Subsurface Flow to Eagle Valley from Vicee, Ash, and Kings Canyons, Carson City, Nevada, Estimated from Darcy's Law and the Chloride-Balance Method

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CONTENTS

FIGURES

TABLES

CONVERSION FACTORS, VERTICAL DATUM, AND WATER-QUALITY UNITS

Multiply	By	To obtain
acre	0.4047	square hectometer
acre-foot (acre-ft)	0.001233	cubic hectometer
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per year
cubic foot per day (ft^3/d)	0.02832	cubic meter per day
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot (ft)	0.3048	meter
foot per foot (ft/ft)	1.000	meter per meter
foot per day (ft/d)	0.3048	meter per day
foot per mile (ft/mi)	0.1894	meter per kilometer
foot per minute (ft/min)	0.3048	meter per minute
foot per year (ft/yr)	0.3048	meter per year
inch (in.)	25.40	millimeter
inch per hour (in/hr)	25.40	millimeter per hour
inch per year (in/yr)	25.40	millimeter per year
mile (mi)	1.609	kilometer
pound per square inch (lb/in^2)	0.07031	kilogram per square centimeter
pound per cubic foot (lb/ft^3)	0.01602	gram per cubic centimeter
square foot (ft^2)	0.0929	square meter
foot squared per day (ft^2/d)	0.0929	meter squared per day
square mile (mi^2)	2.590	square kilometer

Temperature: Degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) by using the formula °F = [1.8(°C)]+32. Degrees Fahrenheit can be converted to degrees Celsius by using the formula °C = 0.556(°F-32).

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929, formerly called "Sea-Level Datum of 1929"), which is derived from a general adjustment of the first-order leveling networks of the United States and Canada.

Water-quality units used in this report:

mg/L, milligram per liter
µS/cm, microsiemens per centimeter at 25 degrees Celsius

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Abstract

Subsurface flow from Vicee, Ash, and Kings Canyons to Eagle Valley in northwestern Nevada was calculated by totaling flows through lithologic units in basin-fill sediments and weathered and fractured bedrock. Flow in each lithologic unit was calculated using Darcy's law, assuming that the hydraulic gradient is the same for all units, and that the distribution and hydraulic conductivity of lithologic units determined in test holes can be extrapolated beneath each canyon. Subsurface flow was calculated to be about 300 acre-ft/yr (acre-feet per year) beneath Vicee Canyon; 200 to 400 acre-ft/yr beneath Ash Canyon; and 2,300 acre-ft/yr beneath Kings Canyon. Subsurface flow also was calculated using the chloride-balance method and a limited data set; the estimates are about 400 acre-ft/yr beneath Vicee Canyon, 200 to 500 acre-ft/yr beneath Ash Canyon, and 600 to 1,000 acre-ft/yr beneath Kings Canyon. Although subsurface flow beneath Kings Canyon based on the chloride-balance method was lower than flow estimated using Darcy's law, both methods estimated more subsurface flow beneath Kings Canyon than beneath Vicee or Ash Canyons, and both estimated more subsurface flow to Eagle Valley than previous estimates.

The estimates of subsurface flow are based on physical properties of aquifer materials near the mouths of Vicee, Ash, and Kings Canyons. Test holes were drilled near selected hydrogeologic sections across each canyon and during drilling, weathered and fractured zones in bedrock underlying the basin-fill sediments were found to be permeable. The water-table gradient in Vicee Canyon is about 10 feet per 100 feet. The gradient in Ash Canyon, estimated from only two wells, ranges from 8 to 14 feet per 100 feet. The gradient beneath Kings Canyon averages 6 feet per 100 feet. Thickness of saturated basin-fill sediments is about 60 feet in Vicee Canyon, 175 feet in Ash Canyon, and 100 to 180 feet in Kings Canyon. Thickness of weathered and fractured bedrock is estimated to be about 50 feet in Vicee Canyon, about 30 feet in Ash Canyon, and about 70 feet in Kings Canyon.

Hydraulic conductivities of lithologic units in basin-fill sediments and in fractured and weathered bedrock are represented by a geometric mean determined from borehole resistivity logs. These borehole logs were correlated with hydraulic conductivities estimated from slug-test analyses. In the basin-fill sediments, hydraulic conductivity ranges from 0.02 to 0.09 ft/d (foot per day) for clay, and from 34 to 46 ft/d for sand and gravel. In bedrock, hydraulic conductivity ranges from 0.06 to 0.91 ft/d for unweathered bedrock or weathered bedrock with closed fractures to 60 ft/d for open-fractured metamorphic rocks. These results indicate that metamorphic rocks with open fractures can be more permeable than basin-fill sediments and weathered granitic rocks.

Surface runoff from the canyons near the hydrogeologic sections averages 200 acre-ft/yr from Vicee Canyon; 2,600 acre-ft/yr from Ash Canyon; and 1,200 acre-ft/yr from Kings Canyon. The sum of surface runoff and subsurface flow estimated using Darcy's law and the chloride-balance method result in a total water yield of 500 to 600 acre-ft/yr from Vicee Canyon; 2,800 to 3,100 acre-ft/yr from Ash Canyon; and 1,800 to 3,500 acre-ft/yr from Kings Canyon. These volumes are greater than previous estimates of water yield from each canyon.

Recharge estimated by the Maxey-Eakin method for each watershed is similar to estimates of infiltration of surface runoff added to estimates of subsurface flow for Vicee and Ash Canyons, but could be underestimated for Kings Canyon where bedrock is more permeable. Results of this study indicate that the metamorphic rocks can be highly permeable and, where permeable, the rocks may act as conduits for subsurface flow to the basin-fill aquifer. Metamorphic rocks crop out over much of the mountainous regions surrounding Eagle Valley. Evaluation of subsurface flow from other watersheds would help in estimating the total water yield to Eagle Valley from the surrounding mountains.

INTRODUCTION

Continued growth of Carson City, the capital of Nevada, is increasing the demand for municipal water. The population was 44,620 as of July 1, 1994 (Nevada State Demographer, 1994). Annual growth between July 1, 1990, and July 1, 1994, averaged about 900 people per year, a 2.2 percent average annual increase. Carson City lies along the eastern base of the Carson Range in Eagle Valley (fig. 1). As much as 80 percent of the water supply for Carson City is from ground water in the basin-fill aquifers beneath Eagle Valley (Dorothy Timian-Palmer, Carson City Utilities Department, oral commun., 1994). Permitted pumping of ground water in Eagle Valley is about 8,400 acre-ft/yr (Matt Dillon, Nevada Department of Conservation and Natural Resources, Division of Water Resources, written commun., 1994); about 6,700 acre-ft/yr of this is allocated to the Carson City municipal supply.

The basin-fill aquifer in Eagle Valley is naturally recharged by subsurface flow from adjacent mountains, by infiltration beneath streams as they flow across the valley, and by infiltration of precipitation falling on the valley floor. Early settlement in the valley changed the distribution of recharge as streams were diverted for irrigation. Diversions resulted in increased recharge to the aquifer because streamflow was spread over a larger area. Further development in the valley has produced continual changes in the distribution and quantity of ground-water recharge; water use has changed from primarily agricultural irrigation with surface water to municipal use of both surface and ground water.

Although little information has been collected on effects of development on recharge in Eagle Valley, the effects probably have been a decrease in recharge beneath stream channels and irrigated fields and an increase in recharge beneath lawns, parks, and golf courses irrigated with a mixture of surface water and ground water. Accuracy of the empirical methods developed by the U.S. Geological Survey and used by the State of Nevada to assess recharge to basin-fill aquifers and to regulate withdrawals from those aquifers (Nevada State Engineer, 1971, p. 40) is not known, nor do the empirical methods account for changes in recharge caused by changes in land use. Physical measurements of aquifer properties beneath canyons where subsurface flow enters the valley would provide a way to evaluate previous estimates of ground-water recharge and thereby aid in management of water resources in the valley. For these reasons, the U.S. Geological Survey, in cooperation with the Carson City Utilities Department, began a study in 1994 to estimate ground-water recharge in Eagle Valley. Because of the complex nature of ground-water recharge, the study has been divided into several phases. The first phase, described in this report, estimates subsurface flow beneath Vicee, Ash, and Kings Canyons on the eastern slope of the Carson Range near the base of the mountains.

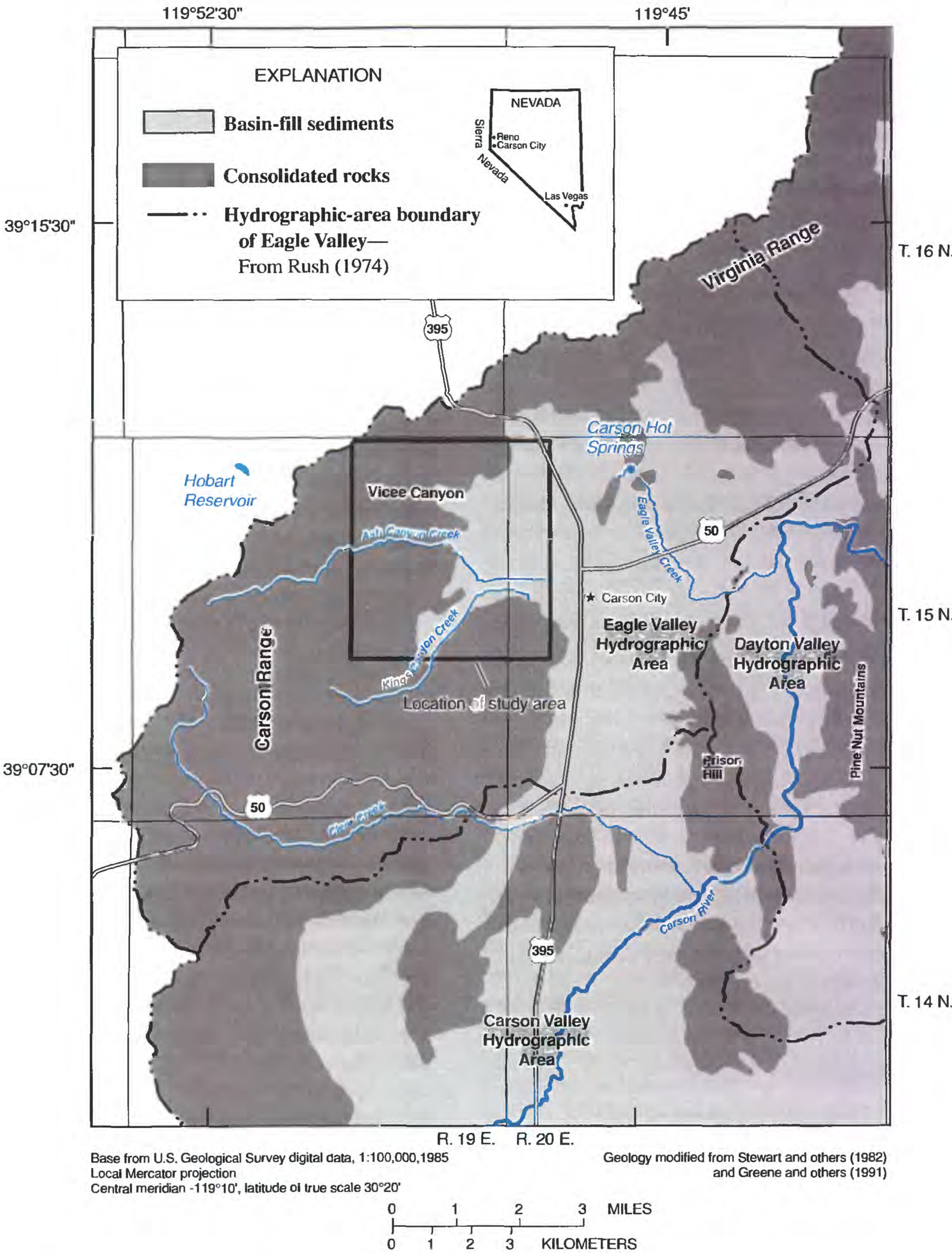


Figure 1. Geographic features, Eagle Valley Hydrographic Area, and study area in Vicee, Ash, and Kings Canyons, Carson City, Nevada.

Purpose and Scope

This report describes the methods used to estimate subsurface flow beneath Vicee, Ash, and Kings Canyons from physical measurements, presents the estimates of subsurface flow beneath each canyon, compares the new estimates with previous estimates, and compares estimates of surface runoff and subsurface flow in each canyon with total precipitation.

To accomplish these goals, the distribution of saturated sediments and weathered or fractured bedrock was estimated from test hole and geophysical data along a hydrogeologic section across the mouth of each canyon near where streamflow is gaged. From these data, the cross-sectional area of saturated sediments and weathered bedrock was calculated. Wells were installed in the test holes and slug tests were done to determine hydraulic conductivity. Electrical resistivity of the saturated sediments and bedrock penetrated in each test hole was correlated with hydraulic conductivities determined from slug tests in each well. Using this correlation, the vertical distribution of hydraulic conductivity was estimated. Basin-fill sediments and bedrock were divided into lithologic units on the basis of hydraulic conductivity. Subsurface flow beneath each canyon was estimated using Darcy's law by calculating the cross-sectional area of each lithologic unit, the geometric-mean hydraulic conductivity of each lithologic unit, and the measured hydraulic (water-table) gradient. Flow beneath each canyon also was estimated from chloride concentrations measured in the well waters, using the chloride-balance method described by Dettinger (1989).

Acknowledgments

The authors thank Dorothy Timian-Palmer, Charles Welch, and many others of Carson City Utilities Department for their support of drilling operations and data collection, and Raymond Bily and family for access to their private well.

DESCRIPTION OF EAGLE VALLEY

Location and Geography

Eagle Valley is a roughly circular basin about 6 mi across with a total area of about 70 mi^2 (Worts and Malmberg, 1966, p. 2). The valley is bounded on the west by the Carson Range of the Sierra Nevada, on the north by the Virginia Range, on the east by low-lying Prison Hill and the flood plain of the Carson River, and on the south by Carson Valley (fig. 1). Clear Creek enters Eagle Valley at the southwest end and flows eastward across the hydrographic area boundary[1] and into Carson Valley, where it discharges into the Carson River. Eagle Valley Creek and other small streams exit Eagle Valley north of Prison Hill. The floor of Eagle Valley is about 4,700 ft above sea level, whereas the top of Prison Hill is about 5,700 ft; the Virginia Range is about 8,000 ft; and the Carson Range is greater than 9,200 ft.

Vegetation

The natural vegetation of sagebrush, rabbitbrush, and grassy meadows on the valley floor has been replaced largely by houses, streets, and lawns. In 1965, Worts and Malmberg (1966, p. 24) estimated that 700 acres of native grass and some alfalfa were irrigated with streamflow from Ash and Kings Canyons. In 1995, the irrigated fields also are being replaced by development; the natural vegetation in the mountains, however, has not been affected greatly. Vegetation in the Carson Range is primarily sagebrush, manzanita, and Jeffrey pine, whereas vegetation in the Virginia Mountains is primarily sagebrush, juniper, and piñon pine.

[1]Formal hydrographic areas in Nevada were delineated systematically by the U.S. Geological Survey and Nevada Division of Water Resources in the late 1960's (Cardinalli and others, 1968; Rush, 1968) for scientific and administrative purposes. The official hydrographic-area names, numbers, and geographic boundaries continue to be used in Geological Survey scientific reports and Division of Water Resources administrative activities.

Precipitation

The floor of Eagle Valley lies in the rain shadow of the Sierra Nevada. Average annual precipitation on the valley floor is about 10 in. In contrast, average annual precipitation along the crest of the Carson Range is about 38 in. (Arteaga and Durbin, 1978, p. 16). The Virginia Range receives much less precipitation than the Carson Range; average annual precipitation is slightly more than 14 in. In both ranges, most precipitation falls as rain or snow during November through April. Snow in the Carson Range accumulates to several feet during most winters and melts in early spring to early summer.

Streams

Streams in Ash and Kings Canyons are perennial and flow onto the floor of Eagle Valley during most years. These streams drain the eastern flank of the Carson Range west of Carson City, and the water is used for agricultural irrigation and municipal water supply. The stream in Vicee Canyon flows downstream from the canyon mouth only during severe storms or during spring snowmelt in years having above-normal precipitation. The only other perennial stream is Clear Creek, which has the largest drainage area (15.5 mi^2) of any stream entering Eagle Valley. The remaining streams entering Eagle Valley are ephemeral, flowing only occasionally onto the valley floor. Where Vicee and Ash Canyons enter Eagle Valley, they are incised into the heads of alluvial fans. Kings Canyon is a relatively broad canyon (fig. 2) formed by faulting and filled with alluvial deposits. The drainage areas of Vicee, Ash, and Kings Canyons upstream from the gaging stations are 1.8, 5.2, and 4.1 mi^2, respectively (Emett and others, 1994, p. 185-188).

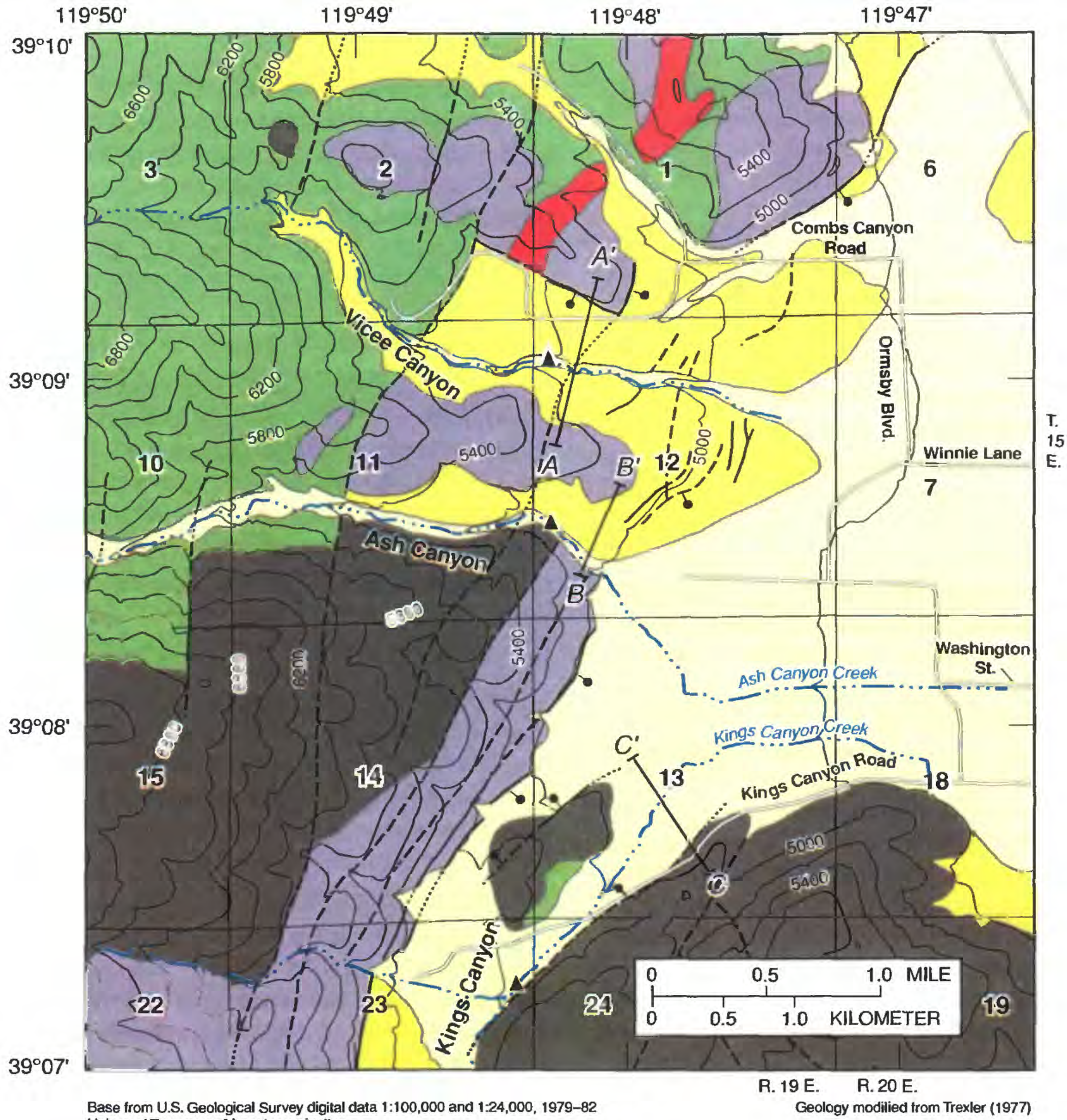
Excess flow from the Nevada State system that brings water from Hobart Creek Reservoir (fig. 1) to Carson City has been diverted periodically into Vicee Canyon and allowed to infiltrate into the ground. Three small detention basins have been constructed by Carson City Utilities Department in the canyon floor to enhance infiltration. Approximately 560 acre-ft of water has been discharged into Vicee Canyon since 1991.

Geology

The mountains surrounding Eagle Valley consist of consolidated rocks that have been uplifted by faulting. The valley floor has been downdropped relative to the mountains, forming a basin that is partly filled by sediments eroded from the surrounding mountains. In this report, the consolidated rocks exposed in the mountains and buried beneath the sediments in the valley are collectively called bedrock; the sediments in the valley are collectively called basin-fill sediments.

Granitic rocks of Cretaceous age and metamorphic rocks of Triassic age are exposed throughout the Carson Range, west of Eagle Valley (Moore, 1969, p. 6, pl. 1). The granitic rocks are mostly granodiorite and are part of the Sierra Nevada batholith. Emplacement of the batholith into older volcanic and sedimentary rocks resulted in the older rocks being metamorphosed by heat and deformation. The metamorphic rocks (fig. 2) have been further subdivided into felsic schist and mafic metavolcanic rocks (Trexler, 1977). Subsequent uplift and erosion removed much of the metamorphic rocks, leaving isolated exposures of the metamorphic rocks overlying the granitic mass (Moore, 1969, p. 3 and 4). A small area of Tertiary volcanic andesite was mapped by Trexler (1977) on the northern side of Vicee Canyon (fig. 2).

Granitic and metamorphic rocks also are exposed on the southwestern flank of the Virginia Range and throughout Prison Hill. Volcanic rocks of Quaternary to Tertiary age were extruded from numerous vents and overlie the granitic and metamorphic rocks in the Virginia Range. The oldest of these volcanic rocks are rhyolites of Miocene age; the younger volcanic rocks consist of andesite and basalt. The rhyolites have columnar partings and are about 1,000 ft thick (Moore, 1969, p. 10). Andesite, younger but also of Miocene age, outcrops on the southern slope and along the crest of the Virginia Range. These volcanic rocks are as much as 2,700 ft thick (Moore, 1969, p. 11). Vesicular basalts of Quaternary age outcrop on the southern slope of the Virginia Range along the northeastern edge of Eagle Valley (Bonham, 1969, p. 40); however, they are less than 50 ft thick 6 mi northeast of Eagle Valley (Thompson, 1956, p. 59) and may not be much thicker elsewhere.



Base from U.S. Geological Survey digital data 1:100,000 and 1:24,000, 1979–82
Universal Transverse Mercator projection
Zone 11

Geology modified from Trexler (1977)

EXPLANATION

Basin-fill sediments:

Younger pediment and alluvial deposits of Quaternary age

Older pediment and alluvial deposits of Quaternary age

Igneous rocks:

Andesite of Tertiary age

Granitic rocks of Cretaceous age

Metamorphic rocks:

Mafic metavolcanic rocks of Triassic age

Felsic schists of Triassic age

5000 — **Altitude of land surface, in feet above sea level. Contour interval is 200 feet**

Fault—Dashed where approximate; dotted where concealed. Ball on downthrown side

A—A' **Line of hydrogeologic section**

▲ **Streamflow gaging station**

7 **Section number**

Figure 2. Surficial geology and location of streamflow gaging stations and hydrogeologic sections in Vicee, Ash, and Kings Canyons, Carson City, Nevada.

Uplift of the mountains relative to Eagle Valley has taken place along numerous faults exposed near the base of the mountains. Movement along some faults within the last 300 to 12,000 years (Trexler, 1977) indicates that uplift of the mountains is continuing. Sediments beneath Eagle Valley are about 400 ft thick near the mouths of Vicee, Ash, and Kings Canyons and as much as 1,200 ft thick about 1 mi east of the canyon mouths (Arteaga, 1986, p. 25).

The basin-fill sediments are divided into younger and older alluvial deposits—both of Quaternary age (Worts and Malmberg, 1966, p. 5; Trexler, 1977). Younger alluvial deposits consist of unconsolidated gravel, sand, and lesser amounts of silt and clay (Arteaga, 1986, p. 5). Older alluvial deposits consist of partly consolidated to unconsolidated gravel, sand, and silt with discontinuous clay layers. The older deposits border the mouths of Vicee and Ash Canyons (fig. 2) and likely extend beneath Eagle Valley at depths greater than about 50 ft below land surface (Worts and Malmberg, 1966, p. 5). Arteaga (1986, p. 5) describes the older deposits as partly consolidated, because the degree of consolidation varies both areally and with depth.

The basin-fill sediments are generally coarse grained near the base of the Carson Range and become finer grained near the center of the valley. Silt and clay content in the basin-fill sediments was estimated by Arteaga (1986, p. 27) to be less than 20 percent 1 mi east of Vicee Canyon and 0.5 mi east of Ash and Kings Canyons and to be more than 30 percent in the center of the valley.

Ground Water

Ground water moving through bedrock and basin-fill sediments in Eagle Valley originates as precipitation that falls within the surrounding drainage area. Because more precipitation falls on the higher altitudes, especially in the Carson Range, much of the ground water in Eagle Valley flows from the mountains to the valley (fig. 3). In the mountains, part of the precipitation evaporates, part is transpired by plants, part runs off as streamflow, and part infiltrates weathered or fractured bedrock. Water that infiltrates bedrock moves toward the canyons and seeps into the streams or moves down the canyon beneath the stream channels to Eagle Valley. Even during prolonged dry periods, streams in Ash and Kings Canyons continue to flow, indicating a continuous supply from ground water. Some ground water in the fractured bedrock moves along deeper flow paths directly into the basin-fill sediments, and some discharges along fractures as thermal springs, such as at Carson Hot Springs in Eagle Valley (fig. 3) where thermal water discharges near an outcrop of metavolcanic rocks (Trexler and others, 1980, p. 23 and 81).

The ability of bedrock to transmit water probably varies greatly and depends on how the bedrock is weathered and fractured. The hydraulic conductivities for fractured to unfractured metamorphic and igneous rocks span 10 orders of magnitude (Freeze and Cherry, 1979, p. 29). Arteaga (1986, p. 6) considered bedrock in Eagle Valley and the surrounding mountains nearly impermeable, whereas Worts and Malmberg (1966, p. 7) considered the weathered granitic rocks sufficiently permeable to supply wells used for domestic and stock-watering purposes. The granitic rocks in the Carson Range are weathered to depths of more than 100 ft (Moore, 1969, p. 17).

Ground water moves eastward across Eagle Valley (Worts and Malmberg, 1966, p. 11; Arteaga, 1986, p. 6). Depth to water ranges from more than 200 ft below land surface near the base of the Carson Range to less than 5 ft near the center of the valley (Worts and Malmberg, 1966, p. 10; Maurer and Fischer, 1988, p. 5). Near the center of the valley, water levels are higher at greater depths below land surface, indicating an upward vertical gradient (Arteaga, 1986, p. 9). In this area, discontinuous clay lenses, as much as 270 ft thick, restrict upward flow and produce artesian conditions (Arteaga, 1986, p. 6). Little information is available on vertical gradients along the mountain front. Because the front is considered a recharge area, downward gradients are expected.

Before ground water was pumped in the valley, the water beneath Eagle Valley was discharged by evapotranspiration through phreatophytes and pasture grasses and by subsurface flow to the Carson River flood plain. In 1964, about 5,000 acres near the center of the valley was covered with phreatophytes and pasture grasses (Worts and Malmberg, 1966, p. 27). Since 1964, some areas of phreatophytes and pasture lands have been replaced with streets, homes, schools, and businesses. Pumping of ground water, mostly for municipal supply, has diverted some ground water that would have either discharged through phreatophytes or flowed eastward to the Carson River flood plain.

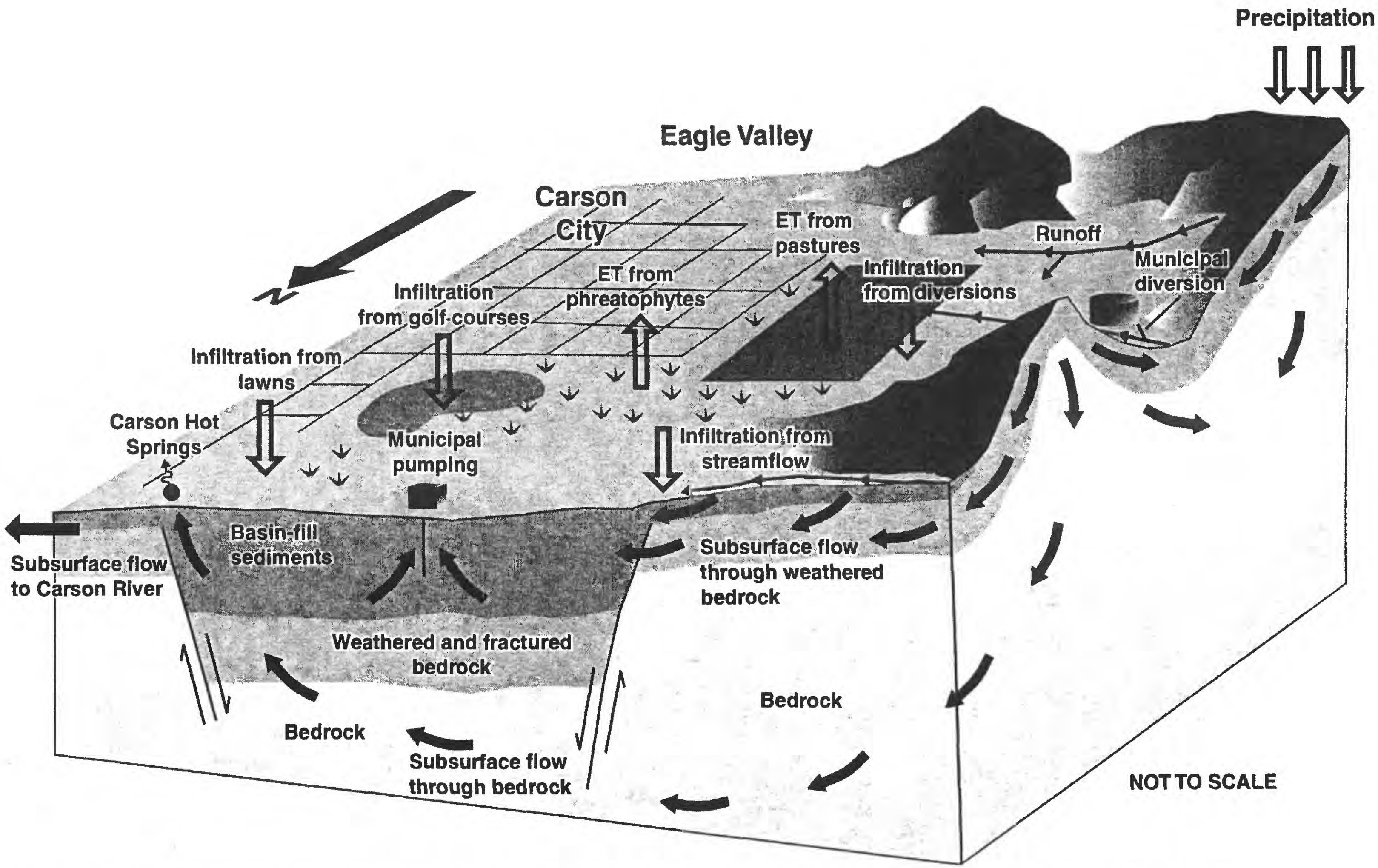


Figure 3. Schematic three-dimensional diagram illustrating flow into and out of basin-fill aquifer in Eagle Valley, Carson City, Nevada. Abbreviation: ET, evapotranspiration.

PREVIOUS RECHARGE ESTIMATES

The first estimate of recharge to Eagle Valley, made by Worts and Malmberg (1966, p. 15), uses an empirical relation among altitude, precipitation, and recharge that had been developed by Maxey and Eakin (1949) to estimate ground-water recharge to basins in eastern Nevada. Worts and Malmberg estimated that 8,700 acre-ft/yr was potential recharge to Eagle Valley in 1965. The term "potential" was used because, in 1965, Worts and Malmberg estimated that about 50 percent of the streamflow entering the valley flowed across the valley to the Carson River and did not contribute to recharge. They estimated that the actual recharge to ground water in 1965 was about 7,200 acre-ft. Their estimates of several recharge components (table 1) included 1,000 acre-ft/yr of subsurface flow from the Carson Range, or 10 to 15 percent of the potential recharge. This amount of subsurface flow was based on estimates of subsurface flow in other areas of Nevada, which range from 5 to 20 percent of total recharge. The 10- to 15-percent range was selected because of the deeply weathered and fractured bedrock in the Carson Range (Worts and Malmberg, 1966, p. 16).

The second estimate of recharge to Eagle Valley was made by Arteaga and Durbin (1978, p. 14) using a relation between precipitation and surface runoff from Clear Creek and creeks in Ash and Kings Canyons. They estimated that total recharge was 5,600 acre-ft/yr during 1967-77 (table 1). Included in this total was an estimate of 1,200 acre-ft/yr largely from the smaller mountain watersheds where streams are ephemeral and subsurface flow was assumed to be derived from infiltration of surface runoff in the upper parts of alluvial fans. In contrast, though, subsurface flow from the larger watersheds with perennial streams was assumed to be minimal (Arteaga and Durbin, 1978, p. 15 and 22).

The third estimate of recharge to Eagle Valley was made by Szecsody and others (1983, p. 56 and 71), who assumed that an increase in electrical conductivity between snow and soil water was caused only by evapotranspiration. They estimated evapotranspiration rates from the measured increase in electrical conductivity and subtracted that value from estimated precipitation to determine recharge from the Carson Range. They qualified their estimate of about 3,900 acre-ft/yr by noting that the measured electrical conductivity of snow was close to the analytical uncertainty of the technique; they also disregarded surface runoff in the estimate. From their estimate of 3,900 acre-ft/yr, they concluded that the empirical method used by Worts and Malmberg (1966) overestimated recharge to Eagle Valley. The discrepancy between the two estimates, however, may be because Szecsody and his coworkers did not include infiltration of the surface water from streams or from irrigated fields.

On the basis of stable-isotope analysis of deuterium and oxygen in surface and ground water, Szecsody and others (1983, p. 95 and 99) found that infiltration from streams crossing the basin-fill sediments and subsurface flow beneath Vicee, Ash, and Kings Canyons recharge the basin-fill sediments on the western side of Eagle Valley. Szecsody and others (1983, p. 106) also hypothesized that deeper flow along fractures recharges the basin-fill sediments beneath the center of the valley.

Table 1. Previous estimates of recharge to basin-fill aquifer in Eagle Valley, Carson City, Nevada

[Symbol: --, not estimated]

Source of recharge	Estimates (acre-feet per year)	
	[1]1965	[2]1977
Infiltration from perennial streams and agricultural irrigation.	4,800	3,100
Subsurface flow from ephemeral streams.	--	[3]1,200
Subsurface flow from Carson Range	1,000	[4]0
Infiltration of precipitation	[5]600	0
Infiltration from lawn watering [6]	800	600
Infiltration from Eagle Valley golf course. [7]	--	700
Total	7,200	5,600

[1] Estimates from Worts and Malmberg (1966, p. 15, 16, 24, 26, and 30).

[2] Estimates from Arteaga and Durbin (1978, p. 6, 23, 27, and 30).

[3] Estimate represents subsurface flow from all ephemeral stream basins tributary to Eagle Valley (Arteaga and Durbin, 1978, p. 23).

[4] Subsurface flow from perennial streams considered minimal (Arteaga and Durbin, 1978, p. 45); subsurface flow from ephemeral streams along Carson Range included in previous line.

[5] Estimate for 1965 includes precipitation on valley floor below 5,000-foot altitude and from Virginia Range and Prison Hill.

[6] Estimates include infiltration from septic tanks and leakage from public-supply lines.

[7] Eagle Valley Golf Course at Centennial Park opened in 1975 and has been irrigated with effluent from the municipal sewage-treatment plant since that fall.

Maurer and Fischer (1988, p. 32) estimated that subsurface flow beneath Vicee Canyon was about 1,000 acre-ft/yr. This estimate is based on an assumed saturated thickness of 80 ft, a width of basin-fill sediments of 1,400 ft, a hydraulic conductivity of 56 ft/d, and a hydraulic gradient of 0.02 ft/ft. The estimate of 1,000 acre-ft/yr from Vicee Canyon alone is the same as the estimate by Worts and Malmberg (1966, p. 16) for the entire Carson Range (table 1).

Accuracy of recharge estimates using the Maxey–Eakin method is not known. The Maxey–Eakin method was initially developed for 13 basins in east–central Nevada (Maxey and Eakin, 1949, p. 40-41). The method was developed by assigning different recharge percentages for each of the major precipitation zones on the annual precipitation map by Hardman (1936), until total recharge for each basin matched the estimated discharge. The method was later modified (Eakin, 1960, p. 12) by relating precipitation to altitude, and altitude zones were used in place of the original precipitation zones from the Hardman map. However, Eagle Valley differs from many other Nevada basins because precipitation in the valley and the adjacent mountains is greater than in most of the basins Maxey and Eakin used for their analysis. Another difference is that precipitation exits the valley as streamflow, unlike the closed basins of east-central Nevada. Therefore, applying the Maxey–Eakin method may not yield reasonable results. These differences were recognized by Worts and Malmberg (1966), who modified the relation between altitude and precipitation in estimating recharge and used the term "potential" recharge when they reported their results. The method for estimating recharge developed by Arteaga and Durbin (1978) relates mean annual precipitation to mean annual water yield and is based only on measured surface flow from the major mountain watersheds. They assume little to no subsurface flow beneath these watersheds. Where subsurface flow occurs, calculations of water yield using their method probably underestimate the actual recharge to the valley.

SUBSURFACE FLOW BENEATH VICEE, ASH, AND KINGS CANYONS

Streamflow from Vicee, Ash, and Kings Canyons is being gaged to determine the available surface-water supply from these watersheds. Determining subsurface flow beneath each of these watersheds will provide a better estimate of the combined surface and subsurface flow into Eagle Valley. When reasonable estimates of the combined yield of the gaged watersheds have been determined, a relation can be developed to estimate water yield from ungaged watersheds. Subsurface flow from the mountains into the basin-fill sediments is largely unknown, because the distribution and physical properties of the rocks and sediments through which ground water flows are largely unknown. Vicee, Ash, and Kings Canyons were selected for geophysical surveys and for drilling test holes.

Estimates of Subsurface Flow Using Darcy's Law

Subsurface flow beneath Vicee, Ash, and Kings Canyons was estimated by applying Darcy's law across a selected hydrogeologic section near the mouth of each canyon. Darcy's law, as modified from Heath (1989, p. 12), can be expressed as:

$$Q = 0.0084KA\left(\frac{dh}{dl}\right), \qquad (1)$$

where Q is quantity of ground water flow, in acre-feet per year;

K is hydraulic conductivity, in feet per day;

A is cross-sectional area through which flow occurs, perpendicular to the direction of flow, in square feet;

$\left(\frac{dh}{dl}\right)$ is the hydraulic gradient, in feet per foot; and

0.0084 is the factor to convert cubic feet per day into acre-feet per year.

Darcy's law was applied by totaling the flows through lithologic units which were selected on the basis of hydraulic conductivity. The hydraulic conductivity of each unit was determined from resistivity logs of the test holes. Flows were totaled using the following equation:

$$Q_T = \sum_{i=1}^{n} Q_i, \qquad (2)$$

where Q_T is total subsurface flow beneath a hydrogeologic section, in acre-feet per year;

Q_i is subsurface flow through selected lithologic unit *i*, in acre-feet per year; and

n is total number of lithologic units.

Replacing Q_i in equation 2 with the right side of equation 1 and assuming the hydraulic gradient is the same for all lithologic units produces:

$$Q_T = 0.0084 \sum_{i=1}^{n} K_g A_i \left(\frac{dh}{dl}\right), \qquad (3)$$

where K_g is the geometric-mean hydraulic conductivity of each lithologic unit, in feet per day; and

A_i is the cross-sectional area of each lithologic unit, in square feet.

The geometric-mean hydraulic conductivity (K_g) for each unit was used because hydraulic conductivity generally has a log-normal distribution in sediments and rocks (Neuman, 1982, p. 83). For log-normal data, simply using the arithmetic average hydraulic conductivity results in estimates that are skewed more toward the largest values within each lithologic unit, whereas the geometric mean tends more toward the median value.

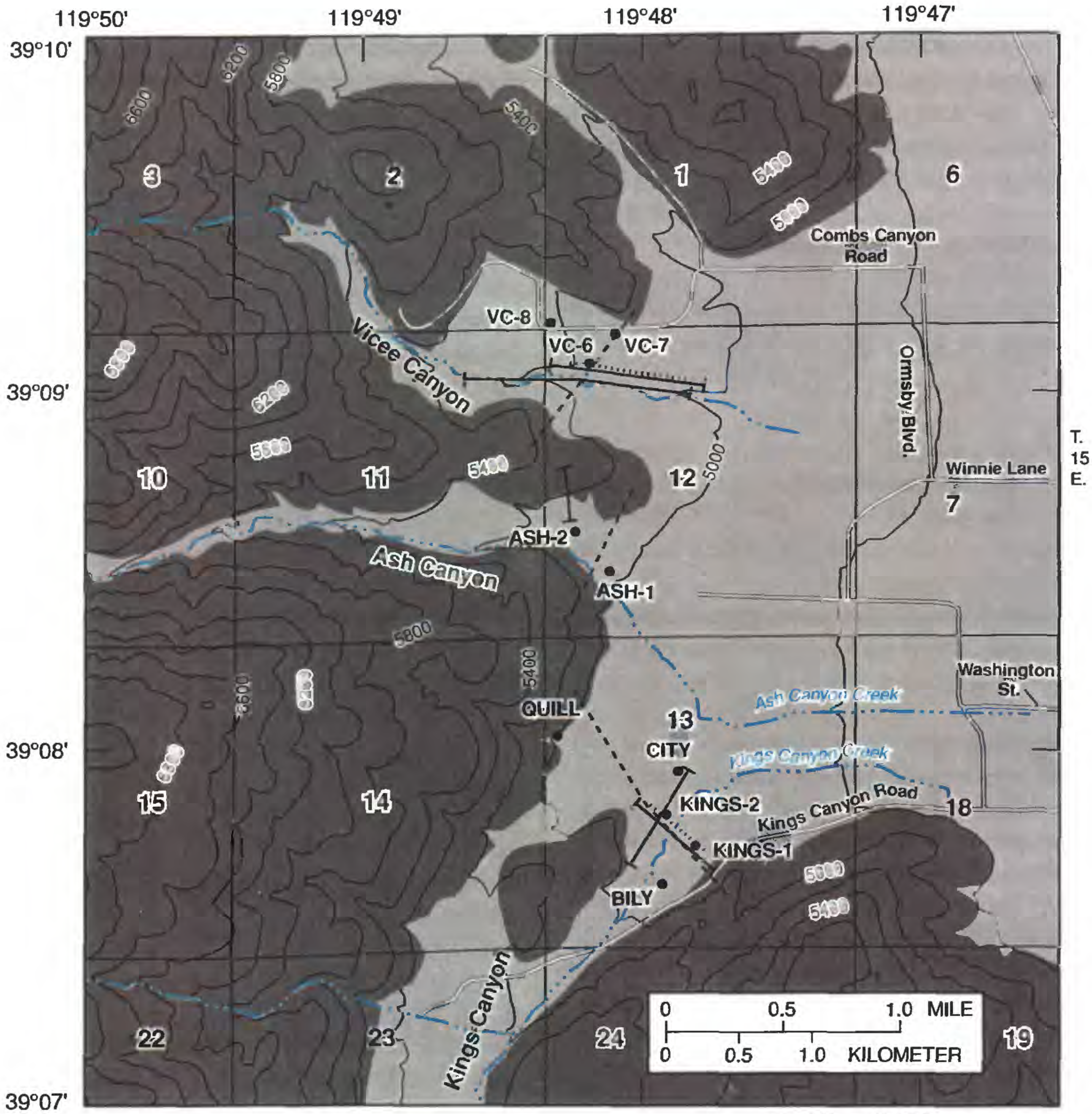
The K_g was calculated for each lithologic unit from the distribution of hydraulic conductivity within the unit. The distribution of hydraulic conductivity was determined from borehole resistivity data collected in each test hole. Borehole resistivity adjacent to gravel-packed intervals of wells was correlated with hydraulic conductivity for the gravel-packed interval determined from slug tests. Throughout this report the term test hole is used to describe the borehole drilled at each site and the term well is used to describe the casing and screen installed in each test hole.

The direction of subsurface flow near the gaging stations in each canyon was determined from water levels in the wells and the cross-sectional area through which flow occurs was scaled from a hydrogeologic section perpendicular to the flow direction. (Section lines are shown in fig. 2.) The hydrogeologic section in Kings Canyon is 0.8 mi downcanyon from the gaging station (fig. 2, *C-C'*) where access for drilling and geophysical surveys was possible. Initially, only the basin-fill sediments beneath each canyon were considered. However, during the drilling of test holes to determine the thickness of basin-fill sediments, weathered and fractured bedrock underlying the canyons were discovered to be permeable. These permeable zones in the bedrock were included in the estimates of flow.

The thickness of basin-fill sediments beneath each section was estimated by drilling test holes into bedrock. The distribution of basin-fill sediments and bedrock was determined from the test holes and extrapolated across each hydrogeologic section. The basin-fill sediments were divided into four lithologic units and bedrock was divided into three lithologic units on the basis of hydraulic conductivities. The area A_i that each lithologic unit represents along hydrogeologic sections of each canyon was determined by multiplying the total area of basin-fill sediments or bedrock with the ratio of (1) the thickness of each lithologic unit penetrated in the test holes divided by (2) the total thickness of basin-fill sediments or bedrock penetrated in the test holes. This was done for all lithologic units except the sandy, silty clay found in Kings Canyon. The distribution of this clay was determined graphically from the hydrogeologic section.

Two test holes were drilled using the mud-rotary method along the section lines in Vicee and Kings Canyons (fig. 4); only one test hole was drilled along the section line in Ash Canyon because of difficulties during drilling. The geology near the mouth of Ash Canyon is complex; test hole Ash-1 penetrated approximately 300 ft of unconsolidated sediments before reaching metamorphic rocks, whereas test hole Ash-2 (800 ft upcanyon from test hole Ash-1) penetrated only 80 ft of unconsolidated sediments before reaching granitic rocks (app. 1). Because depth to water at test hole Ash-1 is 140 ft below land surface and because the drilling method was not designed to penetrate thick sections of competent bedrock, no additional drilling was attempted in Ash Canyon. Further drilling in this canyon will require casing the unconsolidated sediments before using an air hammer to drill through the bedrock.

Lithology of sediments and rocks penetrated in each test hole was recorded during drilling. Core samples of bedrock were taken from the bottom of test holes VC-6 in Vicee Canyon and Kings-1 in Kings Canyon. Geophysical logs of each test hole were obtained prior to installing the wells. Lithologic descriptions and the geophysical logs for each test hole are shown in appendix 1.



R. 19 E. R. 20 E.

Base from U.S. Geological Survey digital data 1:100,000 and 1:24,000, 1979–82
Universal Transverse Mercator projection
Zone 11

Geology modified from Trexler (1977)

EXPLANATION

(light grey)	**Basin-fill sediments**	....	**Seismic-refraction profile**
(dark grey)	**Consolidated rocks**	- - - - - -	**Magnetic profile**
— 5000 —	**Altitude of land surface, in feet above sea level. Contour interval is 200 feet**	VC-8 ●	**Test hole**
├────┤	**Electrical resistivity sounding**	7	**Section number**

Figure 4. Geophysical surveys and test holes used in calculating subsurface flow in Vicee, Ash, and Kings Canyons, Carson City, Nevada.

At most sites, shallow and deep wells were installed in each test hole. Generally, one well was screened within the basin-fill sediments near the water table, and the second well was screened either at the base of the basin-fill sediments or in the underlying weathered or fractured bedrock. Only one well was installed in the northern test hole in Vicee Canyon (fig. 4, test hole VC-7), because bedrock was found at shallow depth. In addition to the test holes drilled along each section line, a test hole was drilled and a well was installed upcanyon from the hydrogeologic section in Vicee and Ash Canyons to determine the hydraulic gradient. The hydraulic gradient in Kings Canyon was determined from measurements in existing wells upcanyon and downcanyon from the section line.

Each well consists of polyvinyl chloride (PVC) pipe (nominal 2-in. diameter, schedule 40). A 10-ft-long screen with 0.02-in. factory-machined slots was attached near the bottom of the PVC pipe for all wells, except the deep well at test hole Ash-1; this well Ash-1 has a 20-ft-long screen (app. 2). A short length (2 to 5 ft) of pipe was attached below the screen to collect sediment entering the well during development. Rounded gravel (0.05- to 0.2-in. diameter) was placed around each screen, and bentonite was used to seal the hole from the uppermost screen to about 5 ft below land surface, as well as between screens in test holes with shallow and deep wells. Neat cement was used to seal the uppermost 5 ft of each hole. A 5-ft section of steel casing with a locking cap was placed over the wells and into the cement to protect the wells from vandalism. Finally, the altitudes of the tops of all wells were surveyed to the nearest 0.1 ft. Information on well construction and measured water levels for the wells is summarized in appendix 2.

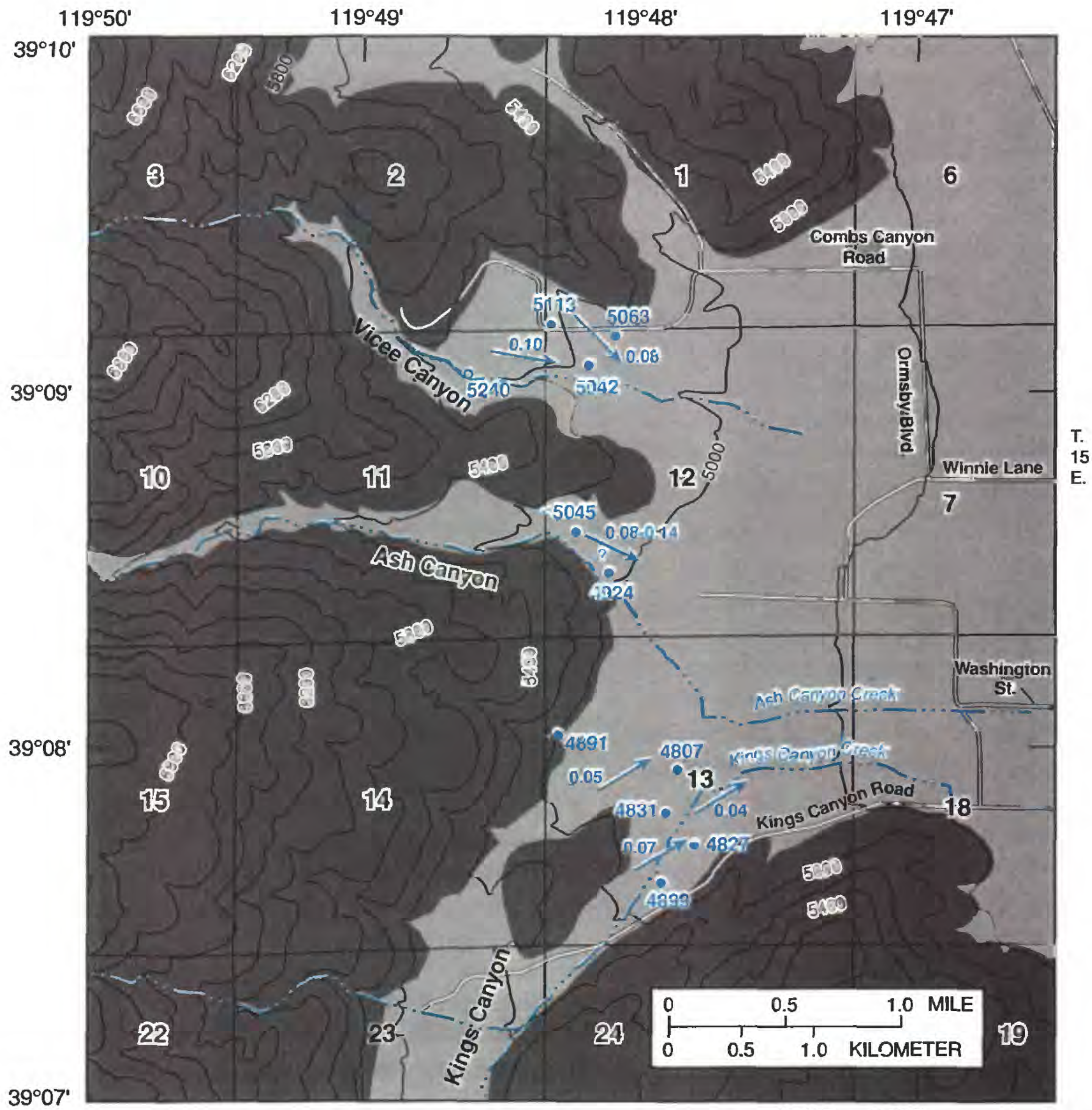
The wells were developed by a combination of air lifting, bailing, and surging and pumping until discharge from the wells was clear of drilling fluid and most suspended sediments. All wells, except the deep well at test holes Ash-1 and VC-7, were developed immediately following their installation. The great depth to water in the deep well at Ash-1 delayed development for several days because of insufficient hose to air lift the water and insufficient pumps to remove water from the well. The relatively thin zone of saturation at test hole VC-7 did not allow development by air lifting or pumping; bailing was the only means available to develop the well.

Direction of Subsurface Flow and Hydraulic Gradients

As previously discussed, the direction of subsurface flow and hydraulic gradient across each hydrogeologic section were determined from water levels in wells along the section and a well or gaining stream reach either upcanyon or downcanyon from the section. In addition to water-table gradients, apparent vertical gradients were determined at the test holes where shallow and deep wells are installed. These gradients were calculated as the difference between water levels in the shallow and deep wells, divided by the difference between midpoints of the gravel packs surrounding the well screens.

Vicee Canyon

Initially, the direction of subsurface flow and hydraulic gradient across Vicee Canyon was estimated using water levels in wells VC-6, VC-7, and VC-8. From these wells, the flow direction calculated is 150 degrees east from true north at a gradient of about 0.08 ft/ft. The direction differs from that calculated using water levels in wells VC-6 and VC-8 along with the assumed altitude of the water table in Vicee Canyon based on the downstream end of a gaining stream reach observed March 28, 1994 (location shown in fig. 5). Using the downstream end of the gaining reach results in a flow direction that is 100 degrees east from true north, which is downcanyon (fig. 5), with a hydraulic gradient of 0.10 ft/ft. This discrepancy suggests that the water level in well VC-7 is higher than would be expected if the well had been completed in the basin-fill sediments. It also suggests that the water-table gradient increases across the contact between the basin-fill sediments and bedrock. Because the water table may not be a flat surface, using the water level in well VC-7 to calculate the direction of flow produces an erroneous result.



Base from U.S. Geological Survey digital data 1:100,000 and 1:24,000, 1979–82
Universal Transverse Mercator projection
Zone 11

Geology modified from Trexler (1977)

EXPLANATION

Basin-fill sediments

Consolidated rocks

— 5000 — Altitude of land surface, in feet above sea level. Contour interval is 200 feet

0.10 Direction of subsurface flow—Determined from water levels in three wells nearest arrow. Number is downslope water-table gradient, in foot per foot. Direction of flow and hydraulic gradient are queried where uncertain

Gaining stream reach—Reach of Vicee Canyon flowing on March 28, 1994

5113 Test hole—Number is water-level altitude, in feet above sea level, on December 9, 1994, in shallow well. Symbol < indicates that water-level altitude is less than listed value

5240 Water table in stream—Estimated water-table altitude, in feet above sea level, at downstream end of gaining reach on March 28, 1994

7 Section number

Figure 5. Water levels at shallow wells in winter 1994 and near gaining stream reach in Vicee Canyon in spring 1994. Also shown are direction of subsurface flow and downslope water-table gradient in Vicee, Ash, and Kings Canyons, Carson City, Nevada.

The water level in the deep well at test hole VC-6 is about 2.3 ft lower than in the shallow well (app. 2), indicating an apparent downward vertical gradient of 0.05 ft/ft. This apparent gradient exceeds what can be explained by the downcanyon water-table gradient. For example, if subsurface flow parallels the water table, then the equipotential or line of equal water-level altitude will be perpendicular to the water table, and the water-table gradient of 0.08 ft/ft will be uniform with depth (fig. 6). Assuming that the test hole is vertical, the deep well in test hole VC-6 would have a water level only 0.3 ft lower than the shallow well. Thus, subsurface flow at test hole VC-6 is downward as well as downcanyon. This result suggests that (1) the weathered bedrock has greater permeability than the basin-fill sediments and acts as a drain across a fault just downcanyon from test hole VC-6 (fig. 2), (2) the thickness of basin-fill sediments or weathered bedrock increases downcanyon, or (3) the water percolating through the unsaturated zone recharges ground water near the hydrogeologic section. The first possibility is unlikely, because estimates of hydraulic conductivity determined from slug tests in the wells and from electrical resistivity logs of the test hole indicate that the basin-fill sediments are more permeable than the weathered bedrock (see section "Hydraulic Conductivity of Basin-Fill Sediments and Weathered and Fractured Bedrock"). Also the thickness of basin-fill sediments is known to increase downcanyon (Arteaga, 1986, p. 26). Therefore, the apparent downward gradient at test hole VC-6 likely results from a combination of increasing thickness of basin-fill sediments downcanyon and recharge through the unsaturated zone.

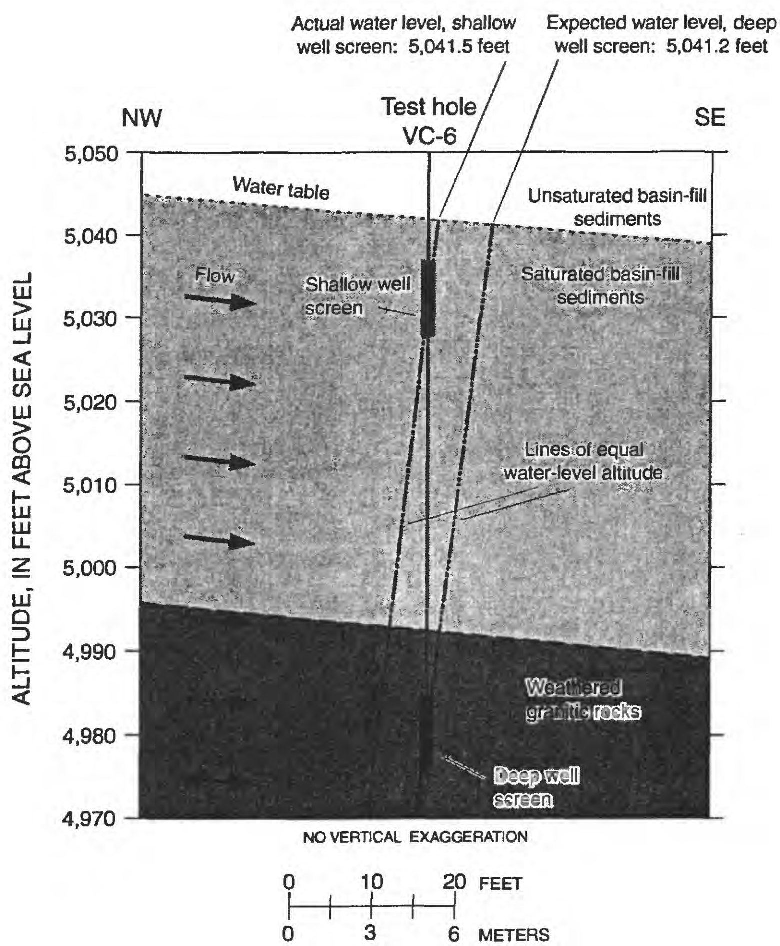


Figure 6. Idealized hydrogeologic section along direction of subsurface flow at test hole in Vicee Canyon, showing expected difference in water levels between shallow and deep wells, assuming subsurface flow parallels water table, Carson City, Nevada.

Ash Canyon

On the basis of water levels in only two wells, the direction of subsurface flow in Ash Canyon is estimated to be about 120 degrees east of true north, which is parallel to Ash Canyon Creek (fig. 5). The approximate water-table gradient in this direction could range from 0.08 to 0.14 ft/ft using the water level in the shallow well at test hole Ash-1 and assuming that the water table at test hole Ash-2 could be either 50 ft below the bottom of the test hole or just below the bottom of the hole. The well in test hole Ash-2 is dry; granitic rocks were found at shallow depth above the water table. The 16-in. normal resistivity log (app. 1) indicates that the bottom of the test hole is probably near the water table, because resistivity becomes less than 500 ohm-meters (compare log for Ash-2 to log for test hole VC-6 in app. 1). At test hole VC-6, also in granitic rocks, the resistivity decreases to less than 500 ohm-meters near the water table.

A shallow and a deep well were installed in test hole Ash-1. The water level in the deep well is about 95 ft lower than in the shallow well (app. 2), indicating an apparent downward gradient of about 0.8 ft/ft from basin-fill sediments to metamorphic rocks. The large downward gradient may be because the well is downcanyon from a mapped fault (fig. 2) across which basin-fill sediments thicken, allowing greater infiltration of streamflow and shallow subsurface flow. Other possibilities for the large downward gradient include (1) the greater permeability of metamorphic rocks than the overlying sediments and (2) the greater permeability of lowermost basin-fill sediments. Because the geology beneath Ash Canyon is complex, the pattern of subsurface flow is similarly difficult to identify.

Kings Canyon

Metamorphic rocks crop out on both sides of Kings Canyon near where the creek enters Eagle Valley (fig. 2). Metamorphic rocks also separate the watershed of Kings Canyon Creek from a smaller watershed to the northwest. The direction of subsurface flow beneath Kings Canyon Creek, as estimated from water levels in wells Kings-1 and Kings-2, and the Bily well is about 55 degrees east from true north (fig. 5). The water-table gradient in this direction is 0.07 ft/ft. The direction estimated from the combination of wells Kings-1, Kings-2, and the City well also is 55 degrees east from true north. The water-table gradient there, however, is 0.04 ft/ft, suggesting increased permeability or increased saturated thickness downcanyon from the section. The water-table gradient across the hydrogeologic section averages 0.06 ft/ft. The direction of subsurface flow northwest of Kings Canyon Creek, as estimated from test hole Kings-2 and the City and Quill wells, is about 70 degrees east of true north (fig. 5). The water-table gradient in this direction is about 0.05 ft/ft.

The water level in the deep well at test hole Kings-1 is about 2.3 ft lower than the shallow well (app. 2), indicating an apparent downward vertical gradient of about 0.03 ft/ft within the basin-fill sediments. The apparent gradient in test hole Kings-1 exceeds what can be explained by the downcanyon water-table gradient, and the direction of subsurface flow is downward as well as downcanyon. The downward gradient at test hole Kings-1 may result from increasing permeability at depth, increasing thickness of basin-fill sediments or weathered bedrock downcanyon, or water percolating through the unsaturated zone that recharges ground water near the hydrogeologic section.

The water level in the deep well at test hole Kings-2 is about 0.2 ft higher than in the shallow well, indicating an apparent upward gradient of about 0.005 ft/ft from the metamorphic rocks to the basin-fill sediments, or 10 times less than the water-table gradient. The negligible vertical gradient between the shallow and deep wells in test hole Kings-2 suggests flow is primarily downcanyon.

Distribution of Basin-Fill Sediments and Weathered and Fractured Bedrock

The distribution of basin-fill sediments and weathered and fractured bedrock within each hydrogeologic section was estimated using borehole geophysical and lithologic data collected during drilling of the test holes. Prior to drilling the test holes, various surface geophysical methods were used along the sections to estimate thickness and extent of basin-fill sediments near and between the planned test holes.

Electrical-resistivity soundings and magnetic profiles were made to determine thickness of basin-fill sediments. Electrical-resistivity soundings, however, produced only approximate thicknesses of the basin-fill sediments, because the resistivity of the unsaturated sediments was much greater than anticipated. The magnetic profiles could not be used to estimate thickness of basin-fill sediments, because magnetic anomalies caused by changes in the basin-fill thickness were masked by large variations in the thickness and magnetic susceptibility of the metamorphic rocks. Seismic-refraction profiles gave some information, but could be made only at a few locations along each hydrogeologic section because of limited space between bedrock outcrops. Thickness estimated from seismic refraction near test hole VC-6 closely approximated that determined from drilling of the test hole. Thickness estimated near test hole Kings-1 also closely agreed with that determined from the test hole. However, the thickness estimated from seismic refraction near test hole Kings-2 was about 70 ft greater than that determined from the test hole. Highly fractured and permeable metamorphic rocks in this test hole could have a seismic velocity similar to that of the saturated basin-fill sediments and may not act as a refractor of seismic waves. The greater depth estimated from the seismic-refraction data could represent the depth to less fractured metamorphic rocks.

Lithologic descriptions of drill cuttings, two core samples, and borehole geophysical data collected at the test holes are the most reliable data available to estimate the thickness of basin-fill sediments beneath each canyon (app. 1). Borehole geophysical data were collected in each test hole after circulating freshwater through the test hole to dilute and displace drilling mud. Logs of each test hole included three-arm caliper, natural-gamma, spontaneous-potential, and long- and short-normal resistivity, recorded at either 0.1- or 0.5-ft intervals.

The three-arm caliper provided a continuous record of the test-hole diameter, which is useful in interpreting other information that may be affected by changes in hole diameter. An average test-hole diameter was estimated for each gravel-pack interval and was used in estimating hydraulic conductivity from slug tests of the wells.

The natural-gamma log is commonly used to identify lithology and correlate stratigraphy. The natural-gamma probe detects, in counts per second, the total naturally occurring gamma radiation within a selected energy range. The most significant naturally occurring radionuclides are potassium-40 and daughter products of the uranium and thorium decay series. Potassium is abundant in minerals that decompose to clay, and uranium and thorium both concentrate in clay by chemical processes; consequently, fine-grained sediments tend to be more radioactive than coarser sediments (Keys, 1990, p. 79). For example, the natural-gamma log for test hole Kings-1 indicates an increase in radioactivity near a depth of 185 ft, corresponding with an increased clay content observed in the drill cuttings (app. 1).

The spontaneous-potential (SP) log also is used to identify lithology and correlate stratigraphy and measures potential voltages, in the millivolt range, that develop at contacts of clay and sand beds. Lithologic contacts are at the point of inflection on the SP log (Keys, 1990, p. 52).

The normal-resistivity log measures the apparent resistivity of the saturated aquifer using two sets of differently spaced electrodes. Short-normal (16-in.) and long-normal (64-in.) electrode spacings were used for this study. In general, the resistivity of sediments and rocks is a function of quantity, salinity, and distribution of water within pores or fractures. The short-normal electrode generally measures resistivity in the zone invaded by drilling mud, whereas the long-normal electrode generally measures resistivity beyond the zone affected by drilling mud. Although electrical-resistivity logs do not allow direct identification of lithologic units, resistivity is sensitive to effective porosity of sediments and rocks. (Effective porosity includes only pores that are interconnected.) This sensitivity enables quantitative estimates of the distribution of particle size in basin-fill sediments. In general, basin-fill sediments having a higher clay content have a lower apparent resistivity. The long-normal resistivity for test hole Kings-1 decreases near 185 ft below land surface in response to an increase in clay content (app. 1).

The vertical distribution of basin-fill sediments and weathered and fractured bedrock along each hydrogeologic section in Vicee, Ash, and Kings Canyons was drawn to scale on graph paper using all available information (fig. 7). Areas of saturated basin-fill sediments and weathered or fractured bedrock beneath each section were determined by totaling the number of grid cells within saturated basin-fill sediments and within weathered or fractured bedrock.

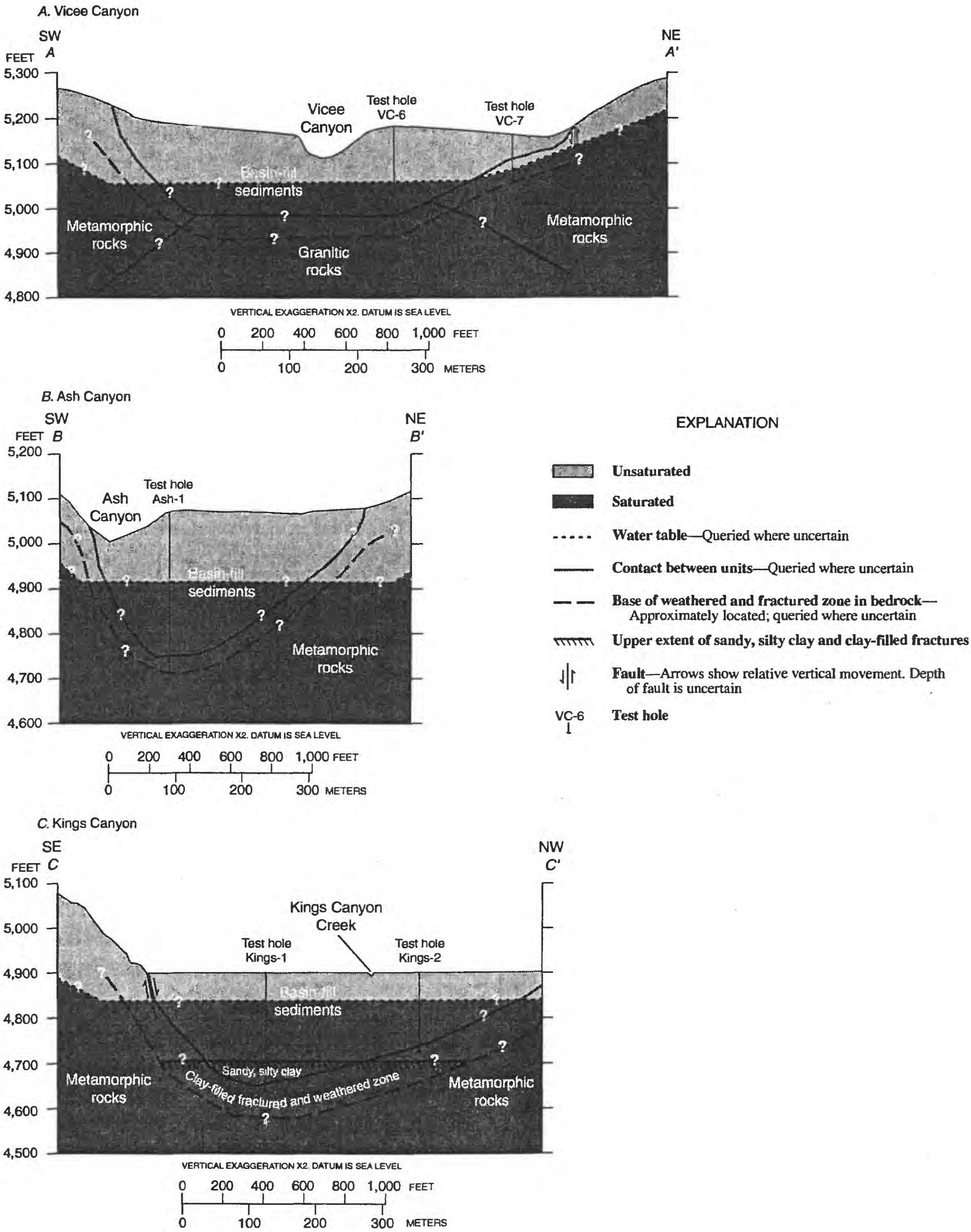


Figure 7. Hydrogeologic sections across (A) Vicee Canyon, (B) Ash Canyon, and (C) Kings Canyon, showing distribution of saturated and unsaturated basin-fill sediments and bedrock, Carson City, Nevada. (Location of sections is shown in fig. 2.)

Vicee Canyon

Metamorphic rocks are exposed at both ends of the hydrogeologic section in Vicee Canyon (*A-A′*; figs. 2 and 7*A*), and also were found at a depth of 50 ft at test hole VC-7. However, granitic rocks were found at a depth of 180 ft at test hole VC-6, indicating that the metamorphic rocks have been eroded away beneath the central area underlying Vicee Canyon. The thickness of basin-fill sediments south of the canyon is not known; it is assumed to be the same as north of the canyon. Weathered and fractured bedrock is assumed to be about 50 ft thick beneath the section, because the drilling rates decreased to less than 0.3 ft/min after drilling about 50 ft into the weathered granitic rocks at test hole VC-6 and into fractured metamorphic rocks at test hole VC-7 (app. 1). The fractured metamorphic rocks in test hole VC-7 are categorized with the weathered bedrock. Some of the fractures in test hole VC-7 probably are filled with fine-grained sediments, because clay, in addition to rock chips, was occasionally recovered in the drill cuttings.

Unweathered granitic rocks with few fractures was recovered from a core collected at the bottom of test hole VC-6. Laboratory measurements of porosity and bulk density were made from a sample of the unweathered granitic rocks. Porosity is only 1.7 percent and bulk density is 160.4 lbs/ft^3; both values are typical of unweathered granitic rocks. Where the unweathered granitic rocks are not fractured, it is minimally permeable. Thus, the saturated area of unweathered granitic rocks is not included in the estimate of subsurface flow beneath the section. Water levels in wells in test holes VC-6 and VC-7 indicate saturated basin-fill sediments beneath Vicee Canyon are relatively thin, about 60 ft thick. The area of saturated basin-fill sediments is about 95,000 ft^2, and the area of weathered or fractured bedrock is about 94,000 ft^2 (table 6).

Ash Canyon

Metamorphic rocks also are exposed at both ends of the hydrogeologic section at Ash Canyon (*B-B′*; figs. 2 and 7*B*) and were found at a depth of 302 ft at test hole Ash-1. Thickness of basin-fill sediments beneath *B-B′* is known only at test hole Ash-1; however, ground water flows through a relatively narrow section of the sediments beneath Ash Canyon. At test hole Ash-1, about 175 ft of saturated basin-fill sediments were penetrated and 30 ft of weathered and fractured metamorphic rocks were penetrated at the bottom of the hole. Drill cuttings in this interval included rock chips and clay, indicating that some of the fractures are filled with fine-grained sediments. The depth of weathering and fracturing is not known, because the drilling rate did not decrease to the low rates observed in test holes drilled in Vicee Canyon; therefore, the zone of weathered or fractured bedrock could be thicker than 30 ft. The area of saturated basin-fill sediments is about 103,000 ft^2, and the area of weathered or fractured metamorphic rocks, assuming a minimum 30-ft thickness, is about 36,000 ft^2 (table 6).

Kings Canyon

Metamorphic rocks are exposed along both sides of Kings Canyon (figs. 2 and 7*C*) and also were found in test holes Kings-1 and Kings-2 at depths of about 240 and 160 ft, respectively. Metamorphic rocks exposed on the low hill north of Kings Canyon Creek (fig. 2) is presumed also to be present at shallow depth near the north end of hydrogeologic section *C-C′*. The thickness of basin-fill sediments north of this section is not known; no test holes were drilled north of the outcrop of metamorphic rocks. Subsurface flow probably occurs in this region as well; however, additional test holes are needed to estimate the flow beneath this region. The thickness of saturated basin-fill sediments beneath section *C-C′* is as much as 100 to 180 ft.

The drill bit and drill stem bounced considerably on fractured metamorphic rocks at the bottom of test hole Kings-2. Unlike cuttings from the other test holes, little clay was in the drill cuttings, so the fractures were probably not filled with fine-grained sediment. The thickness of these fractured rocks is assumed to be 70 ft on the basis of seismic-refraction profiles; the profiles indicate a change in seismic velocity at a depth of about 230 ft near test hole Kings-2. A thick layer of sandy, silty clay below an altitude of about 4,700 ft at test hole Kings-1 extends to the underlying metamorphic rocks (fig. 7*C*, app. 1). The sandy, silty clay is probably confined to the deepest part of the bedrock valley (fig. 7*C*). Beneath the clay, fractured metamorphic rocks were recovered from a core collected at the bottom of Kings-1. Laboratory measurements of porosity and bulk density were made from a sample of unfractured metamorphic rocks; porosity is 6.2 percent and bulk density is 148.6 lbs/ft^3. The greater porosity of the sample of metamorphic rocks compared to the sample of granitic rocks indicates that the metamorphic rocks could have a greater storage capacity than the unweathered granitic rocks. The fractures in the metamorphic rock at the bottom of test hole Kings-1 were filled with sediments—primarily silt and clay. Because the extent of fractures filled with silt and clay is uncertain, all bedrock beneath an altitude of 4,700 ft was assumed to have clay-filled fractures (fig. 7*C*).

The area of saturated basin-fill sediments beneath the section in Kings Canyon, excluding the thick section of sandy clay near test hole Kings-1, is about 180,000 ft^2, whereas the area of saturated sandy, silty clay is about 26,000 ft^2. The area of saturated bedrock totals 155,000 ft^2 (table 6).

Hydraulic Conductivity of Basin-Fill Sediments and Weathered and Fractured Bedrock

Hydraulic conductivity defines how readily water can move through sediments and rocks. In the basin-fill sediments, hydraulic conductivity is generally greatest in coarse-grained, well-sorted deposits and less in fine-grained, poorly sorted deposits. Hydraulic conductivity can range several orders of magnitude between the two extremes (Heath, 1989, p. 11). Similarly, hydraulic conductivities can range several orders of magnitude in bedrock depending on the degree of weathering and width or openness of fractures.

The following sections describe (1) estimates of hydraulic conductivity from slug tests, (2) estimates of hydraulic conductivity from resistivity logs, (3) delineation of lithologic units in the basin-fill sediments and bedrock on the basis of hydraulic conductivity and lithology, and (4) estimates of the geometric-mean hydraulic conductivity of each lithologic unit.

Estimates from Slug Tests

Slug tests were done in each well by quickly lowering a cylinder below the static water level in the well, causing the water level to rise rapidly. The subsequent decline was monitored until the water level returned to its initial level. The cylinder was then quickly raised above the static water level in the well, causing the water level to drop rapidly. The subsequent rise was monitored until the water level in the well returned to its initial level. Water levels in all wells were monitored using a 30-lb/in^2 pressure transducer placed sufficiently below the initial water level so as not to interfere with the lowering and raising of the cylinder. The factory-calibrated relation between millivolts and water level was checked in the laboratory. The relation was programmed into a data logger, which was used to store the data at 1- to 5-second intervals. Data from each well are summarized in appendix 3, and results are listed in table 2.

The slug-test data were analyzed with the computer program AQTESOLV, version 2.0 (Geraghty and Miller, 1994), using the methods of Cooper and others (1967) and Bouwer and Rice (1976).

The method of Cooper and others (1967) was developed for completely penetrating wells (screened through the entire aquifer thickness) and assumes confined conditions, horizontal flow, and that the water and aquifer are compressible. The method involves matching the ratio of residual water level to initial water level plotted against time (with time transformed to log base 10) to a set of type curves, each of which assumes a different value for storage in the aquifer. The resulting estimate of transmissivity is then divided by the length of gravel pack to obtain hydraulic conductivity.

The method of Bouwer and Rice (1976) was developed for partly to fully penetrating wells and assumes that flow through unconfined or confined aquifers is horizontal and that the water and aquifers are uncompressible and there is no delayed yield from the water table. The slope and intercept of a line drawn through the water-level displacement from the pre-test water level plotted against time (with water-level displacement transformed to log base 10) is used to estimate hydraulic conductivity.

Although the method of Bouwer and Rice (1976) accounts for partial penetration, computations in which aquifer thickness was assumed to be the distance from the water level in the well to the bottom of the well gave nearly identical estimates of hydraulic conductivity as computations that assumed thickness was equal to the gravel-packed interval. Therefore, the method of Cooper and others (1967), which does not account for partial penetration, could reasonably be applied by assuming aquifer thickness equals length of the gravel pack. The method of Cooper and others (1967) estimates storage coefficients that range from 1×10^{-4} to 4×10^{-7} (table 2), suggesting that delayed yield from the water table is not greatly affecting the shape of the response curves. Analyses of slug-test data using both methods are summarized in appendix 3.

Table 2. Results of slug tests in wells in Vicee, Ash, and Kings Canyons, Carson City, Nevada, November 1994

Well (2-inch diameter; see fig. 4)	Cylinder position	Cylinder displacement (feet)	Method of Cooper and others (1967)			Method of Bouwer and Rice (1976)	
			Transmissivity (feet squared per day)	Storage coefficient (dimension-less)	Hydraulic conductivity (feet per day)	Hydraulic conductivity (feet per day)	Intercept (feet)
VC-6 shallow .	lowered	2.17	67	3×10^{-5}	4	3	2.1
	raised		78	2×10^{-5}	5	3	2.1
VC-6 deep....	lowered	2.17	15	5×10^{-5}	.6	1	2.2
	raised		13	5×10^{-5}	.5	.9	2.1
VC-7........	lowered	2.17	14	2×10^{-5}	.8	.8	2.1
	raised		8	9×10^{-5}	.5	.5	2.1
VC-8........	lowered	2.17	130	1×10^{-5}	6	5	2.1
	raised		120	1×10^{-6}	6	5	2.3
			[1]130	1×10^{-6}	6	5	1.9
Ash-1 shallow .	lowered	2.17	360	1×10^{-7}	20	10	2.1
	raised		290	1×10^{-6}	10	10	2.2
			[1]440	4×10^{-7}	20	10	2.1
Ash-1 deep ...	lowered	2.17	30	1×10^{-6}	.6	.8	2.2
			[1]29	1×10^{-4}	.6	1	2.0
	raised		53	1×10^{-6}	1	1	2.1
			[1]43	1×10^{-5}	.9	1	2.0
Kings-1 shallow.	lowered	4.06	120	1×10^{-6}	5	4	4.1
	raised		110	1×10^{-6}	5	4	4.1
Kings-1 deep..	lowered	2.17	10	1×10^{-6}	.5	.4	2.0
	raised		7	2×10^{-6}	.4	.3	2.0
Kings-2 shallow.	lowered	4.06	250	1×10^{-6}	10	8	3.9
	raised		220	1×10^{-6}	10	8	4.0
Kings-2 deep..	lowered	4.06	510	1×10^{-6}	30	30	4.2
	raised		480	1×10^{-6}	20	30	4.1

[1] Determined using translation method described by Pandit and Miner (1986).

Water-level oscillations were observed immediately following the quick lowering and raising of the cylinder in most wells. In some cases, water levels oscillated 10 seconds after the cylinder was raised or lowered, and the initial increase or decrease in water level sometimes exceeded the expected displacement of the cylinder. For the analyses, the initial displacement of water was assumed to equal the expected displacement. In a few analyses, data were translated using the method of Pandit and Miner (1986), which ignores early water-level oscillations. Estimates of hydraulic conductivity using the translated data did not differ greatly from estimates based on the original data (table 2). The translated data, however, allowed for a more precise match with the theoretical curves.

Hydraulic conductivity calculated from the slug tests ranges from 0.3 to 30 ft/d (table 2). Similar values were determined from both the Cooper and others (1967) and Bouwer and Rice (1976) methods. Typically, more than one type curve can be matched with the method of Cooper and others (1967). The errors resulting from choosing a type curve are less than 30 percent (Papadopulos and others, 1973, p. 1087). Similarly, more than one straight line can be drawn to fit the data with the method of Bouwer and Rice (1976), resulting in errors comparable to those from choosing a curve. Additional errors in the calculated values result from poor well development (for example, not completely removing drilling mud from well) and from assumptions used in analysis that are not completely applicable to conditions in the aquifer. The hydraulic conductivities determined from the slug tests at wells Ash-1 and VC-7 may be less than their actual values, because conditions did not allow proper development.

Generally, the hydraulic conductivities calculated from slug tests of wells screened in basin-fill sediments are greater than those of wells screened in the weathered or fractured bedrock. Hydraulic conductivities of the basin-fill sediments are between 3 and 20 ft/d—except for the deep well in test hole Kings-1, where the calculated value is between 0.3 and 0.5 ft/d (table 2). This well is completed in finer grained basin-fill sediments. Hydraulic conductivities of the weathered or fractured bedrock are between 0.5 and 1 ft/d—except for the deep well in test hole Kings-2, for which the calculated value is about 30 ft/d. This well was completed in fractured metamorphic rocks.

Although the weathered and fractured bedrock is generally less permeable than the basin-fill sediments, it is not impermeable; where fractures are open, particularly in the metamorphic rocks, the bedrock is highly permeable and could act as a conduit for subsurface flow into the basin-fill aquifer beneath Eagle Valley.

Estimates from Resistivity Logs

The distribution of hydraulic conductivity near each well was estimated by using an empirical relation between resistivity of saturated sediments and bedrock (as measured by a long-normal [64-in.] resistivity tool at 0.1 or 0.5 ft intervals), and hydraulic conductivity, calculated from slug tests. A term called formation factor, developed initially by Archie (1942, p. 55) for brine-filled sandstones, is the ratio of the measured resistivity of saturated sediments and rocks to the resistivity of the pore water:

$$F_r = \frac{R}{R_w}, \qquad (4)$$

where F_r is a formation (resistivity) factor, dimensionless;

R is measured resistivity of the water-saturated sediments or rocks, in ohm-meters; and

R_w is resistivity of water in the sediments or rocks, in ohm-meters.

Archie (1942) found that under highly saline conditions, hydraulic conductivity increases with decreasing formation factor. This relation applies to sediments or rocks that are nonconductive, and the bulk resistivity is controlled by the porosity. When sediments are saturated with freshwater, the hydraulic conductivity increases with increasing formation factor (Jones and Buford, 1951, p. 121). This relation is because of the increased importance of grain-surface conductance of the aquifer matrix and the decreased importance of pore-fluid conductance (Alger, 1966, p. 19; Croft, 1971; Kelly, 1977; Heigold and others, 1979; and Kosinski and Kelly, 1981).

The relation between hydraulic conductivity and formation factor was developed from test-hole data in Vicee and Kings Canyons (fig. 8). The average resistivity adjacent to the screened interval was calculated from the long-normal (64-in.) resistivity logs shown in appendix 1. Measurements of specific conductance of ground-water samples were corrected to ambient ground-water temperatures and converted to resistivity, in ohm-meters (table 3). The formation factor was calculated using Archie's formula (eq. 4) and then plotted against the hydraulic conductivity determined from the Bouwer and Rice (1976) analyses of slug-test data (fig. 8). Average resistivity of the basin-fill sediments, bedrock, and ground water—as well as the formation factor corresponding to the gravel-packed intervals of wells—are listed in table 3 along with the average hydraulic conductivity for each well determined from Bouwer and Rice (1976) analyses of slug-test data (table 2).

Equations describing the relation between hydraulic conductivity and formation factor were developed for test holes in Vicee and Kings Canyons. The relation between hydraulic conductivity and formation factor for wells in Kings Canyon has a coefficient of determination (r^2) of 0.96 (fig. 8, curve 1). The relation for Kings Canyon area can be written as:

$$K = 1.3 \times 10^{-5}\left(F^{7.2}\right), \qquad (5)$$

where K is hydraulic conductivity, in feet per day; and

F is formation (resistivity) factor, dimensionless.

The relation between hydraulic conductivity and formation factor for wells in the Vicee Canyon area has an r^2 of 0.83 (fig. 8, curve 2). The relation for Vicee Canyon can be written as:

$$K = 0.14\left(F^{1.6}\right). \quad (6)$$

Hydraulic conductivities calculated from slug tests in wells Ash-1 shallow, Ash-1 deep, and VC-7 were not used in the regression analyses for curve 2.

Incomplete development at wells Ash-1 deep and VC-7 produced questionable estimates of hydraulic conductivity for these sites. Because a reliable estimate of hydraulic conductivity was available for only one well (Ash-1 shallow) in Ash Canyon, and basin-fill sediments and fractured metamorphic rocks found in Ash Canyon are similar to those in Kings Canyon, the relation described by curve 1 was applied to the Ash Canyon data to estimate the distribution of hydraulic conductivity.

The distribution of hydraulic conductivity determined from the long-normal resistivity logs for five test holes (VC-6, VC-8, Ash-1, Kings-1, and Kings-2) is presented in figure 9. Bar symbols show the length of the gravel pack surrounding each well screen and the hydraulic conductivity estimated from the Bouwer and Rice (1976) analyses of slug-test data. Hydraulic conductivities were estimated every 0.5 ft for test holes in Ash and Kings Canyons using equation 5 and every 0.1 ft for test holes in Vicee Canyon using equation 6. The distribution of hydraulic conductivity for Vicee Canyon is fairly uniform: from about 0.5 to 6 ft/d (figs. 9*A* and 9*B*). In contrast, estimates of hydraulic conductivity for Ash and Kings Canyons range more than four orders of magnitude, from less than 0.01 ft/d to nearly 400 ft/d (figs. 9*C*, 9*D*, and 9*E*). Therefore, the basin-fill sediments derived from metamorphic rocks are probably less homogeneous than those in Vicee Canyon, which originate predominantly from granitic rocks.

Table 3. Comparison of formation factor determined from resistivity of basin-fill sediments, bedrock, and ground water to average hydraulic conductivity determined from slug tests of wells in Vicee, Ash, and Kings Canyons, Carson City, Nevada

[Abbreviation and symbol: µS/cm, microsiemens per centimeter; --, no data available]

Well (see fig. 4)	Interval used for analysis [1] (feet)	Average resistivity of sediments or bedrock, *R* (ohm-meters)	Ground water		Formation factor, *F* (dimensionless)	Average hydraulic conductivity, [2] *K* (feet per day)
			Specific conductance (µS/cm)	Equivalent resistivity, R_w (ohm-meters)		
VC-6 shallow ..	146-163	621	137	73.4	8.46	3
VC-6 deep.....	185-210	260	137	73.4	3.54	1
VC-7	90-107	300	228	43.9	6.83	.7
VC-8	96-117	335	--	[3]43.9	7.63	5
Ash-1 shallow ..	162-185	158	269	37.2	4.25	10
Ash-1 deep	271-321	163	269	37.2	4.35	1
Kings-1 shallow	86-108	315	--	[4]53.2	5.92	4
Kings-1 deep...	170-190	219	--	[4]53.2	4.12	.4
Kings-2 shallow	82-104	356	250	53.2	6.69	8
Kings-2 deep...	155-175	380	250	53.2	7.14	30

[1] Gravel-packed interval for each monitoring well is thickness of gravel placed near each well screen (app. 3).
[2] Average hydraulic conductivity from method of Bouwer and Rice (1976) listed in table 2.
[3] Estimate is from monitoring well in test hole VC-7.
[4] Estimate is from monitoring wells in test hole Kings-2.

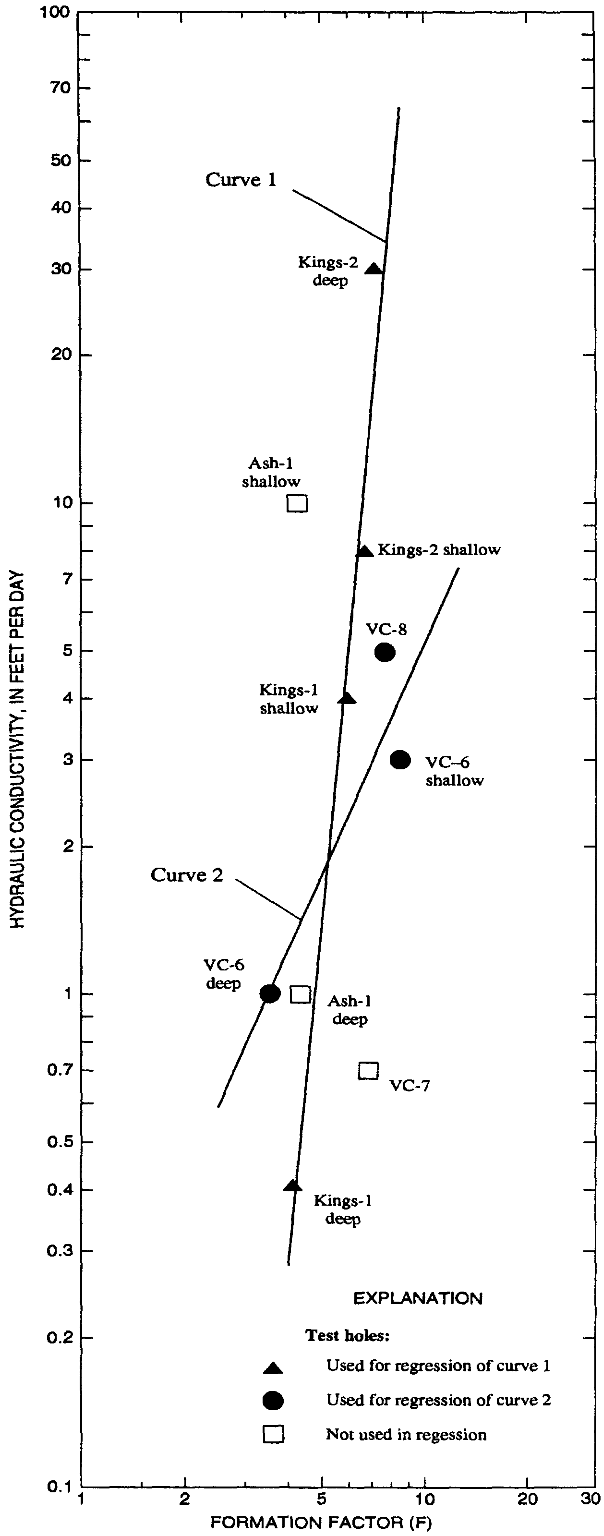


Figure 8. Relation between hydraulic conductivity determined from slug tests of wells and formation factor determined from resistivity of basin-fill sediments, bedrock, and ground water in test holes in Kings Canyon (curve 1) and Vicee Canyon (curve 2), Carson City, Nevada.

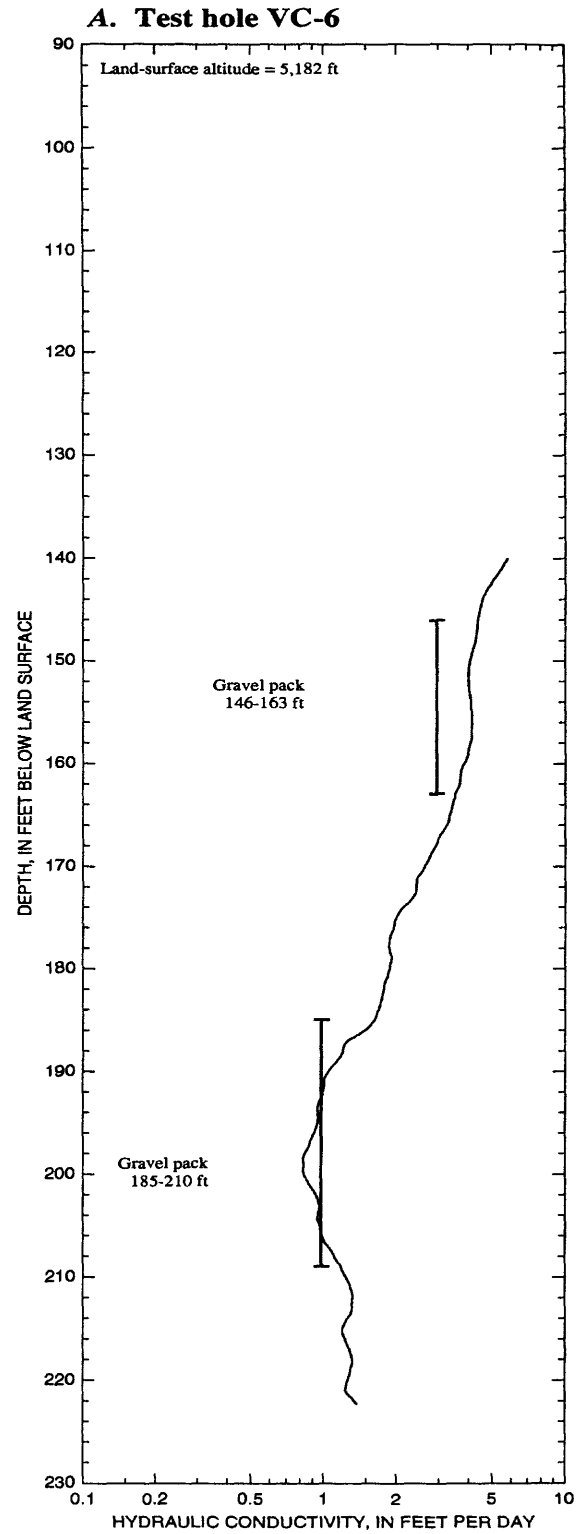
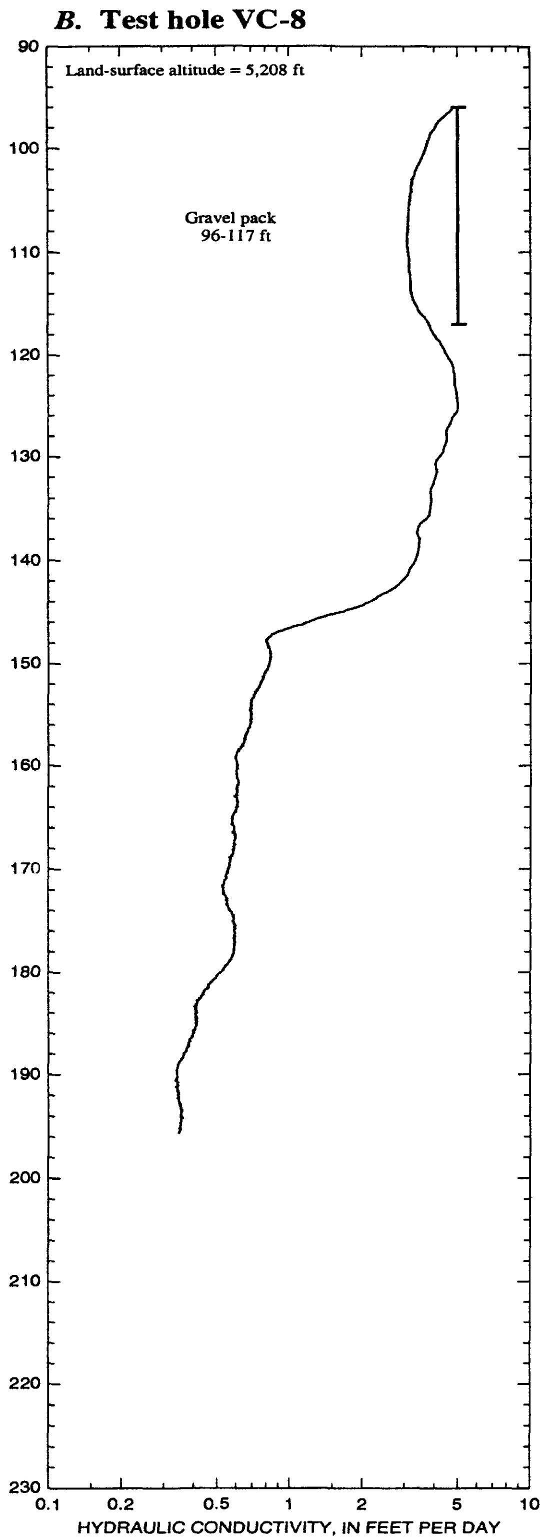


Figure 9. Distribution of hydraulic conductivity calculated from long-normal resistivity logs for test holes in Vicee (*A*, *B*), Ash (*C*), and Kings (*D*, *E*) Canyons, Carson City, Nevada. Vertical bars represent hydraulic conductivity determined from slug tests of wells screened in test hole. (Location of test holes is shown in fig. 4).



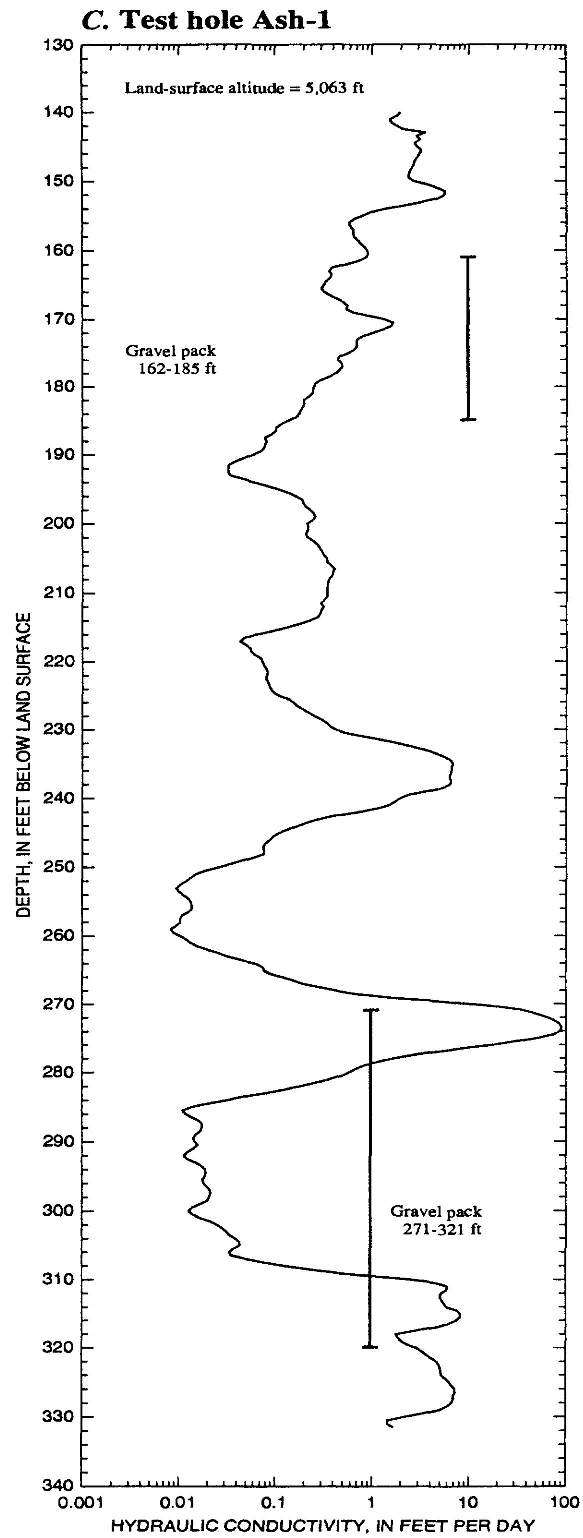


Figure 9. Continued

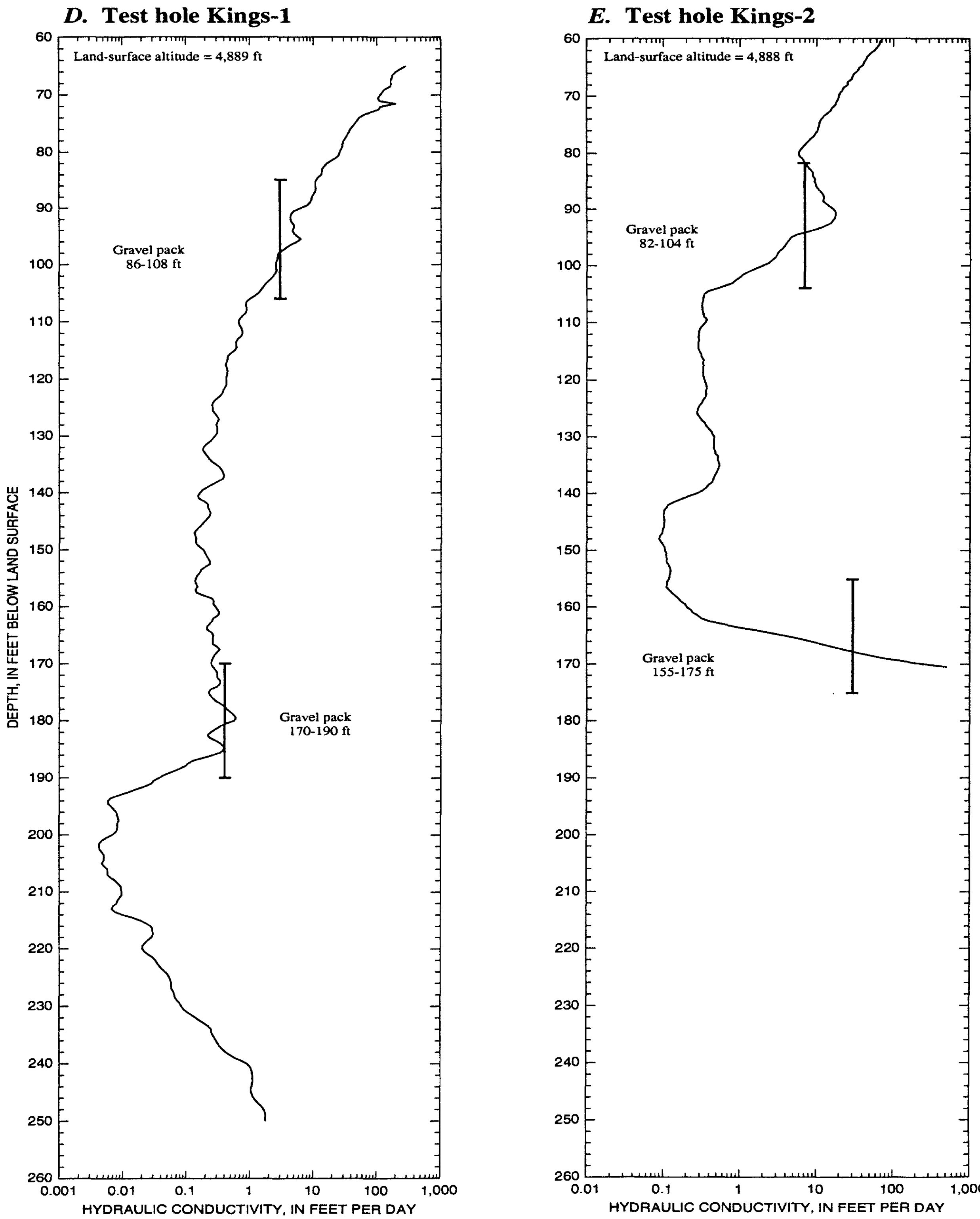


Figure 9. Continued

Lithologic Units Determined From Hydraulic Conductivity

In the basin-fill sediments, coarser grained sediments typically have a greater hydraulic conductivity than finer grained deposits. Basin-fill sediments were grouped into four lithologic units according to hydraulic conductivities estimated from the resistivity logs:

- Values less than 0.1 ft/d were assumed to represent silt and clay to sandy clay; values between 0.1 and 1 ft/d were assumed to represent a clayey to silty sand;
- Values between 1 and 10 ft/d were assumed to represent a fine sand; values greater than 10 ft/d were assumed to represent coarse sand with gravel.

Bedrock was divided into three lithologic units according to hydraulic conductivities:

- Values less than 0.1 ft/d were assumed to represent unweathered bedrock or bedrock with closed fractures;
- Values between 0.1 and 1.0 ft/d were assumed to represent partly-weathered granitic rocks or metamorphic rocks with sediment-filled fractures; and
- Values greater than 1 ft/d were assumed to represent highly-weathered granitic rocks or metamorphic rocks with open fractures.

The thickness of each lithologic unit is listed for basin-fill sediments (table 4) and bedrock (table 5).

Geometric-Mean Hydraulic Conductivity of Lithologic Units

The geometric-mean hydraulic conductivity of the four lithologic units in the basin-fill sediments and the three units in the weathered or fractured bedrock was estimated for each canyon to account for differences in hydraulic conductivity within each unit.

Table 4. Geometric-mean hydraulic conductivity of lithologic units of basin-fill sediments beneath Vicee, Ash, and Kings Canyons, Carson City, Nevada

[Symbol: --, unit not present]

Canyon	Test hole (see fig. 4)	Saturated thickness of basin-fill sediments with resistivity measurements (feet)	Thickness of lithologic unit[1] (feet)				Geometric-mean hydraulic conductivity of lithologic unit (feet per day)			
			Clay	Clayey sand	Fine sand	Sand and gravel	Clay	Clayey sand	Fine sand	Sand and gravel
Vicee ...	VC-6 ...	45.1	0	0	45.1	0	--	--	3.1	--
	VC-8 ...	99.8	0	49.2	50.6	0	--	0.54	3.5	--
Total/mean[2]		**144.9**	**0**	**49.2**	**95.7**	**0**	--	**.54**	**3.3**	--
Ash	Ash-1...	**162.5**	**57.0**	**68.0**	**31.0**	**6.5**	**0.03**	**.32**	**2.8**	**46**
Kings ...	Kings-1 .	179.0	43.0	91.5	22.0	22.5	.02	.30	3.0	46
	Kings-2 .	112.0	4.0	56.0	18.0	34.0	.09	.27	5.0	34
Total/mean[2]......		**291.0**	**47.0**	**147.5**	**40.0**	**56.5**	**.02**	**.29**	**3.8**	**38**

[1] Lithologic units separated on basis of hydraulic conductivity from long-normal resistivity logs. Clay has assigned hydraulic conductivities of less than 0.1 foot per day; clayey sand has assigned values between 0.1 and 1 foot per day; fine sand has assigned values between 1 and 10 feet per day; and sand and gravel have assigned values greater than 10 feet per day.

[2] Total thicknesses for Vicee and Kings Canyons are the sum of thicknesses in test holes; geometric-mean hydraulic conductivity of each lithologic unit is weighted mean.

The geometric-mean hydraulic conductivity for each lithologic unit was computed by converting each estimate of hydraulic conductivity at 0.1 or 0.5 ft intervals from the resistivity logs (K_i) into the base-10 logarithm, totaling logarithmic values, dividing the sum by the number of intervals to obtain an average, and computing the geometric mean as the antilog of the average (Spiegel, 1961, p. 60). This can be expressed as:

$$K_g = 10^{\frac{\sum_{i=1}^{n} \log_{10}(K_i)}{n}}, \qquad (7)$$

where K_g is geometric-mean hydraulic conductivity, in feet per day;

K_i is hydraulic conductivity of i^{th} interval in lithologic unit, in feet per day; and

n is total number of intervals in lithologic unit.

Equation 7 was applied to the distribution of hydraulic conductivity determined from the long-normal resistivity logs in the test holes (fig. 9) for each lithologic unit in basin-fill sediments and bedrock. The geometric-mean hydraulic conductivity for each lithologic unit is listed for basin-fill sediments (table 4) and for bedrock (table 5). For the basin-fill sediments, hydraulic conductivity ranges from 0.02 to 0.09 ft/d for the finer grained sediments and from 34 to 46 ft/d for the coarser grained sediments. For bedrock, hydraulic conductivity ranges from 0.06 to 0.91 ft/d for unweathered bedrock, or bedrock with closed fractures; from 1.2 to 4.2 ft/d for weathered granitic rock, or open bedrock with sediment-filled fractures; and 60 ft/d for fractured metamorphic rocks. Although the estimates of hydraulic conductivity in bedrock are based on thin intervals penetrated by the test holes, results indicate that metamorphic rocks are more permeable than weathered granitic rocks. Hydraulic conductivity of the fractured metamorphic rocks beneath Kings Canyon could be overestimated if the permeable zone found in test hole Kings-2 is a localized fracture zone that does not extend much beyond the test hole.

Table 5. Geometric-mean hydraulic conductivity of bedrock units beneath Vicee, Ash, and Kings Canyons, Carson City, Nevada

[Symbol: --, category not present]

Canyon	Test hole (see fig. 4)	Thickness of bedrock penetrated (feet)	Thickness of lithologic unit [1] (feet)			Geometric-mean hydraulic conductivity of lithologic unit (feet per day)		
			Unweathered bedrock or bedrock with closed fractures	Weathered or fractured bedrock		Unweathered bedrock or bedrock with closed fractures	Weathered or fractured bedrock	
				Weathered or filled fractures	Open fractures		Weathered or filled fractures	Open fractures
Vicee	VC-6	**37.4**	**14.7**	**22.7**	**0**	**0.91**	**1.2**	--
Ash	Ash-1	**30.0**	**7.5**	**22.5**	**0**	**.06**	**4.2**	--
Kings Canyon	Kings-1	6.5	0	6.5	0	--	1.4	--
	Kings-2	9.0	2	2.5	4.5	.51	3.7	60
Total/mean [2]		**15.5**	**2**	**9**	**4.5**	**.51**	**1.8**	**60**

[1] Test holes Ash-1, Kings-1, and Kings-2 penetrated metamorphic rocks; test hole VC-6 penetrated granitic rocks. Lithologic units are separated on basis of hydraulic conductivity from long-normal resistivity logs. Unweathered bedrock and bedrock with closed fractures has assigned hydraulic conductivities of less than 1.0 foot per day; weathered bedrock or bedrock with sediment-filled fractures has assigned values between 1 and 10 feet per day; and bedrock with open fractures has assigned values greater than 10 feet per day.

[2] Total thicknesses for Kings Canyon are the sum of thicknesses in test holes; geometric-mean hydraulic conductivity of each lithologic unit is weighted mean.

Estimates of Subsurface Flow Across Hydrogeologic Sections

Estimates of ground-water flow across each hydrogeologic section were calculated using equation 3 by (1) summing the product of the saturated area (determined by multiplying the fraction of the thickness of each lithologic unit penetrated in the test holes to the total saturated area, except for the sandy, silty clay found in Kings Canyon) and the geometric-mean hydraulic conductivity of each unit; and (2) multiplying the sum by the measured water-table gradient. Estimates of flow are summarized in table 6. Subsurface flow is about 300 acre-ft/yr in Vicee Canyon, about 200 to 400 acre-ft/yr in Ash Canyon, and about 2,300 acre-ft/yr in Kings Canyon. Subsurface flow across Kings Canyon is considerably more than the total estimated for Vicee and Ash Canyons. Furthermore, additional subsurface flow is likely in that part of Kings Canyon north of the hydrogeologic section.

These estimates are limited by the assumptions that (1) available water levels accurately define hydraulic gradient, (2) borehole resistivity provides reasonable estimates of the vertical distribution of hydraulic conductivity, and (3) available lithologic data from test holes can be extrapolated across each hydrogeologic section. Because of the limited number of test holes and the unknown uncertainty in extrapolating data from the test holes across the entire section, the estimates of subsurface flow are uncertain. Therefore, annual subsurface flows from each canyon listed in table 6 are reported only to the nearest 100 acre-ft.

The total estimate of 2,800 to 3,000 acre-ft/yr of subsurface flow beneath the hydrogeologic sections across Vicee, Ash, and Kings Canyons (table 6) exceeds previous estimates of 0 to 1,000 acre-ft/yr of subsurface flow entering the basin-fill aquifer in Eagle Valley from the entire Carson Range (table 1). The sections used to estimate subsurface flow into the basin-fill aquifer of Eagle Valley encompass only a small part of the valley's perimeter. Subsurface flow beneath other watersheds, particularly Clear Creek, likely contributes some water to the basin-fill aquifer. Of particular interest is the subsurface flow through weathered and fractured bedrock between the canyons. Previous reports have suggested that the granitic rocks and metamorphic rocks exposed in the mountains are poorly permeable (Worts and Malmberg, 1966, p. 7; Arteaga and Durbin, 1978, p. 12). Estimates of hydraulic conductivity of the fractured metamorphic rocks indicate that where fractures are open (for example, at test hole Kings-2), the rocks are highly permeable and could transmit considerable subsurface flow. Elsewhere, fractured metamorphic rocks could have sufficient permeability to provide additional subsurface flow to the basin-fill aquifer. Additional test holes in the fractured metamorphic rocks along the base of the mountains would help in applying the method of estimating subsurface flow described in this report to the entire perimeter of Eagle Valley.

Estimates of Subsurface Flow Using Chloride-Balance Method

An independent estimate of subsurface flow beneath each canyon was obtained using the chloride-balance method described by Dettinger (1989). The method assumes that all chloride in ground water reached the watershed from precipitation and dry fallout in the mountains. The method requires that the average annual volume of precipitation and surface runoff for each watershed are known and assumes a balance between chloride deposited from the atmosphere and chloride that exits the canyon, either as surface runoff or as subsurface flow. Subsurface flow from the canyon (modified from Dettinger, 1989, p. 59) can be estimated as:

$$Q_s = \frac{Q_p(C_p)}{C_s} - \frac{Q_r(C_r)}{C_s}, \qquad (8)$$

where Q_s is subsurface flow, in acre-feet per year;

C_s is average chloride concentration in ground water, in milligrams per liter;

Q_p is average annual volume of precipitation, in acre-feet per year;

C_p is average chloride concentration of precipitation, in milligrams per liter;

Q_r is average surface runoff, in acre-feet per year; and

C_r is average chloride concentration of surface runoff, in milligrams per liter.

Table 6. Estimates of subsurface flow beneath Vicee, Ash, and Kings Canyons, Carson City, Nevada, using Darcy's law

[Location of hydrogeologic sections shown in fig. 2. Symbols: <, less than; --, not applicable]

Canyon	Lithology	Saturated area of section [1] (square feet)	Water-table gradient (foot per foot)	Geometric-mean hydraulic conductivity [2] (feet per day)	Subsurface flow [3] (acre-feet per year)
Vicee	Clayey sand	32,300	0.10	0.54	15
	Fine sand	62,700	.10	3.3	173
	Basin-fill sediments (rounded)	**95,000**	--	--	**190**
	Unweathered bedrock	36,900	.10	.91	28
	Weathered bedrock or bedrock with sediment-filled fractures.	57,100	.10	1.2	57
	Bedrock (rounded)	**94,000**	--	--	**80**
	Total (rounded, nearest hundred)				**300**
Ash	Clay	36,100	.08-.14	.03	1
	Clayey sand	43,100	.08-.14	.32	9-16
	Fine sand	19,600	.08-.14	2.8	37-64
	Sand and gravel	4,100	.08-.14	46	127-221
	Basin-fill sediments (rounded)	**103,000**	--	--	**170-300**
	Unweathered bedrock	9,000	.08-.14	.06	<1
	Weathered bedrock or bedrock with sediment-filled fractures.	27,000	.08-.14	4.2	76-133
	Bedrock (rounded)	**36,000**	--	--	**80-130**
	Total (rounded, nearest hundred)				**200-400**
Kings	Clay	26,000	.06	.02	<1
	Clayey sand	111,700	.06	.29	16
	Fine sand	28,300	.06	3.8	56
	Sand and gravel	40,000	.06	38	765
	Basin-fill sediments (rounded)	**206,000**	--	--	**840**
	Unweathered bedrock	20,000	.06	.51	5
	Weathered bedrock or bedrock with sediment-filled fractures.	90,000	.06	1.8	82
	Weathered bedrock or bedrock with open fractures.	45,000	.06	60	1,360
	Bedrock (rounded)	**155,000**	--	--	**1,450**
	Total (rounded, nearest hundred)				**2,300**
Total for Vicee, Ash, and Kings (rounded, nearest hundred)					**2,800-3,000**

[1] Saturated area for each lithologic unit, except for clay unit in Kings Canyon, estimated by multiplying total area of either basin-fill sediments or bedrock with the ratio of (a) the thickness of each lithologic unit penetrated by the test holes in each canyon (tables 4 and 5) to (b) the total thickness of basin-fill sediments or bedrock penetrated by the test holes. Area of clay in Kings Canyon estimated from hydrogeologic section in figure 7C.

[2] Geometric-mean hydraulic conductivities from tables 4 and 5.

[3] Subsurface flow for each lithologic unit computed by substituting values in columns 3-5 into equation 1 in text. Total flow in each canyon is sum of flows computed with equation 3 in text for each lithologic unit and rounded to nearest 100 acre-feet per year.

Average annual volumes of precipitation and surface runoff are listed in table 7, along with chloride concentrations in precipitation, surface runoff, and ground water. A tributary enters Kings Canyon Creek between the gaging station and the hydrogeologic section about 0.8 mi downstream. Estimated surface runoff from this tributary is about 300 acre-ft/yr assuming that 18 percent of annual precipitation becomes surface runoff, as in Kings Canyon (table 9). Although flow from the tributary adds surface runoff to Kings Canyon Creek upstream from the hydrogeologic section, water from Kings Canyon Creek and the tributary infiltrates into the ground between the gaging station and the section. Infiltration between the gaging station and the hydrologic section has not been measured, but was estimated to be about 800 acre-ft/yr (assuming a hydraulic conductivity of 8 ft/d for the streambed sediments, an average width of 3 ft, and a vertical gradient of 1 ft/ft). Thus, with an average annual flow of 1,700 acre-ft/yr of the Kings Canyon gage (table 10), surface runoff near the hydrogeologic section probably averages about 1,200 acre-ft/yr (that is, 1,700 acre-ft/yr plus 300 acre-ft/yr, minus 800 acre-ft/yr).

Subsurface flow based on chloride-balance calculations is about 400 acre-ft/yr beneath Vicee Canyon; 200 to 500 acre-ft/yr beneath Ash Canyon; and 600 to 1,000 acre-ft/yr beneath Kings Canyon (table 7). The estimates of subsurface flow beneath Vicee and Ash Canyons are about the same as that determined by calculating flow using Darcy's law (table 6). The estimate for Kings Canyon, however, is less than half that calculated using Darcy's law. Although these two independent methods of calculation produce somewhat different values for subsurface flow, they both indicate more flow beneath Kings Canyon than beneath either Vicee or Ash Canyons. Both methods indicate that subsurface flow into Eagle Valley is greater than previous estimates.

Table 7. Estimates of subsurface flow beneath Vicee, Ash, and Kings Canyons, Carson City, Nevada, using chloride-balance method

[Flow volumes rounded to nearest 100 acre-feet; chloride concentrations rounded to nearest 0.1 milligram per liter]

Canyon	Average annual precipitation,[1] Q_p (acre-feet)	Average annual surface runoff at hydrogeologic section,[2] Q_r (acre-feet)	Chloride concentration (milligrams per liter)			Estimated average annual subsurface flow,[6] Q_s (acre-feet)
			Precipitation,[3] C_p	Surface runoff,[4] C_r	Ground water,[5] C_s[6]	
Vicee . . .	2,400	200	0.4	0.4-1.0	2.0	400
Ash.	8,300	2,600	.4	.4-1.0	4.6	200-500
Kings . . .	6,700	1,200	.4	.4-1.0	2.3	600-1,000

[1] Average annual precipitation from map by Arteaga and Durbin (1978, p. 16).

[2] Estimates of average annual surface runoff for the three canyons are based on streamflow measurements at continuous-record gaging stations operated on Ash and Kings Canyon Creeks from July 1976 through September 1993, North Kings Canyon Creek from March 1989 through September 1993, and Vicee Canyon Creek from December 1982 through September 1985 and September 1989 through September 1993. Average annual flow at each canyon was adjusted to long-term average flow of West Fork Carson River at Woodfords, Calif. (period of record from October 1900 to May 1907, 1910-11, and October 1938 through September 1993), by dividing the average annual flow at each canyon with the ratio of (a) average annual flow of West Fork Carson River during the period of record at each canyon to (b) the long-term average annual flow of West Fork Carson River. Estimate of Kings Canyon flow includes 1,700 acre-feet per year at gaging station plus 300 acre-feet per year from tributary inflow, less 800 acre-feet per year stream loss between gaging station and hydrogeologic section.

[3] Chloride concentrations in precipitation include dry fallout. Estimate of 0.4 milligram per liter is an average from 74 sampling sites in Nevada (Dettinger, 1989, p. 63), and includes samples collected in and near Carson City. Chloride concentration for 24 analyses from five precipitation sites sampled December 1992 through October 1993 in mountains surrounding Spanish Springs Valley north of Reno, Nev., averaged 0.38 milligram per liter (David L. Berger, U.S. Geological Survey, written commun., 1995). Value of 0.4 milligram per liter is assumed to be representative of amount of chloride deposited from atmosphere in each canyon.

[4] Chloride concentration in surface runoff is based on water samples collected weekly during March 1995 from Ash and Kings Canyon Creeks by Carson City Utilities Department. Chloride was analyzed using argentometric method with a detection limit of 1 milligram per liter (Kelvin Ikehara, Carson City Wastewater/Reclamation Plant, Carson City, Nev., written commun., 1995). All samples collected during March 1995 have chloride concentrations less than 1 milligram per liter; thus, a range of 0.4 to 1 milligram per liter was used in the calculations.

[5] Chloride concentrations in ground water were determined from a water sample collected during November 1994 from each of six monitoring wells. Chloride concentration in ground water from the shallow well at test hole Ash-1 in Ash Canyon is about 4.6 milligrams per liter. Chloride concentration in ground water from the shallow and deep wells at test hole Kings-2 in Kings Canyon is 2.4 and 2.2 milligrams per liter, respectively, and chloride concentration in ground water from the shallow and deep wells at test hole VC-6 in Vicee Canyon is 2.7 and 1.3 milligrams per liter, respectively. Chloride concentration of 10 milligrams per liter is reported for water from test hole VC-7 in Vicee Canyon; this well is near a road where salt is applied during winter months.

[6] Computed by substituting values in columns 2-6 into equation 8 in text.

Estimates of subsurface flow using the chloride-balance method are based on the assumption that no chloride is added from sources other than precipitation and dry fallout. Weathering of the metamorphic rocks to clays, infiltration of effluent from septic systems of private homes, and salting of roads during the winter in Vicee and Kings Canyons could contribute minor quantities of chloride to ground water upgradient from the wells used for sampling. If about half of the 2.3 mg/L of chloride dissolved in ground water beneath Kings Canyon is from any of these additional sources, the estimated subsurface flow beneath the canyon would be 1,300-2,000 acre-ft/yr. Thus, the estimates for Vicee and Kings Canyons, where potential sources of chloride exist, represent minimum values.

Chloride concentrations of ground water are based on one sample taken at the end of an extended period of below-average precipitation (from 1987 through summer 1994). Relatively small changes in low concentrations of chloride in ground water or surface runoff would greatly affect the estimates of subsurface flow using this method. Because much of the recharge to ground water in the mountains is thought to occur during spring snowmelt, chloride concentrations may change seasonally. The chloride concentrations listed in table 7 and used in the chloride-balance method may not represent average concentrations from precipitation and dry fallout, surface runoff, or subsurface flow within each canyon. The number of samples available from wells and streams is insufficient to determine whether seasonal trends in chloride concentrations exist. Thus, to obtain a better estimate of subsurface flow beneath the canyons, additional chloride analyses, at lower detection limits, are needed. Such analyses for surface runoff, ground water, and precipitation, are being done during the second phase of this project.

COMPARISON OF FLOW ESTIMATES WITH RECHARGE ESTIMATED FROM MAXEY–EAKIN METHOD

The most widely used approach to estimate recharge to basin-fill aquifers in Nevada has been the Maxey–Eakin method, which was developed for basins in eastern Nevada. The method was designed to provide a reconnaissance estimate of recharge from infiltration of precipitation and streamflow for an entire basin and was not intended to estimate recharge from individual watersheds surrounding a basin. The error associated with using the Maxey–Eakin method to estimate recharge in individual watersheds, or in regions like Eagle Valley where streamflow leaves the basin and precipitation is greater than in eastern Nevada, is unknown.

In estimating recharge from each canyon using the Maxey–Eakin method, both the percentages of recharge for given precipitation intervals originally derived by Maxey and Eakin (1949, p. 40) and those modified by Worts and Malmberg (1966, p. 15) gave similar results. These percentages for selected intervals of annual precipitation rate are summarized in table 8, along with estimates of the volume of precipitation within each interval and the estimated recharge.

Estimates of recharge by applying the Maxey–Eakin method to the three watersheds are about 500 acre-ft/yr for Vicee Canyon, about 2,000 acre-ft/yr for Ash Canyon, and 1,500 acre-ft/yr for Kings Canyon. Much of the difference between Vicee and Ash Canyons results from Ash Canyon having a larger drainage area. The percentage of total precipitation that this recharge represents ranges from about 21 percent in Vicee Canyon to 24 percent in Ash Canyon (table 8). This uniform percentage results from assuming recharge to ground water is a function only of precipitation, and from the similar distribution of land-surface altitude within the three watersheds, all which have an average annual precipitation exceeding 20 in.

Estimates of recharge using the Maxey–Eakin method differ from estimates of subsurface flow beneath each canyon (tables 6, 7, and 8):

	Subsurface		Recharge
Canyon	Darcy's law	Chloride-Balance method	Maxey-Eakin method
Vicee. .	300	400	500
Ash . . .	200-400	200-500	2,000
Kings .	2,300	600-1,000	1,500

Table 8. Recharge to Eagle Valley from watersheds of Vicee, Ash, and Kings Canyons, Carson City, Nevada, as estimated by the Maxey–Eakin method

[Symbol: --, range not present]

Precipitation (inches per year)	Total precipitation that becomes recharge to basin-fill aquifer (percent)		Annual volume of precipitation in watershed above hydrogeologic section [1] (acre-feet)			Average annual recharge above hydrogeologic section [2] (acre-feet)		
	As presented by Maxey and Eakin (1949, p. 40)	As revised by Worts and Malmberg (1966, p. 15)	Vicee Canyon	Ash Canyon	Kings Canyon	Vicee Canyon	Ash Canyon	Kings Canyon
>20	25	25	2,000	8,000	5,100	500	2,000	1,300
15-20	15	10	300	200	1,300	40	30	200
12-15	7	10	100	100	300	7	7	20
8-12	3	3	--	--	--	--	--	--
<8	0	0	--	--	--	--	--	--
Totals (rounded, nearest hundred)			**2,400**	**8,300**	**6,700**	**500**	**2,000**	**1,500**
Percentage of average annual precipitation that is recharge (rounded)...						**21**	**24**	**22**

[1] Calculated from map by Arteaga and Durbin (1978, p. 16). Volumes, including totals, are rounded to nearest 100 acre-feet.

[2] Estimated by applying percentages of total precipitation in column 2 (Maxey and Eakin) to annual volumes of precipitation in columns 4-6 (rounded to nearest 100 acre-feet for values greater than 100 acre-feet and to one significant figure for values less than 100 acre-feet). Totals also are rounded to nearest 100 acre-feet. Estimates using revised percentages in column 3 (Worts and Malmberg) are the same except for Kings Canyon, which is about 60 acre-feet less.

the most notable difference is in Ash Canyon, where the estimate of recharge from the Maxey–Eakin method is 1,500 to 1,800 acre-ft/yr greater than the estimated subsurface flow from Darcy's law or the chloride-balance method. However, the Maxey–Eakin method includes that part of surface runoff from the mountains that infiltrates into the ground as the streams cross Eagle Valley. Therefore, results from the Maxey–Eakin method cannot be directly compared to estimates of subsurface flow in tables 6 and 7.

In Vicee Canyon, recharge estimated from the Maxey–Eakin method is 100–200 acre-ft/yr greater than the estimated subsurface flow using the chloride-balance method or Darcy's law. However, all the surface runoff from Vicee Canyon (table 7; 200 acre-ft/yr) is lost to infiltration and probably recharges the basin-fill aquifer below the hydrogeologic section; thus, recharge estimated by the Maxey–Eakin method generally agrees with estimates of subsurface flow plus streamflow loss.

Surface runoff from Ash and Kings Canyons is used for irrigation. Recharge from the application of surface runoff on agricultural fields and seepage losses from natural channels and irrigation ditches has been estimated to be 46 percent of the surface runoff (Arteaga and Durbin, 1978, p. 25). Applying this percentage to annual surface runoff from Ash Canyon (table 7; 2,600 acre-ft/yr) yields an estimate of 1,200 acre-ft/yr recharge to Eagle Valley from infiltration of Ash Canyon streamflow. Adding this value to the estimated subsurface flow from Darcy's law and the chloride-balance method results in estimated recharge of 1,400 to 1,700 acre-ft/yr, which is in general agreement with the recharge estimated by the Maxey–Eakin method (table 8).

In Kings Canyon, recharge estimated from the Maxey–Eakin method is 500-900 acre-ft/yr more than that estimated from the chloride-balance method and 800 acre-ft/yr less than that estimated from Darcy's law. If 46 percent (550 acre-ft/yr) of the surface runoff from Kings Canyon (table 7; 1,200 acre-ft/yr) recharges the basin-fill aquifer downcanyon from the hydrogeologic section, then recharge from the Maxey–Eakin method is in general agreement with that from the chloride-balance method, but is 1,200 acre-ft/yr less than that estimated using Darcy's law. Thus, the Maxey-Eakin method could underestimate recharge in areas where bedrock is highly permeable.

In contrast to relatively uniform estimates of recharge based on the Maxey–Eakin method, surface runoff and estimated subsurface flow differ greatly from one canyon to another. Surface runoff from each canyon as a percentage of average annual volume of precipitation ranges from 8 percent in Vicee Canyon to 31 percent in Ash Canyon (table 9). Subsurface flow as a percentage of average annual precipitation ranges from 12 to 17 percent in Vicee Canyon, 2 to 6 percent in Ash Canyon, and 9 to 34 percent in Kings Canyon. The greater range in the percentage of subsurface flow beneath Kings Canyon results from differences in estimates of flow using Darcy's law and the chloride-balance method. This is in part due to uncertainty in the extent of permeable metamorphic rocks that may underlie the Kings Canyon watershed. Greater subsurface flow beneath Kings Canyon than either Vicee or Ash Canyons is possible because metamorphic rocks underlie much of the watershed and because a major fault system that extends through Kings Canyon (fig. 2) could produce zones of greater permeability in the metamorphic rocks—similar to permeability found in test hole Kings-2. Recharge estimated by the Maxey-Eakin method for each watershed is similar to estimates of infiltration of surface runoff combined with estimates of subsurface flow for Vicee and Ash Canyons, but could be underestimated for Kings Canyon where bedrock is more permeable.

ESTIMATES OF WATER YIELD

A water yield for each canyon was estimated by adding surface runoff to estimated subsurface flow. The resulting estimates of water yield (table 10) can be directly compared to estimates reported by Arteaga and Durbin (1978, p. 12-15). Adding estimates of surface runoff to subsurface flow from Darcy's law or from the chloride-balance method produces estimated water yields of 500 to 600 acre-ft/yr for Vicee Canyon; 2,800 to 3,100 acre-ft/yr for Ash Canyon; and 1,800 to 3,500 acre-ft/yr for Kings Canyon (table 10). These yields are greater than those estimated by Arteaga and Durbin (1978, p. 11), because their estimates do not include subsurface flow. Estimates of water yield reported by Arteaga and Durbin (1978) for other watersheds contributing to the Eagle Valley aquifer are based on estimated yields from Ash and Kings Canyons, thus, the reported water yields for the other watersheds also may be underestimated.

Table 9. Average annual precipitation per square mile of drainage area and percentage of precipitation that is surface runoff, subsurface flow, and water yield for Vicee, Ash, and Kings Canyons, Carson City, Nevada

[All values apply to watersheds above hydrogeologic sections shown in fig. 2]

Canyon	Average annual precipitation [1] (acre-feet)	Average annual precipitation (percent)			
		Surface runoff	Subsurface flow	Water yield [2]	Water yield from Arteaga and Durbin (1978)
Vicee .	2,400	8	12-17	21-25	12
Ash. . .	8,300	31	2-6	34-37	31
Kings .	6,700	18	9-34	27-52	18

[1] Average annual precipitation from map by Arteaga and Durbin (1978, p. 16). Values are rounded to nearest 100 acre-feet.

[2] Percentages are rounded to nearest whole percent. Water yield is the sum of average annual surface runoff and subsurface flow (estimated using Darcy's law and chloride-balance method), but total of percentages for surface runoff and subsurface flow may not equal percentage for water yield because of rounding.

Table 10. Estimates of average annual precipitation, surface runoff, subsurface flow, and water yield for watersheds in Vicee, Ash, Kings Canyons, Carson City, Nevada

[Values rounded to nearest 100 acre-feet. Symbol: --, no data available]

Canyon	Drainage area [1] (square miles)	Average annual precipitation [2] (acre-feet)	Average annual surface runoff [3] (acre-feet)	Annual subsurface flow [4] (acre-feet)	Average annual water yield (acre-feet)	Previous estimate of average annual water yield [5] (acre-feet)
Vicee	1.9	2,400	200	300-400	500-600	300
Ash.	5.2	8,300	2,600	200-500	2,800-3,100	2,600
Kings, at stream gaging station	4.1	5,400	1,700	--	--	1,200
Kings, at hydrogeologic section	5.3	6,700	[6]1,200	600-2,300	1,800-3,500	--

[1] Drainage area for Kings Canyon watershed at streamflow gaging station and at hydrogeologic section listed separately; Vicee Canyon includes area 14 from Arteaga and Durbin (1978, p. 14).

[2] Average annual precipitation from map by Arteaga and Durbin (1978, p. 16).

[3] Estimates of average annual surface runoff for three canyons are based on streamflow measurements at continuous gaging stations operated on Vicee Canyon Creek from December 1982 through September 1985 and September 1989 through September 1993, on Ash and Kings Canyon Creeks from July 1976 through September 1993, and on North Kings Canyon Creek from March 1989 through September 1993. Average annual flow at each canyon was adjusted to long-term average flow of West Fork Carson River at Woodfords, California (period of record is October 1900 to May 1907, 1910-11, and October 1938 through September 1993), by dividing average annual flow at each canyon with the ratio of (a) average annual flow of West Fork Carson River during period of record at each canyon to (b) long-term average annual flow of West Fork Carson River. Estimate of Kings Canyon flow at gaging station includes mainstem flow (1,300 acre-feet per year) plus water diverted from North Kings Canyon by Carson City (400 acre-feet per year).

[4] Subsurface flow from Darcy's law (table 6) and chloride-balance method (table 7).

[5] Previous estimate of water yield for each canyon was reported by Arteaga and Durbin (1978, p. 14); Kings Canyon includes flow in North Kings Canyon Creek.

[6] Additional tributary flow enters Kings Canyon Creek below gaging station and is estimated at 300 acre-feet per year; however, stream loses an estimated 800 acre-ft/yr through the reach between gaging station and hydrogeologic section. Thus, surface runoff at the hydrogeologic section is estimated to be about 1,200 acre-feet per year.

SUMMARY AND CONCLUSIONS

Continued growth of Carson City, the capital of Nevada, is increasing the demand for municipal water. Carson City covers much of the valley floor in Eagle Valley, which lies along the east side of the Carson Range in northwest Nevada. The Carson Range is composed of granitic and metamorphic rocks that have been uplifted along numerous faults. The basin-fill sediments beneath Eagle Valley form the principal aquifer for ground-water supply. Flow in the basin-fill aquifer is generally from the Carson Range eastward through the valley to the Carson River.

The U.S. Geological Survey, in cooperation with Carson City Utilities Division, began work in 1994 to more accurately estimate recharge to Eagle Valley. The purpose of this study is to estimate subsurface flow beneath Vicee, Ash, and Kings Canyons from physical measurements. These canyons are major watersheds entering Eagle Valley from the Carson Range. Test holes were drilled along a section across each canyon. During drilling, the weathered and fractured zones in bedrock underlying the basin-fill sediments were found to be permeable. Flow through these zones is included in the reported estimates of subsurface flow to Eagle Valley. Subsurface flow was determined using Darcy's law after measuring the hydraulic (water-table) gradient along each canyon, estimating the saturated thickness of the basin-fill sediments and the weathered fractured intervals in bedrock, and determining the hydraulic conductivity of the sediments and bedrock.

The water-table gradient in Vicee Canyon is about 0.10 ft/ft. On the basis of water levels from only two wells, the gradient in Ash Canyon is estimated to range from 0.08 to 0.14 ft/ft. The gradient averages 0.06 ft/ft beneath Kings Canyon. Beneath the hydrogeologic sections, the thickness of saturated basin-fill sediments is about 60 ft in Vicee Canyon, as much as 175 ft in Ash Canyon, and from 100 to 180 ft in Kings

Canyon. Thickness of weathered and fractured bedrock is estimated to be about 50 ft in Vicee Canyon, about 30 ft in Ash Canyon, and about 70 ft in Kings Canyon. Hydraulic conductivities determined from six slug tests in wells screened in the basin-fill sediments are generally greater than those determined from four slug tests in wells screened in the weathered and fractured bedrock. Except for one value of 0.3 ft/d, hydraulic conductivities of basin-fill sediments range from 3 to 20 ft/d. In contrast, hydraulic conductivities of weathered and fractured rocks are between 0.5 and 1 ft/d, except for one value of 30 ft/d in fractured metamorphic rocks beneath Kings Canyon.

The distribution of hydraulic conductivity within each unit was estimated from borehole resistivity logs, which were correlated to hydraulic conductivities determined from slug-test analyses. The basin-fill sediments and weathered or fractured bedrock were divided into lithologic units on the basis of hydraulic conductivity. A geometric-mean hydraulic conductivity was calculated for each lithologic unit. In the basin-fill sediments, the geometric-mean hydraulic conductivity ranges from 0.02 to 0.09 ft/d for the finer grained sediments and from 34 to 46 ft/d for the coarser grained sediments. In bedrock, hydraulic conductivity ranges from 0.06 to 0.91 ft/d for unweathered bedrock or bedrock with closed fractures; from 1.2 to 4.2 ft/d for weathered granitic rocks or bedrock with sediment-filled fractures; and 60 ft/d for open-fractured metamorphic rocks. These results indicate that the metamorphic rocks, where fractures are open, have greater permeability than the weathered granitic rocks.

Subsurface flow estimated by applying Darcy's law is about 300 acre-ft/yr beneath Vicee Canyon, 200 to 400 acre-ft/yr beneath Ash Canyon, and 2,300 acre-ft/yr beneath Kings Canyon. Estimates of subsurface flow based on the limited chloride data are about 400 acre-ft/yr beneath Vicee Canyon, 200 to 500 acre-ft/yr beneath Ash Canyon, and 600 to 1,000 acre-ft/yr beneath Kings Canyon. Although the chloride-balance method produces a lower estimate of subsurface flow beneath Kings Canyon, the estimates are similar in that more subsurface flow is calculated for Kings Canyon than for either Vicee or Ash Canyons. The estimates of subsurface flow are in addition to infiltration of streamflow in the valley, which is considered the principal source of recharge in Eagle Valley.

Estimates of recharge from the Maxey–Eakin method, applied to the individual watersheds, are 500 acre-ft/yr for Vicee Canyon, 2,000 acre-ft/yr for Ash Canyon, and 1,500 acre-ft/yr for Kings Canyon (table 8). The values represent 21 to 24 percent of the estimated annual average volume of precipitation in each watershed, and include infiltration of surface runoff that becomes recharge on the valley floor and subsurface flow from the canyons. Recharge estimates using the Maxey–Eakin method are similar to estimates of infiltration of surface runoff added to estimates of subsurface flow for Vicee and Ash Canyons, but could be underestimated for Kings Canyon where bedrock is more permeable.

Surface runoff from the canyons was added to the estimates of subsurface flow to estimate water yield from each canyon. Surface runoff from the canyons near the hydrogeologic sections averages 200 acre-ft/yr for Vicee Canyon; 2,600 acre-ft/yr for Ash Canyon; and 1,200 acre-ft/yr for Kings Canyon (table 10). Therefore, the total water yield (surface runoff, plus subsurface flow estimated from Darcy's law and the chloride-balance method) is 500 to 600 acre-ft/yr for Vicee Canyon, 2,800 to 3,100 acre-ft/yr for Ash Canyon, and 1,800 to 3,500 acre-ft/yr for Kings Canyon. These rates are greater than previous estimates of water yield for the canyons.

Metamorphic rocks, which are exposed over large areas surrounding Eagle Valley, have been considered poorly permeable. Results of this study indicate that the weathered and fractured zones in metamorphic rocks common in Kings Canyon can be highly permeable and could conduct large quantities of subsurface flow from the mountains to the basin-fill aquifer in Eagle Valley. Results also indicate that a greater proportion of precipitation moves through the subsurface in Kings Canyon than through either Vicee or Ash Canyons. Estimates of subsurface flow from other watersheds would be useful in estimating the water yield for the mountainous regions surrounding Eagle Valley that have different geology and different quantities of precipitation.

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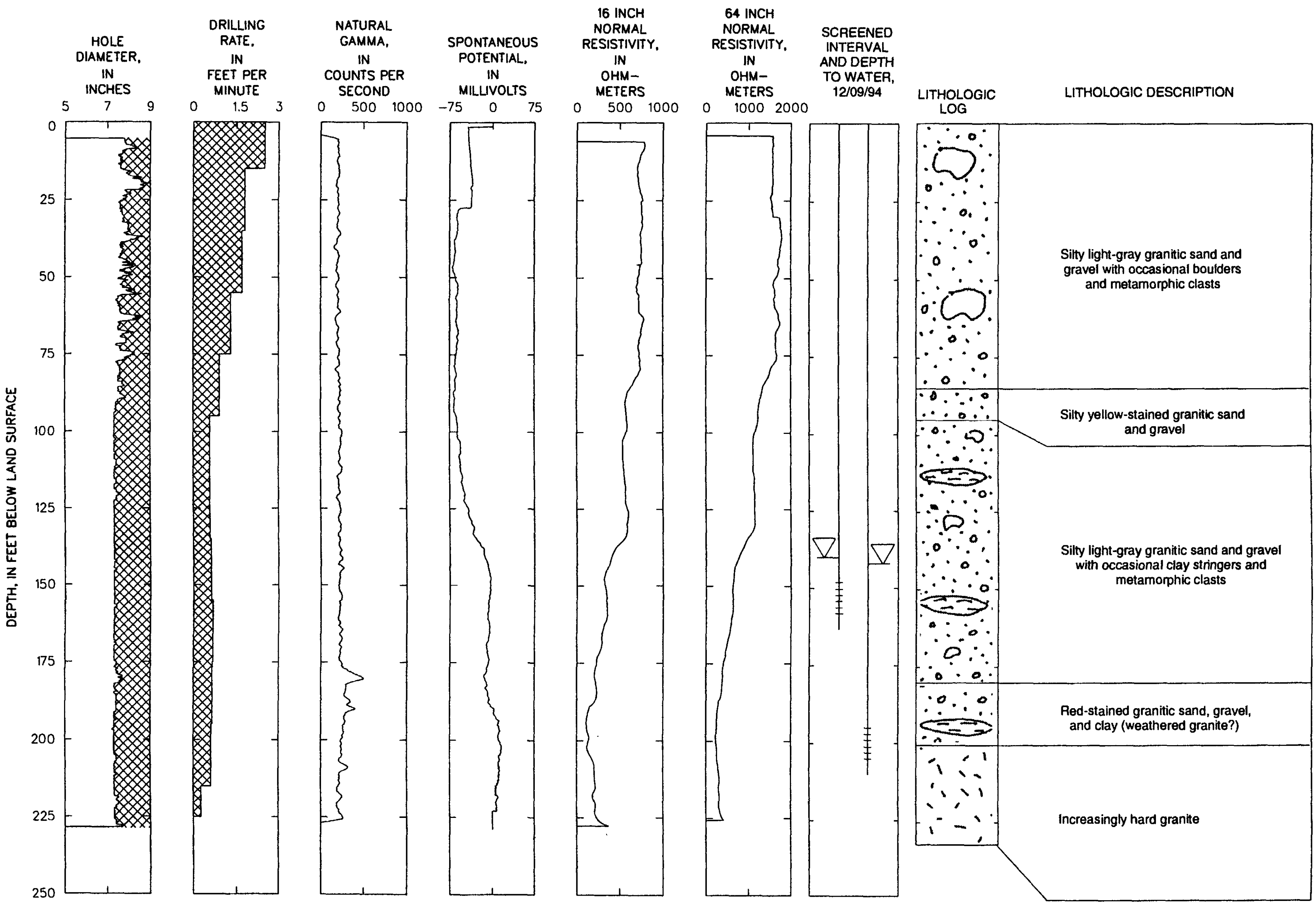
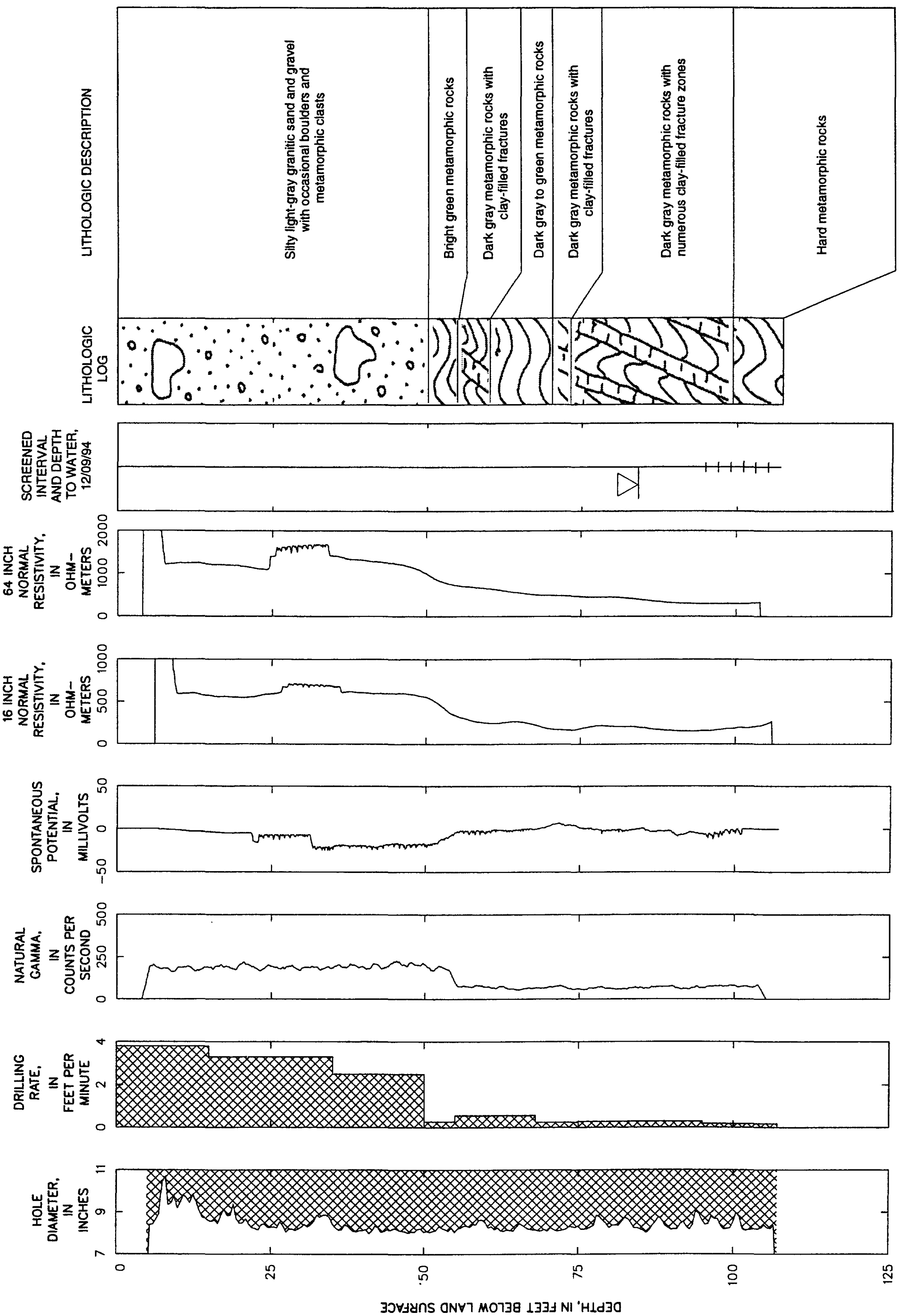
Appendixes

Note: This section summarizes data for wells in Vicee, Ash, and Kings Canyons, Carson City, Nev. Appendix 1 presents borehole geophysical and lithologic logs, screened intervals, and depth to water, December 9, 1994. Appendix 2 lists well identifications, land-surface altitudes, casing diameters, well depth and screened interval, lithology of the hydrogeologic units adjacent to the screened interval, and water levels measured in wells up to December 29, 1994. Appendix 3 includes diagrams and graphs depicting well-construction information, water-level response to quickly lowering and raising a cylinder in each well, and analyses of the water-level response using methods of Cooper and others (1967) and Bouwer and Rice (1976).

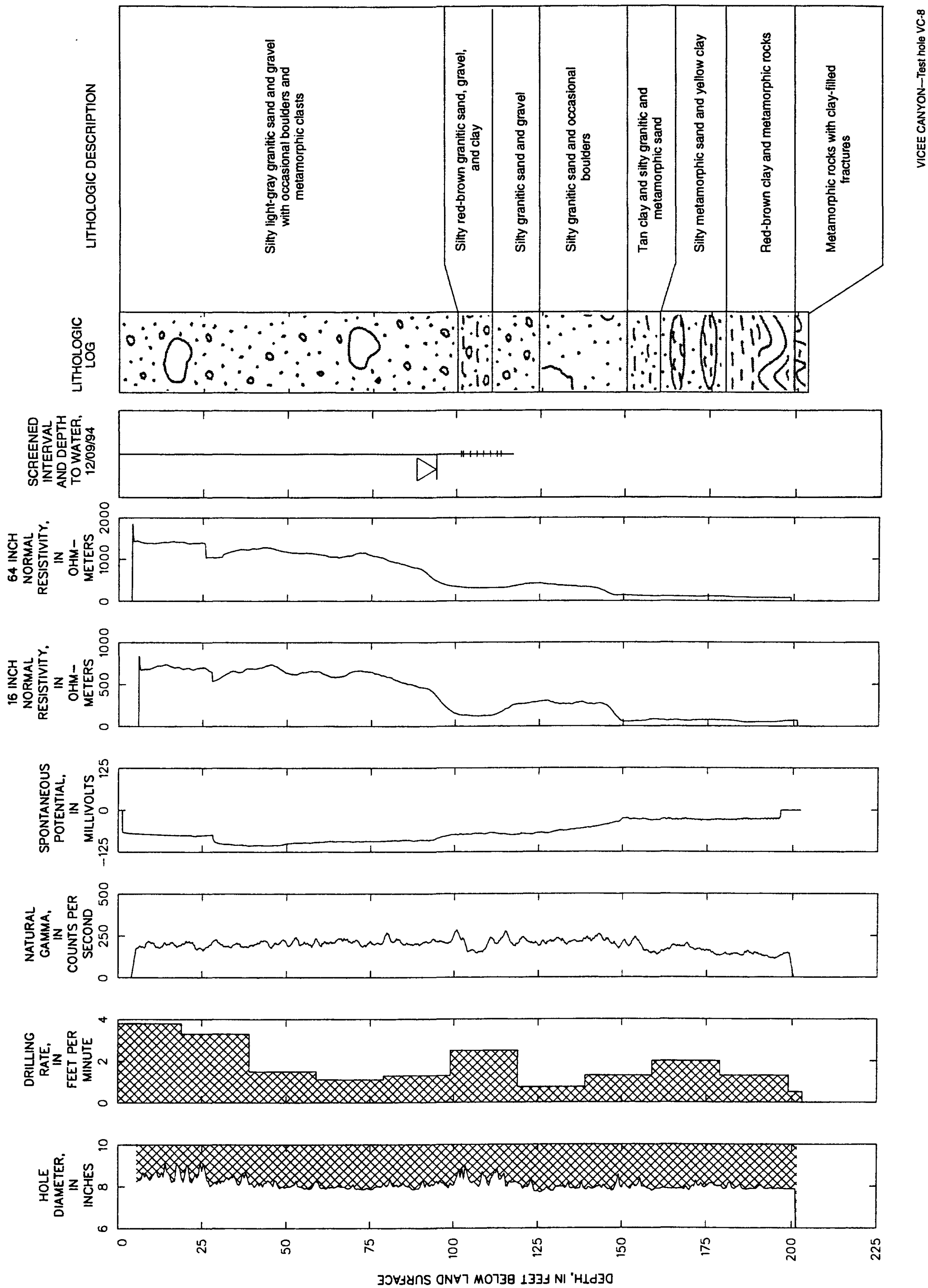
Appendix 1. Borehole geophysical and lithologic data

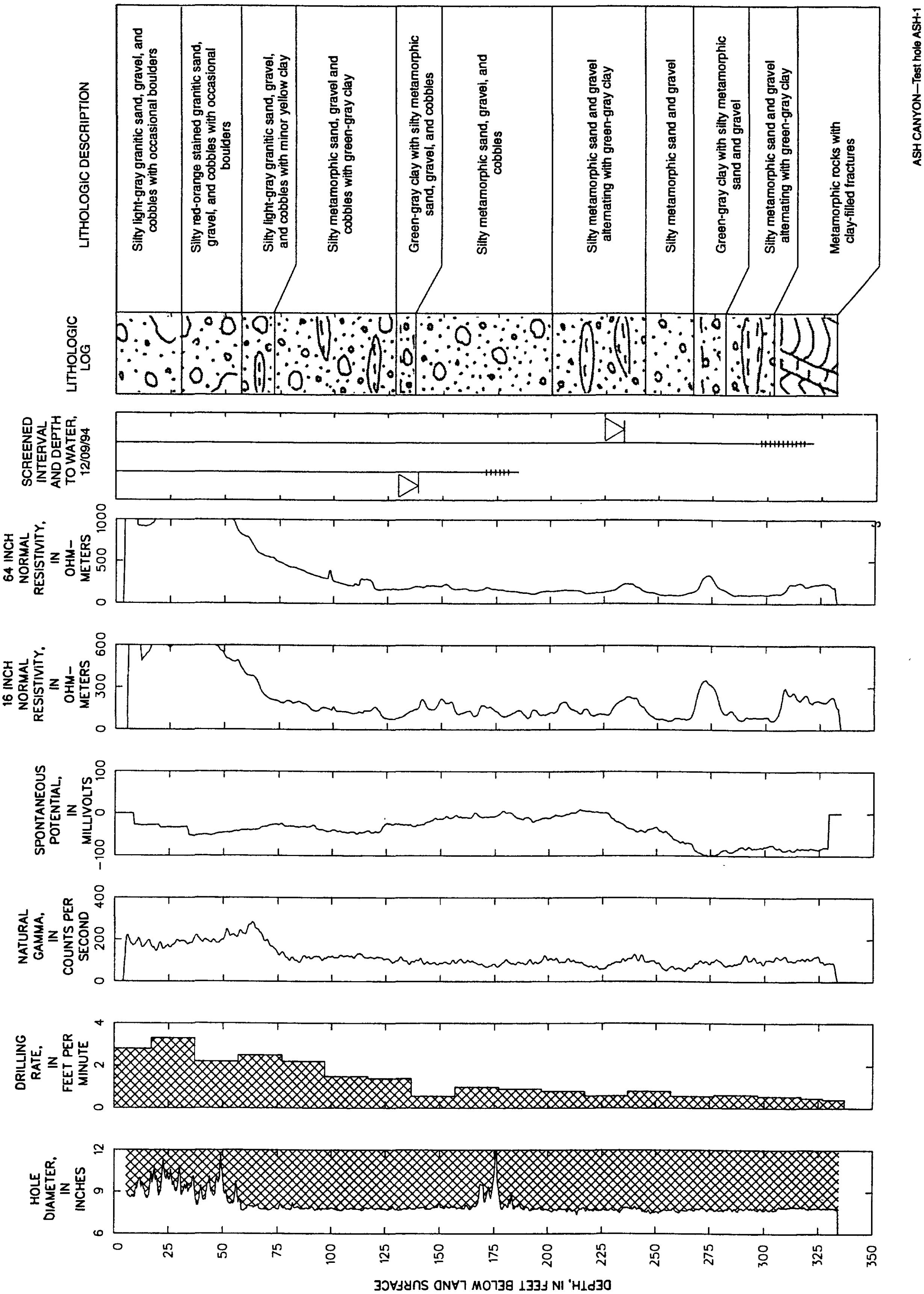


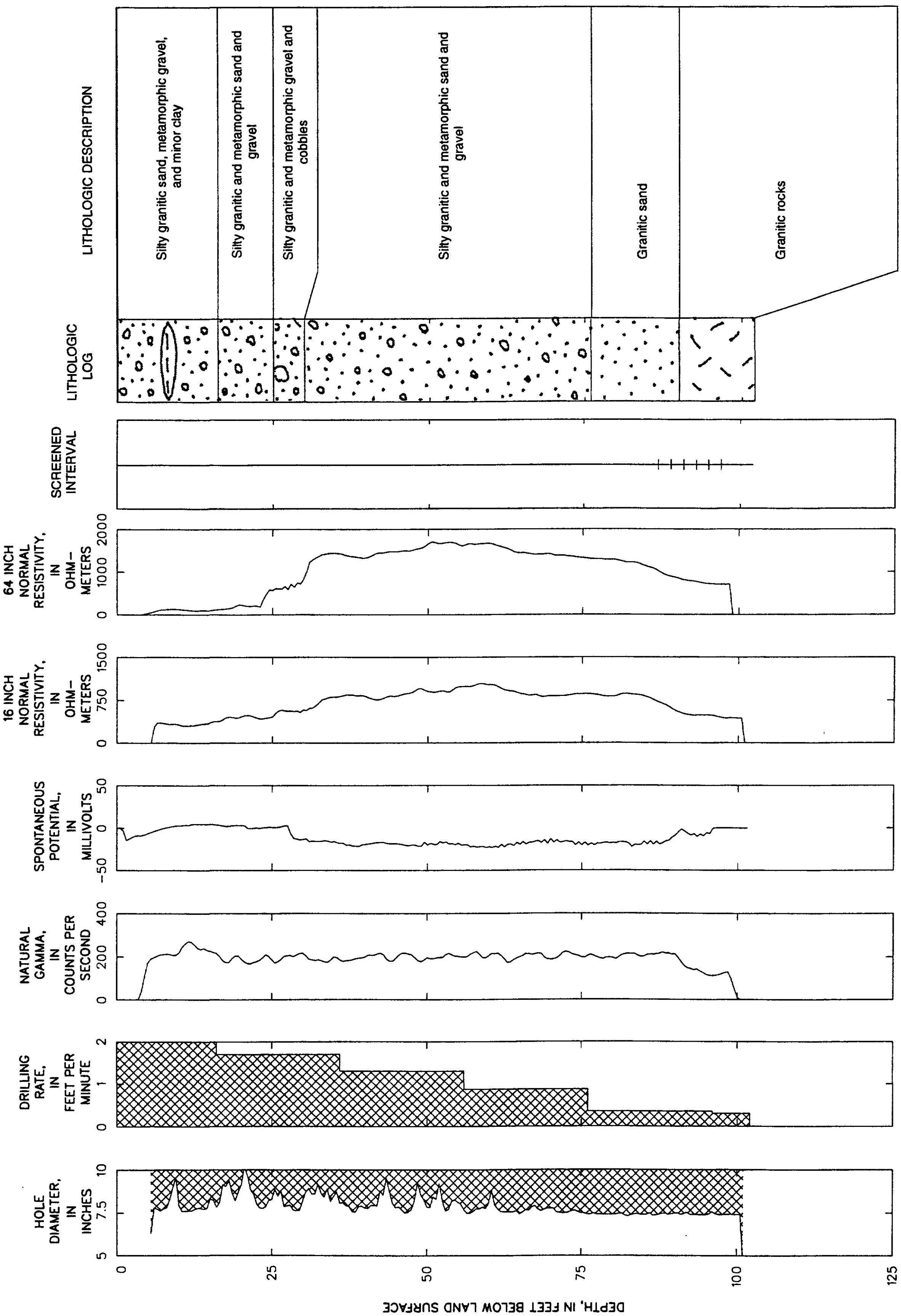
VICEE CANYON—Test hole VC-6



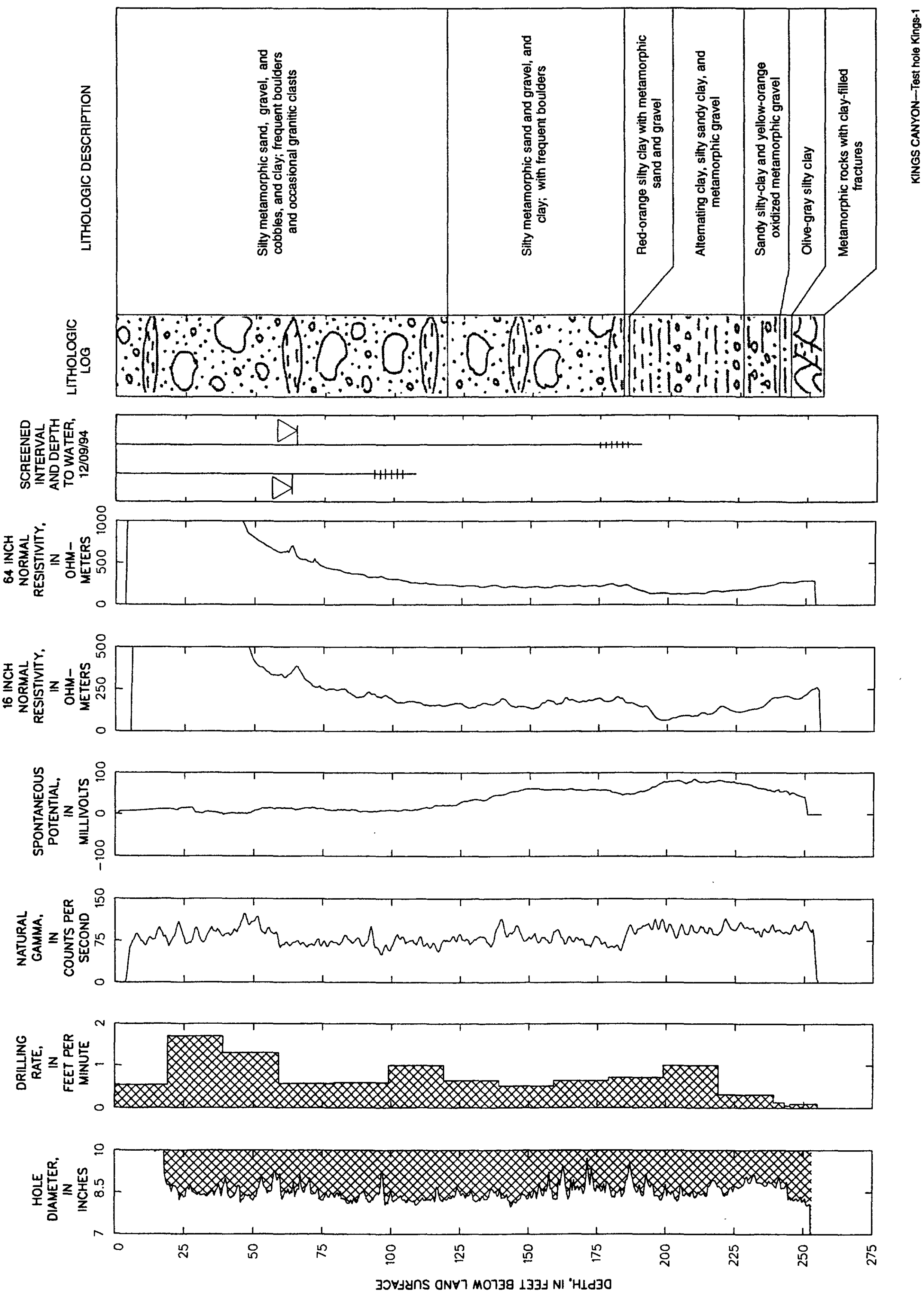
VICEE CANYON—Test hole VC-7

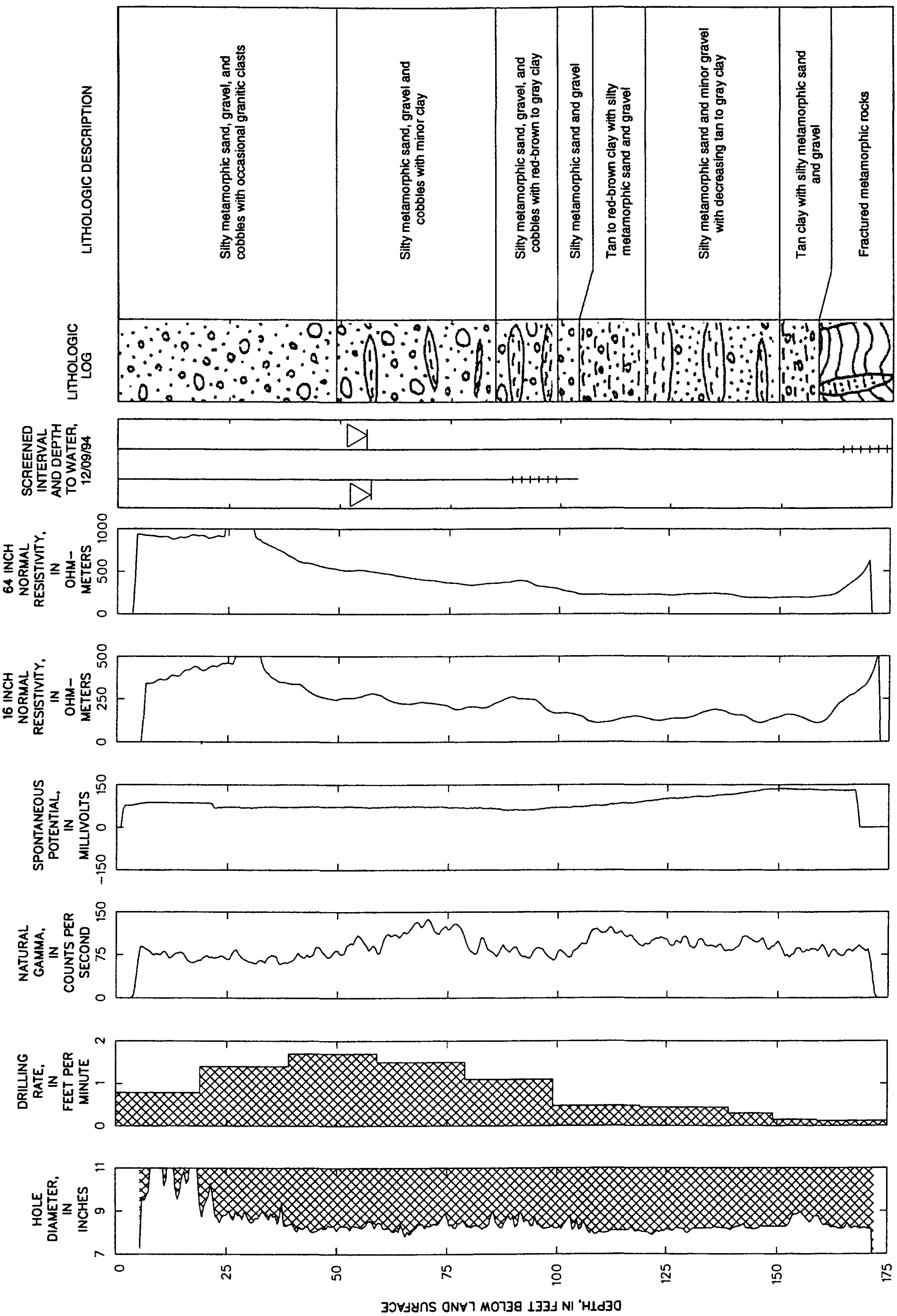

VICEE CANYON—Test hole VC-8
LITHOLOGIC DESCRIPTION
Silty light-gray granitic sand and gravel with occasional boulders and metamorphic clasts
Silty red-brown granitic sand, gravel, and clay
Silty granitic sand and gravel
Silty granitic sand and occasional boulders
Tan clay and silty granitic and metamorphic sand
Silty metamorphic sand and yellow clay
Red-brown clay and metamorphic rocks
Metamorphic rocks with clay-filled fractures
LITHOLOGIC LOG
SCREENED INTERVAL AND DEPTH TO WATER, 12/09/94
64 INCH NORMAL RESISTIVITY, IN OHM-METERS
0
1000
2000
16 INCH NORMAL RESISTIVITY, IN OHM-METERS
0
500
1000
SPONTANEOUS POTENTIAL, IN MILLIVOLTS
-125
0
125
NATURAL GAMMA, IN COUNTS PER SECOND
0
250
500
DRILLING RATE, IN FEET PER MINUTE
0
2
4
HOLE DIAMETER, IN INCHES
6
8
10
0
25
50
75
100
125
150
175
200
225
DEPTH, IN FEET BELOW LAND SURFACE


LITHOLOGIC DESCRIPTION
Silty light-gray granitic sand, gravel, and cobbles with occasional boulders
Silty red-orange stained granitic sand, gravel, and cobbles with occasional boulders
Silty light-gray granitic sand, gravel, and cobbles with minor yellow clay
Silty metamorphic sand, gravel and cobbles with green-gray clay
Green-gray clay with silty metamorphic sand, gravel, and cobbles
Silty metamorphic sand, gravel, and cobbles
Silty metamorphic sand and gravel alternating with green-gray clay
Silty metamorphic sand and gravel
Green-gray clay with silty metamorphic sand and gravel
Silty metamorphic sand and gravel alternating with green-gray clay
Metamorphic rocks with clay-filled fractures
LITHOLOGIC LOG
SCREENED INTERVAL AND DEPTH TO WATER, 12/09/94
64 INCH NORMAL RESISTIVITY, IN OHM-METERS
0
500
1000
16 INCH NORMAL RESISTIVITY, IN OHM-METERS
0
300
600
SPONTANEOUS POTENTIAL, IN MILLIVOLTS
−100
0
100
NATURAL GAMMA, IN COUNTS PER SECOND
0
200
400
DRILLING RATE, IN FEET PER MINUTE
0
2
4
HOLE DIAMETER, IN INCHES
6
9
12
0
25
50
75
100
125
150
175
200
225
250
275
300
325
350
DEPTH, IN FEET BELOW LAND SURFACE
ASH CANYON—Test hole ASH-1



ASH CANYON—Test hole ASH-2


HOLE DIAMETER, IN INCHES
7
8.5
10
DRILLING RATE, IN FEET PER MINUTE
0
1
2
NATURAL GAMMA, IN COUNTS PER SECOND
0
75
150
SPONTANEOUS POTENTIAL, IN MILLIVOLTS
−100
0
100
16 INCH NORMAL RESISTIVITY, IN OHM-METERS
0
250
500
64 INCH NORMAL RESISTIVITY, IN OHM-METERS
0
500
1000
SCREENED INTERVAL AND DEPTH TO WATER, 12/09/94
LITHOLOGIC LOG
LITHOLOGIC DESCRIPTION
Silty metamorphic sand, gravel, and cobbles, and clay; frequent boulders and occasional granitic clasts
Silty metamorphic sand and gravel, and clay; with frequent boulders
Red-orange silty clay with metamorphic sand and gravel
Alternating clay, silty sandy clay, and metamorphic gravel
Sandy silty-clay and yellow-orange oxidized metamorphic gravel
Olive-gray silty clay
Metamorphic rocks with clay-filled fractures
0
25
50
75
100
125
150
175
200
225
250
275
DEPTH, IN FEET BELOW LAND SURFACE
KINGS CANYON—Test hole Kings-1



KINGS CANYON—Test hole Kings-2

Appendix 2. Well location, construction, and water-level data

[Symbol: ?, interval is unknown]

Well (see fig. 4)	Latitude, longitude[1]	Local well number[2]	Altitude of land surface (feet)	Diameter of casing (inches)	Depth of well (feet)	Lithology and perforated interval (feet)	Water level	
							Feet below land surface	Date
VC-6 shallow	391105 1194811	N15 E19 12BBCB1	5181.5	2	163	basin-fill sediments 148-158	137.18	08-26-94
							137.98	10-05-94
							138.16	10-14-94
							138.33	10-21-94
							138.47	10-28-94
							138.91	11-10-94
							139.40	12-02-94
							139.59	12-09-94
							139.73	12-15-94
							140.01	12-29-94
VC-6 deep	391105 1194811	N15 E19 12BBCB2	5181.5	2	210	weathered granitic rocks 195-205	139.58	08-26-94
							140.34	10-05-94
							140.42	10-14-94
							140.67	10-21-94
							140.80	10-28-94
							141.28	11-10-94
							141.73	12-02-94
							141.93	12-09-94
							142.06	12-15-94
							142.32	12-29-94
VC-7	391110 1194807	N15 E19 12BBAA1	5147.4	2	107	metamorphic rocks 95-105	83.16	08-23-94
							83.56	10-05-94
							83.68	10-21-94
							83.69	10-28-94
							83.81	11-10-94
							83.86	12-02-94
							83.95	12-09-94
							83.93	12-15-94
							84.02	12-29-94
VC-8	391111 1194819	N15 E19 01CCCC1	5207.5	2	117	basin-fill sediments 102-112	94.75	08-23-94
							94.61	10-04-94
							94.54	10-21-94
							94.52	10-28-94
							94.44	11-10-94
							94.40	12-02-94
							94.42	12-09-94
							94.41	12-15-94
							94.41	12-29-94

Appendix 2. Well location, construction, and water-level data—Continued

Well (see fig. 4)	Latitude, longitude[1]	Local well number[2]	Altitude of land surface (feet)	Diameter of casing (inches)	Depth of well (feet)	Lithology and perforated interval (feet)	Water level	
							Feet below land surface	Date
Ash-1 shallow	391030 1194808	N15 E19 12CCAA1	5063.2	2	185	basin-fill sediments 170-180	138.00	08-23-94
							138.16	08-26-94
							139.95	10-05-94
							140.30	10-21-94
							140.15	10-28-94
							139.55	11-10-94
							139.74	12-02-94
							138.77	12-09-94
							138.75	12-15-94
							138.62	12-29-94
Ash-1 deep	391030 1194808	N15 E19 12CCAA2	5063.2	2	321	basin-fill sediments/ metamorphic rocks 297-317	231.81	08-23-94
							231.89	08-26-94
							233.07	10-05-94
							233.68	11-10-94
							233.59	12-02-94
							234.26	12-09-94
							234.37	12-15-94
							234.48	12-29-94
Ash-2	301036 1194810	N15 E19 12CBCA1	5147.2	2	102	granitic rocks 90-100		Dry
Kings-1 shallow	390943 1194748	N15 E19 13CADA1	4889.12	2	108	basin-fill sediments 93-103	57.12	08-26-94
							59.90	10-05-94
							60.85	10-21-94
							61.17	10-28-94
							61.68	11-10-94
							62.37	12-02-94
							62.55	12-09-94
							62.66	12-15-94
							62.92	12-29-94
Kings-1 deep	390943 1194748	N15 E19 13CADA2	4889.12	2	190	basin-fill sediments 175-185	59.84	08-26-94
							62.41	10-05-94
							63.31	10-21-94
							63.61	10-28-94
							64.06	11-10-94
							64.68	12-02-94
							64.81	12-09-94
							64.88	12-15-94
							65.22	12-29-94
Kings-2 shallow	390948 1194754	N15 E19 13CAAB1	4887.83	2	104	basin-fill sediments 89-99	50.97	08-26-94
							54.28	10-06-94
							55.18	10-21-94
							55.50	10-28-94
							55.97	11-10-94
							56.52	12-02-94
							56.77	12-09-94
							56.89	12-15-94
							57.12	12-29-94

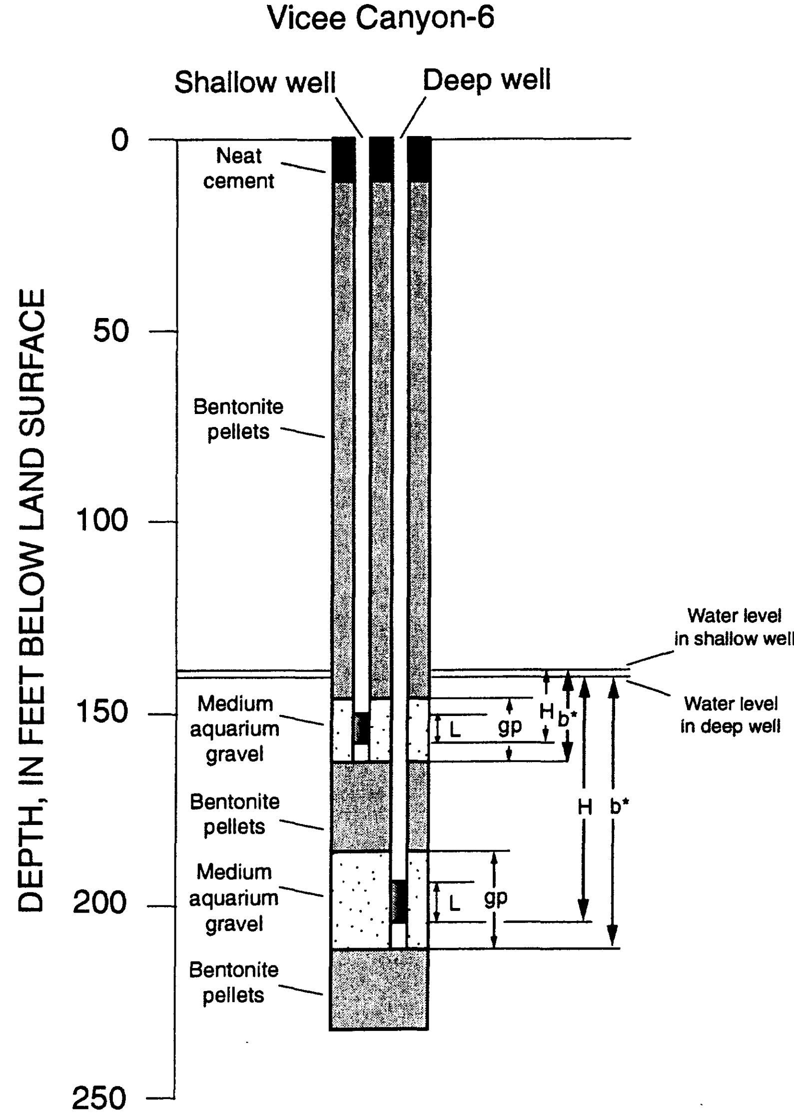
Appendix 2. Well location, construction, and water-level data—Continued

Well (see fig. 4)	Latitude, longitude[1]	Local well number[2]	Altitude of land surface (feet)	Diameter of casing (inches)	Depth of well (feet)	Lithology and perforated interval (feet)	Water level: Feet below land surface	Water level: Date
Kings-2 deep	390948 1194754	N15 E19 13CAAB2	4887.83	2	175	metamorphic rocks 164-174	50.30	08-26-94
							53.56	10-06-94
							54.54	10-21-94
							54.90	10-28-94
							55.38	11-10-94
							56.07	12-02-94
							56.31	12-09-94
							56.49	12-15-94
							56.78	12-29-94
Bily	390937 1194756	N15 E19 13CDAB1	4943.4	6	200	basin-fill sediments 180-200	50	12-19-81
							63.66	08-26-94
							49.64	10-06-94
							52.16	10-21-94
							51.76	10-28-94
							51.66	11-04-94
							48.08	11-28-94
							45.70	12-02-94
							44.50	12-09-94
City	390958 1194755	N15 E19 13BDDB1	4862.21	8	195	basin-fill sediments ?	32.1	01-31-77
							51.15	08-26-94
							53.32	10-06-94
							54.04	10-21-94
							54.31	10-28-94
							54.72	11-10-94
							55.34	12-02-94
							55.57	12-09-94
							55.65	12-15-94
							55.95	12-29-94
Quill	391002 1194817	N15 E19 13BCBC1	4976.52	2	340	basin-fill sediments 270-340	79	07-24-91
							83.30	08-26-94
							84.45	10-06-94
							84.91	10-24-94
							85.00	10-28-94
							85.14	11-10-94
							85.52	12-02-94
							85.61	12-09-94
							85.68	12-15-94
							86.01	12-29-94

[1] Latitude and longitude in degrees, minutes, and seconds.

[2] Local well number consists of three units separated by spaces: The first unit is the Township, preceded by N to indicate north of the base line. The second unit is the Range, preceded by and E to indicate east of the meridian. The third unit consists of the section number and letters designating the quarter section, quarter-quarter section, and so on. The letters A,B,C, and D indicate the northeast, northwest, southwest, and southeast quarters, respectively. The number following the letters indicates the sequence in which the site was recorded. For example, site N15 E19 13BCBC1 is the first site recorded in the southwest 1/4 of the northwest 1/4 of the southwest 1/4 of the northwest 1/4 of section 13, Township 15 North, Range 19 East, Mount Diablo base line and meridian.

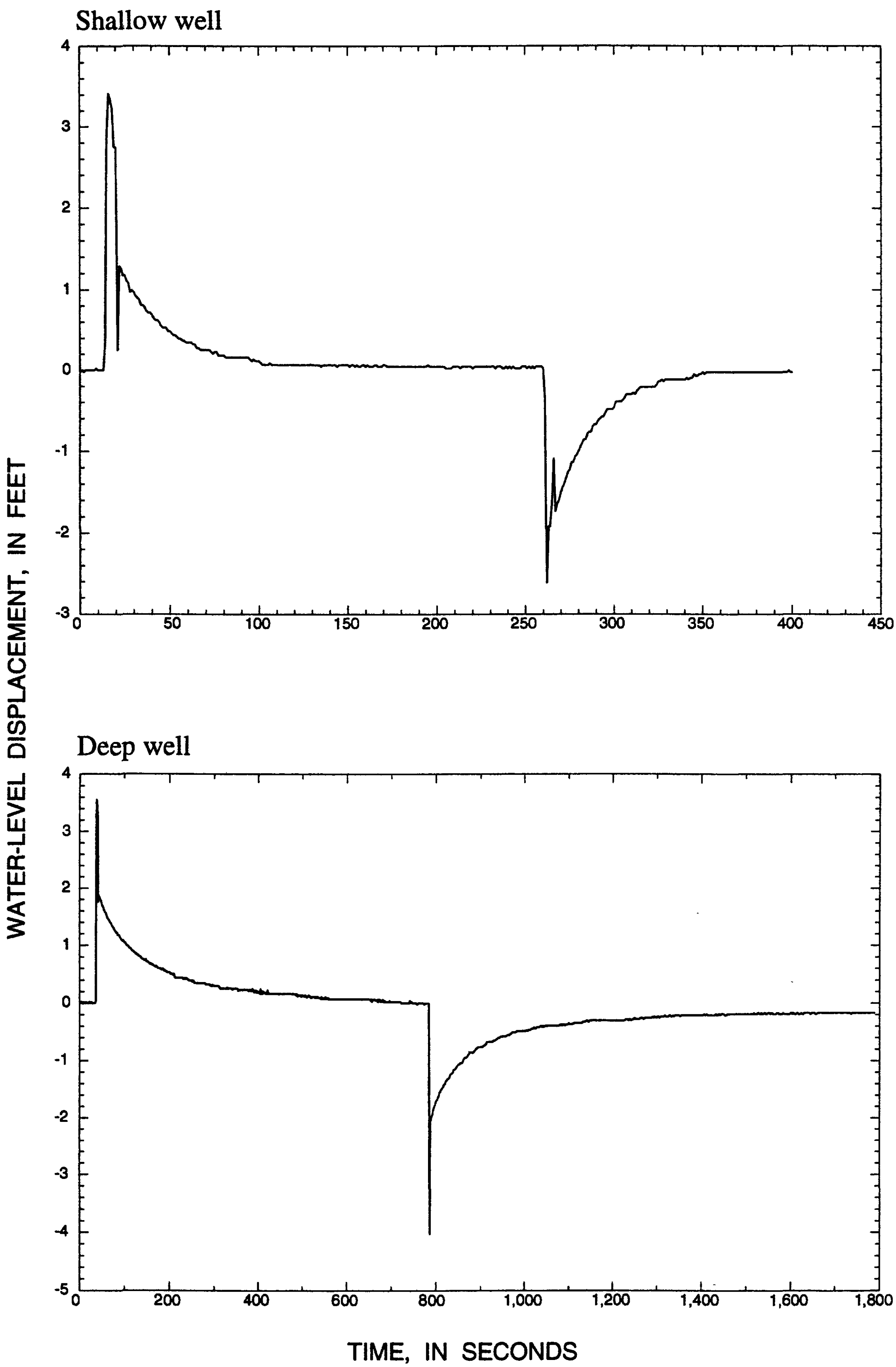
Appendix 3. Slug test and detailed well-construction data



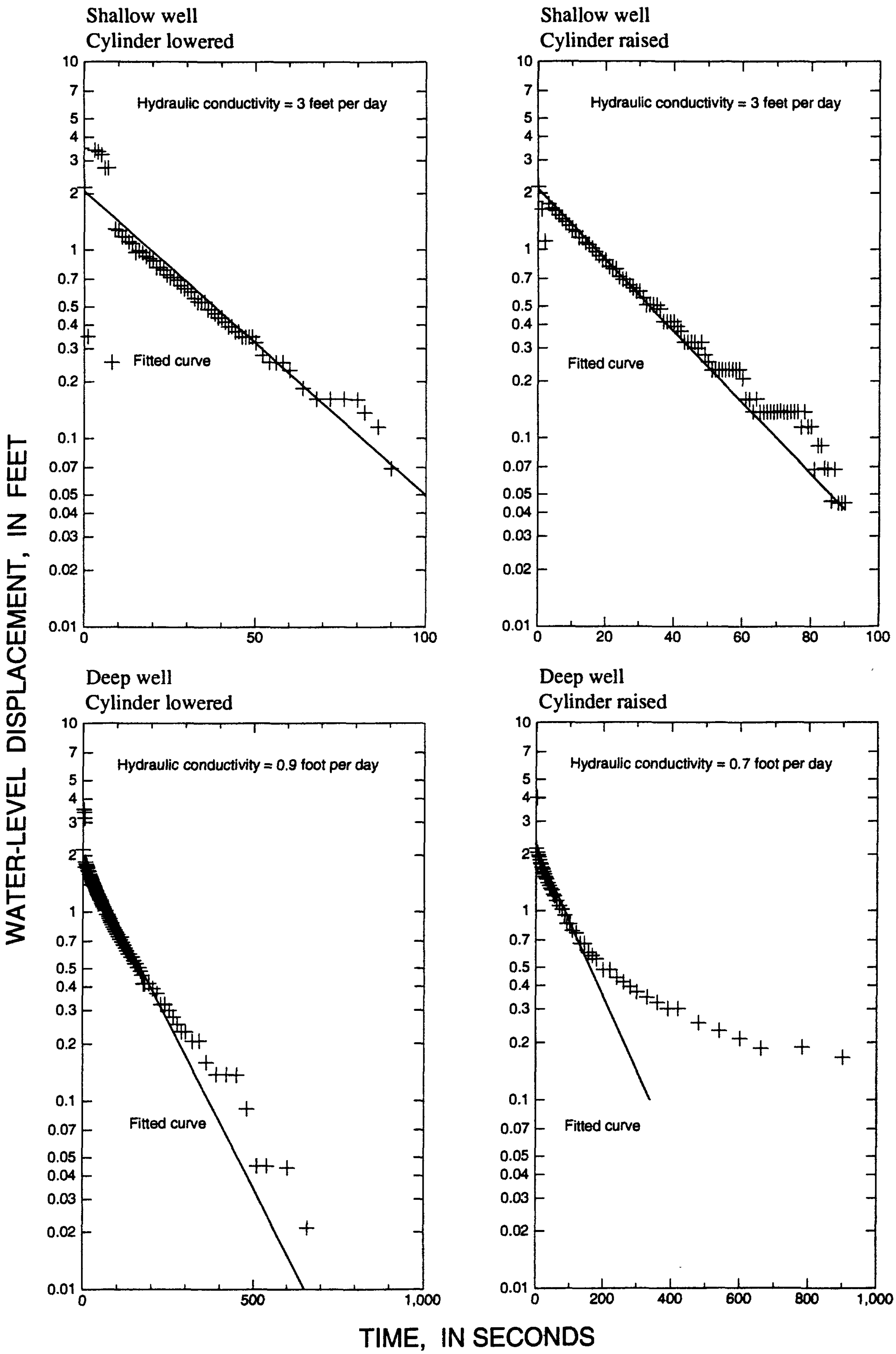
VICEE CANYON-6 on November 29, 1994

Variable used to analyze slug test	Measurement (feet)	
	Shallow well	Deep well
Inside radius of well casing (r_c)	0.086	0.086
Average radius of well bore in gravel-pack interval (r_w)	.307	.307
Screen length (L)	10	10
Gravel-pack interval (gp)	17	25
*Saturated thickness (b^*)	24	69
Height of water above base of screen (H)	19	64
Initial displacement (S_o)	2.17	2.17

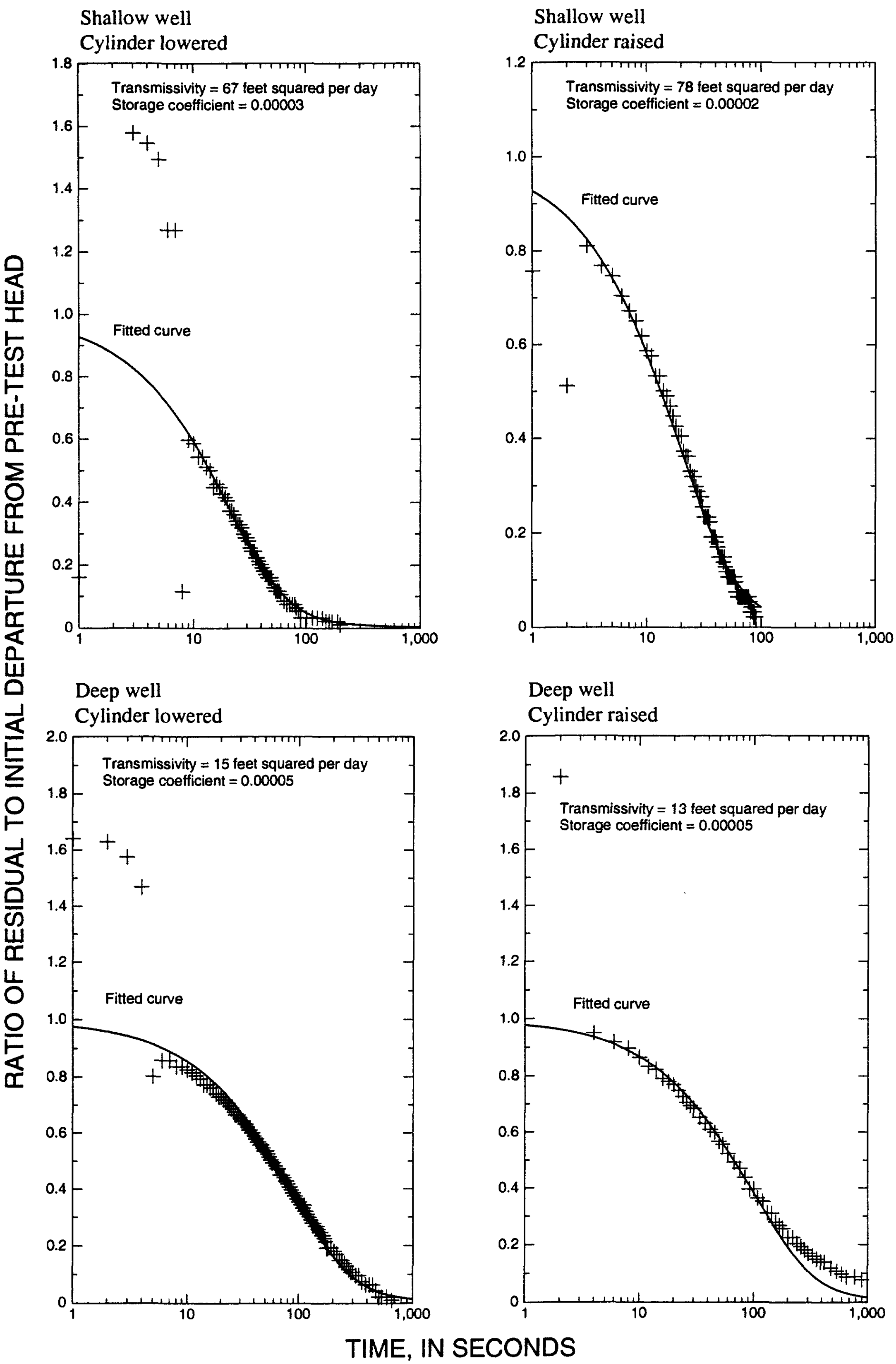
* Saturated thickness is assumed to be from base of gravel pack to water level in well. Increasing saturated thickness in the analyses to 93 feet (depth of test hole less water level in shallow well) had no effect on calculated hydraulic conductivity in either well.

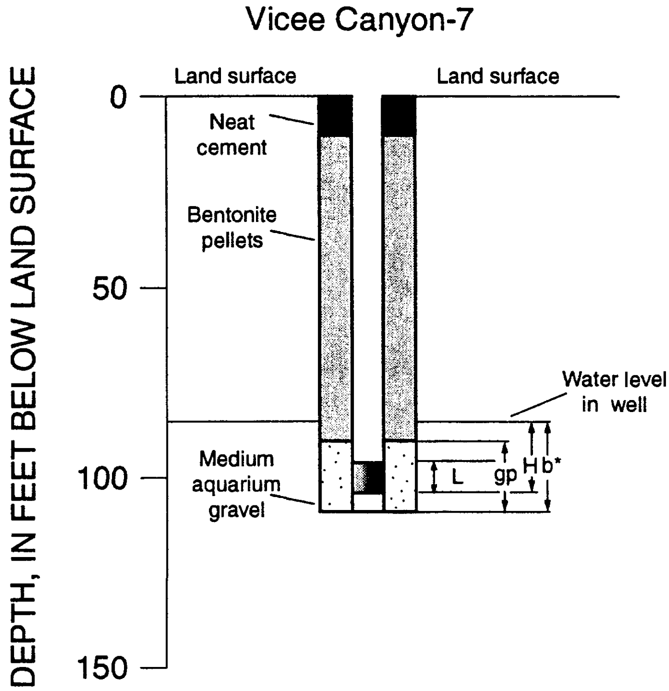

Shallow well
4
3
2
1
0
-1
-2
-3
0
50
100
150
200
250
300
350
400
450
Deep well
4
3
2
1
0
-1
-2
-3
-4
-5
0
200
400
600
800
1,000
1,200
1,400
1,600
1,800
WATER-LEVEL DISPLACEMENT, IN FEET
TIME, IN SECONDS

Method of Bouwer and Rice (1976)



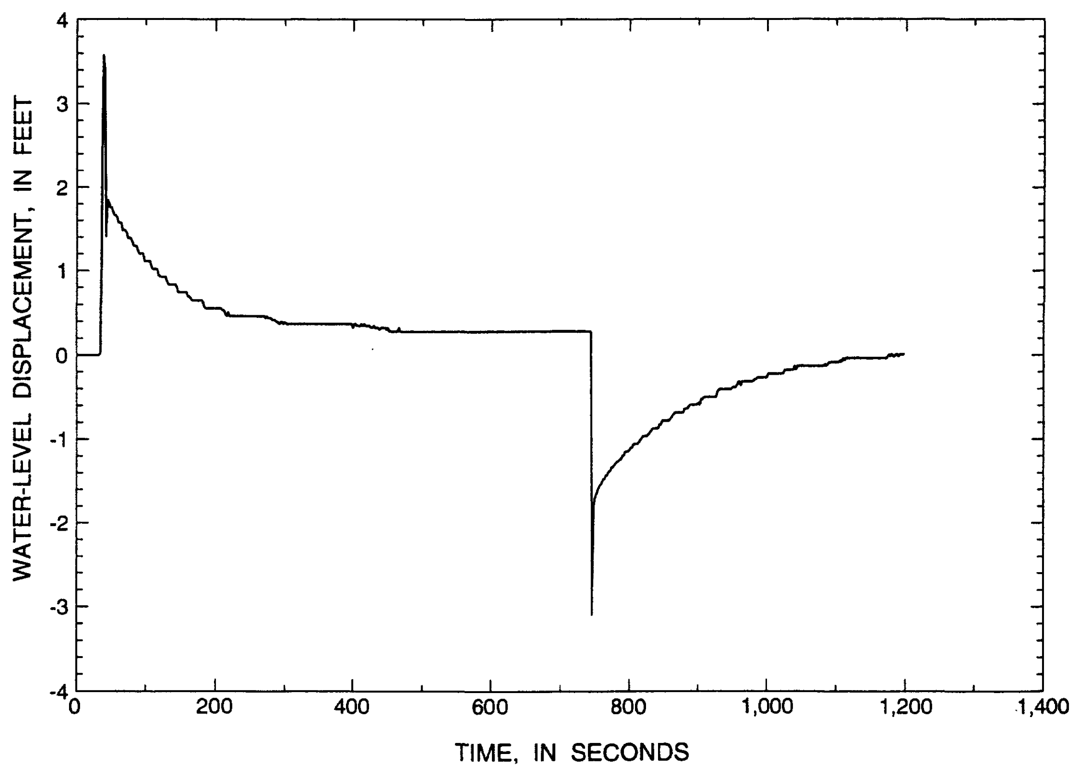
Method of Cooper and others (1967)

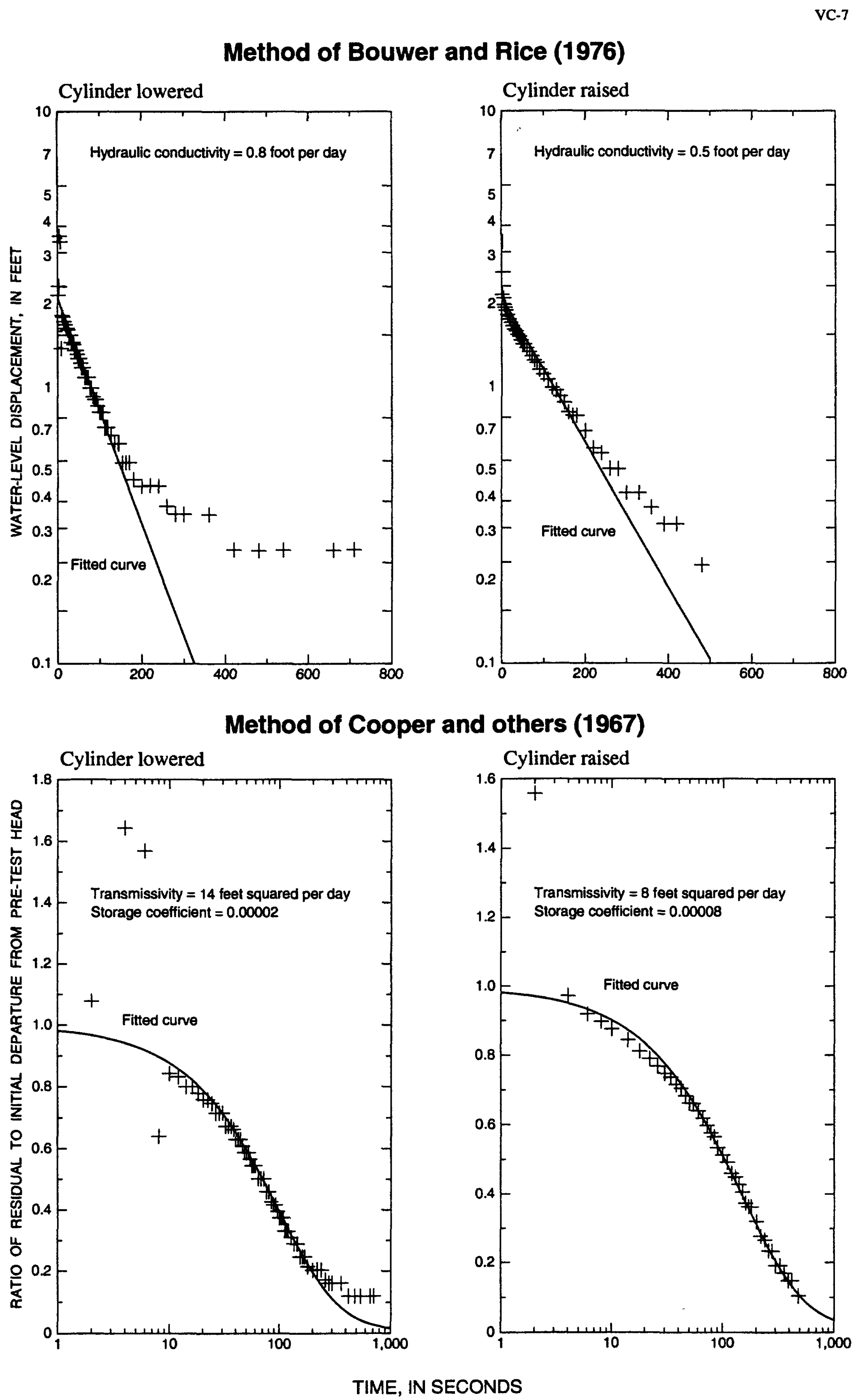


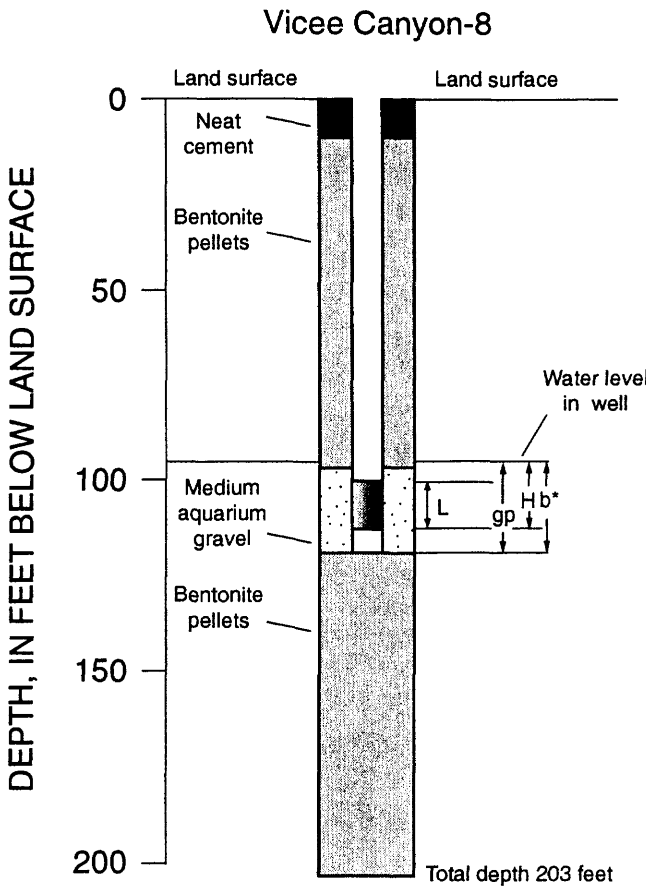


VICEE CANYON-7 on November 29, 1994

Variable used to analyze slug test	Measurement (feet)
Inside radius of well casing (r_c)	0.086
Average radius of well bore in gravel-pack interval (r_w).	.346
Screen length (L)..................	10
Gravel-pack interval (gp)	17
Saturated thickness (b^*)	23
Height of water above base of screen (H).	21
Initial displacement (S_o)	2.17



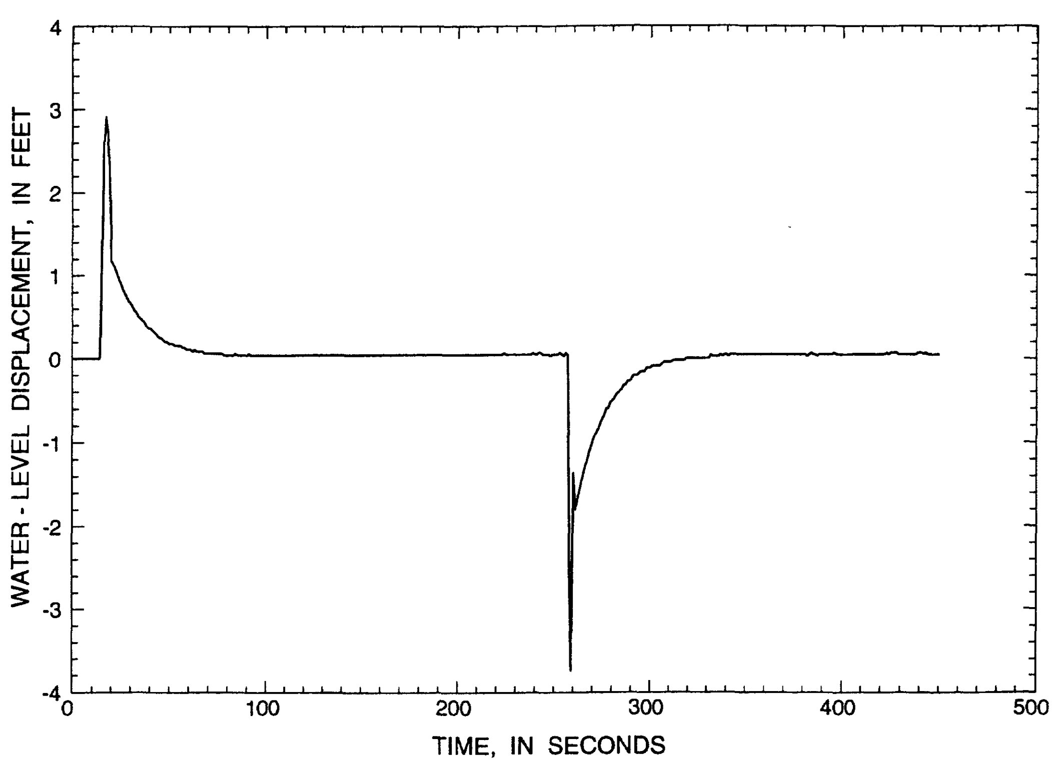

VC-7
Method of Bouwer and Rice (1976)
Cylinder lowered
Hydraulic conductivity = 0.8 foot per day
Fitted curve
Cylinder raised
Hydraulic conductivity = 0.5 foot per day
Fitted curve
WATER-LEVEL DISPLACEMENT, IN FEET
Method of Cooper and others (1967)
Cylinder lowered
Transmissivity = 14 feet squared per day
Storage coefficient = 0.00002
Fitted curve
Cylinder raised
Transmissivity = 8 feet squared per day
Storage coefficient = 0.00008
Fitted curve
RATIO OF RESIDUAL TO INITIAL DEPARTURE FROM PRE-TEST HEAD
TIME, IN SECONDS



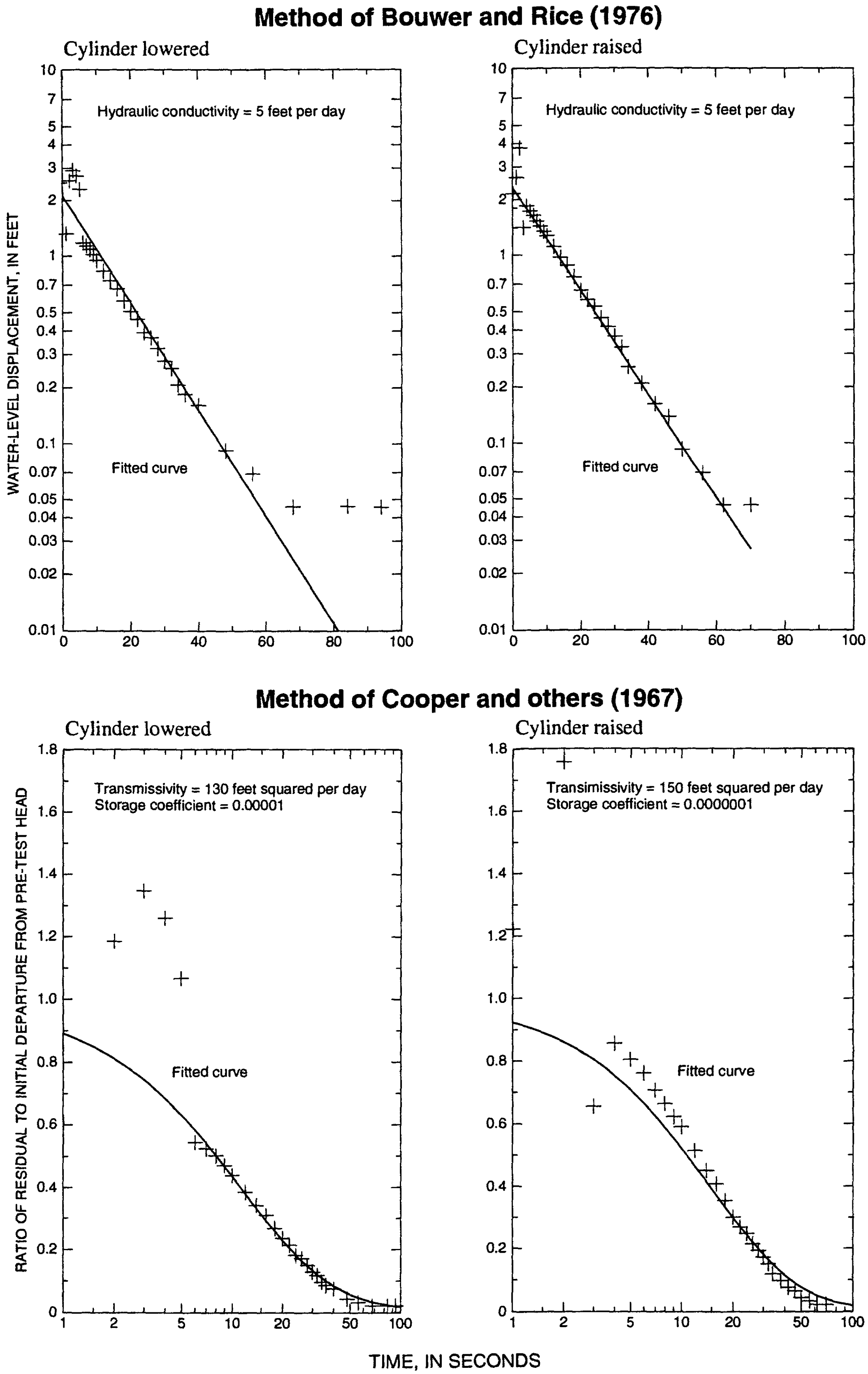
VICEE CANYON-8 on November 29, 1994

Variable used to analyze slug test	Measurement (feet)
Inside radius of well casing (r_c)	0.086
Average radius of well bore in gravel-pack interval (r_w).	.35
Screen length (L)	10
Gravel-pack interval (gp)	21
Saturated thickness (b)	22
Height of water above base of screen (H)	17
Initial displacement (S_o)	2.17

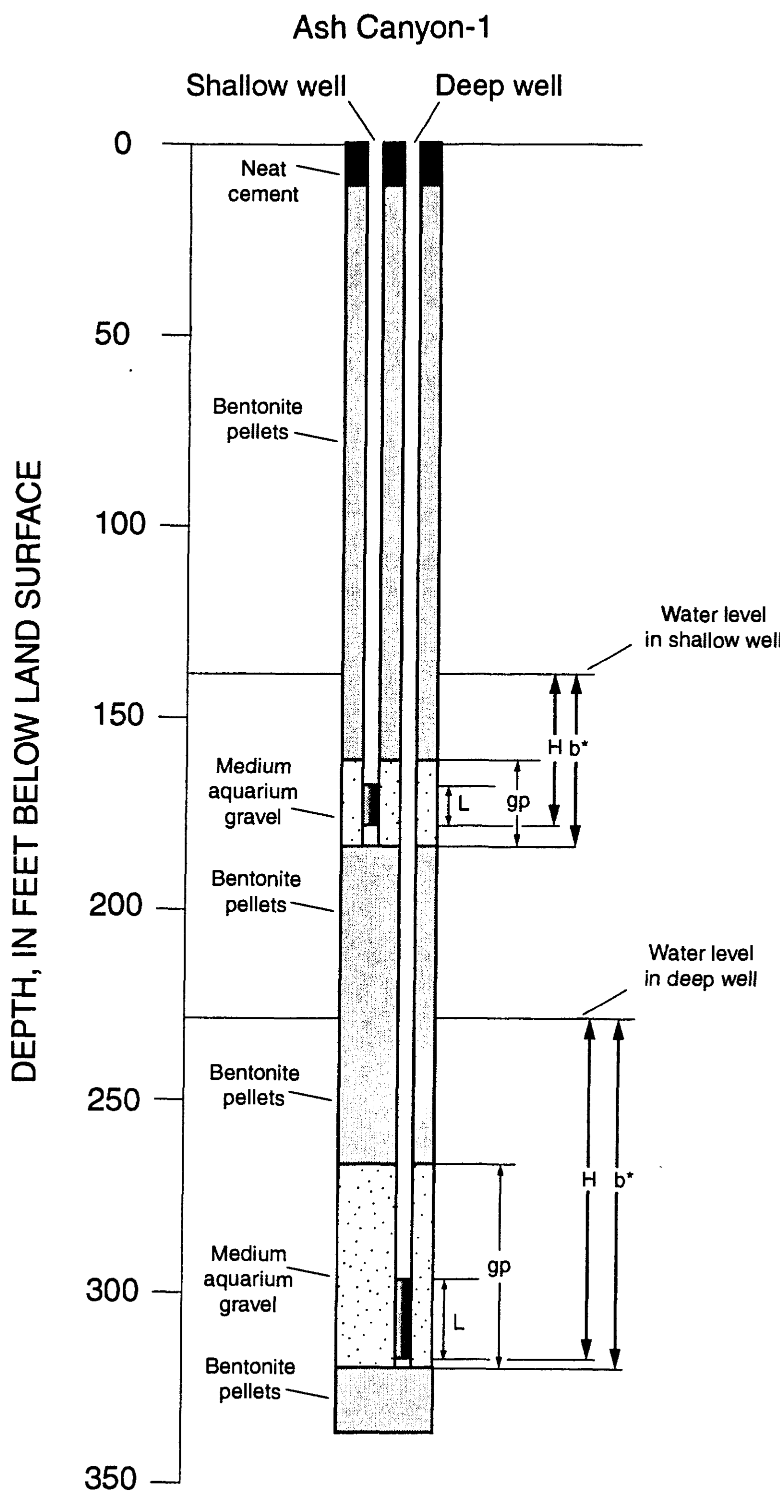
* Saturated thickness is assumed to be from base of gravel pack to water level in well. Increasing saturated thickness in the analyses to 108 feet (distance between water level and bottom of test hole) had no effect on hydraulic conductivity.



VC-8



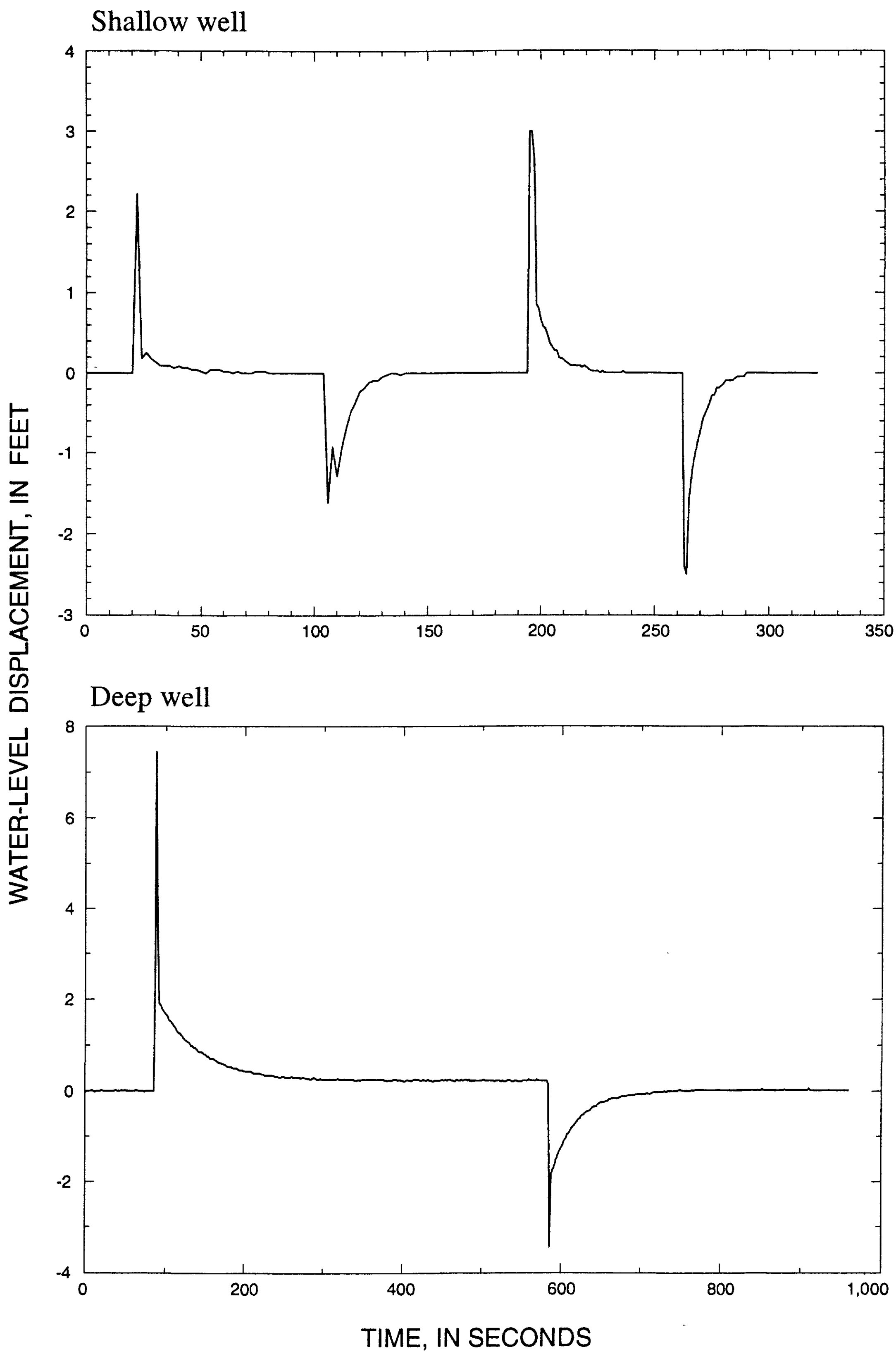
Method of Bouwer and Rice (1976)
Cylinder lowered
Hydraulic conductivity = 5 feet per day
Fitted curve
Cylinder raised
Hydraulic conductivity = 5 feet per day
Fitted curve
WATER-LEVEL DISPLACEMENT, IN FEET
Method of Cooper and others (1967)
Cylinder lowered
Transmissivity = 130 feet squared per day
Storage coefficient = 0.00001
Fitted curve
Cylinder raised
Transimissivity = 150 feet squared per day
Storage coefficient = 0.0000001
Fitted curve
RATIO OF RESIDUAL TO INITIAL DEPARTURE FROM PRE-TEST HEAD
TIME, IN SECONDS

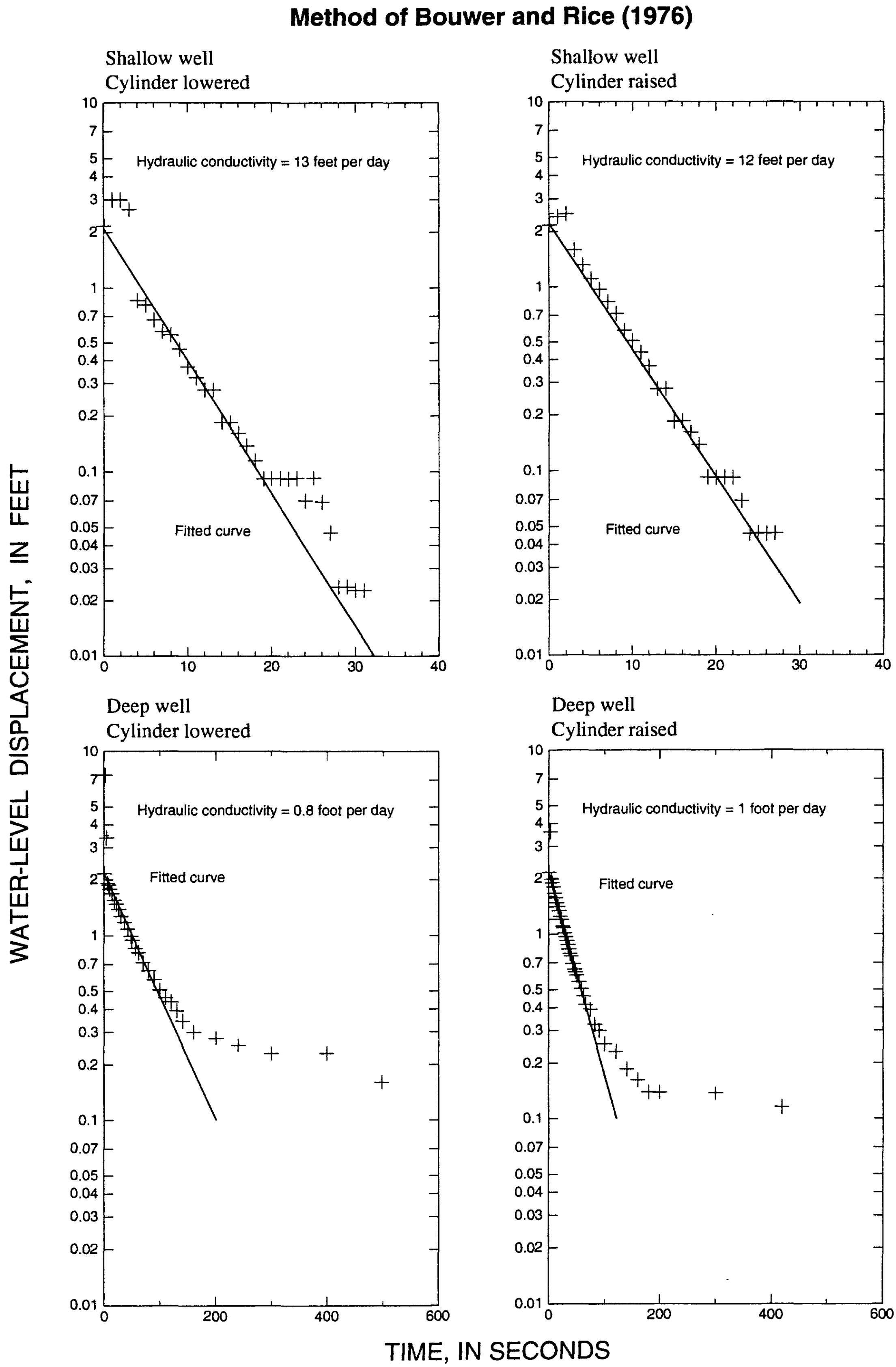

Ash Canyon-1
Shallow well
Deep well
0
50
100
150
200
250
300
350
DEPTH, IN FEET BELOW LAND SURFACE
Neat cement
Bentonite pellets
Medium aquarium gravel
Bentonite pellets
Bentonite pellets
Medium aquarium gravel
Bentonite pellets
Water level in shallow well
Water level in deep well
H
b*
L
gp
H
b*
gp
L

ASH CANYON-1 on November 30, 1994

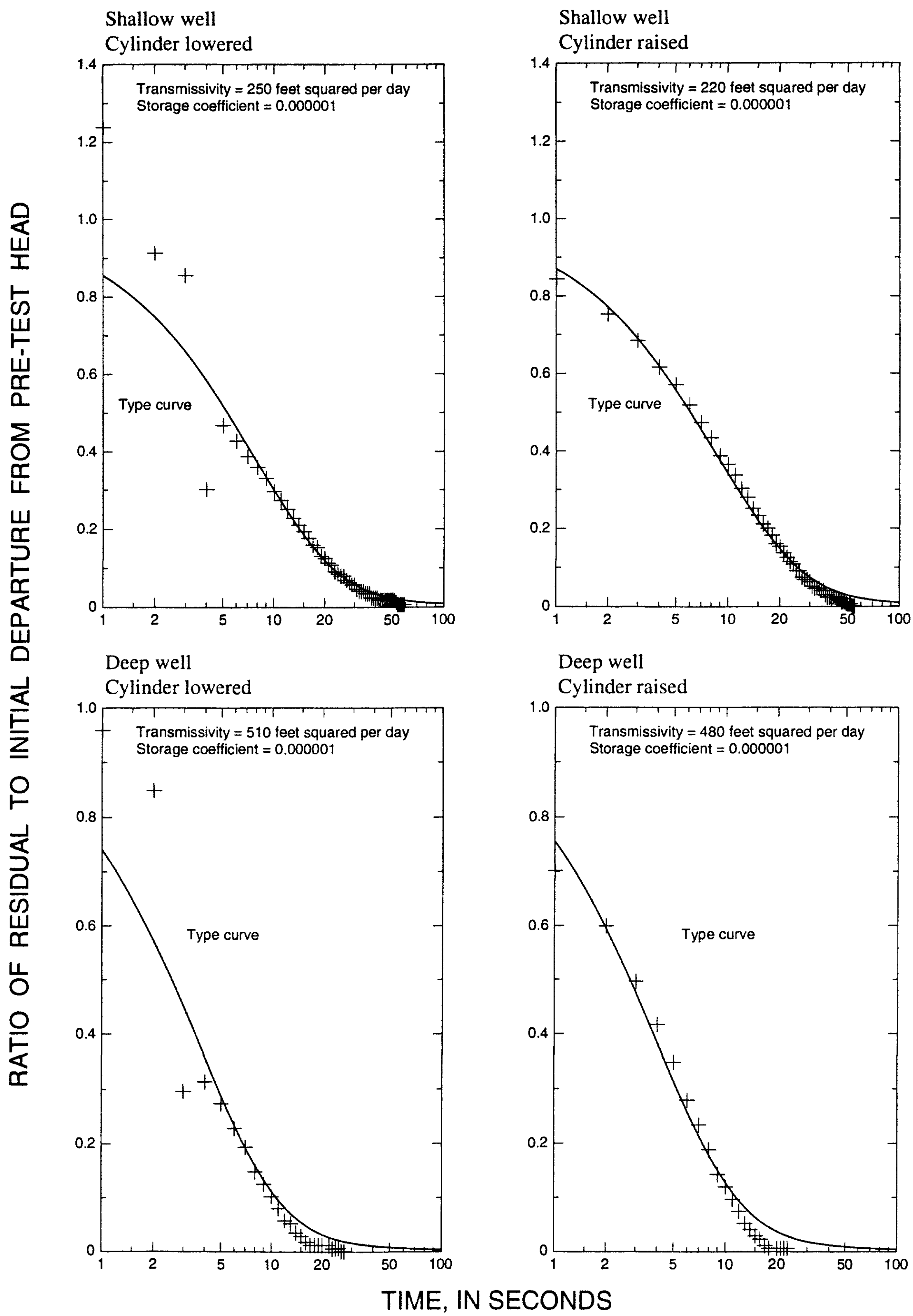
Variable used to analyze slug test	Measurement (feet)	
	Shallow well	Deep well
Inside radius of well casing (r_c)	0.086	0.086
Average radius of well bore in gravel-pack interval (r_w).	.383	.328
Screen length (L)	10	10
Gravel-pack interval (gp)	23	50
Saturated thickness (b)	45	88
Height of water above base of screen (H)	40	83
Initial displacement (S_o)	2.17	2.17

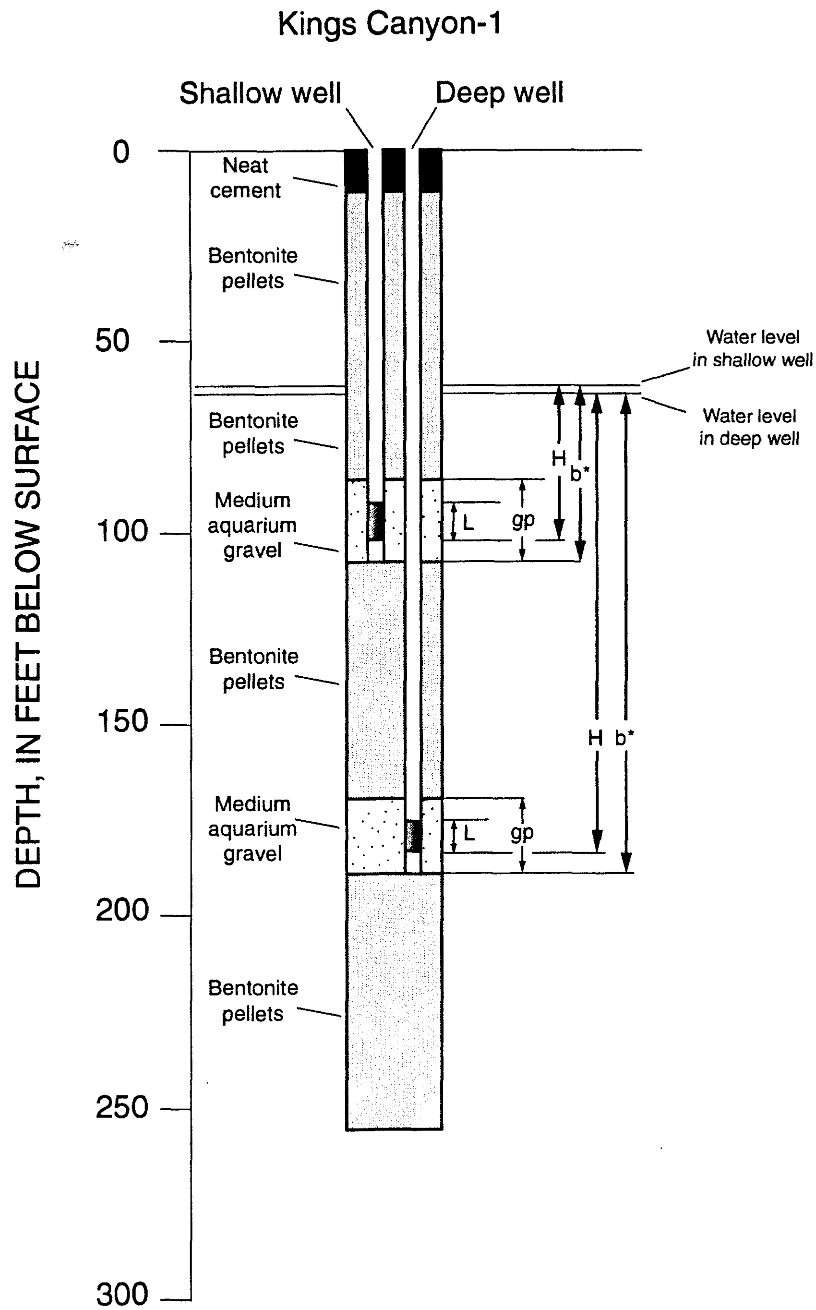
* Saturated thickness is assumed to be from base of gravel pack to water level in well. For the Bouwer and Rice method, the saturated thickness must equal the height of water above base of screen. Increasing saturated thickness in the analyses to 197 feet (water level in shallow well less bottom of hole) had no effect on calculated hydraulic conductivity in either well.


Shallow well
4
3
2
1
0
-1
-2
-3
0
50
100
150
200
250
300
350
Deep well
8
6
4
2
0
-2
-4
0
200
400
600
800
1,000
WATER-LEVEL DISPLACEMENT, IN FEET
TIME, IN SECONDS


Method of Bouwer and Rice (1976)
Shallow well
Cylinder lowered
Hydraulic conductivity = 13 feet per day
Fitted curve
Shallow well
Cylinder raised
Hydraulic conductivity = 12 feet per day
Fitted curve
Deep well
Cylinder lowered
Hydraulic conductivity = 0.8 foot per day
Fitted curve
Deep well
Cylinder raised
Hydraulic conductivity = 1 foot per day
Fitted curve
WATER-LEVEL DISPLACEMENT, IN FEET
TIME, IN SECONDS

Method of Cooper and others (1967)



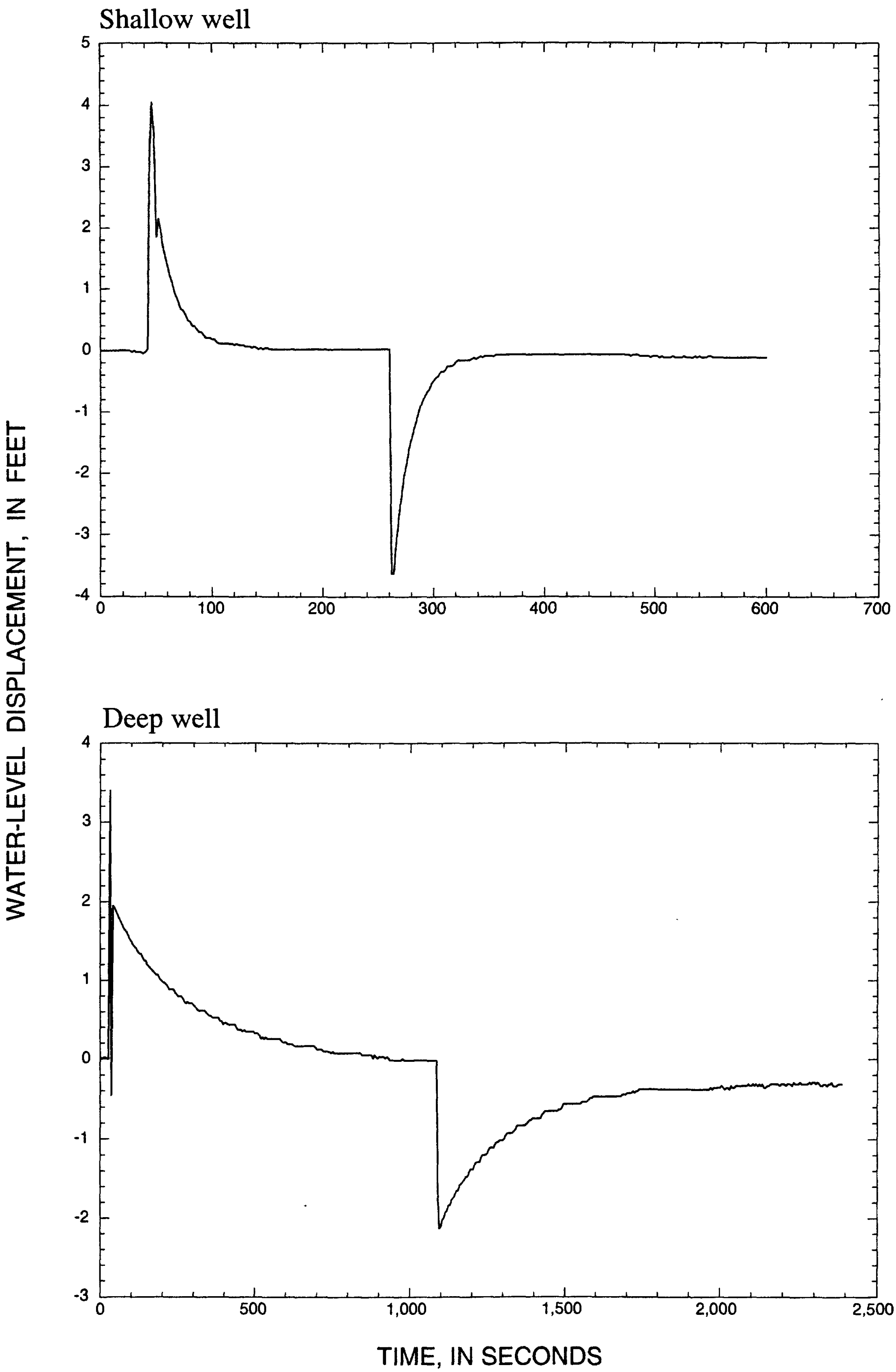


Kings Canyon-1
Shallow well
Deep well
0
50
100
150
200
250
300
DEPTH, IN FEET BELOW SURFACE
Neat cement
Bentonite pellets
Bentonite pellets
Medium aquarium gravel
Bentonite pellets
Medium aquarium gravel
Bentonite pellets
Water level in shallow well
Water level in deep well
H
b*
L
gp
H b*
L
gp

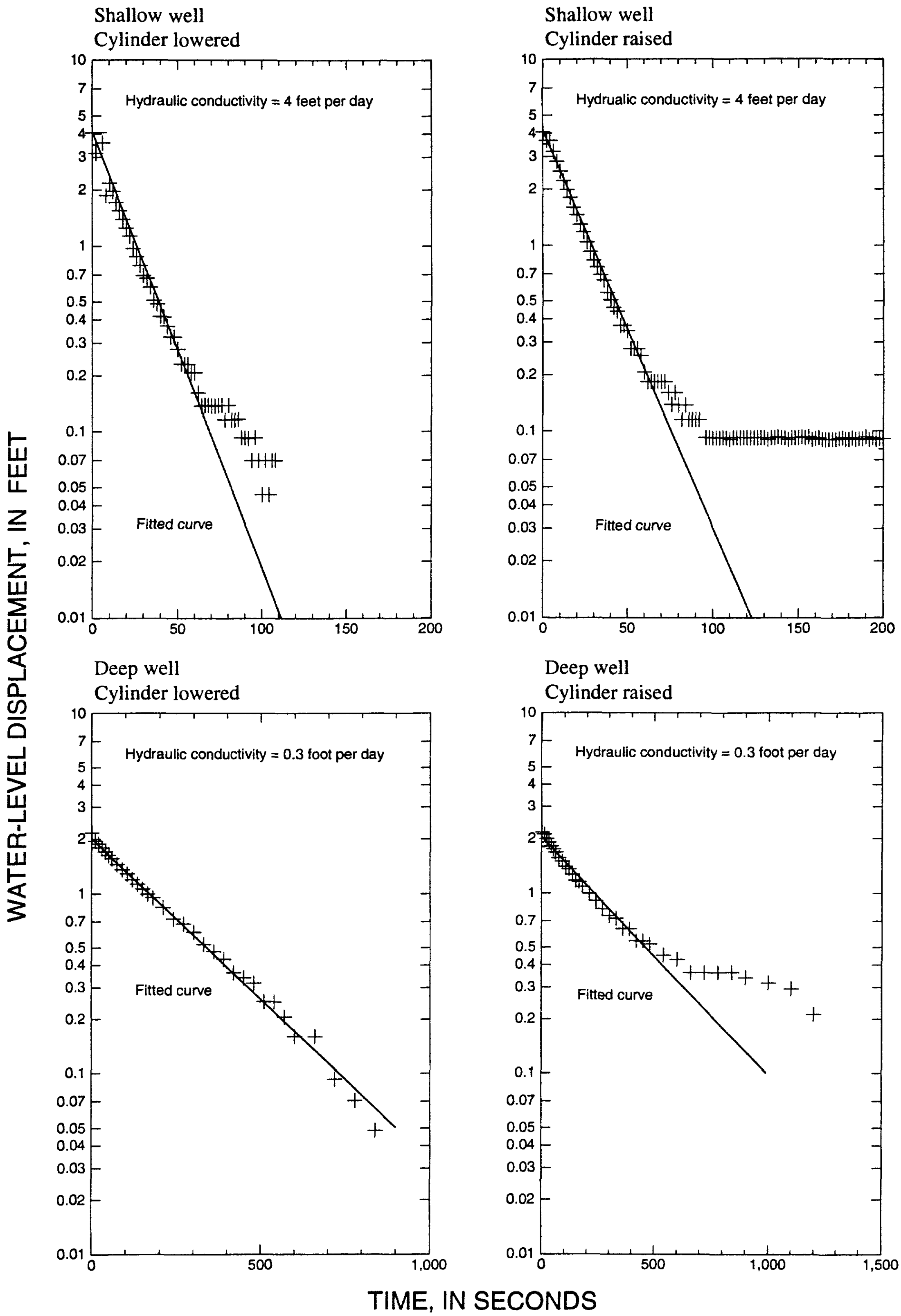
KINGS CANYON-1 on November 23, 1994

Variable used to analyze slug test	Measurement (feet)	
	Shallow well	Deep well
Inside radius of well casing (r_c)	0.086	0.086
Average radius of well bore in gravel-pack interval (r_w).	.354	.354
Screen length (L)	10	10
Gravel-pack interval (gp)	22	20
Saturated thickness (b)	47	126
Height of water above base of screen (H)	42	121
Initial displacement (S_o)	4.06	2.17

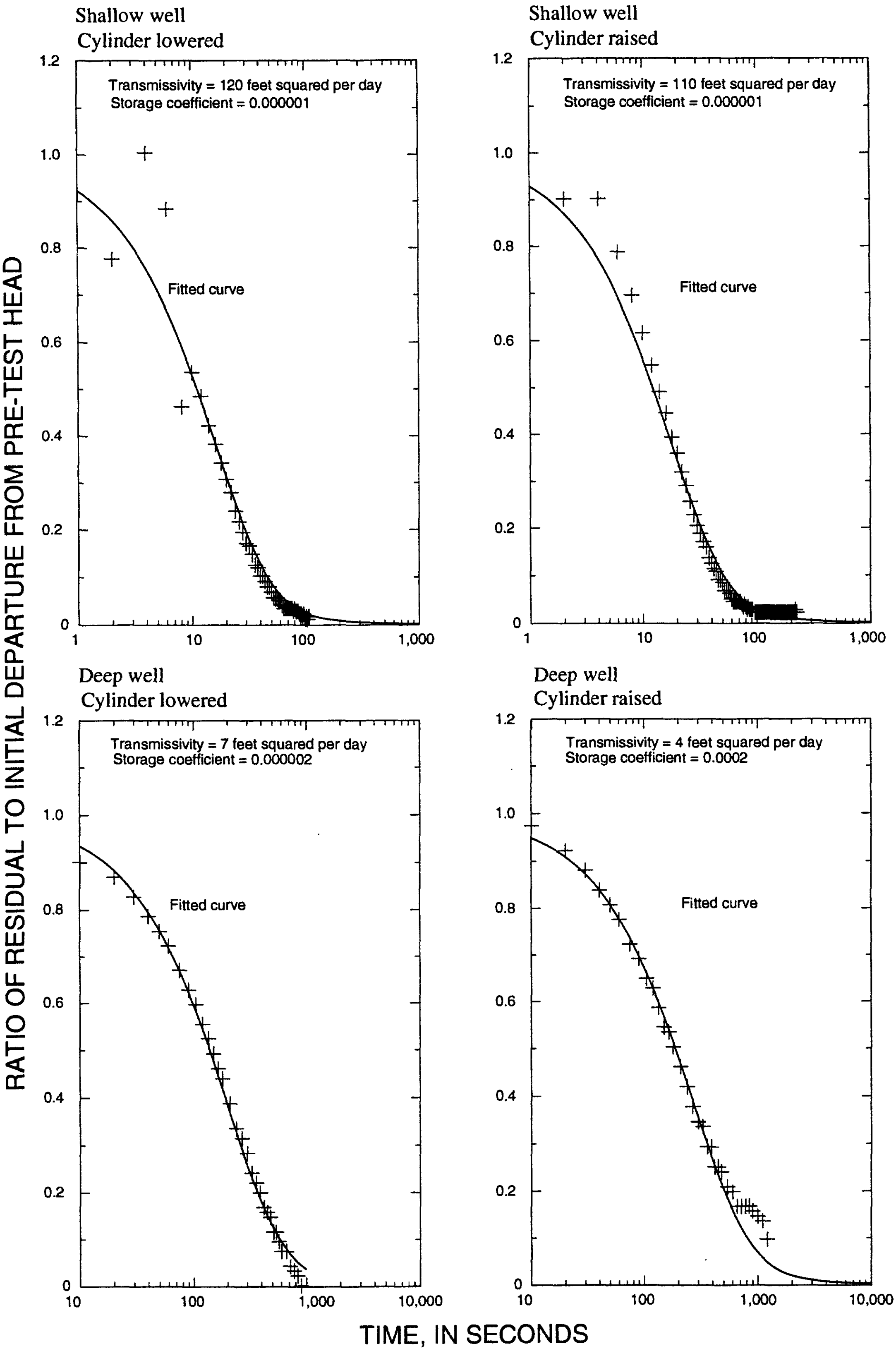
* Saturated thickness is assumed to be from base of gravel pack to water level in well. For the Bouwer and Rice method, the saturated thickness must equal the height of water above base of screen. Increasing saturated thickness in the analyses to 131 feet (water level in shallow well less depth of silty sand clay at 192 feet) had no effect on calculated hydraulic conductivity in either well.

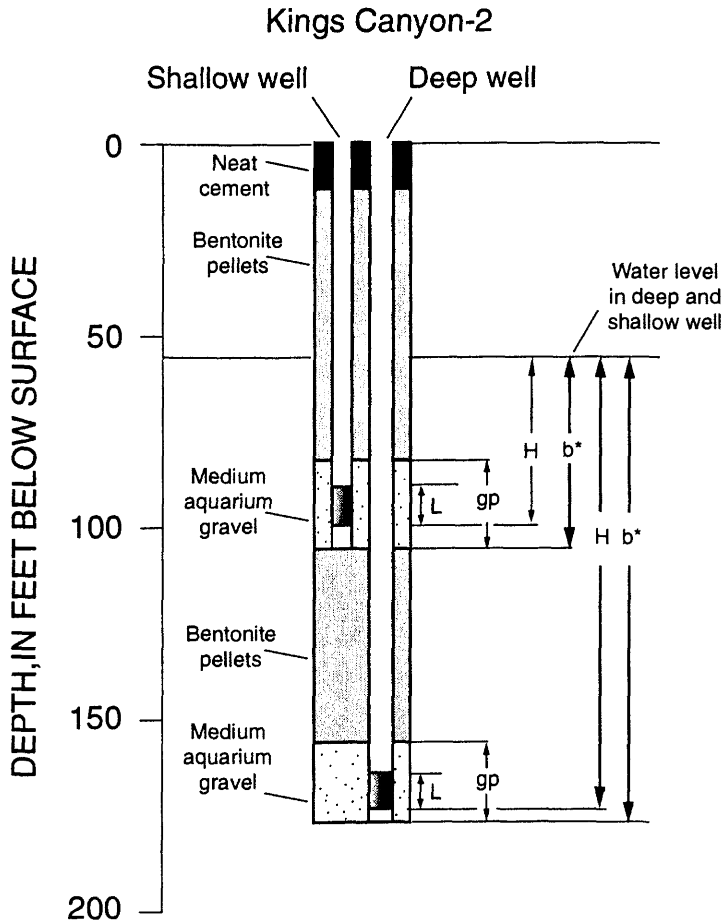

Shallow well
5
4
3
2
1
0
-1
-2
-3
-4
0
100
200
300
400
500
600
700
Deep well
4
3
2
1
0
-1
-2
-3
0
500
1,000
1,500
2,000
2,500
WATER-LEVEL DISPLACEMENT, IN FEET
TIME, IN SECONDS

Method of Bouwer and Rice (1976)



Method of Cooper and others (1967)

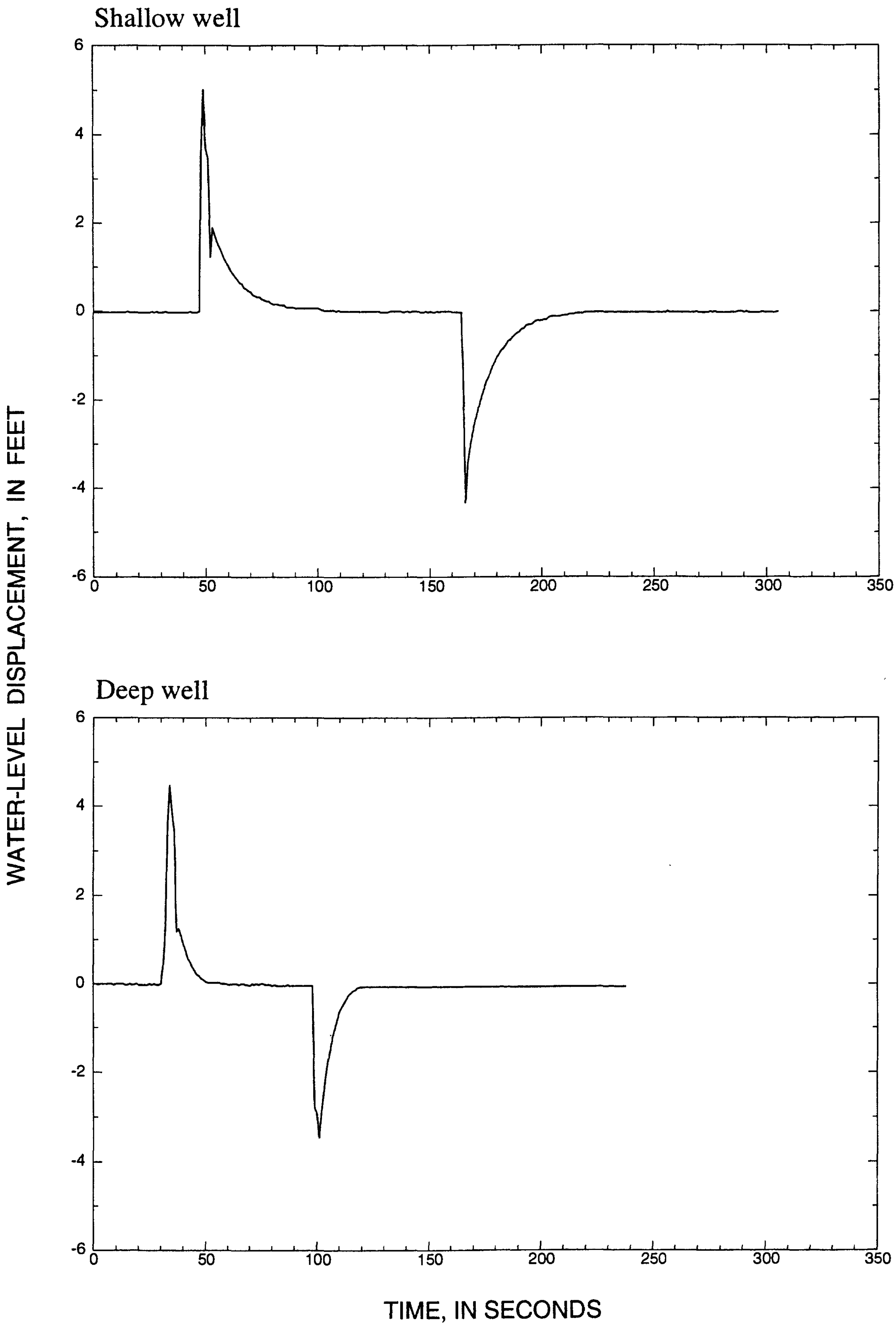




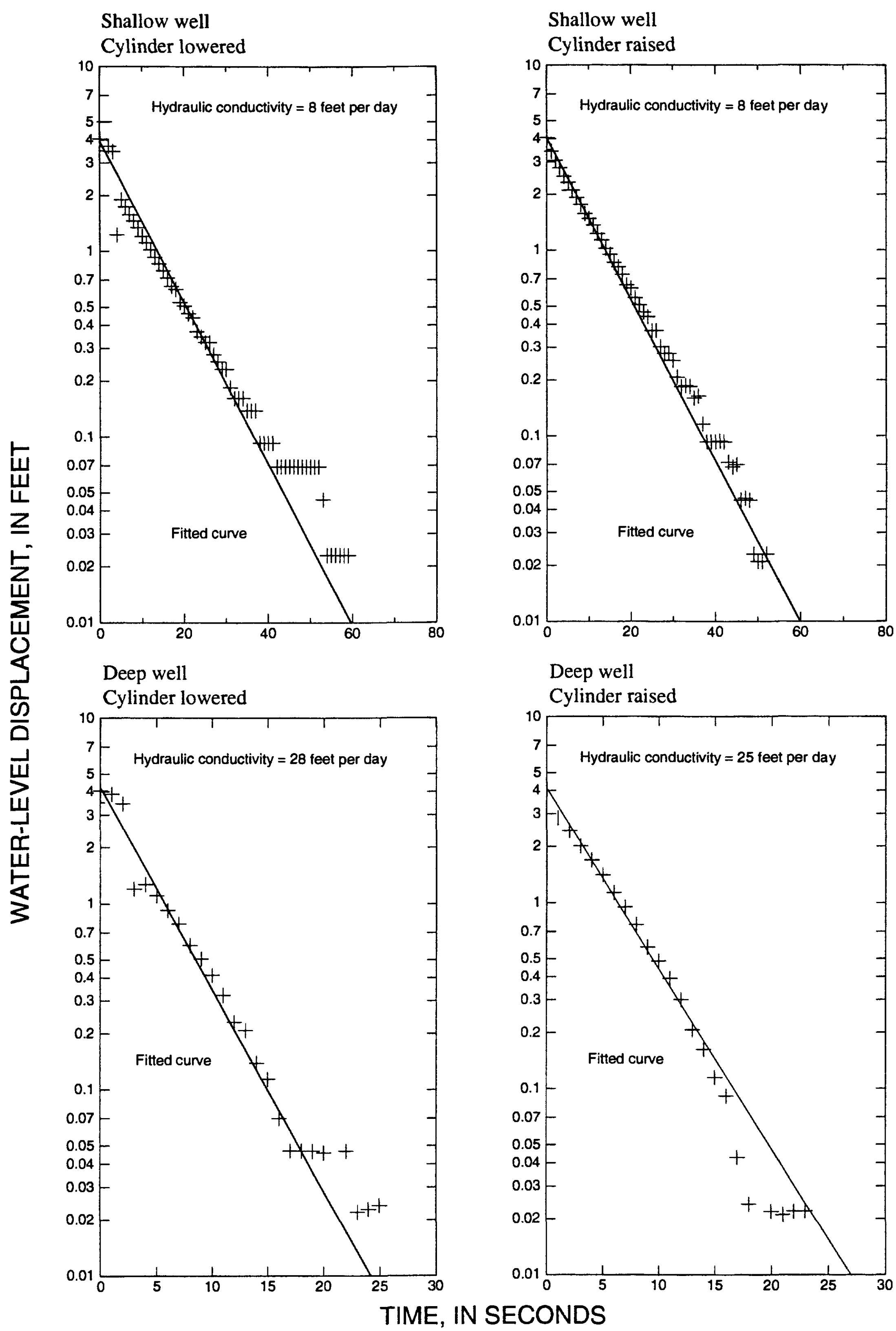
KINGS CANYON-2 on November 23, 1994

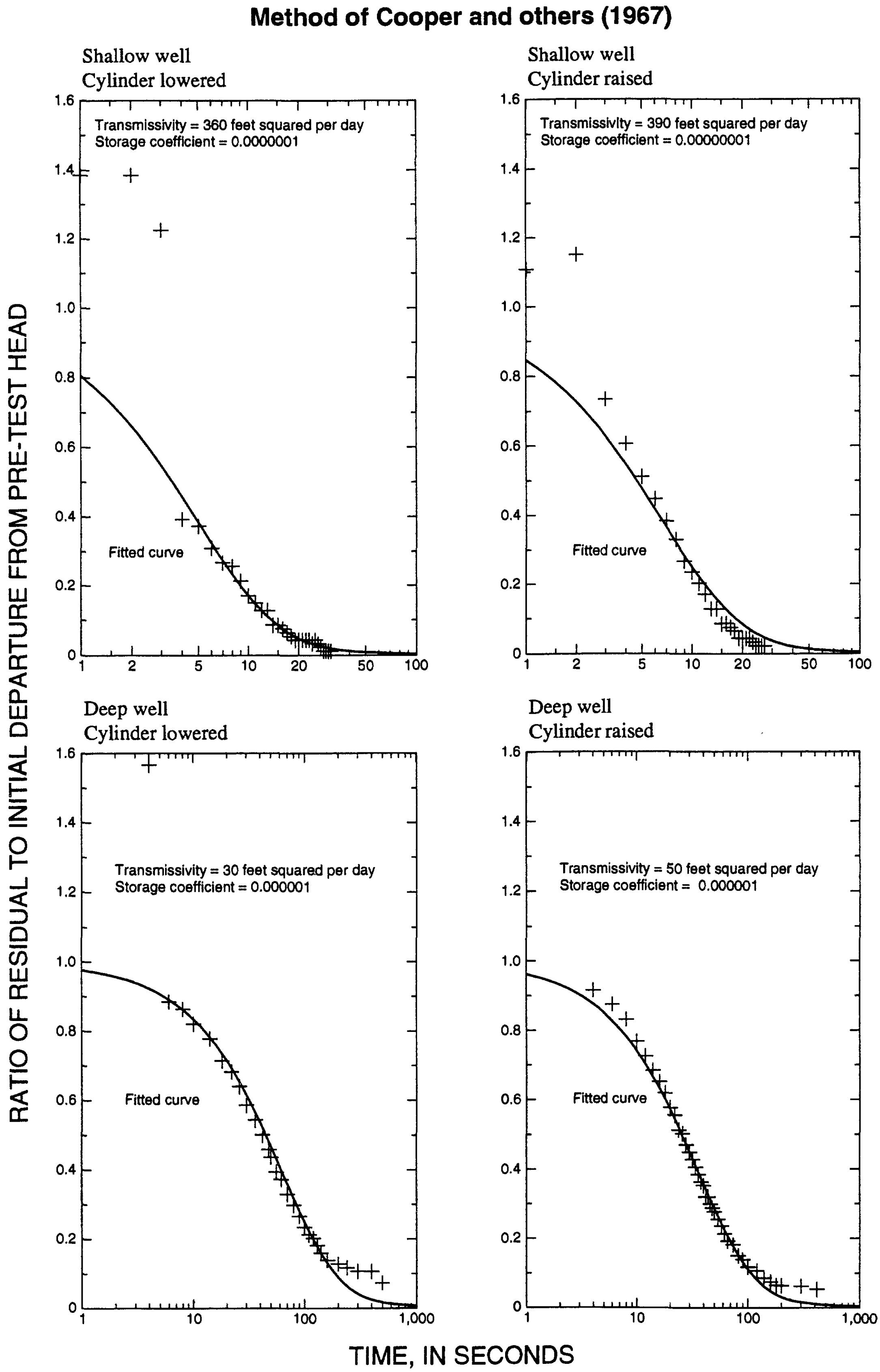
Variable used to analyze slug test	Measurement (feet)	
	Shallow well	Deep well
Inside radius of well casing (r_c)	0.086	0.086
Average radius of well bore in gravel-pack interval (r_w)	.354	.342
Screen length (L)	10	10
Gravel-pack interval (gp)	22	20
Saturated thickness (b)	48	119
Height of water above base of screen (H)	43	118
Initial displacement (S_o)	4.06	4.06

* Saturated thickness is assumed to be from base of gravel pack to water level in well. Increasing saturated thickness in shallow well to equal that in deep well had no effect on calculated hydraulic conductivity.


Shallow well
Deep well
WATER-LEVEL DISPLACEMENT, IN FEET
TIME, IN SECONDS
6
4
2
0
-2
-4
-6
0
50
100
150
200
250
300
350

Method of Bouwer and Rice (1976)





Method of Cooper and others (1967)
Shallow well
Cylinder lowered
Transmissivity = 360 feet squared per day
Storage coefficient = 0.0000001
Fitted curve
Shallow well
Cylinder raised
Transmissivity = 390 feet squared per day
Storage coefficient = 0.00000001
Fitted curve
Deep well
Cylinder lowered
Transmissivity = 30 feet squared per day
Storage coefficient = 0.000001
Fitted curve
Deep well
Cylinder raised
Transmissivity = 50 feet squared per day
Storage coefficient = 0.000001
Fitted curve
RATIO OF RESIDUAL TO INITIAL DEPARTURE FROM PRE-TEST HEAD
TIME, IN SECONDS