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

Analysis of Water Levels in the Frenchman Flat Area, Nevada Test Site

Water-Resources Investigations Report 00-4272

Prepared in cooperation with the
U.S. DEPARTMENT OF ENERGY
NEVADA OPERATIONS OFFICE under
INTERAGENCY AGREEMENT DE-AI08-96NV11967

USGS
science for a changing world

Analysis of Water Levels in the Frenchman Flat Area, Nevada Test Site

By Daniel J. Bright, Sharon A. Watkins, and Barbara A. Lisle

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 00-4272

Prepared in cooperation with the
U.S. DEPARTMENT OF ENERGY
NEVADA OPERATIONS OFFICE under
INTERAGENCY AGREEMENT DE-AI08-96NV11967

Carson City, Nevada
2001

U.S. DEPARTMENT OF THE INTERIOR
GALE A. NORTON, Secretary

U.S. GEOLOGICAL SURVEY
CHARLES G. GROAT, Director

For additional information contact:

District Chief
U.S. Geological Survey
333 West Nye Lane, Room 203
Carson City, NV 89706-0866

email: GS-W-NVpublic_info@usgs.gov

http://nevada.usgs.gov

Copies of this report can be purchased from:

U.S. Geological Survey
Information Services
Building 810
Box 25286, Federal Center
Denver, CO 80225-0286

CONTENTS

FIGURES

TABLES

CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
degrees Fahrenheit per 100 ft	0.549	degrees Celsius per 100 meters
foot (ft)	0.3048	meter
foot per mile (ft/mi)	0.1894	meter per kilometer
foot per year (ft/yr)	0.3048	meter per year
inch (in.)	25.4	millimeter
mile (mi)	1.609	kilometer
million gallons per year (Mgal/yr)	3.785	million liters per year
pound per square inch per year (lb/in^2/yr)	6.895	kilopascal per year

Temperature: 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.

Analysis of Water Levels in the Frenchman Flat Area, Nevada Test Site

By Daniel J. Bright, Sharon A. Watkins, *and* Barbara A. Lisle

Abstract

Analysis of water levels in 21 wells in the Frenchman Flat area, Nevada Test Site, provides information on the accuracy of hydraulic-head calculations, temporal water-level trends, and potential causes of water-level fluctuations. Accurate hydraulic heads are particularly important in Frenchman Flat where the hydraulic gradients are relatively flat (less than 1 foot per mile) in the alluvial aquifer. Temporal water-level trends with magnitudes near or exceeding the regional hydraulic gradient may have a substantial effect on ground-water flow directions.

Water-level measurements can be adjusted for the effects of barometric pressure, formation water density (from water-temperature measurements), borehole deviation, and land-surface altitude in selected wells in the Frenchman Flat area. Water levels in one well were adjusted for the effect of density; this adjustment was significantly greater (about 17 feet) than the adjustment of water levels for barometric pressure, borehole deviation, or land-surface altitude (less than about 4 feet).

Water-level measurements from five wells exhibited trends that were statistically and hydrologically significant. Statistically significant water-level trends were observed for three wells completed in the alluvial aquifer (WW-5a, UE-5n, and PW-3), for one well completed in the carbonate aquifer (SM-23), and for one well completed in the quartzite confining unit (Army-6a).

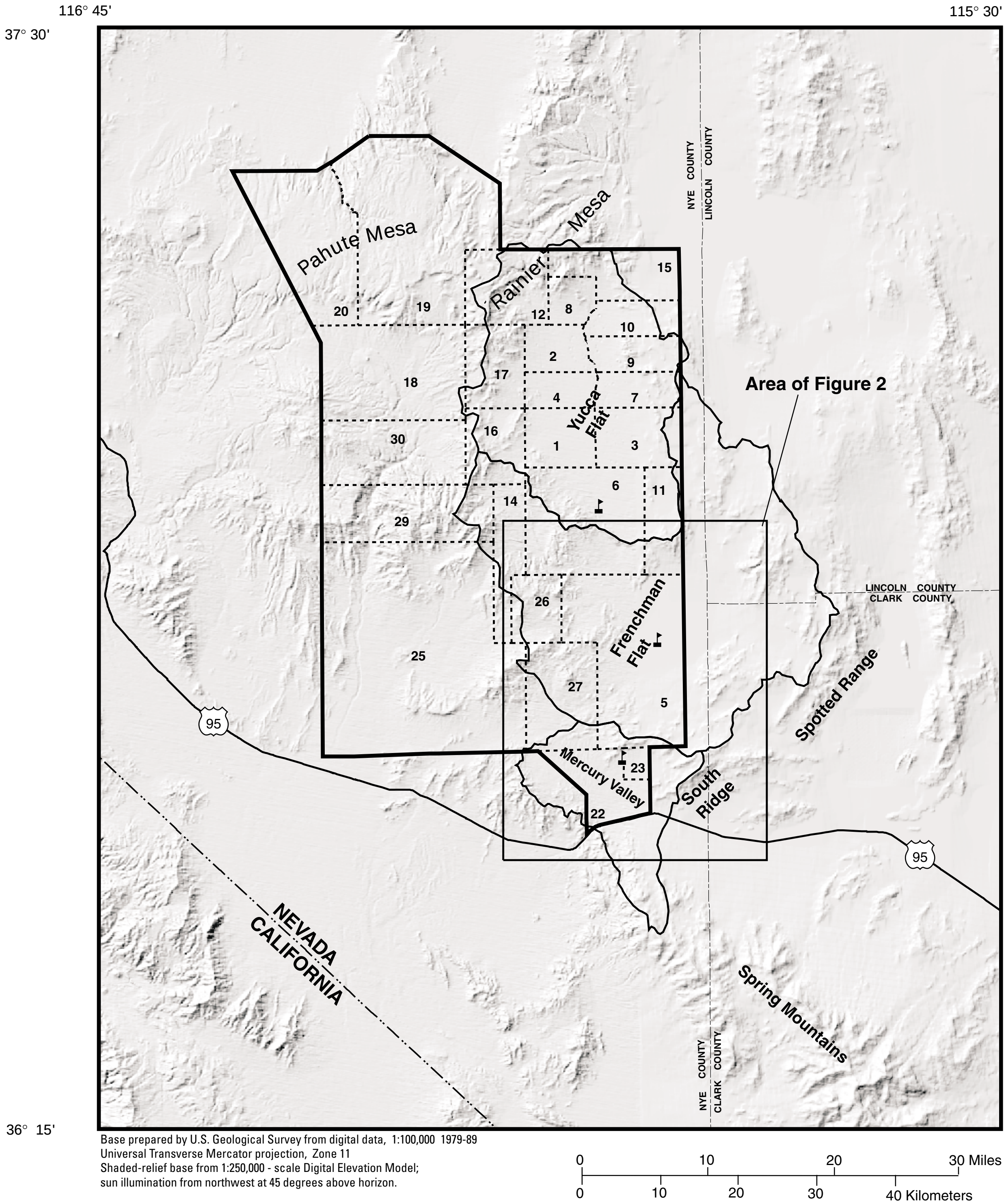
Potential causes of water-level fluctuations in wells in the Frenchman Flat area include changes in atmospheric conditions (precipitation and barometric pressure), Earth tides, seismic activity, past underground nuclear testing, and nearby pumping. Periodic water-level measurements in some wells completed in the carbonate aquifer indicate cyclic-type water-level fluctuations that generally correlate with longer term changes (more than 5 years) in precipitation. Ground-water pumping from the alluvial aquifer at well WW-5c and pumping and discharge from well RNM-2s appear to cause water-level fluctuations in nearby observation wells. The remaining known sources of water-level fluctuations do not appear to substantially affect water-level changes (seismic activity and underground nuclear testing) or do not affect changes over a period of more than 1 year (barometric pressure and Earth tides) in wells in the Frenchman Flat area.

INTRODUCTION

The Nevada Test Site (NTS) is located in Nye County, southern Nevada (fig. 1). The Frenchman Flat area, for purposes of this report, includes parts of administrative areas 5, 6, 11, 22, 23, and 27 in the southern part of NTS. These administrative areas are within the Frenchman Flat, Yucca Flat, and Mercury Valley Hydrographic Areas[1]. The Frenchman Flat Hydrographic Area is a topographically closed basin surrounded by low-lying mountains that, to the south, separate this area from the Mercury Valley Hydrographic Area and, to the north, separate it from the Yucca Flat Hydrographic Area. These hydrographic areas are in the Death Valley ground-water flow system, a regional system of about 15,000 mi^2 in the southern part of the Great Basin geographic province.

Water levels in wells in the Frenchman Flat area, an area of previous underground nuclear testing, have been measured since the 1950's when the first

[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 (Rush, 1968; Cardinalli and others, 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.



EXPLANATION

- Precipitation station
- Nevada Test Site boundary
- Administrative-area boundary within Nevada Test Site–Area number is indicated
- Hydrographic-area boundary

Figure 1. Location of Nevada Test Site, and Frenchman Flat, Mercury Valley, and Yucca Flat Hydrographic Areas, southern Nevada.

water-supply wells were constructed in this area. In Frenchman Flat, water levels generally indicate the existence of relatively flat hydraulic-head gradients (less than 1 ft/mi) in the alluvial aquifer. Determination of ground-water flow direction in areas of flat hydraulic-head gradients requires accurate water-level measurements. The accuracy of these measurements is affected by barometric pressure, formation water density (from water-temperature measurements), borehole deviation, and land-surface altitude. In addition, water levels that vary with time can be analyzed for trends, particularly those trends with magnitudes that exceed the regional hydraulic gradient and may have a substantial effect on ground-water flow directions. Determining accurate water-level measurements and temporal water-level trends will aid ongoing studies concerned with the direction of ground-water flow in these areas and the potential transport of radionuclides.

Purpose and Scope

Temporal trends of water-level measurements from 1954 to 1998 are presented for selected wells in the Frenchman Flat area, Nevada Test Site. Water-level measurements from 21 wells in Frenchman Flat, Mercury Valley, and the southernmost part of Yucca Flat (fig. 2) were compiled and quality assured to (1) provide water-level adjustments for potential causes of water-level fluctuations, (2) determine if statistically and hydrologically significant water-level trends exist, and (3) determine, if possible, the causes of water-level trends or cyclic-type water-level fluctuations. Water-level adjustments for potential causes of water-level fluctuations such as precipitation, barometric pressure, formation water density, borehole deviation, and land-surface altitude are presented for wells with available data. Causes of water-level trends were determined by statistical correlation and by qualitative comparisons of temporal data.

Hydrogeology

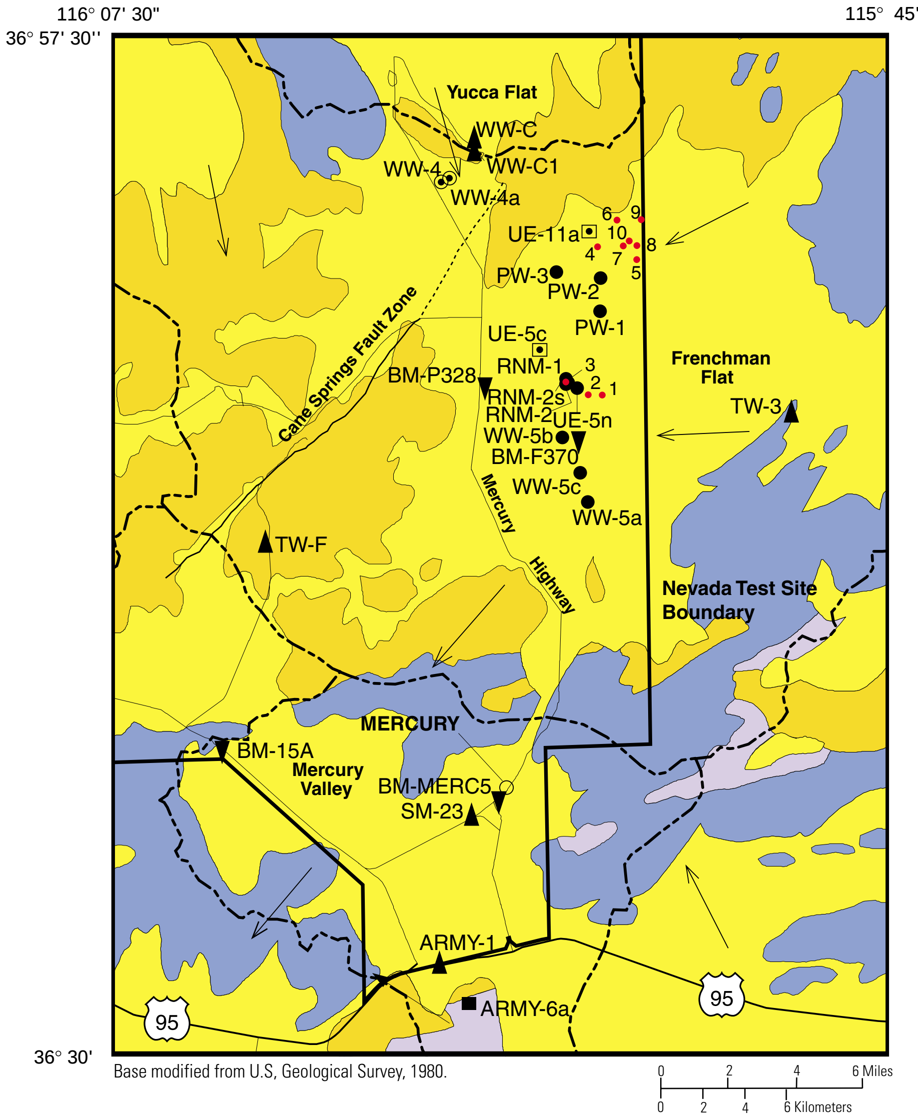
Erosion of the surrounding mountains has resulted in the accumulation of more than a thousand feet of alluvial deposits in some areas of Frenchman Flat and Mercury Valley (Winograd and Thordarson, 1975, p. C37; USGS data files, Las Vegas, Nev.). Volcanic rocks underlie the alluvium in the southern part of Yucca Flat and the northern and western parts of Frenchman Flat and, where exposed, form the surrounding low-lying mountains (fig. 2; Laczniak and others, 1996, pl. 2). Carbonate rocks primarily underlie the alluvium in the eastern and southeastern parts of Frenchman Flat and form much of the surrounding mountains in these areas. Clastic rocks are less abundant, but crop out in areas east and south of Mercury Valley.

For purposes of this report, stratigraphic units in the Frenchman Flat area (Laczniak and others, 1996, fig. 4) were divided into four hydrogeologic units. From oldest to youngest, these units include: Paleozoic clastic rocks that form the quartzite confining unit, Paleozoic limestone and dolomite that form the carbonate aquifer, Tertiary ash-flow tuff that forms the volcanic aquifer, and Tertiary and Quaternary sand and gravel (valley fill) that form the alluvial aquifer. The quartzite confining unit and overlying carbonate aquifer are regionally extensive hydrogeologic units that occur beneath the volcanic and alluvial aquifers throughout NTS.

The primary hydrogeologic units occurring in the open intervals of wells in the Frenchman Flat area are listed in table 1. For the 21 wells evaluated in this study, 10 wells are completed in the alluvial aquifer, 2 wells in the volcanic aquifer, 2 wells in alluvial and volcanic aquifers, 6 wells in the carbonate aquifer, and 1 well in the quartzite confining unit. The shallowest water level in a well occurs in the alluvial aquifer at about 681 ft below land surface (well WW-5b); the deepest water level occurs in the carbonate aquifer at more than 1,700 ft below land surface (well TW-F).

Lateral ground-water movement beneath the Frenchman Flat area primarily occurs within the carbonate aquifer (Laczniak and others, 1996, p. 26). The direction of ground-water flow in this region of the carbonate aquifer generally is from the northeast to southwest (fig. 2). Within the overlying alluvial and volcanic aquifers, lateral ground-water flow occurs from the margins to the center of the basin, and downward into the carbonate aquifer (Laczniak and others, 1996, p. 28). The hydraulic-head gradient in most areas of the alluvial aquifer in Frenchman Flat is relatively flat (less than 1 ft/mi; Winograd and Thordarson, 1975, p. C60), except near water-supply and (or) test wells (table 1).

Hydraulic heads in the only two wells completed in the volcanic aquifer (wells WW-4, WW-4a; fig. 2) are anomalously high — more than 300 ft higher than hydraulic heads in the alluvial or carbonate aquifers. Elevated water levels in these wells may be due, in part, to an extension of an inferred hydraulic barrier formed by the Cane Springs Fault Zone (fig. 2) occurring to the



EXPLANATION

- Valley fill
- Volcanic Rock
- Carbonate Rock
- Clastic Rock
- ← General direction of regional ground-water flow
- Hydrographic-area boundary

WELL AND IDENTIFIER

- ● PW-2 Well open to alluvial aquifer
- ◉ WW-4 Well open to volcanic aquifer
- ▲ TW-F Well open to carbonate aquifer
- ■ ARMY-6a Well open to quartzite confining unit
- ⊡ UE-5c Well open to alluvial and volcanic aquifers

1 ● UNDERGROUND NUCLEAR TEST AND IDENTIFIER– NTS test designations are listed in table 2

BM-F370 ▼ BENCHMARK AND IDENTIFIER–Benchmark for survey of land-surface altitudes. Identifier from NTS Bechtel Nevada data files (Rick Remington, Bechtel Nevada, written commun., 1997)

Figure 2. Surface distribution of rocks in the Frenchman Flat area, Nevada Test Site, Nevada. (Modified from Laczniak and others, 1996, fig. 4 and pl. 1.)

southeast and downgradient from the two volcanic-aquifer wells (Winograd and Thordarson, 1975, p. C60). Reported water-level altitudes in the carbonate aquifer north of the inferred barrier (Winograd and Thordarson, 1975, fig. 31), however, do not appear elevated relative to water-level altitudes in the carbonate or alluvial aquifers south of the inferred barrier.

Acknowledgments

This report is prepared in cooperation with the U.S. Department of Energy under Interagency Agreement DE-AI08-96NV11967. Meteorological data were provided by Doug Soulé of the National Oceanic and Atmospheric Administration. Land-surface altitudes presented in this report were determined from global-positioning-system data collected and evaluated by Armando Robledo, U.S. Geological Survey.

WATER-LEVEL FLUCTUATIONS

Many natural processes and human activities can cause water levels in wells to fluctuate. Natural processes that cause water-level changes in wells are climate (precipitation and atmospheric pressure), Earth tides, and seismic activity (earthquakes). Human activities known to affect water levels in wells at NTS are underground nuclear testing and ground-water withdrawal.

Climate and Earth Tides

Changes in precipitation, atmospheric (barometric) pressure, or Earth tides can cause cyclic water-level fluctuations in wells. The frequency of the cyclic fluctuations differs for each of these natural processes. Precipitation cycles typically occur on annual or seasonal frequencies, barometric-pressure cycles range from annual to diurnal frequencies, and Earth-tide cycles occur at semi-diurnal and diurnal frequencies.

Precipitation

In addition to the annual or seasonal frequency of precipitation, periods of more than 5 years of lesser- or greater-than-normal precipitation have intermittently occurred in southern Nevada. These periods of lesser- or greater-than-normal precipitation have been, in some areas of southern Nevada, a cause of cyclic water-level fluctuations in wells and of long-term water-level trends (Dettinger and Schaefer, 1995, p. 198).

Cumulative departure from mean monthly precipitation for Yucca Flat station (fig. 3; Doug Soulé, National Oceanic and Atmospheric Administration, written commun., 1998) show the long-term dry and wet periods for this area of the NTS (fig. 3*A*). Decreasing cumulative departure periods in figure 3*A* indicate lesser-than-normal (dry) precipitation conditions; increasing cumulative departure periods indicate greater-than-normal (wet) precipitation conditions. Decreasing cumulative departures occurred from the late 1950’s to about 1969 and increasing departures occurred from 1969 to about 1988. From 1988 to 1997, cumulative departure data suggest shorter periods of lesser- or greater-than-normal precipitation conditions.

Recharge to the alluvial aquifer generally is a function of precipitation, evapotranspiration, surface topography, and the thickness, vertical permeability, and heterogeneity of the unsaturated zone. Average-annual precipitation at stations in Mercury, Frenchman Flat (well WW-5b), and Yucca Flat (fig. 1) ranges from 4.85 inches to 6.66 inches (figs. 3*B*-3*D*). Relatively low annual precipitation, high air temperatures, high evapotranspiration rates, and a thick unsaturated zone of more than 600 ft below land surface suggest that precipitation in the Frenchman Flat area is not a likely source of water-level fluctuations in wells completed in the alluvial aquifer. For example, an analysis of soil-water chemistry (Tyler and others, 1996, p. 1487) at wells PW-1, PW-2, and PW-3 in Frenchman Flat indicate that recharge has not occurred in this area since the last two glacial maxima, about 20,000 and 120,000 years before present when the climate was considerably wetter and cooler.

In areas where the downward movement of ground water occurs through fractured rock, the potential for cyclic fluctuations in wells due to precipitation may be greater than that of the alluvial aquifer. In the volcanic and carbonate aquifers, for example, recharge through fracture systems in areas where fractured formations outcrop might provide a mechanism for precipitation-induced water-level fluctuations to occur in wells completed beneath relatively thick unsaturated zones. Lehman and Brown (1996) reported cyclic water-level fluctuations in wells completed in the volcanic aquifer near Yucca Mountain where the unsaturated-zone thickness generally is greater than 1,000 ft. Lehman and Brown (1996, p. 10) concluded that the

Table 1. Well-completion, water-level, and water-use information for wells in the Frenchman Flat area, Nevada Test Site

Depth of well: Depth to bottom of open interval of borehole or to bottom of perforated interval of well at time of completion.

Periodic data type: Water levels measured by wire-line, steel tape, or electric tape.

Continual data type: Water levels measured by pressure transducer.

Water levels: Period of record for water levels used for trend analysis (see section titled "Analysis of Water Levels" in text).

Withdrawal: Period of record for annual water withdrawal (years with zero withdrawal not included); —, not applicable.

Local well name	USGS site identification number [1]	Latitude (degrees, minutes, seconds)	Longitude (degrees, minutes, seconds)	Depth of well (feet)	Year of completion	Hydrogeologic unit	Type of water-level measurement	Use of well	Period of record	
									Water levels	Withdrawal
						Mercury Valley				
Army-1	363530116021401	36°35′30″	116°02′14″	1,953	1962	carbonate	periodic	water-supply	1962–97	[2]1962–97
Army-6a	363437116010801	36°34′37″	116°01′08″	1,228	1955	quartzite confining unit	periodic	observation	1958–97	—
SM-23	363905116005801	36°39′05″	116°00′58″	1,332	1996	carbonate	periodic	observation	1996–97	—
							continual		1996–97	
						Frenchman Flat				
PW-1	365105115565801	36°51′06″	115°56′58″	839	1992	alluvium	periodic	observation	1993–96	—
PW-2	365152115565701	36°51′52″	115°56′57″	920	1992	alluvium	periodic	observation	1993–96	—
PW-3	365201115581601	36°52′01″	115°58′16″	955	1992	alluvium	periodic	observation	1993–96	—
RNM-1	364928115580101	36°49′28″	115°58′01″	[3]999	1974	alluvium	periodic	observation	1975–77	—
RNM-2	364923115575701	36°49′23″	115°57′57″	935	1974	alluvium	periodic	observation	1974–85	—
RNM-2s	364922115580101	36°49′22″	115°58′01″	1,156	1974	alluvium	periodic	test well/observation	1974–97	1975–91
TW-3	364830115512601	36°48′30″	115°51′26″	1,516	1962	carbonate	periodic	observation	1963–97	—
TW-F	364534116065902	36°45′34″	116°06′59″	3,400	[4]1962	carbonate	periodic	observation	1962–97	—
UE-5c	365011115584702	36°50′11″	115°58′47″	2,682	[5]1964	volcanic/alluvium	periodic	water-supply	1971–87	[6]1967–97
UE-5n	364915115574101	36°49′15″	115°57′41″	1,687	1976	alluvium	periodic	observation	1977–97	—
UE-11a	365259115571601	36°52′59″	115°57′16″	1,400	[7]1965	volcanic/alluvium	periodic	observation	1991–96	—
WW-4	365418116012601	36°54′18″	116°01′26″	1,479	1981	volcanic	periodic	water-supply	1983–97	1983–97
							continual		[8]1992–93	
WW-4a	365412116013901	36°54′12″	116°01′39″	1,516	1990	volcanic	periodic	water-supply/observation	1990–97	1993–97
							continual		1991–93	
WW-5a	364635115572901	36°46′35″	115°57′29″	910	1951	alluvium	periodic	water-supply/observation	1959–97	1951–70
							continual		1996–98	
WW-5b	364805115580801	36°48′05″	115°58′08″	900	1951	alluvium	periodic	water-supply	1959–91	[2]1951–97
WW-5c	364708115574401	36°47′20″	115°57′49″	1,200	1954	alluvium	periodic	water-supply	1954–93	[2]1954–97

Table 1. Well-completion, water-level, and water-use information for wells in the Frenchman Flat area, Nevada Test Site—Continued

Local well name	USGS site identification number [1]	Latitude (degrees, minutes, seconds)	Longitude (degrees, minutes, seconds)	Depth of well (feet)	Year of completion	Hydrogeologic unit	Type of water-level measurement	Use of well	Period of record	
									Water levels	Withdrawal
						Southern Yucca Flat				
WW-C	365508116003501	36°55′08″	116°00′35″	1,701	1961	carbonate	periodic	water-supply	1961–75	[2]1961–95
	365508116003502	36°55′08″	116°00′35″							
WW-C1	365500116003901	36°55′07″	116°00′34″	1,707	1962	carbonate	periodic	water-supply	1962–72	[2]1962–97

[1] The U.S. Geological Survey system for site identification is based on the latitude-longitude grid. Each site is identified by a unique 15-digit number: The first six digits denote degrees, minutes, and seconds of latitude; the next seven digitis denote degrees, minutes, and seconds of longitude; and the last two digits are the sequence number of the well or test hole within the 1-second grid of latitude and longitude. The assigned number is retained as a permanent identifier even if a more precise latitude and longitude are later determined. To determine the geographic location of a well or test hole, the latitude and longitude coordinates should be used rather than the site identifier.

[2] Withdrawal data missing for 1972–82.

[3] Equals depth to bridge plug inside casing.

[4] Original well completed in 1961 to a depth of 1,871 ft; well deepened to a depth of 3,400 ft in 1962.

[5] Well recompleted with new perforated interval in April 1966.

[6] Withdrawal data missing for 1968–82.

[7] Well recompleted (borehole cleaned for geophysical logging) in October 1982.

[8] Trend analysis not performed due to short period of record (from December 1992 to March 1993).

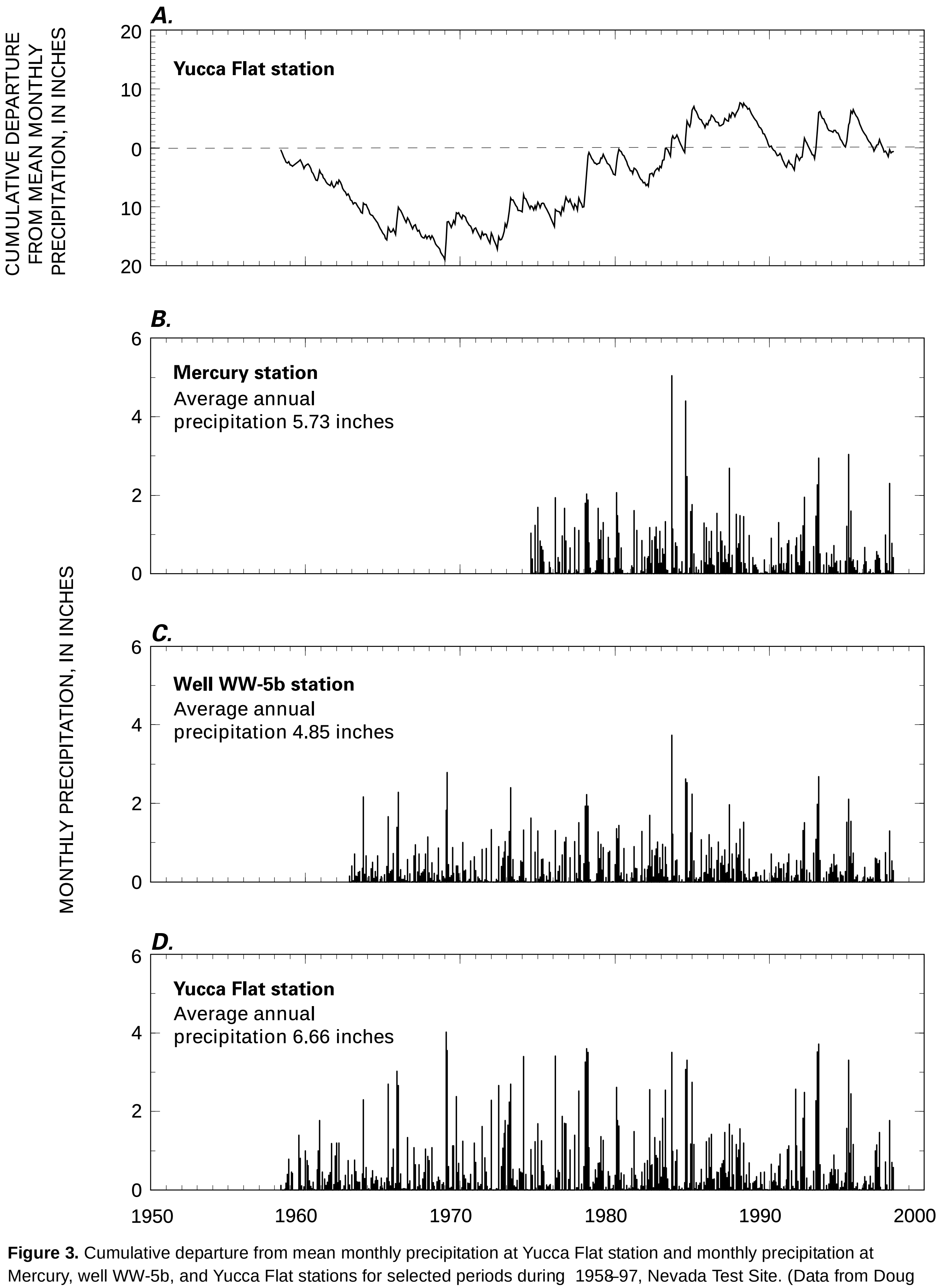


Figure 3. Cumulative departure from mean monthly precipitation at Yucca Flat station and monthly precipitation at Mercury, well WW-5b, and Yucca Flat stations for selected periods during 1958–97, Nevada Test Site. (Data from Doug Soulé, National Oceanic and Atmospheric Administration, written commun., 1998.)

period of cyclic water-level fluctuations in these wells was 2–3 years and suggested that these fluctuations may be the result of recharge from precipitation. However, a subsequent study of water-level fluctuations in the same wells near Yucca Mountain (Graves and others, 1997, p. 69) concluded that the 11-year water-level record used by Lehman and Brown (1996) was not sufficient to determine if a 2- to 3-year period of cyclic water-level fluctuations was present.

Barometric Pressure

Water-levels in numerous wells completed in confined or semi-confined aquifers at NTS fluctuate in response to changes in barometric pressure. Water levels in well WW-5a in the central part of Frenchman Flat, for example, illustrate this relation (fig. 4*A*). Water levels respond inversely to barometric-pressure changes, with an increase in barometric pressure causing a decrease in the water level. The magnitudes of short-term (less than 10 days) water-level fluctuations in wells vary throughout the year but commonly have a maximum amplitude of about 1 ft during the winter season when changes in barometric pressure are greatest.

Water-level fluctuations in wells due to barometric-pressure changes probably are not a significant cause of long-term water-level trends at NTS. Barometric-pressure changes occur at Desert Rock station near Mercury (fig. 4*B*; National Climatic Data Center, National Oceanic Atmospheric and Administration, unpublished data accessed May 6, 1999, on the World Wide Web at URL <http://www.ncdc.noaa.gov>) on an annual frequency with maximum pressures during the winter months. Linear regression of the long-term barometric-pressure records yields a slope of +0.0003 $lb/in^2/yr$, which in equivalent units of head is about +0.0007 ft/yr. This rate of change is less than water-level measurement error and could not be detected in long-term water-level trends.

Earth Tides

Earth tides are caused by the gravitational forces exerted on the Earth's surface by the sun and the moon. As the relative configuration of the sun, moon, and Earth change, gravitational fields fluctuate and cause corresponding deformations in the Earth's crust. Crustal deformation caused by Earth tides can affect aquifer pore pressure, which can result in water-level fluctuations in wells. Five principal Earth tides are strong enough to cause measurable water-level fluctuations in wells (O'Brien, 1997, p. 61). These five principal Earth tides induce water-level fluctuations at semi-diurnal and diurnal frequencies.

The amplitude of Earth-tide induced water-level fluctuations in wells near NTS generally is less than about 0.40 ft, which in comparison to other sources is relatively small. Analysis of water levels in wells 20–50 mi south and southeast of NTS indicated that Earth tides caused water-level fluctuations with amplitudes from 0.0004 to 0.056 ft (Kilroy, 1992, table 5). Reported amplitudes of water-level fluctuations due to Earth tides in wells near Yucca Mountain are as high as 0.40 ft (Geldon and others, 1998, p. 12). Because of the small and consistent amplitude of Earth-tide induced water-level fluctuations, Earth tides are not a likely source of long-term water-level trends at NTS.

Seismic Activity

From 1950 to 1998, 526 earthquakes of magnitude 4 or greater were documented at or near NTS (Seismological Laboratory, University of Nevada, Reno, unpublished data accessed September 10, 1998, on the World Wide Web at URL <http://www.seismic.unr.edu>). Only 33 of these earthquakes occurred after 1992, the year the moratorium on nuclear testing was established. Consequently, many of these earthquakes likely were associated with nuclear testing in the Pahute Mesa and Yucca Flat areas of NTS (fig. 1) where most of the earthquake epicenters were recorded.

Water-level fluctuations in response to earthquakes are relatively common phenomena in wells completed in confined aquifers (Todd, 1980). Generally, high frequency (a continual chart recorder or measurement of less than 1 per second) water-level measurements are necessary for detecting seismically induced water-level fluctuations in wells. Periodic water-level measurements generally are not sufficient for detecting dynamic earthquake-induced fluctuations, but may be adequate for monitoring long-term effects on water levels after a seismic event has occurred.

Continual water-level measurements in wells near Yucca Mountain showed a response to the Landers (magnitude 7.5), Big Bear (magnitude 6.6), and Little Skull Mountain (magnitude 5.6) earthquakes that occurred between June 28 and June 29, 1992. The earthquake epicenters were about 15 to 190 mi away

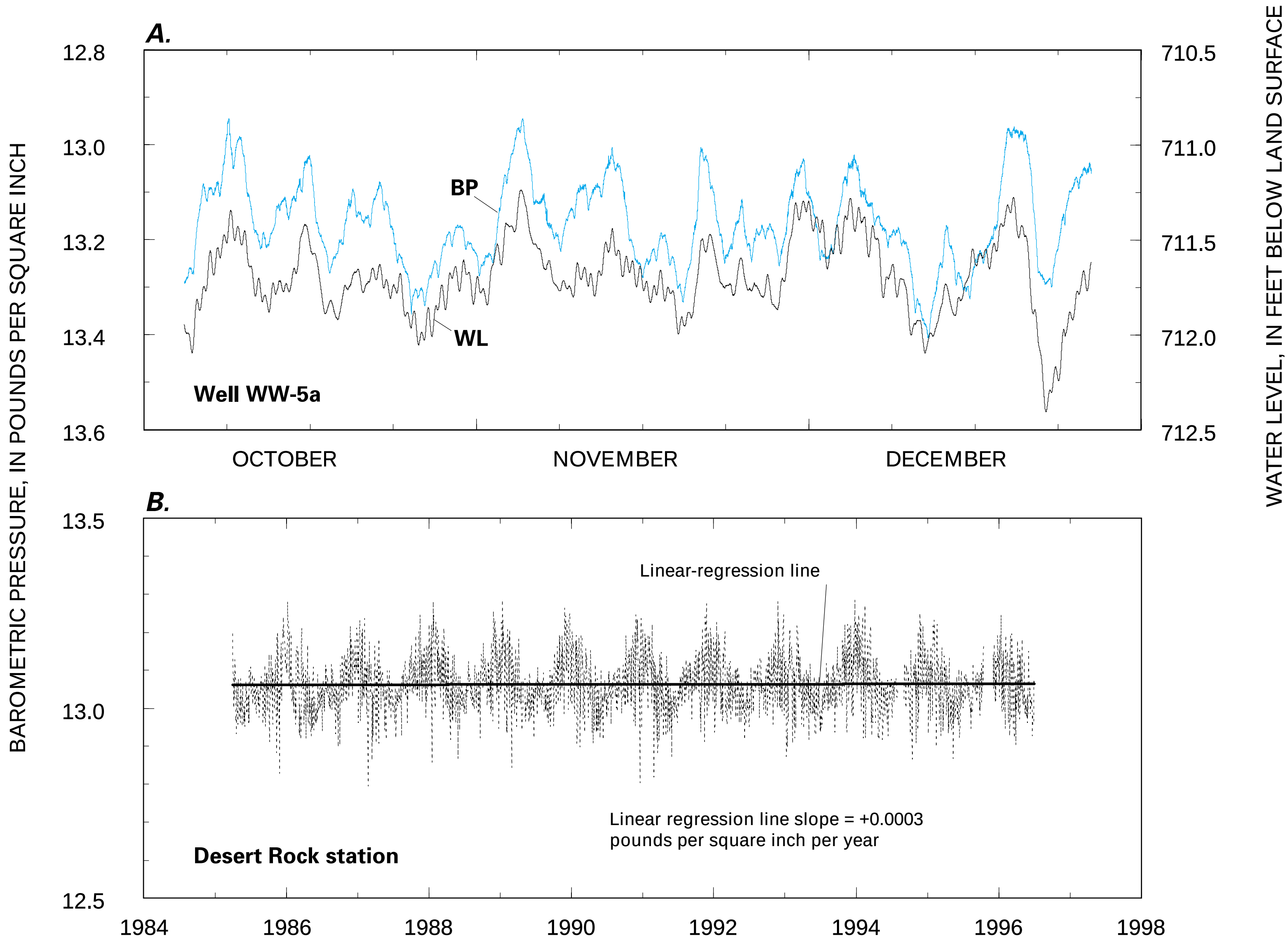


Figure 4. *(A)* Barometric pressure (BP) and water levels (WL) at well WW-5a for 1996 and *(B)* barometric pressure at Desert Rock station near Mercury, Nevada, for 1985–96, Nevada Test Site. (Data from Doug Soulé, National Oceanic and Atmospheric Administration, written commun., 1988.)

from the wells at Yucca Mountain. Water-level fluctuations in response to these earthquakes ranged in amplitude from about 2 to 35 inches (O'Brien, 1993, p. 8). However, continual water-level measurements at 15-minute intervals in well WW-4a, located about the same distance from the earthquake epicenters as the wells at Yucca Mountain, did not show any response to these earthquakes. Water levels in this well are strongly influenced by pumping in nearby well WW-4 and the pumping most likely masked any potential water-level response. Well WW-4a was the only well in the Frenchman Flat area in June 1992 instrumented for continual water-level measurements.

Water levels were monitored in well SM-23 at 15-minute intervals from June 1996 to June 1997, and in well WW-5a at 5-minute intervals from June 1996 to December 1997. During these periods, seven earthquakes of magnitude 4.0 to 5.0 occurred within approximately a 125-mi radius of Frenchman Flat (no earthquakes of magnitudes greater than 5.0 were recorded during this period). Water-level records for these two wells did not show any response to these earthquakes. A lack of water-level response may be due to numerous factors. For example, barometric pressure at well SM-23 or nearby pumping at well WW-5a may have obscured an earthquake-induced water-level response. Additionally, a lack of response in these wells may be due to the long distance or small magnitude of the seismic event.

The long-term effects of seismic activity on water levels may include elevated or depressed water-level altitudes. Typically, seismically induced water-level fluctuations equilibrate with pre-earthquake altitude (Ferris and others, 1962), but cases have been reported where a new equilibrium water-level altitude has been established. For example, the response of water levels differed in wells near Yucca Mountain after the June 28–29, 1992, earthquakes—both elevated and depressed water-level fluctuations were observed and water levels in one well did not return to the pre-earthquake altitude more than 3 years later (Graves and others, 1997, fig. 39). Water-level measurements in wells in the Frenchman Flat area do not indicate any general shifts to a new elevated or depressed equilibrium as a result of seismic activity.

Underground Nuclear Testing

Prior to the moratorium on nuclear testing in September 1992, a reported 828 underground nuclear tests were detonated at NTS (U.S. Department of Energy, 1994). Most underground tests were detonated in Yucca Flat, Rainier Mesa, and Pahute Mesa (fig. 1). Ten nuclear tests were detonated in the Frenchman Flat area between 1965 and 1971 (table 2). Three tests were detonated in the central part of basin (in the vicinity of the RNM and UE-5n wells) and seven tests northeast of well PW-3 (fig. 2) near the border of NTS. These tests were detonated in the alluvial or volcanic aquifers overlying the regional carbonate aquifer (Laczniak, 1996, p. 23).

Similar to the effects of earthquakes, nuclear detonations may cause short-term dynamic water-level fluctuations in wells and (or) long-term effects of elevated or depressed water-level altitudes. The detection of short-term water-level fluctuations in wells requires high-frequency monitoring instrumentation or many manual measurements shortly after the test. These measurements, however, were not collected from wells in the Frenchman Flat area during the period of underground nuclear testing between 1965 and 1971.

Long-term effects of underground nuclear testing on water levels typically include lowered (depressed) levels within the chimney region (borehole "rubble" area above the detonation) of the nuclear test and elevated levels outside the chimney region (Laczniak and others, 1996, p. 44). Documented decreases in water levels within the chimney region can be up to hundreds of feet (Laczniak and others, 1996, p. 44). Lowered water levels in the chimney region have been attributed to increased drainage through the more porous rubble and to the expulsion of water by the explosion. Although highly pulverized rock typically extends radially outward from the chimney region, zones nearest the chimney region after a test often become less permeable than the native (pre-shot) rock. This reduction in permeability is due to tight compaction induced by the compressional shock wave generated by the test and to the local injection of radioactive molten rock along fractures.

Lowered water levels in well RNM-1 in central Frenchman Flat are likely due to the long-term effects of a nuclear detonation. Well RNM-1 was drilled as a re-entry hole into the chimney region of the 1965 Cambric underground nuclear test (Nimz and Thompson, 1992, p. 7). During the period of water-

Table 2. Underground nuclear tests in the Frenchman Flat area, Nevada Test Site

[Sources of data: U.S. Department of Energy (1994) and Drellack (1995). Symbol: <, less than]

Local well number	Cross-reference number (fig. 2)	Test name	Depth of hole (feet)	Detonation		
				Depth (feet)	Date	Yield (kilotons)
Central Frenchman Flat						
U-5a	1	Wishbone	628	574	Feb. 18, 1965	<20
U-5b	2	Diluted Waters	675	632	June 16, 1965	<20
U-5e	3	Cambric	1,000	967	May 14, 1965	.75
Northeast Frenchman Flat						
U-5i	4	Derringer	2,124	837	Sept. 12, 1966	7.8
U-5k	5	Milk Shake	905	868	Mar. 25, 1968	<20
U-11b	6	Pin Stripe	980	970	Apr. 25, 1966	<20
U-11c	7	New Point	835	785	Dec. 13, 1966	<20
U-11e	8	Diana Moon	835	794	Aug. 27, 1968	<20
U-11f	9	Minute Steak	910	868	Sept. 12, 1969	<20
U-11g	10	Diagonal Line	1,155	867	Nov. 24, 1971	<20

level measurements in well RNM-1 (1975–77), the average water-level altitude was more than 50 ft below the average water levels in nearby wells RNM-2 and RNM-2s. The lag in water-level recovery in well RNM-1 to levels measured in nearby wells may be the result of a post-shot, low permeability zone that often forms adjacent to the chimney region.

Water-level data for Frenchman Flat are too sparse to determine elevated water-level altitudes from comparing pre- and post-shot potentiometric surfaces. However, recent (1996) water-level measurements indicate that the difference in water-level altitudes between wells in the central and northeastern parts of Frenchman Flat is less than 3 ft. The minimal difference in water-level altitudes between wells in these areas suggests that elevated water levels currently do not exist in wells within the Frenchman Flat testing areas.

Ground-Water Withdrawal

Ground-water withdrawals from the Frenchman Flat area have been made by 10 production wells. Monthly and annual withdrawal data, however, are incomplete. Excluding well RNM-2s, limited monthly withdrawal data are available for 1958–67 but are not available for 1968–82. Complete monthly withdrawal data are available for 1983–97 (fig. 5). Annual withdrawal data are not available for all wells from 1972 to 1982 except wells UE-5c and RNM-2s. For well UE-5c, annual withdrawal data are not available for 1964–66 and for 1968–82. Annual withdrawal data are available for well RNM-2s for 1975–91. Annual withdrawals are summarized for each production well in table 3 and for each aquifer in figure 6.

Available withdrawal data (table 3) indicate an upward trend in water use in the Frenchman Flat area from an average use of about 130 Mgal/yr for 1951–71 to about 430 Mgal/yr for 1983–97. Since 1989, the year of peak water use (based on existing data), water use has decreased. Ground-water withdrawals in 1996–97 are the lowest since 1961. Relatively low ground-water withdrawals since 1989 coincide with the general decrease in operational activities at NTS following the ban on nuclear testing in 1992.

Ground water in Frenchman Flat, during years in which data are available, primarily has been pumped from wells RNM-2s, WW-5b, WW-5c, UE-5c, WW-4, and WW-4a. Test well RNM-2s was pumped from 1975 to 1991 for a radionuclide migration experiment and the remaining wells have been pumped for water supply (table 1). In Mercury Valley, ground-water withdrawal has been from water-supply well Army-1 and in southern Yucca Flat from water-supply wells WW-C and WW-C1.

Previous investigations in the Frenchman Flat area indicate that ground-water withdrawal from some water-supply wells appears to affect water levels in nearby wells. For example, a tracer experiment at wells WW-C and WW-C1 (fig. 2) showed a direct hydraulic

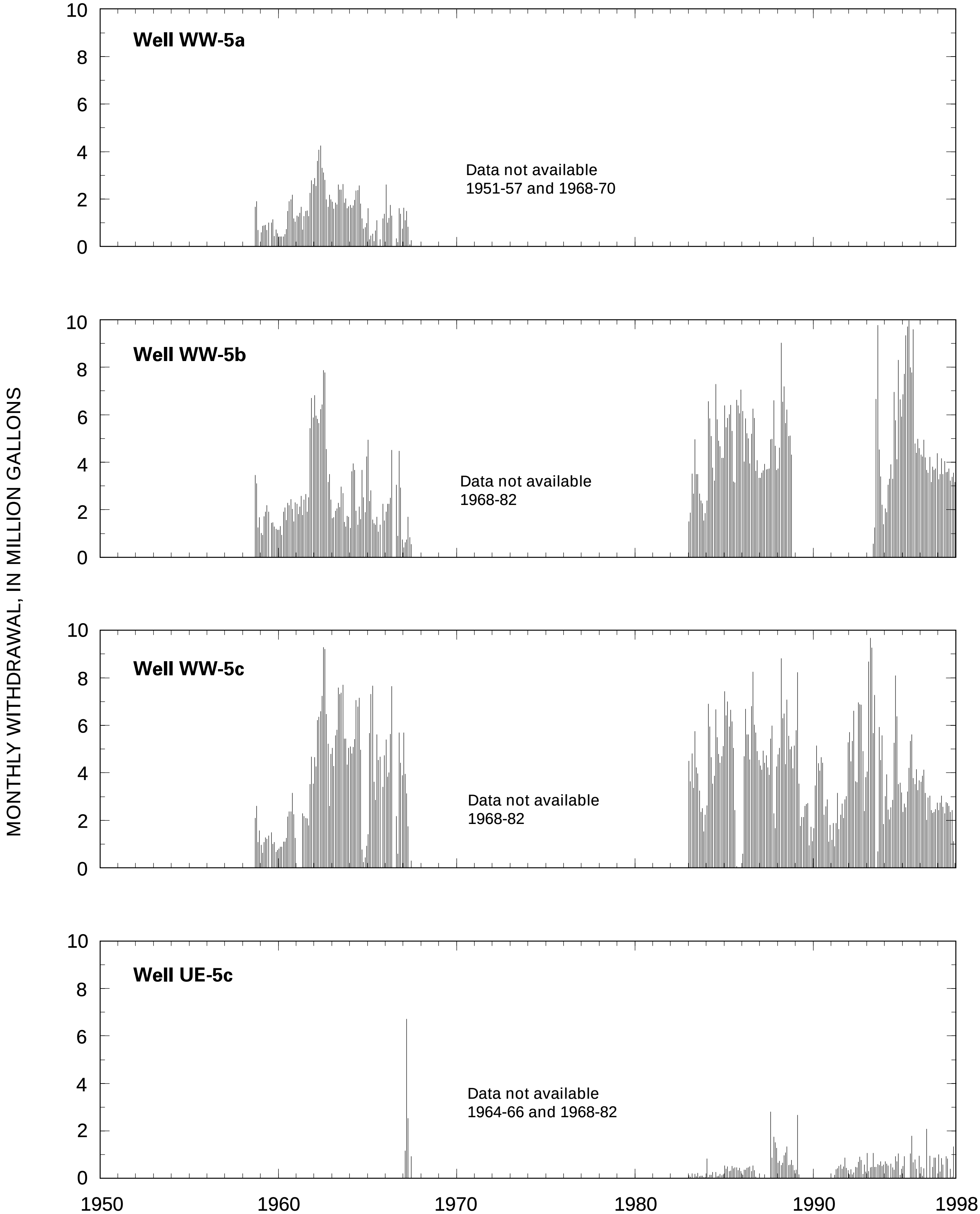


Figure 5. Monthly withdrawals for selected wells in the Frenchman Flat area, Nevada Test Site. Monthly withdrawal data not available for some years in which annual withdrawal data are available.

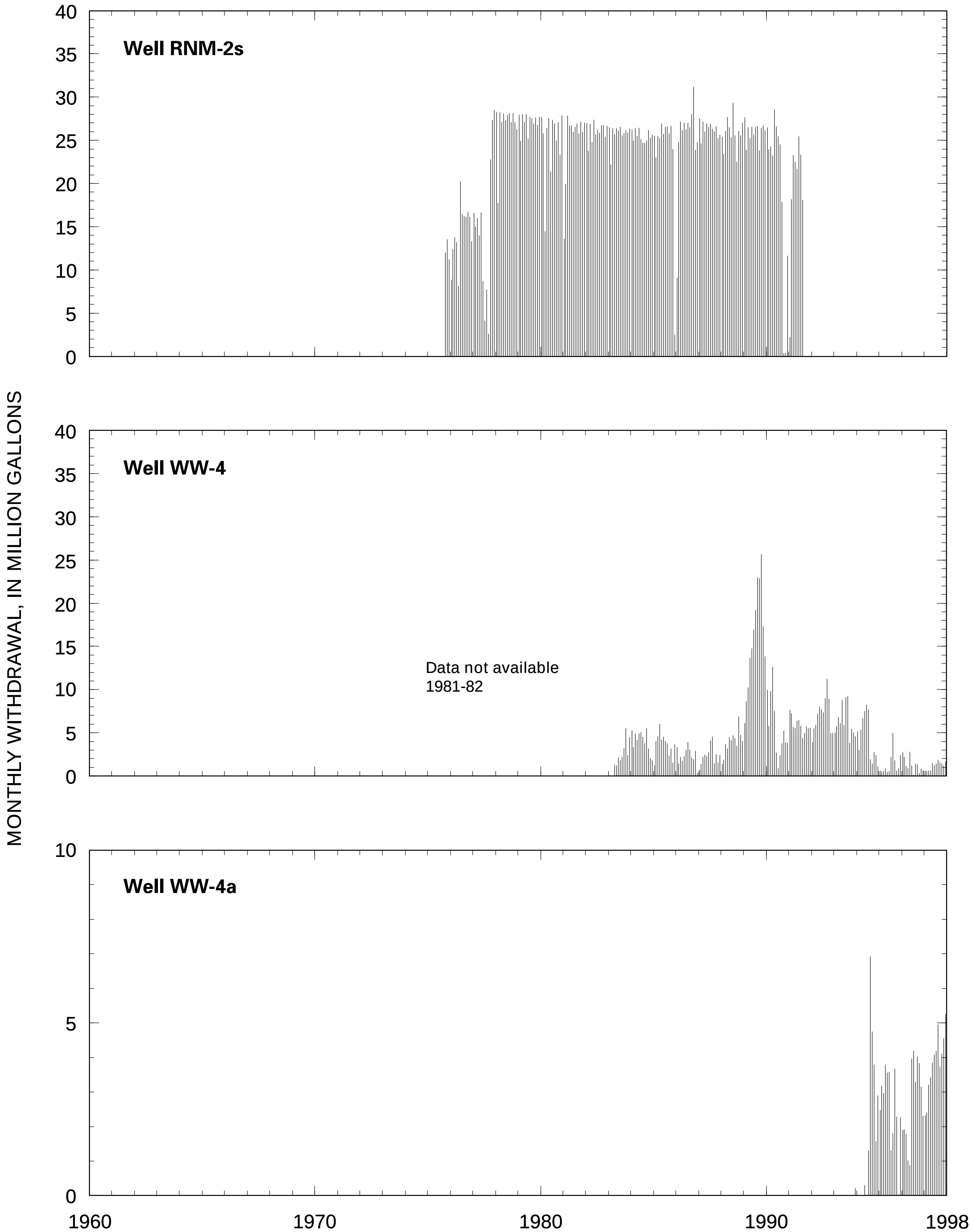


Figure 5. Continued.

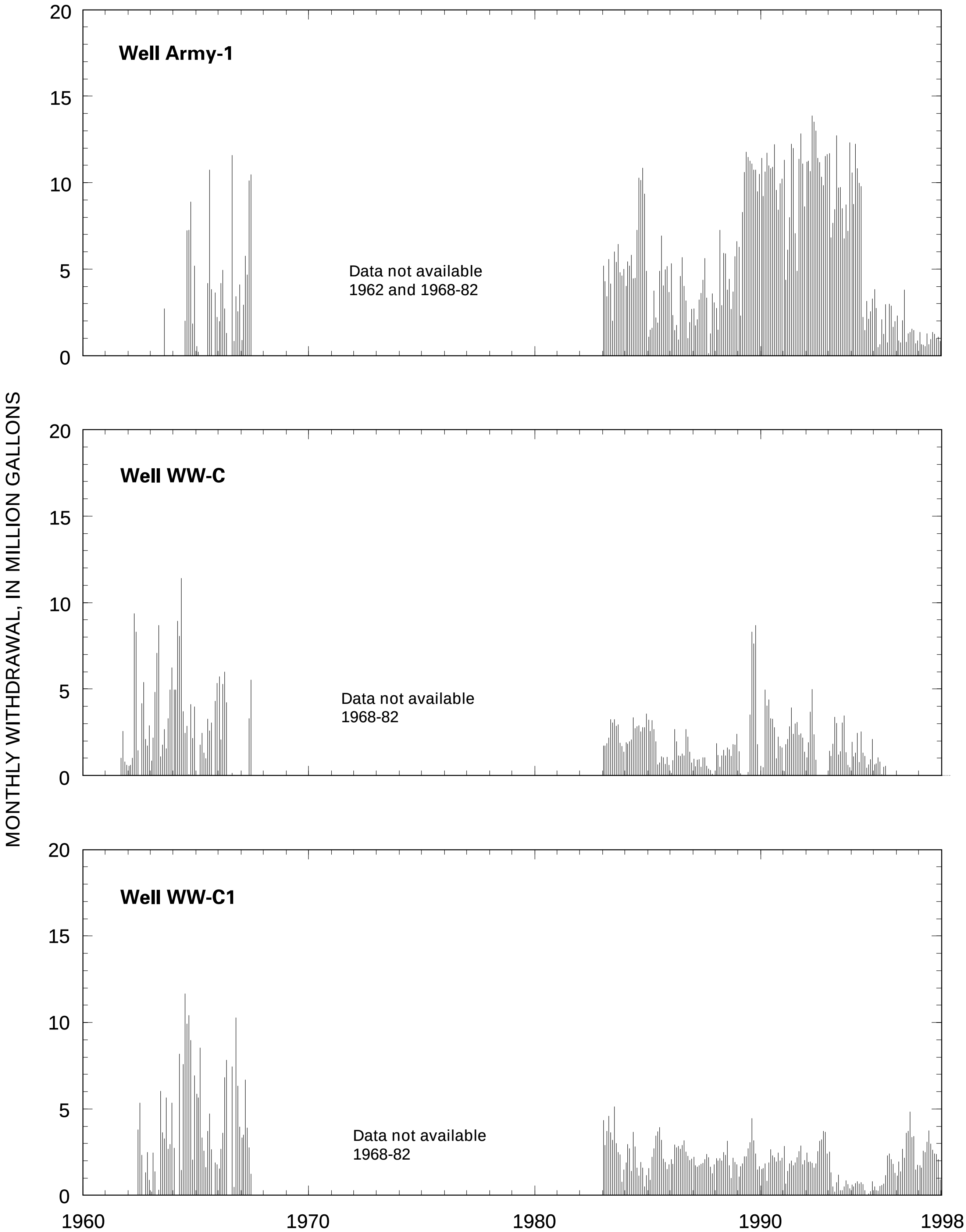


Figure 5. Continued.

Table 3. Annual water withdrawal from water-supply wells and test well RNM-2s in the Frenchman Flat area, Nevada Test Site, 1951–97

[ND, no data (withdrawal data not available); —, well not yet drilled. Total, annual withdrawal for available data]

	Water withdrawal (million gallons)										
Year	**Army-1**	**RNM-2s**	**UE-5c**	**WW-4**	**WW-4a**	**WW-5a**	**WW-5b**	**WW-5c**	**WW-C**	**WW-C1**	**Total**
1951	—	—	—	—	—	[1]9.7	[1]20.3	—	—	—	30.0
1952	—	—	—	—	—	[1]9.7	[1]20.3	—	—	—	30.0
1953	—	—	—	—	—	[1]9.7	[1]20.3	—	—	—	30.0
1954	—	—	—	—	—	[1]9.7	[1]20.3	[2]18.1	—	—	48.1
1955	—	—	—	—	—	[1]9.7	[1]20.3	[2]18.1	—	—	48.1
1956	—	—	—	—	—	[1]9.7	[1]20.3	[2]18.1	—	—	48.1
1957	—	—	—	—	—	[1]9.7	[1]20.3	[2]18.1	—	—	48.1
1958	—	—	—	—	—	7.2	26.3	20.2	—	—	53.7
1959	—	—	—	—	—	9.8	17.9	12.8	—	—	40.5
1960	—	—	—	—	—	12.7	21.7	19.6	—	—	54.0
1961	—	—	—	—	—	19.5	37.2	22.1	4.9	—	83.7
1962	4.2	—	—	—	—	34.5	66.1	72.9	37.4	16.2	231.3
1963	2.7	—	—	—	—	23.8	23.3	69.5	43.0	31.5	193.8
1964	30.7	—	ND	—	—	19.5	30.8	48.3	56.9	70.6	256.8
1965	25.4	—	ND	—	—	9.8	23.2	58.0	30.9	39.1	186.4
1966	47.3	—	ND	—	—	16.6	35.9	56.6	34.0	76.0	266.4
1967	56.1	—	16.5	—	—	14.7	9.0	43.6	28.9	34.0	202.8
1968	52.7	—	ND	—	—	16.2	10.4	59.5	81.0	26.9	246.7
1969	78.1	—	ND	—	—	5.7	6.8	39.9	95.6	36.4	262.5
1970	69.4	—	ND	—	—	3.5	23.6	41.1	62.4	18.3	218.3
1971	96.1	—	ND	—	—	0	8.1	44.2	83.4	20.4	252.2
1972	ND	—	ND	—	—	ND	ND	ND	ND	ND	ND
1973	ND	—	ND	—	—	ND	ND	ND	ND	ND	ND
1974	ND	ND	ND	—	—	ND	ND	ND	ND	ND	ND
1975	ND	36.7	ND	—	—	ND	ND	ND	ND	ND	36.7
1976	ND	171.5	ND	—	—	ND	ND	ND	ND	ND	171.5
1977	ND	179.8	ND	—	—	ND	ND	ND	ND	ND	179.8
1978	ND	321.2	ND	—	—	ND	ND	ND	ND	ND	321.2
1979	ND	325.2	ND	—	—	ND	ND	ND	ND	ND	325.2
1980	ND	300.7	ND	—	—	ND	ND	ND	ND	ND	300.7
1981	ND	300.0	ND	ND	—	ND	ND	ND	ND	ND	300.0
1982	ND	312.9	ND	ND	—	ND	ND	ND	ND	ND	312.9
1983	56.8	309.5	1.3	24.1	—	0	32.2	42.1	27.7	37.6	531.3
1984	82.1	305.9	2.4	48.4	—	0	57.9	58.7	31.2	23.3	609.9
1985	41.6	283.8	5.0	42.9	—	0	67.8	47.1	19.4	29.0	536.6
1986	34.9	301.7	3.5	28.2	—	0	58.5	64.0	17.3	30.1	538.2
1987	34.7	315.3	8.4	28.2	—	0	50.5	50.3	7.2	22.3	516.9
1988	53.1	310.2	8.8	46.7	—	0	57.5	67.8	17.4	24.8	586.3
1989	114.4	311.6	3.2	192.0	—	0	0	35.4	31.6	28.1	716.3
1990	126.0	233.1	0	68.2	0	0	0	38.4	29.7	23.3	518.7

Table 3. Annual water withdrawal from water-supply wells and test well RNM-2s in the Frenchman Flat area, Nevada Test Site, 1951-97—Continued

Year	Water withdrawal (million gallons)										
	Army-1	RNM-2s	UE-5c	WW-4	WW-4a	WW-5a	WW-5b	WW-5c	WW-C	WW-C1	Total
1991	109.9	154.6	4.5	70.7	0	0	0	28.8	27.7	23.8	420.0
1992	139.4	0	5.3	84.5	0	0	0	61.1	14.8	30.3	335.4
1993	110.2	0	7.3	75.4	.2	0	29.8	63.2	22.2	9.4	317.7
1994	76.9	0	6.5	53.0	21.5	0	55.2	46.8	16.5	6.1	282.5
1995	24.1	0	7.1	16.2	30.9	0	87.7	44.3	4.2	13.9	228.4
1996	17.7	0	6.2	15.5	32.2	0	47.8	35.0	0	31.4	185.8
1997	11.4	0	6.3	14.1	46.0	0	42.6	27.2	0	28.6	176.2

[1] Equals average annual withdrawal for 1951–57.
[2] Equals average annual withddrawal for 1954–57.

connection between the two wells, which are about 100 ft apart and completed in the carbonate aquifer (Isaac Winograd and Lewis West, U.S. Geological Survey, written commun., 1962). A hydraulic connection between wells WW-5a and WW-5c can be inferred from similarities in water-level changes, specific capacity, and water chemistry (Claassen, 1973, p. 38). Wells WW-5a and WW-5c are about 1 mile apart and completed in the alluvial aquifer.

WATER-LEVEL MEASUREMENTS

Water levels in wells in the Frenchman Flat area were measured periodically by manual methods and (or) continually (5- or 15-minute measurement intervals) by pressure transducers. Periodic water-level measurements for 21 wells in the Frenchman Flat area are shown in figure 7. The mean, minimum, and maximum static water levels in these wells are summarized in table 4. Continual water-level measurements for three wells in Mercury Valley, Frenchman Flat, and southern Yucca Flat are shown in figure 8.

Water levels in pumping wells at NTS (table 1) generally were not measured for at least 24 hours after pumping to allow the water level in the well to return to the pre-pumping level. A water-level measurement 24 hours after pumping stops may better represent a static-aquifer condition. A water-level measurement within 24 hours of pumping may represent a non-static or recovering aquifer condition. The actual time for water levels in pumping wells to fully recover to a pre-pumping level is, in part, a function of the hydraulic conductivity of the aquifer, the efficiency of the well, and the magnitude of the water-level drawdown in the well. Therefore, the water-level recovery time in wells at NTS varies and may extend beyond 24 hours; as a result, pumping-well water-level measurements may or may not represent static-aquifer conditions. Water-level measurements in pumping wells known to be affected by or likely affected by recent pumping are noted in the hydrographs shown in figure 7.

Water-level measurements made immediately after the well was drilled may not represent static-aquifer conditions. The time required for water levels to equilibrate varies but depends on the type of drilling fluid, the well-developing techniques, and on the permeability of the formation contributing water to the well. Anomalous water-level measurements collected in the same year that the borehole was drilled are noted in the hydrographs shown in figure 7.

Also noted in figure 7 are water levels affected by oil in the well and “anomalous” water-level measurements. Water levels in wells in the Frenchman Flat area have been affected by oil only in well TW-3. Water-level measurements for this well from 1964 to 1997 likely represent the depth below land surface to the top of the oil column in the well. The thickness of the oil column in well TW-3 has been estimated to be less than 1.5 ft (U.S. Geological Survey data files, Las Vegas, Nev.) Anomalous measurements indicate water levels that differ from previous or more recent measurements for unknown reasons. For purposes of this report, anomalous measurements include statistical outliers—water-level measurements that fall outside the 95-percent confidence interval computed for the water-level trend analysis (see “Statistical Analysis Methods” section).

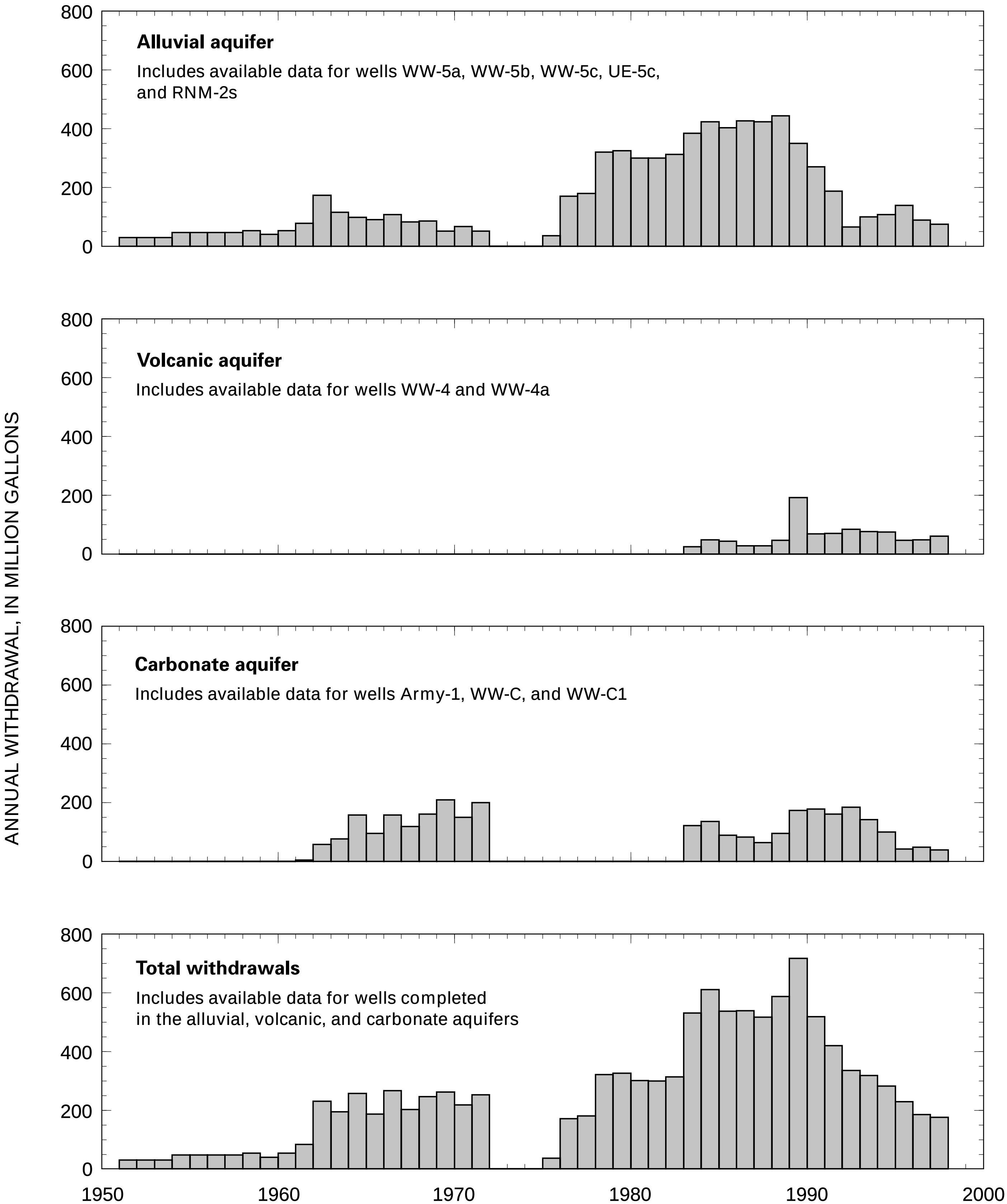
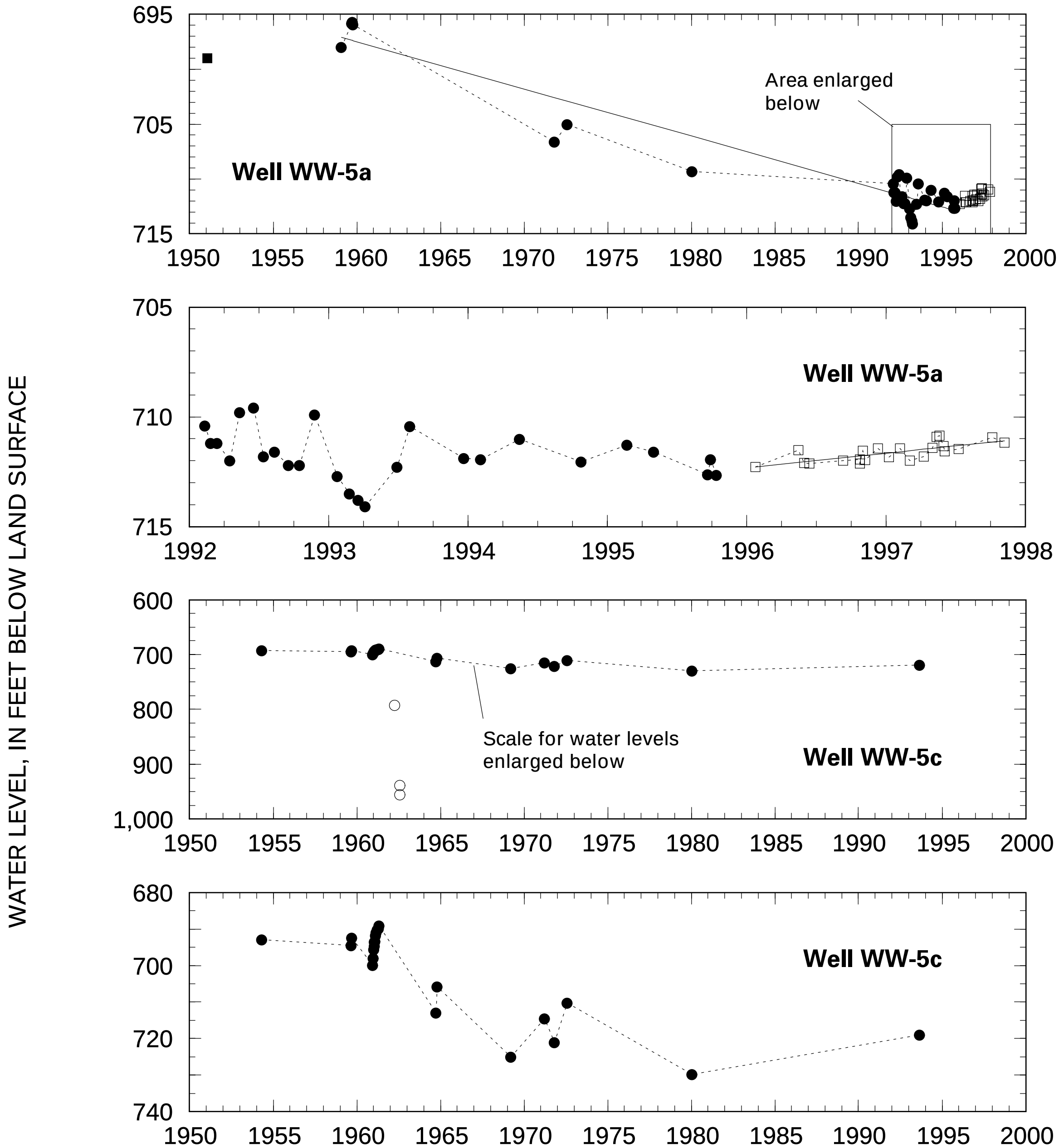


Figure 6. Total annual withdrawals for wells in the Frenchman Flat area, Nevada Test Site.



EXPLANATION

- Water level used for trend analysis
- Water level used for trend analysis of wells WW-5a (1996-97), UE-5n (1991-97), and RNM-2s (1994-97)
- Water level possibly affected by drilling
- Water level affected by pumping/recovery
- Water level affected by oil in well
- Anomalous water level
- Linear regression line

Figure 7. Periodic water-level measurements and associated linear-regression line for selected wells in the Frenchman Flat area, Nevada Test Site.

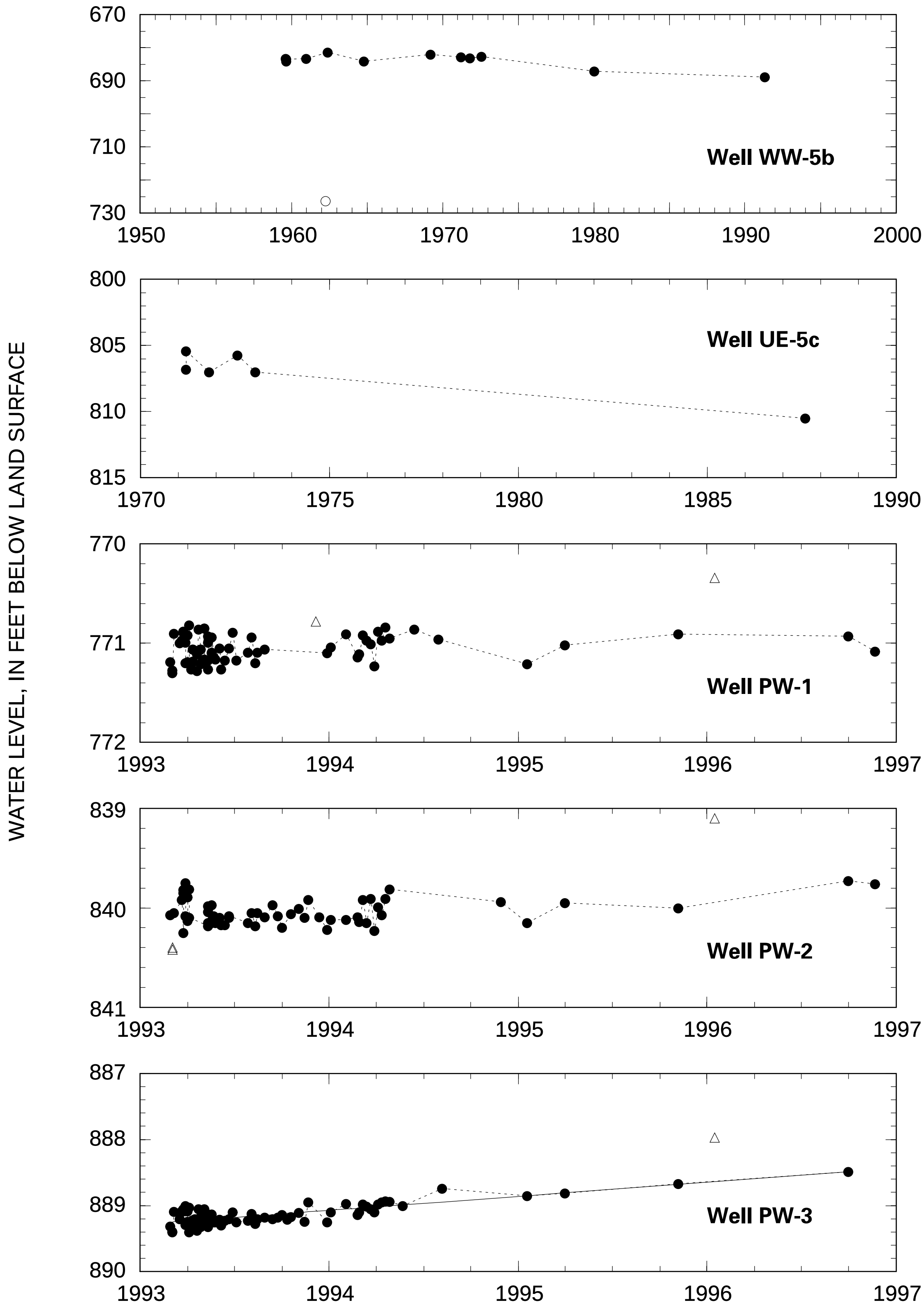


Figure 7. Continued.

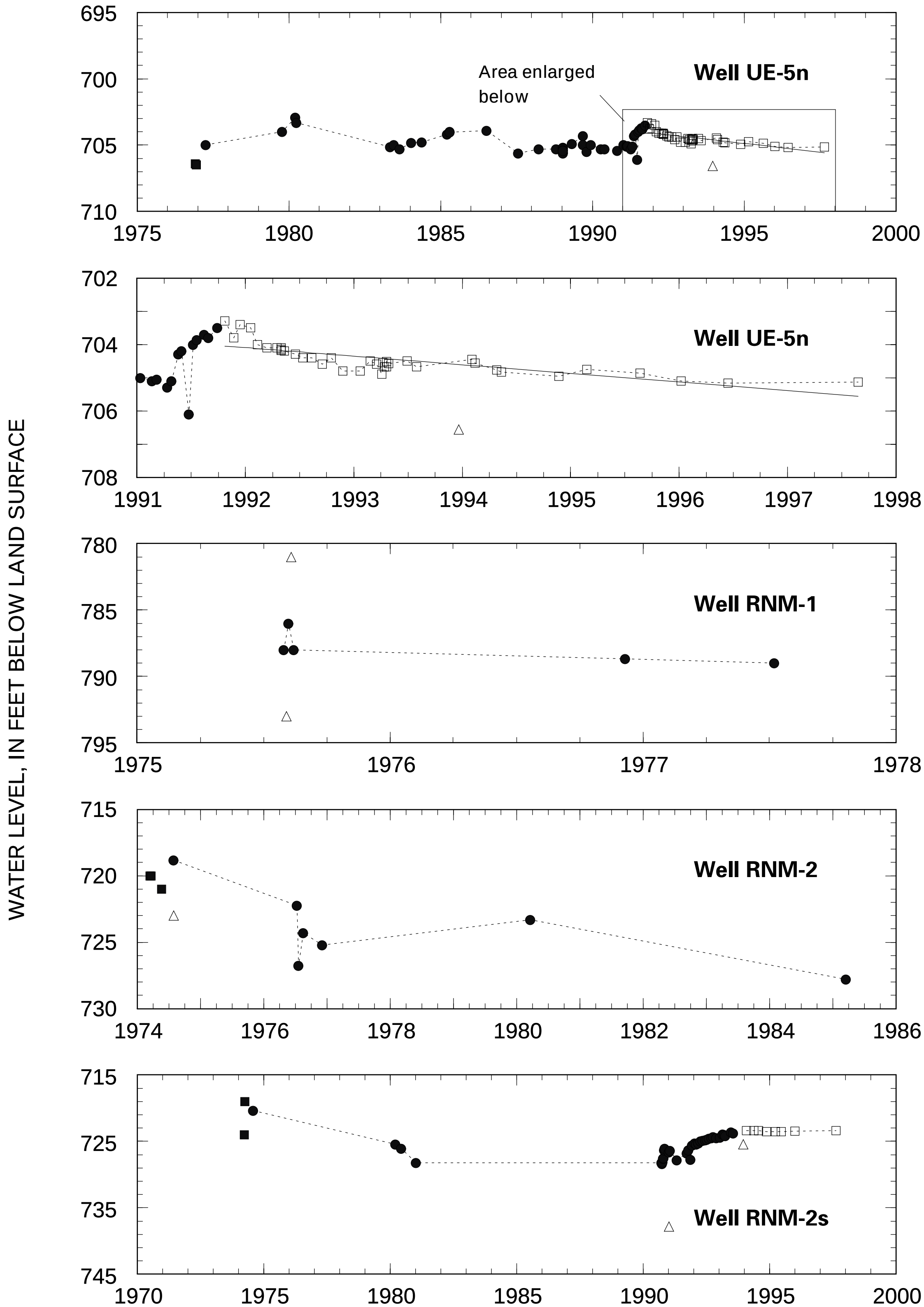


Figure 7. Continued.

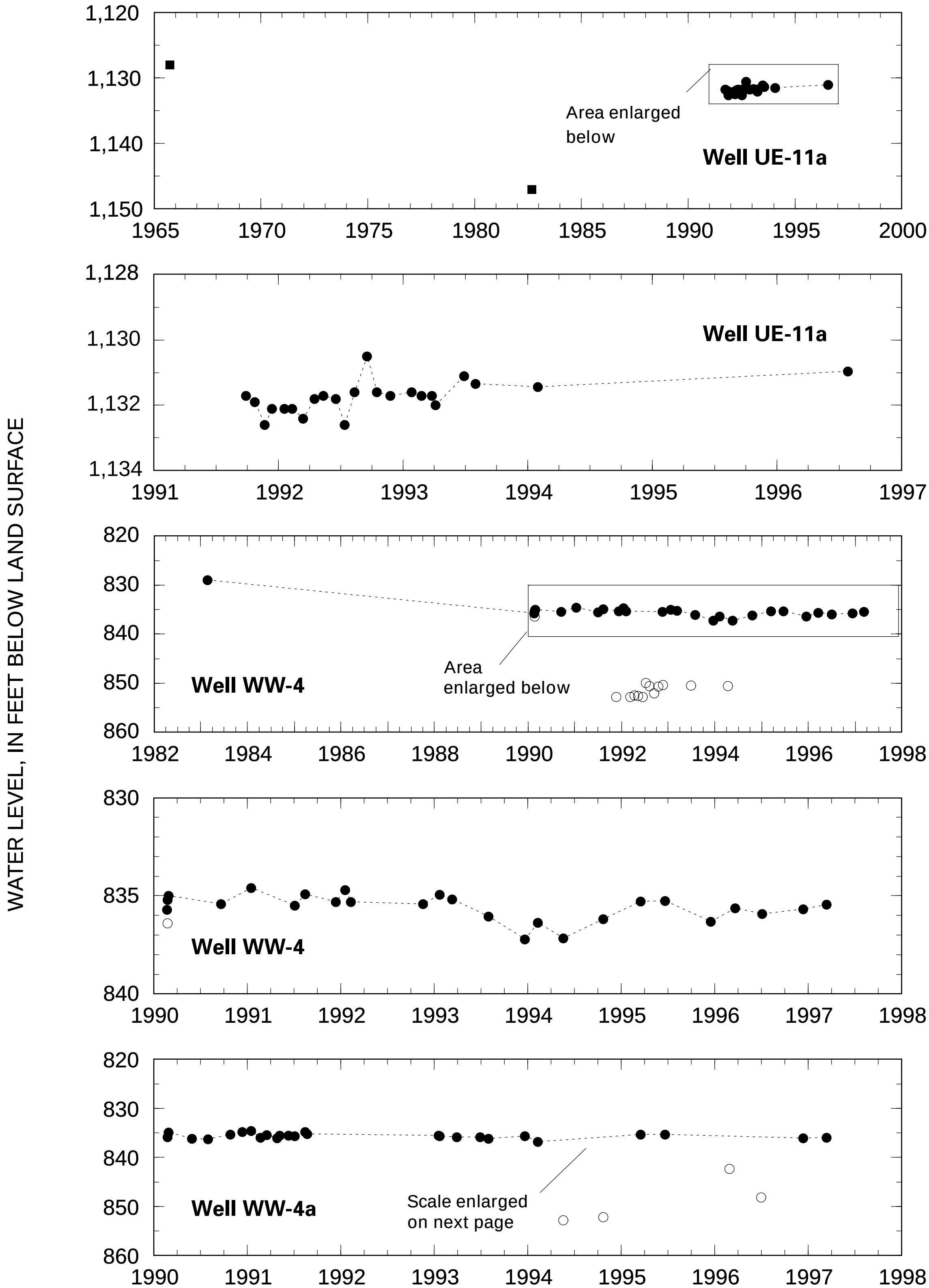


Figure 7. Continued.

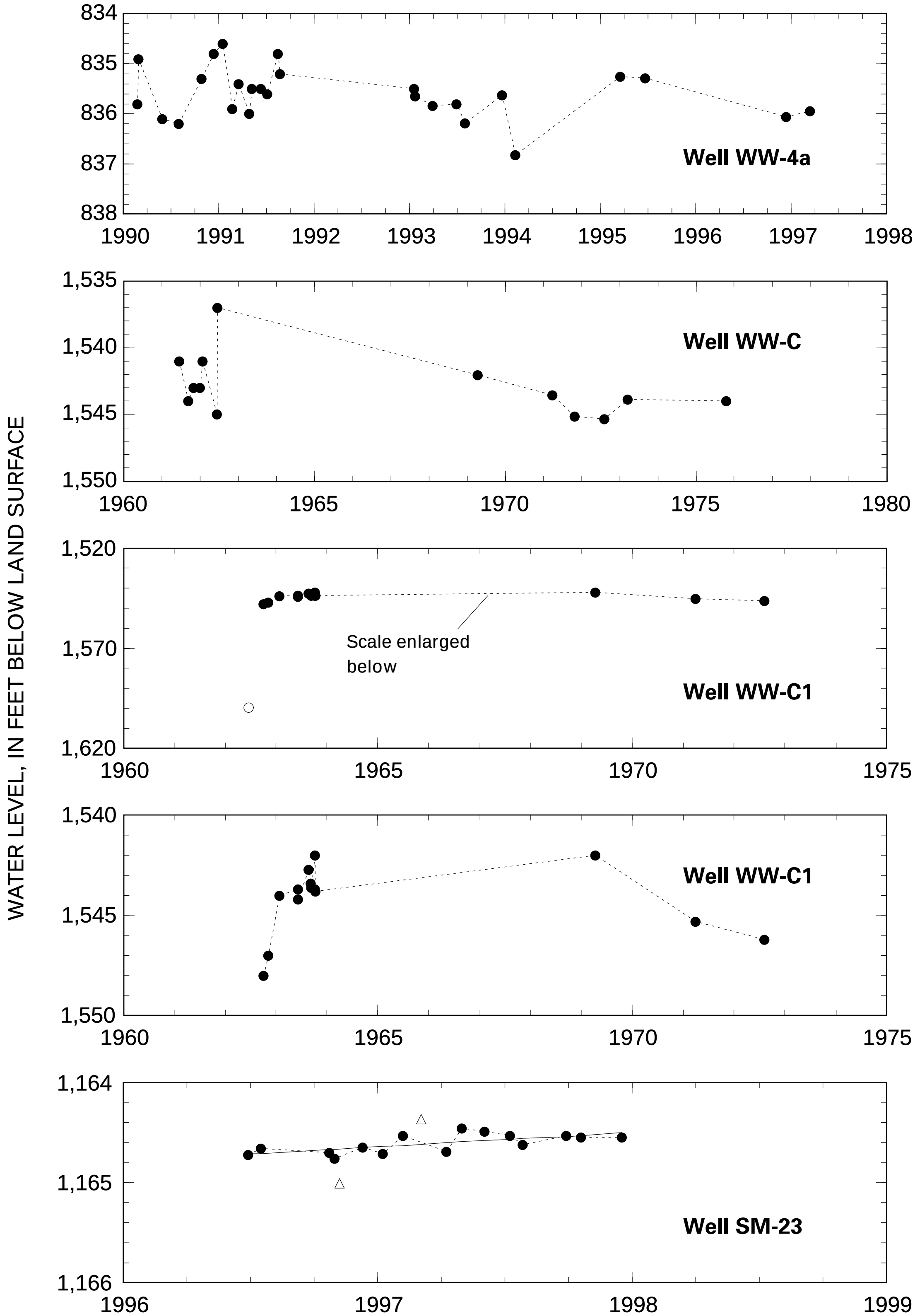


Figure 7. Continued.

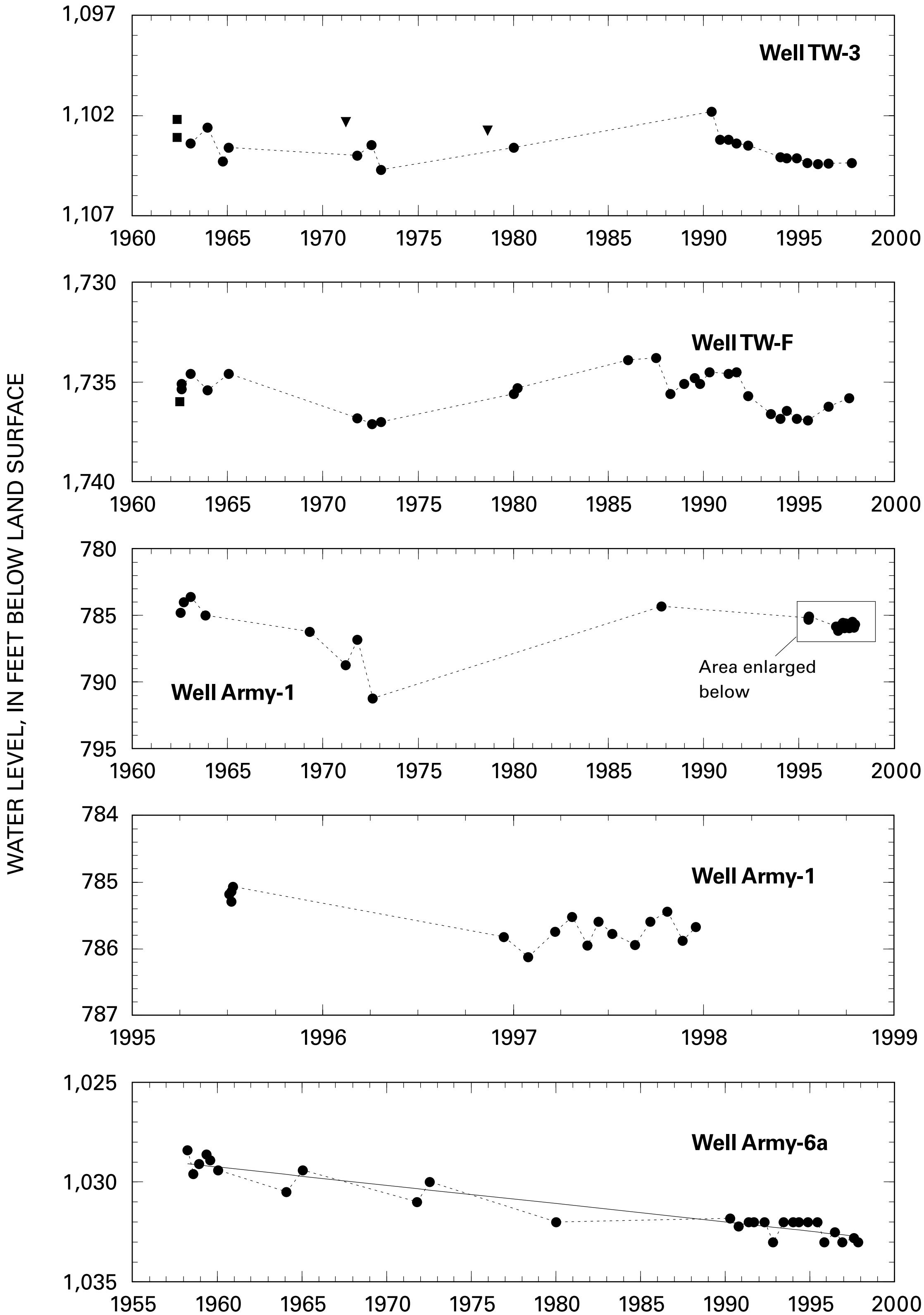


Figure 7. Continued.

Table 4. Mean, minimum, and maximum water levels and land-surface altitudes for wells in the Frenchman Flat area, Nevada Test Site

[Period of record for mean, minimum, and maximum water levels based on “water levels used for trend analysis” data shown in figure 7. Number of measurements: number indicates periodic water-level measurements by wire line, steel tape, or electric tape; continual water-level measurements by pressure transducer. Previously estimated altitude of land surface data from USGS files; GPS and previously estimated land-surface altitudes referenced to the National Geodetic Survey of 1929. Abbreviation: GPS, Global Positioning System. All water-level values rounded to 0.1 foot]

Local well name	Period of record	Number of measurements	Water level: Mean (feet below land surface)	Water level: Minimum (deepest) (feet below land surface)	Water level: Maximum (shallowest) (feet below land surface)	Land surface (feet): GPS altitude	Land surface (feet): Previously estimated altitude	Land surface (feet): Difference in GPS and previously estimated altitude
Mercury Valley								
Army-1	1962–97	25	785.8	791.2	783.6	3,153.50	3,153.30	0.20
Army-6a	1958–97	27	1,031.3	1,033.0	1,028.4	[1] 3,446.22	3,445.00	1.22
SM-23	1996–97	15	1,164.6	1,164.8	1,164.5	3,543.35	3,543.40	-.05
SM-23	Oct 1996 to July 1997	continual	1,164.7	1,164.9	1,164.4			
Frenchman Flat								
PW-1	1993–96	73	771.1	771.3	770.8	(2)	3,178.24	(2)
PW-2	1993–96	60	840.0	840.3	839.7	3,246.41	3,246.52	-.11
PW-3	1993–96	78	889.1	889.4	888.5	3,295.47	3,295.62	-.15
RNM-1	1975–77	5	787.9	789.0	786.0	3,135.03	3,136.40	-1.37
RNM-2	1974–85	7	724.1	727.8	718.8	3,128.76	3,131.73	-2.97
RNM-2s	1974–93	35	725.6	728.4	720.3	[3] 3,131.25	3,133.00	-1.75
RNM-2s	1994–97	8	723.5	723.6	723.4			
TW-3	1963–97	20	1,103.8	1,104.9	1,101.8	3,484.10	3,484.00	.10
TW-F	1962–97	27	1,735.6	1,737.1	1,733.8	4,140.82	4,142.70	-1.88
UE-5c	1971–87	6	807.1	810.5	805.4	3,216.14	3,216.00	.14
UE-5n	1977–91	43	704.8	706.1	702.9	3,112.38	3,112.20	.18
UE-5n	1991–97	38	704.5	705.2	703.3			
UE-11a	1991–96	23	1,131.7	1,132.6	1,130.5	3,538.19	3,538.00	.19
WW-4	1983–97	26	835.3	837.2	829.0	3,604.12	3,601.50	2.62
WW-4a	1990–97	26	835.6	836.8	834.6	3,604.24	3,605.67	-1.43
WW-4a	Aug. 1991 to Mar. 1993	continual	835.8	838.2	834.6			
WW-5a	1959–95	34	709.1	714.1	695.7	3,092.47	3,093.00	-.53
WW-5a	1996–97	22	711.6	712.3	710.9			
WW-5a	1996–98	continual	711.8	712.5	710.3			
WW-5b	1959–91	14	683.8	688.8	681.4	3,092.80	3,092.10	.70
WW-5c	1954–93	23	702.1	729.8	689.1	3,081.42	3,081.00	.42
Southern Yucca Flat								
WW-C	1961–75	13	1,542.9	1,545.4	1,537.0	3,924.06	3,921.00	3.06
WW-C1	1962–72	14	1,544.3	1,548.0	1,542.0	3,923.50	3,921.00	2.50
							Mean of absolute difference in GPS values	1.08

[1] Land-surface altitude from USGS level survey. A nearby surveyed benchmark was not available for level survey; therefore, GPS altitude at well Army-1 was used for level-survey benchmark at well Army-6a.

[2] GPS land-surface altitude survey was in error; previously estimated land-surface altitude at well PW-1 from first-order level survey (Brian Dozier, Bechtel Nevada, written commun., 1997).

[3] GPS land-surface altitude survey was in error; altitude shown in table from USGS level survey. A nearby surveyed benchmark was not available for level survey; therefore, GPS altitude at well RNM-1 was used for level-survey benchmark at well RNM-2s.

Periodic Measurements

Periodic water-level measurements at NTS have been collected by the U.S. Geological Survey (USGS) since 1951 and are maintained in the USGS National Water Information System (NWIS). Periodic water-level measurements are collected using steel tapes, electric tapes, or electric-cable units (wire-line or iron-horse devices; Wood and Reiner, 1996). Water-level measurements prior to 1996 typically were made with electric cable units; after 1996, most measurements were made with electric tapes (Fenelon, 2000, p. 8). The accuracy of the electric tapes and cable units are affected by mechanical stretch, thermal expansion, or damage. To maintain instrument accuracy, tape and cable units have been calibrated annually against a 2,000-ft reference steel tape since at least 1968, when Garber and Koopman (1968, p. 6) reported its use as a calibration standard. The reference steel tape was calibrated in 1997 by the National Institute of Standards and Technology and showed a measurement error of less than about 0.20 ft at a depth of 2,000 ft. Tape and cable units are calibrated at different water-level depths to within 0.10 percent of the reference-tape measurement and assigned an instrument correction factor. At the time of measurement, the depth-to-water reading is adjusted using the appropriate steel tape or cable unit correction factor.

Continual Measurements

Continual water-level data in the Frenchman Flat area for period of records of at least nine months are available for wells WW-4a (1991–93), SM-23 (1996–97), and WW-5a (1996–97; fig. 8). Water-level measurements at these wells were recorded every 5 or 15 minutes using submersible pressure transducers and electronic data loggers. The transducer and data-logger systems were calibrated by recording transducer output at known depths of submergence. Manual water-level measurements were made when transducers were installed and removed from service to reference the depth of submergence to land surface, and during the period of continual measurements to assure proper operation and accurate data collection. The procedure for calibrating pressure transducers is outlined by La Camera and Locke (1997, p. 15).

WATER-LEVEL ADJUSTMENTS

Adjustments of periodic and continual water-level measurements are presented for the effects of barometric pressure, water density (from water-temperature measurements), borehole deviation, and land-surface altitude. These adjustments are not required for the analysis of long-term water-level trends for selected wells in this report, but may be critical for future calculations of hydraulic heads.

Barometric Pressure

Water-level measurements shown in figure 8 for wells SM-23 and WW-5a were adjusted for the effects of barometric pressure prior to evaluating the hydrographs for significant water-level trends. Water-level adjustments were determined from hourly barometric-pressure measurements collected at each well during the same period as the continual water-level measurements.

A graphical procedure (Brassington, 1988, p. 83) was used to adjust water levels for the effects of barometric pressure. As outlined by Brassington (1988), the graphical procedure includes:

(1) determining a constant barometric efficiency of the aquifer at each well. Barometer efficiency is the change in water level divided by the change in barometric pressure, expressed in equivalent units of hydraulic head as a percent,

(2) multiplying the change in barometric pressure between two successive measurements by the barometric efficiency, and

(3) adding the amount calculated in (2) to the water-level measurement if successive barometric-pressure measurements increased, or subtracting the amount calculated in (2) if successive barometric-pressure measurements decreased.

This adjustment for barometric pressure is based on a constant barometric efficiency that represents an average value for the period of record. Some error in the water-level adjustment, therefore, may be introduced in shorter-term periods (for example, daily, monthly, or seasonal periods of the hydrograph) when the constant barometric efficiency used in the graphical procedure differs from the true barometric efficiency. The slope of adjusted water levels, therefore, may be slightly different over short intervals of the hydrograph than the slope of water levels adjusted using a variable barometric efficiency; however, the beginning and ending adjusted water levels would be equivalent.

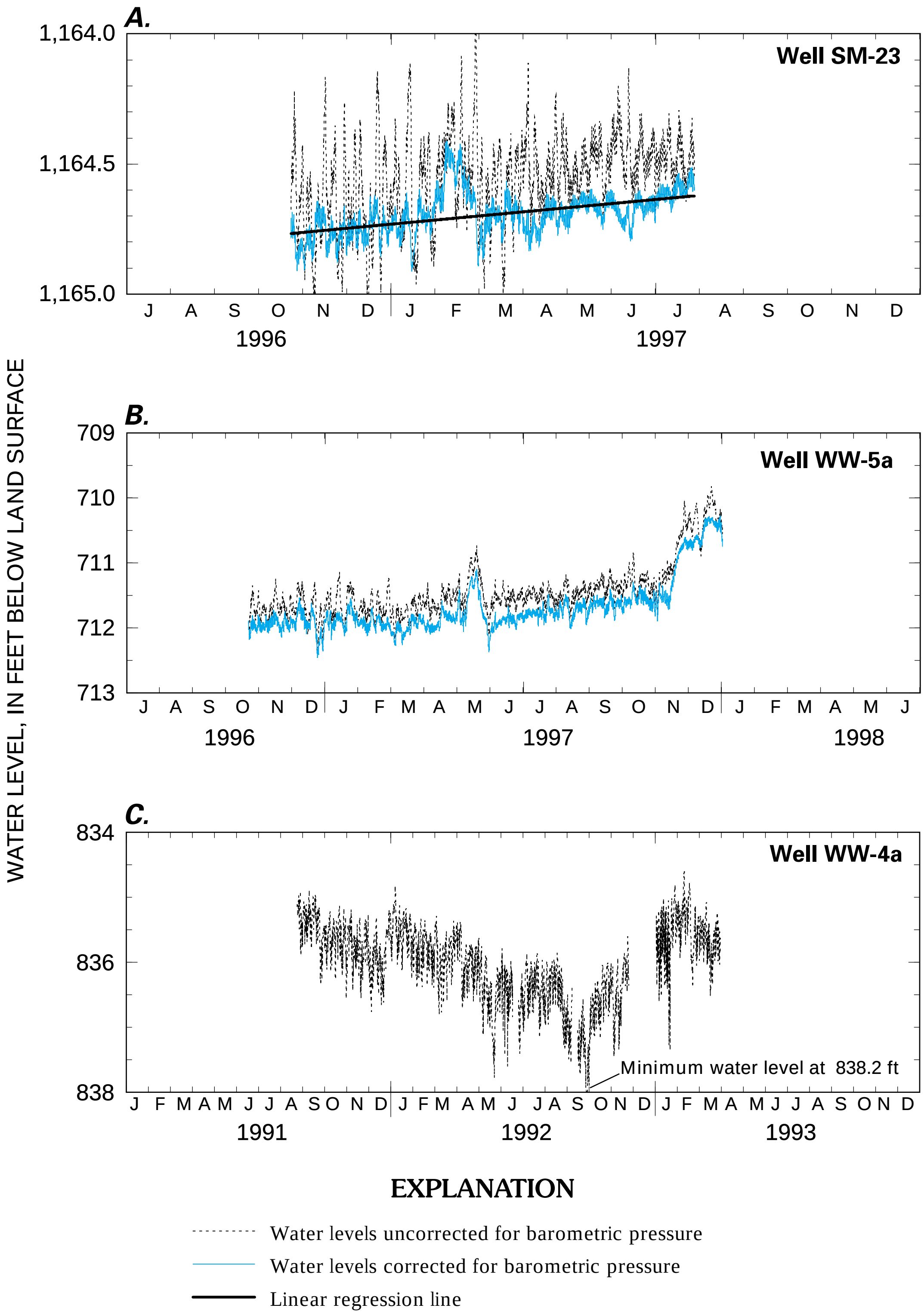


Figure 8. Continual water levels in wells SM-23 (1996–97), WW-5a (1996–98), and WW-4a (1991–93), Nevada Test Site.

A second limitation of the procedure is that the absolute value of the adjusted water level is a function of the initial barometric pressure. Therefore, a change in the initial barometric pressure causes a “shift” in the absolute value of the adjusted water level. However, the relative change in adjusted water levels (the slope or trend of the hydrograph) is unaffected.

The barometric efficiencies of the aquifers at observation wells SM-23 (86 percent) and WW-5a (64 percent) were substantially higher than at observation well WW-4a (about 1 percent). Water-level adjustments for the effects of barometric pressure in wells SM-23 and WW-5a (fig. 8), therefore, resulted in hydrographs that contain lower amplitude water-level fluctuations (figs. 8*A* and 8*B*). Because of a low barometric efficiency, water levels in well WW-4a were not adjusted for the effects of barometric pressure (fig. 8*C*). A water-level response in well WW-4a to barometric pressure likely is masked by the effect of pumping from nearby well WW-4.

Water Density

Variation in water density (from water-temperature measurements) in the study area may affect the accuracy of hydraulic-head measurements. Water density and temperature are inversely related and as water temperature increases, water density decreases. The water level in wells with anomalously high water temperature will be higher than water of lower temperature in nearby wells open to the same aquifer and pressure conditions.

The average temperature of water samples collected from wells in the Frenchman Flat area with available data (Perfect and others, 1994; Rose and others, 1997) is about 94°F for wells open to the carbonate aquifer (excluding well TW-F) and about 75°F for wells open to the alluvial and volcanic aquifers and quartzite confining unit (fig. 9). The average water temperature in well TW-F (147°F) for water samples collected since the well was deepened and completed in the carbonate aquifer in 1962 (Perfect and others, 1994) is substantially higher than in other wells open to the carbonate aquifer. The depth of well TW-F is 3,400 ft, which is more than 1,400 ft deeper than other wells completed in the carbonate aquifer with available temperature data (wells WW-C, WW-C1, TW-3, and Army-1). The greater depth of well TW-F, however, does not completely account for the high temperature in this well. For example, assuming a geothermal gradient of 0.014°F per foot (the average gradient estimated for the Pahute Mesa area; Pottoroff and others, 1987, p. 3), a 2,000-foot increase in the depth of well TW-3 to a depth equal to that of well TW-F would cause a corresponding increase in water temperature of about 28°F. However, water temperatures in well TW-F are almost 50°F higher than temperatures in well TW-3. The anomalous trend of decreasing temperature with increasing depth for the carbonate-aquifer wells shown in figure 9 (not including well TW-F) also illustrates that factors other than depth, such as geologic structure, likely are important in controlling water temperature.

Although temperature likely is the most important factor affecting water density in well TW-F, other factors such as a relatively high dissolved-solids concentration or the compressibility of water caused by pressure from the overlying water column can influence water density. However, the relatively low dissolved-solids concentrations of water in well TW-F (less than about 550 milligrams per liter between 1962–80; Perfect and others, 1994) would not significantly affect water density. Additionally, based on standard relations between water density, pressure, and temperature, Winograd (1970, p. 24) concluded that the effect of pressure on water density in well TW-F is minor in comparison to the effect of temperature.

An adjustment for the effect of water density on water levels in well TW-F was determined using a procedure applied by Winograd (1970). Using this procedure, the density of the water column in well TW-F is adjusted to a standard density that best represents the average density of the water column in nearby wells completed in the carbonate aquifer. The following equation, modified from Winograd (1970, p. 23), was used to adjust water levels in well TW-F to a standard density:

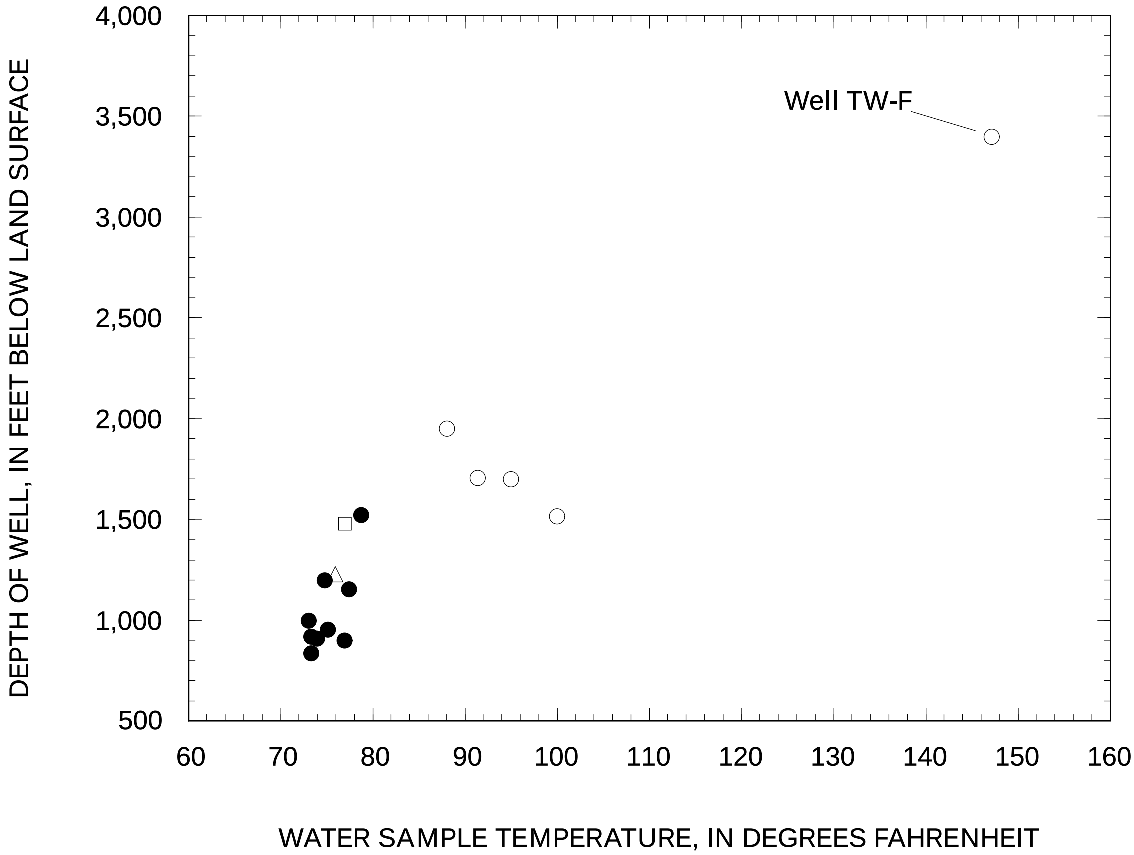
$$WC_{corrected} = (D_{TW}/D_{carb}) * WC_{uncorrected} \qquad (1)$$

where $WC_{corrected}$ is the corrected length of the water column between the static water level and the top of the open interval, in feet;

$WC_{uncorrected}$ is the uncorrected length of the water column between the mean static water level and the top of the open interval, in feet;

D_{TW} is the density of 144°F water in well TW-F, in grams per cubic centimeter (g/cm^3) = 0.98207 g/cm^3 (Chemical Rubber Publishing Co., 1985, p. F-10); and

D_{carb} is the standard density of 94°F water = 0.99425 g/cm^3 (Chemical Rubber Publishing Co., 1985, p. F-10).



EXPLANATION

Principal aquifer or confining unit contributing water to well–

● Alluvial aquifer

□ Volcanic aquifer

○ Carbonate aquifer

△ Quartzite confining unit

Figure 9. Temperature of water samples collected from selected wells in the Frenchman Flat area, Nevada Test Site.

The magnitude of the water-level adjustment using equation 1 depends on the length of the water column to be corrected and on the ratio of the density of water in well TW-F and the standard density. For this report, the length of the water column is based on 1,414 ft of water between the mean static water level in the well for 1962–97 (1,736 ft below land surface) and the top of the open interval (3,150 ft below land surface). The density of water in well TW-F (D_{TW}) is based on the average temperature of the water column (144°F) determined from a borehole geophysical temperature log (Winograd, 1970, p. 24). The average temperature of water in wells TW-3, WW-C, WW-C1, and Army-1 (94°F) was used to determine the standard density. The average temperature of water in these wells was determined from pumped water samples because borehole geophysical temperature logs were not available. Solving equation 1 for $WL_{corrected}$, the length of the water column would be 1,396.7 ft, resulting in a decrease in water level of 17.3 ft. This adjustment is about 15 percent larger than the 15 ft adjustment determined by Winograd (1970, p. 24) using a standard density based on a temperature of 100°F.

Equation 1 can be used to estimate the effect, if any, of temporal changes in water temperature and associated density on water-level fluctuations in well TW-F. For example, the maximum difference in water levels in well TW-F between 1962 and 1997 was about

3.5 ft (fig. 7). During this period, four temperature measurements of water samples collected from well TW-F indicate a maximum change of less than 2°F. Assuming that these temperature measurements are representative of the average water column temperature in well TW-F, a 2°F rise in average temperature from 144° to 146°F, would result in a new water density (D_{TW}) of 0.98149 g/cm^3. Solving equation 1 for $WL_{corrected}$, the length of the water column would be 1,395.9 ft — an increase in the water-level adjustment from 17.3 ft to 18.1 ft. A rise in water temperature of 2°F in well TW-F, therefore, would cause a corresponding rise in water level of about 0.8 ft, or about 23 percent of the maximum water-level change observed during this period.

Borehole Deviation

Most boreholes deviate slightly from true vertical during drilling. If a gyroscopic or "borehole deviation" survey was made during geophysical logging of the borehole, measured water levels can be adjusted to represent the true vertical water-level depth below land surface. Borehole deviation surveys were completed in about half of the wells drilled in the Frenchman Flat area.

Three water-level adjustments were developed using linear equations based on measured cumulative borehole deviation across a selected depth interval (table 5). If a complete deviation survey was available, linear equations were developed to adjust water levels

Table 5. Water-level adjustments for borehole deviation in selected wells in the Frenchman Flat area, Nevada Test Site

Borehole-deviation survey: Complete results, data available for entire borehole; limited results, data for horizontal displacement at bottom of borehole only; depth interval, equals depth interval used to determine linear equation.

Type of water-level adjustment: Adjustment 1, based on a borehole deviation survey (BDS) depth interval that bounds historic water levels; adjustment 2, based on a BDS depth interval from top to bottom of borehole; adjustment 3, no BDS data available; therefore, based on a depth interval from top to bottom of borehole and the horizontal displacement and deviated depth at the bottom of the borehole.

Mean water-level depth: Equals mean water level for period of record based on "water levels used for trend analysis data" shown in figure 7.

Water-level adjustment: Vertical water-level depth (V_d) computed for measured water-level depth (M_d) equal to mean water-level depth. Adjustment equals difference between V_d and mean water-level depth, rounded to nearest 0.01 foot.

Local well name	Borehole-deviation survey		Type of adjustment	Linear equation used for adjustment	Water-level	
	Results	Depth interval (feet)			Mean depth (feet)	Adjustment (feet)
			Mercury Valley			
Army-1	limited	0–1,946	3	$V_d = M_d * 0.99923$	785.8	0.61
			Frenchman Flat			
PW-1	complete	770–775	1	$V_d = M_d * 0.99800 + 1.27$	771.1	.27
PW-1	complete	0–823	2	$V_d = M_d * 0.99960$	771.1	.31
PW-2	complete	835–845	1	$V_d = M_d * 0.99900 + 0.17$	840.0	.67
PW-2	complete	0–878	2	$V_d = M_d * 0.99915$	840.0	.71
PW-3	complete	885–890	1	$V_d = M_d - 0.06$	889.1	.06
PW-3	complete	5–924	2	$V_d = M_d * 0.99994$	889.1	.05
TW-F	complete	1,725–1,750	1	$V_d = M_d * 0.99960 + 0.49$	1,735.6	.20
TW-F	complete	50–1,875	2	$V_d = M_d * 0.99984 + 0.01$	1,735.6	.27
UE-5c	complete	800–825	1	$V_d = M_d - 0.02$	807.1	.02
UE-5c	complete	0–2,360	2	$V_d = M_d * 0.99998$	807.1	.02
UE-11a	complete	1,125–1,150	1	$V_d = M_d * 0.99960 + 0.36$	1,131.7	.09
UE-11a	complete	0–1,370	2	$V_d = M_d * 0.99985$	1,131.7	.17
WW-4	complete	800–1,000	1	$V_d = M_d - 0.05$	835.3	.05
WW-4	complete	0–1,000	2	$V_d = M_d * 0.99995$ [1]	835.3	.04
			Southern Yucca Flat			
WW-C	limited	0–1,540	3	$V_d = M_d * 0.99959$	1,542.9	.63
WW-C1	complete	1,525–1,550	1	$V_d = M_d * 0.98480 + 19.21$	1,544.3	4.26
WW-C1	complete	25–1,707	2	$V_d = M_d * 0.99541 + 0.11$	1,544.3	6.98

[1] Calculated from deviation survey records of borehole inclination angles and depths.

that were based on (1) a depth interval that bounds historic water level measurements (adjustment 1) or (2) a depth interval from the top to the bottom of the deviation survey (adjustment 2). If a limited deviation survey was available (true-vertical depth data not available), the linear equation developed was based on a depth interval from the top to the bottom of the borehole (adjustment 3). For adjustment 3, the true-vertical depth at the bottom of the borehole was determined from the horizontal displacement and deviated (measured) depth of the borehole.

To determine the adjusted water level, measured and true-vertical depth data from the deviation survey were substituted into a linear equation of the form:

$$WL_{adj} = (WL_m - M_{top})*(\Delta V_{int}/\Delta M_{int}) + V_{top}, \quad (2)$$

where WL_{adj} is adjusted water level, in feet below land surface;

WL_m is measured water level, in feet below land surface;

M_{top} is measured top of selected depth interval from borehole deviation survey, in feet below land surface;

V_{top} is true-vertical top of selected depth interval from borehole-deviation survey, in feet below land surface;

ΔV_{int} is difference in top and bottom of true-vertical depth interval from borehole deviation survey, in feet below land surface; and

ΔM_{int} is difference in top and bottom of measured depth interval from borehole deviation survey, in feet below land surface.

For example, the borehole deviation survey for well WW-C1 (U.S. Geological Survey data files, Las Vegas, Nev.) shows that a measured depth interval of 1,525-1,550 ft below land surface can be used to bound historic water-level measurements for this well (table 4). The corresponding true-vertical depths in the deviation survey at the top and the bottom of this interval are 1,521.03 ft and 1,545.65 ft, respectively. Substituting these values into equation 2 gives the linear water-level adjustment for the depth interval that bound historic water levels (table 5):

$$WL_{adj} = (WL_m - 1{,}525 \text{ ft})*(24.62 \text{ ft}/25.00 \text{ ft}) + 1{,}521.03 \text{ ft}. \quad (3)$$

In reduced form, equation (3) becomes:

$$WL_{adj} = (0.98480*WL_m) + 19.21 \text{ ft}. \quad (4)$$

For adjusting historic water levels, adjustment 1 is more accurate than adjustments 2 or 3 because the slope is averaged over a shorter depth interval. For adjustments 2 and 3, some error is introduced by using an average slope across the entire depth interval of the deviation survey. However, adjustments 2 and 3 were included to provide general adjustments if future water levels in wells increase or decrease beyond the depth interval of historic water levels used in adjustment 1.

Additional error to water-level adjustments for borehole deviation may be caused by the accuracy of the borehole deviation equipment in determining true-vertical depth. For example, the accuracy of true-vertical depth data provided by the deviation instrument used in wells PW-1, PW-2, and PW-3 was ± 0.5 ft (Reynolds Electric & Engineering Company, 1994, p. 4–14). This potential error is substantially larger than the actual water-level adjustment for these wells using the mean static water level (table 4). Instrument accuracy was not reported in available deviation survey records and, therefore, the potential error in water-level adjustments for deviation in boreholes other than PW-1, PW-2, and PW-3 is unknown.

Using the mean static water level (table 4), adjustments to measured water levels for borehole deviation are less than 1 ft for all wells except well WW-C1 (table 5). Deviation survey results show that the difference between the measured and vertical depth at the bottom of well WW-C1 is more than 7 ft, resulting in a water-level adjustment of more than 4 ft.

Land-Surface Altitude

In December 1997, global positioning system (GPS) measurements of land-surface altitude at well locations in the Frenchman Flat area were collected by the USGS. These measurements were collected to confirm or improve the accuracy of previously estimated land-surface altitudes. Although land-surface altitudes are not required for water-level trend and correlation analyses, these data are critical when calculating water-level altitudes for potentiometric-surface maps. Accurate land-surface altitudes are particularly important in Frenchman Flat, where small differences in water-level altitude exists for much of the alluvial aquifer (Winograd and Thordarson, 1975, p. C60).

GPS measurements of land-surface altitude were collected using a geodetic grade receiver. A differential GPS procedure was used where one base-station receiver was calibrated to a benchmark of known land-surface altitude while an additional receiver simultaneously collected satellite-transmitted data at one or two well locations. Four benchmark locations of 1st and 2nd order accuracy (maximum relative error of less than about 0.01 ft at the time of original survey) were used for base stations (fig. 2). Satellite-transmitted data were collected at benchmark and well locations for 1.5 to 2 hours. After the land-surface altitude was determined, the location of the measuring point was marked at each well. The GPS land-surface altitudes determined during this survey and previous survey estimates of altitude in the Frenchman Flat area are presented in table 4. A GPS survey was not completed at well Army-6a. At wells PW-1 and RNM-2s, GPS land-surface altitudes were in error. As a result, land-surface altitudes at wells Army-6a, PW-1, and RNM-2s were estimated from level surveys.

Prior to completing the differential GPS surveys at each well location, the accuracy of the GPS system was checked by measuring the land-surface altitude at the benchmark locations. During this accuracy check, each benchmark alternately served as a base station of known altitude while satellite data were collected at two other benchmark locations. A GPS land-surface altitude was determined for each benchmark and compared to the surveyed altitudes. Results of this survey showed a maximum difference in GPS-derived altitude of less than 0.07 ft from the known benchmark altitude.

The mean difference between previously surveyed land-surface altitudes and GPS-derived altitudes (table 4) is about 1 ft. This mean difference is relatively high considering the generally flat potentiometric surface in the alluvial aquifer in Frenchman Flat. The mean altitude difference of about 1 ft is strongly influenced by differences of greater than 2 ft at wells RNM-2, WW-4, WW-C, and WW-C1.

ANALYSIS OF WATER LEVELS

Water-level measurements for wells with available data in the Frenchman Flat area were evaluated to determine (1) if statistically significant temporal trends exist, (2) if water-level fluctuations between wells have been similar over time, and (3) a possible cause for observed trends or cyclic-type water-level changes.

Statistical Analysis Methods

Water-level trends are defined herein as statistically and hydrologically significant rises or declines in the water level over time. Manual measurements collected for at least 1 year and (or) continual measurements collected for at least 9 months were used in the trend analysis. For purposes of this report, water-level records with 10 or less measurements were considered sparse data sets. Statistical analysis of sparse data sets typically result in a higher degree of uncertainty and, therefore, are noted in this report.

Continual water-level records used for trend analysis were available for wells SM-23, WW-5a, and WW-4a (fig. 8). Because water levels in wells SM-23 and WW-5a are affected by barometric pressure (see “Water-Level Adjustments” section), the effect of barometric pressure was removed from continual water-level records for these wells prior to the trend analysis.

Two statistical methods were applied in the trend analysis, simple linear regression (ordinary least squares method) and the Kendall-Theil method (Kendall’s tau rank correlation coefficient). The least squares method was applied when water-level data were collected from observation wells (table 1) and changes in these data generally appeared linear. Although water-level changes in wells may not be perfectly linear, particularly those changes affected by nearby pumping, the least squares method provides a reasonable estimate of the net rate of change in water level over the period of record.

The least squares method (Helsel and Hirsch, 1992, p. 221–263) was applied using water level as the dependent variable and time as the independent variable. The trend was considered statistically significant if the slope of the regression line was significant at a 95-percent confidence interval. Significance of the regression slope was tested using the t-distribution with the null hypothesis being that the slope equalled zero; that is, at the 95-percent confidence interval the slope does not include zero.

Statistical measures of leverage and influence were computed prior to applying the least squares method to help qualitatively evaluate observations with high leverage and (or) erratic water-level measurements (outliers). “Standardized” and “studentized” residuals were used to detect outliers. The statistical parameters “Cook’s D” and “DFFITS” were used to evaluate the influence of outliers on water-level trends.

Outliers outside the 95-percent confidence level were deleted from the water-level data set if the measurement was thought to be in error, particularly if the data point was one of low influence. Outliers with high influence were deleted from the data set only if the data point was isolated in time and likely represented a different population than later or earlier water-level measurements (for example, water levels affected by drilling).

Kendall's tau rank correlation coefficient (Helsel and Hirsch, 1992, p. 212) was applied when water-level data were collected from water-supply wells (table 1) because changes in these data may represent nonlinear recovering water levels. Kendall's tau also was applied if a water-level record appeared to contain nonlinear fluctuations (wells UE-5n and WW-5a) or appeared to contain cyclic-type water-level fluctuations (wells Army-1, TW-F, and TW-3).

Kendall's tau is a robust test that indicates if a significant upward or downward change in water level has occurred over the period of record, but does not imply anything about the magnitude of the change in water level or whether the change in water level is linear. Where data are irregularly spaced or "clustered" in time (for example, wells RNM-2s and Army-1), specific time periods may be over-represented on the overall trend because a higher number of data points per unit time are used in the calculation relative to other parts of the water-level record. A 95-percent confidence level was used in the test to determine a statistically significant upward or downward change in water level.

Trends that were statistically significant were further analyzed for hydrologic significance. A trend was considered hydrologically significant if the total change in water level along the trend slope (regression analysis) or the maximum water-level change over the period of record (Kendall's tau analysis) was greater than three times the accuracy of the measurement instrument. For manual water-level measurements, three times the accuracy of the NTS reference steel tape is 0.60 ft. For continual water-level measurements, three times the accuracy of a submersible pressure transducer at maximum recording pressure (15 lb/in^2) is 0.02 ft. These values were arbitrarily selected, but could indicate water-level trends that are worthy of attention.

To help identify wells with similar hydrologic responses and possible sources of water-level fluctuations, a correlation analysis was completed. Correlations were computed for water levels in nearby wells, water levels and pumpage from nearby wells, and water levels and precipitation. To determine the correlation between two variables the observations must be paired in time. Correlations between water levels in nearby wells typically were from the same day, although sparse data often were matched by week or by month. For most correlations involving pumpage or precipitation, water-level data were lagged by day, week, month, and (or) years. Gaps in the pumpage or precipitation data sets were considered missing data (rather than a value of zero). Water levels matched against a gap in the pumpage or precipitation data set were therefore deleted prior to the correlation analysis. Correlations between periodic and continual data generally were matched using a single periodic value and the mean value of the continual data for the same day.

The exceedance probability (p-value) associated with the statistical parameters "Spearman's rho" and "Pearson's r" (Helsel and Hirsch, 1992, p. 217–219) was used to determine the significance of each correlation. Spearman's rho is a nonparametric, rank correlation coefficient; Pearson's r is a parametric, linear correlation coefficient. Because many data sets used in this analysis are not normally distributed, a greater weight was placed on the parameter Spearman's rho than on the parameter Pearson's r. Therefore, a correlation was considered statistically significant if the p-value associated with Spearman's rho was equal to or less than 0.05. The correlation was considered statistically marginal if the p-value associated with Spearman's rho was between 0.05 and 0.10 and statistically not significant if the p-value was equal to or greater than 0.10.

Trend Analysis Results

Water levels in five wells had both statistically and hydrologically significant trends. Statistically significant trends were observed for three wells completed in the alluvial aquifer (WW-5a, UE-5n, and PW-3), one well completed in the carbonate aquifer (SM-23), and one well completed in the quartzite confining unit (Army-6a). The results of the trend analysis for 21 wells are presented in table 6. Linear-regression lines for the water levels used in the trend analysis are shown in figures 7 and 8.

Table 6. Results of trend analysis of water levels for wells in the Frenchman Flat area, Nevada Test Site

Data type: Periodic, water levels measured by wire-line, steel tape, or electric tape; continual, water levels measured by pressure transducer.
Statistical technique applied: Kendall's tau, Kendall's rank correlation coefficient test; regression, simple linear regression test.
Statistical significance: Linear trend considered statistically significant if null hypothesis of t-distribution rejected at 95-percent confidence interval. Nonlinear trend considered significant if the probability (p) value associated with Kendall's tau is less than 0.05 and the correlatation coefficient (Kendall's tau) is greater than 0.50.
Linear trend: Indicates a general linear decrease (-) or increase (+) of water levels in the well over time.
Water-level change: Equals difference in beginning and ending water-level values along linear trend line (regression analysis) or difference between the maximum and minimum water level over the period of record (Kendall's tau analysis); --, not applicable.
Hydrological significance: Statistically significant trends considered hydrologically significant if total change along linear trend slope (regression analysis) or maximum water-level change over the period of record (Kendall's tau analysis) is greater than three times the accuracy of the measurement instrument; up, significant water level rise; --, not applicable.

Local well name	Data type	Period of record	Statistical technique applied	Statistical significance	Linear trend (feet per year)	Water-level change (feet)	Hydrologic significance
			Mercury Valley				
Army-1[1]	periodic	1962–97	Kendall's tau	none	not estimated	--	--
Army-6a	periodic	1958–97	regression	significant	-0.09	-3.64	significant
SM-23	periodic	1996–97	regression	significant	+.14	+.21	[2]none
SM-23	continual	Oct. 1996 to July 1997	regression	significant	+.19	+.15	significant
			Frenchman Flat				
PW-1	periodic	1993–96	regression	none	not estimated	--	--
PW-2	periodic	1993–96	regression	none	not estimated	--	--
PW-3	periodic	1993–96	regression	significant	+.21	+.76	significant
RNM-1	periodic	[3]1975–77	regression	none	not estimated	--	--
RNM-2	periodic	[3]1974–85	regression	none	not estimated	--	--
RNM-2s	periodic	1974–93	Kendall's tau	none	not estimated	--	--
RNM-2s	periodic	[3]1994–97	regression	none	not estimated	--	--
TW-3[1]	periodic	1963–97	Kendall's tau	none	not estimated	--	--
TW-F[1]	periodic	1962–97	Kendall's tau	none	not estimated	--	--
UE-5c	periodic	[3]1971–87	Kendall's tau	none	not estimated	--	--
UE-5n	periodic	1977–91	Kendall's tau	none	not estimated	--	--
UE-5n	periodic	1991–97	regression	significant	-.26	-1.51	significant
UE-11a	periodic	1991–96	regression	none	not estimated	--	--
WW-4	periodic	1983–97	Kendall's tau	none	not estimated	--	--
WW-4a	periodic	1990–97	Kendall's tau	none	not estimated	--	--
	continual	Aug. 1991 to Mar. 1993	Kendall's tau	none	not estimated	--	--
WW-5a	periodic	1959–95	regression	significant	-.43	-15.33	significant
	periodic	1996–97	regression	significant	+.67	+1.20	significant
	continual	Oct. 1996 to Jan. 1998	Kendall's tau	significant	not estimated	2.18	up
WW-5b	periodic	1959–91	Kendall's tau	none	not estimated	--	--
WW-5c	periodic	1954–93	Kendall's tau	none	not estimated	--	--
			Southern Yucca Flat				
WW-C	periodic	1961–75	Kendall's tau	none	not estimated	--	--
WW-C1	periodic	1962–72	Kendall's tau	none	not estimated	--	--

[1] Water-level measurements show cyclic-type fluctuations.

[2] Water-level change of +0.21ft less than three times measurement error for periodic water-level data (0.60 ft).

[3] Data set has 10 or less water-level measurements.

Alluvial Aquifer

In the central part of Frenchman Flat, several wells had statistically significant trends. The trend analysis indicated that water levels in well WW-5a declined at a rate of about 0.4 ft/yr for 1959–95 with a total decrease in water level of more than 15 ft. The trend analysis of the periodic and continual water-level data for well WW-5a for 1996–98, however, indicates a reversal of the long-term declining water-level trend. From 1996 to 1998, water levels in well WW-5a increased at a rate of about 0.7 ft/yr (table 6).

Water-level fluctuations in observation well WW-5a appear to be related to pumping from nearby water-supply well WW-5c (fig. 10). An increase (decrease) in pumping from WW-5c causes a corresponding decrease (increase) in water levels in well WW-5a. The correlation between water levels in obser-

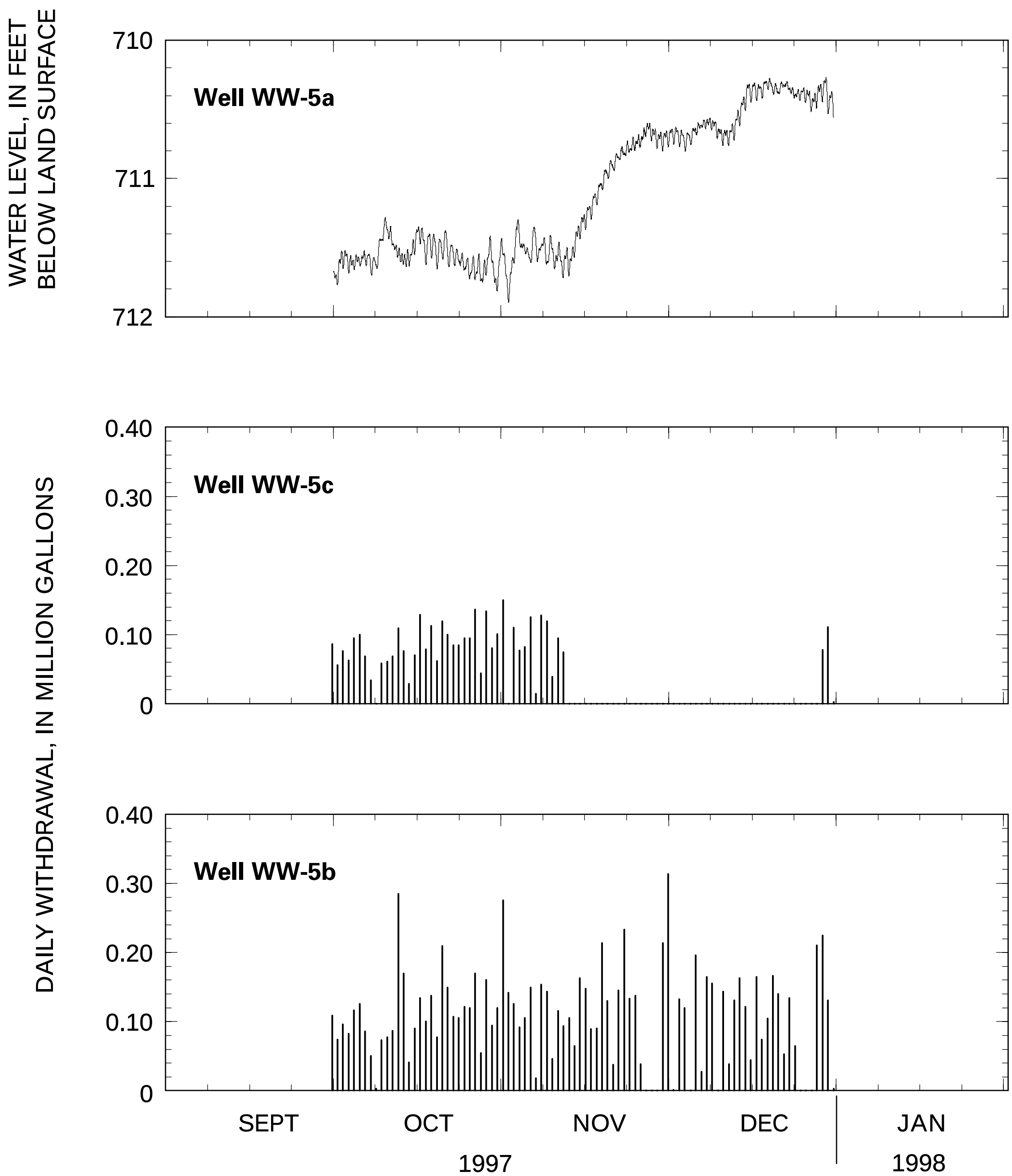


Figure 10. Water levels in observation well WW-5a and withdrawal from water-supply wells WW-5b and WW-5c from September through December 1997, Nevada Test Site. Water levels corrected for barometric pressure.

vation well WW-5a and pumping from water-supply well WW-5c is supported by significant p-values for Spearman and Pearson correlation coefficients.

The water-level response in well WW-5a to pumping from well WW-5b appears to be either nonexistent or masked by the effect of pumping from well WW-5c (fig. 10). In 1996, for example, water levels in well WW-5a began to rise shortly after pumping from well WW-5c stopped (November 1997; fig. 10). During the following 45 days, water-level fluctuations in well WW-5a showed no correlation to pumping from well WW-5b (p-values for Spearman and Pearson correlation coefficients were not significant). The distance from well WW-5b to well WW-5a is about 2 mi and probably contributes to the lack of a direct water-level response in this observation well. Well WW-5c is about 1 mi from well WW-5a.

A statistically significant water-level trend was determined for well UE-5n for 1991–97 (table 6). The 1991-97 period of record was selected for analysis because pumping from nearby test well RNM-2s was stopped in mid-1991. During 1991–97, water levels in well UE-5n declined at a rate of about 0.3 ft/yr (fig. 7).

The frequency of water-level measurements for well UE-5n were not sufficient to establish a long-term correlation with pumping from well RNM-2s. A substantial quantity of water was continuously pumped from well RNM-2s for radionuclide transport tests during 1975–91. Water-level fluctuations in well UE-5n during this period did not decline but appear erratic. For example, water levels increased in well UE-5n during 1983–86 even though pumping from test well RNM-2s generally was constant (fig. 11*A*). Furthermore, after pumping from well RNM-2s stopped in 1991, water levels in well UE-5n continued to rise for a few months and then declined. The water-level response in well UE-5n from 1991 to 1997 generally was opposite to the water-level response in test well RNM-2s (fig. 11*B*).

The erratic water-level fluctuations in well UE-5n may be a response to recharge of water discharged from test well RNM-2s. The water pumped from test well RNM-2s was discharged to an unlined channel near well UE-5n and contained elevated concentrations of tritium (IT Corporation, written commun., 1998). Water in well UE-5n also has contained elevated concentrations of tritium, suggesting that discharged water from well RNM-2s has recharged the alluvial aquifer (IT Corporation, written commun., 1998). Declining water levels in well UE-5n during 1991–97, therefore, may represent the effect of dissipating recharge of water previously discharged from well RNM-2s.

Similar to well RNM-2s, the frequency of water-level measurements in well UE-5n (fig. 11*C*) are not sufficient to accurately determine the influence of pumping from water-supply wells UE-5c or WW-5b. On the basis of available data, however, changes in pumping from wells UE-5c or WW-5b do not appear to cause corresponding water-level changes in well UE-5n. Correlations between water-level fluctuations in well UE-5n and pumping from well WW-5b or well UE-5c were not statistically significant.

The trend analysis indicated that water levels in well PW-3 increased at a rate of about 0.2 ft/yr during 1993–96 (table 6). The cause of the increasing water-level trend (rising water levels in the well) in well PW-3 is not clear. On the basis of soil-water chemistry data, Tyler and others (1996) reported that recharge to the alluvial aquifer at well PW-3 has not occurred since the last glacial maxima, about 20,000 years before present. Furthermore, water withdrawals from wells UE-5c and WW-5b (fig. 5) for 1993–96 do not appear to correlate with rising water levels in well PW-3 (p-values for Spearman and Pearson correlation coefficients were not significant). The rising water-level trend in well PW-3 may be a response to cessation of pumping in well RNM-2s in 1991. However, water-level measurements are not available to determine the potentiometric surface in the area of well PW-3 prior to 1993.

Volcanic Aquifer

The long-term water-level trends for wells WW-4 and WW-4a, completed in the volcanic aquifer, were not statistically significant. However, a comparison of continual water-level records shows similar water-level fluctuations (fig. 12). Water-levels collected in well WW-4 during pumping coincide with declining water levels in observation well WW-4a, and indicates that a hydraulic connection likely exists between these wells. About 3 months of continual water-level data are available for water-supply well WW-4 prior to pumping of well WW-4a. The correlation between water-level fluctuations in these wells is supported by significant p-values for Spearman and Pearson correlation coefficients.

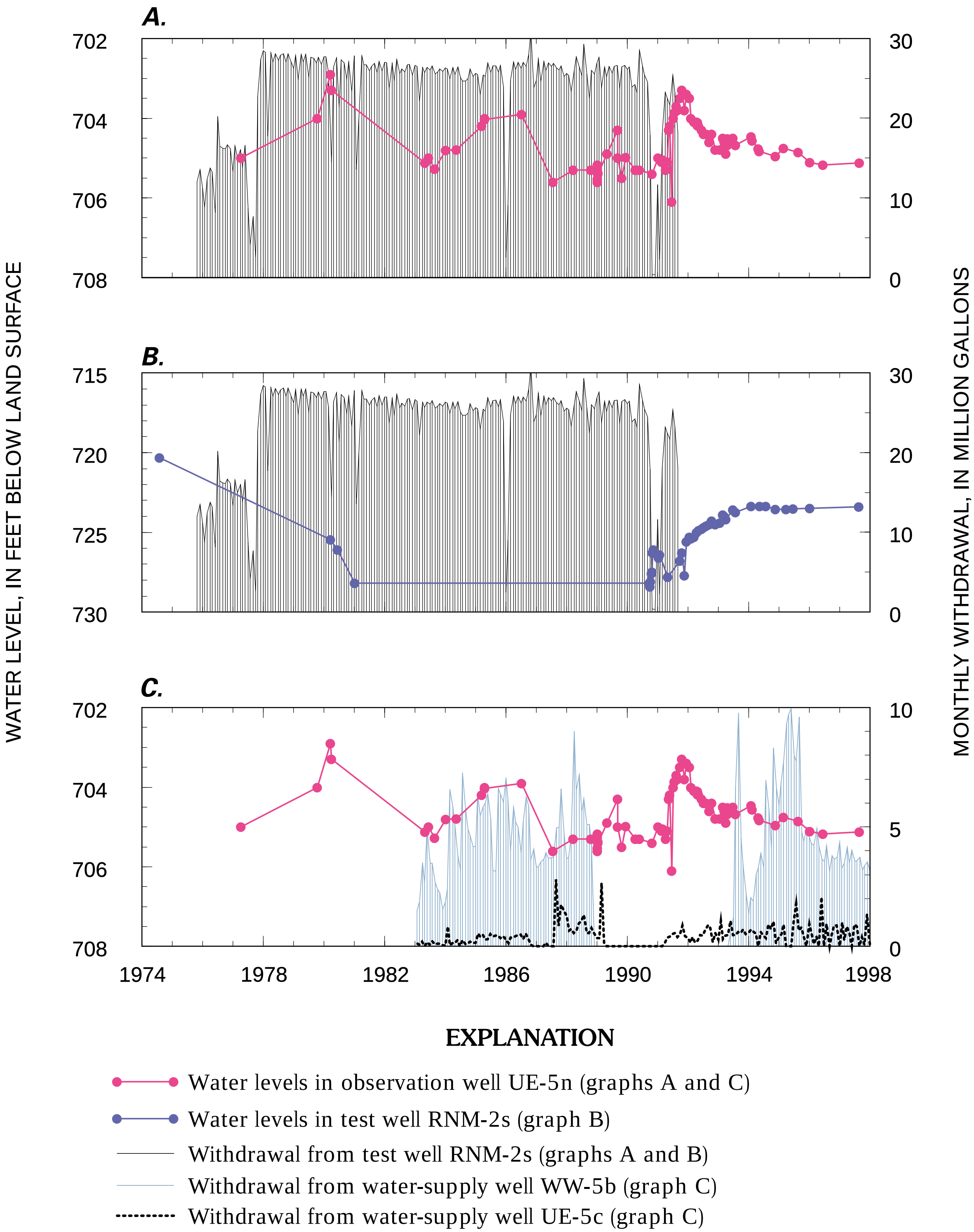


Figure 11. Water levels in wells UE-5n (1977–97) and RNM-2s (1974–97) and withdrawals from wells RNM-2s (1975–91), WW-5b (1983–97), and UE-5c (1983–97), Nevada Test Site.

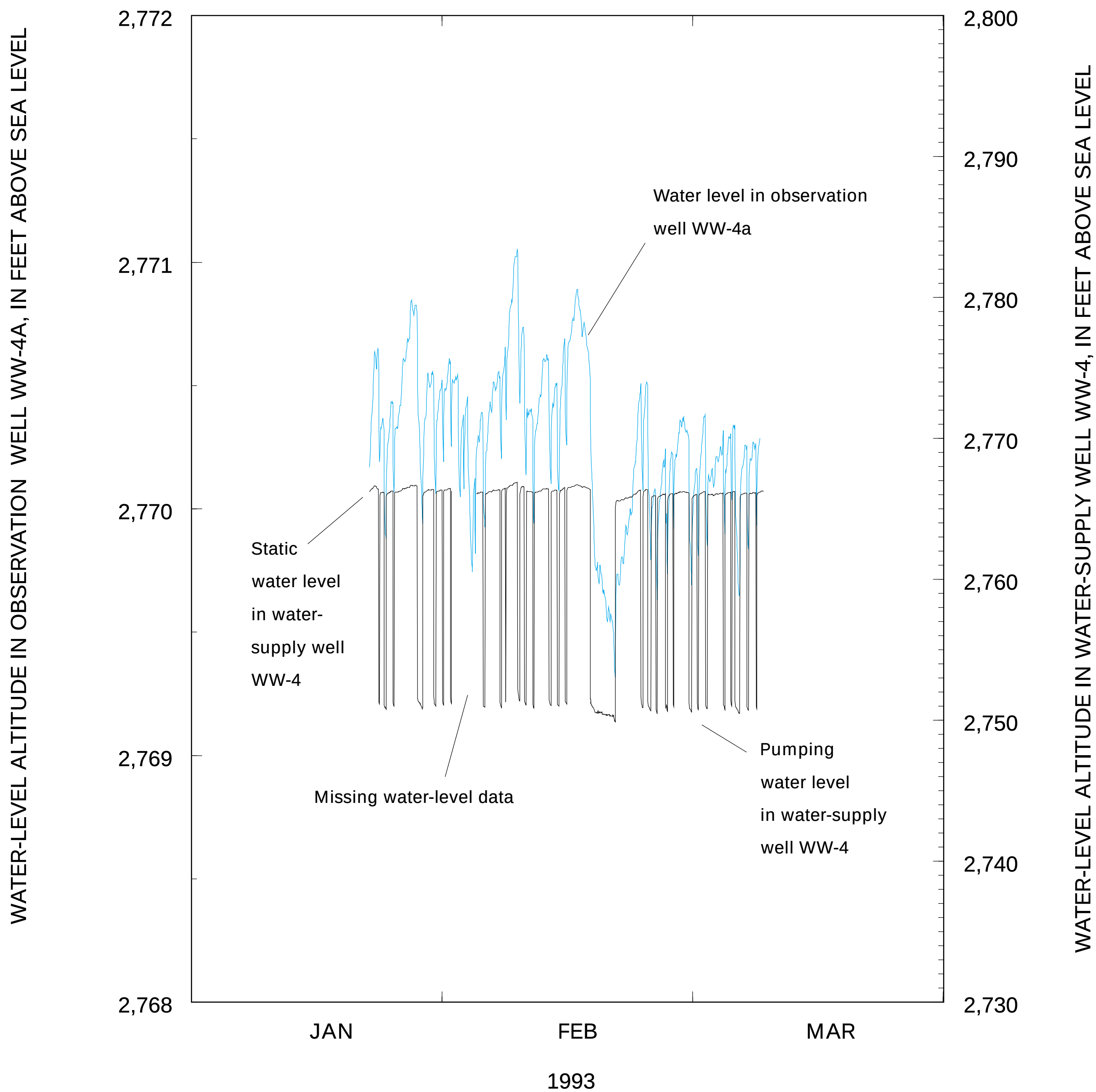


Figure 12. Water-level altitudes in water-supply well WW-4 and observation well WW-4a for January–March 1993, Nevada Test Site.

Carbonate Aquifer

A significant trend of increasing water levels during 1996–97 was observed in well SM-23 (fig. 8), completed in the carbonate aquifer about 4 mi north of well Army-1. Using continual water-level data, the analysis showed an increasing trend of about 0.2 ft/yr for well SM-23 from October 1996 to July 1997 (table 6).

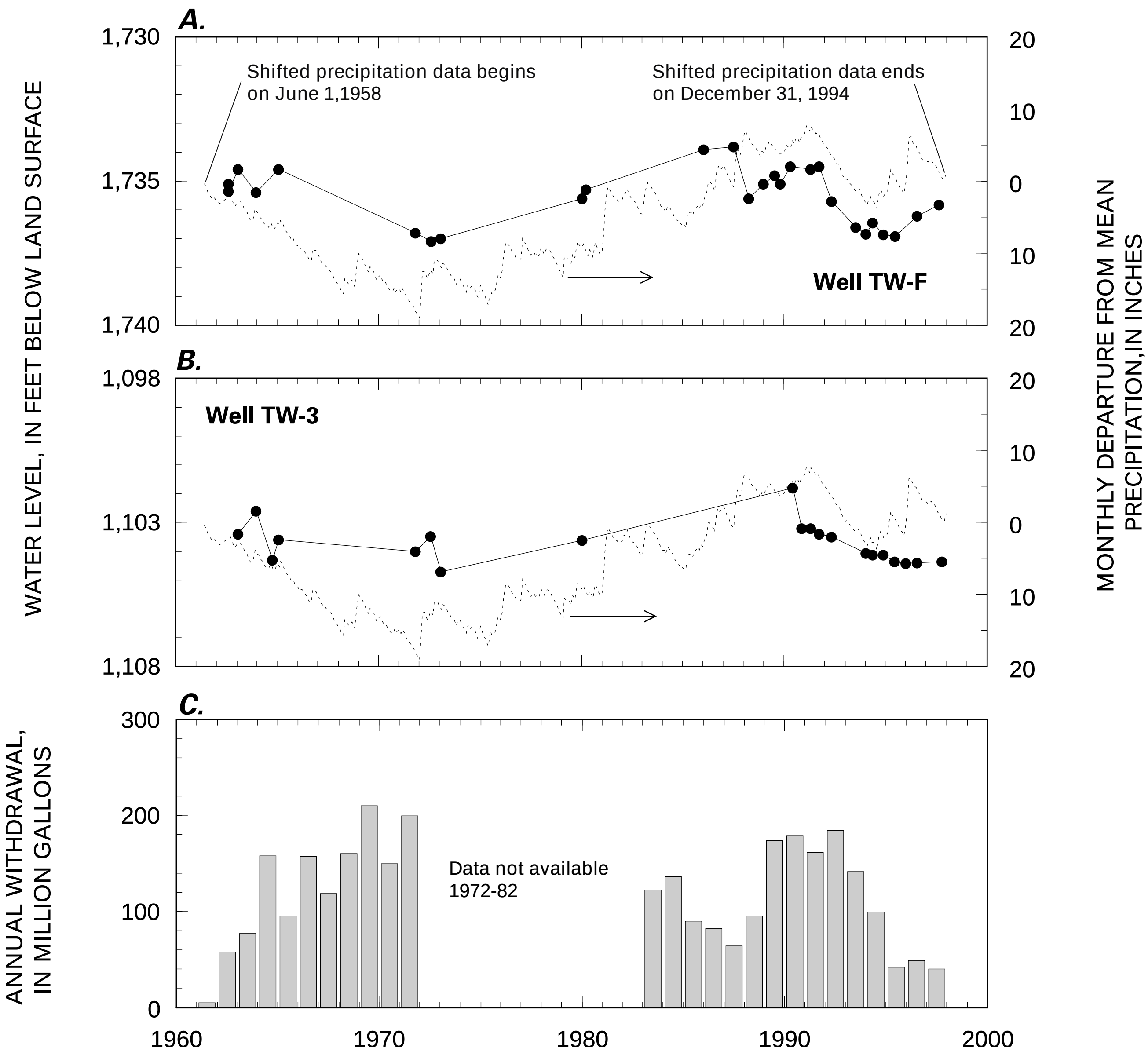
Continual water measurements at observation well SM-23 do not correlate with pumping from water-supply well Army-1 (p-values for Spearman and Pearson coefficients were not significant). This poor correlation may be due to (1) irregular daily pumping of well Army-1, (2) a poor hydraulic connection between the two wells, and (or), (3) the quantity of pumping from well Army-1 being too small to affect water levels in well SM-23. Well Army-1 contains almost 900 ft of open interval, but well SM-23 is open to only 30 ft of the carbonate aquifer. Pumping from well Army-1 generally has decreased since about mid-1994 when withdrawals were reduced by more than 50 percent (fig. 5). These factors would likely produce either a lagged and irregular water-level response or no water-level response in well SM-23.

Statistically significant water-level trends for the period of record were not observed for wells TW-F, TW-3, or Army-1 (table 6). The absence of longer-term trends for these wells may be due to the cyclic nature of water-level fluctuations that are apparent on the hydrographs (fig. 7). Water levels in wells TW-F, TW-3 and Army-1 generally declined during the 1960's, increased during the 1970–80's, and again declined during the 1990's. Similar water-level fluctuations in observation wells TW-F and TW-3 are supported by statistical correlation (p-values for Spearman and Pearson coefficients were significant). Water-level fluctuations between these wells and well Army-1, however, were not statistically significant. The lack of statistical correlation with well Army-1 may be due to the uncertainty associated with recovering water levels in this water-supply well.

Cyclic-type water-level fluctuations in wells TW-F and TW-3 may be the result, in part, of precipitation-induced recharge, ground-water pumping, or some combination of both causes. Infiltration of precipitation in higher altitude recharge areas near the Frenchman Flat area, where fractured carbonate rocks outcrop, might provide a mechanism for the observed water-level fluctuations in these wells. Ground-water flow through the carbonate aquifer largely is controlled by fractures, which increase the permeability of the rock unit (Laczniak and others, 1996, p. 27). Results of aquifer tests at Yucca Mountain show that the permeability of fractured carbonate or volcanic rock typically is several orders-of-magnitude greater than unfractured rock (Luckey and others, 1996, p. 32). Regional ground-water flow through the fractured carbonate aquifer beneath the Frenchman Flat area (fig. 2) is thought to originate to the east and southeast in the Spotted Range, South Ridge, and Spring Mountains (fig. 1) where carbonate rock crops out.

Comparison of water levels in wells TW-F and TW-3 with long-term cycles of precipitation (cumulative monthly departure from mean precipitation) generally support precipitation-induced recharge as a source of water-level fluctuations (fig. 13). Precipitation at Yucca Flat station (fig. 1) was less than normal (declined) in the 1960's and early 1990's and greater than normal (increased) during the 1970–80's. These changes in precipitation generally where similar to long-term changes of water levels in the carbonate aquifer. Precipitation records at Yucca Flat station were chosen because of the relatively long period of record (1958–94). Long-term fluctuations in precipitation at this station are similar to precipitation measured near well WW-5b in Frenchman Flat and at Mercury (fig. 3), and generally coincide with precipitation changes reported for southern Nevada (Dettinger and Schaefer, 1995, fig. 3).

A statistically significant correlation was observed between cumulative monthly departure from mean precipitation and lagged water levels in well TW-F; a marginal statistical correlation was observed for well TW-3 (p-value associated with Spearman's rho equal to 0.06). Although the statistical analysis resulted in more than one lagged time where water levels reasonably fit precipitation data, the most significant correlation occurred when water levels were lagged about 3 years behind precipitation (figs. 13*A* and 13*B*). A lagged water-level response in these wells may represent the time interval for precipitation to (1) infiltrate in higher-altitude areas some distance from the well, (2) move as ground water through unsaturated fractured rock to the water table, and (3) be observed as a confined-system (pressure) response (Davis and DeWiest, 1966, p. 46) at the well. Tritium age-dating of water emanating from springs in the carbonate rocks of the Spring Mountains and from tunnel seepage in volcanic rock beneath Rainier Mesa (fig. 1) suggests that infiltration of precipitation-induced recharge in fractured



EXPLANATION

- Total annual withdrawal from wells WW-C, WW-C1, and Army-1
- Water levels
- Departure from mean monthly precipitation (shifted 3 years)
- Direction of shifted precipitation data

Figure 13. Lagged water levels in wells TW-F and TW-3 (1962–97), cumulative departure from mean monthly precipitation at Yucca Flat station (1958–94), and withdrawal from water-supply wells WW-C1, WW-C, and Army-1 in carbonate-rock aquifer (1961–97), Nevada Test Site.

rocks to depths of more than 1,000 ft may occur in a time interval of less than 6 years (Clebsch, 1961, table 194.1; Winograd and others, 1998, p. 90).

Because of missing withdrawal records for all NTS water-supply wells, pumping from the carbonate aquifer (wells Army-1, WW-C, and WW-C1) could not be confirmed in this evaluation as a possible source of water-level fluctuations in observation wells TW-F and TW-3. Some evidence exists that pumping may influence water levels in these wells: pumping was relatively high in the late 1960's, low in the late 1980's, and was again high in the early 1990's, which generally coincides with water-level fluctuations in these wells (fig. 13*C*). Statistical correlations using available pumping data were significant for well TW-F, but nonsignificant for well TW-3 (p-value associated with Spearman correlation coefficient equal to 0.82).

Quartzite Confining Unit

A significant trend of decreasing water levels for 1958–97 was determined for observation well Army-6a (fig. 7). Water levels in this well declined at a rate of about 0.1 ft/yr for a total water-level change from 1958 to 1997 of 3.6 ft. The cause of the decline in water levels in this well is not clear. Water-level fluctuations do not appear to correlate with pumping from water-supply well Army-1 (p-values associated with Spearman and Pearson correlation coefficients were not significant). For example, water levels in well Army-6a do not respond to a decrease in withdrawal from well Army-1 in 1994 from more than 10 million gallons per month to about 1 million gallons per month (fig. 5). The water-level response in well Army-6a to pumping from well Army-1, which is about 1.5 mi to the northwest (fig. 2), may be subdued, delayed, and (or) difficult to detect if a limited hydraulic connection exists between the two wells. A limited hydraulic connection may occur because the wells are open to different hydrogeologic units. Well Army-6a is completed in the quartzite confining unit that regionally underlies the carbonate aquifer. Also, the interstitial permeability of the quartzite confining unit typically is low (Winograd and Thordarson, 1975, p. C42). Well Army-6a produces only a few gallons per minute when pumped (Thordarson and others, 1967, table 1), indicating that the permeability of the quartzite confining unit in this area probably is low.

SUMMARY

Water-level measurements from 1954 to 1998 were compiled and quality assured for 21 wells in the Frenchman Flat area. Water-level data were evaluated to (1) provide water-level adjustments for potential causes of water-level fluctuations, (2) determine if statistically and hydrologically significant water-level trends exist, and (3) determine, if possible, the causes of water-level trends or cyclic-type water-level fluctuations. Potential causes of water-level fluctuations in the Frenchman Flat area of the Nevada Test Site include changes in atmospheric conditions (precipitation and barometric pressure), Earth tides, seismic activity, underground nuclear testing, and ground-water withdrawals.

Adjustments of periodic and continual water-level measurements for the effects of barometric pressure, water density (from water-temperature measurements), borehole deviation, and land-surface altitude were determined for wells with available data. Continual water-level measurements for wells SM-23 and WW-5a were adjusted for the effects of barometric pressure and resulted in hydrographs that contain lower amplitude water-level fluctuations. Relatively high water temperature and associated low density significantly affect water levels only in well TW-F. The water-level adjustment for well TW-F (adjusted to the average water-sample temperature from wells completed in the carbonate aquifer) was about 17 ft. Water-level adjustment for the effects of borehole deviation ranged from less than 0.1 ft to more than 4 ft. Based on a differential global positioning system (GPS) survey of land-surface altitudes (LSA) at wells included in this study, the difference between previously recorded LSA and GPS derived LSA ranged from 0.10 ft to slightly more than 3 ft.

Water levels in five wells had statistically and hydrologically significant linear trends. Statistically significant trends were observed for three wells (WW-5a, UE-5n, and PW-3) completed in the alluvial aquifer, for one well (SM-23) completed in the carbonate aquifer, and for one well (Army-6a) completed in the quartzite confining unit .

Water levels in observation well WW-5a declined at a rate of about 0.4 ft/yr during 1959–95 and increased at a rate of about 0.7 ft/yr during 1996–98. Water-level fluctuations in well WW-5a appear to be the result of pumping from nearby water-supply well WW-5c (located about 1 mi from well WW-5a).

Water levels in observation well UE-5n declined at a rate of about 0.3 ft/yr from 1991 to 1997. Water-level and water-chemistry data suggest that water discharged from test well RNM-2s has locally recharged the alluvial aquifer near well UE-5n. Declining water levels in well UE-5n from 1991 to 1997, therefore, may represent the effect of dissipating recharge of water previously discharged from well RNM-2s.

Water levels in observation well PW-3 increased (rising water levels in the well) at a rate of about 0.2 ft/yr for 1993–96. The cause of rising water levels in well PW-3 is not clear. Water-level fluctuations in this well do not appear to correlate with pumping from nearby water-supply wells (wells WW-5b and UE-5c). Additionally, data on soil-water chemistry suggest that precipitation-induced recharge has not occurred at well PW-3 in the recent past.

Water levels in observation well SM-23, completed in the carbonate aquifer, increased at a rate of about 0.2 ft/yr from October 1996 to July 1997. A significant correlation could not be established for this period between water-level fluctuations at well SM-23 and pumping from water-supply well Army-1, located about 4 mi south of well SM-23.

Water levels in observation wells TW-F and TW-3 completed in the carbonate aquifer indicate the occurrence of cyclic-type water-level fluctuations—long-term periods (more than 5 years) when water levels decreased or increased. Visual and statistical correlation of water-level and precipitation data generally were supportive of precipitation-induced recharge as a possible source of long-term (1962–97), cyclic-type water-level fluctuations in wells TW-F and TW-3. Statistically significant and marginal correlations were observed between a 3-year lag in water levels in wells TW-F and TW-3, respectively, and cumulative departure from mean monthly precipitation.

A significant trend of decreasing water levels for 1958–97 was determined for observation well Army-6a. Water levels in this well declined at a rate of about 0.10 ft/yr. The cause of the steady decline in water levels in well Army-6a is not clear. Water levels in well Army-6a do not correlate with pumping from water-supply well Army-1, which is about 1.5 mi to the northwest. The poor correlation may be due to a limited hydraulic connection between the two wells, which may subdue or delay the water-level response in well Army-6a to pumping from well Army-1.

REFERENCES CITED

Brassington, R., 1988, Field hydrology: New York, Halsted Press, 175 p.

Cardinalli, J.L., Roach, L.M., Rush, F.E., and Vasey, B.J., comps., 1968, State of Nevada hydrographic areas: Nevada Division of Water Resources map, scale 1:500,000.

Chemical Rubber Publishing Co., 1985, Handbook of chemistry and physics (66th ed.): Boca Raton, Fla., CRC Press, 2,370 p.

Claassen, H.C., 1973, Water quality and physical characteristics of Nevada Test Site water-supply wells: U.S. Geological Survey Open-File Report 474-158, 145 p.

Clebsch, A., 1961, Tritium-age ground water at the Nevada Test Site, Nye County, Nevada *in* Short Papers in the Geologic and Hydrologic Sciences, Articles 147-292: U. S. Geological Survey Professional Paper 424-C, p. C122–C125.

Davis, S.N., and DeWiest, R.J.M., 1966, Hydrogeology: New York, John Wiley, 463 p.

Dettinger, M.D., and Schaefer, D.H., 1995, Decade-scale hydroclimatic forcing of ground-water levels in the central Great Basin, eastern Nevada: Summer Symposium, American Water Resources Association, Honolulu, Hawaii, June 1995, p. 195–204.

Drellack, S.L., 1995, Selected stratigraphic data for drill holes located in Frenchman Flat, Nevada Test Site: Raytheon Services Nevada Report TSP:DGP:111:95, 70 p.

Fenelon, J.M., 2000, Quality assurance and analysis of water levels in wells on Pahute Mesa and vicinity, Nevada Test Site, Nye County, Nevada: U.S. Geological Survey Water-Resources Investigations Report 00-4014, 68 p.

Ferris, J.G., Knowles, D.B., Brown, R.H., and Stallman, R.W., 1962, Theory of aquifer tests: U.S. Geological Survey Water-Supply Paper 1536-E, 174 p.

Garber, M.S., and Koopman, F.C., 1968, Methods of measuring water levels in deep wells: Techniques of Water Resources Investigations of the United States Geological Survey, Chapter A1, Book 8, 23 p.

Geldon, A.L., Umari, A.M.A., Earle, J.D., Fahy, M.F., Gemmell, J.M., and Darnell, Jon, 1998, Analysis of a multiple-well interference test in Miocene tuffaceous rocks at the c-hole complex, May-June 1995, Yucca Mountain, Nye County, Nevada: U.S. Geological Survey Water-Resources Investigations Report 97-4166, 33 p.

Graves, R.P., Tucci, Patrick, and O'Brien, G.M., 1997, Analysis of water-level data in the Yucca Mountain area, Nevada, 1985–95: U.S. Geological Survey Water-Resources Investigations Report 96-4256, 140 p.

Helsel, D.R., and Hirsch, R.M., 1992, Statistical methods in water resources: New York, Elsevier, 522 p.

Kilroy, K.C., 1992, Aquifer storage characteristics of Paleozoic carbonate rocks in southwestern Nevada estimated from harmonic analysis of water-level fluctuations: University of Nevada at Reno, unpublished Ph. D. dissertation, 77 p.

La Camera, R.J., and Locke, G.L., 1997, Selected ground-water data for Yucca Mountain region, southern Nevada and eastern California, through December 1996: U. S. Geological Survey Open-File Report 97-821, 79 p.

Laczniak, R.J., Cole, J.C., Sawyer, D.A., and Trudeau, D.A., 1996, Summary of hydrogeologic controls on ground-water flow at the Nevada Test Site, Nye County, Nevada: U.S. Geological Survey Water-Resources Investigations Report 96-4109, 59 p.

Lehman, L.L., and Brown, T.P., 1996, Summary of State of Nevada-funded studies of the saturated zone at Yucca Mountain, Nevada: Burnsville, Minn., L. Lehman & Associates, Inc., 44 p.

Luckey, R.R., Tucci, Patrick, Faunt, C.C., Ervin, E.M., Steinkampf, W.C., D'Agnese, F.A., and Patterson, G.L., 1996, Status of understanding of the saturated-zone ground-water flow system at Yucca Mountain, Nevada, as of 1995: U.S. Geological Survey Water-Resources Investigations Report 96-4077, 71 p.

Nimz, G.J., and Thompson, J.L., 1992, Underground radionuclides migration at the Nevada Test Site: Reynolds Electrical & Engineering Co., Inc., Report DOE/NV-346 UC-703, 17 p.

O'Brien, G.M., 1993, Earthquake-induced water-level fluctuations at Yucca Mountain, Nevada, June 1992: U.S. Geological Survey Open-File Report 93-73, 12 p.

———1997, Determination of aquifer-system properties based on the water-level frequency response to atmospheric loading and earth tides, Yucca Mountain, Nevada: Colorado School of Mines, unpublished Master's thesis, 280 p.

Perfect, D.L., Faunt, C.C., Steinkampf, W.C., and Turner, A.K., 1994, Hydrochemical data base for the Death Valley region, California and Nevada: U.S. Geological Survey Open-File Report, 13 p. (2 diskettes).

Pottorff, E.J., Erickson, S.J., and Campana, M.E., 1987, Hydrologic utility of borehole temperatures in Areas 19 and 20, Pahute Mesa, Nevada Test Site: University of Nevada, Desert Research Institute Publication 45060, 189 p.

Reynolds Electric & Engineering Company (REECo), 1994, Site characterization and monitoring data from Area 5 pilot wells, Nevada Test Site, Nye County, Nevada: U.S. Department of Energy, Nevada Operations Office, DOE/NV/11432-74, 124 p.

Rose, T.P., Kenneally, J.M., Smith, D.K., Davisson, M.L., Hudson, G.B., and Rego, J.H., 1997, Chemical and isotopic data for groundwater in southern Nevada: Lawrence Livermore National Laboratory Report UCRL-ID-128000, 35 p.

Rush, F.E., 1968, Index of hydrographic areas in Nevada: Nevada Division of Water Resources, Information Report 6, 38 p.

Thordarson, William, Young, R.A., and Winograd, I.J., 1967, Records of wells and test holes in the Nevada Test Site and vicinity (through December 1966): U.S. Geological Survey Open-File Report TEI-872, 26 p.

Todd, D.K., 1980, Groundwater hydrology: New York, John Wiley, 535 p.

Tyler, S.W., Chapman, J.B., Conrad, S.H., Hammermeister, D.P., Blout, D.O., Miller, J.J., Sully, M.J., and Gianni, J.M., 1996, Soil-water flux in the southern Great Basin, United States—Temporal and spatial variations over the last 120,000 years: Water Resources Research, v. 32, no. 6, p. 1481–1499.

U.S. Department of Energy, 1994, United States nuclear tests, July 1945 through September 1992: U.S. Department of Energy, Nevada Operation Office, DOE/NV-209 (rev. 14), 105 p.

Winograd, I.J., 1970, Noninstrumental factors affecting measurement of static water levels in deeply buried aquifers and aquitards, Nevada Test Site: Ground Water, v. 8, no. 2, p. 19–28.

Winograd, I.J., and Thordarson, William, 1975, Hydrogeologic and hydrochemical framework, south-central Great Basin, Nevada-California, with special reference to the Nevada Test Site: U.S. Geological Survey Professional Paper 712-C, 126 p.

Winograd, I.J., Riggs, A.C., and Coplen, T.B., 1998, The relative contributions of summer and cool-season precipitation to ground water recharge, Spring Mountains, Nevada, USA: Hydrogeology Journal, v. 6, p. 77–93.

Wood, D.B., and Reiner, S.R., 1996, Ground-water data for 1990–91 and ground-water withdrawals for 1951-91, Nevada Test Site and vicinity, Nye County, Nevada: U.S. Geological Survey Open-File Report 96-475, 78 p.