas River at U.S. Highway 24 near Leadville, Colorado (U.S. Geological Survey gaging station 07079300).

recharge in mountainous areas of southern Colorado is estimated to be 14–38 percent of the annual precipitation (Wilson and Guan, 2004). Because Leadville is north of the area for which the previous recharge estimates were made, and precipitation rates are generally greater farther to the north in the central Rocky Mountains, recharge conditions near Leadville probably would tend toward the high end of this range. Average annual groundwater recharge was therefore assumed to equal 30 percent of the average annual precipitation for this study. On the basis of deuterium and oxygen isotope ratios, Liu and others (2006) indicate that, in the Leadville area, September–May winter precipitation accounted for about 85 percent of groundwater recharge and June–August summer precipitation accounted for about 15 percent of groundwater recharge. The spatial distribution of average annual precipitation in the study area was calculated using the linear relation between precipitation and altitude (fig. 12) for June–August summer precipitation and for September–May winter precipitation, and the spatial distribution of recharge was then calculated for the respective winter low-flow and summer high-flow conditions. For low-flow conditions, summer precipitation recharge was estimated as 15 percent of 30 percent of the average annual precipitation (0.05 multiplied by average annual precipitation), and for high-flow conditions, recharge was estimated as 85 percent of 30 percent of the average annual precipitation (0.25 multiplied by average annual precipitation) (figs. 14, 15). For low-flow conditions, recharge ranged from 119 to 157 mm/yr across the study area (fig. 14), and for high-flow conditions, recharge ranged from 240 to 486 mm/yr (fig. 15). The largest recharge rates occurred at the highest altitude for both flow conditions consistent with the derived relations between precipitation and altitude.

Geology

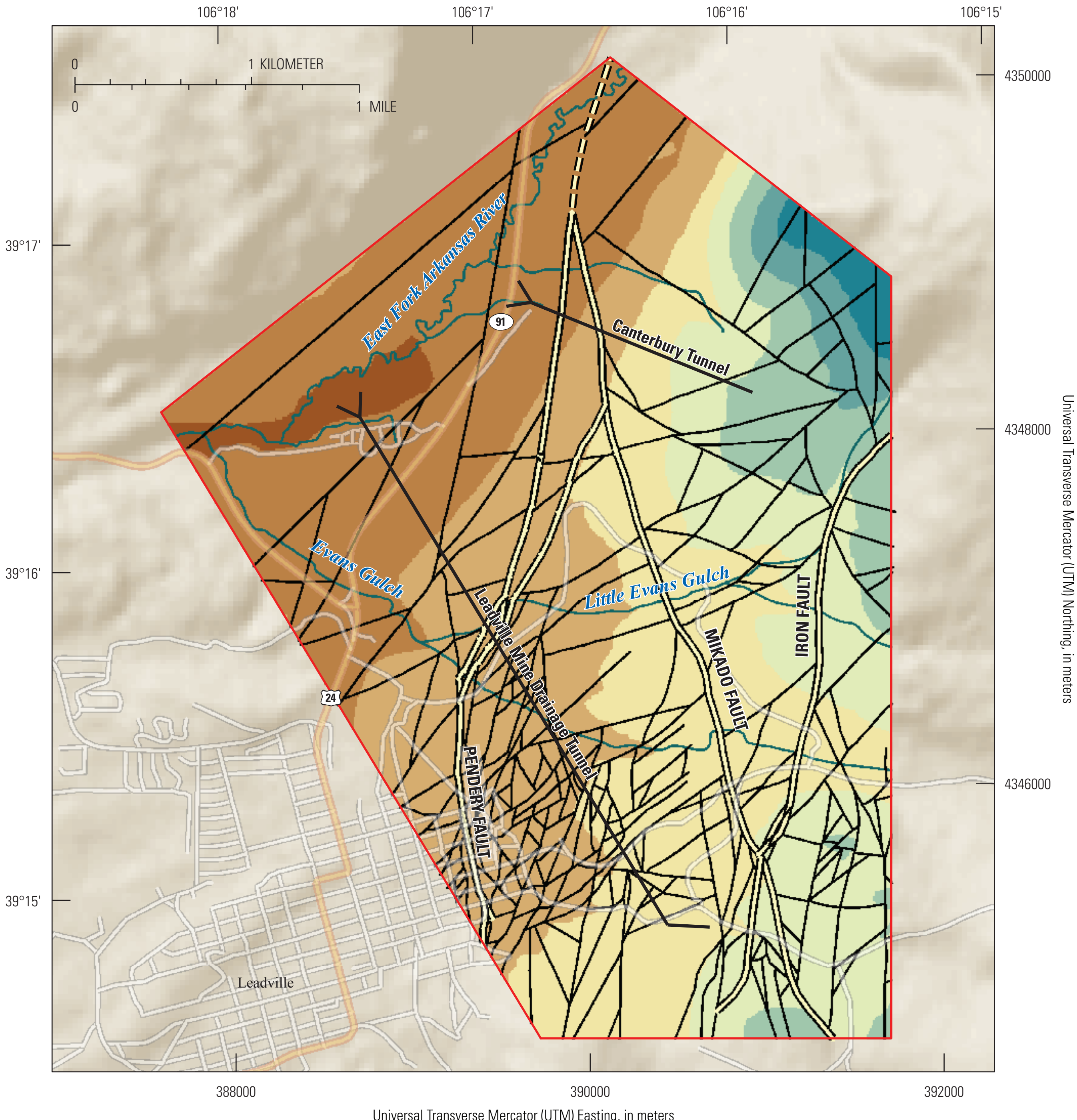
Bedrock in the Leadville area consists of Precambrian granite overlain by Paleozoic sedimentary rocks, which have been folded and faulted during several tectonic episodes. Late Cretaceous and Tertiary igneous intrusive rocks (primarily porphyry) cross cut the older Precambrian and Paleozoic rocks, and hydrothermal fluids associated with the porphyry are related to mineralization in the Leadville mining district. Unconsolidated Quaternary alluvial and glacial deposits overlie the bedrock formations primarily along the East Fork Arkansas River and it tributaries (Tweto, 1974).

Hydrogeologic Units

Groundwater in the study area generally occurs in the fractured Precambrian granite and lower Paleozoic carbonate rocks, although groundwater can also occur in the fractured Paleozoic sandstones and Cretaceous-Tertiary porphyry. Unconsolidated Quaternary valley-fill sand and gravel deposits along the East Fork Arkansas River form a productive alluvial aquifer used for domestic and municipal water supply. Quaternary glacial deposits are generally finer grained than the alluvial deposits and are generally considered confining units in the Leadville area (Wireman and others, 2006).

Precambrian basement rocks compose the oldest group in the section and most commonly are observed at depths greater than 100 m, underlying the younger rock units. In a few small areas, mainly in the southern part of the study area, Quaternary sediments lie directly on Precambrian basement rocks because of mountain-building events and erosion processes. Precambrian rocks consist of a metamorphic and igneous complex about 1.7 billion years old into which was intruded the Precambrian St. Kevin granite batholith (about 1.4 billion years old; table 2). The Precambrian rocks form a fractured-rock aquifer in the study area.

Paleozoic sedimentary rocks overlie the Precambrian basement rocks beneath most of the study area and consist of dolomite, limestone, quartzite, and sandstone with a total section thickness of 15 to 210 m. From oldest to youngest, the Paleozoic rocks include the Sawatch Quartzite (Cambrian age), the Peerless Formation, the Manitou Dolomite (Ordovician age), the Dyer Dolomite and Parting Quartzite of the Chaffee Formation (Devonian age), the Leadville Limestone (Mississippian age), and the Belden and Minturn (Weber) Formations (Pennsylvanian age) (Emmons, 1927; Behr, 1953; Tweto, 1974, 1980a, 1980b; Zogg, 1977; Epis and others, 1980; Teller and Welder, 1983; Romberger, 1980; table 2). Cretaceous- to Tertiary-age porphyry rocks intruded into the Precambrian and Paleozoic host rocks range from 15 to 610 m in thickness and are generally thickest in the north-central part of the study area (Tweto, 1974, 1980a, 1980b). The Manitou Dolomite, Dyer Dolomite, and Leadville Limestone are permeable formations that constitute important local and regional karst aquifers (Teller and Welder, 1983; Wireman and others, 2005). These formations also are host rocks for



Base from U.S. Geological Survey digital data, 2009, 1:100,000
Universal Transverse Mercator projection, Zone 13
Colorado Department of Transportation digital data, 2004, 1:100,000
Universal Transverse Mercator projection, Zone 13
U.S. Environmental Protection Agency digital data, 2008, 1:100,000
Geographic coordinate system

EXPLANATION

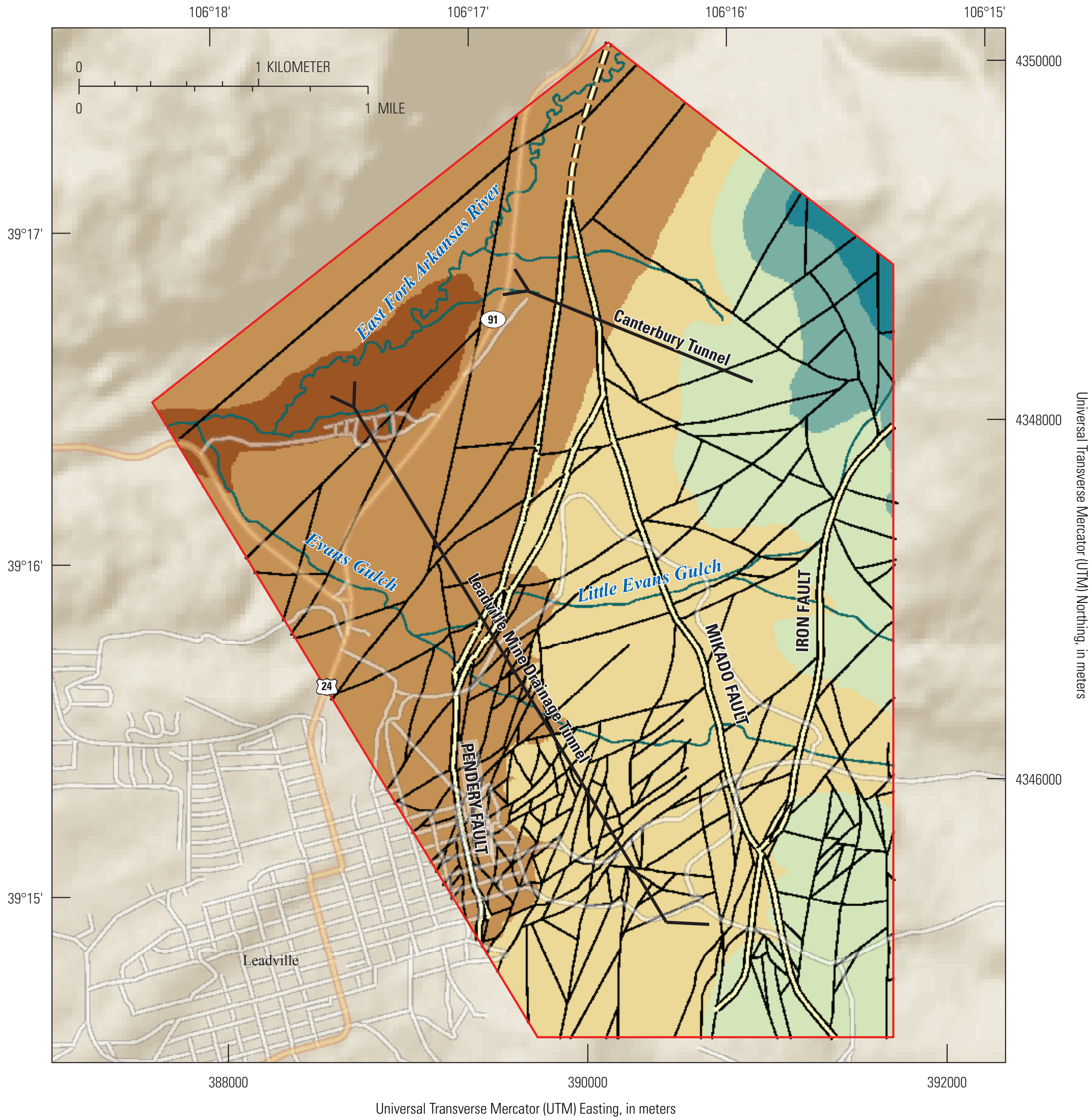
Recharge—In millimeters per year
- 119 to 120
- >120 to 125
- >125 to 130
- >130 to 135
- >135 to 140
- >140 to 145
- >145 to 150
- >150 to 157

Study area

Major fault—Dashed where inferred

Fault

Figure 14. Spatial distribution of estimated recharge for winter (September–May) low-flow conditions.



Base from U.S. Geological Survey digital data, 2009, 1:100,000
Universal Transverse Mercator projection, Zone 13
Colorado Department of Transportation digital data, 2004, 1:100,000
Universal Transverse Mercator projection, Zone 13
U.S. Environmental Protection Agency digital data, 2008, 1:100,000
Geographic coordinate system

EXPLANATION

Recharge—In millimeters per year

240 to 250
>250 to 300
>300 to 350
>350 to 400
>400 to 450
>450 to 486

Study area
Major fault—Dashed where inferred
Fault

Figure 15. Spatial distribution of estimated recharge for summer (June–August) high-flow conditions.

Table 2. Generalized stratigraphy, geologic history, and hydrogeologic characteristics of bedrock and surficial deposits, Leadville, Colorado (adapted from Emmons and others [1927], Behre [1953], Tweto [1974, 1980a, 1980b], Zogg [1977], Epis and others [1980], Romberger [1980], Wireman and others [2006]).

Era	Period	Epoch	Million years before present	Geologic event or unit	Formation name and (or) lithologic description	Range of thickness (meters)	Hydrogeologic description
Cenozoic	Quaternary	Holocene	1.5 to present	Alluvial, floodplain, terrace, colluvial, and eolian sand, gravel, and clay deposits	Unconsolidated sand and gravel with clay lenses primarily along present-day stream channels	As much as 80 meters in East Fork Arkansas River valley	Productive unconfined alluvial aquifer where saturated
		Pleistocene	1.5	Glaciation, moraines, glacial lakes	Poorly consolidated, very poorly sorted glacial deposits and lacustrine clay deposits	Generally less than 100 meters	Variably saturated confining unit
	Tertiary	Pliocene	5	Extensional tectonics, block faulting, and rifting	Dry Union Formation, poorly consolidated sand with lenses of gravel, clay, and volcanic ash	Generally less than 300 meters	Variably saturated
		Miocene	29	Volcanic and hydrothermal activity, mineralization, intrusive rhyolite and dikes	Fine-grained white rhyolite and rhyolite breccias of Miocene age are youngest intrusive rocks in the area. Rhyolite porphyry Oligocene in age	Variable	Variably saturated fractured-rock aquifer
		Oligocene	37–38				
		Eocene	53–54	Regional erosion of Paleozoic rocks following Laramide uplift. Eocene erosional surface			
		Paleocene	65	Continued Laramide uplift, reverse faulting, Laramide intrusions	Eagle River, Lincoln, and Johnson Gulch Porphyries composition includes granodioriteand quartz monzonite porphyry deposits	Variable	Variably saturated fractured-rock aquifer
Mesozoic	Cretaceous		81	Laramide uplift of Sawatch Range uplift	Elk Mountain, Sacramento, and Pando Porphyries composition includes granodiorite, quartz monzonite, and quartz latite		
Paleozoic	Pennsylvanian		600	Erosion of underlying Mississippian limestone and widespread deposition of marine sandstone, shale, and limestone on top of erosional unconformity	Minturn (Weber) Formation arkosic grit, conglomerate, shale, and sandstone with interbedded dolomite and limestone. Grey to maroon in color.	As much as 1,525 meters	Confined bedrock aquifer
					Belden Formation, interbedded gray and black shale and thin-bedded dark limestone and sandstone lie on a karst erosional surface at the top of the Leadville Limestone	Generally less than 70 meters	Confining unit
	Mississippian			Shallow marine limestone deposition	Leadville Limestone, massive gray to blue-black limestone is the principal host rock of ore deposits in the Leadville area and is known locally as “Blue Limestone”	3 to 50 meters	Confined karst aquifer
	Devonian			Shallow marine dolomite and sandstone deposition	Chaffee Formation consists of two dissimilar members—the Dyer Dolomite and the Parting Quartzite—deposited on erosional unconformity on top of the Manitou Dolomite	25 to 50 meters	

Table 2. Generalized stratigraphy, geologic history, and hydrogeologic characteristics of bedrock and surficial deposits, Leadville, Colorado (adapted from Emmons and others [1927], Behre [1953], Tweto [1974, 1980a, 1980b], Zogg [1977], Epis and others [1980], Romberger [1980], Wireman and others [2006]).—Continued

Era	Period	Epoch	Million years before present	Geologic event or unit	Formation name and (or) lithologic description	Range of thickness (meters)	Hydrogeologic description
	Ordovician			Shallow marine dolomite and sandstone deposition	Manitou Dolomite, white to gray medium bedded crystalline dolomite with irregularly distributed white chert is a host rock of ore deposition in the Leadville area and is known locally as “White Limestone”	Less than 35 meters	Confined bedrock aquifer
	Cambrian		600	Marine deposition of sandstone, shale, and limestone	Peerless Formation, thin-bedded buff, green, and maroon sandstone, sandy dolomite, and dolomitic shale	23 to 34 meters	
					Sawatch Quartzite, medium-bedded, fine-grained vitreous white quartzite deposited on unconformity on top of Precambrian rocks	30 to 56 meters	Confined bedrock aquifer
Precambrian			1,400	Intrusion of St. Kevin Granite batholith in Sawatch Range	St. Kevin Granite batholith is about 40 kilometers long and 20 kilometers wide in the Sawatch range and consists of mixtures of granite facies	Not known	Confined to unconfined fractured-rock aquifer
			1,700	Intrusion and metamorphism of oldest Precambrian rocks in Sawatch Range	Biotite gneiss and schist with pegmatite	Not known	

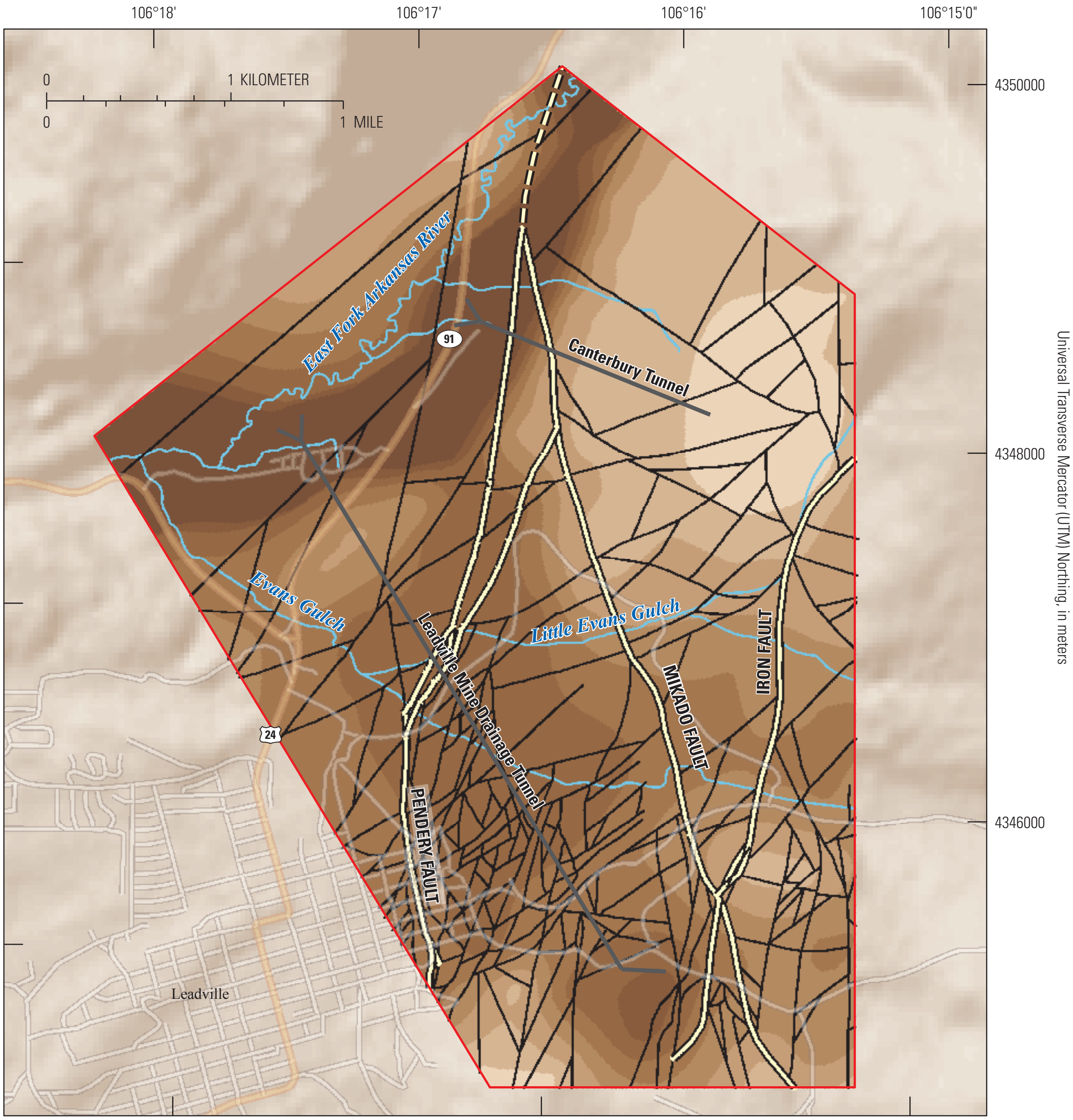
the regional mineralization because hydrothermal fluids more readily entered the paleokarst present in these layers (Wallace, 1993). The Minturn and Belden Formations consist of shale and sandstone units that overlie the Leadville Limestone and are generally considered an overlying confining layer of the Leadville Limestone (Teller and Welder, 1983; Wallace, 1993). Mining activity followed mineralization such that many mine workings occur in the lower Paleozoic sedimentary rocks. After the cessation of mining, many of the historical mine workings filled with groundwater and now form the mine pools associated with the Leadville Mine Drainage Tunnel (Wireman and others, 2005).

Quaternary alluvial and glacial deposits overlie the bedrock in thicknesses ranging from about 1 to 60 m in most of the study area (fig. 16). Quaternary glacial deposits consist of moraines, terraces, and lake-bed sediments with Quaternary alluvial deposits located along surface-water drainages mainly within the valley of East Fork Arkansas River. The thickest Quaternary sediments identified within the study area are along the East Fork Arkansas River valley and near the Leadville Mine Drainage Tunnel.

Geology of the study area was classified into five major hydrostratigraphic units for input to the groundwater-flow model following the convention of Tweto (1974): (1) Quaternary alluvial and glacial deposits, (2) Cretaceous-Tertiary porphyry rocks, (3) Pennsylvanian sedimentary rocks, (4) Paleozoic carbonate rocks, and (5) Precambrian basement rocks. The Quaternary alluvial deposits form an unconfined alluvial aquifer in the East Fork Arkansas River, whereas the glacial deposits are poorly sorted with substantial clay and generally form confining units. The Cretaceous-Tertiary porphyry rocks and the Precambrian basement rocks form fractured-rock aquifers. The Paleozoic carbonate rocks form karst aquifers, which are overlain and confined by the Pennsylvanian sedimentary rocks (Belden and Minturn Formations). All of the hydrostratigraphic units were simulated as equivalent porous media in the groundwater-flow model.

Geologic Structure

The Sawatch mountain range about 16 km west of Leadville is a Laramide uplift with Precambrian rocks at its core (Zogg, 1977; Epis and others, 1980; Tweto, 1980b). Paleozoic sedimentary rocks of the Leadville mining district form the eastern limb of the Sawatch anticline dipping, on average, about 12 degrees toward the east (Wallace, 1993). The region has been intensively fractured. Primary fault orientations trend northeast-southwest and northwest-southeast, and secondary fault orientations trend nearly north-south and east-west (fig. 17, Wallace, 1993). Most of the faults in the region dip steeply (80–90 degrees) and extend hundreds of meters below land surface (Tweto, 1974; Thompson and Arehart, 1990). The movement along faults was complex and produced both normal and reverse displacement, lateral shifting, and sequential offsetting during periods of fault reactivation (figs. 18, 19). Normal displacement along the steeply dipping faults that



Base from U.S. Geological Survey digital data, 2009, 1:100,000
Universal Transverse Mercator projection, Zone 13
Colorado Department of Transportation digital data, 2004, 1:100,000
Universal Transverse Mercator projection, Zone 13
U.S. Environmental Protection Agency digital data, 2004, 1:100,000
Geographic coordinate system

EXPLANATION

Quaternary sediment estimated thickness—In meters

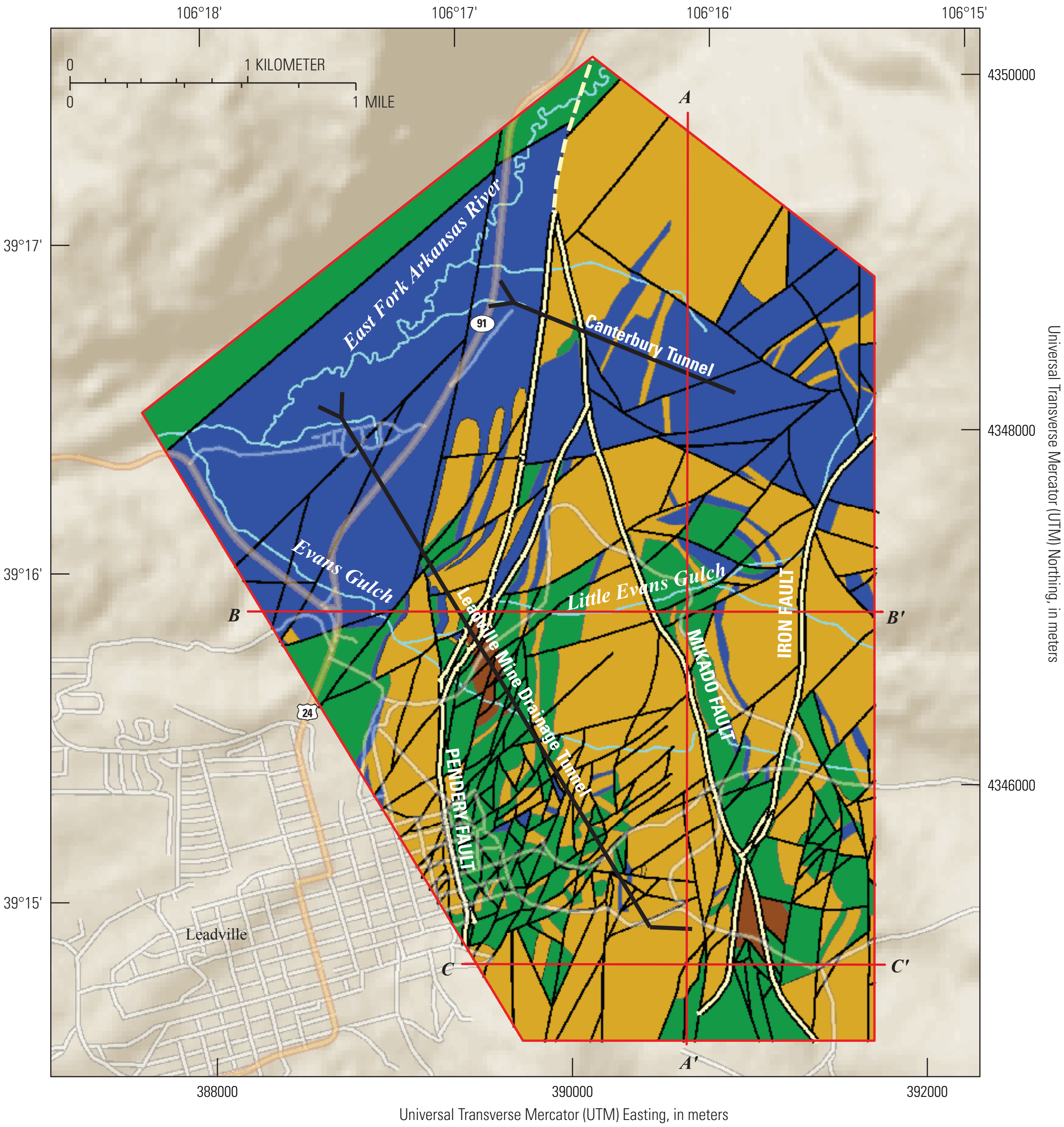
- <5
- 5 to 10
- >10 to 20
- >20 to 30
- >30 to 40
- >40 to 50
- >50 to 60
- >60 to 61

Study area

Major fault—Dashed where inferred

Fault

Figure 16. Estimated thickness of Quaternary alluvial and glacial deposits.



Base from U.S. Geological Survey digital data, 2009, 1:100,000
Universal Transverse Mercator projection, Zone 13
Colorado Department of Transportation digital data, 2008, 1:100,000
Universal Transverse Mercator projection, Zone 13
U.S. Environmental Protection Agency digital data, 2004, 1:100,000
Geographic coordinate system

EXPLANATION

Cretaceous-Tertiary—Porphyry

Pennsylvanian—Minturn and Belden Formations

Mississippian-Ordovician—Leadville Limestone, Chaffee Formation, Harding Quartzite, Manitou Dolomite, Sawatch Quartzite

Precambrian—Undivided

Study area

Major fault—Dashed where inferred

Fault

Figure 17. Generalized bedrock geology in the Canterbury Tunnel study area near Leadville, Colorado (modified from Tweto, 1974), and locations for cross sections *A–A′*, *B–B′*, and *C–C′* shown in figure 19.

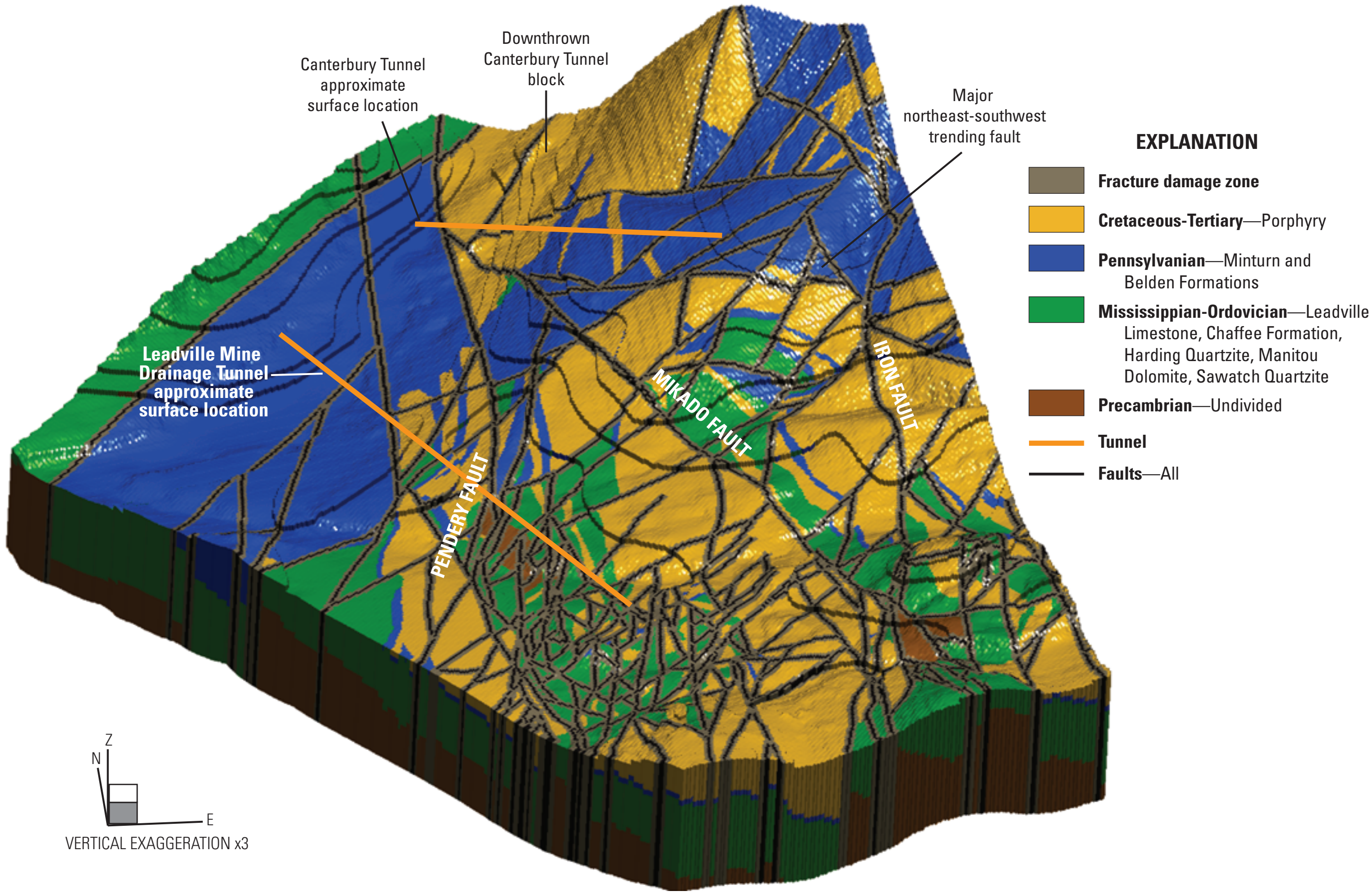


Figure 18. Block diagram generated from geologic reconstruction showing generalized bedrock geology in the Canterbury Tunnel study area, Leadville, Colorado.

trend north-northwest created a fault-block structure that steps downward toward the west and the Arkansas River valley. The Pendery, Mikado, and Iron faults are the major north-south-trending features that partition the bedrock aquifers within the study area (fig. 17).

The geologic structure encountered during drilling of the Canterbury Tunnel was documented by Chapman and Stevens (1927) and Behre (1953). From northwest to southeast, the Canterbury Tunnel was bored through about 355 m of unconsolidated, poorly sorted glacial material, then about 75 m of Tertiary porphyry, and then a zone of substantial faulting (Behre, 1953). The zone of substantial faulting discussed by Behre (1953) was shown as an extension of the Mikado fault by Tweto (1974) (fig. 17). Southeast of the Mikado fault and the Roseville Shaft, the Canterbury Tunnel intersected about 530 m of Leadville Limestone before reaching a second faulted zone, identified initially as the Pendery fault by Behre (1953). Subsequent mapping by Tweto (1974), however, showed the Pendery fault is northwest of the Mikado fault, which is the interpretation used in this investigation (fig. 17). Farther to southeast, the Canterbury Tunnel intersected Sawatch Quartzite and Manitou Dolomite (Behre, 1953). No substantial mineralized rock was observed along the Canterbury Tunnel bore (Behre, 1953).

Geologic interpretations by Tweto (1974) revealed substantial vertical displacement of the fault blocks, resulting in offset of the Paleozoic rocks. Paleozoic rocks near Little Evans Gulch were upthrown approximately 150 m relative to the Leadville Mine Drainage Tunnel (fig. 19; Universal Transverse Mercator (UTM) northing 4346800–4347800 m) and downthrown about 200 m north of a major northeast-southwest-trending fault (fig.19; UTM northing 4347800–4348200 m). On the basis of Tweto (1974), the Paleozoic rocks intersected by the Canterbury Tunnel are downthrown compared to the Paleozoic rocks intersected by the Leadville Mine Drainage Tunnel (fig. 19; near UTM northing 4345000 m) such that the Paleozoic rocks are not continuous between the two tunnels.

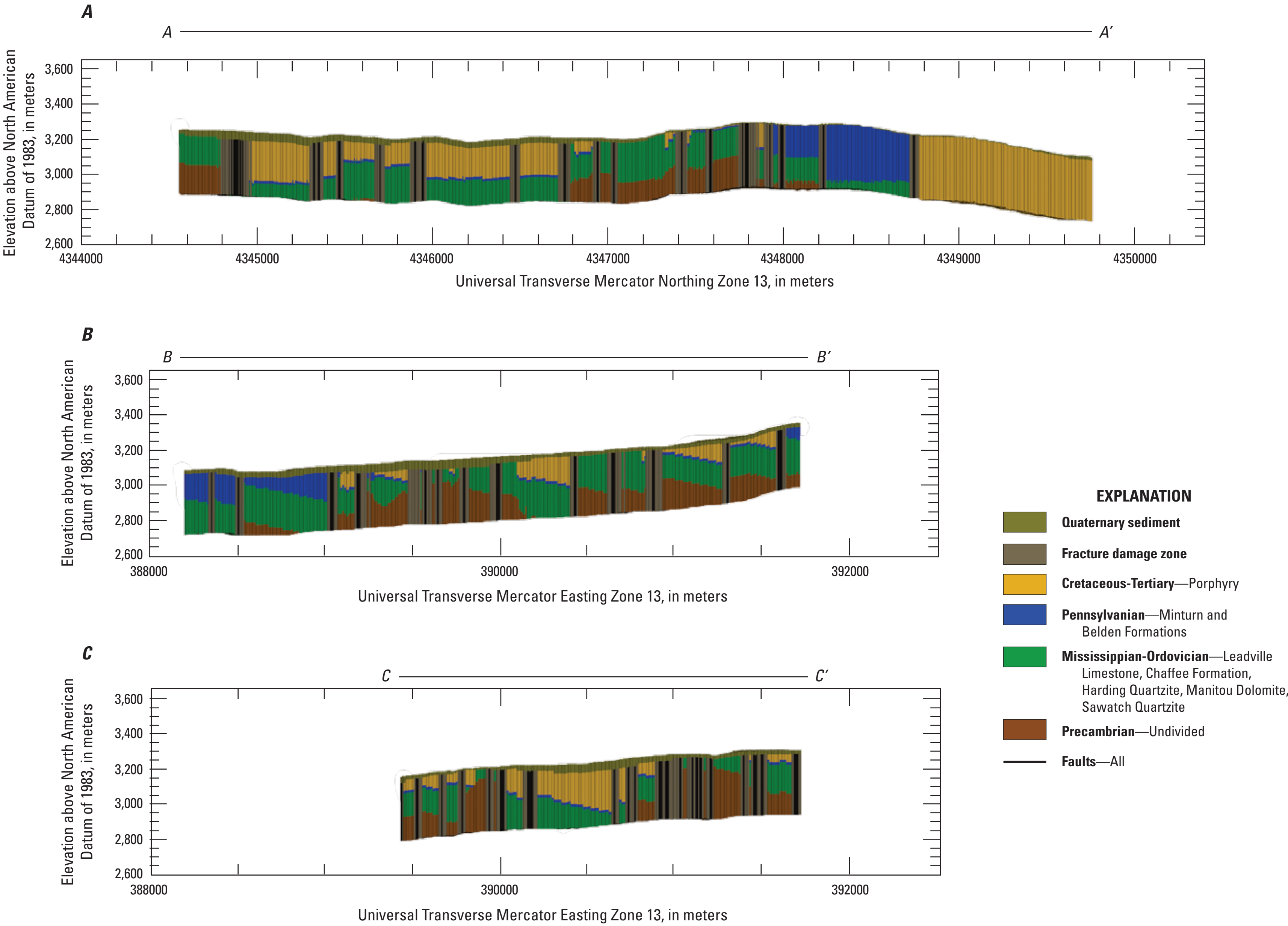


Figure 19. Geologic cross sections *A-A′*, *B-B′*, and *C-C′* generated from geologic reconstruction.

Interpretation of the DC resistivity data was consistent with geologic interpretations by Tweto (1974). The resistivity survey indicates an area of high electrical resistivity near the surface on the south end of the line; this high resistivity gradually transitioned to lower resistivity near the transect center, about 800 m (fig. 8; near UTM northing 4347000 m) along the transect. This high-resistivity near-surface layer matched the geographic location of thick Quaternary glacial-moraine deposits and likely is indicative of near-surface water, substantial clay content, and high porosity relative to the surrounding rock. Lower electrical-resistivity values (greater electrical conductivity; shown in blue on fig. 8) were found near the surface from approximately 800 m to 1,600 m along the line, and they generally corresponded with the area north of Little Evans Gulch that contains thin surficial deposits overlying Cretaceous-Tertiary porphyry and Paleozoic rocks (fig. 8, near UTM northing 4347000–4348000 m). The transition back to more electrically resistive subsurface materials at the northern end of the line corresponds with the location of a northeast-southwest-trending fault that separates porphyry and Paleozoic rocks to the south from the downthrown block of Paleozoic rocks to the north (Tweto, 1974). The geophysical survey results support the interpretations of Tweto (1974) and the conclusion that the Canterbury Tunnel is located in a structural block that is downthrown relative to Paleozoic rocks near the Leadville Mine Drainage Tunnel. The variation and magnitude of vertical displacement between the Canterbury Tunnel structural block and the succession of structural blocks to the south indicate a likely restriction in groundwater flow through laterally continuous bedrock units between the Canterbury Tunnel and the Leadville Mine Drainage Tunnel.

Water Levels and Groundwater Flow Directions

Topography, recharge, and large-scale geologic structures control the depth to groundwater and the regional groundwater flow directions in the study area. Previous studies (Bureau of Reclamation, 1979, 2008) conceptualized that prior to mining, groundwater flowed from east-northeast to west-southwest generally following topography across the Leadville area. The faulted boundaries of various structural blocks also likely controlled regional and local groundwater flow (Bureau of Reclamation, 2008). Intersecting faults created structural blocks filled with groundwater, and groundwater circulation between the structural blocks or basins was likely limited by low-permeability gouge along faults (Bureau of Reclamation, 2008). Recent data from the Leadville Mine Drainage Tunnel also indicate a regional bedrock groundwater flow direction from the area surrounding the tunnel toward the southwest, although tunnels in the area serve as groundwater drains, which alter the pre-mining groundwater flow directions (Wireman and others, 2005). Mine workings and tunnels connected many of the previously compartmentalized structural basins, also possibly changing local groundwater flow directions.

Water-level measurements indicate that groundwater levels in the bedrock responded more slowly to annual spring snowmelt than the surficial Quaternary deposits. This differential was probably caused by the low permeability of some bedrock formations that restrict water movement and also by the greater depths to the saturated zone in the bedrock units. The lag between spring snowmelt and maximum bedrock hydraulic heads ranged from 2 to 6 months depending on the depth and location of the monitoring well (Wireman and others, 2005). During the fall months, stream base flow consists of groundwater discharge. The annual spring snowmelt and associated stream runoff caused stream discharge and hydraulic head in the Quaternary sediment to maximize during the early summer and minimize in the fall (Wireman and others, 2005). On the basis of the selected data set, the average annual difference between observed hydraulic heads for low-flow and high-flow conditions was about 4 m.

After excluding water-level data at wells with screens that span a large vertical interval of the aquifer (sites MAB and OU6MP–ELK; fig. 7), the correlation between well screen altitude and water level under high-flow conditions was significant, with a coefficient of determination (R^2) value of 0.93 (fig. 20). The relation between water levels and land-surface altitude was also substantial but less significant with an R^2 value of 0.73. These correlations indicate that decreasing hydraulic head with increasing distance between land surface and well opening was not entirely a function of topographic variation and that water movement likely has a substantial vertical flow component from higher hydraulic potential at the land surface to lower hydraulic potential at depth within the aquifer during high-flow recharge conditions.

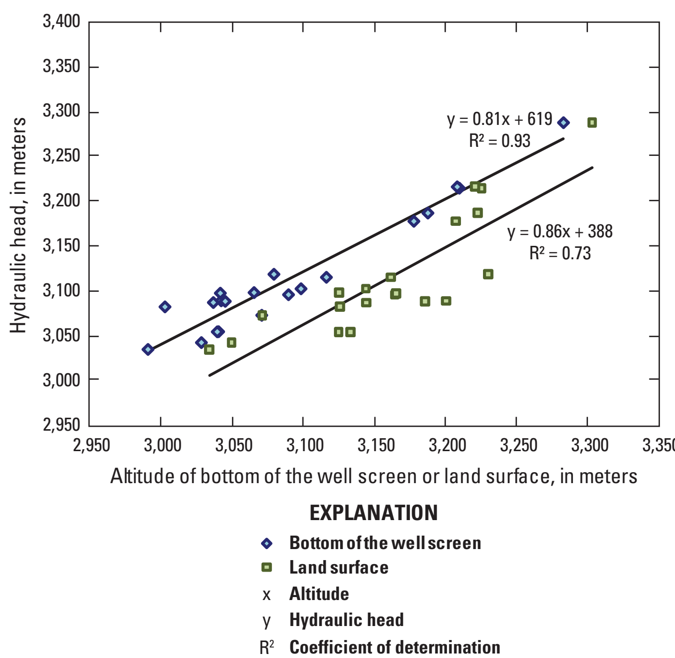


Figure 20. Relation between the altitude of the bottom of the well screen and land surface to hydraulic head observations, 1999–2007.

Groundwater flow between the Canterbury Tunnel and Leadville Mine Drainage Tunnel cannot be characterized with accuracy because of the absence of hydrologic data in the area near the eastern part of the Canterbury Tunnel and in the area between the Canterbury Tunnel and Leadville Mine Drainage Tunnel. The absence of such data in the region creates uncertainty in the findings of this report that cannot be remedied without additional data collection. The available hydrologic data were from monitoring wells near the Leadville Mine Drainage Tunnel. Monitoring of hydraulic head in the Leadville Mine Drainage Tunnel and mine pools began in 2003 as part of the USEPA OU6 hydrogeologic characterization. Monitoring results indicate that bedrock and mine pool water levels have increased substantially since 2003 (Source Water Consulting, oral commun., January 30, 2008). In response to the rising water levels in the upper Leadville Mine Drainage Tunnel, a relief well was drilled into the tunnel at well LDT46+96 approximately 9.1 m (30 ft) east and upgradient from well LDT46+66. The USEPA conducted a drawdown test of the relief well in early June 2008, and then began pumping from the relief well on June 24, 2008 (Mike Wireman, U.S. Environmental Protection Agency, written commun., 2008). Data records of water levels in wells installed in the Leadville Mine Drainage Tunnel and surrounding bedrock indicate that different depths and locations of the groundwater system responded differently to pumping from the Leadville Mine Drainage Tunnel relief well. Well LDT46+66, located downgradient from the relief well, wells LDT75+05 and LDT96+44, and well MAB near the mine pools, located upgradient from the relief well, clearly responded to the relief-well pumping (Mike Wireman, U.S. Environmental Protection Agency, written commun., 2008). However, no change in hydraulic head was noted in the bedrock wells LDT36+77, which is located about 305 m down-tunnel from the relief well and west of the Pendery fault or at wells BMW–5, BMW–3, and OU6MP–ELK, which are located away from the Leadville Mine Drainage Tunnel (Mike Wireman, U.S. Environmental Protection Agency, written commun., 2008). The results indicate that pumping from the relief well lowered hydraulic head near the Leadville Mine Drainage Tunnel and upgradient mine pools, but that the effects from pumping did not extend west of the Pendery Fault (Mike Wireman, U.S. Environmental Protection Agency, written commun., 2008) or toward the Canterbury Tunnel. This observation supports the proposal that there is not a substantial hydraulic connection between the Canterbury Tunnel and the Leadville Mine Drainage Tunnel.

Since 1991, increased groundwater levels near the Leadville Mine Drainage Tunnel coincided with increased annual precipitation. Data records of well BMW–3 since 1991 indicate that hydraulic head peaked at 3,084 m in 1996, likely in response to above-average precipitation in 1995 and 1996. Hydraulic head in well BMW–3 since the 2002 drought year displayed variations in seasonal highs and lows that were observed at other locations. In wells BMW–3 and BMW–5, seasonal highs and lows of hydraulic head have both continued to increase since 2002 in response to increased precipitation on the basis of water-level data provided by CDPHE and the USEPA (Colorado Department of Public Health and Environment, written commun., October 2008; U.S. Environmental Protection Agency, written commun., October 2008). The pattern of increasing seasonal highs and lows in hydraulic head since 2002 also was observed for several bedrock wells in the California Gulch NPL site and in the Yak Tunnel, which indicate that increased hydraulic head in the Leadville Mine Drainage Tunnel since 2002 is affected by the regional increase in precipitation.

Fault Controls on Groundwater

Brittle faults have been conceptualized in previous investigations as containing a central fault core of cataclasite, gouge, and breccia that is surrounded by a damage zone of smaller faults and fractures (for example, Caine and others, 1996). The accumulation of low-permeability material within the fault core has been found to restrict the movement of water across these faults, whereas fracturing within the damage zone is thought to promote groundwater movement along (parallel to) the faults.

Prior to mining activities within the Leadville mining district, intersecting faults created structural blocks that filled with groundwater, and water movement between the structural blocks or basins was likely limited by low-permeability gouge alongside the faults (Bureau of Reclamation, 2008). The Pendery and Mikado faults, which dip steeply, are intersected at depth by the western part of the Canterbury Tunnel. Observed hydraulic head was greatest at a monitoring site (well OU6MP–ELK; fig. 7) east and upgradient from the Mikado fault, which indicates that the Mikado fault probably is a barrier to west-southwest groundwater flow (Wireman and others, 2005). The Leadville Mine Drainage Tunnel intersects the Pendery fault between monitoring wells LDT36+77 and LDT46+66, and the Mikado fault at depth near its easternmost end (Wireman and others, 2005). Recorded hydraulic heads were greater on the east side than on the west side of the Pendery fault at the intersection with the Leadville Mine Drainage Tunnel, and groundwater is thought to move from the Leadville Mine Drainage Tunnel toward California Gulch (Wireman and others, 2005). However, groundwater movement across and along the Pendery fault near the Leadville Mine Drainage Tunnel possibly has been affected by tunnel collapse. If the Mikado and Pendery faults function similarly to faults in the proposed conceptual model, then groundwater typically will mound on the upgradient side of the fault, and water will move preferentially downgradient along the fault damage zones. The Iron fault, although structurally important in a regional context, was not considered as a possible substantial groundwater flow path between the two tunnels because it is not intersected by either tunnel.

Tunnel Discharge

Regional groundwater discharge in the study area is primarily to the Canterbury Tunnel and Leadville Mine Drainage Tunnel. The Arkansas River valley also likely receives regional subsurface groundwater discharge. Discharge was measured at or near the portals of the Yak Tunnel, the Leadville Mine Drainage Tunnel, and the Canterbury Tunnel as part of previous investigations conducted by the USEPA and BOR. Discharge measured at the Leadville Mine Drainage Tunnel water-treatment plant was a combination of water from the tunnel portal and local relief wells. Before 2005, discharge from the Leadville Mine Drainage Tunnel was typically more than 3.8 m^3/min (1,000 gal/min) and as much as 5.7 m^3/min (1,500 gal/min) (Wireman and others, 2005). The Bureau of Reclamation reported a discharge of about 4.2 m^3/min (1,120 gal/min) from the Leadville Mine Drainage Tunnel in March 2008. For the high-flow conditions simulated by the groundwater-flow model, 5.7 m^3/min (1,500 gal/min) was used as the measured discharge through the Leadville Mine Drainage Tunnel, and all of the Leadville Mine Drainage Tunnel discharge was assumed ultimately to enter the East Fork Arkansas River. From 1962 to 2005, water flowing within the Canterbury Tunnel has discharged from its portal at a generally constant rate of at least 2.4 m^3/min (625 gal/min); almost all of this flow was used in the municipal water system. Observations from 2007 and 2008 suggest that water flow from the Canterbury Tunnel is blocked (HDR Engineering, 2007; this study).

Groundwater Quality

Groundwater and surface-water samples were collected from seven sites near the Canterbury Tunnel (fig. 7) on September 15 and 16, 2008, to evaluate whether mining activities had affected water quality and to characterize the sources of groundwater. The limited availability of sites for groundwater sampling limited the number of samples collected; however, the results contributed to the understanding of groundwater flow near the Canterbury tunnel and were used to support the groundwater flow model. Sample locations and sampling and analytical methods are described in the *Methods* section of this report, and results for major-ion chemistry, acid mine drainage indicators, stable isotopes of hydrogen and oxygen, and apparent groundwater age are discussed in this section. Complete water-quality results for the samples collected by this study can be obtained from the USGS National Water Information System database (*http://nwis.waterdata.usgs.gov/co/nwis/qwdata*) using the site identification numbers listed in table 1.

Major-Ion Chemistry and Acid-Mine-Drainage Indicators

Total dissolved solids, major-ion concentrations, metals, and pH for groundwater samples near the Canterbury Tunnel indicate that the groundwater total dissolved solids and major ion concentrations are substantially less than drinking water standards and that groundwater was not affected by acid mine drainage in 2008. Total-dissolved-solids concentrations for the seven samples near the Canterbury Tunnel ranged from 103 to 140 mg/L (table 3), less than the USEPA Secondary Drinking Water standard of 500 mg/L (*http://ecfr.gpoaccess.gov/cgi/t/text/text-idx?c=ecfr&sid=c94e15e6da619c2bc625490da388470d&rgn=div8&view=text&node=40:22.0.1.1.5.0.39.3&idno=40*, accessed May 9, 2011). Concentrations of major ions (calcium, magnesium, potassium, sodium, bicarbonate, sulfate, and chloride) also were dilute, and concentrations of individual constituents were similar among the samples (table 3). Calcium and bicarbonate were the primary dissolved cation and anion, respectively, such that all of the samples can be classified as a calcium-bicarbonate type (fig. 21).

The pH and concentrations of selected indicator constituents in water are commonly used to identify the effects of acid mine drainage in surface water or groundwater. Groundwater affected by acid mine drainage in the Leadville area generally has pH less than 6 (Paschke and others, 2001; Wireman and others, 2005); contains manganese concentrations greater than 10,000 micrograms per liter (µg/L), lead concentrations greater than 10 µg/L, zinc concentrations greater than 10,000 µg/L, and sulfate concentrations greater than 1,000 mg/L (Wireman and others, 2005). Because it generally contains elevated concentrations of sulfate, water affected by acid mine drainage commonly is classified as a calcium-sulfate type (Paschke and others, 2001). Regional groundwater quality not affected by acid-mine drainage near the Leadville Mine Drainage Tunnel generally is of calcium-bicarbonate type, with concentrations of acid-mine-drainage indicator constituents that are substantially less than the indicator values, and with pH values greater than 6 (Wireman and others, 2005).

The pH of the seven groundwater samples collected near the Canterbury Tunnel in September 2008 was nearly neutral to slightly basic (7.2 to 8.2) (table 3). Concentrations of manganese, lead, and zinc were less than the acid mine drainage indicator values in the area near the Leadville Mine Drainage Tunnel (Wireman and others, 2005). Sulfate concentrations (9.2 to 35.5 mg/L) were substantially less than the USEPA Secondary Drinking Water standard of 250 mg/L (*http://ecfr.gpoaccess.gov/cgi/t/text/text-idx?c=ecfr&sid=c94e15e6da619c2bc625490da388470d&rgn=div8&view=text&node=40:22.0.1.1.5.0.39.3&idno=40*, accessed May 9, 2011) and the acid mine drainage indicator value of 1,000 mg/L. The relatively dilute total-dissolved-solids and major-ion concentrations, the calcium-bicarbonate type, and the lack of acid-rock-drainage indicator constituents lead to the conclusion that groundwater near the Canterbury Tunnel is not affected by acid mine drainage.

Table 3. Selected water-quality results for groundwater samples near the Canterbury Tunnel, Leadville, Colorado, September 2008.

[Temp, temperature; °C, degrees Celsius, DO, dissolved oxygen; mg/L, milligrams per liter; TDS, total dissolved solids; Ca, calcium; Mg, magnesium; HCO_3, bicarbonate; SO_4, sulfate; Mn, manganese; µg/L, micrograms per liter; Cu, copper; Pb, lead; Zn, zinc; <, less than; E, estimated concentration below long-term method detection limit; nd, no data; DOC, dissolved organic carbon; --, not calculated for data sets with censored values; δ^2H, delta deuterium, ratio of $^2H/^1H$; $\delta^{18}O$, delta oxygen-18, ratio of $^{18}O/^{16}O$; per mil, parts per thousand; CH_4, methane gas; CO_2, carbon dioxide gas; N_2, nitrogen gas, O_2, oxygen gas; Ar, argon gas; cc STP/L, cubic centimeters at standard pressure and temperature per liter; pmc, percent modern carbon; pCi/L, picocuries per liter; pmol/kg, picomoles per kilogram; pptv, parts per trillion by volume]

Site name	USGS site number	Field pH	Field, Sc, in µS/cm	Field temp, in °C	DO, in mg/L	TDS, in mg/L	Ca, in mg/L	Mg, in mg/L	HCO_3, in mg/L	SO_4, in mg/L	Fe, in µg/L	Mn, in µg/L	Cu, in µg/L	Pb, in µg/L	Zn, in µg/L	SiO_2, in mg/L	DOC, in mg/L
Tunnel portal	391651106164301	8.1	217	9.4	8.2	130	24.4	10.5	93	32.7	<8	0.14E	<1.0	<.08	4.1	8.96	<0.4
Portal spring	391650106164301	8.2	224	10.6	6.7	140	26.2	11.3	90	35.5	<8	0.3	<1.0	<.08	14.9	9.38	<0.4
Highway seep	391653106164901	7.7	217	12.0	6.2	131	27.4	9.3	93	32.1	23	1.6	<1.0	0.05E	10.5	8.65	0.4E
Domestic well #1	391656106164701	7.2	170	7.5	6.5	103	21.7	6.2	76	22.1	37	3.7	2.3	0.14	18.3	8.26	0.4
Parkville well #2	391640106170801	8.0	227	9.2	6.8	137	26.3	12.0	121	21.0	<8	0.6	3.6	0.24	3.4	6.16	0.3E
Elkhorn shaft	391537106154301	7.6	219	5.3	5.8	126	26.2	11.6	130	9.2	5.5E	1.2	1.1	0.38	1.9	8.17	0.3E
Domestic well #2	391550106160001	8.1	205	5.7	2.8	118	24.2	10.9	117	10.4	<8	<0.2	14.9	0.75	nd	8.44	<0.4
	Minimum	7.2	170	5.3	2.8	103	21.7	6.2	76	9.2	5.5	0.14	<1	0.05	1.9	6.16	0.3
	Maximum	8.2	227	12.0	8.2	140	27.4	12.0	130	35.5	37	3.7	14.9	0.75	18.3	9.38	0.4
	Mean	7.8	211	8.5	6.1	126	25.2	10.3	103	23.3	--	--	--	--	--	8.3	--
	Median	8.0	217	9.2	6.5	130	26.2	10.9	93	22.1	--	--	--	--	--	8.44	--

Site name	USGS site number	δ^2H, per mil	$\delta^{18}O$, per mil	Dissolved gas results						
				CH_4, in mg/L	CO_2, in mg/L	N_2, in mg/L	O_2, in mg/L	Ar, in mg/L	Excess air, cc STP/L	Calculated recharge temp, in °C
Tunnel portal	391651106164301	−139.8	−18.84	nd	nd	nd	nd	nd	nd	nd
Portal spring	391650106164301	−140.1	−18.89	0.000	2.626	16.088	2.588	0.583	1.7	3.5
Highway seep	391653106164901	−140.3	−18.87	0.000	7.003	13.956	1.097	0.522	0.5	6.7
Domestic well #1	391656106164701	−138.4	−18.52	0.000	14.122	15.675	1.866	0.574	1.3	3.9
Parkville well #2	391640106170801	−134.3	−18.05	0.008	3.651	13.739	3.292	0.518	0.3	6.7
Elkhorn shaft	391537106154301	−138.8	−18.39	0.000	9.566	17.501	2.822	0.608	3.1	2.6
Domestic well #2	391550106160001	−141.0	−18.66	nd	nd	nd	nd	na	nd	nd
	Minimum	−141.0	−18.89							
	Maximum	−134.3	−18.05							
	Mean	−139.0	−18.60							
	Median	−139.8	−18.66							

Table 3. Selected water-quality results for groundwater samples near the Canterbury Tunnel, Leadville, Colorado, September 2008.—Continued

[Temp, temperature; °C, degrees Celsius, DO, dissolved oxygen; mg/L, milligrams per liter; TDS, total dissolved solids; Ca, calcium; Mg, magnesium; HCO_3, bicarbonate; SO_4, sulfate; Mn, manganese; µg/L, micrograms per liter; Cu, copper; Pb, lead; Zn, zinc; <, less than; E, estimated concentration below long-term method detection limit; nd, no data; DOC, dissolved organic carbon; --, not calculated for data sets with censored values; δ^2H, delta deuterium, ratio of $^2H/^1H$; $\delta^{18}O$, delta oxygen-18, ratio of $^{18}O/^{16}O$; per mil, parts per thousand; CH_4, methane gas; CO_2, carbon dioxide gas; N_2, nitrogen gas, O_2, oxygen gas; Ar, argon gas; cc STP/L, cubic centimeters at standard pressure and temperature per liter; pmc, percent modern carbon; pCi/L, picocuries per liter; pmol/kg, picomoles per kilogram; pptv, parts per trillion by volume]

Site name	Carbon-14, pmc	Tritium, pCi/L	CFC–11 concentration in solution, pmol/kg	CFC–12 concentration in solution, pmol/kg	CFC–113, concentration in solution, pmol/kg	CFC–11 calculated atmospheric mixing ratio, pptv	CFC–12 calculated atmospheric mixing ratio, pptv	CFC–113 calculated atmospheric mixing ratio, pptv
Tunnel portal	36.7	16.9	nd	nd	nd	nd	nd	nd
Portal spring	36.78	18.8	0.82	0.44	0.06	38.7	83.0	7.7
Highway seep	39.52	18.6	1.65	1.06	0.16	94.9	239	28.5
Domestic well #1	49.82	19.4	2.19	1.48	0.23	106	285	33.9
Parkville well #2	65.71	22.6	3.51	8.12	0.21	201	1,826	38.4
Elkhorn shaft	76.25	31.6	5.69	2.81	0.48	259	507	67.0
Domestic well #2	62.05	31.6	2.96	1.65	0.24	163	355	40.9

Site name	Chlorofluorocarbon Apparent-Age Results						
	Piston-flow model apparent age, in years	Piston-flow model apparent recharge date	Basis for piston-flow model apparent age	Binary-mixing model percent young water in mixture	Binary-mixing model apparent age of young (post-1953) fraction, in years	Binary-mixing model apparent recharge year of young (post-1953) fraction	Basis for apparent age for young fraction
Tunnel portal	nd				nd		
Portal spring	42	1967	CFC–12	23	26	1983–1987	Ratio CFC–113/CFC–12
Highway seep	33	1976	CFC–12	60	23	1986	Ratio CF–C113/CFC–12
Domestic well #1	31	1978	CFC–12	70	23	1986	Ratio CFC–113/CFC–12
Parkville well #2	25	1984	CFC–113	100	25	1984	CFC–113
Elkhorn shaft	18	1991	CFC–12	100	18	1991	CFC–12
Domestic well #2	26	1983	CFC–12	90	23	1986	Ratio CFC–113/CFC–12

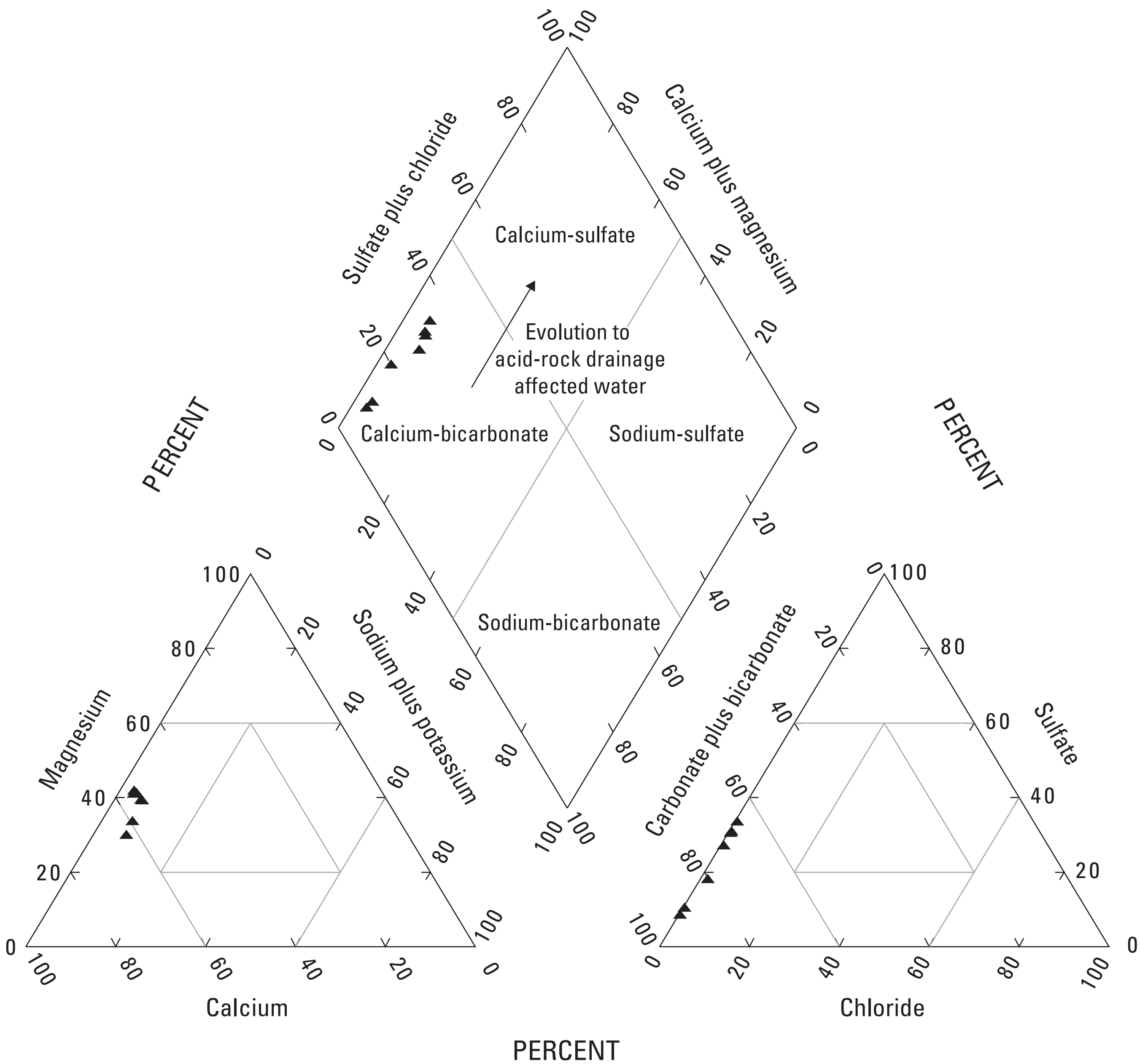


Figure 21. Tri-linear graph of major-ion chemistry for groundwater samples collected near the Canterbury Tunnel, Leadville, Colorado, September 2008.

Groundwater samples represent ambient regional groundwater quality in the bedrock formations and alluvial aquifer near the Canterbury Tunnel. Water-quality results from this study indicate that groundwater drained from the Canterbury Tunnel and pumped from the alluvial aquifer near the Canterbury Tunnel is suitable for its use as a drinking-water supply.

Hydrogen and Oxygen Stable Isotopes

The stable isotopes for hydrogen (^1H and ^2H) and oxygen (^{18}O and ^{16}O) in water were examined as indicators of groundwater sources (Coplen, 1993). Stable isotopic compositions are expressed in parts per thousand (per mil units), as the difference in the isotopic ratio of the sample relative to a standard, by using delta (δ) notation in the form:

$$\delta = \left(\frac{R_{sample}}{R_{reference}} - 1 \right) \cdot 1000, \qquad (2)$$

where R is the measured isotopic ratio, $^2H/^1H$ or $^{18}O/^{16}O$ (Clark and Fritz, 1997). This report uses the δ symbol followed by the chemical symbol for the heavier isotope of the isotopic pair to represent isotopic composition. For example, the symbol δ^2H is used for the hydrogen isotope ratio because ^2H is the heavier of the two hydrogen isotopes. The symbol $\delta^{18}O$ is used for the oxygen isotope ratio. Per mil values in this report were presented relative to the standardized reference, which is Vienna Standard Mean Ocean Water (VSMOW; Coplen, 1994).

The $\delta^{18}O$ values for the seven groundwater samples near the Canterbury Tunnel ranged from −18.89 to −18.05, indicating that the samples were generally depleted in ^{18}O. The $\delta^{18}O$ values for groundwater samples measured by this study were similar to those measured for groundwater (−18.65 to −16.81 per mil, mean −18.15 per mil) by Wireman and others (2005). The $\delta^{18}O$ values observed by this study also were within in the range of $\delta^{18}O$ values measured for snow (−21.94 to −13.97 per mil, mean −18.87 per mil) and were less than the range of $\delta^{18}O$ values measured for rain (−16.81 to −4.28 per mil, mean −9.7 per mil) in the Leadville area (Wireman and others, 2005). The δ^2H values of the seven groundwater samples near the Canterbury Tunnel (−141.1 to −134.3 per mil) were near the range of δ^2H values for groundwater (−143.2 to −136.90 per mil, mean −137.06 per mil) and snow (−165.12 to −148.15 per mil, mean −148.15 per mil) but substantially less than the range of δ^2H values for rain (−94.77 to −23.63 per mil, mean −60.82 per mil) observed in the Leadville area (Wireman and others, 2005). Previous studies have indicated that snowmelt is the primary source of recharge to bedrock groundwater in the Leadville area on the basis of hydrogen and oxygen isotope ratios (Wireman and others, 2005; Liu and others, 2006). The δ^2H and $\delta^{18}O$ values measured in groundwater samples for this study were similar to those measured by previous studies or bedrock groundwater and snow in the area, which indicates that snowmelt also is the primary source of recharge to bedrock and alluvial groundwater near the Canterbury Tunnel.

Apparent Groundwater Age

Groundwater age (time since recharge) can be estimated on the basis of measured concentrations of atmospheric tracers such as chlorofluorocarbons (CFCs) and tritium (^3H) in groundwater samples. Groundwater age is also termed “apparent groundwater age” because an age is calculated on the basis of models that use simplifying assumptions regarding transport process that can affect tracer concentrations in an aquifer (Plummer and Busenberg, 1999). The piston-flow model is a simple and commonly used method for calculating groundwater age that assumes that the tracer moved through the aquifer in a piston-flow manner and is not altered by mixing or dispersion from the point of recharge to the point of measurement (Rupert and Plummer, 2004). All groundwater pumped from a well is, to some extent, mixed within the well bore (Plummer and Busenberg, 1999). Wells with long screened intervals can draw water of different ages from multiple parts of an aquifer, where it mixes in the well bore. The mixing of water in the well bore produces mixed groundwater ages, which can complicate the calculation of apparent groundwater ages (Rupert and Plummer, 2004). The simplest case of mixing occurs if the water is a binary mixture of young (post-1953) and old (pre-1953) water, and the binary mixing model is used to estimate the young fraction of a mixed water because it is difficult to quantify the mixing of more than two waters (Rupert and Plummer, 2004).

Young water is generally defined as post-1953 in age and is indicated by detections and concentrations of CFCs and tritium (Clark and Fritz, 1997). Chlorofluorocarbons are stable, synthetic organic compounds that were developed in the early 1930s for refrigeration and have been used in a wide range of industrial and refrigerant applications (Plummer and Friedman, 1999). Production of CFC–12 (dichlorodifluoromethane, CF_2Cl_2) began in 1931, followed by CFC–11 (trichlorofluoromethane, $CFCl_3$) in 1936, and then by many other CFC compounds, most notably CFC–113 (trichlorotrifluoroethane, $C_2F_3Cl_3$) (Rupert and Plummer, 2004). The use of CFC refrigerants, their release to the atmosphere, and the subsequent recharge of CFCs to groundwater make these compounds excellent tracers for estimating the apparent age of groundwater recharged since the 1950s. Groundwater-age dating with CFCs is based on Henry’s Law of gas solubility, which is affected by recharge temperature and excess air in the water samples (Plummer and Busenberg, 1999). Recharge temperature is considered to be the water temperature at the water table at the time of recharge (Rupert and Plummer, 2004). Dissolved gases in groundwater were measured and used to estimate recharge temperature and excess air of the water samples for this study (table 3) following the methods of Plummer and Busenberg (1999). Recharge altitude was assumed equal to land-surface altitude at the sampling location.

For six of the seven groundwater samples collected near the Canterbury Tunnel, chlorofluorocarbons CFC–11, CFC–12, CFC–113, and tritium concentrations were interpreted to estimate apparent piston-flow groundwater ages, binary mixing of young (post-1953) and old (pre-1953) groundwater, and the apparent age of the young fraction of the binary mixes (table 3). A CFC sample was not collected from the tunnel portal because portal discharge was in contact with the atmosphere and therefore would not provide CFC concentrations representative of groundwater. The portal spring sample was collected from below land surface through a drive point and tubing so that the sample was not exposed to the atmosphere during sample collection and is considered representative of discharge from the Canterbury Tunnel. At Parkville well #2, the CFC–12 concentration was greater than that expected for the sample and was considered "contaminated" (Eurybiades Busenberg and Neil Plummer, U.S. Geological Survey, written commun., 2009) likely owing to contact between the sample and the atmosphere during sampling. The apparent ages and binary mixing calculated for Parkville well #2 are therefore based on the concentrations of CFC–113. The extent of mixing of young and old groundwater was evaluated by using the ratios of chlorofluorocarbons CFC–11, CFC–12, CFC–113, and tritium.

The atmospheric concentrations of CFCs from 1940 through 2010 for Niwot Ridge, Colorado (U.S. Department of Commerce, 2002; Eurybiades Busenberg and Neil Plummer, U.S. Geological Survey, written commun., 2009), along with the concentrations of CFCs for groundwater samples collected from sites near the Canterbury Tunnel are shown in figure 22. On the basis of CFC concentrations and a piston-flow model of groundwater recharge (table 3), young groundwater unmixed with old groundwater was sampled from the Elkhorn shaft (apparent age of 18 years, 1991 recharge) and Parkville well #2 (apparent age of 25 years, 1984 recharge) (fig. 22). These results indicate groundwater samples from the Elkhorn shaft and Parkville well #2, both of which are pumped for public-water supply, are well-mixed young water. Piston-flow model apparent ages for the other four sites sampled by this study ranged from 26 to 42 years (1967 to 1983 recharge) with the oldest piston-flow apparent groundwater age calculated for the portal spring (table 3, fig. 22). However, binary-mixing model results indicate that the four samples are mixtures of young and old water (table 3), and that the piston-flow model is an oversimplification of apparent ages for these samples.

The piston-flow and binary-mixing models for CFC–12 and CFC–113 concentrations for the four samples indicated as mixtures of young and old water are shown in figure 23. The solid black line represents unmixed piston flow, and the dashed lines represent binary mixing of young and old water where the apparent age of the young fraction is indicated by the intersection of the binary-mixing line with the piston-flow curve. The relative distance along the binary-mixing line from the origin indicates the percentage of young water in each sample, so that samples with zero percent young water plot at the origin and samples with 100 percent young water plot along at the intersection of the binary-mixing line with piston-flow line. Samples for Domestic wells #1 and #2, the highway seep, and the portal spring plot approximately along the same binary-mixing line, which shows that the young fraction of water is about 23 years old with a recharge date of 1986. For

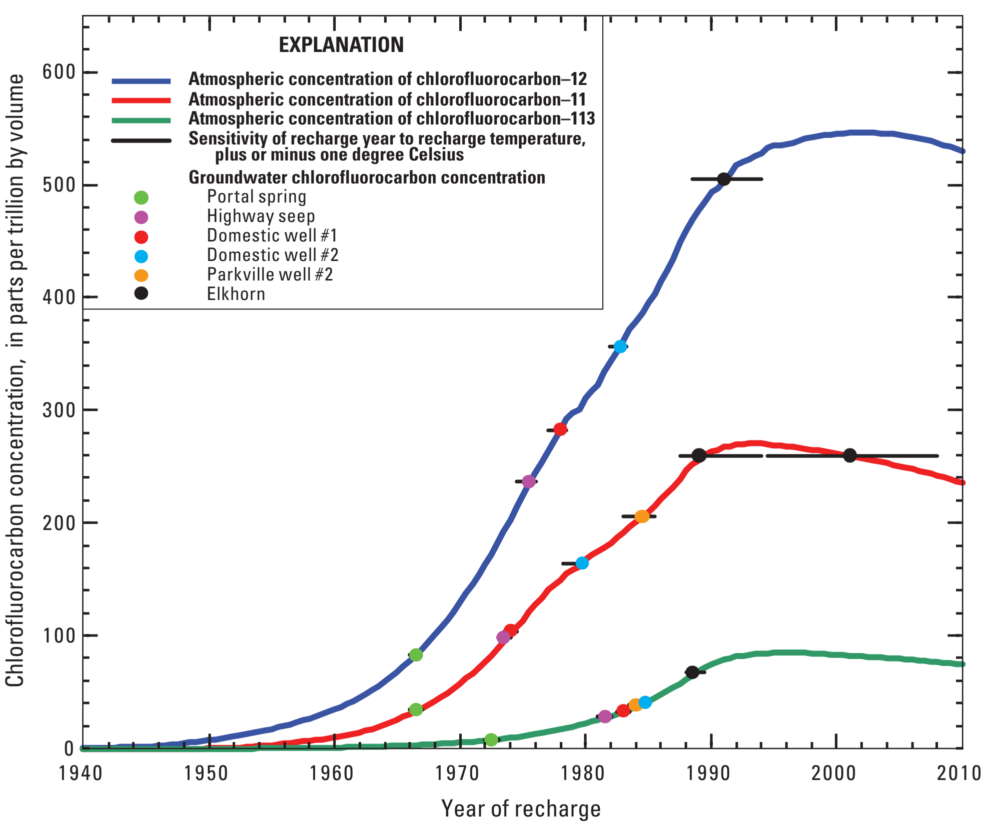


Figure 22. Atmospheric concentrations of CFC–11, CFC–12, and CFC–113 in North America, and concentrations of CFC–11, CFC–12, and CFC–113 in groundwater samples collected from sites near the Canterbury Tunnel, Leadville, Colorado, September 2008.

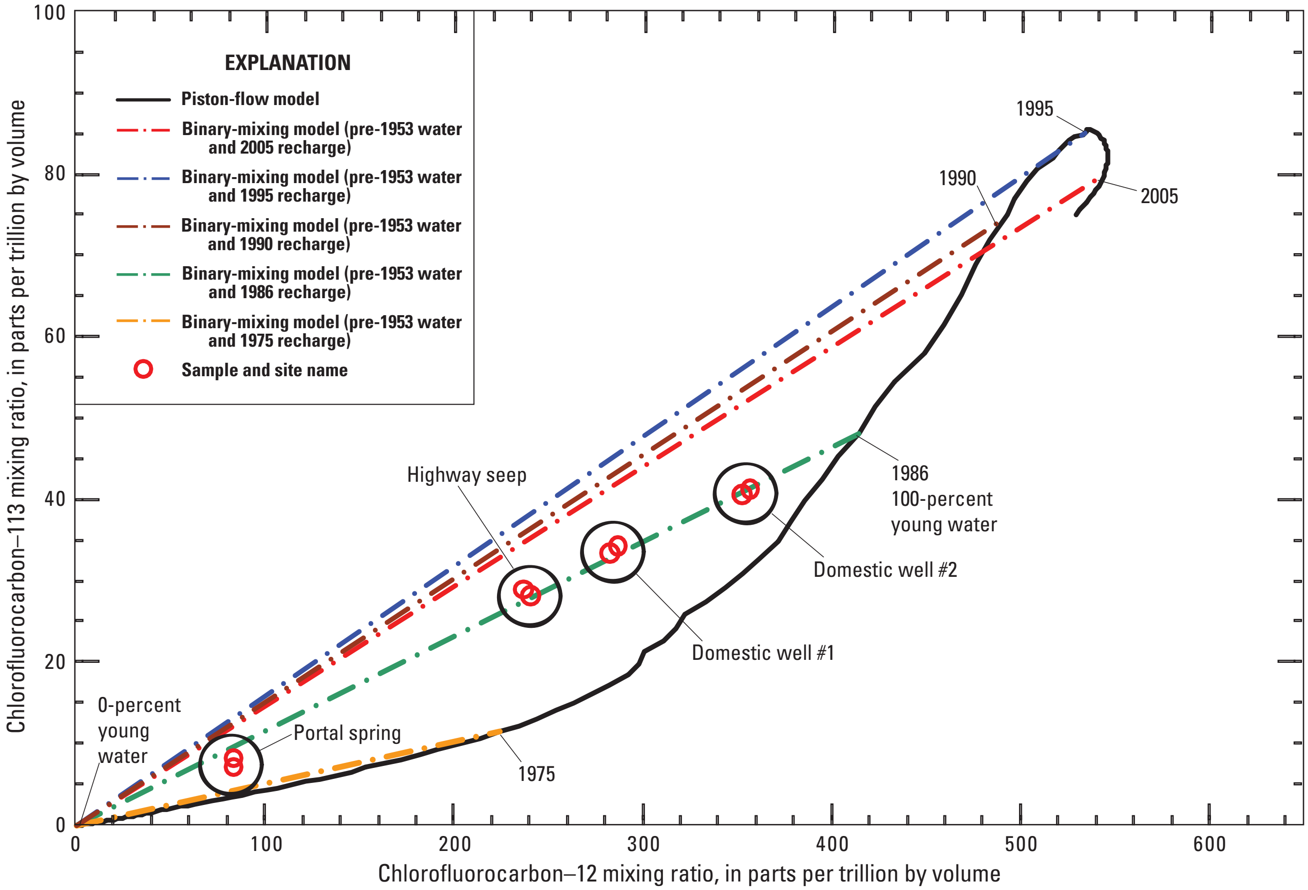


Figure 23. Measured concentrations of CFC–12 and CFC–113 and models of piston flow and binary mixing of modern (post-1953) and old (pre-1953) water for groundwater samples collected from sites near the Canterbury Tunnel, Leadville, Colorado, September 2008.

the portal spring, apparent ages for the young fraction of water range from 23 to 26 years with recharge dates ranging from 1983 to 1987 (table 3). Domestic well #2 is located upgradient from the Canterbury Tunnel and is completed in the same bedrock structural block as the Elkhorn shaft; it contains as much as 90 percent young water on the basis of the binary-mixing model (table 3). Domestic well #1 is completed in the Arkansas River alluvial aquifer downgradient from the Canterbury Tunnel Portal, and it is located near the highway seep (fig. 7). As indicated by CFC concentrations and the binary-mixing model, the sample from Domestic well #1 is 70 percent young (1986 recharge date) water and 30 percent old water (table 3). The highway seep sample contains about 10 percent more old water than Domestic well #1 (60 percent young (1986) water, table 3), indicating that the seep may represent more old water discharging from upgradient regional groundwater flow than the sample from the alluvial aquifer. Of the six groundwater-age samples collected near the Canterbury Tunnel, results for the portal spring sample returned the greatest percentage of old water. The mixing ratio of CFC–12 and CFC–113 indicates that 23 percent (about one quarter) of the recharge was from young (1986) water, whereas about 77 percent (about three quarters) of the water was from pre-1953 recharge for the portal spring. This finding supports the conceptual understanding that the Canterbury Tunnel collects old water from the Paleozoic and Precambrian bedrock aquifers beneath Canterbury Hill as well as younger snowmelt recharge from land surface.

Atmospheric thermonuclear testing from 1952 through the 1960s resulted in the release of tritium to the atmosphere and to precipitation recharge such that the presence and concentrations of tritium in groundwater can also be used to estimate the apparent age and mixtures of groundwater recharged since 1953 (Clark and Fritz, 1997). Atmospheric tritium concentrations peaked in 1963 (Clark and Fritz, 1997) and have been decreasing since that time because of the exchange of water with the oceans, short half-life of tritium, and because most atmospheric thermonuclear weapons testing has been discontinued (Rupert and Plummer, 2004). Tritium concentrations in precipitation prior to thermonuclear weapons testing are not well known but probably did not exceed 2 to 8 tritium units (TU) (Plummer and others, 1993). Because tritium has a half-life of 12.32 years, water derived from precipitation before thermonuclear weapons testing would contain a maximum tritium concentration of 0.12 to 0.5 TU by the early 2000's (Rupert and Plummer, 2004). Waters with tritium activities greater then about 30 TU contain a considerable component of recharge from the 1960's, and waters with no tritium activity (less than a detection limit of about 1 TU) are considered old (pre-1953) waters (Clark and Fritz, 1997).

For the groundwater samples near the Canterbury Tunnel, tritium concentrations ranged from 5.8 to 9.8 TU (16.9 to 31.9 picoCuries per liter [pCi/L], table 3) indicating that the waters were recharged after 1953 or contain a fraction of water recharged after 1953. The piston-flow and binary-mixing models for tritium and CFC–12 concentrations for the five samples with uncontaminated CFC–12 concentrations are shown in figure 24 and are consistent with the CFC results. The Elkhorn shaft plots along the piston-flow model line (fig. 24) indicating a well-mixed sample of young water with a recharge date of 1991. The four mixed samples plot approximately along the binary-mixing line with an apparent recharge date of 1986 for the young fraction of water. The sample from the portal spring contains the least percentage of young water (about 23 percent, table 3) and the greatest percentage of old water (about 77 percent).

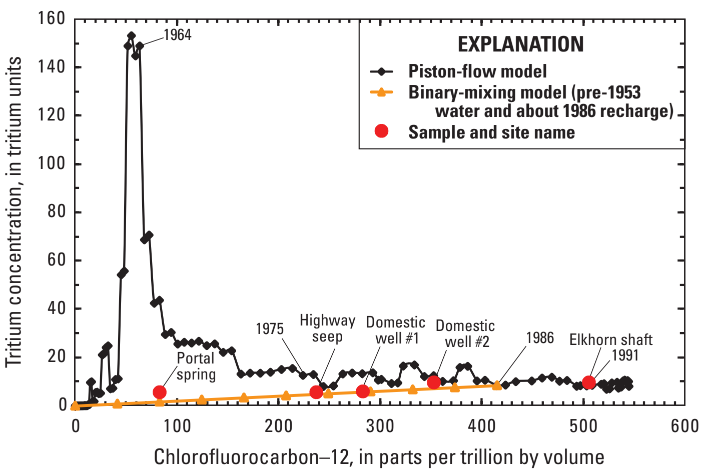


Figure 24. Measured tritium and CFC–12 concentrations and models of piston flow and binary mixing of modern (post-1953) and old (pre-1953) water for groundwater samples collected from sites near the Canterbury Tunnel, Leadville, Colorado, September 2008 (modified from J.K. Böhlke, U.S. Geological Survey, written commun., 2006).

The groundwater-age results indicate that bedrock groundwater in the upgradient wells (Elkhorn shaft and Domestic well #2), which are completed in a fault block separate from the Canterbury Tunnel, contains a greater percentage of young water than the Canterbury Tunnel. Samples from wells completed in the Arkansas River alluvial aquifer (Domestic well #1 and Parkville well #2) and the highway seep also contained substantial percentages of young water and likely represent snowmelt recharge mixed with older regional groundwater that discharges from the bedrock units to the Arkansas River valley. Groundwater discharge from the Canterbury Tunnel portal spring is considered representative of groundwater draining from the tunnel and contained a greater fraction of old water than the other samples. These results indicate that the Canterbury Tunnel likely drains older groundwater from bedrock formations beneath Canterbury Hill as well as young snowmelt recharge.

Simulation of Groundwater Flow

Groundwater flow in the study area was simulated by using the U.S. Geological Survey finite-difference modeling program MODFLOW–2000 (Harbaugh and others, 2000). The primary goals of the three-dimensional modeling were to assess large-scale groundwater flow patterns within the study area and to evaluate whether head and flow fluctuations in the Canterbury Tunnel could cause substantial hydraulic changes within the Leadville Mine Drainage Tunnel. If such an effect was verified, it would indicate a strong hydraulic connection between the tunnels. Particle tracking was used in conjunction with the groundwater-flow model to simulate the flow trajectories of groundwater that enters the drainage tunnels.

Model Grid

A five-sided polygon was used to delineate the active model area that surrounded the Canterbury and Leadville Mine Drainage Tunnels in plan view (fig. 25). The active model grid was defined in three dimensions by extending the five-sided polygon vertically with depth. The grid location was given in the UTM coordinate system (North American Datum of 1983; units, meters; Zone 13N) and rotated 30° west of north such that grid columns were collinear to the Leadville Mine Drainage Tunnel, and grid rows were approximately parallel to the primary groundwater flow direction (northeast to southwest). The model grid geometry was constructed with 396 columns and 560 rows; each grid cell measured 10 by 10 m. The model grid was divided into 29 layers to account for variable thicknesses of the Quaternary deposits, a dip in the bedrock strata of about 12° to the east, an approximate 15-m thickness of the Belden Shale unit in most locations, and fault geometry. Model layer thicknesses were incrementally increased with depth from the land surface at 1 m, 2 m, 2 m, 5 m, and 5 m for layers 1–5, respectively, totaling 15 m for layers 1–5; each of the remaining lower model layers (6–29) were assigned a constant thickness of 15 m. The total vertical extent of the model ranged from the land surface to a depth of 375 m, and the lateral extent of the active model area contained approximately 13 km^2.

Geology of the study area was digitally reconstructed in a ARC Geographic Information System (GIS) geodatabase (described in the *Methods* section of this report) which was used to develop the three-dimensional groundwater-flow model grid. A polygon lattice created in ArcGIS was used to record spatial information of the land-surface altitude, Quaternary sediment thicknesses, bedrock unit thicknesses, and delineations of the geologic units, fault network, and fracture-damage zones. The lattice geometry was created such that it replicated

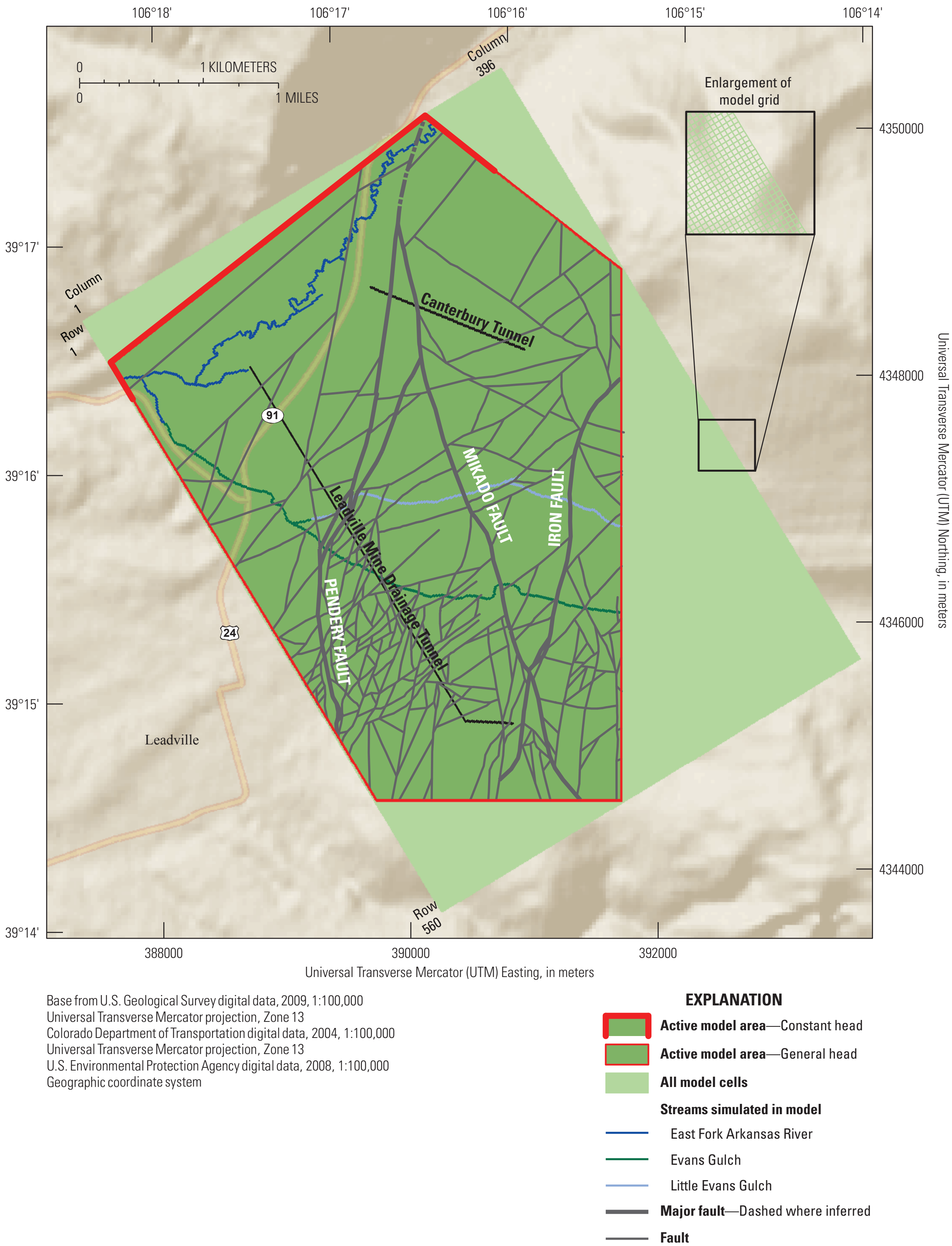


Figure 25. Model grid showing all model cells and boundary containing active model cells.

the groundwater model grid structure, orientation, and location in two-dimensional space. Each data type was given an attribute in a polygon feature class. The lattice cell addresses were sent information from each GIS data layer by using an identity-and-join function on each lattice cell identifier. Land-surface altitude acquired through a USGS 10-m digital elevation model (Gesch and others, 2002; Gesch, 2007) was assigned to the top surface of the model grid. The number of model layers that were designated as Quaternary sediment at each location was determined from the interpolated deposit thicknesses (fig. 16). Bedrock units were defined for model layers below those representing Quaternary sediment, according to the recorded bedrock unit thicknesses and observed stratigraphic sequences for a given location. For the purposes of this investigation, the Belden Formation was assumed to be 15 m thick and to underlie the Minturn Formation at locations where the section thickness exceeded 15 m. If the approximated section thickness was limited to 15 m, it was assumed to be only Belden Formation. Once defined, the bedrock layers were given a 12° dip to the east to approximate the average dip in the region. In most areas, faults were represented discretely as a single grid cell width in ArcGIS by using a search distance of 10 m from digitally traced fault locations. In certain circumstances the curvature and location of intersecting faults were such that a two-grid cell representation was created. For simplicity, the faults were represented as vertical features that penetrated all bedrock units in the model. A fracture-damage zone typically of one cell thickness was placed on each side of the faults and at the intersections of faults. Figure 18 shows a replica of the model structure.

Model Design

Groundwater movement in the study area is controlled by the temporal and spatial variation of hydrologic stresses that cause recharge into the aquifer system and discharge out of the aquifer system. The hydrologic stresses simulated in the MODFLOW groundwater-flow model included net recharge from precipitation by using the Recharge Package (RCH), stream interaction with the underlying groundwater by using the River Package (RIV), flow across the active model boundary near the East Fork Arkansas River valley (model rows 1–80 of 560) by using the Constant-Head Package (CHD) (fig. 25, active model area bounded by thick red line), flow across the upper regions of the active model boundary (model rows 80–560 of 560) by using the General-Head Boundary Package (GHB) (fig. 25, active model area bounded by thin red line), and drainage to the Canterbury and Leadville Mine drainage tunnels by using the Drain Package (DRN). The majority of the aquifer geometry and properties developed in the ArcGIS were ultimately processed through the MODFLOW utility for ARGUS (Winston, 2000) to create the necessary model input files. This utility included processing of geologic units and fault delineations, defining stream locations of the East Fork Arkansas River, Evans Gulch, and Little Evans Gulch, and establishing the locations of the Canterbury Tunnel, Leadville Mine Drainage Tunnel, and observation wells.

Model Simplifications and Limitations

A variety of factors jointly influenced the design of the groundwater-flow model; they include the degree of geologic complexity within the study area, available field data, model capabilities, and project duration and budget. The simplifications used for the groundwater-flow model were deemed acceptable to address the interests of this investigation.

A steady-state condition was simulated for evaluating high-flow groundwater conditions. Because long-term or transient hydrological conditions were not the focal point of this investigation, a steady-state representation was considered reasonable. High-flow aquifer conditions were ultimately selected for the analysis as being most representative for evaluating the likelihood of a hydraulic connection between the Canterbury Tunnel and Leadville Mine Drainage Tunnel.

Confined conditions were assumed to exist throughout the modeled area under conditions of no pumping at well locations. The Belden Formation, portions of the Minturn Formation, and the fault network were represented as having low permeability in comparison with the surrounding units and to function as low-permeability layers that support a confined-aquifer representation intermittently within the aquifer. In addition, the overlying Quaternary sediment is believed to form a confined aquifer in many of the glacial regions with heavy clay content. The use of continuously confined conditions was judged reasonable for the purposes of this study and was advantageous for improving numerical stability during model calibration.

The active model area was defined to encompass the major features of interest in an area for which geologic maps were available. The model boundary was not coincident with local watershed divides or known hydrologic boundaries. The location of the model boundary was advantageous in avoiding the uncertainty of geologic characterization in regions where mapping was unavailable. However, this location introduced sensitivity to the simulated head-dependent fluid fluxes across the boundary that were based on the difference between modeled and referenced head values and a specified conductance term (see Harbaugh and others, 2000). A constant reference-head specification with depth led to a departure from the observed vertical hydraulic gradient and edge effects at the model boundaries in some instances. A vertical to horizontal anisotropy parameter was established to approximate the vertical hydraulic gradient while leaving the reference head constant with depth.

A representative geologic description of the aquifer was considered important for modeling purposes because the extensive faulting and displacement of bedrock units are considered to exert strong control on groundwater movement. The representation of the geologic structure in the groundwater-flow model approximated the major geologic units but also notably simplified observed conditions. All geologic contacts could not be honored accurately in the model given the shallow and variable dip of the bedding and geologic complexity in the region. The groundwater-flow model is simplified by the representation of hydrostratigraphic units as effective porous media, but the model is reasonably detailed and spatially constrained by an array of geologic observations throughout the model area. The simplified representation of faults as purely vertical features created the need to extend the eastern part of the Leadville Mine Drainage Tunnel approximately 100 m to the east to intersect the fault cluster nearest to the Mikado fault because the Mikado fault cluster penetrates the tunnel at depth (figs. 17, 25). Relics from the mining activities other than the mine drainage tunnels, such as exploration holes, mining drifts, and mine pools were not considered and therefore did not affect the simulated patterns of groundwater flow. The model was deemed beneficial for examining major groundwater flow paths within the study area at the kilometer scale.

Use of Hydrologic Observations

The observation process function in MODFLOW–2000 was used to incorporate data observations into the modeling procedure. A representative set of aquifer conditions was derived from the available data to constrain parameter representation and parameter values during the calibration procedure (tables 4 and 5). Constraints on volumetric flow through the aquifer were provided from recorded discharge from the Canterbury and Leadville Mine Drainage Tunnel, estimated recharge, and estimated base flow for the East Fork Arkansas River. Hydraulic-head observations in wells provided constraints on the model-calculated hydraulic-head distribution. A representative high-flow water-level was used for each of the hydraulic-head observations based on review of the available water-level record for each well. The water-level data spanned the time period from 1990–2007 for all wells.

Model Calibration

Model calibration is the process by which model parameter values are adjusted within reasonable limits to minimize the difference between observed and model-calculated hydrologic characteristics (for example, Hill and Tiedeman, 2007). Calibration was accomplished by using numerical calibration tools integrated within MODFLOW–2000 (McDonald and Harbaugh, 1988; Harbaugh and others, 2000). The fit between observed and simulated values was quantified by a weighted least-squares objective function S (Hill and Tiedeman, 2007) expressed as

$$S(b) = \left(x - x_b'\right)^T \omega \left(x - x_b'\right), \tag{3}$$

where

- b is a vector of each of the parameters being estimated,
- x is a vector of observations,
- x' is a vector of simulated values,
- T is the transport operation, and
- ω is the square weight matrix.

The sensitivity equation method is an integral component of calibration in MODFLOW–2000 that is used to calculate sensitivities of heads and flows to each parameter following the approach described in Hill (1998). This method has been shown to be highly accurate relative to numerical approaches in certain circumstances. Observation sensitivities of model-calculated heads and flows were produced for each observation specified in the observation process function. Model-calculated observation sensitivities were represented as the scaled derivatives of head or flow with respect to each model parameter. Dimensionless sensitivities (d_{ss}) quantified the influence of individual parameters on predicting model observations, expressed in log-transformed form as

$$d_{ss_{ij}} = \left[\left(\frac{\partial x_i'}{\partial b_j}\right) b_j\right] \left|\ln\left(b_j\right)\right| \sqrt{\omega_{ii}} \tag{4}$$

where

- b_j, is a parameter being estimated,
- x_i' is the simulated value, and
- ω_{ii} is the weight of the i-th observation.

Composite-scaled sensitivities (c_{ssj}) gage the total information provided by the observations for the estimation of a parameter, which is a useful measure of control of each parameter on the overall model fit to the available data, and is given in the form

$$c_{ss_j} = \sum_{i=1}^{N} \sqrt{\left[\frac{\left(d_{ss_{ij}}\right)^2}{N}\right]} \tag{5}$$

where

- j is a parameter index, and
- N is the number of observations.

Sensitivities were used to determine which parameters could be reasonably estimated from available data observations and to assess which observations were useful in the parameter-estimation process.

Model calibration was performed iteratively by using the calibration tools integrated within MODFLOW–2000 in combination with manual adjustment of parameters that proved resistant to calibration by automated methods. Model fit during calibration was evaluated by comparing model-simulated values to the observed hydrologic conditions. For each pair of observed and corresponding model-simulated values, a residual was determined by subtracting the simulated value from the observed value (table 4). An appropriate fit criterion was established where the average absolute residual of the hydraulic head observations was less than a few percent of the hydraulic head variation across the modeled region, and observed flows were within a tenth of an order of magnitude to the observed conditions.

Table 4. Flow and hydraulic-head observations and calibrated model-simulated values for average high-flow conditions, 1990–2007, Leadville, Colorado.

[m^3/yr, cubic meters per year; m, meters; h_{obs}, observed head value; h_{cal}, model-simulated head value; z, altitude; Q, discharge]

Site name	Observation type	Observed value	Model-simulated value	Residual (observed minus model-simulated value)
		River		
East Fork Arkansas River	Base flow [m^3/yr]	9.60×10^6	9.73×10^6	-1.3×10^5
			Relative error (Q), in percent (eq. 6)	−1.35
		Tunnels		
Canterbury Tunnel	Discharge [m^3/yr]	1.24×10^6	1.22×10^6	2.4×10^4
Leadville Mine Drainage Tunnel	Discharge [m^3/yr]	3.00×10^6	2.55×10^6	4.5×10^5
			Average relative error (Q), in percent (eq. 6)	8.48
		Wells		
MAB	Hydraulic head [m]	3,088.7	3,094.5	−5.9
WMW–1	Hydraulic head [m]	3,288.1	3,287.0	1.1
LDT96+44	Hydraulic head [m]	3,089.4	3,090.0	−0.7
HM1TMW–4	Hydraulic head [m]	3,102.7	3,101.0	1.7
WMW–4	Hydraulic head [m]	3,115.6	3,109.5	6.1
BMW–3	Hydraulic head [m]	3,084.0	3,088.7	−4.7
PZ–10	Hydraulic head [m]	3,097.0	3,088.7	8.3
LDT75+05	Hydraulic head [m]	3,088.7	3,084.5	4.2
BMW–4	Hydraulic head [m]	3,096.1	3,096.9	−0.8
BMW–5	Hydraulic head [m]	3,097.8	3,096.2	1.7
OU6MP–ELK	Hydraulic head [m]	3,118.0	3,125.3	−7.3
LDT46+66	Hydraulic head [m]	3,087.4	3,079.0	8.4
DW2	Hydraulic head [m]	3,108.9	3,108.1	0.8
LDT36+77	Hydraulic head [m]	3,054.9	3,058.6	−3.8
LDT25+15	Hydraulic head [m]	3,054.7	3,047.7	7.0
PW2	Hydraulic head [m]	3,035.1	3,041.4	−6.3
DW1	Hydraulic head [m]	3,042.7	3,051.0	−8.3
Altitude range (Δz) [m]	500		Average absolute residual ($\lvert h_{cal}-h_{obs}\rvert$) [m]	4.5
Hydraulic head range (Δh_{obs}) [m]	253		Average residual ($h_{cal}-h_{obs}$) [m]	0.1
			Average relative error (h), in percent (eq. 7)	1.8
			Average relative error (z), in percent (eq. 8)	0.9

Table 5. Groundwater-flow model calibration parameters and results, Leadville, Colorado.

[m^2/yr, square meters per year; m/yr, meters per year; Penn, Pennsylvanian age; Cret-Tert, Cretaceous to Tertiary age; Hyd. Cond., hydraulic conductivity; Vanistrpy, vertical anisotropy; H, horizontal hydraulic conductivity; V, vertical hydraulic conductivity; -, unitless]

Parameter name	Parameter type and [units]	Adjustable or fixed parameter	Value used in model
River			
East Fork Arkansas	Conductance [m^2/yr]	Adjustable	2.53×10^3
Evans	Conductance [m^2/yr]	Fixed	1.00×10^2
Little Evans	Conductance [m^2/yr]	Fixed	1.00×10^1
Tunnel (Drain)			
Canterbury Tunnel	Conductance [m^2/yr]	Fixed	1.00×10^5
Leadville Mine Tunnel	Conductance [m^2/yr]	Adjustable	1.00×10^2 to 10^5
Boundary Flux			
Flux—Quaternary	Conductance [m^2/yr]	Fixed	1.00×10^5
Flux—Bedrock	Conductance [m^2/yr]	Fixed	1.00×10^5
Geologic Units			
Alluvium (Quaternary)	Hyd. Cond. [m/yr]	Adjustable	8.51×10^2
Leadville (Paleozoic)	Hyd. Cond. [m/yr]	Adjustable	1.97×10^1
Precambrian	Hyd. Cond. [m/yr]	Fixed	3.20×10^{-1}
Minturn (Penn)	Hyd. Cond. [m/yr]	Adjustable	3.28×10^1
Porphyry (Cret-Tert)	Hyd. Cond. [m/yr]	Fixed	3.20×10^{-2}
Faults	Hyd. Cond. [m/yr]	Adjustable	3.18×10^{-3} to 10^0
Fracture-damage zone	Hyd. Cond. [m/yr]	Adjustable	2.37×10^0 to 10^3
Belden (Penn)	Hyd. Cond. [m/yr]	Fixed	1.00×10^{-3}
Anisotropy Ratio			
Vanistrpy (H:V)	Anisotropy [-]	Adjustable	1.20×10^{-1}

Parameter Representation and Refinement

Parameter representations were initiated with the simplest conceivable configurations and refined iteratively until a basic agreement with the observed hydrologic data was attained. The geologic parameters selected for the groundwater model followed the major geologic units: (1) Quaternary sediments, (2) Tertiary-Cretaceous porphyry rock, (3) Pennsylvanian sedimentary rock, (4) Paleozoic sedimentary rock, and (5) Precambrian basement rock. The fault structure was idealized as an internal region that included the fault core, described in this investigation as simply a "fault," and a fracture-damage zone adjacent to each side of the "fault." Each component of the fault network was represented by an individual model parameter.

The representation effectively described the geologic structure of the aquifer by using seven model parameters, which was a simple and desirable configuration given the limited field data in the region. In the first set of analyses, river conductance for the East Fork Arkansas River, Evans Gulch, and Little Evans Gulch was represented by a single model parameter, the conductance controlling head-dependent flow across general-head boundaries (all boundary cells) was represented by a single model parameter, and the conductance controlling head-dependent flow into the Canterbury Tunnel and Leadville Mine Drainage Tunnel was represented by a single parameter. These initial parameter representations were then refined as the model evolved.

During preliminary testing, both low- and high-flow conditions were evaluated at steady state by using uncalibrated values of hydraulic conductivity derived from the literature (for example, Freeze and Cherry, 1979). The model exhibited little sensitivity to hydraulic-head variations on the order of 4 m, which was the average observed difference between hydraulic head for low- and high-flow aquifer conditions at the base of the watershed. This difference was considered small compared with the range of hydraulic head across the study area, which was about 250 m for the well observations and about 300 m within the active model area as a whole. High-flow aquifer conditions were ultimately selected for the analysis as being most representative for evaluating the likelihood of a hydraulic connection between the Canterbury Tunnel and Leadville Mine Drainage Tunnel.

It was discovered during initial data analysis that hydraulic-head observations from wells completed in the alluvial and glacial deposits near the southern part of the Leadville Mine Drainage Tunnel were affected by mining ponds and surface water that emanated mainly from Stray Horse Gulch. These near-surface processes created intermittently saturated regions in the glacial deposits that were not explicitly represented in the steady-state model. The shallow-water-level observations near the southern part of the Leadville Mine Drainage Tunnel were thus removed from the calibration procedure (see fig. 7), and the modified data set represented primarily hydraulic heads from the bedrock units.

One set of simulations involved calibration to the data observations using different parameter representations until an approximate agreement was obtained between simulated and observed processes that could facilitate the final model calibration. In the initial representation, river fluxes for the East Fork Arkansas River, Evans Gulch, and Little Evans Gulch were controlled by a single river conductance parameter. The approach proved insufficient to represent the observed data, because of the varying character of stream channels from the upper mountain reach to the riparian region along the East Fork Arkansas River alluvial valley floor. Streams in the upper mountain region flow over glacial deposits and(or) bedrock with little to no surrounding alluvial aquifer, whereas the East Fork Arkansas River is incised in a thick alluvial aquifer. To accommodate these differences, three separate parameters were used to represent the conductance of the East Fork Arkansas River, Evans Gulch, and Little Evans Gulch. The locations of tributaries also were manually altered to refine the model representation of streams.

To control calibration of groundwater flux across the lateral model boundaries, initial simulations used a single conductance parameter. Analyses showed that the approach was not optimal, in most instances, because the conductance of the Quaternary sediment differed appreciably from that of the bedrock. A second type of parameter representation was tested to control boundary fluxes by using two separate general-head parameters: one conductance parameter for the Quaternary sediment and another for the underlying bedrock units and faults. Although this representation offered a notable improvement to the single-parameter representation in nearly all regions of the model, a constant-head boundary was deemed better suited near the East Fork Arkansas River to allow for unlimited flow out of the watershed. The final approach used a constant-head representation along the active model boundary at the base of watershed near the East Fork Arkansas River (model rows 1–80) and a two-parameter general-head-boundary designation to represent the remaining active boundary cells (model rows 81–560) (fig. 25). The parameter selection process then evolved through a series of additional refinements that included an iterative adjustment in the reference head values for the general-head boundaries that influenced water flux across the lateral margins of the model. The general-head boundary conductance parameters were found to increase monotonically with successive simulations and eventually became insensitive to calibration. They were ultimately prescribed with large numerical values (1×10^5 m^2/yr) that mimic constant-head conditions. The interpretation of this effect was that, under high-flow conditions, the study area at the base of the watershed receives sufficient amounts of water from the upgradient regions that the study area can be considered as having a constant source of water.

Initially, a single drain conductance parameter was used to control head-dependent discharge of groundwater from the Canterbury Tunnel and Leadville Mine Drainage Tunnel. Preliminary analyses showed that the discharge of groundwater into the Canterbury Tunnel was different than that of the Leadville Mine Drainage Tunnel owing to differences in local bedrock hydraulic conductivity, fault patterns, and density of the faults intersecting the tunnels. A separate drain conductance parameter was therefore created for each tunnel. Further analysis of the results showed that the variation of observed hydraulic head along the Leadville Mine Drainage Tunnel was not well represented by using a constant conductance parameter with depth, even though the bulk discharge from the tunnels was well represented. In an initial attempt to achieve an improved model fit to observed tunnel heads, drain conductance of the Leadville Mine Drainage Tunnel was assumed to decrease exponentially with depth using a multiplier function. The approach of reducing drain conductance exponentially with depth was successful in limiting discharge to the Leadville Mine Drainage Tunnel in the sections of greatest depth and improved the fit between observed and model-calculated hydraulic heads. Conceptually, this adjustment was considered nonrepresentative of true aquifer conditions because it was not aquifer permeability that controlled simulated water inflow to the tunnels, but rather a model-specified depth dependant variation in drain conductance. A multiplier depth relation was also evaluated that decreased both the hydraulic conductivity of the geologic units and fault network. This representation produced results similar to the original single conductance representation for both tunnels where model simulations did not adequately represent the two observed tunnel discharges and variation in hydraulic head along the Leadville Mine Drainage Tunnel. Ultimately, the representation that proved most effective used an exponential depth-dependent multiplier for hydraulic conductivity of the faults and fracture damage zones (fig. 26), while leaving the hydraulic conductivities of the geologic units constant with depth, and a reduction in conductance in the upper reaches of the Leadville Mine Drainage Tunnel above the relief well by three orders of magnitude from 1×10^5 to 1×10^2. The reduction of drain conductance in the upper section of the Leadville Mine Drainage Tunnel and subsequent improvement in overall model fit implies that a blockage is present within the upper reaches of the tunnel that inhibits groundwater flow. The improved fit to the data also used an additional parameter controlling the ratio of horizontal to vertical anisotropy of hydraulic conductivity to approximate the observed vertical gradient in the study area.

Differences in hydraulic-head observations across major faults in the region indicate a limitation in flow across the faults (Wireman and others, 2005), which is consistent with the conceptual model of fault structure. During the initial simulation, faults were set manually as impermeable flow

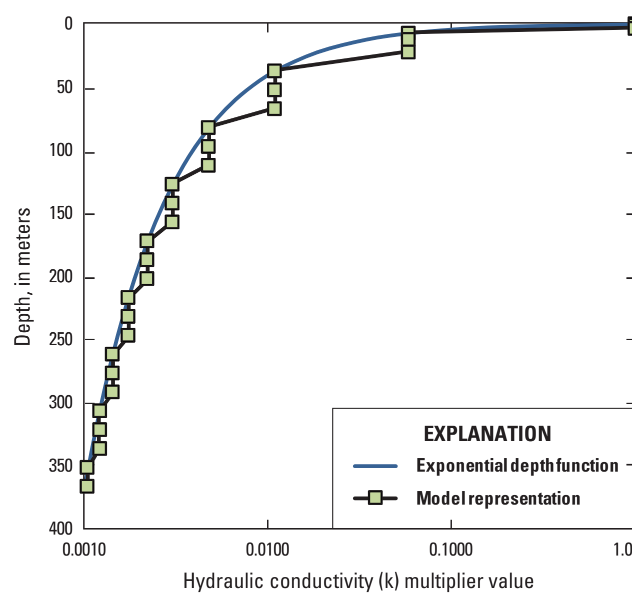


Figure 26. Exponential depth-dependent hydraulic-conductivity (K) multiplier values used in the model for faults and fault-damage zones.

barriers, and the simulation did not adequately represent either the observed discharge from the Canterbury Tunnel and Leadville Mine Drainage Tunnel or the relatively young water ages derived from the geochemical analyses. This lack of congruence indicated that the faults, as a whole, probably restrict water movement relative to the fracture damage zones but do not fully prevent water movement through the groundwater system. The permeability contrasts between the faults and fracture damage zones vary spatially, but under the current parameter representation, spatial variability of permeability in the fault network was not considered, in part for reasons of maintaining model simplicity and also because of the limited data set that was evaluated in the investigation. Simulated head differences across faults are considered to represent average conditions.

The initial model used 16 individual parameters that were refined iteratively by a succession of calibration runs (table 5). The parameters determined important in the final calibrated model are (1) hydraulic conductivity of Quaternary alluvium, (2) hydraulic conductivity of Paleozoic sedimentary bedrock, (3) hydraulic conductivity of Pennsylvanian sedimentary bedrock, (4) hydraulic conductivity of faults, (5) hydraulic conductivity of fault damage zones, (6) conductance of the East Fork Arkansas River, (7) anisotropy in the horizontal to vertical hydraulic conductivity, and (8) drain conductance of the Leadville Mine Drainage Tunnel. The remaining parameters were fixed by using estimates from the literature and by considering parameter trends during calibration. The refinement procedure reduced the original set of 16 model parameters to 8 adjustable parameters in the final model calibration (table 5). The model simulations indicate that the four most conductive units are (1) Quaternary alluvium; (2) the Paleozoic rock unit that includes the Leadville Limestone, Dyer Dolomite of the Chaffee Group, Harding Quartzite, Manitou Dolomite, and Sawatch Quartzite; (3) Pennsylvanian sedimentary rock of the Minturn Formation; and (4) fracture-damage zones that lie alongside the fault cores. The assigned permeability of the faults was three orders of magnitude less than the assigned permeability of the fracture-damage zones, which was consistent with data observations and the basic conceptual model of fault networks (table 5). The Belden unit composed primarily of shale and thin-bedded limestone and sandstone was fixed within the model as a low-permeability layer. Although the Minturn was reported to be a confining unit at some locations where it contained shale deposits, it was shown overall in the model calibration to be a conductive unit, likely owing to its content of sandstone, conglomerate, limestone, and dolomite.

Model error was assessed in terms of discharge (Q), hydraulic head (h), and land-surface altitude (z) by using the calibrated model results and data observations to evaluate the effectiveness of the groundwater-flow model (table 4). Errors were determined by the average flow residuals normalized to observed discharge (Q_{obs}), average head residuals normalized to the range in observed hydraulic head (Δh_{obs}), and average head residuals normalized to the range in land-surface altitude (Δz) expressed in the form

$$\text{Average Relative Error \% } (Q) = \frac{100}{N}\sum_{i=1}^{N}\frac{|Q_{cal}-Q_{obs}|}{Q_{obs}} \quad (6)$$

$$\text{Average Relative Error \% } (h) = \frac{100}{N}\sum_{i=1}^{N}\frac{|h_{cal}-h_{obs}|}{\Delta h_{obs}} \quad (7)$$

$$\text{Average Relative Error \% } (z) = \frac{100}{N}\sum_{i=1}^{N}\frac{|h_{cal}-h_{obs}|}{\Delta z}, \quad (8)$$

where

N is the number of comparisons,
cal is the model-simulated value, and
obs is the observed value.

The average relative discharge error (Q) between observed (*obs*) and simulated (*cal*) tunnel discharge for both tunnels was collectively about 9 percent. Discharge through the Canterbury Tunnel was simulated more accurately; with a 2 percent error between observed and simulated conditions. There was less agreement between the observed and simulated discharge flowing into the Leadville Mine Drainage Tunnel, but the simulated value was still within a tenth of an order of magnitude of the estimated observed condition and was within the range of reported discharge values. The calibration analysis also revealed acceptable agreement with the observations of river base flow and hydraulic head at well locations. The error between observed and simulated river base flow was approximately 1 percent. Normalized to the range of observed hydraulic head (Average Relative Error % (Δh)), the average absolute error in simulated hydraulic head was less than 2 percent and, normalized to the total topographic variation in altitude (Average Relative Error % (Δz)), the average absolute error was less than 1 percent. The error analyses indicate that the simulated results are within reasonable and acceptable limits. The relatively low errors support the usefulness of the groundwater model in assessing large-scale flow processes.

Following Hill and Tiedeman (2007), calibration to observed data yield a correlation of 0.963 between the ordered weighted residuals and normal order statistics for observations. This correlation indicates within a 5-percent confidence limit that the weighted residuals cannot be rejected as independent and normally distributed. Moreover, the weighted residuals as compared with weighted simulated values were about evenly distributed above and below a weighted residual of zero, which indicates that the weighted residuals are approximately random (noncorrelated). Cook's d statistic (Hill and others, 2000) was used to assess the important observations used in the model. Large values identified observations that, if omitted, would result in greater changes to the set of parameter estimates. The most influential observations were found to be the hydraulic-head observations in wells along the Leadville Mine Drainage Tunnel, discharge to each tunnel, and discharge to the East Fork Arkansas River. DFBeta statistics (Hill and others, 2000) were determined for each parameter of each observation. The largest DFBbeta values identified observations with the most influence on each parameter estimate. The estimation of hydraulic conductivity for the Quaternary sediment was controlled mostly by the observed discharge to the East Fork Arkansas River. The estimation of the Minturn sedimentary group hydraulic conductivity was influenced primarily by the observed discharge to the Canterbury Tunnel under antecedent conditions. The estimation of hydraulic conductivity of the Leadville group, fault network, and fault buffer zone and the vertical anisotropy of the groundwater system were controlled mostly by the observed discharge to the Leadville Mine Drainage Tunnel, which was the strongest overall influence on the system. Estimations of the fault buffer zone and East Fork Arkansas River conductance were also influenced by the observed discharge to the East Fork Arkansas River. The added control of river discharge on the estimation of the fault buffer zone hydraulic conductivity implies that the fault buffer zone is a primary control on regional outflow of groundwater that ultimately discharges to the river.

Simulated Steady-State Water Budget

The simulated high-flow steady-state water budget provided estimates of the total water inflow, total water outflow, and the contributions by each inflow and outflow component of the hydrologic system (fig. 27). The simulated total flow into the aquifer combined the influence of precipitation recharge, infiltration from rivers, and lateral inflow across the model boundaries. Simulated total flow out of the aquifer was a result of the discharge to rivers, discharge to the mine drainage tunnels, and lateral outflow across the model boundaries. Other influences such as pumpage from wells and changes in aquifer storage were assumed negligible and were not simulated by this steady-state model. The results indicate that the total annual volumetric discharge of water passing through the watershed was approximately 5×10^7 m^3/yr. In disaggregating the flow components, the general-head boundaries controlled the majority of discharge into and out of the aquifer at 79 percent and 63 percent of the water budget, respectively. The general-head boundaries accounted for recharge into the aquifer from the high-altitude mountainous regions and discharge out of the aquifer mainly along the southwestern edge of the active model area. Recharge to the valley floor accounted for 17 percent of the total inflow to the aquifer along the East Fork Arkansas River at the base of the watershed. Discharge to the East Fork Arkansas River from groundwater in the Quaternary sediment accounted for 19 percent of the total outflow water. The simulated discharge to the river was consistent with the understanding that it was gaining water along the section. The upper altitude drainages (Evans and Little Evans Gulch) were assigned estimates of conductance and contributed less than 1 percent to the total inflow water budget.

Overall, approximately 96 percent of the simulated total inflow and 74 percent of the total outflow were controlled by lateral subsurface fluxes across the active model boundaries. When the river outflow was also considered, the combined outflow contributions accounted for 93 percent of the total

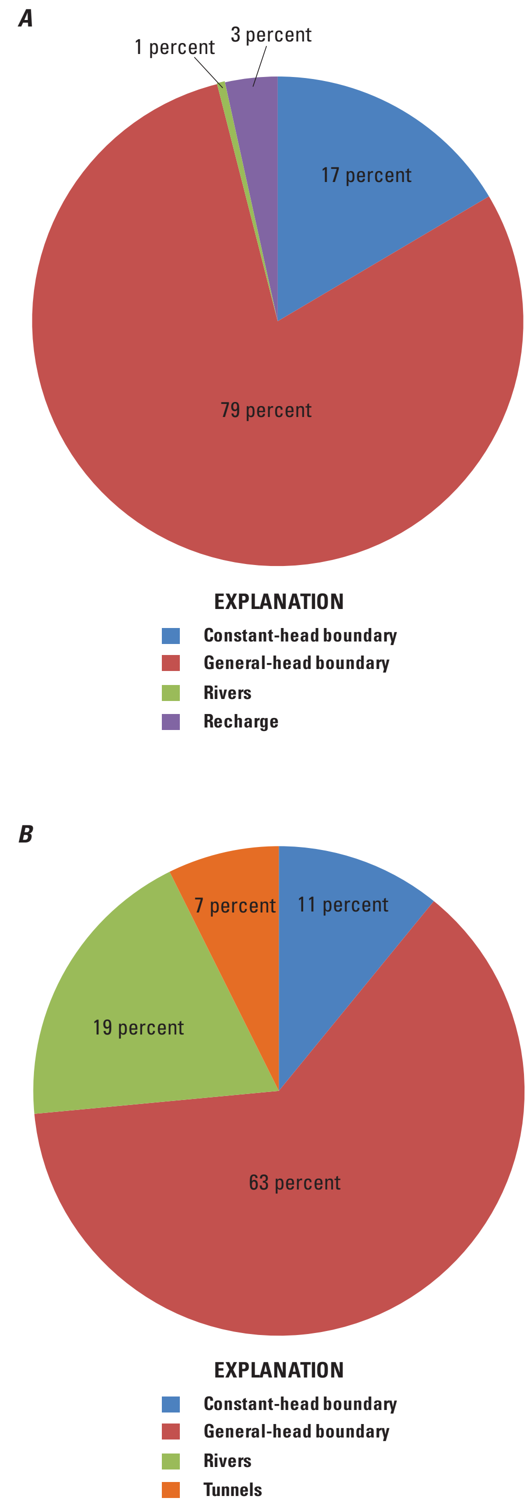


Figure 27. Percentage of simulated volumetric discharge of the major components of the groundwater budget for *A*, inflow and *B*, outflow.

water budget. The largest contributions to the water budget were subsurface flow entering the modeled region from the upper reaches of the watershed and hydrologic interaction of the groundwater with the East Fork Arkansas River. Precipitation recharge within the area of investigation contributed only 3 percent to the total water budget. The influence of recharge was limited by the location of the study area at the base of watershed where significant lateral flow from high-altitude regions provided the primary groundwater inflow to the active model area. Although recharge from rain and snowmelt is the major source of groundwater recharge on a regional scale, the majority of recharge water from high altitudes has infiltrated into the groundwater before reaching the study area, which rendered the lateral fluxes across the area of investigation a more important contribution to the water budget than precipitation recharge. Moreover, the hydraulic-head difference between low- and high-flow recharge condition varied by 4.0 m and, given the 250-m range of observed hydraulic head, the influence of recharge at low- and high-flow conditions was assumed to be minimal (figs. 14, 15). The volume of subsurface drainage to the Canterbury Tunnel and Leadville Mine Drainage Tunnel accounted for approximately 7 percent of the total outflow from the system, 3 percent of which was discharge from the Canterbury Tunnel. Discharge from the Canterbury Tunnel is therefore also small in relation to the volume of groundwater passing between the tunnels.

Groundwater Flow Directions

The area of investigation in the Leadville mining district receives substantial inflow of groundwater and surface water from high-altitude regions of the watershed. Surface water enters the area of investigation from the East Fork Arkansas River, Evans Gulch, Little Evans Gulch, and other tributaries, and exits mainly to the southwest along the East Fork Arkansas River at the base of the watershed. Shallow groundwater moves through the Quaternary sediments primarily within flat-lying areas along the base of the mountain fronts and in the East Fork Arkansas River valley. The bedrock units receive a lateral influx of water from the upper reaches of the watershed along a series of compartmentalized fault blocks with displacement offsets that restrict bedrock-unit continuity.

Potentiometric-surface maps derived from the model simulations were used to evaluate the spatial distribution of hydraulic head and physical controls on groundwater movement (figs. 28, 29, and 30). Potentiometric surfaces were interpolated from the model-calculated hydraulic heads for depths of 50 m, 150 m, and 250 m below land surface. The maps at multiple depths were used to evaluate the vertical variation of simulated hydraulic head within the aquifer. At all aquifer depths, contours of equal hydraulic head were consistently observed to be nearly perpendicular to the tunnels, which indicates that simulated groundwater flow is generally parallel to the Canterbury Tunnel and the Leadville Mine Drainage Tunnel and that flow between the tunnels would likely be limited through the bedrock units. Simulated hydraulic-head contours whose curvature was smooth and gradual at their intersection with faults and other geologic discontinuities were interpreted to indicate minor influence by the fault network and a response similar to that of a porous medium. In regions where head contours were erratic or offset at the intersection of faults and other geologic discontinuities, the aquifer was interpreted to be structurally controlled.

Simulated hydraulic head in most areas of the 50-m-depth potentiometric surface intersected Quaternary sediment or were near the contact between Quaternary sediment and bedrock, and flow through these regions appeared to be mildly influenced by the underlying geology. Only in the northeast section of the area of investigation, where Quaternary glacial deposits had thicknesses of a few meters, were head contours noticeably offset at their intersection with faults and bedrock transitions. At progressively lower depths, increasing control of the bedrock structure on groundwater movement is evident, most notably in the southeastern region of the study area near the intersection of the Iron fault and Mikado fault (figs. 29, 30). The critical depth transition into structurally controlled groundwater was spatially variable because of the variable distribution of Quaternary sediment thicknesses across the study area, contrasts in bedrock permeability, and hydrologic conditions controlling hydraulic head. At depths greater than approximately 100–150 m, however, groundwater flow is structurally controlled.

Particle-Tracking Analysis

Backwards particle tracking, determined using the program MODPATH (Pollack, 1994), was used in conjunction with the calibrated groundwater model to characterize large-scale flow entering the Canterbury Tunnel and Leadville Mine Drainage Tunnel (fig. 31). The procedure in backwards particle tracking is to assign particles at the final locations of interest and reverse the direction of simulated flow velocities to determine where particles originated. Ending locations of particles were assigned near each tunnel within a zone that extended five model columns (50 m) in each direction. A total of 6,369 particles were used in the analysis. Effective porosity was assigned an assumed value of 0.1.

The vertically integrated representation of particle flow paths revealed the overall patterns of groundwater flow and the average time for all of the particles at each grid location to arrive at either tunnel. The sets of particle paths for each of the two tunnels were easily distinguished because particle trajectories did not cross one another. The implication from the sets of particle trajectories that do not cross is that no major hydraulic connections were present between the tunnels near the time of this investigation as simulated in the model. Direct examination of particle simulations also indicated that while the fault network generally restricted groundwater movement locally, hydrologic conditions were such that groundwater was able to cross fault planes at many locations, indicating that the

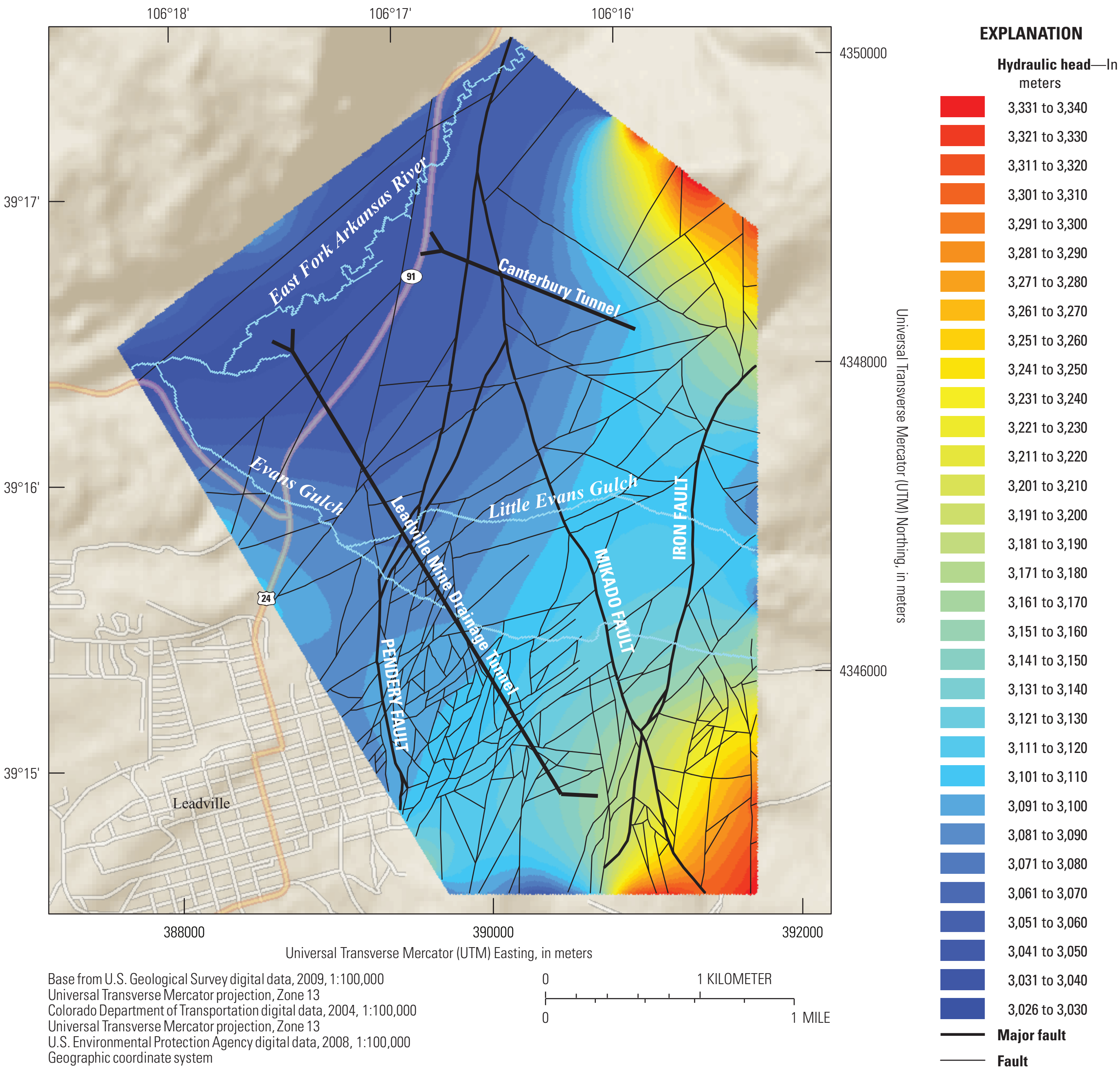


Figure 28. Model results showing interpolated hydraulic-head distribution at a depth of 50 meters.

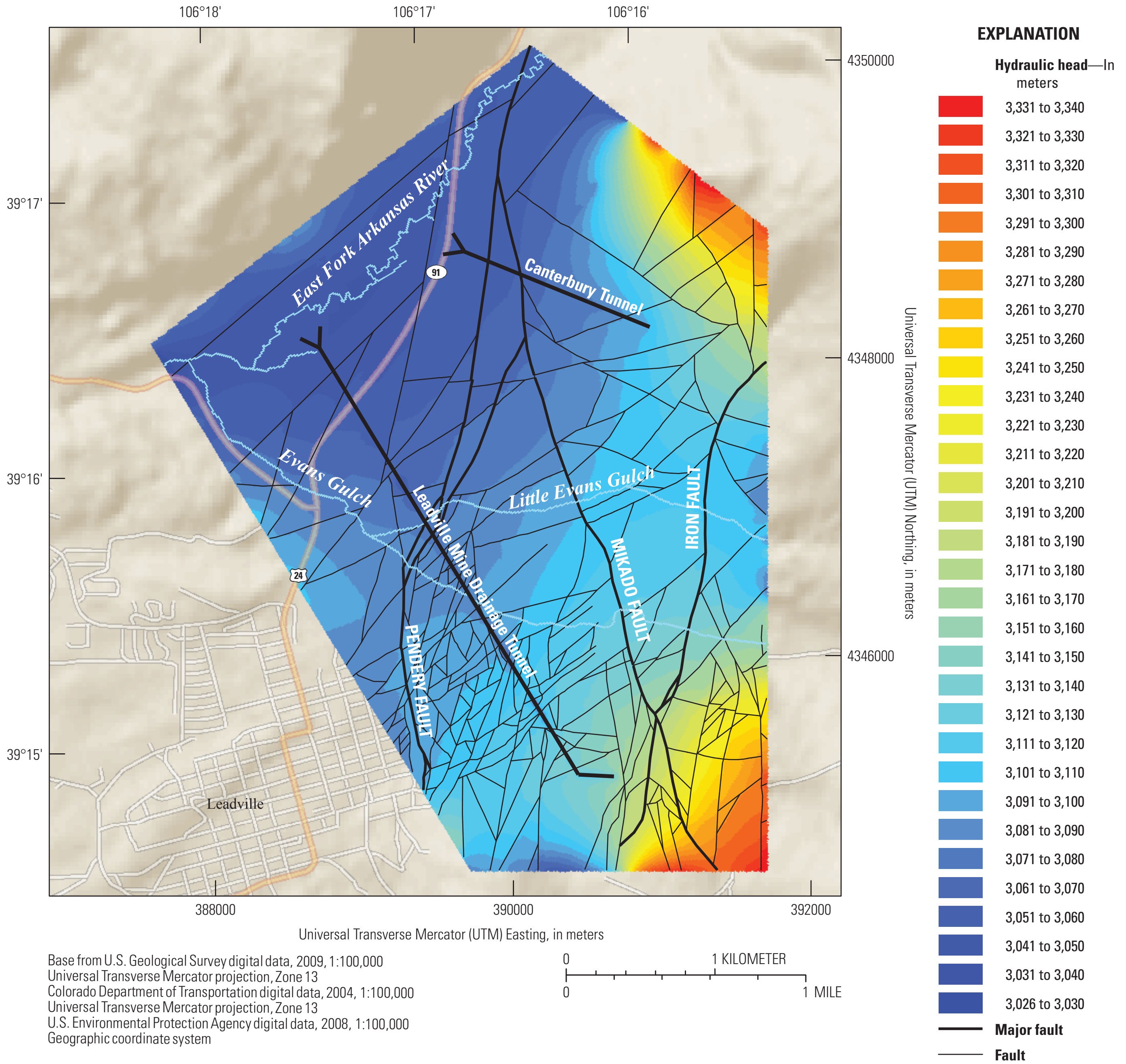


Figure 29. Model results showing interpolated hydraulic-head distribution at a depth of 150 meters.

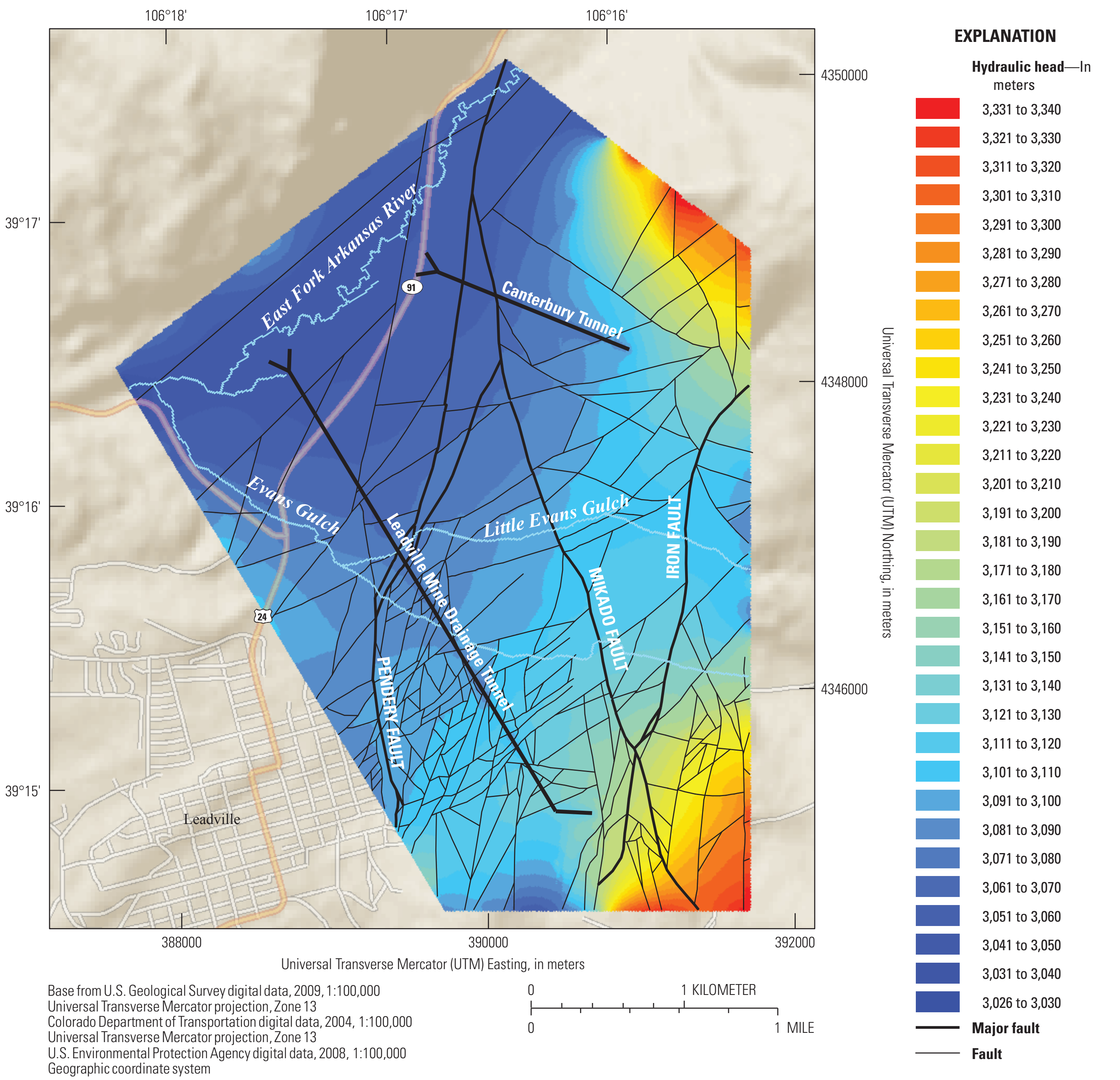
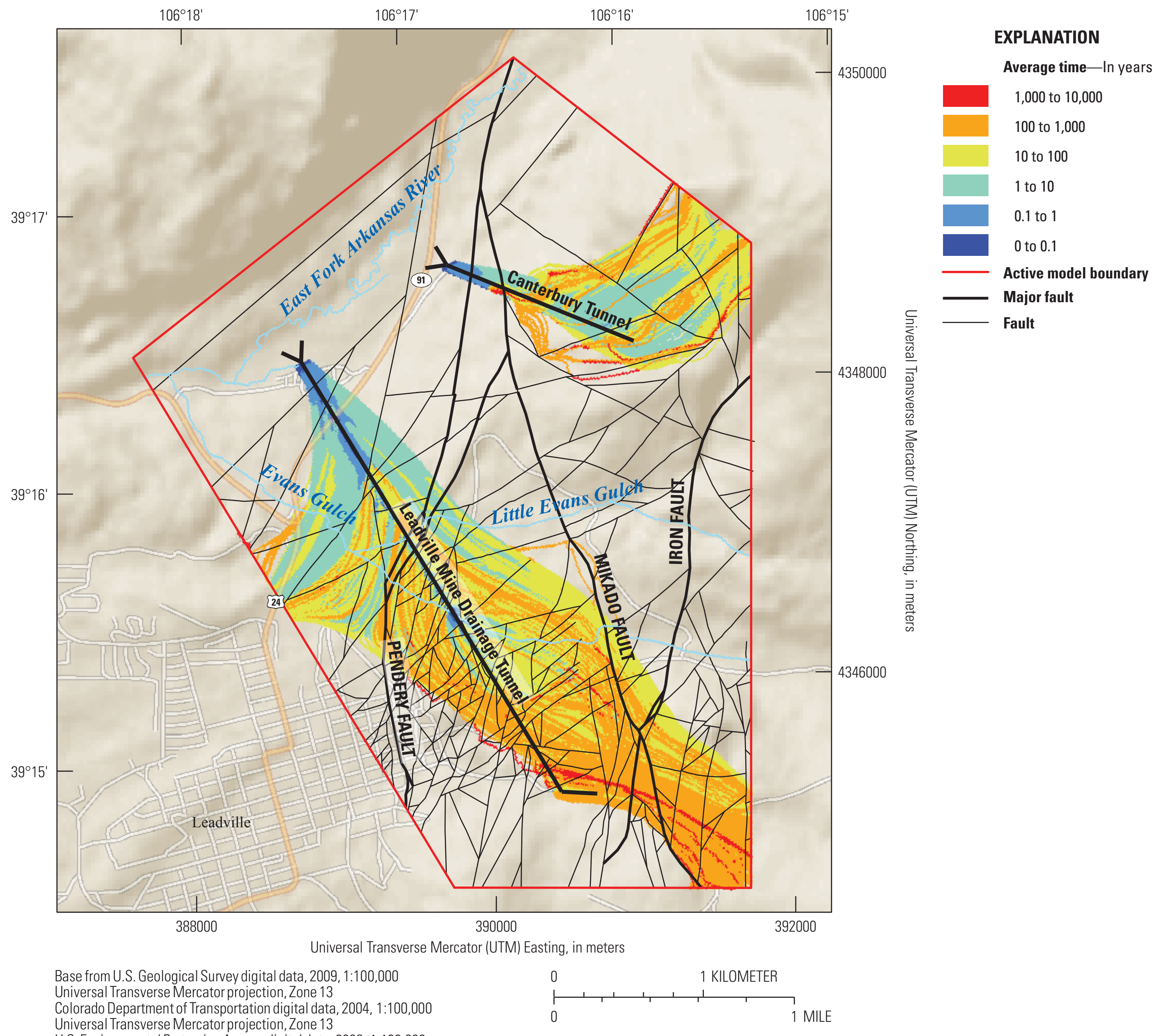


Figure 30. Model results showing interpolated hydraulic-head distribution at a depth of 250 meters.



Base from U.S. Geological Survey digital data, 2009, 1:100,000
Universal Transverse Mercator projection, Zone 13
Colorado Department of Transportation digital data, 2004, 1:100,000
Universal Transverse Mercator projection, Zone 13
U.S. Environmental Protection Agency digital data, 2008, 1:100,000
Geographic coordinate system

Figure 31. Vertically integrated groundwater-flow paths generated by using backwards particle tracking.

fault network, as a whole, alters flow routes but does not act as an impermeable barrier to flow in the bedrock aquifer system. The source regions for the particles that entered the tunnels were located in three zones along the active model boundary. One of the source zones for the Leadville Mine Drainage Tunnel was situated at the southwest edge of the active model boundary where drawdown from the tunnel induces the flow of water into the watershed. The position of the watershed divide and estimated reference head at the active model boundary contributed to this effect. The two remaining source zones were located within high-altitude regions adjacent to each tunnel, which indicate lateral-inflow recharge to the bedrock units.

Cumulative age distributions of individual particles were used to examine the time required for groundwater to travel from the active model boundary to locations within five model-grid columns of each drainage tunnel (fig. 32). The distributions excluded the particles whose source location was within the study area. The simulated travel times of individual particles (without spatial averaging) ranged more than six orders of magnitude (10^0 to 10^6 years) and provided an estimate of the range in effective pathway velocities from flow entering laterally across the active model boundary, because most travel distances were within the same order of magnitude at the kilometer scale. Because the distribution of particle travel was controlled exclusively by the advection of groundwater, late-time arrivals were interpreted mainly for

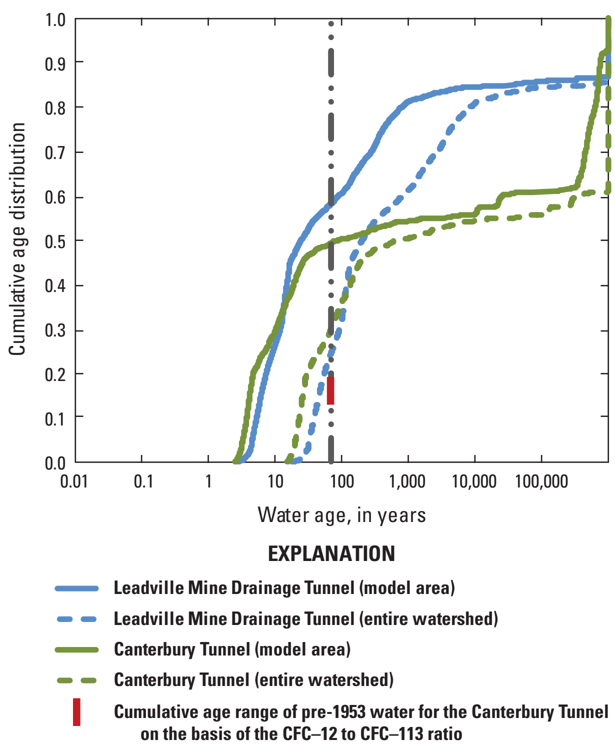


Figure 32. Simulated flow-path age distributions of water traveling from the groundwater-model boundaries to the Canterbury Tunnel and Leadville Mine Drainage Tunnel.

categorical purposes of defining old water, as opposed to a precise interpretation of water age that would require the consideration of additional influences such as subgrid dispersion and molecular diffusion.

Simulated travel times were adjusted to account for the truncated portion of flow paths outside of the active model area. In this approximation, it was assumed that the mean travel time through the entire watershed was approximately 10 times as great as mean simulated travel time in the model area, given that the area of the watershed was 10 times as great as the area of the model. Under a linear increase, macroscale plume dispersion increases with travel distance, and the variance of particles travel times was also estimated to increase by a factor of 10. A log-transformed correction procedure was used to adjust travel-time results to be representative of the complete travel paths in the watershed in the form

$$\log_{10} Age_w = \left(\frac{\log_{10} Age_m - \mu_{\log_{10} Age_m}}{\sigma_{\log_{10} Age_m}} \right) \cdot \sigma_{\log_{10} Age_w} + \mu_{\log_{10} Age_w} \quad (9)$$

where

$\log_{10} Age_w$ is the log-transformed water age of the total flow path in the watershed,

$\left(\frac{\log_{10} Age_m - \mu_{\log_{10} Age_m}}{\sigma_{\log_{10} Age_m}} \right)$ represents the log-normalized water age of the truncated flow path simulated in the model,

$\sigma_{\log_{10} Age_w}$ is the standard deviation of the log-transformed water ages in the watershed, and

$\mu_{\log_{10} Age_w}$ represents the mean of the log-transformed water ages in the watershed.

This transformation, although an estimate, allowed for the adjustment of the travel-time distribution to be more representative of the entire watershed.

The adjusted age results indicated that approximately 30 percent of the flow pathways transmitted groundwater that was younger than 68 years old (that is, recharged after 1941). The cumulative distributions of adjusted age results for the watershed indicate that approximately 30 percent of the flow pathways transmit groundwater that was younger than 68 years old (post-1941) and that about 70 percent of the flow pathways transmit old (pre-1941) groundwater. The particle-tracking results are consistent with the apparent ages and mixing ratios of CFC–12 and CFC–113 for the portal spring, which indicated that about 77 percent of the Canterbury Tunnel discharge is old (pre-1953) water. Model simulations further indicated that approximately 50 percent of the flow paths transported groundwater that was less than 200 years old. The simulated percentage of water less than 200 years old was similar in both tunnels, which indicated that moderate- to fast-velocity flow paths are present throughout the study region. In the Canterbury Tunnel, groundwater was mainly less than 200 years in age, and about 45 percent of the flow paths transmitted groundwater greater than 10^5 years in age that were simulated to originate from Canterbury Hill. For the Leadville Mine Drainage Tunnel, about 80 percent of the flow paths delivered groundwater that was younger than 10^5 years old, which emphasized that there was substantially more water between 10^2 to 10^5 years old within the Leadville Mine Drainage Tunnel than in the Canterbury Tunnel. The division between young and old water was most pronounced for water in the Canterbury Tunnel. The $\log_{10}$ distribution of the age of water in the Canterbury Tunnel was bimodal, whereas the $\log_{10}$ distribution of the age of water in the Leadville Mine Drainage Tunnel was more continuously distributed.

As a final examination, the model conductance parameters of the Canterbury Tunnel and Leadville Mine Drainage Tunnel were manually adjusted from the calibrated values to determine if altering flow discharge in one of the drainage tunnels affected the hydraulic behavior in the other. In the first examination, the conductance of the Canterbury Tunnel was set to zero, which halted drainage from the tunnel and allowed groundwater heads to increase around the tunnel. No effect was detected in discharge from the Leadville Mine Drainage Tunnel or simulated hydraulic heads at the local well locations near it. Furthermore, repeating the process in a reverse manner by setting the Leadville Mine Drainage Tunnel conductance to zero produced no substantial variation in discharge from the Canterbury Tunnel. The hypothesis that a structural blockage within the Canterbury Tunnel could affect the hydrological conditions in or near the Leadville Mine Drainage Tunnel was therefore not supported by the direct modification of tunnel conductance.

Summary

The Leadville mining district is located within the headwaters of the Arkansas River watershed approximately 120 kilometers (km) southwest of Denver, Colorado, at an altitude of about 3,020 meters or about 10,000 feet. The Leadville mining district was historically one of the most extensively mined districts in the world producing gold, silver, lead, zinc, copper, and manganese from the 1860s through the 1990s. Three major tunnels—the Yak Tunnel, the Leadville Mine Drainage Tunnel, and the Canterbury Tunnel—were constructed in the area to facilitate mineral exploration and drain water from the mines. The Yak Tunnel and the Leadville Mine Drainage Tunnels discharge acid mine drainage, and water-treatment plants are operated at the portals of the Yak and Leadville Mine Drainage Tunnels to raise the pH and remove metals from the discharge. In contrast, the Canterbury Tunnel drains an area outside the mining district, and water from the tunnel has been used as a drinking-water supply for Leadville since 1961.

Near the Leadville Mine Drainage Tunnel, groundwater levels have risen and portal discharge has decreased since 2005. In 2008, the U.S. Environmental Protection Agency implemented an emergency response program to lower water levels in the Leadville Mine Drainage Tunnel. Coincident with rising water levels in the Leadville Mine Drainage Tunnel, flow from the Canterbury Tunnel decreased substantially after 2005, raising questions as to whether there was a hydraulic connection between the Canterbury Tunnel and the Leadville Mine Drainage Tunnel. In response to local concerns, in 2008, the Colorado State Legislature directed the Colorado Department of Public Health and Environment (CDPHE) to investigate whether a possible groundwater connection exists between the Canterbury Tunnel and the Leadville Mine Drainage Tunnel. The U.S. Geological Survey performed a multidisciplinary investigation in cooperation with CDPHE, to address groundwater conditions near the Canterbury Tunnel and the Leadville Mine Drainage Tunnel.

This report describes the hydrogeologic setting and simulation of groundwater flow near the Canterbury Tunnel and the Leadville Mine Drainage Tunnel. The primary objective is to evaluate whether a substantial hydraulic connection likely exists between the Canterbury Tunnel and the Leadville Mine Drainage Tunnel. The following tasks provide multiple lines of evidence to evaluate the hydrogeology and water quality near the drainage tunnels: (1) compilation and analysis of existing hydrologic data; (2) site reconnaissance near the Canterbury Tunnel to locate groundwater and surface-water sampling locations and surficial expressions of the tunnel; (3) compilation of existing geologic maps and data into an electronic format for manipulation and display of the geologic framework; (4) a geophysical survey between the Canterbury Tunnel and the Leadville Mine Drainage Tunnel to evaluate subsurface conditions; (5) water-quality sampling of seven sites (surface water, seeps, and wells) near the Canterbury Tunnel to evaluate whether mining has affected water quality of the tunnel discharge; and (6) simulation of steady-state groundwater flow in a study area encompassing the Canterbury Tunnel and the Leadville Mine Drainage Tunnel.

The study area consists of a 13-km^2 region about 3 km northeast of Leadville, Colorado that includes the Canterbury Tunnel, the Leadville Mine Drainage Tunnel, parts of Evans Gulch, Little Evans Gulch, and Stray Horse Gulch watersheds, and a 3-km segment of the East Fork Arkansas River. The study area is situated in the headwaters of the upper Arkansas River on the western flank of the Mosquito Range. Altitude in the Leadville area ranges from about 3,018 m (9,900 ft) along the Arkansas River valley to about 4,270 m (14,000 ft) along the Continental Divide east of Leadville, and the high altitude of the area results in a moderate subpolar climate.

Monthly and annual precipitation data for four weather stations near Leadville from 1990 to 2007 were examined for temporal and spatial trends and used to develop recharge estimates for the groundwater system. Precipitation fell primarily as snow from September through May of each year (defined herein as winter precipitation), and precipitation fell primarily as rain during the months of June through August (defined herein as summer precipitation). Winter precipitation was about three times greater than summer precipitation. Comparing precipitation data between sites indicates that, in general, both winter and summer precipitation were greatest at higher altitudes, and a linear relation between precipitation and altitude was developed for winter and summer conditions. The effect of a regional drought that began in 1999 was most pronounced in the summer precipitation record of 2002. Since 2002, winter and summer precipitation have increased coinciding with the observed water-level rise near the Leadville Mine Drainage Tunnel that began in 2003.

The weather patterns and hydrology exhibit strong seasonality with an annual cycle of cold winters with large snowfall, followed by spring snowmelt, runoff, and recharge (high-flow) conditions, and then base-flow (low-flow) conditions in the fall prior to the next winter. Streamflow data for the East Fork Arkansas River (USGS gaging station 07079300) from 1991 to 2007 were examined to evaluate discharge variability and estimate base-flow conditions. The discharge record from 1991 to 2007 shows annual peak runoff near the end of May and beginning of June during spring snowmelt, although discharge varied seasonally and annually. The minimum annual peak discharge for the period (6.2×10^7 m^3/yr) occurred in May 2002 during the drought, and the maximum peak discharge for the period (7.2×10^8 m^3/yr) occurred in June 1997. Streamflow generally increased after the 2002 drought year

Groundwater flow in the study area is controlled by topography, the locations and quantity of recharge, the locations and orientations of geologic and mining features, and the locations of streams and tunnels. On a basinwide scale, melting snow and rain at higher altitudes in the Mosquito Range recharges a bedrock groundwater system, which flows generally southwestward following topography toward the Arkansas River valley at the base of the watershed. Bedrock groundwater discharges to surface water and to alluvial sand and gravel deposits along the Arkansas River valley. The valley-fill deposits form an unconfined alluvial aquifer at the base of the mountains. Stratigraphy, geologic structure, fracture and fault networks, karst features, mine workings, and tunnels affect groundwater flow directions on a local scale.

Bedrock in the Leadville area consists of Precambrian granite overlain by Paleozoic sedimentary rocks, which have been folded and faulted during several tectonic episodes. Late Cretaceous and Tertiary igneous intrusive rocks (primarily porphyry) cross cut the older Precambrian and Paleozoic rocks, and hydrothermal fluids associated with the porphyry are related to mineralization in the Leadville mining district. Unconsolidated Quaternary alluvial and glacial deposits overlie the bedrock formations primarily along the East Fork Arkansas River and its tributaries. Geology of the study area was classified into five major hydrostratigraphic units for input to the groundwater-flow model: (1) Quaternary alluvial and glacial deposits, (2) Cretaceous-Tertiary porphyry rocks, (3) Pennsylvanian sedimentary rocks, (4) Paleozoic carbonate rocks, and (5) Precambrian basement rocks. The Quaternary alluvial deposits form an unconfined alluvial aquifer in the East Fork Arkansas River, whereas the glacial deposits are poorly sorted with substantial clay and generally form confining units. The Cretaceous-Tertiary porphyry rocks and the Precambrian basement rocks form fractured-rock aquifers. The Paleozoic carbonate rocks form karst aquifers, which are overlain and confined by the Pennsylvanian sedimentary rocks (Belden and Minturn Formations).

Paleozoic sedimentary rocks of the Leadville mining district form the eastern limb of the Sawatch anticline dipping, on average, about 12 degrees toward the east, and the region has been intensively fractured. Primary fault orientations trend northeast-southwest and northwest-southeast, and secondary fault orientations trend nearly north-south and east-west. Most of the faults in the region dip steeply (80–90 degrees) and extend hundreds of meters below land surface. The Pendery, Mikado, and Iron faults are the major north-south-trending features that partition the bedrock aquifers within the study area. Previous mapping indicates that a succession of faults have caused substantial vertical displacement (about 200 m) of the Paleozoic rocks between the Canterbury Tunnel and the Leadville Mine Drainage Tunnel The Canterbury Tunnel was found to be situated in a downthrown structural block such that the Paleozoic rock units intersected by the Canterbury Tunnel are not continuous with the the Paleozoic rocks intersected by the Leadville Mine Drainage Tunnel. The geophysical survey results were consistent with previous interpretations of the geologic structure and support the conclusion that the Canterbury Tunnel is located in a structural block that is downthrown relative to Paleozoic rocks near the Leadville Mine Drainage Tunnel. The estimated vertical displacement between the Canterbury Tunnel structural block and the structural blocks to the south indicates a likely restriction in groundwater flow through laterally continuous bedrock units between the Canterbury Tunnel and the Leadville Mine Drainage Tunnel.

Groundwater flow between the Canterbury Tunnel and Leadville Mine Drainage Tunnel cannot be characterized with accuracy because of the absence of hydrologic data in the area near the eastern part of the Canterbury Tunnel and in the area between the Canterbury Tunnel and Leadville Mine Drainage Tunnel. The absence of such data in the region creates uncertainty in the findings of this report that cannot be remedied without additional data collection. The available hydrologic data were from monitoring wells near the Leadville Mine Drainage Tunnel for the period 1991–2003. Analysis of available water-level records by this and previous studies indicate that although rising groundwater levels near the Leadville Mine Drainage Tunnel were likely caused by collapse in the Leadville Mine Drainage Tunnel, the water-level rises also coincided with increased precipitation since 2003. Examination of water-level response measured in monitoring wells north of the Leadville Mine Drainage Tunnel showed that the effects of pumping from its relief well did not extend toward the Canterbury Tunnel supporting the proposal that there is not a substantial hydraulic connection between the Canterbury Tunnel and the Leadville Mine Drainage Tunnel.

Groundwater and surface-water samples were collected from seven sites near the Canterbury Tunnel on September 15 and 16, 2008, to evaluate whether mining activities had affected water quality and to characterize the sources of groundwater. Water samples were analyzed for major ions, metals, and total dissolved solids as indicators of general water quality and for isotopes of hydrogen and oxygen in water, dissolved gases, chlorofluorocarbons (CFC), and tritium as indicators of groundwater origin and age. The total dissolved solids and major ion concentrations were substantially less than drinking water standards, pH was near neutral to slightly basic, and acid-mine drainage indicator concentrations were substantially less than indicator values leading to the conclusion that groundwater near the Canterbury Tunnel is not affected by acid mine drainage. Stable-isotope ratios of hydrogen and oxygen were similar to those measured by previous studies for the bedrock groundwater and snow, which indicated that snowmelt was the primary source of recharge to the bedrock groundwater. Apparent groundwater ages were calculated on the basis of chlorofluorocarbon (CFC) and tritium concentrations and ratios. The groundwater-age results indicate that bedrock groundwater in the upgradient wells (Elkhorn shaft and Domestic well #2), which are completed in a fault block separate from the Canterbury Tunnel, contains a greater percentage of young (post-1953) water than the Canterbury Tunnel. Samples from wells completed in the Arkansas River alluvial aquifer (Domestic well #1 and Parkville well #2) and the highway seep also contained substantial percentages of young water and likely represent snowmelt recharge mixed with older regional groundwater that discharges from the bedrock units to the Arkansas River valley. Groundwater discharge from the Canterbury Tunnel portal spring is considered representative of groundwater draining from the tunnel and contained a greater fraction of old (pre-1953) water than the other samples. These results indicate that the Canterbury Tunnel likely drains older groundwater from bedrock formations beneath Canterbury Hill as well as young snowmelt recharge.

A calibrated three-dimensional groundwater model under high-flow conditions was used to evaluate large-scale flow characteristics of the groundwater and to assess whether a substantial hydraulic connection was present between the Canterbury Tunnel and Leadville Mine Drainage Tunnel. The model calibration indicated that the four most conductive geologic units were (1) surface deposits of Quaternary sediment from glacial and alluvial origin, (2) Paleozoic rock that includes the Leadville Limestone, Chaffee Group, Harding Quartzite, Manitou Dolomite, and Sawatch Quartzite, (3) Pennsylvanian sedimentary rock of the Minturn Formation, and (4) fracture-damage zones adjacent to the faults or fault cores. As simulated, the faults restrict local flow in many areas, but the fracture-damage zones adjacent to the faults allow groundwater to move along faults. Water-budget results indicate that groundwater flow across the lateral edges of the model controlled the majority of flow in and out of the aquifer (79 percent and 63 percent of the total water budget, respectively). The largest contributions to the water budget were groundwater entering from the upper reaches of the watershed and the hydrologic communication of the groundwater with the East Fork Arkansas River.

Potentiometric-surface maps of the simulated model results were generated for depths of 50, 100, and 250 m. The surfaces revealed a positive trend in hydraulic head with land-surface altitude and evidence of increased control on fluid movement by the fault network structure at progressively greater depths in the aquifer. Advective particle tracking was used to characterize flow paths within the aquifer that ultimately drain into the Canterbury Tunnel and Leadville Mine Drainage Tunnel. The sets of simulated flow paths for each tunnel were mutually exclusive of one another, which suggested that no major hydraulic connection was present between the tunnels. Particle-tracking simulations also revealed that while the fault network generally restricted groundwater movement locally, hydrologic conditions were such that groundwater did cross the fault network at many locations. This cross-fault movement indicates that the fault network controls regional groundwater flow to some degree but is not a complete barrier to flow. The cumulative distributions of adjusted age results for the watershed indicate that approximately 30 percent of the flow pathways transmit groundwater that was younger than 68 years old (post-1941) and that about 70 percent of the flow pathways transmit old groundwater. The particle-tracking results are consistent with the apparent ages and mixing ratios of CFC–12 and CFC–113 for the portal spring, which indicated that about 77 percent of the Canterbury Tunnel discharge is old (pre-1953) water. The model simulations also indicate that approximately 50 percent of the groundwater flowing through the study area was less than 200 years old and about 50 percent of the groundwater flowing through the study area is old water stored in low-permeability geologic units and fault blocks. As a final examination of model response, the conductance parameters of the Canterbury Tunnel and Leadville Mine Drainage Tunnel were manually adjusted from the calibrated values to determine if altering the flow discharge in one tunnel affects the hydraulic behavior in the other tunnel. The examination showed no substantial hydraulic connection.

The multidisciplinary investigation yielded an improved understanding of groundwater characteristics near the Canterbury Tunnel and the Leadville Mine Drainage Tunnel. Movement of groundwater between the Canterbury Tunnel and Leadville Mine Drainage Tunnel that was central to this investigation could not be evaluated with strong certainty owing to the structural complexity of the region, study simplifications, and absence of observation data within the upper sections of the Canterbury Tunnel and between the Canterbury Tunnel and the Leadville Mine Drainage Tunnel. There was, however, collaborative agreement between all of the analyses performed during this investigation that a substantial hydraulic connection did not exist between the Canterbury Tunnel and the Leadville Mine Drainage Tunnel under natural flow conditions near the time of this investigation.

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