Hydrogeology and Geochemistry of Acid Mine Drainage in Ground Water in the Vicinity of Penn Mine and Camanche Reservoir, Calaveras County, California: Summary Report, 1993–95

By Charles N. Alpers, Scott N. Hamlin, *and* Michael P. Hunerlach

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CONVERSION FACTORS, WATER-QUALITY INFORMATION, VERTICAL DATUM, ABBREVIATIONS AND ACRONYMS, AND WELL-NUMBERING SYSTEM

Multiply	By	To obtain
acre	0.4047	hectare
acre	4,047	square meter
cubic foot (ft^3)	0.02832	cubic meter
cubic foot per day (ft^3/d)	0.02832	cubic meter per day
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot squared per day (ft^2/d)	0.0929	meter squared per day
gallon (gal)	3.785	liter
gallon per day (gal/d)	0.004546	cubic meter per day
gallon per minute (gal/min)	0.004546	cubic meter per minute
inch (in.)	25.4	millimeter
mile (mi)	1.609	kilometer
square foot (ft^2)	0.09290	square meter

Temperature is given in degrees Celsius (°C), which can be converted to degrees Fahrenheit (°F) by the following equation:

$$°F = 1.8(°C)+32.$$

Water-Quality Information

Chemical concentrations in water are given in milligrams per liter (mg/L) or micrograms per liter (µg/L). One thousand micrograms per liter is equivalent to 1 milligram per liter. For concentrations less than about 7,000 mg/L, milligrams per liter is equivalent to "parts per million," and micrograms per liter is equivalent to "parts per billion."

Vertical Datum

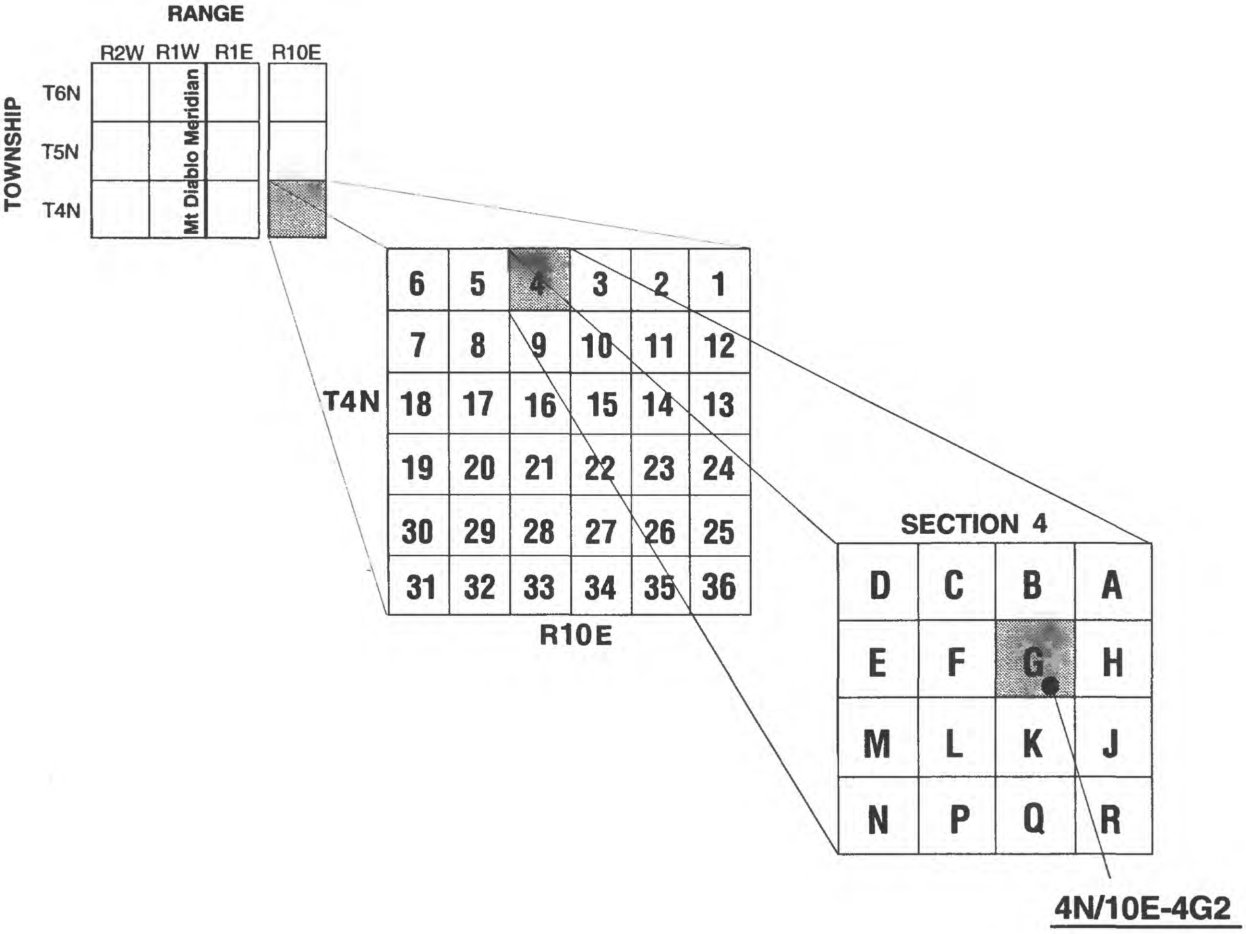
Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

Abbreviations and Acronyms

CDT, Canyon Diablo Troilite
CFC, chlorofluorocarbon
D, deuterium
g/d, gram per day
H, ^{1}H, hydrogen
^{2}H, hydrogen-2
HR, Hinckley Run
MR, Mine Run
mg/L, milligram per liter
mL, milliliter
mm, millimeter
mV, millivolt
NWQL, National Water Quality Laboratory
Eh, oxidation-reduction potential
^{16}O, oxygen-16
^{18}O, oxygen-18
redox, oxidation-reduction
^{32}S, sulfur-32
^{34}S, sulfur-34
USGS, U.S. Geological Survey
µg/L, microgram per liter
µm, micrometer
µS/cm, microsiemen per centimeter

Well-Numbering System

Wells are identified and numbered according to their location in the rectangular system for the subdivision of public lands. Identification consists of the township number, north or south; the range number, east or west; and the section number. Each section is divided into sixteen 40-acre tracts lettered consecutively (except I and O), beginning with "A" in the northeast corner of the section and progressing in a sinusoidal manner to "R" in the southeast corner. Within the 40-acre tract, wells are sequentially numbered in the order they are inventoried. The final letter refers to the base line and meridian. In California, there are three base lines and meridians; Humboldt (H), Mount Diablo (M), and San Bernardino (S). All wells in the study area are referenced to the Mount Diablo base line and meridian (M). Well numbers consist of 15 characters and follow the format 004N010E04G002M. In this report, well numbers are abbreviated and written 4N/10E-4G2. Wells in the same township and range are referred to only by their section designation, 4G2. The following diagram shows how the number for well 4N/10E-4G2 is derived.



Hydrogeology and Geochemistry of Acid Mine Drainage in Ground Water in the Vicinity of Penn Mine and Camanche Reservoir, Calaveras County, California: Summary Report, 1993-95

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ABSTRACT

Acid drainage from the Penn Mine in Calaveras County, California, has produced a zone of contamination in ground water between Mine Run Dam and Camanche Reservoir. Historically, contaminated surface runoff from the mine flowed directly into the Mokelumne River and into Camanche Reservoir after the construction of Camanche Dam in 1963. Interaction of surface water with sulfide-bearing waste rock and mill tailings has produced acidic drainage with pH values between 2.3 and 2.8 and high concentrations of sulfate and metals such as aluminum, cadmium, copper, iron, and zinc. Diversions and impoundments were constructed in 1978 to prevent or reduce surface runoff from the mine. Some of the impounded mine drainage infiltrates to the ground water through fractures in bedrock and flows toward Camanche Reservoir, although acid drainage has only rarely been detected in samples from Camanche Reservoir. The lowermost impoundment (Mine Run Reservoir) was treated with lime for a brief interval during 1993 to raise pH and to immobilize contaminants, but the impoundment has since been allowed to resume its untreated condition.

This report presents results from the ground-water investigation at the Penn Mine by the U.S. Geological Survey from October 1991 to April 1995. The specific objectives of the investigation were to evaluate (1) the quantity and quality of ground water flowing toward Camanche Reservoir from the Penn Mine area; (2) the ground-water transport of metals, sulfate, and acidity between Mine Run and Camanche Reservoirs; and (3) the hydrologic interactions between the flooded mine workings and other ground water and surface water in the vicinity.

The distribution of ground water at the Penn Mine is controlled by geologic features, hydraulic properties of rocks and fractures, and hydraulic gradients at the site. Geologic controls include fractures in bedrock, faults, and the contact between the two principal rock types in the area. Most flow occurs through fractures in the metavolcanic unit and along the contact zone with the underlying metasedimentary (slate) unit. The median hydraulic conductivity was about 15 to 75 times higher in the metavolcanic unit (0.15 foot per day) than in the slate unit (about 0.002 to 0.01 foot per day). The hydraulic conductivity in the metavolcanic unit was as high as 50 feet per day. The general direction of the hydraulic gradient in the contaminated ground-water zone between Mine Run Reservoir and Camanche Reservoir is westward toward Camanche Reservoir.

The composition of water from two wells that penetrate the mine workings upgradient from Mine Run Dam indicates a relatively reducing geochemical environment, in contrast to the relatively oxidizing environment indicated by ground-water samples from wells in the

contaminated zone near Mine Run Dam. Copper concentrations in water from the mine workings were 30 to 150 micrograms per liter; in contrast, copper concentrations were 34,000 to 120,000 micrograms per liter in the contaminated ground-water zone downgradient from Mine Run Dam. However, the range of zinc concentrations in the mine workings, 33,000 to 400,000 micrograms per liter, was similar to that of zinc concentrations in the zone near Mine Run Dam. Another distinctive characteristic of the mine water was the presence of exsolving gas that contains trace amounts of hydrogen and methane and little oxygen, indicating reducing conditions. Variations of stable-isotope ratios of sulfur and oxygen in aqueous sulfate suggest microbial reduction of sulfate in the underground mine workings. In contrast, water samples from wells in the contaminated ground-water zone near Mine Run Dam showed no chemical or isotopic evidence of sulfate reduction.

Ground-water discharge for the contaminated ground-water zone was estimated to be about 52 gallons per day for a hydraulic conductivity of 0.1 foot per day and gradient of 0.07. Actual values for discharge would vary with plume width, hydraulic gradient, and the water level of Camanche Reservoir. Corresponding fluxes of dissolved metals toward Camanche Reservoir for the discharge estimate of 52 gallons per day are: cadmium, 0.4 grams per day; copper, 2.2 grams per day; and zinc, 35 grams per day. These estimates could be refined by additional ground-water monitoring and by numerical modeling of ground-water flow. Concentrations of cadmium, copper, and zinc declined through the course of the study, probably reflecting dilution and dispersion of the plume. Approximately 12,000 gallons of contaminated water was pumped from the plume during aquifer tests in May 1994. Concentrations of cadmium, copper, and zinc declined by about one-half during the course of this pumping.

INTRODUCTION

Background

The Penn Mine is an abandoned mine in the Foothill copper–zinc belt in northwestern Calaveras County, California (Peterson, 1985) (fig. 1). This belt consists of massive-sulfide ore bodies that are composed primarily of pyrite, chalcopyrite, and sphalerite and that are associated with metavolcanic rocks of Jurassic age (Peterson, 1985; Martin, 1988). The Penn Mine property encompasses about 140 acres (Finlayson and Rectenwald, 1978) of the Mine Run and Hinckley Run drainages (fig. 2), which are intermittent tributaries to Mine Run Reservoir, an unlined impoundment that occasionally has spilled to Camanche Reservoir. The area has 20 or more shafts, several adits, and numerous open pits and cuts; two smelters and several mills were operated at the site (Clark and Lydon, 1962). About 10.5 mi of underground workings were excavated to a depth of 3,300 ft (Heyl and others, 1948). Several acres of mill tailings and unmilled waste rock from these mine workings are exposed on the surface (Bond, 1988); smelter slag averaging more than 6 weight-percent zinc (Wiebelt and Ricker, 1949) was dumped in a 1,500-foot-long area immediately adjacent to a former channel of the Mokelumne River. (Finlayson and Rectenwald, 1978). The distribution of waste rock, tailings, and mixed and affected soils was determined by Davy Environmental (1993a) (fig. 2). The history of the Penn Mine was presented in more detail by Hamlin and Alpers (1995).

Historically, contaminated surface runoff from the Penn Mine flowed directly from the Hinckley Run and Mine Run drainages into the channel of the Mokelumne River (now Camanche Reservoir). Some of this acidic surface runoff probably infiltrated into ground water through fractures in bedrock. Pardee Dam was completed on the Mokelumne River, about 3 mi upstream from the Penn Mine, in 1929. Camanche Dam, completed in 1963 about 9 mi downstream from the mine, flooded part of the Mokelumne River basin to approximately 0.5 mi upstream of Penn Mine. The altitude of the spillway of Camanche Dam is 236 ft above sea level (fig. 2). The slag pile adjacent to the former Mokelumne River channel ranges in altitude

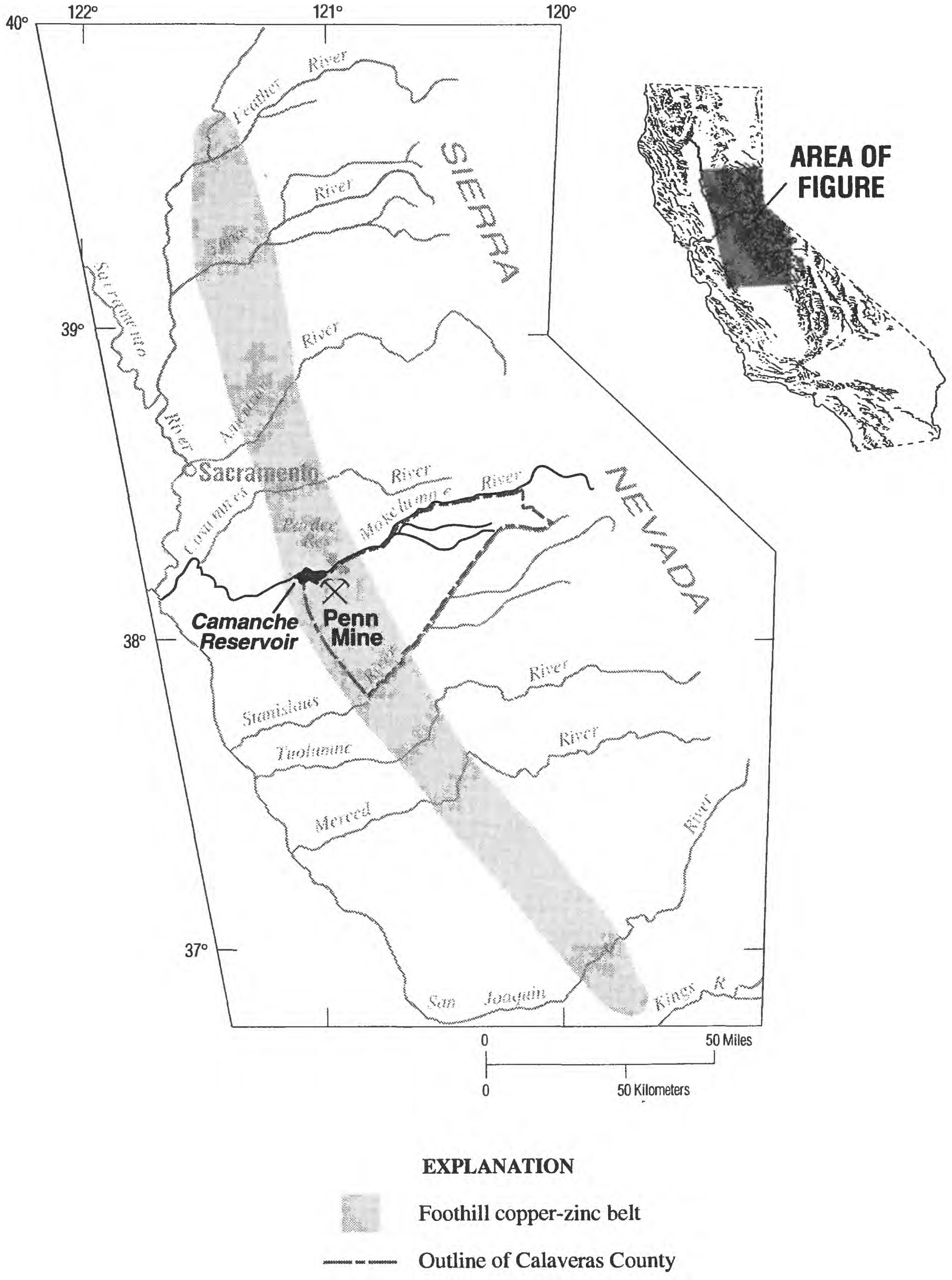


Figure 1. Location of Penn Mine and Camanche Reservoir in Foothill copper-zinc belt of California (after Peterson, 1985).

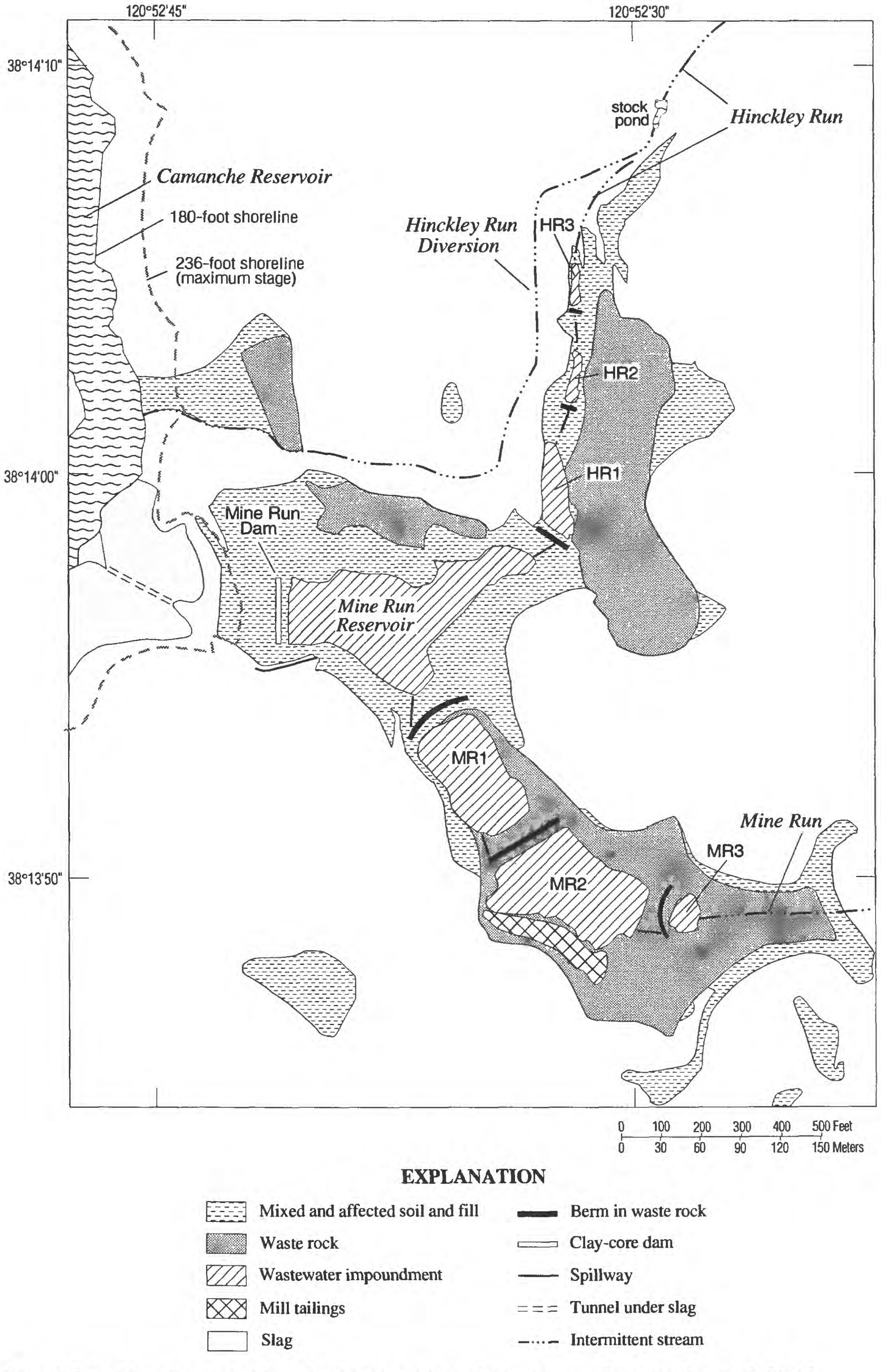


Figure 2. Penn Mine site and location of unlined wastewater impoundments, Calaveras County, California (modified from Davy Environmental, 1993a).

from about 190 to 220 ft (Davy Environmental, 1993a); consequently, flooding of the slag pile begins when the water level of Camanche Reservoir rises above about 190 ft.

In response to incidents of fish mortality, several channels were constructed in 1978 at the Penn Mine site to divert unpolluted water from upstream areas on the Hinckley Run (HR) and Mine Run (MR) drainages to Camanche Reservoir (California Regional Water Quality Control Board–Central Valley Region, written commun., 1978, 1979). Hinckley Run drains from the northeast into Mine Run Reservoir and contains impoundments HR1, HR2, and HR3 (fig. 2). Mine Run drains from the southeast into Mine Run Reservoir and contains impoundments MR1, MR2, and MR3 (fig. 2). The seven impoundments (Mine Run Reservoir, HR1-3, and MR1-3) were constructed to capture contaminated runoff from the site in 1978, replacing two or more previously existing impoundments. Mine Run Dam was constructed from nonreactive earth materials with a clay core. The remaining dams or dikes were constructed from available soil, sulfide-bearing waste rock, and mill tailings. The impoundments were unlined, except for MR1, which had a leaky and ineffective plastic liner. Some infiltration of acidic surface water into the underlying ground water probably occurred in Mine Run and Hinckley Run before construction of the surface impoundments in 1978.

Construction of the impoundments reduced, but did not eliminate, releases of surface runoff to Camanche Reservoir. Surface water discharged from Mine Run Reservoir to Camanche Reservoir during 1979 to 1984, 1986, and 1993; the 1993 discharge was treated with hydrated lime [$Ca(OH)_2$] (Richard Sykes, East Bay Municipal Utility District, oral comm., 1993). To reduce the volume of surface drainage in the impoundments, water was recirculated from the lowest impoundment (Mine Run Reservoir) to a higher impoundment (MR3) (Bond, 1988). The recirculation of water in the ponds enhanced the evaporation of contaminated waters and also increased the contact time of acid drainage with the reactive waste rock and tailings (Bond, 1988). The operation of the impoundment system was described in greater detail by Hamlin and Alpers (1995, 1996).

Some acid water from Mine Run Reservoir has infiltrated to ground water, forming an acidic ground-water plume in the area of Mine Run Dam (Hamlin and Alpers, 1995). Characterization of the acidic ground-water plume downgradient from Mine Run Dam will facilitate management and remediation of the contamination. This study was done by the U.S. Geological Survey (USGS) in cooperation with the California Regional Water Quality Board–Central Valley Region (herein referred to as the Regional Water Board) and the East Bay Municipal Utility District (herein referred to as the Utility District).

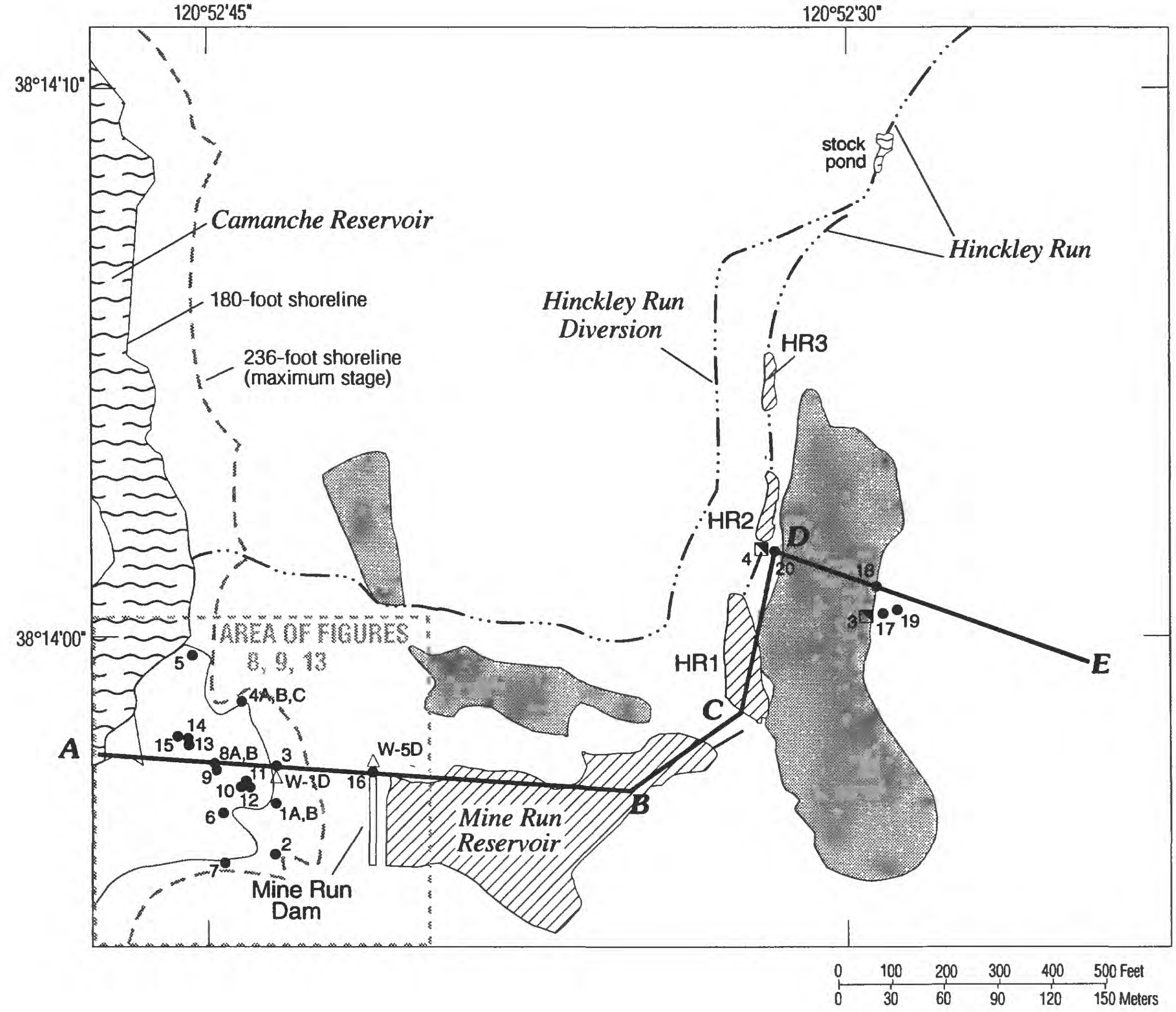
Purpose and Scope

The goals of the ground-water investigation by the USGS in the Penn Mine area were to evaluate (1) the quantity and quality of ground water flowing toward Camanche Reservoir from the Penn Mine area; (2) the transport of metals, sulfate, and acidity in ground water between Mine Run and Camanche Reservoirs; and (3) the hydrologic interactions between the flooded mine workings and other ground water and surface water in the vicinity. This report summarizes the findings of 3 1/2 years of study (October 1991 through April 1995), with emphasis on the results from December 1993 to April 1995. Other USGS reports (Hamlin and Alpers, 1995, 1996) presented findings from the first and second years of the investigation. Results of this USGS investigation provide data and information about the ground-water system at Penn Mine that are needed to develop effective pollution-abatement measures and remediation plans for the site.

The USGS investigation was designed to complement and supplement other investigations being done in support of remediation at Penn Mine. A report that characterized mine wastes, surface water, and shallow ground water at Penn Mine was prepared by Davy Environmental (1993a). Calculation of hydrologic-response estimates for the watersheds at Penn Mine were prepared by James Luzier and R. Koch (1992, written communication to Davy Environmental). Davy Environmental (1993b) also prepared a report that screened selected remedial alternatives for Penn Mine. The Bureau of Reclamation (1995) provided a preliminary review and analysis of the proposed remedial action alternatives described by Davy Environmental (1993b). A draft environmental impact report that evaluated additional remedial action alternatives was prepared (Golder Associates, 1996a) and a specific alternative that involved waste removal with an onsite landfill (alternative 5A) was selected by the Regional Water

Board and the Utility District (Golder Associates, 1996b). Public comments on the draft environmental impact report were received and commented upon (Golder Associates, 1997), after which the report was certified as "final" by the respective Boards of Directors of the Regional Water Board and the Utility District. Construction of the onsite landfill began during 1998.

Previous reports (Hunerlach and Alpers, 1994; Hamlin and Alpers, 1995, 1996) described the ground-water quality, hydrogeology, geologic structure, ground-water movement, and the distribution of acid mine drainage in the ground-water system on the basis of data from 20 boreholes drilled by the USGS (fig. 3). This report includes additional water-level and water-quality data for the period December 1993



EXPLANATION

▨ **Waste rock**

▨ **Wastewater impoundment**

☐ **Slag**

—··· — **Intermittent stream**

A*——*E **Line of section**

●2 **USGS well and number** - Letters denote depth intervals separated by inflatable packers

3◪ **Mine shaft and number**

△W-5D **EBMUD well and number**

Figure 3. Location of monitoring wells and conceptual hydrogeologic section line, Calaveras County, California.

through March 1995. Water-level data collected during the entire period of study to assess hydraulic gradients and seasonal changes in the ground-water system are discussed. Composite and depth-specific water-quality samples were collected once or twice per year during the study period from several of the USGS wells and are evaluated in this report. Water-quality data are compiled and analyzed to determine chemical relations and to evaluate mineral-water equilibria. This report also presents results from an aquifer test completed during May 1994 to evaluate hydraulic characteristics of the fractured bedrock (appendixes 1 and 3).

Acknowledgments

The authors gratefully acknowledge several USGS colleagues for assistance with this study. Paul A. Hsieh (Menlo Park, Calif.) assisted with the design, procurement, and installation of downhole inflatable packers. Frederick L. Paillet (Denver, Colo.) supervised field measurements and data analysis of borehole geophysics, including conventional logs (caliper, gamma, etc.), acoustic televiewer logs, and heat-pulse flowmeter tests; assistance from Roger H. Morin and Richard E. Hodges on these tasks also is appreciated. Sampling and analysis for chlorofluorocarbons was done with field and laboratory assistance by Eurybiades (Ed) Busenberg (Reston, Va.). Stable-isotope values for oxygen and sulfur in dissolved sulfate (reported by Hamlin and Alpers, 1996) were determined under the supervision of Robert O. Rye (Denver, Colo.). Interpretation of aquifer-test results was facilitated by discussions with Allen Shapiro (Reston, Va.), Clark Londquist (Sacramento, Calif.), and Anthony Buono (San Diego, Calif.). Interpretation of geochemical correlations was improved by discussions with Terry Rees (San Diego, Calif., and Carson City, Nev.).

METHODS

Drilling, Geophysical Logging, and Well Construction

The USGS completed a total of 20 boreholes by air-rotary drilling at Penn Mine (labeled GS-1 through -20 in figure 3). Intervals in boreholes to monitor ground water were left uncased and ranged in depth from 10 to 260 ft. Visual inspection of drill cuttings, caliper logs, and natural gamma logs were used to evaluate lithologic variations. In addition, an acoustic televiewer was used to determine the magnitude and direction of individual fractures at different depths in the monitoring wells, and a heat-pulse flowmeter was used to identify fractures that were hydraulically active. Details of well construction and lithologic logs were presented by Hamlin and Alpers (1996).

Segments of selected boreholes were isolated for additional testing to distinguish flow and chemical characteristics of individual fracture zones. Four inflatable packers were installed for the duration of the study in three of the fractured-rock monitoring wells. Once inflated, the packers virtually eliminate vertical ground-water flow and mixing. Additional details on the construction of the packers were reported by Hamlin and Alpers (1995). Single packers were installed at sites GS-1 and -8. Upper intervals were designated as "A" and lower intervals as "B" or “C”. The packer at site GS-1, set at a depth of 80 ft below land surface, separates the upper well (GS-1A) from the lower well (GS-1B). The upper well monitors the metavolcanic unit and the metavolcanic-slate contact at a depth of 70 ft below land surface. The lower well monitors the slate unit exclusively. The packer at site GS-8 was set at a depth of 76 ft below land surface. Well GS-8A monitors the metavolcanic unit and the metavolcanic-slate contact; GS-8B monitors ground water in the slate unit. Two packers (a "straddle" assembly) were installed at site GS-4 at depths of 55 and 80 ft below land surface. The wells are designated GS-4A, -4B, and -4C from shallow to deep levels. Well GS-4A monitors ground water in the upper part of the metavolcanic unit; GS-4B monitors the lower part of the metavolcanic unit and the metavolcanic-slate contact; and GS-4C monitors the slate unit exclusively.

Well Measurements and Aquifer Test

Water-level measurements in wells were made using a hand-held electric sounder. Measurements were made periodically between December 1993 and June 1994, and a complete series of measurements was made in most wells on March 1, April 4, May 9, and June 14, 1994. Wells GS-1 through -15, in the slag area downgradient from Mine Run Dam, became inundated and inaccessible for the purposes of water-level measurements when water level in Camanche Reservoir rose above 220 ft above sea level. This inundation occurred during the following periods: May

26 to October 21, 1993; March 16 to April 5, 1995; and June 1 to October 2, 1995 (East Bay Municipal Utility District, oral comm., 1996). During these periods of inundation, the USGS wells in the slag area were sealed to prevent direct interchange of water through the well bores between the reservoir and contaminated ground water.

An aquifer test was done in well GS-8A during May 10–12, 1994, to evaluate hydraulic connection with adjacent wells. Well GS-8A was pumped with a 2-inch-diameter electrical vertical-lift centrifugal pump at a rate of 1.8 to 4.4 gal/min for about 24 hours. Pumping rate, determined using a 5-gallon bucket, was 1.8 to 2.5 gal/min for the first 34 minutes of the test and was then increased to 4.2 ± 0.2 gal/min for the remainder of the test (appendix 1). During the aquifer test, water levels were measured at 5-minute intervals in wells GS-11, -13, -14, and -15 using automated data loggers with floats, counterweights, and shaft encoders. Additionally, manual measurements were made with an electric sounder at wells GS-1A, -1B, -3, -4A, -4B, -4C, and -8B. Water levels before, during, and after the aquifer test are given in appendix 1. Hourly data are reported for wells where water levels did not change rapidly.

Geochemical Sampling and Analysis

During the first year of the study, wells at sites GS-1 through -8 were sampled during January–February 1992 and April 1992 (Hamlin and Alpers, 1995). Wells GS-9 through -20 were drilled and constructed during November 1992, and selected wells at sites GS-1 to -20 were sampled during December 1992 (Hamlin and Alpers, 1996). Mine Run Reservoir also was sampled at that time, as were two wells (W-1D and W-5D, fig. 3) that had been installed to depths of 48 and 49 ft, respectively, by the Utility District in 1989 and 1990 (Brown and Caldwell Consultants, 1991). Methods used for sampling during 1991–92 were described by Hamlin and Alpers (1995, 1996).

Additional water-quality sampling was done during December 1993 and May–June 1994. Specific conductance, pH, temperature, dissolved oxygen, and oxidation-reduction (redox) potential (Eh) were measured in the field for samples collected during pumping or bailing. These properties were measured during pumping using a flow-through chamber to prevent aeration. The redox potentials were measured using a platinum electrode and then converted to Eh values using the methods described by Makita and Fujii (1992). After field properties stabilized, water samples were collected and processed using standard methods adopted by the USGS (Wood, 1976). As part of the quality control program, an equipment blank (or "field-blank sample") was run through the sampling process, including filtration and preservation, during each round of sampling. Traces of calcium, magnesium, sodium, sulfate, chloride, silica, zinc, aluminum, and iron were detected in one or more of the four field-blank samples (see table 5 at back of report). In all analyses, the detected concentrations of these constituents in the field-blank samples were near detection limits and did not present a significant contamination problem; other dissolved constituents—including potassium, fluoride, cadmium, copper, lead, manganese, and silver—were determined to be less than detection limits in the field blanks. Samples for both anion and cation analyses were filtered using 0.10-μm (micrometer) membranes of 142-millimeter diameter mounted in a plate filter assembly; samples for cation analyses also were acidified with hydrochloric or nitric acid to pH values of about 1. Samples for nutrient analysis were filtered, preserved with mercuric chloride, and chilled. All samples were analyzed by the USGS National Water Quality Laboratory (NWQL) in Denver, Colo.

The USGS NWQL analyzed nine cations (cadmium, calcium, copper, iron [total], magnesium, manganese, potassium, sodium, and zinc) by flame atomic–absorption spectroscopy (AAS) and one element (lead) by graphite furnace AAS. The other cation analyzed (aluminum) was done by direct-current plasma atomic-emission spectroscopy. Three anions (chloride, fluoride, and sulfate) were analyzed by ion chromatography. Bromide was analyzed at the NWQL by a colorimetric method using fluorescein with an auto-fluorimetric device. Silica was determined by a colorimetric method using molybdate blue. Dissolved total and ferrous iron were determined by the USGS in Sacramento, Calif., using a colorimetric method with FerroZine as the complexing agent.

Ground water was sampled at the Penn Mine in December 1993 to determine its age, using chlorofluorocarbon (CFC) methods described by Busenberg and Plummer (1992). The CFCs have been used recently as environmental tracers in dating ground water less than 50 years old (Plummer and others, 1993). These chemically stable, man-made compounds have been manufactured since the 1930s and 1940s (Dunkle and others, 1993). Two chlorofluoromethanes (CFC-11 and CFC-12) and one chlorofluoroethane (CFC-113) were detected in the ground-water samples using purge-and-trap gas chromatography.

Sampling for CFC analysis required special handling to avoid atmospheric contamination. Aluminum tubing, cleaned with methanol, was used with a Bennett pump. After several well volumes were pumped from each well, ground-water samples were collected and sealed in 50-mL (milliliter) glass ampules that had been purged with inert gas. A total of three to five ampules were were collected at each well. The ground-water samples were analyzed by the USGS in Reston, Va.

Stable isotopes of hydrogen and oxygen were determined by the USGS NWQL using raw samples (not filtered or acidified) collected in glass bottles that had been predried in an oven at 110°C. The most abundant isotopes that compose the water molecule are oxygen-16 (^{16}O), oxygen-18 (^{18}O), hydrogen (^{1}H or H), and hydrogen-2 (^{2}H; also known as deuterium, D). The heavy isotopes ^{18}O and ^{2}H exist naturally in global average proportions of about 0.2 percent of total oxygen and 0.07 percent of total hydrogen in water molecules.

Ratios of the heavy to light isotopes, *R*, are expressed in delta units (δ), which are parts per thousand (per mil) differences relative to an arbitrary standard known as standard mean ocean water (V-SMOW):

$$\delta(‰) = [(R-R_{std})/R_{std}] \times 1000, \qquad (1)$$

where R and R_{std} are the isotope ratios (D/H or $^{18}O/^{16}O$) of the sample and standard, respectively. Relative concentrations of ^{2}H and ^{18}O, expressed as δD and $\delta^{18}O$, generally correlate in a linear fashion. Graphic representation of this relation for global precipitation data produces a straight line known as the global meteoric water line (Craig and others, 1963), defined by

$$\delta D = 8\delta^{18}O + 10. \qquad (2)$$

The most abundant stable isotopes of sulfur are sulfur-34 (^{34}S) and sulfur-32 (^{32}S). The composition of the ratio $^{34}S/^{32}S$ relative to the standard Canyon Diablo Troilite (CDT) is commonly expressed as $\delta^{34}S$ (Krouse, 1980) using a definition similar to that in equation 1.

HYDROGEOLOGY

The study area is in the western metamorphic belt of the Sierra Nevada (Clark, 1964). Rocks in the vicinity of the mine include the Gopher Ridge Volcanics, a metavolcanic complex composed of one intrusive and five extrusive units, and the metasedimentary Salt Spring Slate, both of Jurassic age (Peterson, 1985). The metavolcanic-slate contact strikes northwest and dips about 20 degrees to the northeast; the contact was encountered at depths between 45 and 183 ft below land surface in boreholes GS-1 through -16 in the area west of Mine Run Reservoir (Hamlin and Alpers, 1996). In the area west of Mine Run Reservoir, this contact has been mapped as the Campo Seco Fault (Heyl and others, 1948), a low-angle fault that may be responsible for the relatively intense fracturing in this zone. In the mine workings, the Campo Seco Fault was encountered within the metavolcanic unit in shaft 3 (figs. 3 and 4) at an altitude between 600 and 700 ft below sea level (Heyl and others, 1948). Geology and mineralogy of the area were described in more detail by Hamlin and Alpers (1995, 1996).

Water Levels and Hydraulic Gradients

A conceptual hydrogeologic section showing possible and probable directions of ground-water flow is shown in figure 4. The overall hydraulic gradient in the ground-water system is toward the west (Hamlin and Alpers, 1995). Water levels for Camanche Reservoir and the USGS wells in the study area for December 1993 to June 1994 are given in appendix 2. Water levels in Camanche Reservoir were measured at the dam about 8 mi west of Penn Mine (East Bay Municipal Utility District, written commun., 1994, 1996). A comparison of water levels in selected USGS wells, Camanche Reservoir, and Mine Run Reservoir for December 1991 through June 1994 is shown in figures 5 and 6. During the study, water levels in well GS-16 (north abutment of Mine Run Dam, see fig. 3), although 2 to 4 ft lower than the level of Mine Run Reservoir (figs. 5 and 6), show a general correlation with the levels of this impoundment. Also, water levels in several of the wells in the slag area (fig. 3) showed direct correlation with levels of Camanche Reservoir, thus indicating a hydraulic connection, probably through fractures in the metavolcanic rock. Other wells showed either no correlation or correlation only when water levels in Camanche Reservoir were higher than about 190 ft above sea level.

During November 1991 through December 1992, the water level of Camanche Reservoir was relatively low, ranging between about 173 and 188 ft above sea level. As shown in figure 5, water levels in well GS-8A, which is representative of most of the wells open to fractured metavolcanic rocks, were within 2 ft of those of Camanche Reservoir. In contrast, water levels in some of the wells on the eastern and southern sides of the slag area (wells GS-1A, -2, and -6) were several feet higher than those of Camanche Reservoir (Hamlin and Alpers, 1995). Well GS-3 (open to metavolcanic rocks and slate), located on the eastern edge of the slag pile (fig. 3), was the only well in the slag area in which water levels were

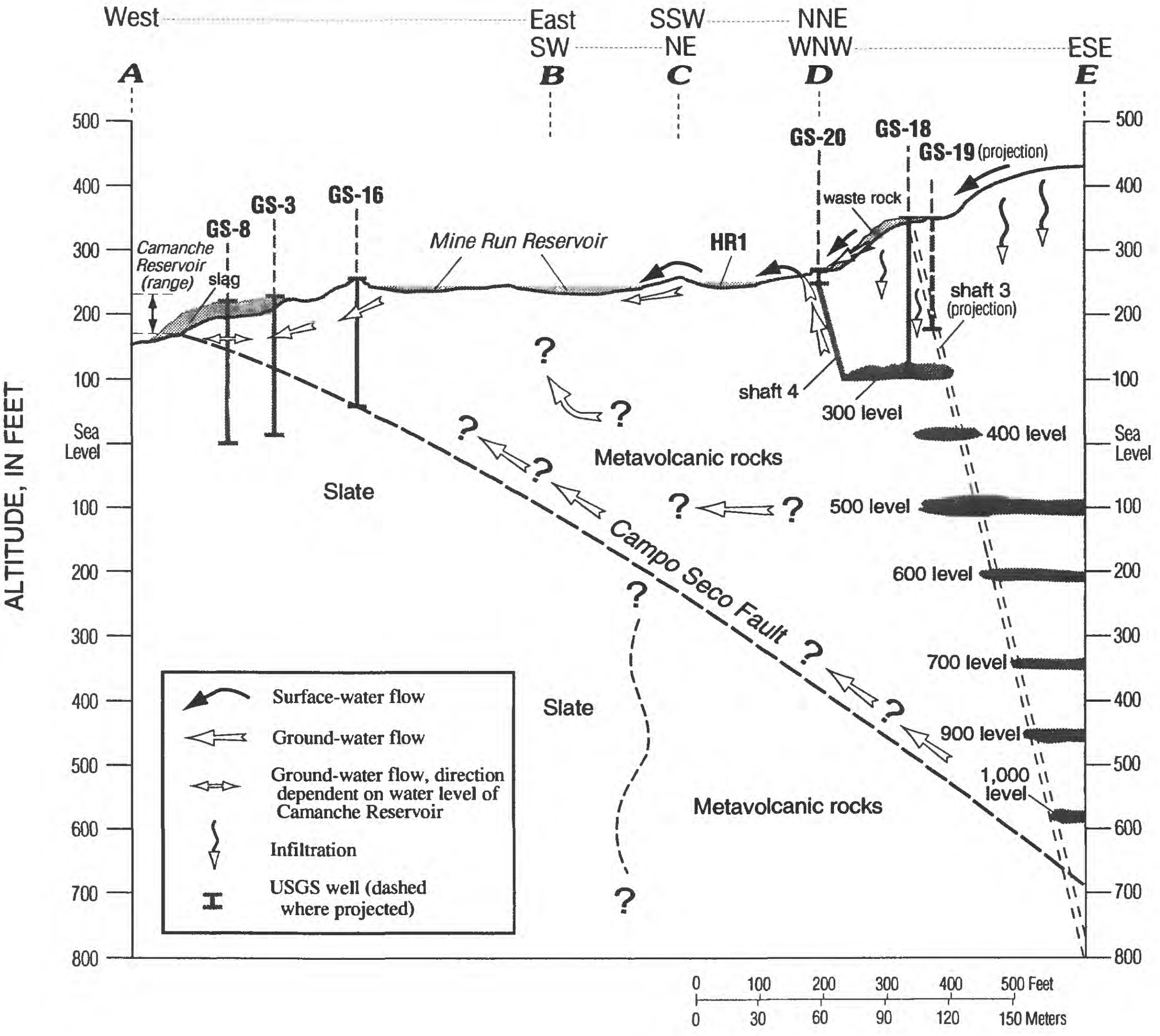


Figure 4. Conceptual hydrogeologic section A-B-C-D-E between Camanche Reservoir and the underground mine workings. Section is based on data from Camanche and Mine Run Reservoirs and wells GS-3, -8, -14, and -16.

consistently higher than those of Camanche Reservoir and those in the other wells in the slag area (figs. 5 and 6). During May to October 1993, water levels in Camanche Reservoir rose above 220 ft, inundating all the wells in the slag area. As the reservoir level declined to about 203 ft in June 1994, water levels in most slag-area wells (except GS-1B [open to slate] and -3 [open to metavolcanic rocks and slate]) also declined (fig. 6 and appendix 2) maintaining water levels within 2 ft of those of Camanche Reservoir. These wells include GS-1A, -2, and -6, which were the only wells that showed water levels significantly higher than those

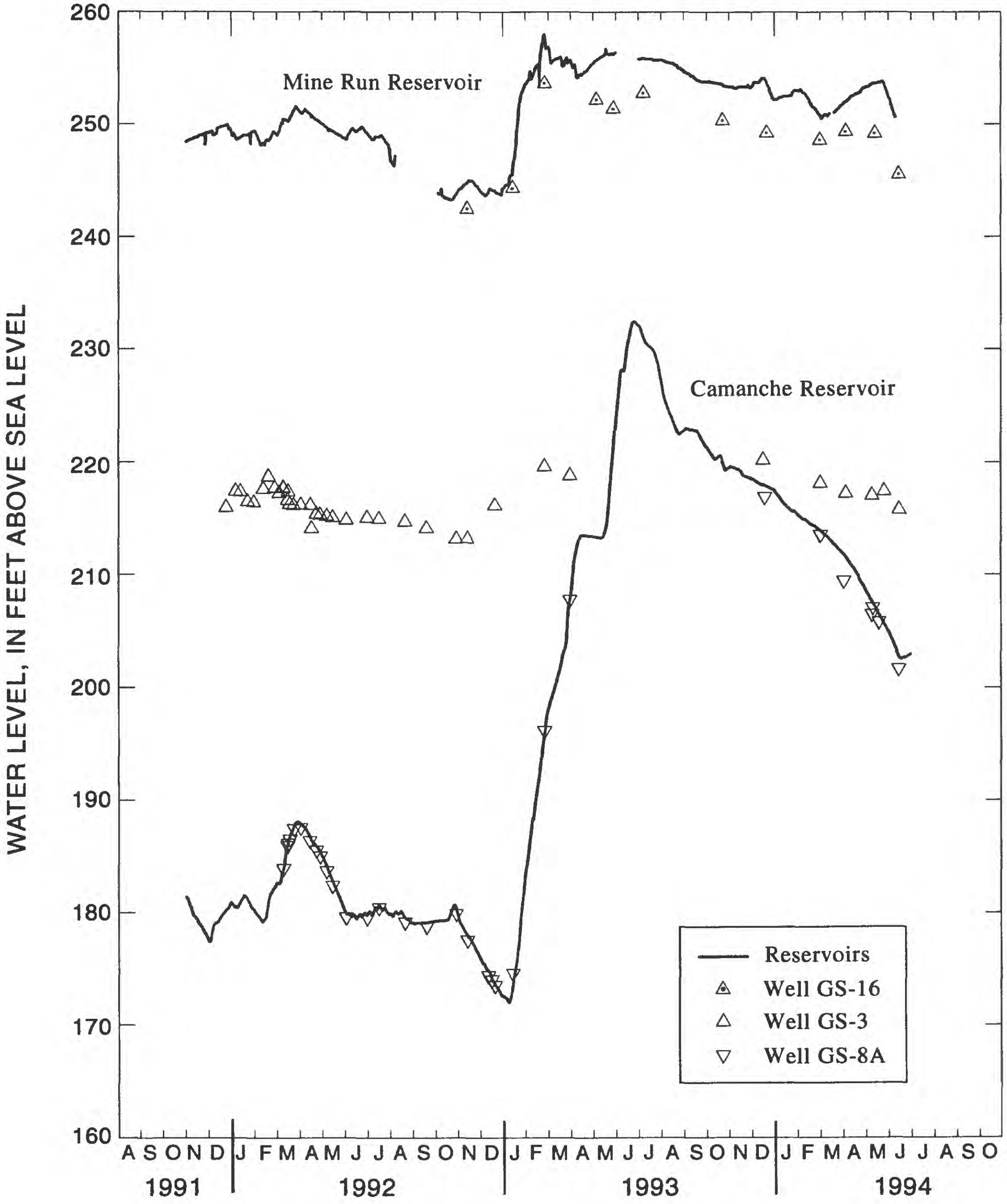


Figure 5. Variation in water levels in Camanche Reservoir, Mine Run Reservoir, and selected wells at the Penn Mine, Calaveras County, California, December 1991 through June 1994.

of Camanche Reservoir when reservoir levels were below about 190 ft (see appendix 2). Because these wells are open to either metavolcanic rocks or a combination of metavolcanic rocks and slate, it is possible that, as water in Camanche Reservoir rises above a certain level (possibly about 190 ft), fractures higher in these well bores become saturated, causing these wells to maintain water levels within 2 ft of those of Camanche Reservoir. This response is similar to that of other wells open to metavolcanic rocks in the slag area.

Although water levels in many of the wells tracked within 2 ft of the water level of Camanche

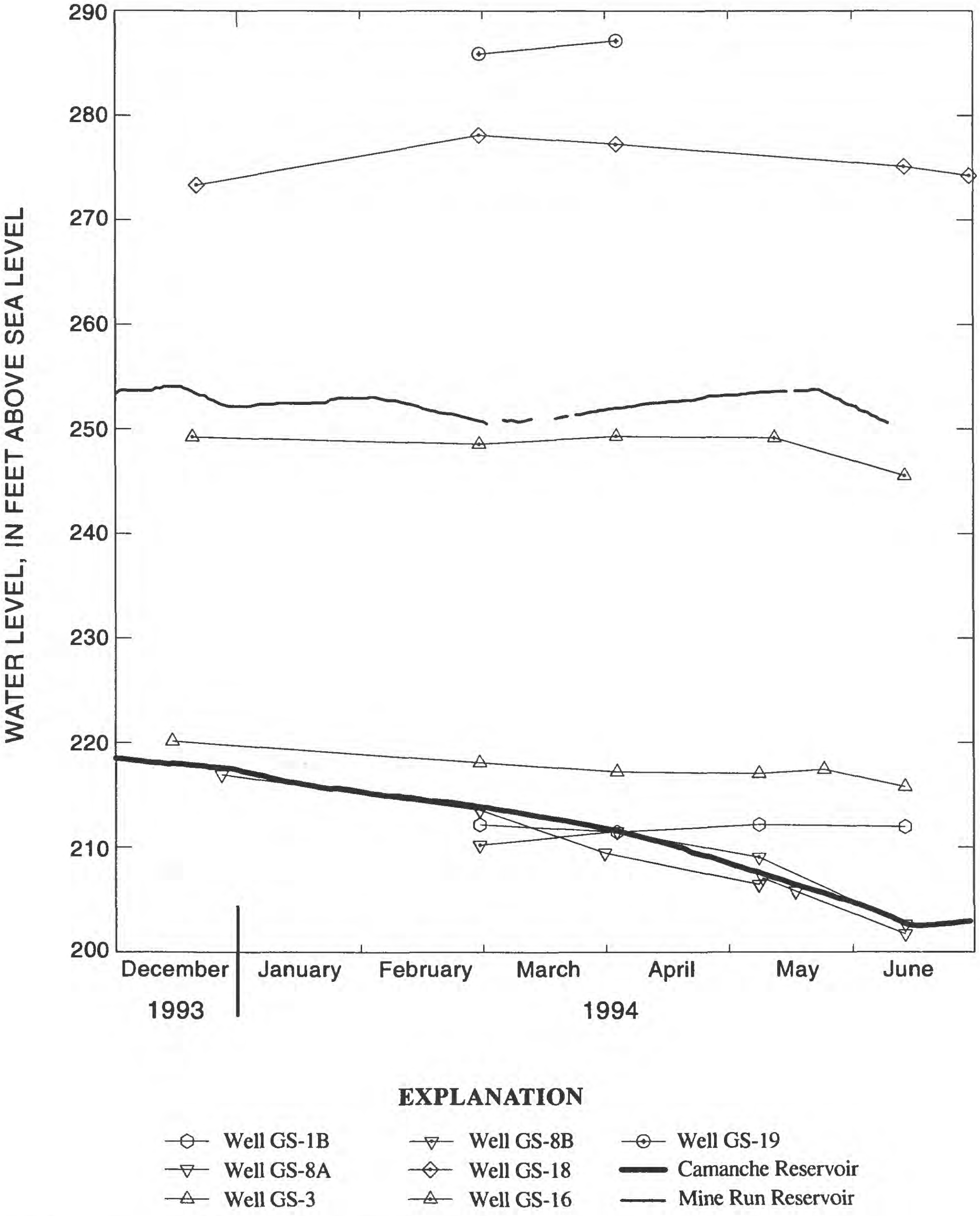


Figure 6. Water levels in Camanche Reservoir, Mine Run Reservoir, and selected wells at the Penn Mine, Calaveras County, California, December 1993 through June 1994.

Reservoir, the direction of ground-water flow in the area is uncertain. Gradients seem to be sometimes eastward and sometimes westward. Another factor that may influence water levels and ground-water gradients is variable water density. However, because the water table is relatively flat in the slag area, tighter altitude control between the wells and Camanche Dam (8 mi from Penn Mine) is needed; the altitude control for the USGS wells, a secondary benchmark on top of Mine Run Dam, was removed during a construction operation in 1993 (possibly introducing a control error). Installation of a staff gage in Camanche Reservoir near the Penn Mine site would eliminate this uncertainty for any future studies. Despite this possible control error, water levels tracked closely, indicating good hydraulic connection between the reservoir and these wells. Also, when levels in Camanche Reservoir decline, the westward hydraulic gradient from Mine Run Reservoir increases, as would be expected, therefore increasing the potential for transport of contaminants toward Camanche Reservoir.

Results of Aquifer Testing

On May 10–12, 1994, an aquifer test (24-hour pumping and 24-hour recovery) was undertaken at the site. Except for the first 34 minutes of the test, well GS-8A was pumped at a rate of 4.0 to 4.4 gal/min (appendix 1). Also, on six occasions during the test, the pump was off for between 2 and 11 minutes because of mechanical failure. Water levels were measured during the aquifer test at several wells in the area west of Mine Run Reservoir (fig. 7, appendix 1).

During the first 45 minutes of the test, the water level in well GS-8A declined from 14.23 ft to 14.64 ft below the measuring point, and then slowly declined to about 14.77 ft during the remainder of the pumping period. The only observation well to respond to the pumping was GS-11, which is about 50 ft southeast of GS-8A. The water level in this well declined from 14.05 ft to 14.25 ft below the measuring point during the first 99 minutes of the test, and to 14.39 ft at 10:17 a.m. May 11 (1,150 minutes into the test), the last measurement of the well during pumping. This latter rate of decline in water level (about 0.12 ft/d) was observed during the aquifer test in other wells open to fractured metavolcanic rocks (GS-1A, -4A, -4B, -4C, -13, and -14), and in one well open to fractured slate (GS-15). A similar rate of decline was also observed for several weeks in Camanche Reservoir prior to and after the test. Therefore, it is interpreted as a general water-level decline for the area west of Mine Run Reservoir. Furthermore, these observations indicate that Camanche Reservoir has good connection with, and likely controls, ground-water levels in wells open to fractured metavolcanic rocks west of Mine Run Reservoir. Some of the other wells in the slag area (GS-1B, -3, and -8B) did not respond to the pumping, nor did they show the gradual decline observed in other wells and in Camanche Reservoir. These wells are completed either in slate or in metavolcanic rocks of relatively low hydraulic conductivity (Hamlin and Alpers, 1995) in which rapid response would not be expected.

After pumping ceased on May 11, 1994, the water levels in wells GS-8A and -11 recovered quickly, and then resumed a gradual decline at a rate similar to that observed during most of the pumping period (fig. 7). In analyzing the test (appendix 3), the general areal decline was subtracted from the total water-level decline in wells GS-8A and -11 to determine the drawdown caused by pumping.

The highest estimates of hydraulic conductivity determined at Penn Mine are in the highly fractured metavolcanic rocks associated with the Campo Seco Fault zone (contact between the metavolcanic rocks and the slate) in the area west of Mine Run Reservoir. An analysis of drawdown during the aquifer test in well GS-8A (pumped well), which derives water principally from this highly fractured zone, indicates a hydraulic conductivity of 39 ft/d (appendix 3). This value compares favorably with results obtained using other methods of estimating hydraulic conductivity that utilized drawdown and recovery data during water sampling (Hamlin and Alpers, 1995). The Cooper-Jacob straight-line method (Driscoll, 1987) yielded 11 ft/d, and the Huntley-Nommenson-Steffey methods of analysis of specific-capacity data (Huntley and others, 1992) yielded 42 ft/d. For seven other wells open to metavolcanic rocks, the values ranged from 0.01 to 57 ft/d, with a median value of 0.15 ft/d (Hamlin and Alpers, 1995). By comparison, for three wells open to the less permeable slate, estimates of hydraulic conductivity ranged from 0.0005 to 0.02 ft/d, with a median value of 0.005 ft/d (Hamlin and Alpers, 1995).

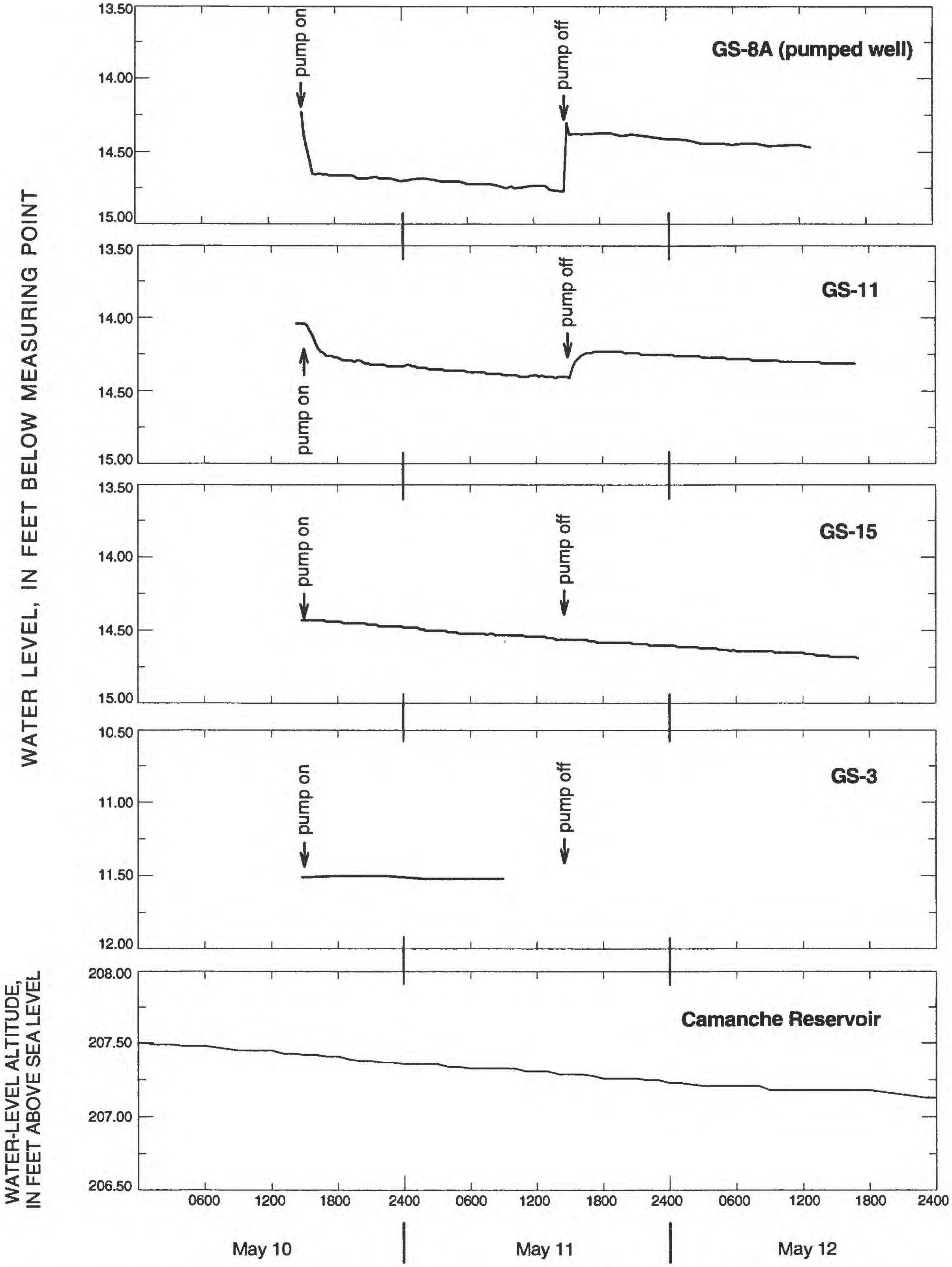


Figure 7. Water levels in Camanche Reservoir and selected wells at the Penn Mine, Calaveras County, California, during the aquifer test, May 10–12, 1994.

Ground Water in the Mine Workings

The hydraulic heads in the area of shafts 3 and 4 (fig. 3), as measured in well GS-18, were about 60 to 75 ft higher than those in the area west of Mine Run Dam. This could be sufficient to drive ground-water flow from the underground mine workings to the slag area along the Campo Seco Fault. During mining, pumping of about 20 gal/min was required to dewater the mine to a depth of about 1,400 ft below land surface (Wisser, 1961). Most of the mine was observed to be relatively dry during underground operations, with most of the inflow coming in discrete, highly fractured zones. It is possible that ground-water flows from the underground mine workings to Mine Run Reservoir along bedrock fractures (fig. 4). Additional monitoring wells would need to be constructed to investigate this possibility.

Within the mine workings, shaft 3 (fig. 3) plunges 70 to 80 degrees to the northeast and connects numerous tunnels and stopes (fig. 4) to a depth of more than 3,000 ft below land surface (Heyl and others, 1948). In 1978, the upper part of this shaft was filled with mine waste and soil from the surface to an unknown depth (Bond, 1988). Wells GS-17 and -19 intersect shaft 3 at depths of 74 and 140 ft, respectively, below land surface; both wells encountered orange, clay-rich mud at the depth of the mine workings. Well GS-18 intersects the 300 level of the mine workings at a depth (251 ft) where no mud was encountered, indicating that this part of the mine workings was not backfilled or caved. (Levels of the mine were named to correspond to approximate distance down the shaft, which corresponds roughly to depth below land surface [Heyl and others, 1948].) Water-level differences between wells GS-17, -18, and -19 indicate that these wells are not in direct hydrologic connection through the mine workings.

Shaft 4 (figs. 3 and 4) also plunges about 70 to 80 degrees to the east-northeast and connects with the 300 level of the underground mine workings in the vicinity of shaft 3 (Heyl and others, 1948). The upper part of shaft 4 was filled with mine waste and soil in 1978 (as described above for shaft 3), but it was not sealed with respect to water flow. Well GS-20 intersects shaft 4 at a depth of 11 to 23 ft below land surface. During 1992–93, water-level altitudes in well GS-20 were very similar to those in well GS-18 (Hamlin and Alpers, 1996), indicating that the primary hydraulic connection between these two wells is probably though the open mine workings rather than through fractured metavolcanic rocks. As a result of this connection, artesian flow occurs from shaft 4 and well GS-20 when the hydraulic head in the mine workings, as measured in well GS-18, exceeds the altitudes of these discharge points (Hamlin and Alpers, 1996), which are about 280 and 281 ft above sea level, respectively. A positive correlation between water levels in well GS-18 and the artesian flow rates from shaft 4 seeps and well GS-20 was noted for data collected from January to May 1993 (Hamlin and Alpers, 1996). Additional data from March 1995 showed a combined flow from the shaft 4 seeps and well GS-20 of about 40 gal/min, corresponding to a ground-water altitude in well GS-18 about 1 ft lower than the altitude observed for a similar rate of seepage during 1993. This may indicate an improvement in the subsurface connection between shafts 3 and 4 between 1993 and 1995.

GEOCHEMISTRY

Distribution of Water-Quality Constituents

Water-quality data for samples collected from wells, seeps, and Mine Run Reservoir during April and December 1992; January, July, and December 1993; and May–June 1994 are given in table 5 (at back of report). Water-quality data for December 1993 and May–June 1994 are similar to the data for April and December 1992 and January 1993 presented in previous reports (Hamlin and Alpers, 1995, 1996). During December 1993 and May–June 1994, field values of specific conductance ranged from 2,280 μS/cm (microsiemens per centimeter) at well GS-2 to 9,060 μS/cm at well GS-6. Field values of pH of sampled water ranged from 3.4 at well GS-16 to 7.9 at well GS-2. Water temperatures ranged from 15.6°C at well GS-1A to 23.5°C at well GS-3.

Values of pH for water samples from Mine Run Reservoir and from wells open to metavolcanic rocks in the slag area collected in April and December 1992, December 1993, and May 1994 are summarized in table 1. The available data for April and December 1992 and December 1993 were used (fig. 8) to help determine possible directions of movement and the potential sources of acidic water. Previously reported values of pH in Mine Run Reservoir, a possible source

Table 1. Values of pH for water samples from wells GS-1 through GS-16 and wells W-1D and W-5D for April and December 1992, December 1993, and May 1994 at the Penn Mine, Calaveras County, California

[pH determined in the field at time of sample collection, except asterisk (*) indicates lab determination. —, no data]

Well name	April 1992	December 1992	December 1993	May 1994
GS-1A	5.1	4.6	5.9	—
GS-2	7.8	—	7.3	7.9
GS-3	4.8	5.1	5.7	5.1
GS-4B	6.6	6.2	6.3	6.2
GS-5	5.4	4.6	5.6*	5.2
GS-6	4.2	—	4.0	—
GS-7	4.9	—	4.3	—
GS-8A	3.7	3.8	3.9	3.9[1]
GS-11	—	3.9	5.6	4.3
GS-14	—	3.6	4.0	3.7
GS-15	—	3.5	4.3	4.0
GS-16	—	3.4	3.4	3.4
W-1D	—	3.5	—	—
W-5D	—	3.6	—	—

[1] Value for sample collected May 10, 1994, at 16:55, 108 minutes after start of aquifer test.

of acidic drainage to the ground-water system, range from 2.3 to 2.7 (Bond, 1988; Davy Environmental, 1993a). In this study, a pH value of 2.8 was determined for water samples from two depths in Mine Run Reservoir in December 1992. During the period December 1992 through May 1994, water collected from well GS-16, located on the north abutment of Mine Run Dam, had a constant pH value of 3.4. Water sampled from wells GS-8A and -14 was consistently acidic, with pH values less than or equal to 4.0 throughout the study period. Some of the samples from wells W-1D, W-5D, GS-6, -11 and -15 (which were sampled less frequently) also had pH values less than or equal to 4.0 (tables 1 and 5). The areal distribution of pH values for December 1992 (fig. 8*A*) shows that the lowest (most acidic) pH values were in samples from wells in a discrete zone directly to the west of the north abutment of Mine Run Dam. The pH values for December 1993 (fig. 8*B* and table 1) were 0.1 to 1.7 units higher than values for December 1992, apparently showing the effects of the inundation of the slag area by Camanche Reservoir from May to October 1993. Nevertheless, in December 1993 (fig. 8*B*) an area with pH values less than or equal to 4.0 was identified in the western part of the slag area (wells GS-6, -8A, and -14). In May 1994, after a relatively dry winter characterized by declining water levels (figs. 5 and 6), the pH values had returned to conditions similar to those found in April and December 1992 (table 1, fig. 8A). In the area of shafts 3 and 4, the pH of water from well GS-18 was consistently near 4.0, as were pH values for water from the GS-20 seep and water from well GS-20 during artesian flow conditions in January 1993 (table 5). In December 1992, prior to the onset of artesian flow, water from well GS-20 had a pH value of 2.8, which is similar to values for water from ponds HR1 and HR2 (Davy Environmental, 1993a).

Sulfate is the dominant anion in the ground-water and surface-water samples from the Penn Mine area. Sulfate concentrations ranged from 450 mg/L (milligrams per liter) in well GS-2 to 8,300 mg/L in well GS-16 (table 5). Sulfate concentrations in Mine Run Reservoir were highly variable. In December 1992, dissolved sulfate concentrations of 4,800 and 8,500 mg/L were determined for samples of Mine Run Reservoir from depths of 1 and 6 ft, respectively. In contrast, the ambient sulfate concentrations in Camanche Reservoir were very low. Slotton and others (1994) determined sulfate concentrations of 1.3 and 4.9 mg/L in June and October 1992, respectively, for a control site in Camanche Reservoir about 1.2 mi upstream from Penn Mine, and somewhat higher concentrations of 3.5 and 9.6 mg/L in June and October 1992, respectively, for a surface-water site about 0.3 mi downstream from Penn Mine. The data of Slotton and others (1994) suggest that a significant part of the sulfate loading to Camanche Reservoir may be coming from the Penn Mine area. Dissolved-sulfate concentrations consistently exceeded 2,000 mg/L in wells GS-1A, -3, -6, -8A, -14, and -15, which are located in the central part of the slag area, west of Mine Run Dam (fig. 3), and GS-16, which is located on the north abutment of Mine Run Dam (fig. 3). Sulfate concentrations for samples taken in December 1993 were lower than those determined from samples taken in December 1992, consistent with dilution associated with the inundation by Camanche Reservoir during 1993. Sulfate concentrations were unchanged or slightly higher in May 1994 in comparison with December 1993 for most wells in the slag area; however, wells GS-8A and -14, -15, and -16 showed progressively lower sulfate concentrations in the four successive sampling periods.

The distribution of dissolved-copper concentrations in ground-water samples from the slag area is similar to the distribution of dissolved-sulfate concentrations and pH. The highest copper concentrations observed during the study period were 120 and 130 mg/L in wells GS-16 and W-5D, respectively, located on the north abutment of Mine Run Dam, in December 1992. Dissolved-copper concentrations in two samples from Mine Run Reservoir were 62 and 110 mg/L for water depths of 1 and 6 ft, respectively. Wells GS-8A, -14 and -15, located on the western side of the slag area (fig. 3), yielded water samples with dissolved-copper concentrations equal to or greater than 80 mg/L in April

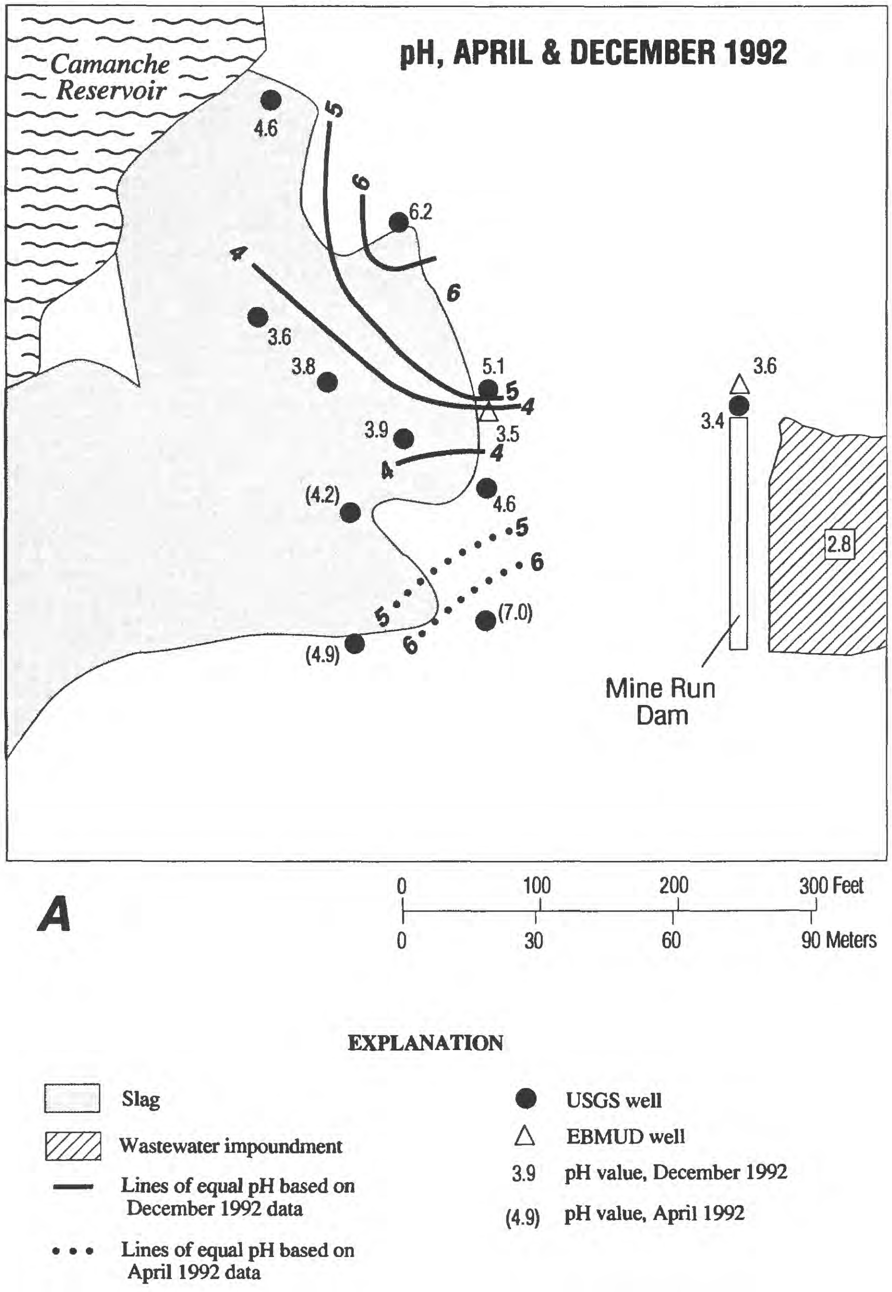


Figure 8. Areal distribution of pH in ground water from wells monitoring metavolcanic rocks at the Penn Mine, Calaveras County, California, **A**, April and December 1992; **B**, December 1993.

and December 1992. Copper concentrations in these three wells were considerably more dilute in December 1993, ranging from 9.7 to 61 mg/L, but increased again to 34 to 63 mg/L in May 1994. Wells GS-6 and -7, near the southern edge of the study area, also yielded water samples with copper concentrations greater than 30 mg/L during December 1993. In contrast, dissolved-copper concentrations in Camanche Reservoir were extremely low in October 1992 (Slotton and others, 1994)—less than 0.001 mg/L at the control site 1.2 miles upstream of Penn Mine and 0.004 mg/L at the site 0.3 mi downstream. Wells GS-1B and -2 were the

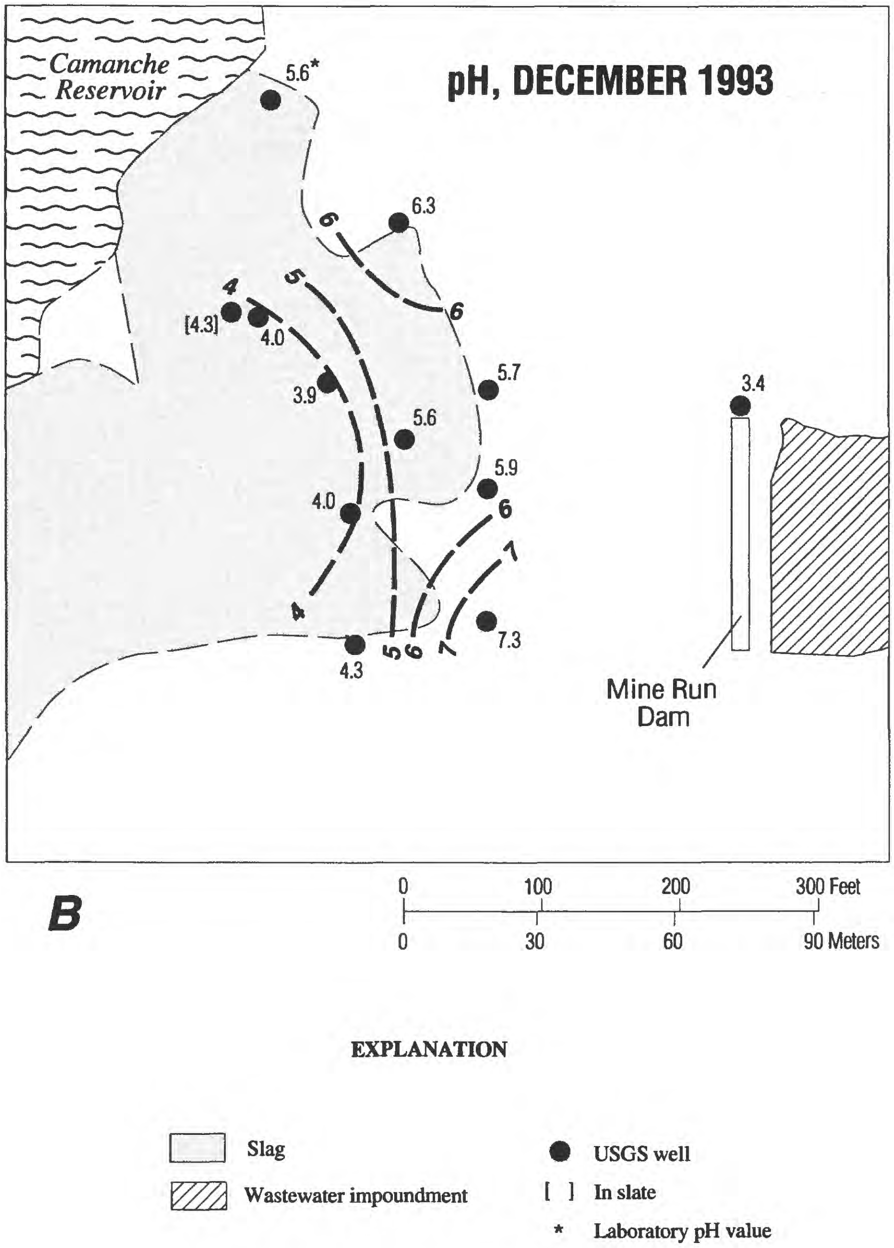


Figure 8.—Continued.

only sampled wells for which the copper concentrations were at or below the detection limit of 0.010 mg/L. In the area of shafts 3 and 4, copper concentrations were equal to or less than 0.3 mg/L in the water pumped from the mine workings through well GS-18 and in the artesian flow from well GS-20 and the GS-20 seep in the vicinity of shaft 4 in January 1993 (table 5). In December 1992, prior to artesian flow from well GS-20, the copper concentration in water from this well was 36 mg/L, which is similar to concentrations reported by Davy Environmental (1993a) for ponds HR1 and HR2 (fig. 2).

The distribution of dissolved zinc in ground water at Penn Mine is similar in many respects to the distribution of dissolved copper, but with some notable exceptions. The areal distribution of zinc

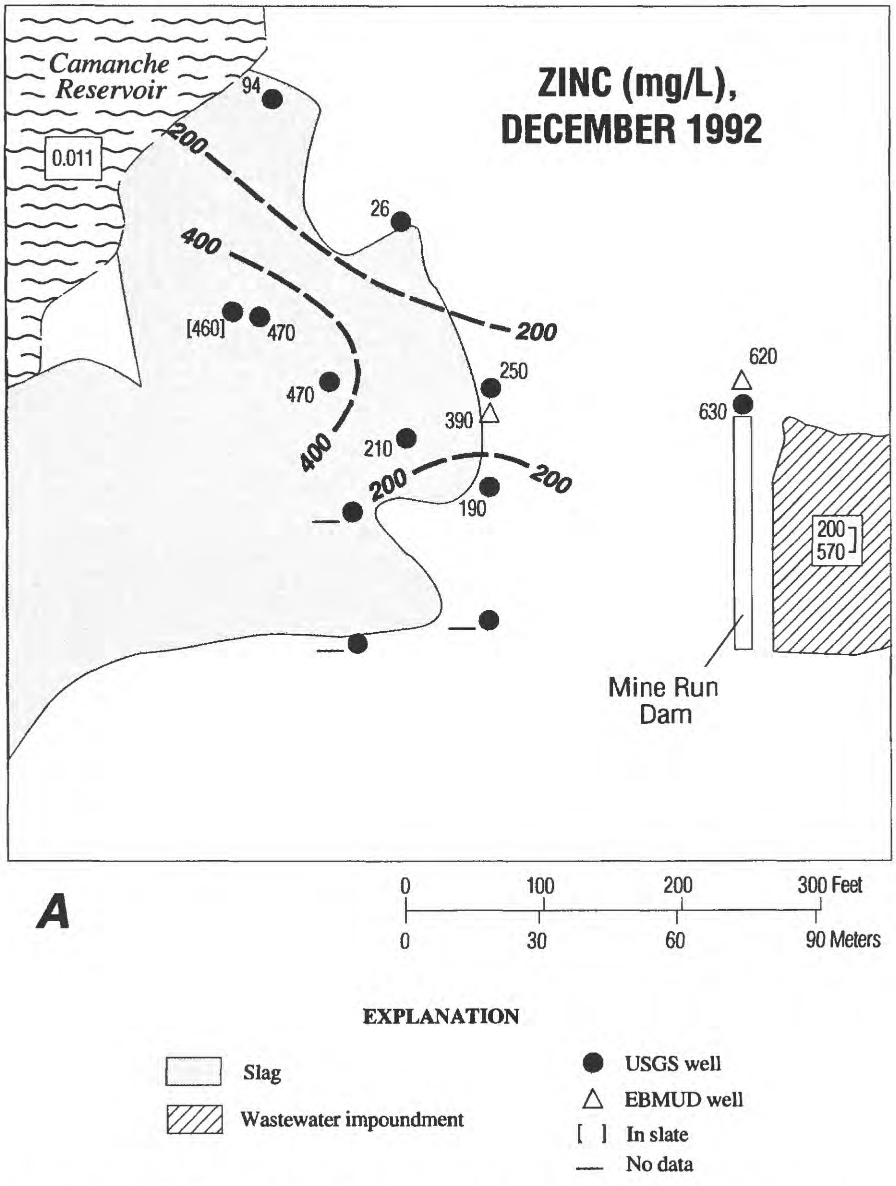


Figure 9. Areal distribution of dissolved zinc in ground water from wells monitoring metavolcanic rocks at the Penn Mine, Calaveras County, California, **A**, December 1992; **B**, December 1993.

concentrations in ground water in the slag area in December 1992 and in December 1993 is shown in figure 9. The dissolved-zinc concentrations were highest (as were dissolved-copper concentrations) in wells GS-16 and W-5D (north abutment of Mine Run Dam); zinc concentrations were 630 and 620 mg/L, respectively, in those wells. Zinc concentrations in water samples from Mine Run Reservoir were 200 and 570 mg/L. Dissolved-zinc concentrations in samples from Camanche Reservoir collected in October 1992 (Slotton and others, 1994) were less than 0.010 mg/L at the upstream site and 0.011 mg/L at the site 0.3 mi downstream from Penn Mine. As with the distribution of copper, sulfate, and pH, the wells in the central part of the slag pile consistently yielded the water samples with the highest zinc concentrations in 1992 and 1994. The December 1993 samples were more dilute, especially for wells GS-1A and -3, which had zinc

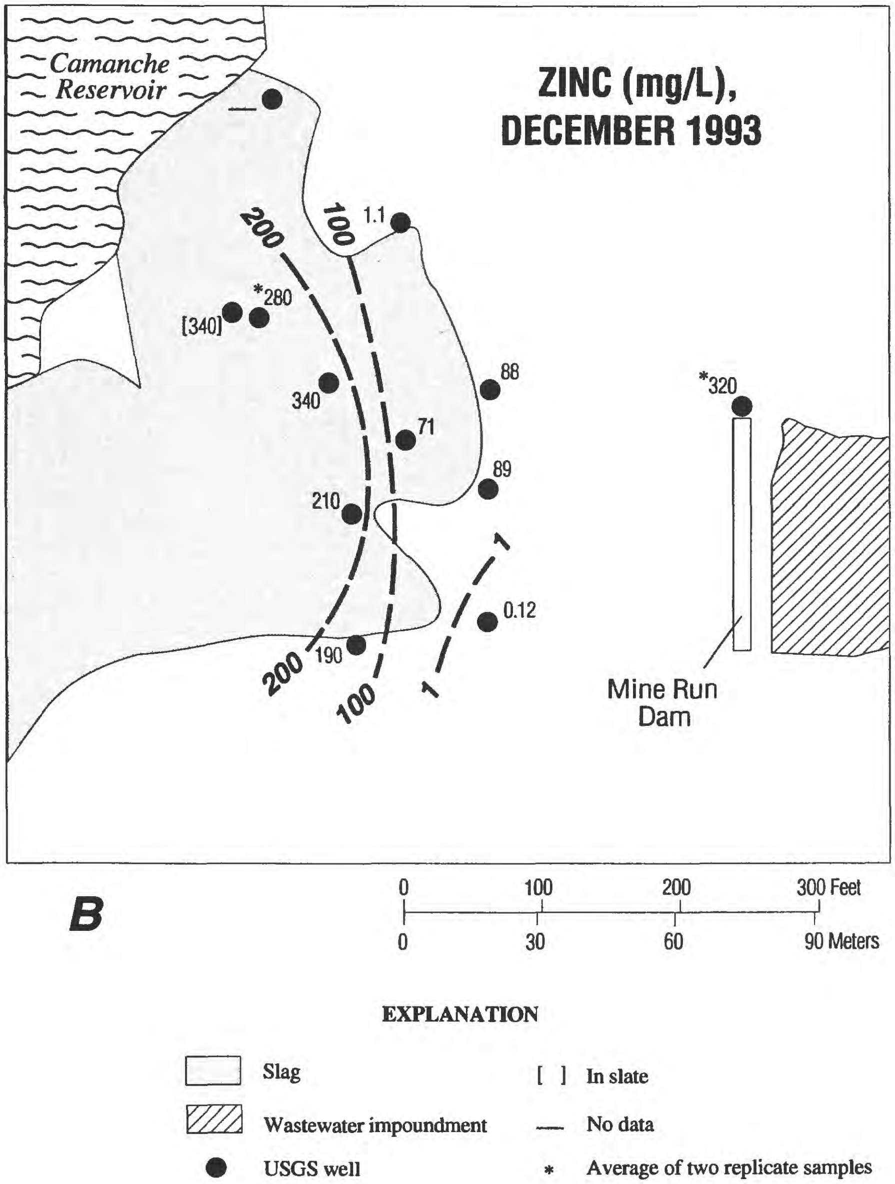


Figure 9.—Continued.

concentrations less than 100 mg/L during that sampling period, but had zinc concentrations greater than 100 mg/L in 1992 and 1994.

Dissolved iron exists in two valence states, the more reduced ferrous (Fe^{2+}) state and the oxidized ferric (Fe^{3+}) state. Ferric iron is much less soluble than ferrous iron at a given pH. As dissolved iron oxidizes from ferrous to ferric with the assistance of microbes such as *Thiobacillus ferroxidans*, secondary minerals containing ferric iron will form. Data for dissolved ferrous and total iron (table 5) indicate that most dissolved iron in Penn Mine ground water is in the ferrous state. This is consistent with the range of field pH values (3.4 to 7.9) of the sampled ground water; over this pH range, the solubility of ferric iron is limited by secondary mineral formation.

On the basis of geochemical calculations using the program WATEQ4F (Ball and Nordstrom, 1991), dissolved iron probably is in equilibrium with a form of hydrous ferric oxide [nominally $Fe(OH)_3$] (Hamlin and Alpers, 1995). Sulfate concentrations increase at low pH, and iron concentrations can be limited by solubility with a sulfate mineral such as hydronium-bearing jarosite [$(K,Na,H_3O)Fe_3(SO_4)_2(OH)_6$] (Alpers and others, 1989) or schwertmannite [$Fe_8O_8(OH)_6SO_4$] (Bigham, 1994). Similarly, aluminum concentrations appear to be in equilibrium with gibbsite [$Al(OH)_3$], except in ground water with pH values less than 5. High sulfate concentrations at low pH suggest that aluminum could be in equilibrium with an aluminum-sulfate mineral, but this possibility was not rigorously evaluated.

Correlations of Water-Quality Constituents

The relation between the concentrations of dissolved zinc and copper for Penn Mine water samples reveals that the most concentrated samples from the Mine Run Reservoir and slag areas (designated as "Group A" in figure 10 and subsequent figures) have fairly consistent zinc/copper weight ratios, ranging between 4 and 6. A group of more dilute samples (designated as "Group B") has zinc/copper ratios generally greater than 10. Water samples from the area of shafts 3 and 4, including wells GS-18 and -20, are excluded from these two groups. The relatively low copper concentrations in water samples from wells GS-18 and -20 (when artesian) cause extremely elevated values of the zinc/copper ratio for these samples.

Variations in the stable isotopes of sulfur and oxygen in aqueous sulfate (Alpers and others, 1994; Hamlin and Alpers, 1996) are best explained by the microbial reduction of sulfate in the underground mine workings. Preferential reduction of ^{32}S and ^{16}O would result in heavier values of $\delta^{34}S$ and $\delta^{18}O$ in residual aqueous sulfate in the mine waters. On the basis of the relative solubility of mono-sulfide minerals (DiToro and others, 1990), the hydrogyen sulfide evolved would preferentially scavenge copper and cadmium from the mine waters relative to zinc and iron. The stable-isotope data indicate that sulfate reduction is a likely cause for the relatively low copper and cadmium concentrations in the underground mine workings and the relatively high values of the ratios zinc/copper and zinc/cadmium (Alpers and others, 1994; Hamlin and Alpers, 1996).

Data for stable isotopes of oxygen (reported as $\delta^{18}O$) in water for selected USGS wells and for Camanche Reservoir are given in tables 2 and 3, respectively. During the evaporation process, water molecules containing heavier isotopes tend to become concentrated in the residual water, and molecules containing lighter isotopes become enriched in the water vapor. Hence, isotopic values for bodies of surface water exposed to evaporation tend to be enriched in heavy isotopes relative to most ground water. The process of evaporative isotopic enrichment generally produces δD and $\delta^{18}O$ data that lie on a line with a slope between 3 and 6 to the right of the meteoric water line, which has a slope of 8 (equation 2) (Craig and others, 1963). Such a distinct evaporative trend is observed in a plot of stable-isotope data for ground water at the Penn Mine, and water from Mine Run and Camanche Reservoirs (fig. 11). Excluding the Camanche Reservoir data and the data from well GS-8A during the aquifer test, the data can be fit by least-squares linear regression (R^2=0.99), giving a line described by the equation

$$\delta D = 4.3\ \delta^{18}O - 21.2\ . \qquad (3)$$

The slope of this line suggests that the ground water downgradient from Mine Run Reservoir represents the mixing of partially evaporated water from Mine Run Reservoir with nonevaporated ground water.

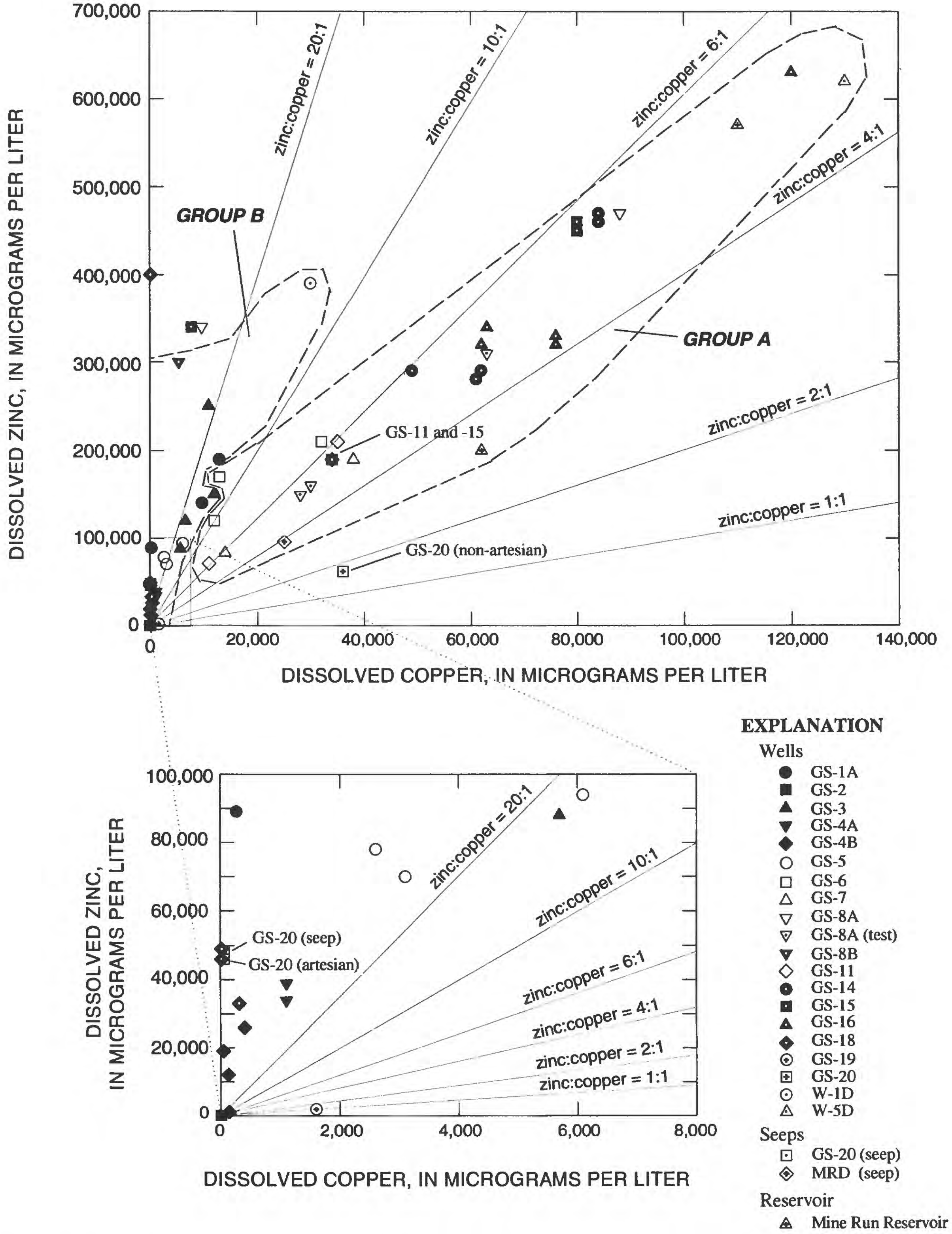


Figure 10. The relation between dissolved-zinc and dissolved-copper concentrations in ground water and in Mine Run Reservoir at the Penn Mine, Calaveras County, California, April 1992 through May 1994.

Water samples from Camanche Reservoir have δD and $\delta^{18}O$ values (table 3) that plot near the meteoric water line and that are significantly depleted in heavy isotopes relative to shallow ground water at Penn Mine (fig. 11). These data reflect the origin of the water in Camanche Reservoir at higher altitudes in the Mokelumne River watershed. Stable-isotope data reported by Ingraham and Taylor (1991) indicate that values of δD near -80 per mil and of $\delta^{18}O$ between -10 and -12 per mil are associated with surface waters and shallow ground waters at an altitude of about 3,000 ft in this part of the Sierra Nevada.

Table 2. Delta oxygen-18 values for water samples from wells GS-1 through GS-16 for April and December 1992 and May 1994 at the Penn Mine, Calaveras County, California

[Values in per mil relative to V-SMOW. —, no data]

Well name	April 1992	December 1992	May 1994
GS-1A	–3.40	–3.31	—
GS-2	–7.65	—	–7.54
GS-3	–3.45	–2.32	–3.34
GS-4B	–6.30	–6.01	–6.19
GS-5	–5.40	–5.04	–5.89
GS-6	–2.90	—	—
GS-7	–8.20	—	—
GS-8A	–2.65	–2.61	–4.67[1]
GS-11	—	–5.84	–6.01
GS-14	—	–1.38	–4.23
GS-15	—	–1.42	–4.75
GS-16	—	+1.40	–0.75

[1] Value for sample collected May 10, 1994, at 16:55, 108 minutes after start of aquifer test.

Graphs of the relations between the concentrations of dissolved constituents and the $\delta^{18}O$ value of the water provide additional insights into possible ground-water mixing trends. A graph of the relation between copper concentration and $\delta^{18}O$ (fig. 12) shows the separation of two apparently distinct mixing trends, designated as sample groups A and B. The areal distribution of the wells in groups A and B is shown in figure 13. Graphs of the relations of zinc concentration and $\delta^{18}O$ (fig. 14), and of sulfate concentration and $\delta^{18}O$ (fig. 15), are included to show the independent nature of the sample groups A and B for other dissolved constituents (see also fig. 10).

Indicators of Ground-Water Age

Chlorofluorocarbon (CFC) and tritium concentrations were analyzed in ground-water samples from Penn Mine to determine limits on the timing of ground-water recharge. The use of both of these substances for this purpose is based on the premise that their concentrations have been anomalously high in the atmosphere during the past few decades because of human activities, such that water in contact with the atmosphere during this period will contain elevated concentrations. Results of CFC and tritium analyses are given in table 4.

Tritium concentrations ranged from 6.3 to 10.8 tritium units. These values are higher than values associated with ground-water recharge prior to the

Table 3. Delta oxygen-18 and delta deuterium values and chemical data for water samples from Camanche Reservoir, Calaveras County, California, October 1992

[Sample locations and chemical data are from Slotton and others (1994). $\delta^{18}O$, delta oxygen-18; δD, delta deuterium; µg/L, microgram per liter; mg/L, milligram per liter; <, less than value shown]

Sample no.	Depth[1] (feet)	$\delta^{18}O$ (per mil)	δD (per mil)	Copper, dissolved (µg/L as Cu)	Zinc, dissolved (µg/L as Zn)	Sulfate, dissolved (mg/L as SO_4)
M4-3B	49	–11.1	–81.5	1.5	18	5.0
U4-1B	11	–11.9	–85.1	1.7	<10	9.1
U7	2	–12.3	–87.2	<1.0	<10	4.9
W2-2B	82	–10.9	–79.0	1.4	38	6.7
W4-4B	59	–10.9	–79.7	1.6	33	7.5

[1] Samples collected with grab sampler, within three feet of reservoir bottom (Slotton and others, 1994).

onset of above-ground testing of nuclear explosives in the late 1940s, but lower than the values associated with recharge during the 1950s and 1960s. Water containing less than 5 tritium units probably was recharged prior to 1953 (Freeze and Cherry, 1979). Thus, the tritium data are consistent with recharge of Penn Mine ground water after 1970.

The CFC data are interpreted, where possible, in terms of three separate model recharge ages for each water sample based on the dissolved concentrations of the gases CFC-11, CFC-12, and CFC-113. For CFC-11, model ages (in years A.D.) were computed for 3 of the 10 wells sampled and ranged from 1974.5 (well GS-1A) to 1985.5 (well GS-2). In samples from the

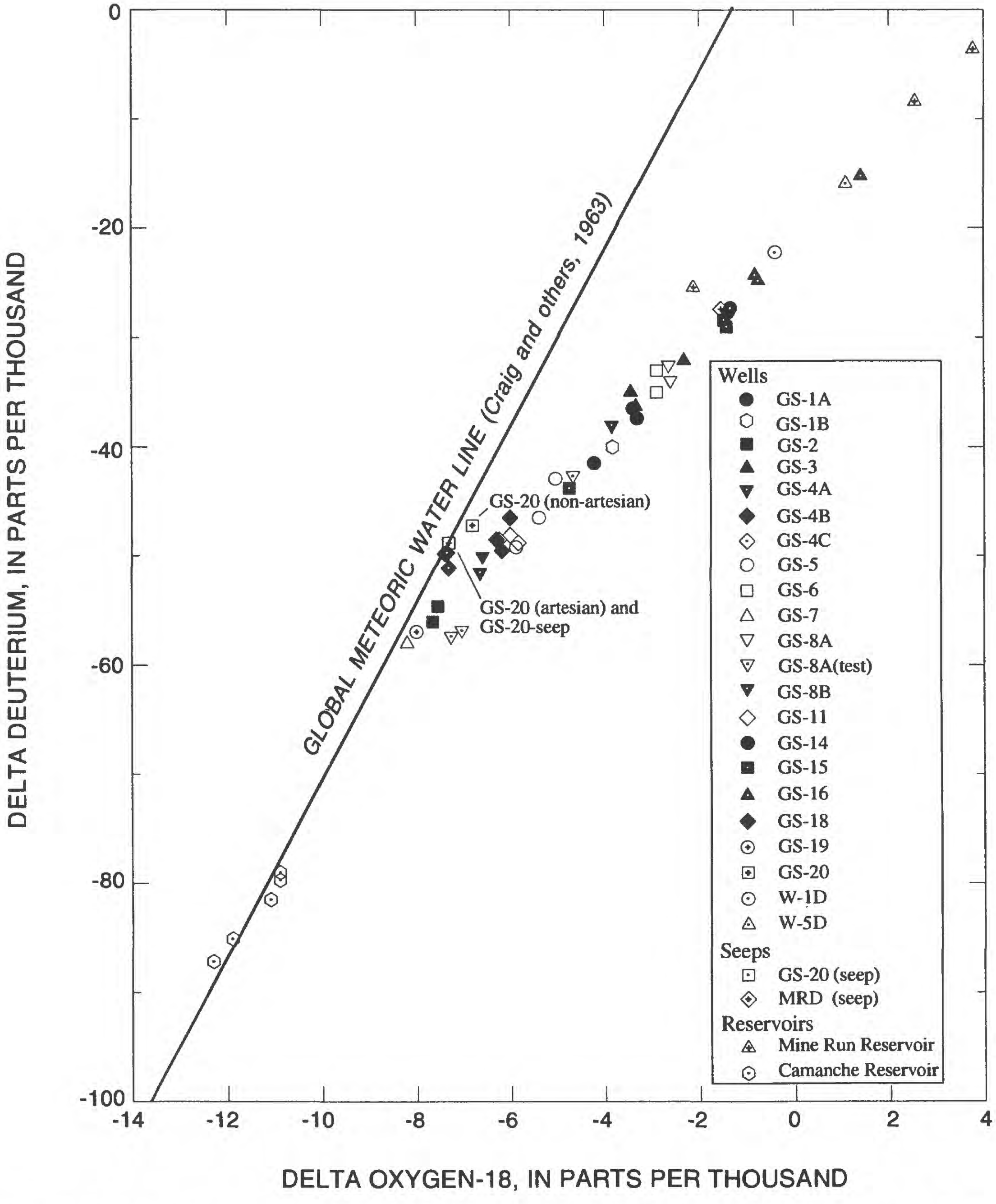


Figure 11. Stable-isotopic composition of ground water at the Penn Mine and water from Mine Run Reservoir, April 1992 through May 1994, and Camanche Reservoir, October 1992, Calaveras County, California.

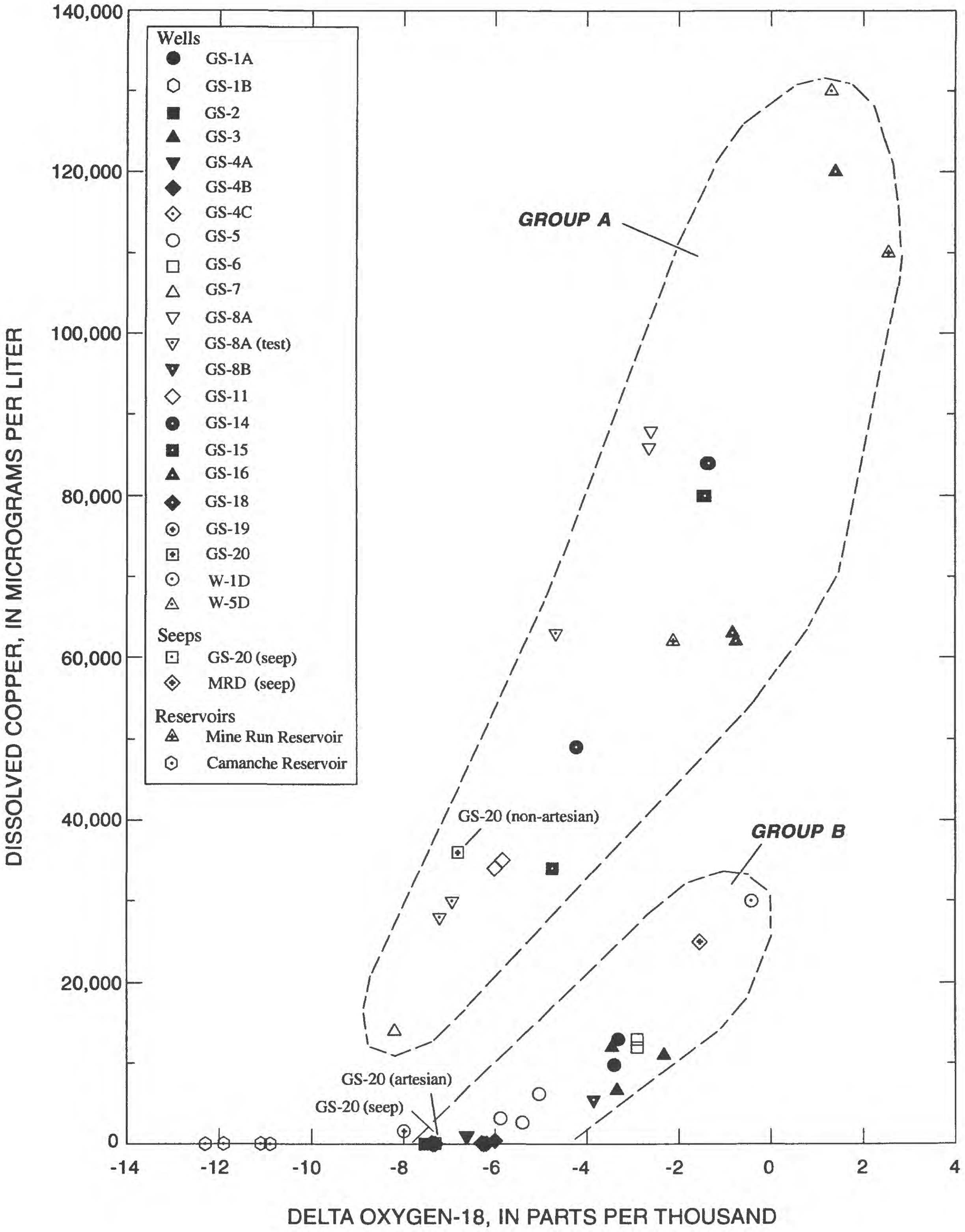


Figure 12. Relation between dissolved-copper concentration and delta oxygen-18 in ground water and in water from Mine Run Reservoir at the Penn Mine, April 1992 through May 1994, and Camanche Reservoir, October 1992, Calaveras County, California.

other seven wells, concentrations of CFC-11 exceeded likely atmospheric values and are interpreted as indicating contamination of CFC-11 after recharge; model ages were not computed for these samples. For CFC-12, model ages were computed for 9 of the 10 wells sampled and ranged from 1969.5 (well GS-1A) to modern (wells GS-3, -14 and -16). For CFC-113, model ages were computed for only 2 of 10 wells sampled and ranged from 1988.0 to 1990.5 (both values from well GS-5). Apparent contamination with CFC-113 was noted in 8 of 9 wells; in one well, analytical interferences precluded the determination of CFC-113 concentration. The apparent CFC contamination at Penn Mine is most likely to have

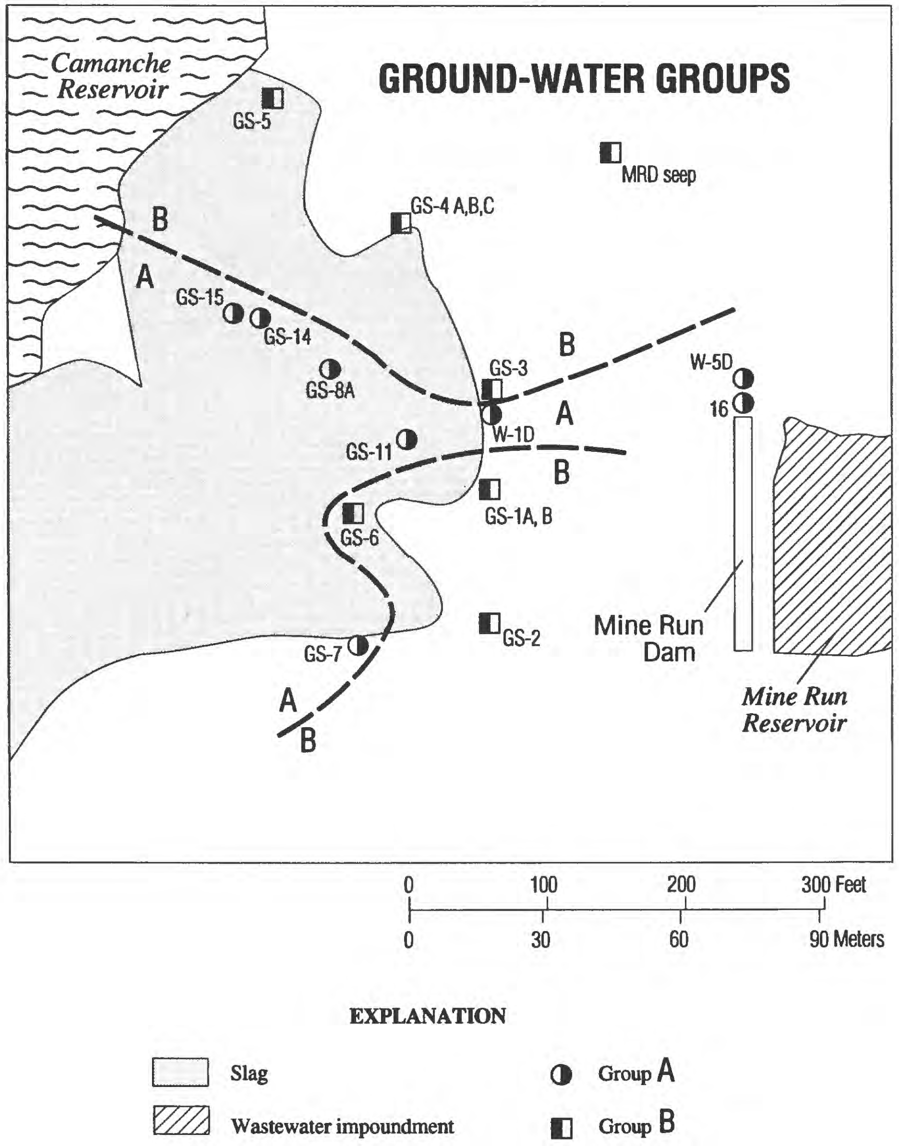


Figure 13. Disribution of wells separated into groups **A** and **B**, Calaveras County, California.

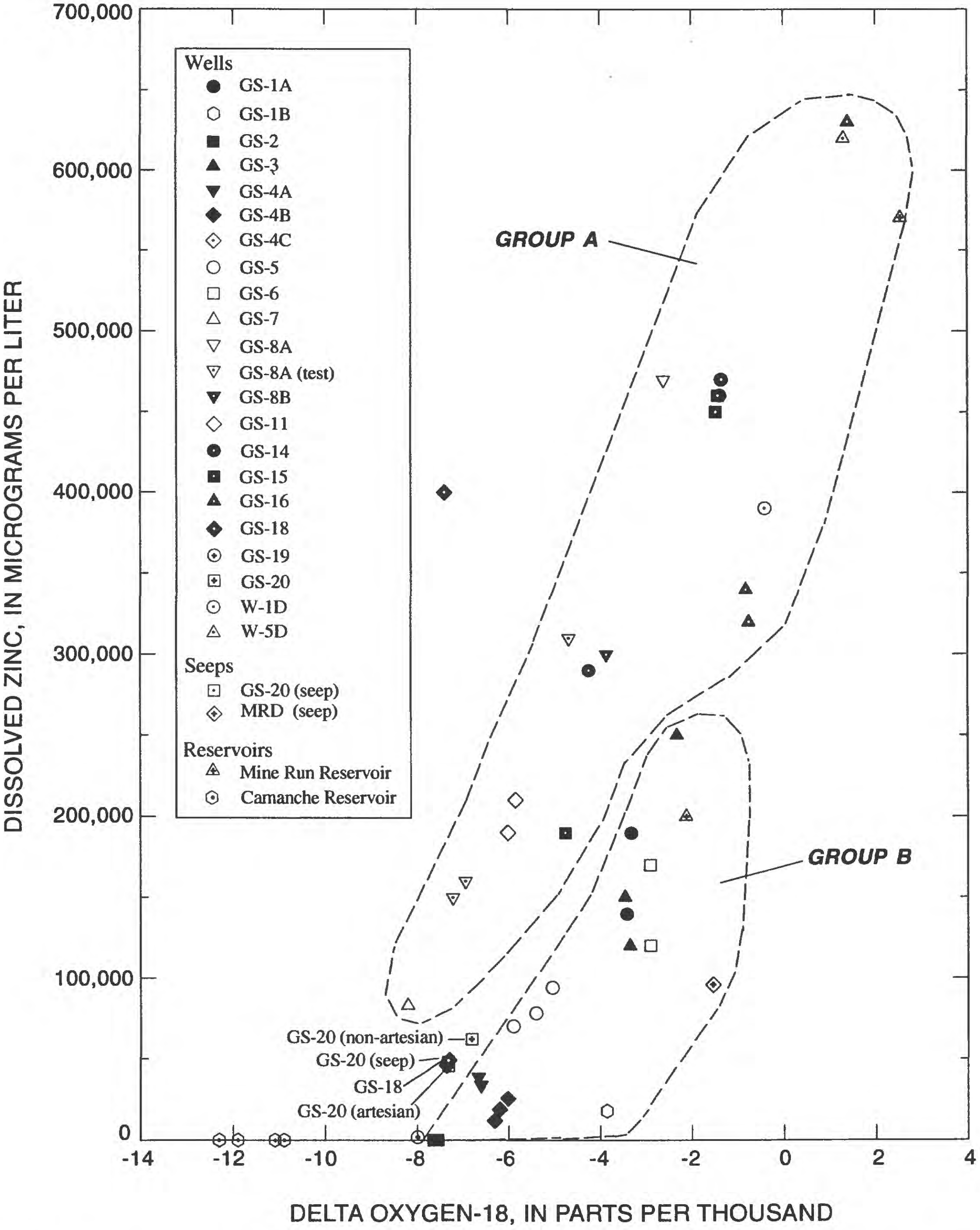


Figure 14. Relation between dissolved-zinc concentration and delta oxygen-18 in ground water and in water from Mine Run Reservoir at the Penn Mine, April 1992 through May 1994, and Camanche Reservoir, October 1992, Calaveras County, California.

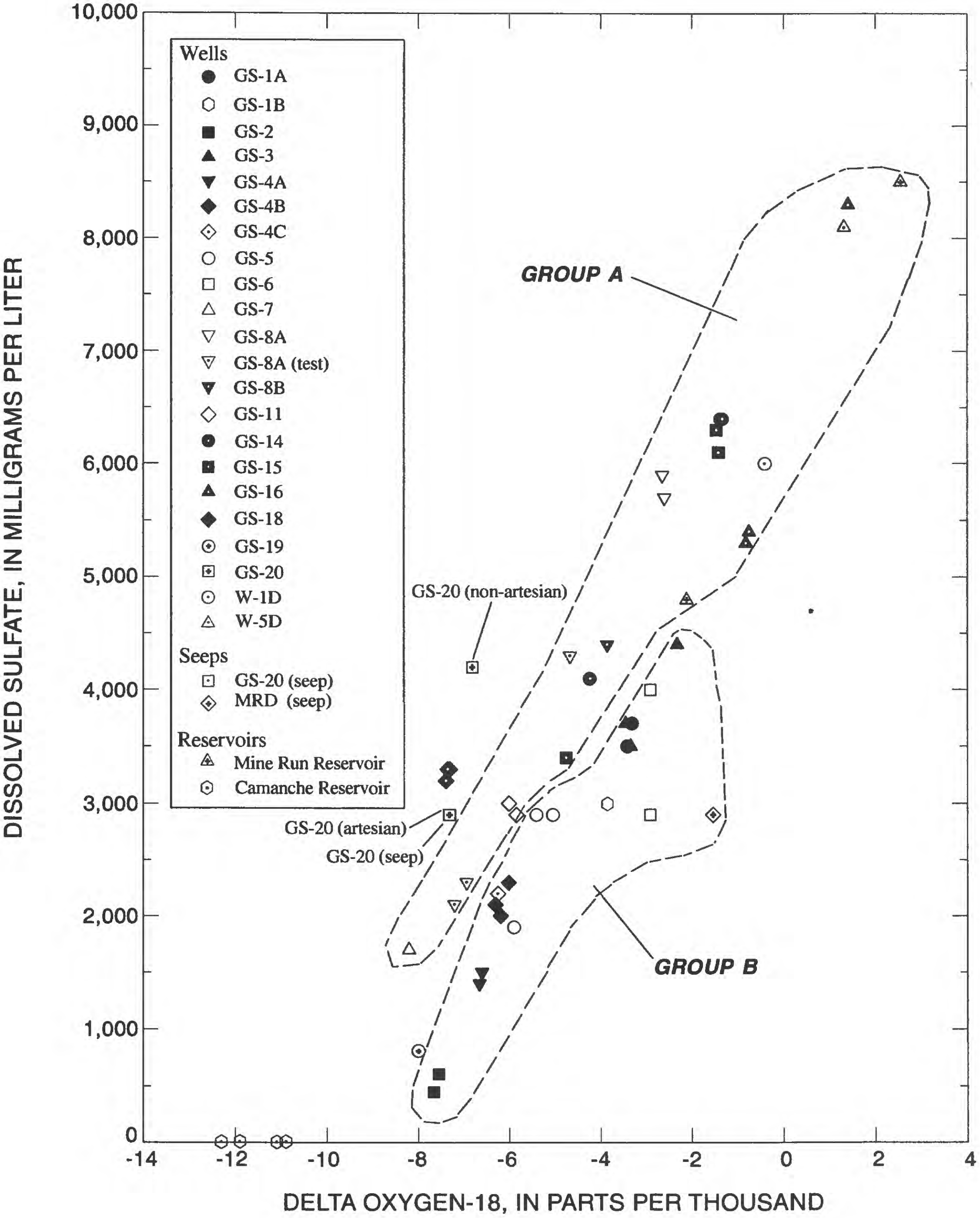


Figure 15. Relation between dissolved-sulfate concentaration and delta oxygen-18 in ground water and in water from Mine Run Reservoir at the Penn Mine, April 1992 through May 1994, and Camanche Reservoir, October 1992, Calaveras County, California.

Table 4. Results of chlorofluorocarbon and tritium analyses for ground water at the Penn Mine, Calaveras County, California

[Standard used for calibration: Rasmussen 1991 Standard Oregon Coastal Air. Values assumed for calculations: recharge temperature, 16 degrees Celsius; barometric pressure, 752.8 millimeters of mercury; and altitude, 260 feet above sea level. Date format, mm-dd-yy, month-day-year; CFC, chlorofluorocarbon; *, model CFC-age not calculated because of likely CFC contamination after recharge; —, CFC concentration not evaluated because of analytical inteferences. pg/kg, picogram per kilogram; ppt, part per trillion (volume)]

Well name	Sampling date	Time	CFC concentrations in solution (pg/kg)			Calculated atmospheric partial pressure (ppt)			Model CFC-ages of waters (years A.D.)			Tritium (tritium units)
			CFC-11	CFC-12	CFC-113	CFC-11	CFC-12	CFC-113	CFC-11	CFC-12	CFC-113	
GS-1A	12-18-93	1618	235.7	63.4	94.0	111.7	127.2	111.2	1974.5	1969.5	*	7.3 ±0.5
GS-1A	12-18-93	1629	275.2	70.9	58.5	130.4	142.2	69.2	1976.0	1970.5	1988.5	
GS-2	12-19-93	1025	471.3	169.8	366.8	223.4	340.6	433.7	1985.5	1982.0	*	8.3 ±0.5
GS-2	12-19-93	1037	470.7	168.9	355.6	223.1	338.9	420.5	1985.5	1982.0	*	
GS-2	12-19-93	1050	443.7	153.3	462.5	210.3	307.5	546.9	1984.5	1980.0	*	
GS-3	12-19-93	1205	4,419.4	275.7	712.1	2,094.5	553.1	842.0	*	Modern	*	7.1 ±0.5
GS-3	12-19-93	1216	4,378.6	239.1	677.4	2,075.2	479.8	801.1	*	1989.5	*	
GS-3	12-19-93	1226	4,354.1	220.0	747.8	2,063.6	441.4	884.2	*	1987.0	*	
GS-4B	12-18-93	1210	1,533.3	221.8	617.0	726.7	445.0	729.6	*	1987.5	*	8.2 ±0.4
GS-4B	12-18-93	1225	1,515.9	206.0	586.7	718.5	413.4	693.8	*	1986.0	*	
GS-4B	12-18-93	1240	1,557.4	227.3	647.0	738.1	456.0	765.1	*	1988.0	*	
GS-5	12-19-93	1351	2,076.5	242.4	66.0	984.1	486.4	78.1	*	1990.0	1990.0	6.5 ±0.4
GS-5	12-19-93	1402	2,664.4	244.8	68.6	1,262.8	491.2	81.2	*	1990.0	1990.5	
GS-5	12-19-93	1410	3,213.0	242.7	56.7	1,522.8	486.9	67.1	*	1990.0	1988.0	
GS-8A	12-18-93	1455	940.5	214.8	392.8	445.8	431.0	464.5	*	1987.0	*	10.8 ±0.5
GS-8A	12-18-93	1506	1,120.9	243.6	845.3	531.2	488.7	999.6	*	1990.0	*	
GS-8A	12-18-93	1514	1,133.0	249.1	485.1	537.0	499.9	573.7	*	1991.0	*	
GS-8A	12-18-93	1524	1,194.4	237.9	686.9	566.1	477.4	812.2	*	1989.5	*	
GS-11	12-20-93	1200	8,607.4	121.0	207.2	4,079.4	242.8	245.0	*	1976.0	*	10.4 ±0.5
GS-11	12-20-93	1210	7,606.8	130.2	3,269.9	3,605.1	261.1	3,866.6	*	1977.0	*	
GS-14	12-19-93	1456	3,174.4	286.4	546.5	1,504.5	574.7	646.2	*	Modern	*	8.8 ±0.4
GS-14	12-19-93	1505	3,566.2	329.2	135.1	1,690.1	660.6	159.8	*	*	*	8.6 ±0.4
GS-14	12-19-93	1516	3,243.9	393.1	87.7	1,537.4	788.8	103.7	*	*	*	
GS-16	12-20-93	1443	14,984.0	304.9	117.2	7,101.5	611.8	138.6	*	*	*	6.8 ±0.4
GS-16	12-20-93	1453	14,753.7	291.9	124.5	6,992.4	585.7	147.2	*	Modern	*	
GS-18	12-21-93	1535	320.8	2,379.1	—	152.1	4,773.4	—	1978.0	*	—	6.3 ±0.4
GS-18	12-21-93	1540	325.4	2,490.0	—	154.2	4,995.9	—	1978.0	*	—	
GS-18	12-21-93	1548	333.8	2,566.8	—	158.2	5,150.0	—	1978.5	*	—	

occurred after recharge, and before sampling, on the basis of the consistent results for multiple samples from individual wells (table 4). The source of contamination is unknown, but may include common refrigerants (freons) either disposed of in the unlined ponds or leaked from air conditioning units on vehicles accessing the site.

The model ages in table 4 can be divided into groups before and after 1978, the year of construction of Mine Run Dam, to test for consistency with the hypothesis that Mine Run Reservoir has been a source of recharge to the ground-water system in the slag area. Of the nine wells sampled in the area west of Mine Run Reservoir, model recharge ages prior to 1978 were computed for only two wells, GS-1A and GS-11. The model ages for the other seven wells in this area ranged from 1980 to modern. Wells GS-1A and -11 are located near the center of Mine Run Dam (fig. 3), suggesting a possible zone of somewhat older ground water in the vicinity of these two wells.

It should be emphasized that interpretation of CFC data in fractured-rock systems is problematic, given the likely mixing of water from several discrete fractures during sampling, such that there is not a well-defined age of recharge. The CFC techniques are fairly new (Busenberg and Plummer, 1992; Dunkle and others, 1993; Plummer and others, 1993), and interpretations of CFC data are subject to modification as more experience is gained with application of the method to ground-water systems. Both the CFC and tritium methods are designed to put limits on the timing of recharge, but they do not identify recharge sources.

Overall, the results of tritium and CFC analyses at Penn Mine are consistent with the interpretation that most ground water in the slag area was recharged during the late 1970s and 1980s. The results are not definitive, but are consistent with the concept that considerable recharge to the ground-water system in this area has occurred after the construction of Mine Run Reservoir in 1978, and that some of that recharge could have come from Mine Run Reservoir.

Possible Sources of Ground-Water Constituents

Discussion of the possible sources of water and dissolved constituents in the ground water in the area between Mine Run Reservoir and Camanche Reservoir is summarized in terms of five hypotheses:

Hypothesis 1: Leakage and seepage of partially evaporated, metal-rich, acidic drainage took place from Mine Run Reservoir through fractured bedrock beneath the north abutment of Mine Run Dam.

Hypothesis 2: Some recharge of metal-rich, acidic drainage took place in this area prior to the construction of Mine Run Dam in 1978.

Hypothesis 3: The slag pile was a dumping ground for wastes other than slag, including possibly metal-rich acid solutions, or concentrated acids that could have leached metals from slag and (or) other wastes.

Hypothesis 4: Flow along the Campo Seco Fault or similar structures could have delivered water from the underground mine workings to the slag area.

Hypothesis 5: Some combination of hypotheses 1 through 4.

The strongest supporting evidence for hypothesis 1 is the close match in the chemistry of major and trace elements among the water samples from Mine Run Reservoir, from wells GS-16 and W-5D on the north abutment of Mine Run Dam, and from wells GS-8A, -14 and -15 in the central-west part of slag pile. The partially evaporated acid drainage in Mine Run Reservoir was the only water body observed to be enriched in heavy isotopes of oxygen and hydrogen during this study. Hence, Mine Run Reservoir is the most probable source of partially evaporated acid drainage to ground water in the slag area. CFC and tritium data suggest that the recharge age of most ground-water samples is post-1978. Two wells (GS-1A and -11) contain water that could have recharged during the 1970s; however, the presence of water recharged in the 1950s or 1960s is highly unlikely. One explanation of the trends in figures 10 through 15 is that the chemistry and stable-isotope characteristics of water in Mine Run Reservoir evolved with time from 1978 to 1994, owing to less-advanced evaporation during the late 1970s and early 1980s and more-pronounced evaporation during the drought years of the late 1980s. This evolution could have resulted in recharge of water less-affected by evaporative concentration of heavy isotopes during the earlier years of Mine Run Reservoir; such water may be represented by samples from the group B wells plotted in figures 10 and 12 through 15.

In support of hypothesis 2, the sulfide oxidation processes and the composition of the resulting acid drainage at Penn Mine were probably very similar during the period prior to 1978 compared with the period after 1990. It is probable that a small amount of evaporation took place during mining operations in the tailings impoundment present in the area of pond MR2 (fig. 2), but it is unknown whether any kind of circulation system existed that was similar to the one operated by the Utility District and the Regional Water Board after the construction of Mine Run Dam in 1978. The distinct correlations defining ground-water groups A and B in figures 10 and 12 through 15 could be explained in part by pre-1978 contamination representing group B and post-1978 contamination representing group A. The group B wells are generally lower in hydraulic conductance; therefore, they probably yield ground water that has a longer residence time. For several decades prior to 1978, acid drainage in Mine Run flowed through an unlined tunnel beneath the slag pile (fig. 2). The tunnel might have been a source of recharge to the slag area.

There is no direct evidence either to support or to rebut hypothesis 3. The slag is known to contain elevated concentrations of metals, including zinc and copper (Wiebelt and Ricker, 1949) as well as arsenic, cadmium, and lead (Parsons and others, 1998). The close similarity in chemistry of water from wells W-5D and GS-8A, -11, -14, -15, and -16 indicates the likelihood that a single source of metal contamination existed. A comparison of pH and dissolved metals in samples from wells in the slag area (see figs. 8*A* and 8*B*; and 9*A* and 9*B*) suggests that the system might be responding to two principal recharge sources: Mine Run Reservoir (presumably the source of metals and partially evaporated water) and Camanche Reservoir (likely a source of dilution and of water that is relatively depleted in heavy stable isotopes).

With regard to hypothesis 4, the hydraulic-head gradients (appendix 2) are favorable for driving subsurface flow along the Campo Seco Fault (fig. 4). Acid drainage from the mine workings upgradient from Mine Run Reservoir (wells GS-18 and -20 and GS-20-seep) is depleted in heavy stable isotopes of H and O, and plots near the global meteoric water line (fig. 11). The stable-isotope data do not rule out entirely the possibility that some of the ground water in the slag area is derived from subsurface flow from the underground mine workings, perhaps along structures such as the Campo Seco Fault. The chemistry of the mine water is distinct in terms of anomalously high ratios of zinc/copper and zinc/cadmium, which are thought to have been caused by sulfate reduction that fixed copper and cadmium in solid phases (Alpers and others, 1994; Hamlin and Alpers, 1996). The correlation plots (figs. 10–12, 14, 15) do not indicate any clear mixing trends involving the mine water as a likely end-member.

In summary, the contaminated ground-water plume in the slag area that is enriched in heavy stable isotopes, such as in the group A water samples (wells GS-7, -8A, -11, -14, -15, -16, W-5D, and the Mine Run Dam seep), very likely derives a significant part of its water and dissolved metals from the evaporated acid drainage in Mine Run Reservoir. Wells GS-2 and -7 in the slag area show the least enrichment in heavy isotopes and among the lowest levels of contamination by acid mine drainage. Samples from Mine Run Reservoir and wells GS-14, -15, and -16 in the slag area show the highest enrichment in heavy isotopes and the highest levels of acid-mine-drainage contamination.

Water-quality samples were collected at well GS-8A on three occasions during May 1994 (table 5). Samples were collected on May 10 at 16:55 and on May 11 at 13:00, near the beginning and the end of the aquifer test, respectively. A total of about 6,000 gal of contaminated water was pumped during the test. Metal concentrations in the sample collected on May 11 were about one-half of those in the sample collected on May 10. During May 18–20, another 6,000 gal was pumped at well GS-8A, and a third water-quality sample was collected at 11:08 on May 20; metal concentrations in this sample were similar to those in the May 11 sample (table 5). One interpretation of these data is that the May 10 sample represents water originally present in the highly fractured zone adjacent to well GS-8A, and that the May 11 and May 20 samples represent mixing of that water with more dilute water from Camanche Reservoir and local ground water. The distribution of the data in figures 12, 14, and 15 for samples taken from well GS-8A during the aquifer test indicates that mixing with dilute water with a $\delta^{18}O$ value of about -9 to -10 per mil would account for the observed dilution in copper, zinc, and sulfate. The data for the water sample from well GS-7 collected in April 1992 plot close to the lines connecting the GS-8A data from May 1994, suggesting that water entering well GS-8A during the aquifer test(s) either came from fractures connected to well GS-7 or from other areas with a very similar chemical and stable-isotopic signature.

Aqueous sodium and chloride concentrations generally increased with depth in the slag area and were consistently highest in wells open to the slate unit (Hamlin and Alpers, 1995, 1996). In the 200-foot-deep boreholes where the rock units were separated by inflatable packers (wells GS-1A, B, -4A, B, C, and -8A, B), sodium concentration ranged from 360 to 810 mg/L in the lower slate intervals and from 29 to 320 mg/L in the upper metavolcanic rock intervals; chloride ranged from 290 to 570 mg/L in the lower slate intervals and from 8.1 to 98 mg/L in the upper metavolcanic intervals (Hamlin and Alpers, 1996). The highest concentrations of sodium (3,200 mg/L) and chloride (5,000 mg/L) were in water samples from the 400-foot borehole (GS-6), which penetrated more than 300 ft of the slate unit. These results suggest that the slate unit is the principal source of dissolved sodium and chloride.

The relations among dissolved copper, zinc, sulfate, δD, and $\delta^{18}O$ shown in figures 10, 11, 12, 14, and 15 suggest a complex origin for ground water downgradient from Mine Run Dam. Mixing between evaporated, acidic drainage from Mine Run Reservoir and nonevaporated, uncontaminated ground water in the slag area is likely to be the dominant process. It is possible that the chemical and isotopic composition of Mine Run Reservoir has varied considerably in both space and time, such that the water recharged to ground water through the north abutment of Mine Run Dam would have had varying composition with time. This is one possible explanation for the differences between groups A and B.

FLOW RATE AND METAL LOADING OF CONTAMINATED GROUND WATER

The flow rate of ground water in the fractured metamorphic-rock aquifer between Mine Run Dam and Camanche Reservoir was estimated by Hamlin and Alpers (1995, 1996) using mathematical relations developed for porous media. According to Darcy's law,

$$q = KIA, \tag{4}$$

where q is the flow rate through a given cross-sectional area of aquifer, K is the hydraulic conductivity averaged over the thickness of the aquifer, I is the hydraulic gradient, and A is the cross-sectional area (Driscoll, 1987). Wells GS-1A and -8A (fig. 3) are oriented roughly along the axis of the contaminated plume (fig. 8*A*) and parallel to the direction of maximum hydraulic gradient for the ground-water system, which was about 0.14 in August 1992. The width of the plume was estimated to be about 100 ft on the basis of areal distribution of pH (values less than 5; fig. 8*A*) and zinc (concentrations greater than 200 mg/L; fig. 9*A*).

The primary fractures that transport ground water are in a zone about 10 ft thick that is associated with the metavolcanic-slate contact. The cross-sectional area of the flow path, therefore, is about 1,000 ft^2. The hydraulic gradient (a unitless quantity) probably ranges from zero (flat) during periods of submergence by Camanche Reservoir (such as August 1992) to about 0.14 westward toward Camanche Reservoir (Hamlin and Alpers, 1995, 1996) when water levels in Camanche Reservoir decline below about 185 ft above sea level. Therefore, a value of 0.07 is used to represent the average gradient. The median value of hydraulic conductivity for the metavolcanic rocks is about 0.1 ft/d (Hamlin and Alpers, 1995, 1996). Therefore, q=(0.1 ft/d) (1,000 ft^2) (0.07) = 7 ft^3/d. This rate is equivalent to about 52 gal/d. Using the value of 0.14 for the hydraulic gradient yields a discharge of about 14 ft^3/d (105 gal/d). The actual value for q is proportional to the width of the plume and to the effective hydraulic conductivity along the flow path. Seasonal changes in the hydraulic gradient also will affect the discharge rate. The hydraulic gradient for ground water between wells GS-3 and GS-14 also parallels the axis of the plume and was determined to be 0.19 in February 1993. This difference between 0.19 and 0.14 (+0.05) would not significantly change the estimates of flow along the plume. However, the hydraulic gradient for ground water was probably substantially flatter when the wells in the slag area were inundated by Camanche Reservoir during May–October 1993, and March–April and June–October 1995. Depending on the degree of hydraulic connection, flow during such periods of submergence could have been from Camanche Reservoir to the ground-water system.

The composition of the acid plume in ground water downgradient from Mine Run Reservoir may result from a mixing of water from several sources. The most obvious components of the mixed ground water are native ground water and water that has infiltrated from Mine Run Reservoir. Another potential component of mixed ground water could be underflow of acid drainage from the mine workings that has migrated along the metavolcanic-slate contact or along the Campo Seco Fault, which constitutes the metavolcanic-slate contact in the slag pile area. Maps of the mine workings (Heyl and others, 1948) indicate that the Campo Seco Fault intersects the mine workings in the shaft 3 area at an altitude between 600 and 700 ft below sea level (fig. 4).

On the basis of the estimates of ground-water flow along a path leading to Camanche Reservoir, ranges for metal-transport rates can be estimated using values for metal concentration determined for the contaminant plume (Hamlin and Alpers, 1995, 1996). A line connecting wells GS-1A, W-1D, and GS-3 is roughly perpendicular to the axis of the plume. Average estimated metal concentrations in ground-water samples collected between April 1992 and May 1994 for these wells were as follows: cadmium, 2.2 mg/L; copper, 11 mg/L; and zinc, 180 mg/L. Average cadmium and copper concentrations in ground-water samples collected in December 1993 and May 1994 from well GS-3 and nearby wells GS-4B and -14 were lower than for concentrations in samples collected during 1992. The lower cadmium and copper concentrations in 1993 and 1994 relative to 1992 are consistent with dilution and dispersion of the contaminant plume over the course of the study period in response to the inundation of the slag area by Camanche Reservoir. The lack of comparable decrease in zinc concentrations in the 1993 and 1994 sampling periods relative to the 1992 sampling period suggests the possibility of a different source for some of this dissolved metal. Other possible sources for zinc are the slag, which is 6 to 7 percent zinc (Wiebelt and Ricker, 1949) and may be leachable by low pH waters, and subsurface flow from the underground mine workings, which have water with high concentrations of zinc and relatively low concentrations of cadmium and copper (for example, well GS-18 and the GS-20-seep).

Metal loads in acid ground water were calculated for the period April 1992 to May 1994 using a value of 0.1 ft/d for hydraulic conductance (Hamlin and Alpers, 1995, 1996); a discharge rate of 52 gal/d; and average metal concentrations for cadmium, copper, and zinc of 2.2, 11, and 180 mg/L, respectively. On the basis of these data, daily metal loading rates for cadmium, copper, and zinc were approximately 0.4, 2.2, and 35 g/d (grams per day), respectively. Average loads for cadmium and copper for 1992–94 were less than those for computed for 1992 (Hamlin and Alpers, 1995) because of lower concentrations and a lower assumed flow rate in 1992–94. Although concentrations of zinc for wells GS-4A and -14 were higher in 1994 than in 1992, the lower assumed discharge rate (52 gal/d in comparison with 300 gal/d) resulted in an overall lower estimated average daily load for zinc in 1992–94.

SUMMARY

The Penn Mine site encompasses an area of about 140 acres and is located in the Foothill copper–zinc belt in northwestern Calaveras County, California. About 10.5 mi of underground workings were excavated to yield several acres of mill tailings and waste rock exposed on the surface. Slag from smelters was deposited in a 1,500-foot-long area adjacent to the former channel of the Mokelumne River. Historically, contaminated surface runoff from the mine flowed directly to the Mokelumne River and into Camanche Reservoir, which was formed by the construction of Camanche Dam in 1963. In an attempt to control discharge of contaminated surface water from the mine, diversions and impoundments were constructed in 1978. Use of sulfidic waste rock and mine tailings to construct dams, dikes, and basins, coupled with recirculation of contaminated water between impoundments, may have unintentionally enhanced the formation of acidic, metal-rich water. Although the impoundment system reduced (but did not eliminate) surface discharges from the mine, the results of this study indicate that contamination of ground water down-gradient from Mine Run Reservoir occurs through fractures in bedrock under Mine Run Reservoir, the lowermost unlined impoundment. Contamination of ground water probably occurred to a lesser extent prior to construction of the surface impoundments. Both before and after construction of Mine Run Dam in 1978, contaminated ground water has flowed through the fractured-rock aquifer toward Camanche Reservoir.

Geologic controls over the movement and distribution of ground water at Penn Mine include fractures in bedrock, faults, and the contact between the two principal rock types in the area. Fractures that transmit ground water occur chiefly near the base of the metavolcanic unit that overlies a metasedimentary (slate) unit, which is substantially less permeable. This contact zone acts as a conduit that transmits water along its strike, which is generally N. 20° W.

Hydraulic conductivity was estimated to be highest, about 50 ft/d, in the fractured intervals of the metavolcanic unit. Much lower values of hydraulic conductivity were estimated for the metasedimentary slate unit; median values determined by two independent methods were 0.002 to 0.01 ft/d. The median hydraulic conductivity for the metavolcanic unit was about 10 to 50 times higher than the hydraulic conductivity in the slate unit. An aquifer test indicated a hydraulic conductivity of 36 to 44 ft/d for the metavolcanic unit in the vicinity of a well located in the contaminant plume. These observations support the concept of a relatively narrow, hydraulically active fracture zone, either along or subparallel to the lithologic contact zone, as a conduit for ground-water flow.

The hydraulic gradient for ground water in the area downgradient from Mine Run Dam is generally from Mine Run Reservoir toward Camanche Reservoir. The steepness and direction of this gradient are affected by seasonal changes in recharge and in the water level of Camanche Reservoir. The gradient in the slag area is probably near zero (flat) during periods of submergence by Camanche Reservoir and was determined to be 0.14 and 0.19 during low stages of Camanche Reservoir in August 1992 and September 1994, respectively. The hydraulic gradient in the vicinity of shafts 3 and 4 generally follows the topography toward and along the Hinckley Run drainage. During the winter months of 1993 and 1995, water levels rose in these shafts, and numerous seeps developed in the area of shaft 4 and well GS-20. The flow from these seeps apparently increased in winter 1995 relative to water elevation increases in well GS-18 (near shaft 3), possibly indicating an improvement in the subsurface connection between shafts 3 and 4 between 1993 and 1995.

Acid drainage from surface impoundments forms a contaminant plume in ground water in the metavolcanic unit between Mine Run Dam and Camanche Reservoir. The plume is characterized by low pH values; enriched heavy isotopes of hydrogen and oxygen in a distinct relation, indicating an evaporative component; and high concentrations of sulfate and dissolved metals. Most wells in the slag area showed a decrease in dissolved metals and sulfate after a period of inundation during the summer of 1993. This observation is consistent with dilution and dispersion of the plume. The highest concentrations of dissolved sodium, chloride, and bromide were found in the slate unit, indicating a source in this unit. The enrichment of heavy stable isotopes of hydrogen and oxygen in the plume suggests that Mine Run Reservoir is the primary source of contaminated, partially evaporated water.

Correlations among geochemical data help define sources and conditions of formation for dissolved ionic species. In general, copper concentrations are correlated with zinc concentrations although systematic spatial variations in the ratio zinc/copper were found. Elevated concentrations of dissolved metals and sulfate correlate with low pH values and with high values of delta oxygen-18. In the slag area, two water types were distinguished (groups A and B) on the basis, in part, of zinc/copper ratios. Group A was characterized by zinc/copper ratios between 4 and 6; group B was characterized by ratios greater than 10. Groups A and B also showed distinct trends on plots of dissolved constituents (copper, zinc, and sulfate) versus delta oxygen-18.

The composition of water from wells GS-18 and -20, which penetrate the underground mine workings, indicates a geochemical environment different from that found in ground water downgradient from Mine Run Dam. Water from well GS-18 and from the artesian flow at well GS-20 had low concentrations of dissolved copper (less than 0.310 mg/L [milligrams per liter]). Prior to artesian flow, water from well GS-20 in December 1992 had a copper concentration of 36 mg/L. Another distinctive characteristic of the underground mine water is the presence of exsolving gas containing hydrogen and methane, probably produced under strongly reducing conditions. Isotopes of sulfur and oxygen in dissolved sulfate also support the presence of reducing conditions and active sulfate reduction in the underground mine workings. The relatively low copper and cadmium and high zinc concentrations in wells GS-18 and -20 in the area of shafts 3 and 4 are probably due to scavenging by hydrogen sulfide formed by sulfate reduction. In contrast, water samples from wells below Mine Run Dam showed oxidizing redox potentials and no evidence of sulfate reduction.

Ground water in the slag area, acidic water in unlined surface impoundments, ground water in the mine workings, and Camanche Reservoir water were differentiated on the basis of stable-isotope data for hydrogen and oxygen in water. The greatest enrichment in heavy isotopes of hydrogen and oxygen, caused by evaporation, was observed in the acidic ground-water plume in the slag area and in acidic drainage contained in the impoundments. Tritium and chlorofluorocarbon (CFC) data are consistent with most recharge to ground water having occurred after 1970. CFC data indicate contamination with one or more CFC's at most ground-water sites at the Penn Mine. However, tritium and CFC data are consistent with the occurrence of significant recharge to ground water in the slag area after construction of Mine Run Reservoir in 1978.

Five hypotheses were developed to help define possible sources of dissolved constituents to ground water in the slag area: (1) infiltration of acid drainage from Mine Run Reservoir, (2) some recharge of acid drainage from Mine Run prior to construction of Mine Run Dam in 1978, (3) dumping of acid wastes in the slag area, (4) flow from the underground mine workings along the Campo Seco Fault or similar structures, and (5) some combination of these processes. Geochemical data, particularly stable isotopes, strongly support hypothesis 1.

Ground-water discharge toward Camanche Reservoir in the slag area west of Mine Run Dam was estimated to be 52 gal/d on the basis of a hydraulic conductivity of 0.1 ft/d and a hydraulic gradient of 0.07. Actual values for discharge vary with hydraulic gradient, which is determined primarily by the level of Camanche Reservoir. Average metal concentrations for three wells in a cross-section of the acid ground-water plume (GS-1A, W-1D, and GS-3) for the period April 1992 to May 1994 were 2.2 mg/L for cadmium, 11 mg/L for copper, and 180 mg/L for zinc. Corresponding fluxes of dissolved metals to Camanche Reservoir for the discharge estimate of 52 gal/d are cadmium, 0.4 g/d (gram per day); copper, 2.2 g/d; and zinc, 35 g/d. Concentrations of cadmium and copper were generally lower in these wells in 1993 and 1994 than in 1992, probably reflecting dilution and dispersion of the plume in response to inundation of the slag area by Camanche Reservoir in 1993. Approximately 12,000 gal of contaminated water were pumped from the slag area during aquifer tests in May 1994. Concentrations of cadmium, copper, and zinc declined by about one-half during the course of this pumping. Estimates of ground-water flow and metal transport could be refined by additional ground-water monitoring and by numerical modeling of ground-water flow. Such modeling also would allow predictions of system response to additional pumping of contaminated ground water from the area downgradient from Mine Run Dam, which may be considered as a remedial option in combination with water treatment.

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TABLE 5

Table 5. Chemical data for wells, Mine Run Reservoir, and two seeps at Penn Mine, Calaveras County, California

[State well number: All wells in township 4N/ range 10E. MRR, Mine Run Reservoir; MRD, Mine Run Dam; NGVD, National Geodetic Vertical Datum of 1929. °C, degrees Celsius; mV, millivolt; ft, foot; µS/cm, microsiemens per centimeter; mg/L, miligrams per liter; µg/L, micrograms per liter (divided by 1,000 = milligrams per liter); δD, delta deuterium; $\delta^{18}O$, delta oxygen-18; <, actual value is less than shown; —, no data. No water-quality data were collected for wells GS-9, -10, 12, -13, and -17; multiple entries for certain dates represent field replicates]

Sample site	State well no.	Date (mm-dd-yy)	Temperature, water (° C)	Eh, redox potential (mV)	Specific conductance, field (µS/cm)	Specific conductance, lab (µS/cm)	Oxygen, dissolved (mg/L)	pH, water whole, field (standard units)	pH, water whole, lab (standard units)
USGS wells									
GS-1A	4G1A	04-17-92	18.0	460	4,950	5,140	—	5.1	4.9
		12-15-92	18.5	500	4,980	5,090	0.2	4.6	4.4
		12-17-93	15.6	370	4,560	5,010	—	5.9	6.2
GS-1B	4G1B	04-18-92	18.5	260	5,980	6,690	—	7.2	7.0
GS-2	4G2	04-14-92	18.5	320	1,810	2,060	.9	7.8	7.5
		12-15-93	18.4	340	2,280	2,320	1.4	7.3	7.5
		05-12-94	19.5	280	2,830	2,890	1.4	7.9	7.5
GS-3	4G3	04-15-92	19.5	450	4,600	4,800	1.7	4.8	4.7
		12-19-92	19.5	450	5,660	5,550	.2	5.1	5.1
		12-15-93	19.5	400	4,590	4,730	1.2	5.7	6.1
		05-25-94	23.5	500	4,700	4,600	4.0	5.1	5.1
GS-4A	4G4A	04-16-92	18.5	390	2,430	2,450	—	5.7	6.3
		04-16-92	18.5	390	2,430	2,390	—	5.7	5.7
GS-4B	4G4B	04-16-92	19.0	400	3,120	3,210	—	6.6	7.0
		12-15-92	16.5	430	3,360	3,420	2.0	6.2	6.4
		12-17-93	19.0	420	3,000	3,080	.6	6.3	6.8
		05-24-94	21.5	340	2,860	3,060	.4	6.2	6.4
GS-4C	4G4C	04-18-92	19.0	290	4,380	4,340	—	7.3	7.2
GS-5	4G5	04-13-92	17.5	440	3,430	3,580	.5	5.4	5.6
		12-18-92	18.0	470	4,300	3,950	.5	4.6	4.6
		12-15-93	—	—	—	2,740	—	—	5.6
		05-23-94	16.0	400	2,550	2,770	1.4	5.2	4.8
GS-6	4G6	04-15-92	18.5	480	18,000	18,400	.5	4.2	3.0
		04-15-92	18.5	480	18,000	18,400	—	4.1	3.0
		12-16-93	19.4	490	9,060	8,570	.9	4.0	3.3
GS-7	4G7	04-14-92	18.5	570	2,390	2,190	1.0	4.9	4.8
		12-16-93	18.6	480	3,780	3,830	1.0	4.3	4.0

Table 5. Chemical data for wells, Mine Run Reservoir, and two seeps at Penn Mine, Calaveras County, California—Continued

Sample site	State well no.	Date (mm-dd-yy)	Temperature, water (° C)	Eh, redox potential (mV)	Specific conductance, field (µS/cm)	Specific conductance, lab (µS/cm)	Oxygen, dissolved (mg/L)	pH, water whole, field (standard units)	pH, water whole, lab (standard units)
USGS wells—Continued									
GS-8A	4G8A	04-14-92	18.5	500	5,660	6,520	0.2	3.7	3.0
		12-14-92	18.0	430	6,230	6,480	.2	3.8	2.9
		12-18-93	16.3	—	6,070	5,980	.3	3.9	2.9
		05-10-94	19.0	—	4,900	5,250	.2	3.9	2.9
		05-11-94	18.5	—	3,300	3,200	2.0	4.0	3.1
		05-20-94	18.5	580	3,750	2,930	.9	3.6	3.1
GS-8B	4G8B	04-17-92	18.5	420	6,200	6,640	—	4.3	3.9
GS-11	4G11	12-13-92	19.0	450	3,940	4,210	1.0	3.9	3.0
		12-17-93	18.5	340	2,770	2,970	—	5.6	6.1
		05-25-94	20.5	440	4,020	4,070	.2	4.3	3.0
GS-14	4G14	12-14-92	18.0	—	6,750	6,900	.3	3.6	3.0
		12-14-92	18.0	—	6,750	6,920	.3	3.6	3.0
		12-18-93	18.0	290	5,450	5,370	—	4.0	3.0
		12-18-93	18.0	290	5,450	5,380	—	4.0	3.0
		05-23-94	17.5	500	4,670	4,770	.1	3.7	3.1
GS-15	4G15	12-19-92	18.0	540	6,380	6,870	.1	3.5	3.1
		12-19-92	18.0	540	6,380	6,870	.1	3.5	3.1
		12-16-93	18.0	420	7,020	6,810	—	4.3	3.3
		05-25-94	20.0	570	4,180	4,130	1.5	4.0	3.6
GS-16	4G16	12-16-92	18.0	550	8,300	8,270	—	3.4	3.0
		12-20-93	18.6	420	6,330	6,360	—	3.4	2.9
		12-20-93	18.6	420	6,330	6,360	—	3.4	2.9
		05-13-94	19.5	520	6,700	5,900	.1	3.4	3.0
		05-13-94	19.5	520	6,700	5,900	.1	3.4	3.0
GS-18	4G18	12-16-92	19.5	420	4,480	4,410	.2	3.8	2.6
		12-21-93	19.7	370	3,980	4,230	—	3.9	2.5
		06-30-94	22.5	300	4,370	4,270	.1	4.0	3.6
		06-30-94	22.5	300	4,340	4,270	.1	4.0	3.6
GS-19	4G19	12-16-92	18.5	664	1,710	1,650	6.1	3.1	3.0
GS-20	4G20	12-16-92	18.0	604	5,490	5,040	—	2.8	2.6
		01-28-93	—	—	3,850	—	—	4.2	—

Table 5. Chemical data for wells, Mine Run Reservoir, and two seeps at Penn Mine, Calaveras County, California—Continued

Sample site	State well no.	Date (mm-dd-yy)	Temperature, water (° C)	Eh, redox potential (mV)	Specific conductance, field (µS/cm)	Specific conductance, lab (µS/cm)	Oxygen, dissolved (mg/L)	pH, water whole, field (standard units)	pH, water whole, lab (standard units)
					Surface waters				
GS-20-Seep		01-28-93	—	—	3,880	—	—	4.2	—
MRD-Seep		07-07-93	30.0	—	4,000	3,900	—	3.7	3.9
MRR-A[1]		12-22-92	14.0	—	8,000	5,540	4.7	2.8	2.8
MRR-A[2]		12-22-92	14.0	686	8,000	8,410	4.7	2.8	2.7
MRR-B[2]		12-22-92	13.5	728	9,300	9,050	3.9	2.8	2.7
					EBMUD wells [3]				
W-1D		12-19-92	20.5	594	6,330	6,450	2.1	3.5	3.1
W-5D		12-22-92	17.0	508	8,080	8,080	0.5	3.6	3.1
					Field blanks				
Blank		04-21-92	—	—	—	6	—	—	7.3
Blank		12-22-92	—	—	—	13	—	—	5.6
Blank		12-21-93	—	—	—	2	—	—	7.5
Blank		05-24-94	—	—	—	—	—	—	5.9

Sample site	Date	Alkalinity, field (mg/L as $CaCO_3$)	Alkalinity, lab (mg/L as $CaCO_3$)	Nitrogen, nitrate, dissolved (mg/L as N)	Phosphorus, ortho, dissolved (mg/L as P)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Potassium, dissolved (mg/L as K)
				USGS wells					
GS-1A	04-17-92	—	3.8	<0.010	<0.010	480	350	280	11
	12-15-92	—	<1.0	—	—	470	400	270	10
	12-17-93	—	42	—	—	500	370	320	10
GS-1B	04-18-92	110	92	<.010	<.010	480	260	810	18
GS-2	04-14-92	155	152	.030	.010	72	34	320	5.5
	12-15-93	—	127	—	—	89	39	350	3.3
	05-12-94	—	—	—	—	90	35	480	5.4
GS-3	04-15-92	7	2.2	<.010	.010	440	550	57	3.9
	12-19-92	—	5.9	—	—	510	690	100	5.8
	12-15-93	—	35	—	—	460	450	180	4.0
	05-25-94	—	—	—	—	440	480	110	3.8

Table 5. Chemical data for wells, Mine Run Reservoir, and two seeps at Penn Mine, Calaveras County, California—Continued

Sample site	Date	Alkalinity, field (mg/L as $CaCO_3$)	Alkalinity, lab (mg/L as $CaCO_3$)	Nitrogen, nitrate, dissolved (mg/L as N)	Phosphorus, ortho, dissolved (mg/L as P)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Potassium, dissolved (mg/L as K)
USGS wells—Continued									
GS-4A	04-16-92	19	9.8	0.010	0.030	210	260	29	2.7
	04-16-92	19	9.8	<.010	.020	200	240	31	2.7
GS-4B	04-16-92	85	85	.080	.010	360	250	83	2.8
	12-15-92	—	50	—	—	390	310	63	2.7
	12-17-93	—	75	—	—	370	260	77	2.7
	05-24-94	—	—	—	—	340	260	87	3.3
GS-4C	04-18-92	110	84	<.010	<.010	380	270	360	7.6
GS-5	04-13-92	18	15	<.010	<.010	360	320	49	6.4
	12-18-92	—	2.2	—	—	430	380	62	6.3
	12-15-93	—	4.1	—	—	812	270	35	6.3
	05-23-94	—	—	—	—	290	250	35	6.9
GS-6	04-15-92	—	<1.0	<.010	.010	560	290	3,200	19
	04-15-92	—	<1.0	<.010	.010	600	270	3,100	20
	12-16-93	—	<1.0	—	—	470	380	910	8.2
GS-7	04-14-92	10	4.2	.020	<.010	300	170	28	3.1
	12-16-93	—	<1.0	—	—	500	290	32	4.0
GS-8A	04-14-92	—	<1.0	<.010	.130	480	580	60	2.6
	12-14-92	—	<1.0	—	—	440	620	64	2.3
	12-18-93	—	<1.0	—	—	460	500	62	2.2
	05-10-94	—	—	—	—	420	430	58	2.5
	05-11-94	—	—	—	—	230	240	36	1.4
	05-20-94	—	—	—	—	200	230	32	1.4
GS-8B	04-17-92	—	<1.0	<.010	.010	460	460	390	9.1
GS-11	12-13-92	—	<1.0	—	—	400	300	64	2.3
	12-17-93	—	21	—	—	290	250	77	1.4
	05-25-94	—	—	—	—	390	320	60	2.1
GS-14	12-14-92	—	<1.0	—	—	490	710	67	2.8
	12-14-92	—	<1.0	—	—	480	700	67	2.6
	12-19-93	—	<1.0	—	—	410	470	55	2.0
	12-19-93	—	<1.0	—	—	430	470	56	2.1
	05-23-94	—	—	—	—	350	420	50	2.0

Table 5. Chemical data for wells, Mine Run Reservoir, and two seeps at Penn Mine, Calaveras County, California—Continued

Sample site	Date	Alkalinity, field (mg/L as $CaCO_3$)	Alkalinity, lab (mg/L as $CaCO_3$)	Nitrogen, nitrate, dissolved (mg/L as N)	Phosphorus, ortho, dissolved (mg/L as P)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Potassium, dissolved (mg/L as K)
				USGS wells—Continued					
GS-15	12-19-92	—	<1.0	—	—	480	690	110	5.7
	12-19-92	—	<1.0	—	—	480	690	110	5.1
	12-16-93	—	<1.0	—	—	450	520	290	8.8
	05-25-94	—	—	—	—	330	360	65	2.6
GS-16	12-16-92	—	<1.0	—	—	460	940	72	2.5
	12-20-93	—	<1.0	—	—	450	540	59	1.6
	12-20-93	—	<1.0	—	—	440	530	59	1.5
	05-13-94	—	—	—	—	460	520	57	1.8
	05-13-94	—	—	—	—	460	540	59	1.9
GS-18	12-16-92	—	<1.0	—	—	460	150	67	16
	12-21-93	—	<1.0	—	0.04	490	130	58	2.8
	06-30-94	—	—	—	—	510	150	68	15
	06-30-94	—	—	—	—	500	150	67	15
GS-19	12-16-92	—	<1.0	—	—	30	120	11	13
GS-20	12-16-92	—	<1.0	—	—	380	240	46	8.5
	01-28-93	—	—	—	—	540	130	54	13
				Surface waters					
GS-20-Seep	01-28-93	—	—	—	—	500	130	54	13
MRD-Seep	07-07-93	—	<1.0	—		510	270	43	2.3
MRR-A[1]	12-22-92	—	<1.0	—	—	280	450	45	1.4
MRR-A[2]	12-22-92	—	<1.0	—	—	430	810	73	<0.10
MRR-B[2]	12-22-92	—	—	—	—	—	—	—	—
				EBMUD wells [3]					
W-1D	12-19-92	—	21.0	—	—	490	720	57	1.6
W-5D	12-22-92	—	21.0	—	—	450	920	71	2.0
				Field blanks					
Blank	04-12-92	—	2.4	—	—	0.07	0.03	<0.20	<0.10
Blank	12-22-92	—	1.7	—	—	<.02	<.01	<.20	<.10
Blank	12-21-93	—	1.5	—	—	.03	<.01	<.20	<.10
Blank	05-24-94	—	—	—	—	.11	.01	.20	<.10

Table 5. Chemical data for wells, Mine Run Reservoir, and two seeps at Penn Mine, Calaveras County, California—Continued

Sample site	Date	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO_4)	Fluoride, dissolved (mg/L as F)	Bromide, dissolved (mg/L as Br)	Cadmium, dissolved (µg/L as Cd)	Copper, dissolved (µg/L as Cu)	Iron,[4] dissolved (µg/L as Fe)	Iron,[4] total dissolved (µg/L as Fe)	Iron,[4] ferrous, dissolved (µg/L as Fe)
					USGS wells					
GS-1A	04-17-92	97	3,500	1.5	0.88	2,100	9,800	160	—	—
	12-15-92	78	3,700	1.3	.39	2,300	13,000	1,900	<300	<10
	12-17-93	98	3,400	0.70	.36	1,600	270	5,000	6,100	5,100
GS-1B	04-18-92	570	3,000	.90	4.5	440	<10	<10	—	—
GS-2	04-14-92	240	450	.20	1.6	<10	<10	<10	—	—
	12-15-93	350	550	.30	1.1	10	<10	21	<300	11
	05-12-94	450	610	.30	1.6	<10	10	30	<300	<10
GS-3	04-15-92	21	3,700	.30	.10	2,600	12,000	60	—	—
	12-19-92	36	4,400	.40	.15	3,700	11,000	80	<300	<10
	12-15-93	58	3,400	.70	.19	1,600	5,700	50	<300	<10
	05-25-94	41	3,500	.50	.18	2,200	6,600	50	<300	<10
GS-4A	04-16-92	8.1	1,400	<.10	.26	1,100	1,100	<10	—	—
	04-16-92	9.2	1,500	.10	.27	1,000	1,100	<10	—	—
GS-4B	04-16-92	54	2,100	.20	1.3	530	130	20	—	—
	12-15-92	26	2,300	.20	.24	900	400	10	70	<10
	12-17-93	27	2,000	<.10	.38	450	140	50	—	—
	05-24-94	23	2,000	<.10	.33	620	50	200	830	320
GS-4C	04-18-92	320	2,200	.30	1.3	520	30	<10	—	—
GS-5	04-13-92	16	2,900	.20	.22	3,000	2,600	130	—	—
	12-18-92	25	2,900	.30	.13	2,900	6,100	3,200	—	—
	12-15-93	11	1,900	.20	.070	2,000	3,100	360	410	450
	05-23-94	12	1,900	—	.10	2,200	3,100	1,000	1,200	950
GS-6	04-15-92	4,100	4,000	2.8	8.3	680	12,000	930	—	—
	04-15-92	5,000	2,900	3.2	6.5	690	13,000	950	—	—
	12-16-93	1,100	4,200	3.7	2.2	950	32,000	25,000	240	14
GS-7	04-14-92	20	1,700	.80	.39	630	14,000	100	—	—
	12-16-93	14	3,000	3.1	.070	1,300	38,000	150	220	<10
GS-8A	04-14-92	60	5,900	9.8	.48	1,400	86,000	110,000	—	—
	12-14-92	51	5,700	4.8	.32	1,500	88,000	150,000	150,000	120,000
	12-18-93	61	5,300	6.8	.28	1,300	9,700	110,000	130,000	120,000
	05-10-94	48	4,300	2.1	.31	1,000	63,000	99,000	92,000	86,000
	05-11-94	20	2,300	1.4	.13	510	30,000	39,000	38,000	32,000
	05-20-94	17	2,100	1.5	.13	470	28,000	30,000	29,000	23,000
GS-8B	04-17-92	290	4,400	6.4	3.9	970	5,400	94,000	—	—

Table 5. Chemical data for wells, Mine Run Reservoir, and two seeps at Penn Mine, Calaveras County, California—Continued

Sample site	Date	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO_4)	Fluoride, dissolved (mg/L as F)	Bromide, dissolved (mg/L as Br)	Cadmium, dissolved (µg/L as Cd)	Copper, dissolved (µg/L as Cu)	Iron,[4] dissolved (µg/L as Fe)	Iron,[4] total dissolved (µg/L as Fe)	Iron,[4] ferrous, dissolved (µg/L as Fe)
USGS wells—Continued										
GS-11	12-13-92	25	2,900	2.9	0.42	500	35,000	83,000	85,000	72,000
	12-17-93	12	2,000	1.1	.54	240	11,000	27,000	31,000	27,000
	05-25-94	20	3,000	2.0	124[5]	560	34,000	69,000	66,000	61,000
GS-14	12-14-92	36	6,400	6.4	.51	1,500	84,000	92,000	100,000	80,000
	12-14-92	35	6,400	7.0	.46	1,500	84,000	89,000	100,000	79,000
	12-19-93	36	4,600	3.9	.13	1,100	61,000	54,000	68,000	58,000
	12-19-93	71	4,600	4.2	.12	1,200	62,000	57,000	69,000	—
	05-23-94	26	4,100	1.2	.050	950	49,000	45,000	44,000	38,000
GS-15	12-19-92	67	6,100	6.8	.32	1,500	80,000	64,000	71,000	56,000
	12-19-92	67	6,300	4.5	.34	1,500	80,000	63,000	71,000	55,000
	12-16-93	130	5,700	7.7	.33	1,100	7,800	48,000	57,000	49,000
	05-25-94	27	3,400	1.2	.20	780	34,000	6,800	11,000	6,800
GS-16	12-16-92	40	8,300	7.0	1.3	1,900	120,000	—	79,000	52,000
	12-20-93	32	5,900	3.6	.050	1,300	76,000	67,000	77,000	48,000
	12-20-93	32	5,900	6.0	.050	1,300	76,000	63,000	—	—
	05-13-94	30	5,300	—	.23	1,100	63,000	69,000	68,000	58,000
	05-13-94	28	5,400	—	.32	1,100	62,000	67,000	67,000	57,000
GS-18	12-16-92	23	3,200	1.7	7.3	50	130	82,000	760,000	740,000
	12-21-93	21	3,100	—	16	50	310	670,000	660,000	650,000
	06-30-94	25	3,300	.20	.14	20	20	850,000	740,000	710,000
	06-30-94	25	3,300	.10	<.010	20	20	850,000	760,000	740,000
GS-19	12-16-92	24	810	.70	.47	80	1,600	22,000	24,000	15,000
GS-20	12-16-92	18	4,200	.80	49	410	36,000	540,000	540,000	510,000
	01-28-93	22	2,900	1.3	—	20	60	660,000	—	—
Surface waters										
GS-20-Seep	01-28-93	21	2,900	1.3	—	20	60	620,000	—	—
MRD-Seep	07-07-93	22	2,900	2.3	.060	510	25,000	90	250	<100
MRR-A[1]	12-22-92	22	4,800	.90	.94	940	62,000	110,000	—	—
MRR-A[2]	12-22-92	38	8,500	.40	1.9	1,700	110,000	160,000	—	—
MRR-B[2]	12-22-92	—	—	—	—	—	—	—	—	—
EBMUD wells [3]										
W-1D	12-19-92	29	6,000	6.8	.24	1,300	30,000	54,000	—	—
W-5D	12-22-92	38	8,100	.90	.080	1,800	130,000	62,000	76,000	61,000
Field blanks										
Blank	04-12-92	.30	<0.10	<0.10	<0.01	<10	<10	4	—	—
Blank	12-22-92	.10	.50	<.10	<.01	<10	<10	<3	—	—
Blank	12-21-93	<.10	<.10	<.10	<.01	<10	<10	27	—	—
Blank	05-24-94	<.10	.20	<.10	<.01	<10	<10	5	—	—

Table 5. Chemical data for wells, Mine Run Reservoir, and two seeps at Penn Mine, Calaveras County, California—Continued

Sample site	Date	Silica, dissolved (mg/L as SiO_2)	Lead dissolved (µg/L as Pb)	Manganese, dissolved (µg/L as Mn)	Silver, dissolved (µg/L as Ag)	Zinc, dissolved (µg/L as Zn)	Aluminum, dissolved (µg/L as Al)	Solids residue at 180 deg. C, dissolved (mg/L)
				USGS wells				
GS-1A	04-17-92	42	<1	27,000	<1.0	140,000	3,800	5,580
	12-15-92	47	<1	33,000	<1.0	190,000	10,000	5,540
	12-17-93	22	<1	25,000	<1.0	89,000	70	5,270
GS-1B	04-18-92	13	<1	20,000	<1.0	18,000	30	6,090
GS-2	04-14-92	16	<1	70	<1.0	20	<10	3,750
	12-15-93	20	<1	42	<1.0	120	20	1,520
	05-12-94	18	<1	40	—	60	20	1,840
GS-3	04-15-92	59	<1	25,000	<1.0	150,000	4,800	5,290
	12-19-92	72	<1	38,000	<1.0	250,000	3,800	6,590
	12-15-93	40	<1	18,000	<1.0	88,000	470	5,260
	05-25-94	51	3	21,000	—	120,000	1,200	5,160
GS-4A	04-16-92	42	<1	980	<1.0	39,000	40	2,320
	04-16-92	42	<1	850	<1.0	34,000	50	2,340
GS-4B	04-16-92	32	<1	260	<1.0	12,000	20	3,190
	12-15-92	37	<1	120	<1.0	26,000	60	3,510
	12-17-93	33	<1	150	<1.0	1,100	30	3,080
	05-24-94	36	<1	270	—	19,000	10	3,040
GS-4C	04-18-92	22	<1	790	<1.0	—	30	3,870
GS-5	04-13-92	41	<1	1,900	<1.0	78,000	240	3,840
	12-18-92	44	<1	4,600	<1.0	94,000	3,800	4,320
	12-15-93	42	<1	1,700	<1.0	—	610	2,740
	05-23-94	44	1	1,800	—	70,000	810	2,770
GS-6	04-15-92	34	4	24,000	<1.0	120,000	52,000	15,000
	04-15-92	35	4	25,000	<1.0	170,000	51,000	14,500
	12-16-93	93	9	27,000	<1.0	210,000	100,000	8,110
GS-7	04-14-92	38	<1	23,000	<1.0	83,000	3,600	2,610
	12-16-93	73	<1	37,000	<1.0	190,000	25,000	4,590
GS-8A	04-14-92	120	<1	58,000	<1.0	—	220,000	9,020
	12-14-92	110	<1	52,000	<1.0	470,000	250,000	8,670
	12-18-93	90	<4	49,000	<1.0	340,000	190,000	8,040
	05-10-94	96	2	47,000	—	310,000	120,000	6,530
	05-11-94	92	1	24,000	—	160,000	61,000	3,480
	05-20-94	64	1	21,000	—	150,000	53,000	3,130
GS-8B	04-17-92	48	7	44,000	<1.0	300,000	89,000	7,530
GS-11	12-13-92	56	<1	37,000	<1.0	210,000	49,000	4,570
	12-17-93	32	<1	25,000	<1.0	71,000	1,200	2,980
	05-25-94	61	2	41,000	—	190,000	58,000	4,640

Table 5. Chemical data for wells, Mine Run Reservoir, and two seeps at Penn Mine, Calaveras County, Californai—Continued

Sample site	Date	Silica, dissolved (mg/L as SiO_2)	Lead dissolved (µg/L as Pb)	Manganese, dissolved (µg/L as Mn)	Silver, dissolved (µg/L as Ag)	Zinc, dissolved (µg/L as Zn)	Aluminum, dissolved (µg/L as Al)	Solids residue at 180 deg. C, dissolved (mg/L)
USGS wells—Continued								
GS-14	12-14-92	140	<1	55,000	<1.0	460,000	370,000	10,000
	12-14-92	140	<1	57,000	<1.0	470,000	350,000	9,540
	12-18-93	120	<1	40,000	<1.0	280,000	160,000	6,940
	12-18-93	120	<1	41,000	<1.0	290,000	150,000	7,010
	05-23-94	120	1	40,000	—	290,000	140,000	6,200
GS-15	12-19-92	130	3	52,000	<1.0	460,000	360,000	9,560
	12-19-92	140	3	51,000	<1.0	450,000	380,000	9,660
	12-16-93	84	10	48,000	<1.0	340,000	180,000	8,690
	05-25-94	100	6	27,000	—	190,000	99,000	5,080
GS-16	12-16-92	140	3	170,000	<1.0	630,000	560,000	12,800
	12-20-93	120	11	84,000	<1.0	320,000	260,000	8,870
	12-20-93	120	11	83,000	<1.0	330,000	260,000	8,920
	05-13-94	130	10	84,000	—	340,000	190,000	7,990
	05-13-94	130	10	80,000	—	320,000	200,000	8,010
GS-18	12-16-92	53	170	2,600	<1.0	400,000	210,000	5,060
	12-21-93	42	24	10,000	<1.0	33,000	14,000	4,540
	06-30-94	83	14	13,000	—	46,000	8,600	5,500
	06-30-94	83	13	12,000	—	49,000	8,600	5,500
GS-19	12-16-92	77	25	1,300	<1.0	1,800	38,000	1,230
GS-20	12-16-92	120	14	15,000	<1.0	62,000	280,000	6,230
	01-28-93	60	13	9,100	<1.0	46,000	6,000	1,280
Surface waters								
GS-20-Seep	01-28-93	60	13	9,100	<1.0	48,000	5,900	3,690
MRD-Seep	07-07-93	70	5	14,000	<1.0	96,000	33,000	4,460
MRD-A[1]	12-22-92	130	7	28,000	<1.0	200,000	280,000	3,820
MRR-A[2]	12-22-92	190	<1	51,000	<1.0	570,000	720,000	13,200
MRR-B[2]	12-22-92	—	—	—	—	—	—	—
EBMUD wells [3]								
W-1D	12-19-92	150	190	62,000	<1.0	390,000	290,000	8,990
W-5D	12-22-92	150	<1	150,000	<1.0	620,000	500,000	12,200
Field blanks								
Blank	04-21-92	<0.1	<1	<1	<1.0	<3	<10	5
Blank	12-22-92	.30	<1	<1	<1.0	5	30	<1
Blank	12-21-93	<.1	<1	<1	<1.0	<3	<10	6
Blank	05-24-94	<.1	<1	<1	—	12	60	<1

Table 5. Chemical data for wells, Mine Run Reservoir, and two seeps at Penn Mine, Calaveras County, California—Continued

Sample site	Date	Altitude of land surface datum (ft. above NGVD)	Depth of well, total (feet)	Depth of water level below land surface (feet)	δD (per mil)	$\delta^{18}O$ (per mil)
			USGS wells			
GS-1A	04-17-92	217	80	24.36	–36.5	–3.40
	12-15-92	217	80	—	–37.4	–3.31
	12-17-93	217	80	0.69	—	—
GS-1B	04-18-92	217	200	8.01	–40.0	–3.85
GS-2	04-14-92	222	200	28.69	–56.0	–7.65
	12-15-93	222	200	3.64	—	—
	05-12-94	222	200	14.12	–54.6	–7.54
GS-3	04-15-92	226	200	10.16	–35.0	–3.45
	12-19-92	226	200	10.17	–32.1	–2.32
	12-15-93	226	200	6.20	—	—
	05-25-94	226	200	8.92	–36.3	–3.34
GS-4A	04-16-92	221	55	34.42	–51.5	–6.60
	04-16-92	221	55	34.42	–50.0	–6.65
GS-4B	04-16-92	221	80	35.18	–48.5	–6.30
	12-15-92	221	80	46.18	–46.5	–6.01
	12-17-93	221	80	19.40	—	—
	05-24-94	221	80	16.50	–49.5	–6.19
GS-4C	04-18-92	221	200	23.70	–48.5	–6.25
GS-5	04-13-92	218	201.5	31.65	–46.5	–5.40
	12-18-92	218	201.5	44.59	–42.9	–5.04
	12-15-93	218	201.5	—	—	—
	05-23-94	218	201.5	13.85	–49.2	–5.89
GS-6	04-15-92	220	401	32.72	–35.0	–2.90
	04-15-92	220	401	32.72	–33.0	–2.90
	12-16-93	220	401	3.10	—	—
GS-7	04-14-92	220	202	31.14	–58.0	–8.20
	12-16-93	220	202	2.16	—	—
GS-8A	04-14-92	219	76	32.91	–32.5	–2.65
	12-14-92	219	76	43.18	–33.9	–2.61
	12-18-93	219	76	—	—	—
	05-10-94	219	76	12.23	–43.1	–4.67
	05-11-94	219	76	—	–56.9	–6.94
	05-20-94	219	76	—	–57.3	–7.21
GS-8B	04-17-92	219	200	23.78	–38.0	–3.85
GS-11	12-13-92	219	61	—	–48.8	–5.84
	12-17-93	219	61	1.09	—	—
	05-25-94	219	61	15.01	–48.1	–6.01

Table 5. Chemical data for wells, Mine Run Reservoir, and two seeps at Penn Mine, Calaveras County, California—Continued

Sample site	Date	Altitude of land surface datum (ft. above NGVD)	Depth of well, total (feet)	Depth of water level below land surface (feet)	δD (per mil)	$\delta^{18}O$ (per mil)
USGS wells—Continued						
GS-14	12-14-92	219	66	44.92	–27.7	–1.38
	12-14-92	219	66	44.92	–27.3	–1.34
	12-18-93	219	66	—	—	—
	12-18-93	219	66	—	—	—
	05-23-94	219	66	14.15	–41.5	–4.23
GS-15	12-19-92	218	120	42.50	–29.0	–1.42
	12-19-92	218	120	42.50	–28.4	–1.47
	12-16-93	218	120	0.98	—	—
	05-25-94	218	120	—	–43.8	–4.75
GS-16	12-16-92	262	183	21.41	–15.2	1.40
	12-20-93	262	183	—	—	—
	12-20-93	262	183	12.95	—	—
	05-13-94	262	183	—	–24.3	–0.75
	05-13-94	262	183	13.01	–24.8	–0.82
GS-18	12-16-92	362	260	—	–49.8	–7.39
	12-21-93	362	260	89.14	—	—
	06-30-94	362	260	—	–49.7	–7.35
	06-30-94	362	260	88.26	–51.1	–7.31
GS-19	12-16-92	362	162	90.49	–56.9	–7.99
GS-20	12-16-92	281	23	10.22	–47.2	–6.81
	01-28-93	281	23	—	–48.8	–7.31
Surface waters						
GS-20-Seep	01-28-93	281	—	—	–48.8	–7.32
MRD-Seep	07-07-93	242	—	—	–27.4	–1.54
MRR-A[1]	12-22-92	242	—	—	–25.4	–2.12
MRR-A[2]	12-22-92	242	—	—	–8.4	2.55
MRR-B[2]	12-22-92	242	—	—	–3.6	3.78
EBMUD wells [3]						
W-1D	12-29-92	227	48	16.42	–21.7	–.41
W-5D	12-22-92	264	49	20.87	–15.9	1.31
Field blanks						
Blank	04-21-92	—	—	—	—	—
Blank	12-22-92	—	—	—	—	—
Blank	12-21-93	—	—	—	—	—
Blank	05-24-94	—	—	—	—	—

Table 5. Chemical data for wells, Mine Run Reservoir, and two seeps at Penn Mine, Calaveras County, California—Continued

Sample site	State well No.	Date	Nitrogen, ammonia, dissolved (mg/L as N)	Nitrogen, nitrite, dissolved (mg/L as N)	Nitrogen, ammonia plus organic, dissolved (mg/L as N)	Nitrogen, nitrite plus nitrate, dissolved (mg/L as N).	Phosphorus, dissolved (mg/L as P))	Phosphorus, ortho, dissolved (mg/L as P)
GS-18	4G18	12-21-93	1.4	<0.01	1.6	<0.05	0.08	0.04
Pond HR2		12-21-93	.77	<.01	.8	.55	.11	.11

[1] One foot below water surface.

[2] Six feet below water surface.

[3] "EBMUD wells" drilled during 1989 and 1990 on the property of the East Bay Municipal Utility District (Brown and Caldwell, 1991).

[4] "Iron, dissolved" determined by atomic absorption spectroscopy by USGS in Arvada, Colo. "Iron, total" and "Iron, ferrous" determined by spectrophotometry by USGS in Sacramento, Calif., using FerroZine as a complexing agent.

[5] Elevated bromide concentration at conclusion of tracer test indicates residual bromide in injection well.

APPENDICES

Appendix 1. Water levels and other field data for aquifer test, May 1994

[Date format, mm-dd-yy, month-day-year; time in 24-hour format. All depths in feet below measuring point. See appendix 2 for altitudes of measuring points. ft, foot; gal/min, gallons per minute]

A. Initial water levels

Date 05-09-94, Time 1700

Well No.	GS-1A	GS-1B	GS-2	GS-3	GS-6	GS-7	GS-8A	GS-10	GS-13	GS-14	GS-15
Depth	13.86	8.50	15.43	11.49	15.61	14.88	14.83	11.21	12.76	12.78	14.32

Date 05-10-94

GS-1A		GS-1B		GS-3		GS-4A		GS-4B		GS-4C	
Time	Depth	Time	Depth	Time	Depth	Time	Depth	Time	Depth	Time	Depth
1445	13.87	1446	8.45	1448	11.51	1455	17.41	1454	16.34	1453	16.65

GS-8A		GS-8B		GS-11		GS-13		GS-14		GS-15	
Time	Depth	Time	Depth	Time	Depth	Time	Depth	Time	Depth	Time	Depth
1501	14.23	1501	12.61	1402	14.04	1410	12.68	1420	13.54	1432	14.43
				1441	14.04	1459	12.69	1458	13.53	1456	14.43

B. Aquifer Test—Drawdown Data

[Pumping at well GS-8A began at 1507 on 05-10-94 and ended at 1500 on 05-11-94; drawdown data during pumping; time refers to 05-10-94 continuing to 05-11-94; —, no measurement]

GS-8A		
Time	Depth	Pump rate (gal/min)
1507	14.23	0. -pump on
1513	14.39	1.8
1517	14.39	1.8
1518-1519	—	pump off
1523	14.46	2.5
1526	14.48	2.5
1533	14.48	2.5
1541	14.56	4.0
1545	14.56	4.0
1552	14.64	4.25
1600	14.65	4.25
1611	14.66	4.3
1622	14.64	4.0
1629	14.65	—
1648	14.65	4.2
1654	14.66	—
1708	14.65	—
1727-1729	—	pump off
1730	14.66	—
1804	14.66	4.3
1835	14.66	—
1900	14.66	4.3
1930-1935	—	pump off
1936	14.66	—
2000	14.68	4.3
2100	14.68	4.3
2140-2143	—	pump off
2143	14.67	—
2200	14.68	4.3

GS-8A		
Time	Depth	Pump rate (gal/min)
2300	14.68	4.3
2400	14.70	4.3
0005-0010	—	pump off
0010	14.68	—
0010	14.70	4.4
0154	14.68	—
0200	14.68	4.4
0240	14.69	—
0300	14.69	4.4
0320	14.70	—
0359	14.70	—
0400	14.70	—
0500	14.70	—
0514	14.70	—
0601	14.72	—
0658	14.72	4.4
0801	14.72	4.4
0845	14.73	4.4
0847	14.73	—
0932	14.75	—
0934-0945	—	pump off
1010	14.73	—
1014	14.75	—
1210	14.73	—
1230	14.73	4.4
1305	14.73	—
1329	14.76	—
1423	14.77	—
1459	14.77	—

(see also figure 7)

Appendix 1. Water levels and other field data for aquifer test, May 1994—Continued

B. Aquifer test--drawdown data—*Continued*

GS-1A		GS-1B		GS-3		GS-4A		GS-4B		GS-4C	
Time	Depth	Time	Depth	Time	Depth	Time	Depth	Time	Depth	Time	Depth
1815	13.93	1816	8.43	1817	11.50	1819	17.43	1819	16.37	1820	16.67
2213	13.93	2215	8.41	2220	11.50	2221	17.46	2224	16.40	2226	16.70
0136	13.93	0135	8.42	0144	11.52	0149	17.48	0150	16.43	0148	16.72
0228	13.94	0230	8.42	0235	11.52	0221	17.48	0220	16.45	0223	16.72
0310	13.93	0312	8.43	0315	11.52	0302	17.50	0300	16.45	0303	16.73
0412	13.94	0410	8.42	0408	11.52	0406	17.49	0406	16.45	0404	16.73
0541	13.94	0540	8.42	0537	11.52	0532	17.44	0534	16.44	0530	16.74
0610	13.94	0609	8.42	0612	11.52	0614	17.50	0616	16.44	0617	16.74
1021	14.06	1023	8.43	0859	11.52	1100	17.51	1058	16.44	1101	16.75
1248	14.06	1249	8.41	(see also figure 7)		1256	17.53	1254	16.47	1257	16.77

GS-8B		GS-11		GS-11 *(cont.)*		GS-13		GS-14		GS-15		GS-16	
Time	Depth	Time	Depth	Time	Depth	Time	Depth	Time	Depth	Time	Depth	Time	Depth
1625	12.60	1510	14.05	1741	14.27	1523	12.69	1500	13.54	1500	14.43	0200	13.60
0156	12.58	1516	14.06	1802	14.28	1524	12.70	1600	13.56	1600	14.43	0300	13.60
0245	12.58	1522	14.07	1825	14.28	1653	12.71	1700	13.58	1700	14.44	0400	13.60
0330	12.58	1525	14.08	1827	14.28	1735	12.71	1800	13.58	1800	14.44	0510	13.59
0402	12.60	1530	14.09	1930	14.30	1827	12.71	1900	13.59	1900	14.45	0625	13.59
0515	12.60	1535	14.10	1934	14.29	1955	12.72	2000	13.59	2000	14.45	0805	13.60
0604	12.58	1540	14.11	2002	14.30	2009	12.72	2100	13.61	2100	14.46	0858	13.60
0847	12.59	1543	14.12	2007	14.30	2042	12.73	2200	13.61	2200	14.47	1442	13.60
1015	12.57	1547	14.13	2052	14.31	2134	12.74	2300	13.62	2300	14.47		
		1550	14.14	2136	14.32	2212	12.74	2400	13.63	2400	14.48		
		1553	14.15	2229	14.33	2220	12.74	0100	13.63	0100	14.48		
		1555	15.16	2306	14.33	2314	12.74	0200	13.63	0200	14.50		
		1558	14.17	0108	14.34	0110	12.75	0300	13.64	0300	14.50		
		1601	14.18	0208	14.34	0212	12.76	0400	13.65	0400	14.51		
		1605	14.19	0337	14.36	0339	12.76	0500	13.67	0500	14.52		
		1609	14.20	0415	14.36	0430	12.76	0600	13.66	0600	14.52		
		1614	14.21	0500	14.36	0553	12.77	0700	13.67	0700	14.52		
		1621	14.22	0540	14.37	0806	12.78	0800	13.67	0800	14.52		
		1628	14.23	0722	14.38	0808	12.79	0900	13.68	0900	14.53		
		1635	14.24	1017	14.39	1050	12.78	1000	13.67	1000	14.53		
		1646	14.25	(see also figure 7)				1100	13.68	1100	14.54		
		1657	14.26					1200	13.71	1200	14.54		
								1300	13.68	1300	14.55		
								1400	13.71	1400	14.56		
								1500	13.70	1500	14.56		
										(see also figure 7)			

C. Aquifer test—Recovery Data

[Pumping of well GS-8A stopped at 1500 on 05-11-94. Time refers to 05-11-94 continuing to 05-12-94]

GS-1A		GS-1A *(Cont.)*		GS-4B		GS-8A		GS-8A *(Cont.)*		GS-11
Time	Depth	Time	Depth	Time	Depth	Time	Depth	Time	Depth	(See figure 7)
1500	14.04	0808	14.45	1536	16.47	1500	14.30	0914	14.46	
1507	14.03	0830	14.16	1754	16.49	1501–10	14.27–14.30	1150	14.45	
1518	14.03	0924	14.16	1900	16.49	1512	14.37	1314	14.47	
1530	14.02	1156	14.16	1957	16.50	1513	14.38	(See also figure 7)		
1552	14.01	1318	14.15	2100	16.50	1515–1750	14.34–14.38			
1751	14.03			2206	16.51	1855	14.37			
1857	14.03			2303	16.52	1955	14.39			
2001	14.02			2357	16.53	2058	14.38			
2103	14.03			0100	16.53	2203	14.39			
2209	14.03			0209	16.54	2300	14.40			
2307	14.02			0306	16.54	2355	14.41			
2400	14.04			0402	16.54	0057	14.41			
0104	14.04			0500	16.55	0208	14.42			
0210	14.04			0601	16.55	0305	14.44			
0307	14.04			0700	16.56	0401	14.44			
0403	14.04			0805	16.56	0456	14.44			
0459	14.06			0922	16.59	0600	14.45			
0602	14.08			1151	16.58	0658	14.44			
0703	14.18			1315	16.59	0803	14.44			
0730	14.17									

GS-14		GS-15	
Time	Depth	Time	Depth
1600	13.70	1600	14.56
1700	13.70	1700	14.57
1800	13.70	1800	14.58
1900	13.70	1900	14.58
2000	13.72	2000	14.58
2100	13.72	2100	14.59
2200	13.72	2200	14.59
2300	13.72	2300	14.60
2400	13.73	2400	14.60
0100	13.74	0100	14.61
0200	13.74	0200	14.61
0300	13.75	0300	14.62
0400	13.75	0400	14.62
0500	13.75	0500	14.63
0600	13.77	0600	14.64
0700	13.77	0700	14.64
0800	13.76	0800	14.64
0900	13.77	0900	14.64
1000	13.78	1000	14.65
1100	13.77	1100	14.65
1200	13.78	1200	14.65
1300	13.79	1300	14.66
1400	13.80	1400	14.67
1500	13.80	1500	14.68
1600	13.81	1600	14.68
1700	13.81	1700	14.69
		(See also figure 7)	

Appendix 1. Water levels and other field data for aquifer test, May 1994—Continued

D. Camanche Reservoir water levels

[Data provided by the East Bay Municipal Utility District, written communication, 1996]

Date	Time	Water Level (ft above sea level)
05-10-94	0100	207.49
05-10-94	0200	207.49
05-10-94	0300	207.49
05-10-94	0400	207.48
05-10-94	0500	207.48
05-10-94	0600	207.48
05-10-94	0700	207.47
05-10-94	0800	207.46
05-10-94	0900	207.45
05-10-94	1000	207.45
05-10-94	1100	207.45
05-10-94	1200	207.45
05-10-94	1300	207.43
05-10-94	1400	207.43
05-10-94	1500	207.42
05-10-94	1600	207.42
05-10-94	1700	207.41
05-10-94	1800	207.41
05-10-94	1900	207.39
05-10-94	2000	207.38
05-10-94	2100	207.38
05-10-94	2200	207.37
05-10-94	2300	207.37
05-10-94	2400	207.36
05-11-94	0100	207.36
05-11-94	0200	207.36
05-11-94	0300	207.36
05-11-94	0400	207.34
05-11-94	0500	207.34
05-11-94	0600	207.33
05-11-94	0700	207.33
05-11-94	0800	207.33
05-11-94	0900	207.33
05-11-94	1000	207.33
05-11-94	1100	207.31
05-11-94	1200	207.31
05-11-94	1300	207.31
05-11-94	1400	207.29
05-11-94	1500	207.29
05-11-94	1600	207.29
05-11-94	1700	207.28
05-11-94	1800	207.26
05-11-94	1900	207.26
05-11-94	2000	207.26
05-11-94	2100	207.26
05-11-94	2200	207.25
05-11-94	2300	207.25
05-11-94	2400	207.23
05-12-94	0100	207.23
05-12-94	0200	207.22
05-12-94	0300	207.21
05-12-94	0400	207.21
05-12-94	0500	207.21
05-12-94	0600	207.21
05-12-94	0700	207.21
05-12-94	0800	207.21
05-12-94	0900	207.18
05-12-94	1000	207.18
05-12-94	1100	207.18
05-12-94	1200	207.18
05-12-94	1300	207.18
05-12-94	1400	207.18
05-12-94	1500	207.18
05-12-94	1600	207.18
05-12-94	1700	207.18
05-12-94	1800	207.18
05-12-94	1900	207.17
05-12-94	2000	207.16
05-12-94	2100	207.15
05-12-94	2200	207.14
05-12-94	2300	207.13
05-12-94	2400	207.13

Appendix 2. Static water levels for U.S. Geological Survey monitoring wells at the Penn Mine and for Camanche Reservoir, December 1993 to June 1994

[Water levels, measuring point, and land-surface altitude in feet above sea level; monitored depth in feet below land surface. mv, metavolcanic rocks; sl, slate; ug, underground mine workings in metavolcanic rock; —, no data; date format, mm-dd-yy month-day-year. Camanche Reservoir water levels provided by the East Bay Municipal Utility District, written communication, 1996]

USGS well	GS-1A	GS-1B	GS-2	GS-3	GS-4A	GS-4B	GS-4C	GS-5	GS-6	GS-7	GS-8A	GS-8B
Measuring point	220.3	220.7	222.6	228.6	223.2	223.3	223.3	220.2	222.7	221.8	221.3	221.7
Land-surface altitude	217.5	217.5	221.6	226.4	220.9	220.9	220.9	218.2	219.7	219.8	219.3	219.3
Monitored depth	40–80	80–200	40–200	30–200	20–55	55–80	80–200	30–200	30–400	40–55	30–76	76–200
Lithology	mv	sl	mv+sl	mv+sl	mv	mv	sl	mv+sl	mv+sl	mv+sl	mv	sl
Date												
12-15-93	—	—	217.94	220.17	—	—	—	—	—	—	—	—
12-16-93	—	—	—	—	—	—	—	—	216.63	217.67	—	—
12-17-93	216.80	—	—	—	—	—	—	—	—	—	216.98	—
12-18-93	—	—	—	—	—	216.38	—	—	—	—	—	—
12-20-93	—	—	—	—	—	—	—	—	—	—	—	—
12-21-93	—	—	—	—	—	—	—	—	—	—	—	—
03-01-94	212.84	212.18	213.67	218.13	213.09	213.75	213.57	213.63	213.42	213.63	213.60	210.22
04-04-94	211.65	212.48	211.05	217.26	210.71	211.35	211.23	211.03	211.09	210.91	209.48	211.54
05-09-94	206.43	212.18	207.15	217.08	205.78	207.01	206.70	—	207.12	206.95	206.49	209.07
05-10-94	—	—	—	—	—	—	—	—	—	—	207.09	—
05-12-94	—	—	207.46	—	—	—	—	—	—	—	—	—
05-13-94	—	—	—	—	—	—	—	—	—	—	—	—
05-18-94	—	—	—	—	—	—	—	—	—	—	205.84	—
05-23-94	—	—	—	—	—	—	—	204.32	—	—	—	—
05-24-94	—	—	—	—	—	204.45	—	—	—	—	—	—
05-25-94	—	—	—	217.45	—	—	—	—	—	—	—	—
06-14-94	201.75	211.94	—	—	201.02	201.11	—	202.13	201.31	—	201.72	202.64
06-30-94	—	—	—	—	—	—	—	—	—	—	—	—

Appendix 2. Static water levels for U.S. Geological Survey monitoring wells at the Penn Mine and for Camanche Reservoir, December 1993 to June 1994—Continued

USGS well	GS-9	GS-10	GS-11	GS-12	GS-13	GS-14	GS-15	GS-16	GS-17	GS-18	GS-19	GS-20	Camanche Reservoir
Measuring point	219.5	220.0	219.5	220.1	219.8	220.1	220.2	262.7	364.7	363.5	362.3	281.2	—
Land-surface altitude	219.0	219.5	219.2	219.6	218.3	219.1	217.7	262.2	363.7	362.5	361.8	279.2	—
Monitored depth	0-10	5-25	24-61	71-113	20-63	56-66	71-120	8-183	74-80	251-260	140-162	11-23	—
Lithology	slag-soil	mv	mv	sl	mv	mv+sl	sl	mv (+2 ft sl)	ug	ug	mv+ug	ug	—
Date													
12-15-93	—	—	—	—	—	—	—	—	—	—	—	—	218.1
12-16-93	—	—	—	—	—	—	216.74	—	—	—	—	—	218.0
12-17-93	—	—	218.14	—	—	—	—	—	—	—	—	—	218.0
12-18-93	—	—	—	—	—	217.67	—	—	—	—	—	—	218.0
12-20-93	—	—	—	—	—	—	—	249.22	—	—	—	—	217.9
12-21-93	—	—	—	—	—	—	—	—	—	273.33	—	—	217.9
03-01-94	213.67	213.66	213.73	214.22	213.42	213.64	212.50	248.56	—	278.11	285.90	—	214.3
04-04-94	210.93	211.08	210.97	211.82	211.15	211.28	209.88	249.33	—	277.25	287.16	—	211.5
05-09-94	—	208.79	206.98	—	207.04	207.28	205.90	—	—	—	—	—	207.6
05-10-94	—	—	—	—	—	—	—	—	—	—	—	—	207.5
05-12-94	—	—	—	—	—	—	—	—	—	—	—	—	207.2
05-13-94	—	—	—	—	—	—	—	249.16	—	—	—	—	207.1
05-18-94	—	—	—	—	—	—	—	—	—	—	—	—	206.4
05-23-94	—	—	—	—	—	204.91	—	—	—	—	—	—	205.9
05-24-94	—	—	—	—	—	—	204.11	—	—	—	—	—	205.7
05-25-94	—	—	204.22	—	—	—	—	—	—	—	—	—	205.6
06-14-94	202.51	203.84	200.67	202.91	202.42	201.76	201.05	245.55	—	275.10	—	—	202.6
06-30-94	—	—	—	—	—	—	—	—	—	274.21	—	—	203.0

APPENDIX 3. INTERPRETATION OF AQUIFER TEST DATA, MAY 1994

Water levels and other field data collected during the aquifer test on May 10–12, 1994, are given in appendix 1. The water level in Camanche Reservoir declined at a rate of about 0.12 ft/d (0.005 ft/hr) during the aquifer test. A similar rate of decline can be seen in the water levels for wells GS-8A (the pumped well) and GS-11 (an observation well) during pumping, once steady-state conditions were established (fig. 7). Rapid water-level rise in well GS-11 after the pump was turned off was followed by decline at a rate similar to that observed during pumping, which can be attributed to the decline in the water level of Camanche Reservoir. These data strongly suggest hydraulic connectivity between wells GS-8A and -11.

The minimal response of water levels at other wells (parts B and C of appendix 1) during the aquifer test are an indication of the heterogeneity of the fractured-rock system. Hydraulic connection between wells GS-8A and -11 is indicated by the drawdown (about 0.35 ft) observed in well GS-11 (fig. 7) during pumping of well GS-8A. Water-level declines in wells GS-1A, -4A, -4B, -4C, -13, -14, and -15 were similar to the decline in the water level of Camanche Reservoir (0.12 ft) during the 24-hour aquifer test. In several other wells (GS-1B, -3, and -8B), water levels remained fairly constant during the test, indicating poor hydraulic connection with well GS-8A and with Camanche Reservoir.

The Thiem equation (Driscoll, 1987) was used to estimate hydraulic condutivity of the fractured-rock aquifer using results from the aquifer test on May 10–12, 1994. For steady-state radial flow to a pumped well, the well yield is

$$Q = \frac{KH^2 - h^2}{1,055\left[\log\left(\frac{R}{r}\right)\right]} \qquad \text{(A3-1)}$$

where Q is the volumetric flow rate (gal/min),
r is the radius of the pumped well (ft),
R is the radius of the cone of depression (ft),
h is the pumping hydraulic head, measured from the bottom of the aquifer (ft),
H is the static hydraulic head, measured from the bottom of the aquifer (ft), and
K is the hydraulic conductivity [gal/(d · ft^2)].

Equation A3-1 can be used to derive

$$K = \frac{1,055\left[\log(R/r)Q\right]}{H^2 - h^2}. \qquad \text{(A3-2)}$$

Conversion of K from gal/(d · ft^2) to ft/d yields

$$K = \frac{141\left[\log(R/r)Q\right]}{H^2 - h^2}. \qquad \text{(A3-3)}$$

For the aquifer test, the radius, r, of the pumped well (GS-8A) is 0.25 ft. After pumping at a rate, Q, of 4.3 gal/min, the resultant steady-state pumping hydraulic head, h, was 48.35 ft, measured from the bottom of the metavolcanic rock aquifer in well GS-8A. The static hydraulic head, H, was 48.77 ft. During the period of the aquifer test on May 10–12, 1994, the water level of Camanche Reservoir declined at a rate of 0.12 ft/d (0.005 ft/h) (appendix 1D). Approximate steady-state conditions with regard to water depth in the pumped well were established during the aquifer test within the first hour of pumping (fig. 7; appendix 1B). During this period, the level of Camanche Reservoir declined only about 0.005 ft and had minimal effect on the heads used in this calculation. The water level in well GS-8A declined an additional 0.11 ft over the final 23 hours of the test (appendix 1B), a rate that correlates with the rate of decline of the water level of Camanche Reservoir.

A value for R, the radius of the cone of depression, can be estimated on the basis of water-level measurements in observation wells during the aquifer test (appendix 1B). Drawdown and recovery were observed in well GS-11, at a distance of 50 ft from the pumped well, but were not observed in other observation wells at distances of 50 to 100 ft. These observations were used to estimate a value of R=100 ft. Substituting the above values into equation A3-3 gives a computed value for hydraulic conductivity, K, of 39 ft/d. Although the estimated value for R is somewhat uncertain, the logarithmic term in equations A3-1 through A3-3 results in relatively small changes in computed values of K for large changes in R. Using a range of values for the radius of the cone of depression, R, produces the following estimates of K (in ft/d): 36 (R=50 ft) and 44 (R=200 ft). These estimates of K

apply to the entire uncased interval of metavolcanic rocks in well GS-8A; however, on the basis of downhole flowmeter testing in well GS-8A (Hamlin and Alpers, 1995), most of the hydraulic conductance is probably associated with the highly fractured contact zone. These estimates of *K* are in good agreement with the range of values for *K* estimated from previous tests at GS-8A (Hamlin and Alpers, 1995), 11 to 42 ft/d.

Because of the heterogenous nature of fractured-rock aquifer systems, these relatively high estimates for hydraulic conductivity (*K*), 36 to 44 ft/d, probably apply only to the fractured-rock aquifer in the immediate vicinity of wells GS-8A and -11. A highly conductive zone is present between and near these wells. However, this zone is not extensive, and the properties of the bulk of the metavolcanic rock unit probably are best represented by a *K* value closer to the estimated median of 0.1 ft/d (Hamlin and Alpers, 1995).

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