U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Trend Analysis of Ground-Water Levels and Spring Discharge in the Yucca Mountain Region, Nevada and California, 1960–2000

Water-Resources Investigations Report 02-4178

Prepared in cooperation with the
NEVADA OPERATIONS OFFICE of the
U.S. DEPARTMENT OF ENERGY, under
Interagency Agreement, DE-AI08-01NV13944

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(Back of Cover)

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By Joseph M. Fenelon and Michael T. Moreo

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Carson City, Nevada
2002

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
square mile (mi^2)	2.590	square kilometer
acre	0.4047	hectare
	Volume	
acre-foot (acre-ft)	1,233	cubic meter
million gallons (Mgal)	3,785	cubic meter
million gallons (Mgal)	3.069	acre-foot
	Hydraulic gradient	
foot per mile (ft/mi)	0.1894	meter per kilometer
	Transmissivity	
cubic foot per day per foot width of aquifer (ft^2/d)	0.09290	cubic meter per day per meter width of aquifer
	Rate	
foot per year (ft/yr)	0.3048	meter per year
inch per year (in/yr)	2.54	centimeter per year
	Volumetric Rate	
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
gallon per minute (gal/min)	0.06309	liter per second
million gallons per year (Mgal/yr)	3,785	cubic meters per year

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.

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

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ABSTRACT

Ground-water level and discharge data from 1960 to 2000 were analyzed for the Yucca Mountain region of southern Nevada and eastern California. Included were water-level data from 37 wells and a fissure (Devils Hole) and discharge data from five springs and from a flowing well. Data were evaluated for variability and for upward, downward, or cyclic trends with an emphasis on the period 1992–2000. Potential factors causing trends in water levels and discharge include ground-water withdrawal, infiltration of precipitation, earthquakes, evapotranspiration, barometric pressure, and earth tides.

Statistically significant trends in ground-water levels or spring discharge from 1992 to 2000 were upward at 12 water-level sites and downward at 14 water-level sites and 1 spring-discharge site. In general, the magnitude of the change in water level from 1992 to 2000 was small (less than 2 feet), except where influenced by pumping or local effects such as possible equilibration from well construction or diversion of nearby surface water.

Seasonal trends are superimposed on some of the long-term (1992–2000) trends in water levels and discharge. Factors causing seasonal trends include barometric pressure, evapotranspiration, and pumping. The magnitude of seasonal change in water level can vary from as little as 0.05 foot in regional aquifers to greater than 5 feet in monitoring wells near large supply wells in the Amargosa Farms area.

Three major episodes of earthquake activity affected water levels in wells in the Yucca Mountain region between 1992 and 2000: the Landers/Little Skull Mountain, Northridge, and Hector Mine earthquakes. The Landers/Little Skull Mountain earthquakes, in June 1992, had the largest observed effect on water levels and on discharge during the study period. Monthly measurements of wells in the study network show that earthquakes affected water levels from a few tenths of a foot to 3.5 feet.

In the Ash Meadows area, water levels remained relatively stable from 1992 to 2000, with some water levels showing small rising trends and some declining slightly. Possible reasons for water-level fluctuations at sites AD-6 (Tracer Well 3), AM-5 (Devils Hole Well), and AM-4 (Devils Hole) from 1960 to 2000 include climate change, local and regional ground-water withdrawals, and tectonic activity.

In Jackass Flats, water levels from 1992 to 2000 in six wells adjacent to Fortymile Wash displayed either small upward trends or no upward or downward trend. Comparison of trends in water levels from 1983 to 2000 for these six wells shows good correlations between all wells and suggests a common mechanism controlling water levels in the area. Of the likely controls on the system—precipitation or pumping in Jackass Flats—precipitation appears to be the predominant factor controlling water levels near Fortymile Wash.

Water levels in the heavily pumped Amargosa Farms area declined from about 10 to 30 feet from 1964 to 2000. Water-level declines accelerated beginning in the early 1990’s as pumping rates increased substantially. Pumping in the Amargosa Farms area may affect water levels in some wells as far away as 5–14 miles.

The water level at site DV-3 (Travertine Point 1 Well) and discharge at site DV-2 (Navel Spring), both in the Death Valley hydrographic area, had downward trends from 1992 to 2000. The cause of these downward trends may be linked to earthquakes, pumping in the Amargosa Farms area, or both.

INTRODUCTION

Since the late 1970's, investigations to determine the potential suitability of Yucca Mountain for storage of high-level nuclear waste have been done by the U.S. Geological Survey (USGS) and other organizations. The U.S. Department of Energy (DOE) has stated that all facilities and activities associated with such investigations of Yucca Mountain will be operated in a manner that maintains or protects environmental quality, and has established programs to assess environmental quality. In April 1989, the USGS began a cooperative program with DOE to develop a ground-water-resources Environmental Monitoring Program in the vicinity of Yucca Mountain. The purposes of the Environmental Monitoring Program are to: (1) document historical and current conditions of ground-water resources, including water levels and water quality, (2) detect changes in these resources, and (3) provide a basis for analyzing and identifying potential adverse effects on ground-water resources. The primary focus of the Environmental Monitoring Program is on Jackass Flats, where ground water is withdrawn to support several DOE activities, including Yucca Mountain site characterization. If these withdrawals affect ground-water levels, the effects may be detected in Jackass Flats before they are detected elsewhere within the Yucca Mountain region.

The USGS has monitored two Yucca Mountain ground-water networks through 2000. The earliest-monitored network is a local Yucca Mountain network that was first monitored in 1981 as part of a site-characterization plan (U.S. Department of Energy, 1988). The purpose of this network is to gain a better understanding of the ground-water flow system at Yucca Mountain for site characterization purposes. The focus of this report, however, is a regional network, part of the Environmental Monitoring Program described previously. Seven wells in Jackass Flats are included in the Environmental Monitoring Program network and the site-characterization network. Water levels from the remaining wells in the site-characterization network were not analyzed for this report.

The study area is within the Yucca Mountain region of southern Nevada and eastern California (fig. 1*A*). For the purpose of study, this area includes all of Crater Flat and Jackass Flats to the north; all of Rock Valley, Mercury Valley, and eastern Amargosa Desert to the east; and parts of western Amargosa Desert and Death Valley to the south and west. The southern and western extents of the study area are approximately denoted by Death Valley Junction and Furnace Creek Ranch, respectively (fig. 1*B*). The study area includes Yucca Mountain as well as the southwestern part of the Nevada Test Site (NTS), which lies immediately east of Yucca Mountain. The Yucca Mountain region is within the Great Basin, a subdivision of the Basin and Range Physiographic Province (Fenneman, 1931, p. 328).

Purpose and Scope

This report analyzes ground-water level and spring-discharge data collected or compiled as part of the cooperative USGS/DOE Environmental Monitoring Program for Yucca Mountain. Data collected between 1960 and 2000 from the primary monitoring network include water levels at 37 wells and a fissure (Devils Hole), and discharge at 5 springs and a flowing well. Total reported ground-water withdrawals within the study area (Crater Flat, Jackass Flats, Mercury Valley, and Amargosa Desert) and from the surrounding regional area (Pahrump, Las Vegas, NTS, Penoyer Valley, and Pahranagat Valley) were compiled. Most of the water-level and withdrawal data analyzed for this report were previously published in a series of annual reports (La Camera and Westenburg, 1994; Hale and Westenburg, 1995; Westenburg and La Camera, 1996; La Camera and others, 1996; La Camera and Locke, 1998; La Camera and others, 1999; Locke, 2001a; and Locke, 2001b). Also compiled were precipitation data from major recharge areas in the Spring Mountains, Pahute Mesa area, and Pahranagat Valley area. Miscellaneous water levels and discharge from several wells and springs were included to aid in interpretation of trends in the primary monitoring network.

The principal emphasis of this report is to explain the various trends or fluctuations in water levels or discharge collected or compiled as part of the Environmental Monitoring Program. The report provides a

basis for comparing water levels and discharge between primary monitoring sites and for determining how the data fit into a regional understanding of the ground-water flow system. Anomalous changes in water levels or discharge for individual wells or springs that do not appear to be caused by regional effects are identified and explained, if possible. Special attention is given to the discussion of water-level trends in Jackass Flats, their possible causes, and any noticeable effects on water levels from ground-water withdrawals in Jackass Flats.

Water levels and spring discharge were analyzed for variability and for upward, downward, or cyclic trends with an emphasis on the period 1992–2000, when water levels were measured monthly for the Environmental Monitoring Program. Measurements prior to 1992 generally were made sporadically, with few wells or springs having data for the entire period of 1960–2000.

Trends were analyzed statistically to detect significant upward or downward changes and graphically to compare trends between sites. For many of the wells and springs with significant trends, an attempt was made to identify the cause. Potential causes of change in water levels and spring discharge may be local or regional. Local causes include possible improper well construction, nearby diversions of surface water, and pumping in or nearby the monitoring well. Regional causes include ground-water withdrawal, recharge from precipitation, earthquakes, evapotranspiration, barometric pressure, and earth tides.

Acknowledgments

Several organizations and programs contributed to this report. Specifically, data were provided by the National Park Service (NPS); U.S. Fish and Wildlife Service (USFWS); Nevada Department of Conservation and Natural Resources, Division of Water Resources (NDWR); Nevada Department of Transportation; Barrick Bullfrog, Inc.; Bechtel Nevada; Cathedral Gold U.S. Corporation; Cind-R-Lite Company; Daisy Gold Mining Company; U.S. Borax Corporation; U.S. Nevada Gold Search; USGS–Hydrologic Resources Management and Environmental Restoration Programs; and USGS–Yucca Mountain Project Branch studies of saturated-zone site hydrology and saturated-zone regional hydrology.

Individuals who provided data and information for this study include Bradley Gillies (NPS), Tim Mayer and Wendy Yao (USFWS), Desiree Brantley (NDWR), Hans Arlt (U.S. Nuclear Regulatory Commission), and David Buesch (USGS–Yucca Mountain Project Branch). The authors also acknowledge the cooperation of property owners throughout the Amargosa Desert who allowed access to their property to collect hydrologic data.

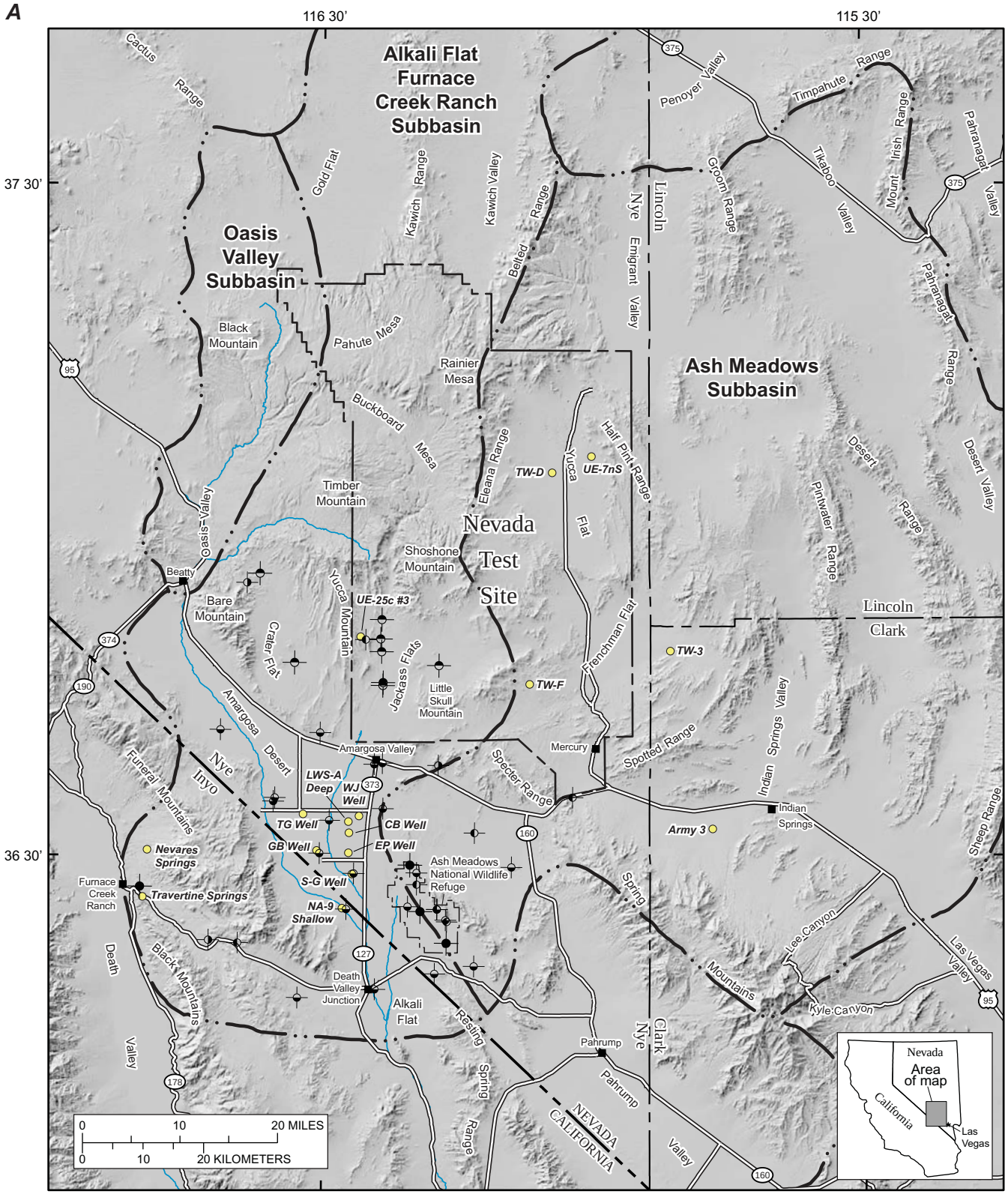
Additionally, the following USGS employees contributed significantly to the design, management, or collection of data for the primary monitoring network: John Armino, Richard J. La Camera, Glenn L. Locke, Rodney H. Munson, Charles S. Savard, and Craig L. Westenburg. Special thanks go to Randell J. Laczniak (USGS) for general guidance in the analysis and interpretation of data; to Peggy E. Elliott (USGS) for contributing to the earthquake section of the report and reviewing early drafts; and to Donald P. Harper (USGS) for creating the maps used in the report.

DESCRIPTION OF STUDY AREA AND GENERAL HYDROGEOLOGY

The study area is within the Death Valley regional ground-water flow system (Harrill and others, 1988, sheet 1) and, more specifically, within the southern Alkali Flat–Furnace Creek Ranch and southwestern Ash Meadows ground-water subbasins (fig. 1*B*). Each ground-water subbasin defines an area of ground-water recharge and flow paths to major area(s) of discharge at land surface (Waddell and others, 1984, p. 36; Laczniak and others, 1996, p. 16, pl. 1). Boundaries of the subbasins (fig. 2) are based on the location of recharge areas, discharge areas, low-permeability rocks, hydraulic gradients, and water chemistry. These boundaries are general indicators of restrictions on ground-water movement in the region.

The study area also is subdivided by hydrographic areas[1] (fig. 1*B*). As defined by Rush (1968, p. 4), hydrographic areas generally consist of valleys (topographic lows) extending to surrounding surface-water drainage divides (topographic highs). Hydrographic

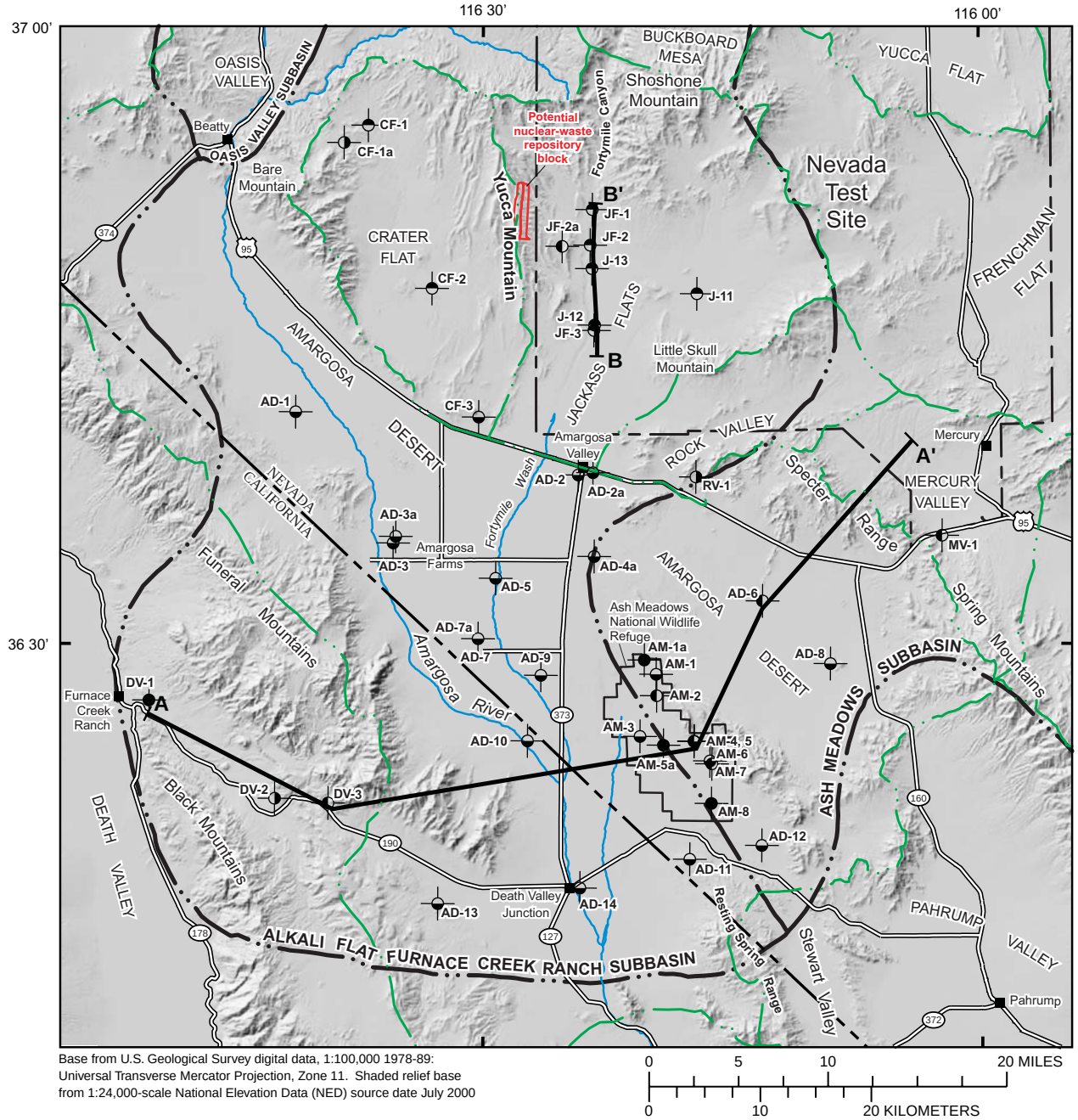
[1]Formal hydrographic areas in Nevada were delineated systematically by the U.S. Geological Survey and Nevada Division of Water Resources in the late 1960's (Rush, 1968; Cardinalli and others, 1968) for scientific and administrative purposes.



Base from U.S. Geological Survey digital data, 1:100,000 1978 - 89:
Universal Transverse Mercator Projection, Zone 11. Shaded relief base
from 1:24,000-scale National Elevation Data (NED) source date July 2000

Figure 1. Yucca Mountain region, southern Nevada and eastern California, showing (*A*) regional area and location of primary and miscellaneous monitoring sites and (*B*) study area and location of primary monitoring sites.

B



Base from U.S. Geological Survey digital data, 1:100,000 1978-89: Universal Transverse Mercator Projection, Zone 11. Shaded relief base from 1:24,000-scale National Elevation Data (NED) source date July 2000

0 5 10 20 MILES

0 10 20 KILOMETERS

EXPLANATION

Primary monitoring site—Site number (table 1) and primary contributing unit are indicated

- AD-6 — Carbonate rock
- CF-1a — Undifferentiated sedimentary rock
- AD-1 — Valley fill
- JF-1 — Volcanic rock
- DV-1 — Combined carbonate rock and valley fill

TG Well — **Miscellaneous monitoring site—Site name (table 3) indicated**

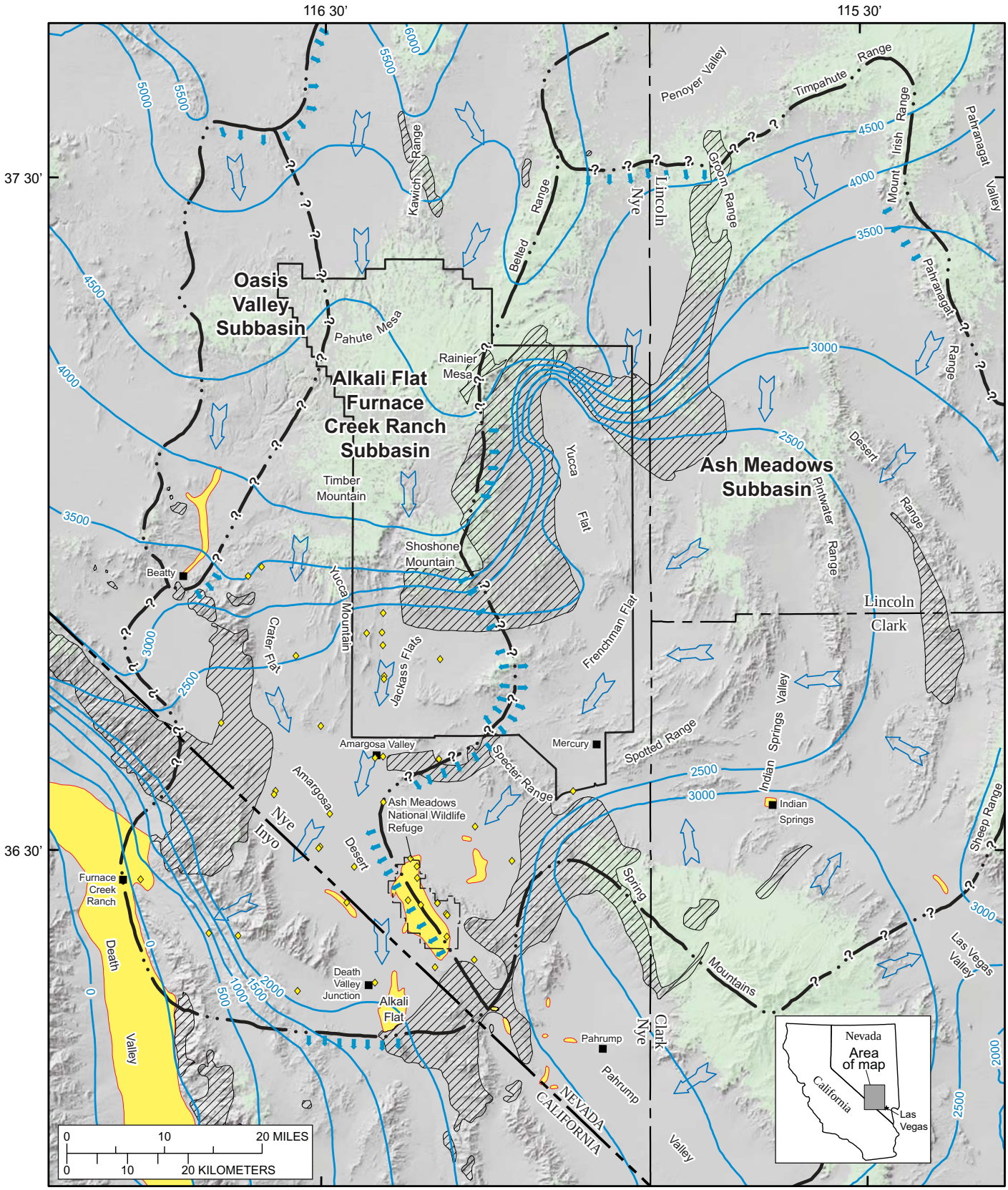
Ground-water subbasin boundary—From Laczniak and others (1996, pl. 1)

Nevada Test Site boundary

A — A' **Trace of section. Sections shown in figs. 3 and 21**

Hydrographic area boundary—Hydrographic-area names in capital letters

Figure 1. Continued



Base from U.S. Geological Survey digital data, 1:100,000 1978 89:
Universal Transverse Mercator Projection, Zone 11. Shaded relief base
from 1:24,000-scale National Elevation Data (NED) source date July 2000

Figure 2. Major factors controlling ground-water flow in the Yucca Mountain region, southern Nevada and eastern California.

areas in the study area include Crater Flat, Jackass Flats, Rock Valley, Mercury Valley, most of Amargosa Desert, and part of Death Valley (Rush, 1968; Harrill and others, 1988, sheet 2).

Three primary aquifer types are present within the study area: Cenozoic valley fill, Tertiary volcanic rock, and Paleozoic carbonate rock. Valley-fill aquifers consist of poorly consolidated alluvial fan and fluvial deposits and fractured and bedded Tertiary carbonates. The valley-fill aquifers are present in most of the valleys or basins in the study area (fig. 3). Fine-grained lakebed and playa deposits, volcanic-ash beds, and mudflows may function as valley-fill confining units for the valley-fill aquifers. Volcanic-rock aquifers, consisting of unaltered, partly to densely welded ash-flow tuff, typically are found in the northern part of the study area. These aquifers commonly are interlayered with confining units consisting of altered or non-welded ash-flow tuffs and bedded ash-fall tuff. Lithologic variations, extent, and thickness of basin-filling rocks (valley-fill deposits and volcanic rocks) in the study area are described in Sweetkind and others (2001). The carbonate-rock aquifer underlying the carbonate-rock province, which covers almost 100,000 mi^2 of the Great Basin (Plume, 1996, p. 4), is the principal regional aquifer in the Death Valley ground-water flow system (Laczniak and others, 1996, p. 19). Flow in this aquifer is predominately controlled by fractures, fault zones, and solution channels. Because the aquifer is regional, ground water is able to move laterally across basins as interbasin flow (fig. 3). The aquifer is confined beneath most intermontane basins and commonly unconfined beneath ridges. The saturated thickness throughout most of the study area probably is at least 4,000 ft (Winograd and Thordarson, 1975, p. 62). The carbonate-rock aquifer is underlain by a confining unit consisting of Cambrian and pre-Cambrian quartzite and siltstone (Laczniak and others, 1996, p. 14). This semi-permeable basement confining unit is present throughout the study area but is particularly important to ground-water flow in areas in which it occurs at the water table (fig. 2). In these areas, the confining unit impedes lateral ground-water flow, causing large ground-water gradients as water moves through the unit.

EXPLANATION

Area of ground-water discharge—From Laczniak and others (1996, pl. 1)

Area of ground-water recharge—Modified from D'Agnese and others (1997, fig. 25)

Known distribution of confining units at water table—From Laczniak and others (1996, pl. 1)

General direction of regional ground-water flow—Modified from Laczniak and others (1996, pl. 1)

Ground-water subbasin boundary—Arrow indicates location and direction of lateral flow across boundary. Queried where uncertain. Modified from Laczniak and others (1996, pl. 1)

3000 **Water-level contour**—Shows altitude of regional water-level. Interval 500 feet. Datum is sea level. Modified from Laczniak and others (1996, pl. 1)

Primary monitoring site

Ash Meadows Ground-Water Subbasin

Part of Rock Valley, Mercury Valley, and the eastern part of the Amargosa Desert are within the Ash Meadows ground-water subbasin (fig. 1*B*). The principal aquifer controlling flow in the subbasin is the regional Paleozoic carbonate-rock aquifer (fig. 3). However, nearer to the Ash Meadows discharge area, where most of the study area lies, valley-fill deposits also are an important aquifer (Laczniak and others, 1996, p. 16).

Regional ground-water flow in the subbasin (fig. 2) is generally to the south, west, or southwest (Harrill and others, 1988, sheet 2; Laczniak and others, 1996, p. 16–18, pl. 1). A major trough in the potentiometric surface extends for about 40 mi from eastern Frenchman Flat, through the Specter Range, to Ash Meadows. In general, the trough is highly transmissive, and, in the area between the Specter Range and Ash Meadows, the hydraulic gradient is about 0.3 ft/mi (Winograd and Thordarson, 1975, p. 73–74). About 17,000 acre-ft/yr (5,500 Mgal/yr) of ground water flows through the Specter Range, an estimate approximating the volume of spring discharge at Ash Meadows (Winograd and Thordarson, 1975, p. 115). Minor flow from valley-fill aquifers to the carbonate-rock aquifer occurs in some basins such as Yucca Flat and Frenchman Flat (Winograd and Thordarson, 1975, p. 62). In other basins, such as southern Indian Springs Valley, east-central Amargosa Desert, and possibly eastern Jackass Flats, valley-fill aquifers are recharged predominately by upward flow from the carbonate-rock aquifer (Winograd and Thordarson, 1975, p. 62).

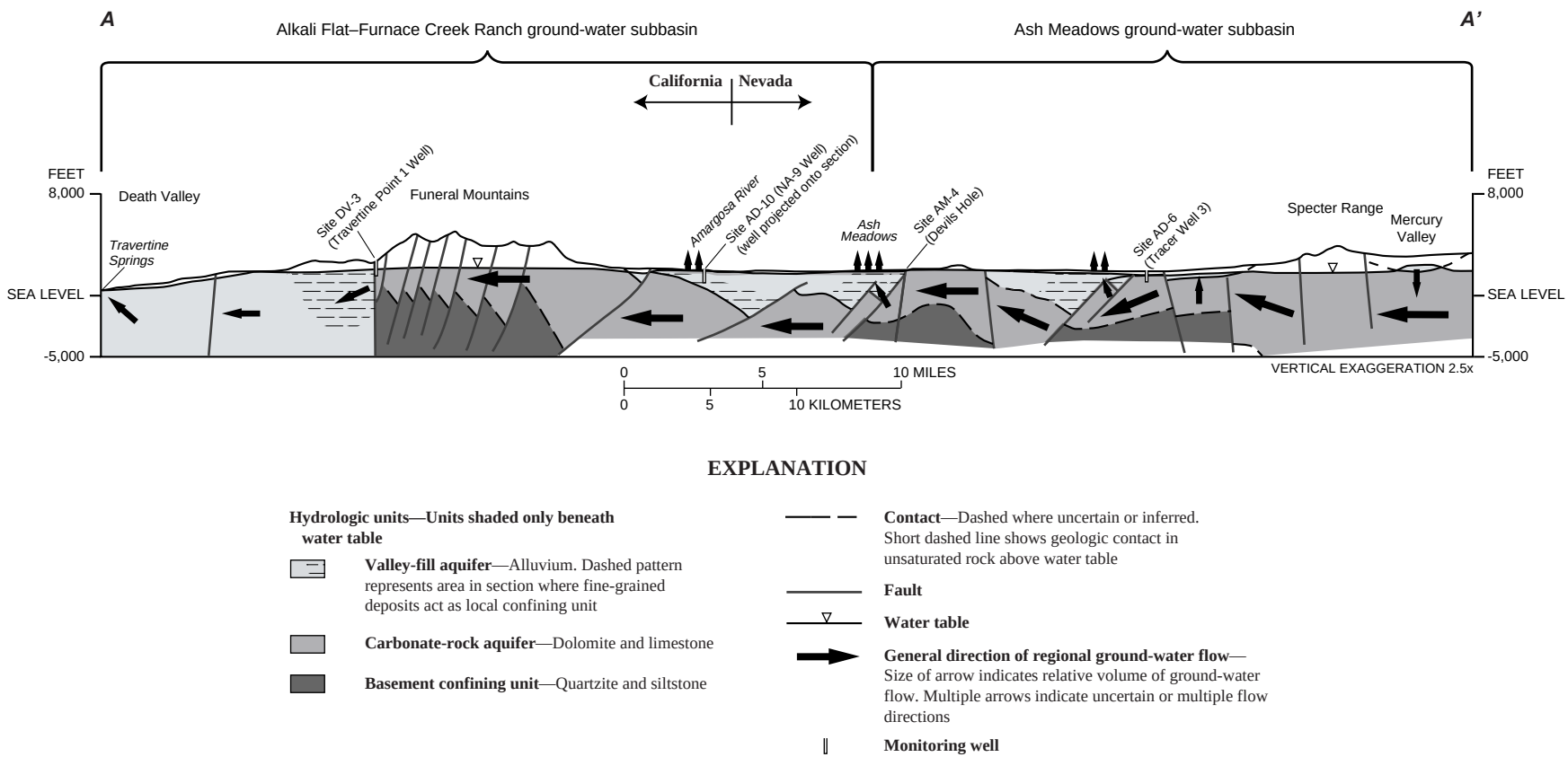


Figure 3. Hydrogeologic section from Death Valley to Mercury Valley showing major controls on flow system. (Modified from Laczniak and others, 1996, pl. 2.) Line of section is shown in figure 1*B*.

Sources of ground-water recharge to the Ash Meadows subbasin are precipitation and subsurface inflow (fig. 2). Recharge from precipitation occurs on the higher mountains within and on the fringes of the subbasin, and, to a lesser extent, as focused recharge from episodic flooding of major washes. Most recharge occurring within the subbasin is probably in the highly fractured carbonate rocks beneath the Spring Mountains. Lesser contributions are made by the Pahranagat, Mount Irish, Timpahute, Groom, Belted, Desert, Pintwater, and Spotted Ranges, and possibly the Sheep Range. Subsurface inflow occurs from several valleys predominately along the basin's north and northeast boundaries (about 100 mi northeast of Ash Meadows). Winograd and Thordarson (1975) estimate that subsurface inflow accounts for almost half of the 17,000 acre-ft/yr of spring discharge from Ash Meadows. Approximately 35 percent of Ash Meadows spring discharge may enter the subbasin through Pahranagat Valley from the White River flow system, 4 percent from Penoyer Valley, a few percent from the area near Pahrump Valley, and less than 3 percent from the flow of semi-perched ground water into the carbonate-rock aquifer from various valleys within the subbasin (Winograd and Thordarson, 1975). Subsequent analysis in Thomas and others (1996) concludes, based on deuterium and water-chemistry data as well as hydrologic and geologic framework information, that about 60 percent of the spring discharge at Ash Meadows is probably derived from the Spring Mountains; the remaining 40 percent is probably derived from underflow through Pahranagat Valley from the White River flow system to the east.

Ground water in the Ash Meadows ground-water subbasin discharges principally as spring flow and evapotranspiration in the Ash Meadows area, from wells on the NTS and in Indian Springs, and as underflow into the Alkali Flat–Furnace Creek Ranch ground-water subbasin (fig. 2). Ash Meadows contains about 30 springs along a 10-mile-long spring line that trends north-northwest. The springs are mainly in Quaternary and Tertiary lakebed deposits but the water originates in the underlying carbonate-rock aquifer (Winograd and Thordarson, 1975, p. 80). Water from the carbonate-rock aquifer is diverted to the land surface by one or more normal faults that create a barrier to ground-water flow by juxtaposing low permeability Cenozoic valley-fill deposits against the carbonate-rock aquifer (fig. 3). Discharge from these springs, as a group, probably has remained relatively constant for the last 100 years (Walker and Eakin, 1963; Winograd and Thordarson, 1975). Some ground water moving through the relatively thick carbonate-rock aquifer may move into the Alkali Flat–Furnace Creek Ranch subbasin as underflow (figs. 2 and 3), without being forced upward into the valley fill (Winograd and Thordarson, 1975, p. 82). Immediately west of the Ash Meadows subbasin boundary, valley-fill sediments become saturated by upward flow from the carbonate-rock aquifer as well as by recycled spring flow infiltrating the shallow valley-fill deposits (Laczniak and others, 1999, p. 9). Shallow ground water in the valley-fill deposits is available for evapotranspiration.

Alkali Flat–Furnace Creek Ranch Ground-Water Subbasin

Crater Flat and Jackass Flats hydrographic areas (which are separated by Yucca Mountain), most of Rock Valley, the west-central part of the Amargosa Desert, and part of Death Valley are in the Alkali Flat–Furnace Creek Ranch ground-water subbasin (fig. 1*B*). All three primary aquifer types are present within this subbasin. The volcanic-rock aquifers are located primarily in Jackass Flats and Crater Flat. The valley-fill and Paleozoic carbonate-rock aquifers are the principal aquifers in the Amargosa Desert to the south (fig. 3). In general, much of the valley fill in the Amargosa Desert functions as a regional confining unit on top of the carbonate rock (Naff and others, 1974, p. 12). However, where deposits are more permeable, such as the Amargosa Farms area, the valley fill can yield large amounts of water to wells.

Principal sources of ground water within the Alkali Flat–Furnace Creek Ranch ground-water subbasin are precipitation and subsurface inflow (Laczniak and others, 1996, p. 17; Waddell and others, 1984, p. 36; Harrill and others, 1988, sheet 2). Recharge occurs at the northern and northeastern boundaries of the subbasin in areas that include the Kawich Range, Belted Range, and Rainier Mesa (fig. 2). Recharge also occurs from within the subbasin in eastern Pahute Mesa, the southern part of Kawich Range, and Shoshone and Timber Mountains. Furthermore, recharge may occur as infiltration of surface runoff in major drainage ways, including the Amargosa River and Fortymile Wash (Savard, 1998). Localized recharge occurring at intermediate altitudes within the subbasin, such as the northern part of Yucca Mountain, is considered

relatively minor. In addition to recharge from precipitation, the subbasin likely receives subsurface inflow from north of the subbasin and from the Ash Meadows and Oasis Valley subbasins (Laczniak and others, 1996, p. 18–19). Ground water in the subbasin generally flows to the south, southeast, or southwest (fig. 2) and discharges principally as spring flow in Death Valley, as evapotranspiration from Alkali Flat and Death Valley, and through wells in pumping centers including the NTS and Amargosa Farms area (Laczniak and others, 1996, pl. 1; Tucci and Burkhardt, 1995, p. 8; Harrill and others, 1988, sheet 2).

DATA COLLECTION

Ground-water levels and discharge data for monitoring sites were compiled from the USGS National Water Information System (NWIS) data base and from measurements made by USGS Environmental Monitoring Program personnel. Data-collection procedures and equipment are described briefly in this report; for more detail see Locke (2001b). Sources of precipitation and water-use data are described in the sections "Precipitation Data" and "Ground-Water Withdrawal Data."

Stringent quality assurance is required in all studies pertaining to Yucca Mountain to establish adequate confidence in the reliability of data collection, processing, and reporting. In addition to standard USGS practices and procedures, formal unpublished technical procedures associated with the Yucca Mountain Site Characterization Project were developed for the collection of ground-water levels and discharge data. These technical procedures include equipment tests and calibrations and measurement techniques to ensure that necessary and expected precision and accuracy are attained. The principal technical procedures that apply to the collection of data by project personnel are listed in La Camera and Westenburg (1994, p. 17).

Monitoring Sites

Most of the data presented in this report are derived from the primary monitoring sites (table 1; fig. 1*B*). These sites comprise the network for the Yucca Mountain Environmental Monitoring Program. All primary sites are wells or springs except site AM-4 (Devils Hole), which is an open fissure that intersects the water table. Information on site identification, site location, site owner, and types of data in this report is in table 1 for each primary site. Well-construction data and contributing lithologic units are in table 2.

Data from miscellaneous monitoring sites were used in this report as a supplemental data set (table 3; fig. 1*A*). Miscellaneous sites are not part of the Yucca Mountain Environmental Monitoring Program (thus are not the focus of this report) but were used to aid in interpretation of trends in the data from the primary sites. Table 3 provides information on site identification, site location, well construction, and contributing lithologic units for miscellaneous monitoring sites.

Primary monitoring sites (table 1) are identified by an alphanumeric identifier consisting of two parts. The alphabetic part represents the hydrographic area in which the site is located: "CF" represents Crater Flat; "JF" or "J," Jackass Flats; "RV," Rock Valley; "MV," Mercury Valley; "AD" or "AM," Amargosa Desert; and "DV," Death Valley. "AM" further indicates that the site is located in the Ash Meadows spring-discharge area. The numeric part of the identifier represents the relative location of the site within the hydrographic area (or Ash Meadows spring-discharge area). Within each hydrographic area, sites generally are numbered sequentially in a north-to-south, then west-to-east order. Sites added subsequent to the initial numbering also are numbered as indicated above or are assigned the number of a nearby site and given the suffix "a." Exceptions are sites J-11, J-12, and J-13, which are or were intended to serve as water-supply wells and were previously numbered by Raytheon Services Nevada; they were not renumbered for this report. The sequence of sites in table 1 is followed throughout the report. Discussions generally refer to a site by its site number; however, in cases in which the site name is more commonly used in the literature and more easily recognized (such as Devils Hole), the site name may be used. Miscellaneous sites in this report use existing names and were not renumbered.

Contributing units (table 2) are the principal lithologic intervals at the site that yield water to the well. For purposes of this report, contributing units are one of or a combination of four general types. Wells characterized as having a contributing unit of carbonate or volcanic rock are wells with open intervals in those consolidated rocks. In and near the Amargosa Desert, wells characterized as having a contributing unit of valley fill are those with open intervals in unconsolidated alluvial materials, including lakebed deposits. Wells

Table 1. Index to primary monitoring sites in Yucca Mountain region monitored between 1992 and 2000

Site number: Sites are grouped by hydrographic area and, within each area, are listed in general north-to-south, then west-to-east order. See "Monitoring Sites" section for further discussion.

U.S. Geological Survey site identification: Unique identification number for sites as stored in files and data bases of U.S. Geological Survey.

Owner: BLM, Bureau of Land Management; NDOT, Nevada Department of Transportation; NPS, National Park Service; private, privately owned; DOE, U.S. Department of Energy; USFWS, U.S. Fish and Wildlife Service; USGS, U.S. Geological Survey.

Data type: D, ground-water discharge; L, ground-water level.

Site number (see fig. 1*B*)	U.S. Geological Survey site identification	Site name	Latitude	Longitude	Owner	Data type	Hydrographs of site (figure numbers)
CF-1	365520116370301	GEXA Well 4	36° 55′ 20″	116° 37′ 03″	private	L	12*M*, 13*A*, 28*A*
CF-1a	365445116383901	GEXA Well 3	36° 54′ 42″	116° 38′ 41″	private	L	14*A*, 30*A*
CF-2	364732116330701	USW VH-1	36° 47′ 32″	116° 33′ 07″	DOE	L	13*B*, 28*B*
CF-3	364105116302601	Crater Flat 3	36° 41′ 06″	116° 30′ 26″	private	L	14*B*, 29*A*
JF-1	365116116233801	UE-25 WT #15	36° 51′ 16″	116° 23′ 38″	DOE	L	13*C*, 22, 28*C*
JF-2	364945116235001	UE-25 WT #13	36° 49′ 43″	116° 23′ 51″	DOE	L	13*D*, 22, 28*D*
JF-2a	364938116252102	UE-25 p #1	36° 49′ 38″	116° 25′ 21″	DOE	L	12*I*, 13*E*, 22, 27*A*
J-13	not available	J-13 WW	not available		DOE	L	15*A*, 22, 28*E*
J-11	364706116170601	J-11 WW	36° 47′ 06″	116° 17′ 06″	DOE	L	13*F*, 28*F*
J-12	not available	J-12 WW	not available		DOE	L	15*B*, 22, 28*G*
JF-3	364528116232201	JF-3 Well	36° 45′ 28″	116° 23′ 22″	DOE	L	5, 15*C*, 18, 22, 23, 24, 28*H*, 31
RV-1	363815116175901	TW-5	36° 38′ 15″	116° 17′ 59″	DOE	L	12*L*, 13*G*, 30*B*
MV-1	not available	Army 1 WW	not available		DOE	L	13*H*, 19, 27*B*
AD-1	364141116351401	NA-6 Well (BGMW-10)	36° 41′ 31″	116° 41′ 14″	USGS	L	14*C*, 29*B*
AD-2	363830116241401	Airport Well	36° 38′ 25″	116° 24′ 33″	private	L	14*D*, 29*C*
AD-2a	not available	NDOT Well	not available		NDOT	L	15*D*, 29*D*
AD-3	363434116354001	Amargosa Desert 3	36° 34′ 56″	116° 35′ 25″	private	L	15*E*, 29*E*
AD-3a	363521116352501	Amargosa Desert 3a	36° 35′ 25″	116° 35′ 30″	private	L	14*E*, 25, 29*F*
AD-4a	363428116234701	Amargosa Desert 4a	36° 34′ 30″	116° 23′ 45″	private	L	12*A*, 14*F*, 29*G*
AD-5	363310116294001	USBLM Well	36° 33′ 25″	116° 29′ 45″	BLM	L	14*G*, 25, 29*H*

Table 1. Index to primary monitoring sites in Yucca Mountain region monitored between 1992 and 2000—Continued

Site number (see fig. 1*B*)	U.S. Geological Survey site identification	Site name	Latitude	Longitude	Owner	Data type	Hydrographs of site (figure numbers)
AD-6	363213116133800	Tracer Well 3	36° 32′ 13″	116° 13′ 38″	USGS	L	5, 12*F*, 14*H*, 18, 20*E*, 27*C*, 31
AD-7	363009116302701	Amargosa Desert 7	36° 30′ 10″	116° 30′ 30″	private	L	14*I*, 25, 29*I*
AD-7a	363009116302702	Amargosa Desert 7a	36° 30′ 10″	116° 30′ 30″	private	L	14*I*, 25, 29*I*
AD-8	362929116085701	Amargosa Desert 8	36° 29′ 30″	116° 08′ 55″	private	L	15*F*, 29*J*
AD-9	362848116264201	Amargosa Desert 9	36° 28’50″	116° 26′ 45″	private	L	14*J*, 25, 29*K*
AD-10	362525116274301	NA-9 Well	36° 25′ 30″	116° 27′ 40″	USGS	L	12*E*, 14*K*, 25, 26, 29*L*
AD-11	361954116181201	GS-3 Well	36° 19′ 57″	116° 17′ 52″	USGS	L	13*I*, 29*M*
AD-12	362014116133901	GS-1 Well	36° 20′ 21″	116° 13′ 30″	USGS	L	14*L*, 29*N*
AD-13	361724116324201	S-1 Well	36° 17′ 20″	116° 32′ 40″	USGS	L	13*J*, 29*O*
AD-14	361817116244701	Death Valley Jct Well	36° 18′ 16″	116° 24′ 47″	private	L	8, 13*K*, 29*P*
AM-1	362858116195301	Rogers Spring Well	36° 28′ 55″	116° 19′ 50″	USFWS	L	8, 15*G*, 29*Q*
AM-1a	362924116203001	Fairbanks Spring	36° 29′ 26″	116° 20′ 28″	USFWS	D	16*A*, 16*B*, 32
AM-2	362755116190401	Five Springs Well	36° 27′ 55″	116° 19′ 05″	USFWS	D, L	12*D*, 15*H*, 16*C*, 27*D*, 33
AM-3	362555116205301	Ash Meadows 3	36°25′ 55″	116° 20′ 55″	private	L	8, 15*I*, 29*R*
AM-4	362532116172700	Devils Hole	36° 25′ 32″	116° 17′ 27″	NPS	L	12*B*, 15*J*, 18, 20*F*, 27*E*
AM-5	362529116171100	Devils Hole Well	36° 25′ 30″	116° 17′ 15″	USFWS	L	12*C*, 15*K*, 29*S*
AM-5a	362502116192301	Crystal Pool	36° 25′ 15″	116° 19′ 25″	USFWS	D	16*D*, 16*E*, 32
AM-6	362432116165701	Point of Rocks North Well	36° 24′ 30″	116° 16′ 55″	USFWS	L	8, 12*G*, 14*M*, 29*T*
AM-7	362417116163600	Point of Rocks South Well	36° 24′ 20″	116° 16′ 40″	USFWS	L	12*H*, 13*L*, 27*F*
AM-8	362230116162001	Big Spring	36° 22′ 29″	116° 16′ 25″	USFWS	D	16*F*, 16*G*, 32
DV-1	362728116501101	Texas Spring	36° 27′ 28″	116° 50′ 11″	NPS	D	16*H*, 16*I*, 34
DV-2	362252116425301	Navel Spring	36° 22′ 52″	116° 42′ 53″	private	D	12*J*, 14*O*, 26, 33
DV-3	362230116392901	Travertine Point 1 Well	36° 22′ 31″	116° 39′ 32″	private	L	12*N*, 14*N*, 26, 27*G*

Table 2. Well-completion data at monitoring sites in Yucca Mountain region

Site number: Sites are grouped by hydrographic area and, within each area, are listed in general north-to-south, then west-to-east order. See “Monitoring Sites” section for further discussion.

U.S. Geological Survey site identification: Unique identification number for site as stored in files and data bases of U.S. Geological Survey.

Top of open interval: Depth to top part(s) of well that can receive ground water from lithologic interval. Uncased borehole is designated open interval in this table. Open interval may be deeper than accessible well depth, which may reflect original drilled depth. U, unknown, no data.

Bottom of open interval: Depth to bottom part(s) of well that can receive ground water from lithologic interval. Uncased borehole is designated open interval in this table. Open interval may be deeper than accessible well depth, which may reflect original drilled depth. U, unknown, no data.

Diameter of open interval: Inside casing diameter; rounded to nearest inch. Hole diameter is listed where no casing is present. U, unknown, no data.

Type of open interval: Description of open interval. P, perforated or slotted casing; S, screened casing, type not known; U, unknown, no data; X, uncased borehole.

Contributing unit: Saturated lithologic interval yielding water to well. C, carbonate rock; F, valley fill; S, undifferentiated sedimentary rock; V, volcanic rock. See “Monitoring Sites” section for further discussion.

Site number (fig. 1*B*)	U.S. Geological Survey site identification	Site name	Land-surface altitude (feet above sea level)	Accessible well depth (feet below land surface)	Open interval				Contributing unit
					Feet below land surface		Diameter (inches)	Type	
					Top	Bottom			
CF-1	365520116370301	GEXA Well 4	3,930.9	1,600	800	1,600	10	P	V
CF-1a	365445116383901	GEXA Well 3	4,080.9	700	208	313	6	P	S
					513	618	6	P	
					658	700	6	P	
CF-2	364732116330701	USW VH-1	3,161	2,501	911	912	9	X	V
					912	2,501	6	X	
CF-3	364105116302601	Crater Flat 3	2,725.6	460	320	460	8	P	F
JF-1	365116116233801	UE-25 WT #15	3,553.8	1,360	127	130	15	X	V
					130	1,360	9	X	
JF-2	364945116235001	UE-25 WT #13	3,387.5	1,160	222	224	15	X	V
					224	1,150	9	X	
					1,150	1,160	8	X	
JF-2a	364938116252102	UE-25 p #1	3,655.5	5,923	4,256	4,279	10	X	C
					4,279	5,900	7	X	
					5,900	5,923	6	X	

Table 2. Well-completion data at monitoring sites in Yucca Mountain region—Continued

Site number (fig. 1*B*)	U.S. Geological Survey site identification	Site name	Land-surface altitude (feet above sea level)	Accessible well depth (feet below land surface)	Open interval				Contributing unit
					Feet below land surface		Diameter (inches)	Type	
					Top	Bottom			
J-13	not available	J-13 WW	3,317.9	3,488	996	1,301	13	P	V
					1,301	1,386	11	P	
					2,690	3,312	5	P	
					3,385	3,488	8	X	
J-11	364706116170601	J-11 WW	3,442.8	1,327	1,075	1,095	12	P	V
					1,242	1,298	12	P	
J-12	not available	J-12 WW	3,128.4	1,139	793	868	12	P	V
					887	1,139	12	X	
JF-3	364528116232201	JF-3 Well	3,098.3	1,138	735	1,138	8	P	V
RV-1	363815116175901	TW-5	3,056	800	735	800	6	P	S
					800	916	U	X	
MV-1	not available	Army 1 WW	3,153.3	1,953	800	1,050	11	P	C
					1,368	1,370	10	X	
					1,370	1,684	9	X	
					1,684	1,953	7	X	
AD-1	364141116351401	NA-6 Well BGMW-10	2,627.9	960	930	940	2	S	F
AD-2	363830116241401	Airport Well	2,638.8	750	360	777	14	P	F
AD-2a	not available	NDOT Well	2,656.8	495	395	495	8	P	F
AD-3	363434116354001	Amargosa Desert 3	2,385.4	243	100	250	12	P	F
AD-3a	363521116352501	Amargosa Desert 3a	2,395.3	240	120	250	15	P	F
AD-4a	363428116234701	Amargosa Desert 4a	2,477.8	269	147	213	12	P	F
					238	286	12	P	
AD-5	363310116294001	USBLM Well	2,376.4	348	U	U	U	U	F
AD-6	363213116133800	Tracer Well 3	2,402.3	678	620	807	6	X	C
AD-7	363009116302701	Amargosa Desert 7	2,305	112	73	131	15	P	F
AD-7a	363009116302702	Amargosa Desert 7a	2,305	210	U	U	U	U	F
AD-8	362929116085701	Amargosa Desert 8	2,394.3	215	U	U	U	U	F

Table 2. Well-completion data at monitoring sites in Yucca Mountain region—Continued

Site number (fig. 1*B*)	U.S. Geological Survey site identification	Site name	Land-surface altitude (feet above sea level)	Accessible well depth (feet below land surface)	Open interval				Contributing unit
					Feet below land surface		Diameter (inches)	Type	
					Top	Bottom			
AD-9	362848116264201	Amargosa Desert 9	2,264.8	396	60	90	12	P	F
					154	244	12	P	
					245	396	15	X	
AD-10	362525116274301	NA-9 Well	2,190.9	1,090	1,063	1,066	2	S	F
AD-11	361954116181201	GS-3 Well	2,351.3	2,000	1,969	1,979	2	S	F
AD-12	362014116133901	GS-1 Well	2,430.3	1,580	1,549	1,559	2	S	F
AD-13	361724116324201	S-1 Well	2,703.2	2,000	1,969	1,979	2	S	F
AD-14	361817116244701	Death Valley Jct Well	2,041.8	225	160	200	12	S	F
AM-1	362858116195301	Rogers Spring Well	2,265.9	202	100	240	12	P	F
					240	420	16	X	
AM-2	362755116190401	Five Springs Well	2,367.4	123	0	100	13	P	C
					100	140	14	X	
AM-3	362555116205301	Ash Meadows 3	2,157	202	140	180	8	P	F
AM-5	362529116171100	Devils Hole Well	2,404.1	200	48	248	16	P	F
AM-6	362432116165701	Point of Rocks North Well	2,318.8	500	139	500	16	P	F
AM-7	362417116163600	Point of Rocks South Well	2,333.5	586	132	467	14	P	C
					468	818	U	X	
DV-3	362230116392901	Travertine Point 1 Well	2,728.4	650	100	970	5	X	C

Table 3. Characteristics of miscellaneous monitoring sites with water-level or spring-discharge data

U.S. Geological Survey site identification: Unique identification number for sites as stored in files and data bases of U.S. Geological Survey.

T**op of open interval**: Depth to top part(s) of well that can receive ground water from lithologic interval. Uncased borehole is designated open interval in this table. Open interval may be deeper than accessible well depth, which may reflect original drilled depth. U, unknown, no data; NA, not applicable.

Bottom of open interval: Depth to bottom part(s) of well that can receive ground water from lithologic interval. Uncased borehole is designated open interval in this table. Open interval may be deeper than accessible well depth, which may reflect original drilled depth. U, unknown, no data; NA, not applicable.

Diameter of open interval: Inside casing diameter; rounded to nearest inch. Hole diameter is listed where no casing is present. U, unknown, no data; NA, not applicable.

Type of open interval: Description of open interval. P, perforated or slotted casing; S, screened casing, type not known; X, uncased borehole; NA, not applicable.

Data type: Type of data presented in this report. D, ground-water discharge; L, ground-water level; W, withdrawal.

Contributing unit: Saturated lithologic interval yielding water to well or spring. C, carbonate rock; F, valley fill; V, volcanic rock. See “Monitoring Sites” section for further discussion.

U.S. Geological Survey site indentification	Site name	Latitude	Longitude	Land-surface altitude (feet above sea level)	Accessible well depth (feet below land surface)	Open interval: Feet below land surface: Top	Open interval: Feet below land surface: Bottom	Open interval: Diameter (inches)	Open interval: Type	Data type	Contributing unit	Hydrographs of site (figure numbers)
Ash Meadows ground-water subbasin												
363238115464601	Army 3	36° 32′ 38″	115° 46′ 46″	3,617	826	310	435	10	P	L	F	19
						453	826	U	X			
364830115512601	TW-3	36° 48′ 30″	115° 51′ 26″	3,489	1356	1,192	1,516	7	P	L	C	20*A*
370418116044501	TW-D	37° 04′ 28″	116° 04′ 30″	4,152	1,950	1,772	1,882	10	P	L	C	20*C*
						1,900	1,950	9	X			
364534116065902	TW-F	36° 45′ 34″	116° 06′ 59″	4,143	3,400	3,150	3,400	8	X	L	C	20*D*
370556116000901	UE-7nS	37° 05′ 56″	116° 00′ 09″	4,370	2,205	1,995	2,199	7	P	L	C	20*B*
						2,199	2,205	11	X			
						1,960	2,020	3	P			

Table 3. Characteristics of miscellaneous monitoring sites with water-level or spring-discharge data—Continued

U.S. Geological Survey site indentification	Site name	Latitude	Longitude	Land-surface altitude (feet above sea level)	Accessible well depth (feet below land surface)	Open interval: Feet below land surface: Top	Open interval: Feet below land surface: Bottom	Open interval: Diameter (inches)	Open interval: Type	Data type	Contributing unit	Hydrographs of site (figure numbers)
Alkali Flat–Furnace Creek Ranch ground-water subbasin												
363212116270401	CB Well	36° 32′ 17″	116° 26′ 58″	2,368	250	100	245	16	P	L	F	25
363028116270201	EP Well	36° 30′ 28″	116° 27′ 02″	2,304	350	160	350	14	P	L	F	25
363039116303501	GB Well	36° 30′ 39″	116° 30′ 35″	2,306	200	55	161	14	P	L	F	25
363317116270801	LWS-A Deep	36° 33′ 17″	116° 27′ 08″	2,396	1,859	1,706	1,827	2	P	L	F	25
362525116274302	NA-9 Shallow	36° 25′ 31″	116° 27′ 45″	2,180	23	20	23	1	S	L	F	26
363045116491601	Nevares Springs	36° 30′ 45″	116° 49′ 16″	937	NA	NA	NA	NA	NA	D	C	12*K*
362835116264101	S-G Well	36° 28′ 35″	116° 26′ 41″	2,267	415	55	200	10	P	L	F	25
						200	415	10	X			
363346116322801	TG Well	36° 34′ 00″	116° 32′ 06″	2,381	295	60	140	14	P	L	F	25
						146	158	13	P			
						170	195	13	P			
						240	295	13	P			
362630116494701	Travertine Springs	36° 26′ 30″	116° 49′ 47″	400	NA	NA	NA	NA	NA	D	C	26
364947116254501	UE-25 c #3	36° 49′ 45″	116° 25′ 44″	3,715	3,000	1,323	3,000	11	X	W	V	--
363348116254901	WJ Well	36° 33′ 48″	116° 25′ 49″	2,440	390	150	390	13	P	L	F	25

with open intervals in clastic rock (including argillite, limey sandstones and siltstones, or silty, sandy, and shaley limestones) are characterized as having a contributing unit of undifferentiated sedimentary rock.

Robison and others (1988) describe the contributing units at sites CF-2, JF-1, JF-2, JF-2a, and J-13. McKinley and others (1991) describe the contributing units at sites J-11, J-12, MV-1, AD-4a, AD-5, AD-6, AD-8, and AM-4. Thordarson and others (1967) describe the contributing unit at site RV-1. Dudley and Larson (1976) describe the contributing units at sites AM-2, AM-5, and AM-7. Contributing-unit data are not available from listed data sources for some wells; the contributing units indicated for these wells are derived from drillers' logs or well-completion reports that describe geology in the boreholes, open intervals in the wells, and measurements of depth to water.

Contributing units for springs (fig. 1*B*, table 3) indicate sources of water discharged at the sites. Winograd and Thordarson (1975, p. 75–97) describe sources of discharge at sites AM-1a, AM-5a, AM-8, and DV-1. McKinley and others (1991) describe the source of discharge at site DV-2.

Periodic Water-Level Data

Periodic water levels measured at primary sites from 1992 to 2000 generally were made by USGS personnel using a calibrated electric or steel tape. The electric tapes were calibrated using steel tapes. Calibrated electric tapes were used at wells when: (1) frequent repetitive measurements were required due to fluctuating water levels, (2) depths to water were greater than 500 ft, or (3) wet conditions inside a well prevented measurements using chalked steel tapes. Periodic water levels at primary and miscellaneous sites prior to 1992 generally were measured by USGS personnel using calibrated electric or steel tapes, or calibrated electric-wireline devices. Water-level measurements from 1960 to 2000 also were made at selected primary and miscellaneous sites using electric or steel tapes by the USFWS and by NDWR.

Land surveys were made by USGS personnel at the monitoring sites to determine the altitudes of land surface or the measuring point. Land-surface altitude is a representative altitude of land at or near the site. An exception is site AM-4 (Devils Hole), where the land-surface altitude represents the altitude of the measurement point (a bolt fastened to the south wall of the fissure) that is not referenced to land surface. Land-surface altitudes for sites are listed in tables 2 and 3.

Water-level hydrographs from 1960 to 2000 for all sites in the primary monitoring network are shown in figures 27–30 (app. A) at the end of this report. Vertical and horizontal scales on all hydrographs are the same to enable comparison between sites. Periodic data are plotted on the hydrographs except at sites where continual data were collected (see next section); at these sites, monthly mean water levels were plotted instead of periodic data for periods when continual data were available. Hydrographs are grouped by the primary contributing unit to the well: carbonate rock, volcanic rock, valley fill, and undifferentiated sedimentary rock. Data that may reflect non-static water-level conditions in a well (that is, short-term variations in water levels) are excluded from figures 27–30. Pumping of water from or injecting water into a well or nearby well generally were the causes of non-static conditions.

Continual Water-Level Data

Sites JF-3 and AD-6 (Tracer Well 3) are instrumented for the Yucca Mountain Environmental Monitoring Program to continually record ground-water level and atmospheric pressure at 15-minute intervals. Instrumentation includes a gage (vented) pressure sensor installed below the water surface, a barometer, and a data logger. Gage pressure sensors are vented so that fluid pressure or head is relative to atmospheric pressure. During regular site visits, depth to water is measured with a calibrated steel or electric tape. Any difference between the manual measurement and pressure-sensor value is applied as a correction to the continual record by linearly prorating the difference with time between consecutive visits to account for drift in pressure-sensor output. Pressure sensors are periodically recalibrated and a new linear-regression equation is applied to convert water pressure to a water level.

Continual water-level data have been collected at site JF-3 since May 1992 and at site AD-6 since July 1992. At both sites, occasional problems with instrumentation were the source of small gaps in the data. Both sites are currently (2002) active. Hydrographs of continual water-level data through 2000 for the two sites are shown in figure 31 (app. A).

Continual water-level data were collected by other government agencies or USGS programs at sites AM-4 (Devils Hole), JF-2 (UE-25 WT #13), JF-2a (UE-25 p #1), and AM-5 (Devils Hole Well). Data for Devils Hole from 1989 to 2000 were obtained from NPS. The site is currently (2002) active. Data for sites JF-2 and JF-2a were collected for the USGS Yucca Mountain Site Characterization Program. Data are available for site JF-2 from 1985 to 1993 and for site JF-2a from 1985 to 1995 (Luckey and others, 1993; Lobmeyer and others, 1995; O'Brien and others, 1995; Graves and others, 1996; Tucci, Goemaat, and Burkhardt, 1996; Tucci, O'Brien, and Burkhardt, 1996; R.P. Graves and J.M. Gemmell, U.S. Geological Survey, written communs., 1995–98). Data for Devils Hole Well were collected from 1993 to 1998 for other USGS/DOE studies.

Ground-Water Discharge Data

Measurements of ground-water discharge at primary monitoring sites were collected and compiled for five springs (AM-1a, AM-5a, AM-8, DV-1, and DV-2) and one flowing well (AM-2). Discharge measurements were made by NPS, USFWS, and USGS–Environmental Monitoring Program personnel. Periodic and monthly mean discharge data were determined by the use of current meters, flumes, and volumetric techniques. Discharge measurements by USFWS for sites AM-1a, AM-5a, and AM-8 were made more frequently than measurements by USGS and, therefore, are considered more reliable for determining trends in discharge from 1992 to 2000. USGS measured discharge quarterly at these three sites using a current meter, whereas USFWS measured discharge continually at AM-1a by use of a flume and monthly at the remaining two sites using current meters. Hydrographs of ground-water discharge measurements at the six primary monitoring sites are shown in figures 32, 33, and 34 (app. A).

Measurements of spring discharge at two miscellaneous monitoring sites, Travertine and Nevares Springs in Death Valley, were collected by NPS from 1989 to 2000. These monthly-mean discharge data were determined by the use of flumes.

Precipitation Data

Precipitation patterns for various periods from 1960 to 2000 were compared to trends in ground-water levels and spring discharge. Long-term (at least 30 years) records of precipitation data were compiled and analyzed for selected precipitation stations within the Yucca Mountain region. Location and elevation information for all precipitation sites used for this report are listed in table 4 and shown in figure 4. The sites were selected to represent three general areas of recharge to the study area: the Spring Mountains, the Pahranagat Valley area, and the Pahute Mesa area.

NDWR provided annual precipitation records (collected once each year around June) for a network located primarily within the Spring Mountains at altitudes between 4,000 and 9,000 ft. The network consists of eight precipitation stations with annual measurements from the early 1960's to present. Three of the eight stations were selected for this report to represent precipitation in the Spring Mountains—Kyle Canyon (7,500 ft), Lee Canyon (8,400 ft), and Adams Ranch (9,050 ft)—based on their high altitudes, coverage of the east and west slopes, and continual periods of record. Gaps in NDWR precipitation data records were estimated by regressing data from one station (station *A*) against data from all other stations in the network to find two stations that best correlated to station *A*. The following formula from Dunne and Leopold (1978, p. 40–41) then was applied to estimate data for gaps in a record:

$$P_A = \tfrac{1}{2}\,[(N_A/N_B) * P_B + (N_A/N_C) * P_C], \qquad (1)$$

where

P_A is estimated precipitation at station *A*, in inches,

P_B and P_C are precipitation, in inches, recorded at the two best-correlated stations, and

N_A, N_B, and N_C are long-term mean precipitation at each of the three stations.

Once missing data had been estimated for the stations at Kyle Canyon, Lee Canyon, and Adams Ranch, annual data for the three stations were averaged to create a Spring Mountain precipitation index. An index using the average of multiple stations minimizes errors in data estimation as well as data collection. A plot of cumulative departure from mean annual precipitation then was constructed for the Spring Mountain

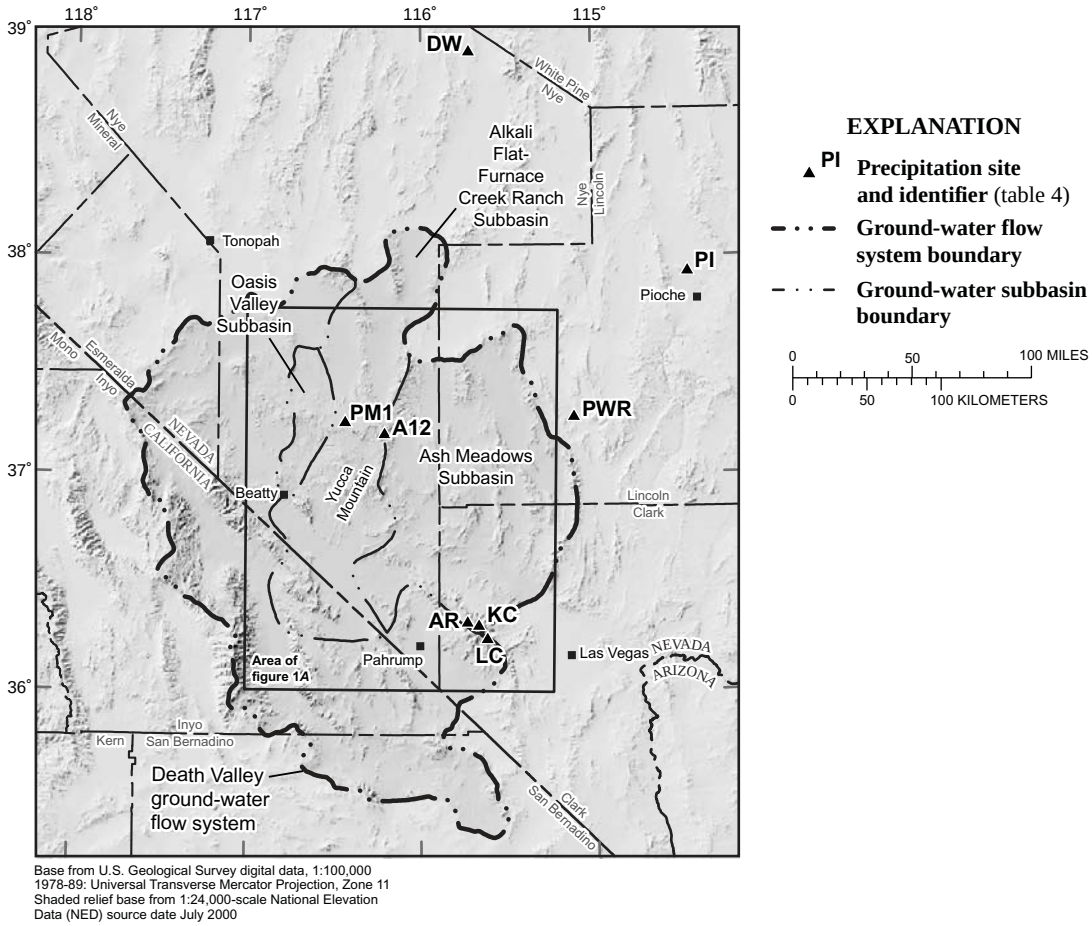
Table 4. Location and elevation information for precipitation sites used to create precipitation indices

I**ndex**: Precipitation index in which precipitation station is included.

Reporting agency: NDWR, Nevada Division of Water Resources; ARL/DOE, Air Resources Laboratory/U.S. Department of Energy; NOAA/NWS, National Oceanic and Atmospheric Administration/National Weather Service.

[Abbreviation: NWR, National Wildlife Refuge]

Precipitation station	Map identifier (fig. 4)	Index	Latitude	Longitude	Elevation (feet above sea level)	Reporting agency
Lee Canyon	LC	Spring Mountains	36° 18′	115° 41′	8,400	NDWR
Kyle Canyon	KC	Spring Mountains	36° 16′	115° 37′	7,500	NDWR
Adams Ranch	AR	Spring Mountains	36° 19′	115° 44′	9,050	NDWR
Pahute Mesa 1	PM1	Pahute Mesa area	37° 14′	116° 26′	6,550	ARL/DOE
Rainier Mesa	A12	Pahute Mesa area	37° 11′	116° 12′	7,490	ARL/DOE
Pahranagat NWR	PWR	Pahranagat area	37° 16′	115° 07′	3,400	NOAA/NWS
Pioche	PI	Pahranagat area	37° 56′	114° 27′	6,180	NOAA/NWS
Duckwater	DW	Pahranagat area	38° 57′	115° 43′	5,610	NOAA/NWS



Base from U.S. Geological Survey digital data, 1:100,000
1978-89: Universal Transverse Mercator Projection, Zone 11
Shaded relief base from 1:24,000-scale National Elevation
Data (NED) source date July 2000

Figure 4. Precipitation sites used to create precipitation indices in the Yucca Mountain region, southern Nevada and eastern California.

precipitation index. This type of plot is useful for identifying precipitation trends over a number of years that are either drier or wetter than average. If the curve slopes upward, regardless of its position in relation to the zero line, the trend indicates a wetter-than-average period, whereas a downward-trending slope represents a drier-than-average period relative to the period of record. A steep slope represents a greater departure from the mean than a shallow slope, and, therefore, an extreme wet or dry period relative to the period of record.

Semi-annual precipitation measurements, made by the USGS, were evaluated for this study because most ground-water recharge may occur semi-annually rather than throughout the year. For example, Winograd and others (1998, p. 92) report that about 90 percent of recharge into the fractured Paleozoic carbonate rocks in the Spring Mountains occurs from snowmelt. Semi-annual precipitation measurements from a high-altitude network of precipitation stations in the Spring Mountains and Sheep Range were collected in cooperation with the Las Vegas Valley Water District (LVVWD) from 1985 to 2000. These measurements were compared to annual measurements from the NDWR Spring Mountain precipitation stations to determine if annual measurements were of sufficient frequency to accurately evaluate those trends in precipitation that influence recharge. Precipitation data from the USGS/LVVWD network are collected in May or June for the winter precipitation component (primarily snow) and again in October for the summer precipitation component (primarily monsoonal rains). Comparing plots of cumulative departure from mean winter precipitation to cumulative departure from mean annual precipitation at each USGS/LVVWD station indicates that winter precipitation dominates the annual precipitation totals. Therefore, use of the NDWR annual measurements, with their longer period of record, was considered acceptable for evaluating trends and associated periods with an excess or deficit of potential recharge relative to the period of record.

A LOcally WEighted Scatterplot Smooth (LOWESS) line was fitted to the cumulative departure data to identify significant and relatively long-term (greater than 5 years) trends in precipitation that might affect regional ground-water levels. In addition to using a LOWESS line to smooth precipitation data, LOWESS lines were used to determine long-term trends in water levels and discharge (see “Analysis of Trends in Ground-Water Levels and Spring Discharge” section). LOWESS is a nonparametric method of fitting a curved line to data (Helsel and Hirsch, 1992, p. 288–291). At each data point, a predicted value is computed using a weighted linear regression. Predicted values are then connected to create a smoothed line. This approach is preferable to linear regression for determining cyclic or nonlinear trends in data. A LOWESS line is helpful for identifying similarities and differences in trends between sites. The line especially is useful for discerning a pattern or trend from data with high scatter.

Additional precipitation indices were developed for the Pahranagat area, the Pahute Mesa area, and the entire Yucca Mountain region. The Pahranagat area precipitation index was constructed because 35–40 percent of Ash Meadows springflow may originate as underflow from the White River Flow System (northeast of the study area) through Pahranagat Valley (Winograd and Thordarson, 1975; Thomas and others, 1996). Three precipitation stations from the National Oceanic and Atmospheric Administration (NOAA)—National Weather Service cooperative observer network were selected (table 4) based on a period of record of at least 30 years, active to the year 2000. The stations selected are about 70–170 mi northeast of the study area (fig. 4). The three precipitation stations were processed using equation 1 and averaged to create a Pahranagat Valley area index.

The best available precipitation records for Alkali Flat–Furnace Creek Ranch ground-water subbasin were obtained from the Air Resources Laboratory, Special Operations and Research Division (SORD). SORD conducts basic and applied research on problems of mutual interest to DOE and NOAA that relate to the NTS. Two precipitation stations, one on Pahute Mesa and one on Rainier Mesa, were selected because of their location within a recharge area and the unavailability of other precipitation stations within high-recharge areas north of the study area. Although the source of the water recharging the aquifers in the Alkali Flat–Furnace Creek Ranch ground-water subbasin may not be derived solely from the Pahute Mesa area, this area was used to represent precipitation trends for any area to the north where recharge may originate. Data from the Pahute Mesa and Rainier Mesa stations were processed using equation 1 and averaged to create a Pahute Mesa area precipitation index.

In addition to the three precipitation indices described above, a South-Central Nevada Precipitation Index representing the entire Yucca Mountain region was obtained from the Western Regional Climate

Center, a cooperative program between NOAA and the Desert Research Institute. This South-Central Nevada Precipitation Index was created from precipitation stations in the South-Central Nevada Climate Division, one of four climate divisions delineated for Nevada (Western Regional Climate Center, 2001).

Ground-Water Withdrawal Data

Ground-water withdrawal data compiled for the study area include Amargosa Desert, Mercury Valley, Crater Flat, and Jackass Flats. Withdrawal data also were compiled from NDWR annual pumpage inventories for major pumping areas in the Yucca Mountain region. For some years in which NDWR pumpage inventories were not available, irrigation withdrawals were estimated using remote sensing data (R.J. La Camera, U.S. Geological Survey, written commun., 2002). Table 5 summarizes the sources for all withdrawal data. Specific sources of withdrawal data for the study area and the NTS are given in Wood and Reiner (1996, p. 7–9) and Locke (2001b, p. 16–17).

The point of diversion for each water-supply well was estimated from NDWR pumpage-inventory and permit data bases. For water-supply wells not inventoried by NDWR, the point of diversion was obtained from the USGS National Water Information System. The point of diversion was located within a township, range, and section. Annual withdrawals from each section were totaled and assigned to the centroid for the section. The withdrawal total for each centroid (square-mile area) was then used as part of a geographic information system to analyze withdrawal and water-level trends.

Table 5. Hydrographic areas and data sources for available withdrawal data

Hydrographic area number: Numbers are assigned to each valley in Nevada and are used by Nevada Division of Water Resources for water management purposes.

Ground-water subbasin: AFFCR, Alkali Flat–Furnace Creek Ranch.

Data source: USGS, U.S. Geological Survey; NDWR, Nevada Division of Water Resources; Mines, withdrawals reported from privately owned mines.

Hydrographic area number	Hydrographic area name	Ground-water basin	Ground-water subbasin	Data source
147	Gold Flat (Nevada Test Site)	Death Valley	AFFCR	USGS
159	Yucca Flat (Nevada Test Site)	Death Valley	Ash Meadows	USGS
160	Frenchman Flat (Nevada Test Site)	Death Valley	Ash Meadows	USGS
162	Pahrump Valley	Death Valley	Pahrump Valley	NDWR
170	Penoyer Valley (Sand Spring Valley)	Death Valley	Penoyer Valley	NDWR
209	Pahranagat Valley	Colorado River	White River	NDWR
212	Las Vegas Valley	Colorado River	Las Vegas Valley	NDWR
225	Mercury Valley (Nevada Test Site)	Death Valley	Ash Meadows	USGS
229	Crater Flat	Death Valley	AFFCR	USGS, Mines
230	Amargosa Desert	Death Valley	AFFCR	NDWR
227A	Jackass Flats (Nevada Test Site)	Death Valley	AFFCR	USGS
227B	Buckboard Mesa (Nevada Test Site)	Death Valley	AFFCR	USGS

SOURCES OF FLUCTUATIONS IN WATER LEVELS AND SPRING DISCHARGE

Fluctuations in ground-water levels and spring discharge in the Yucca Mountain region are caused by a number of natural and human factors. These include barometric pressure, earth tides, recharge from precipitation, ground-water withdrawals, and seismic activity. Some of these factors, such as recharge, can have relatively slow response times that may cause long-term changes in regional water levels or discharge. Other factors, such as evapotranspiration, are seasonal and may cause annual fluctuations in water levels or discharge. Still other factors, such as seismic activity and barometric pressure, may be relatively instantaneous and have no lasting effect on water levels or discharge.

Barometric Pressure and Earth Tides

Changes in barometric pressure and earth tides cause water-level fluctuations in wells throughout the study area. These fluctuations typically are largest in wells open to confined aquifers and smallest in wells open to shallow unconfined aquifers. Barometric-induced fluctuations commonly are caused by instantaneous responses to atmospheric loads transferred directly to the aquifer and to the water column in an open well (Brassington, 1998, p. 102). However, water-level responses also can be lagged because of drainage effects and the time necessary for air moving through the unsaturated zone to transfer the load to the water table (Rojstaczer, 1988; Weeks, 1979). Instantaneous changes in water level that result from atmospheric loading are the balance of two opposing effects. The load associated with an increase in barometric pressure will (1) push down on the water column in an open well, resulting in a relatively large drop in water level, and (2) pressurize the aquifer, resulting in a relatively small rise in water level. Typically, in a well open to the atmosphere, an increase in barometric pressure causes an instantaneous drop in water level, and a decrease causes an instantaneous rise.

Water levels were corrected for instantaneous barometric-pressure changes using a method outlined by Brassington (1998, p. 103–104). This method involves calculating barometric efficiency by regressing water level against barometric pressure. The slope of the regression line is assumed to be the barometric efficiency. An efficiency of 1.0 indicates that an inch of change in barometric pressure (in equivalent inches of water) will result in an inch of change in water level, whereas an efficiency of 0.0 indicates that barometric-pressure changes have no effect on water levels. For sites presented in this report, efficiencies were calculated by creating multiple 10-day data sets of hourly barometric pressure and water level, regressing each data set separately, and then averaging the efficiencies of all data sets for a site into an average efficiency. Changes in measured water levels not attributed to barometric pressure were assumed minimal during each 10-day period and were not removed prior to calculating efficiencies. Calculated barometric efficiencies were 0.48 for site AD-6 (Tracer Well 3), 1.0 for site JF-3, and 0.40 for site AM-4 (Devils Hole). The calculated barometric efficiency, particularly at sites showing a lagged response to barometric pressure, may be biased low relative to the confined barometric efficiency. This is because only changes in barometric pressure and water level for a specific range of frequencies defined by hourly measurements over a 10-day period were used to calculate barometric efficiency.

Instantaneous barometric response is clearly illustrated in the water levels from site JF-3, in which the measured water level (uncorrected water level) is almost a mirror image of barometric pressure (fig. 5). Most of the short-term, water-level fluctuations at this site, which typically are several tenths of a foot in magnitude, are attributed to changes in barometric pressure. Water levels at site AD-6 (Tracer Well 3) also respond to barometric pressure, although to a much lesser degree than at site JF-3. Only about half of the short-term fluctuations at site AD-6 are attributed to fluctuations in barometric pressure. After applying an assumed instantaneous barometric correction to the measured water levels at site JF-3, small water-level fluctuations remain (fig. 5). The corrected water-level curve shows 7- to 10-day cycles that lag equivalent cycles in the barometric pressure. This cyclic pattern in corrected water levels is assumed to be a lagged response to barometric pressure that was not removed with the barometric correction.

Seasonal differences in barometric pressure also can affect water levels, lowering water levels in the winter and raising levels in the summer. These barometric-induced seasonal variations generally are less than 0.5 ft. In addition, daily barometric-pressure swings tend to be greater in the winter than in the summer, causing relatively large short-term fluctuations in water level. Long-term (10-year), non-cyclic trends in

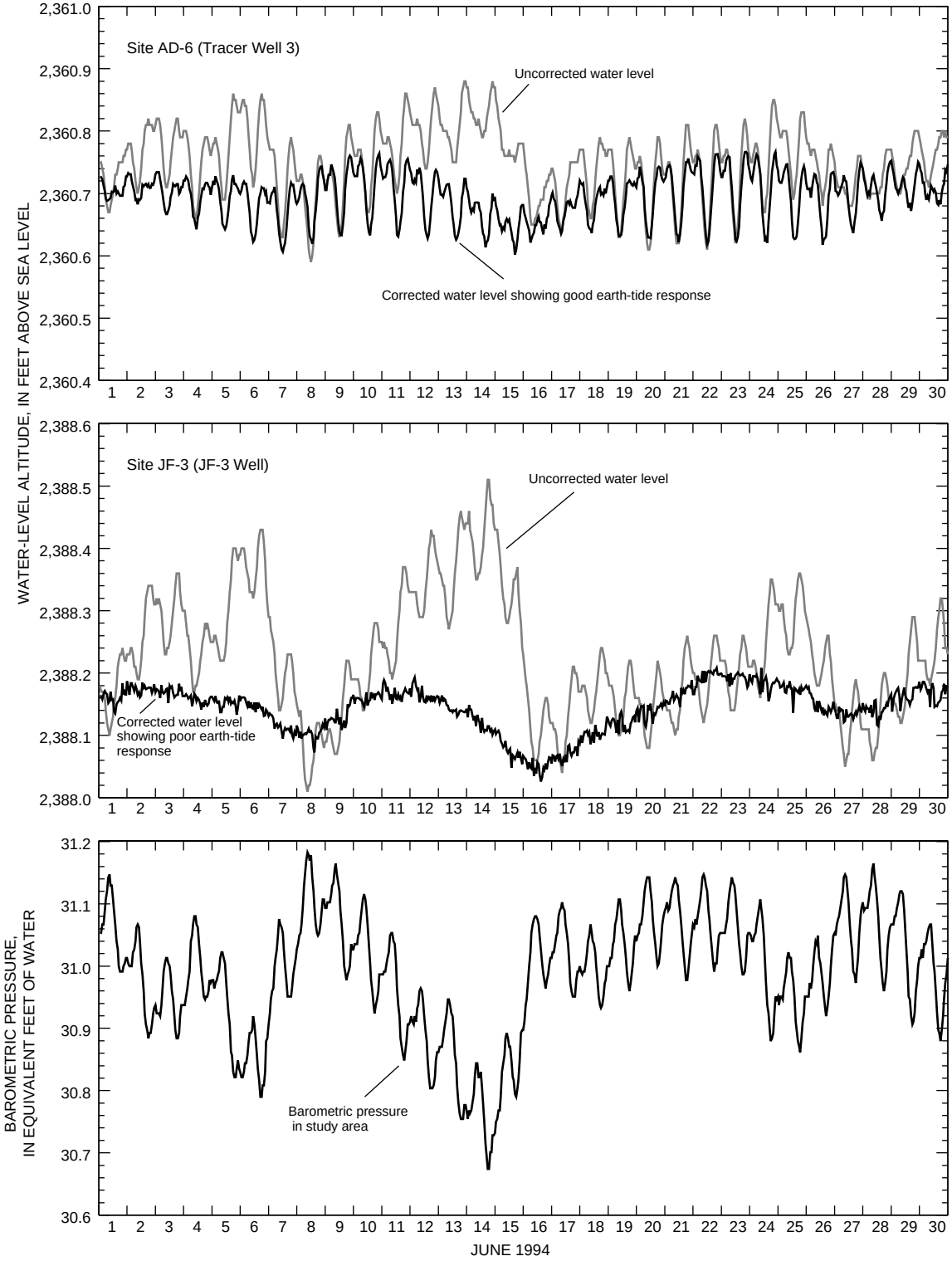


Figure 5. Response of water levels at sites AD-6 (Tracer Well 3) and JF-3 to barometric pressure and earth tides, June 1994. Water levels were corrected for instantaneous effects of barometric pressure.

water levels, however, are not likely to be caused by barometric pressure because pressure remains relatively constant from one year to the next (Bright and others, 2001, p. 10).

Earth tides are caused by the forces exerted on the earth's surface by the Moon and the Sun. The tide-generating effect of the Moon is about twice as great as that of the Sun (Defant, 1958, p. 32). Water-level fluctuations in a well resulting from earth tides are the result of hydraulic-head fluctuations caused by volume strain of the aquifer that occur on semi-daily, daily, and 2-week cycles. The water-level response to earth tides at site AD-6 is evident in the water-level curve corrected for effects of instantaneous barometric pressure (fig. 5). The short-term fluctuations that remain in the corrected curve are attributed to earth tides and are about the same order of magnitude as fluctuations attributed to barometric-pressure changes. At site JF-3, the tidal component is minor (0.01–0.02 ft) compared to the barometric response (fig. 5).

Precipitation

Precipitation in southern Nevada ranges from less than 4 in/yr in some of the low-lying valleys, including much of the Amargosa Desert and Death Valley, to more than 20 in/yr in high-altitude areas of the Spring Mountains and Sheep Range. Within the study area, precipitation generally ranges from 3 to 8 in/yr (Prudic and others, 1995, p. 8).

Precipitation in southern Nevada is derived from two principal sources. In the winter, low atmospheric-pressure systems move from the Pacific Ocean to inland areas, where orographic lifting in the Sierra Nevada depletes much of their moisture before reaching Nevada. As a result, the area immediately east of the Sierra Nevada is in a rain shadow, which extends in a broad arc that includes the NTS (Quiring, 1965). Winter storms in southern Nevada are usually of low intensity, are areally extensive, and account for about two-thirds to three-quarters of annual precipitation. In the summer, monsoonal flow originating in the Gulf of Mexico moves into eastern Nevada and causes high-intensity, short-duration convective storms that typically are of limited areal extent.

Plots of cumulative departure from mean precipitation were developed for the Yucca Mountain region using precipitation indices for the Spring Mountains, Pahranagat Valley area, and Pahute Mesa area. These plots (fig. 6) show annual variations and regional, long-term trends in precipitation. The plots of cumulative departure from mean precipitation indicate that trends are essentially the same for all three indices, although the magnitude of the change in trend is greater for the Spring Mountains because of higher precipitation amounts. In general, the 36-year precipitation trend indicates drier-than-average precipitation from the early 1960’s to the mid-1970’s and the mid-1980’s to the early 1990’s. The overall trend was wetter than average from the mid-1970’s to the mid-1980’s and the early 1990’s through 2000.

A qualitative comparison was made between the cumulative departure from mean precipitation for the South-Central Nevada Precipitation Index and the three precipitation indices used in this study. The precipitation index for south-central Nevada is similar to all three indices for the period 1964–2000 (fig. 7*A*). Moreover, precipitation records indicate that the beginning of the 1960–2000 period chosen for this study marks the end of a 64-year drier-than-average trend and the start of a relatively wet trend when compared to precipitation for the entire 20th century (fig 7*B*).

Long-term fluctuations in precipitation on the Spring Mountains and on recharge areas to the north of the study area are likely to affect regional ground-water levels. In shallow alluvial aquifers in east-central Nevada, water levels responded to long-term (10 years) drier- or wetter-than-normal periods of precipitation (Dettinger and Schaefer, 1995). In deeper aquifers (greater than 1,000 ft below land surface), water levels also may show evidence of responding to drier- or wetter-than-normal periods of precipitation. On the east side of the NTS, water levels in the regional Paleozoic carbonate-rock aquifer may correlate, after a lag time of about 3 years, to departures from normal precipitation (Bright and others, 2001). At Yucca Mountain, Lehman and Brown (1996) suggested precipitation as a possible cause of apparent cyclic water-level fluctuations in wells penetrating volcanic rocks at depths from 1,200 to 4,000 ft.

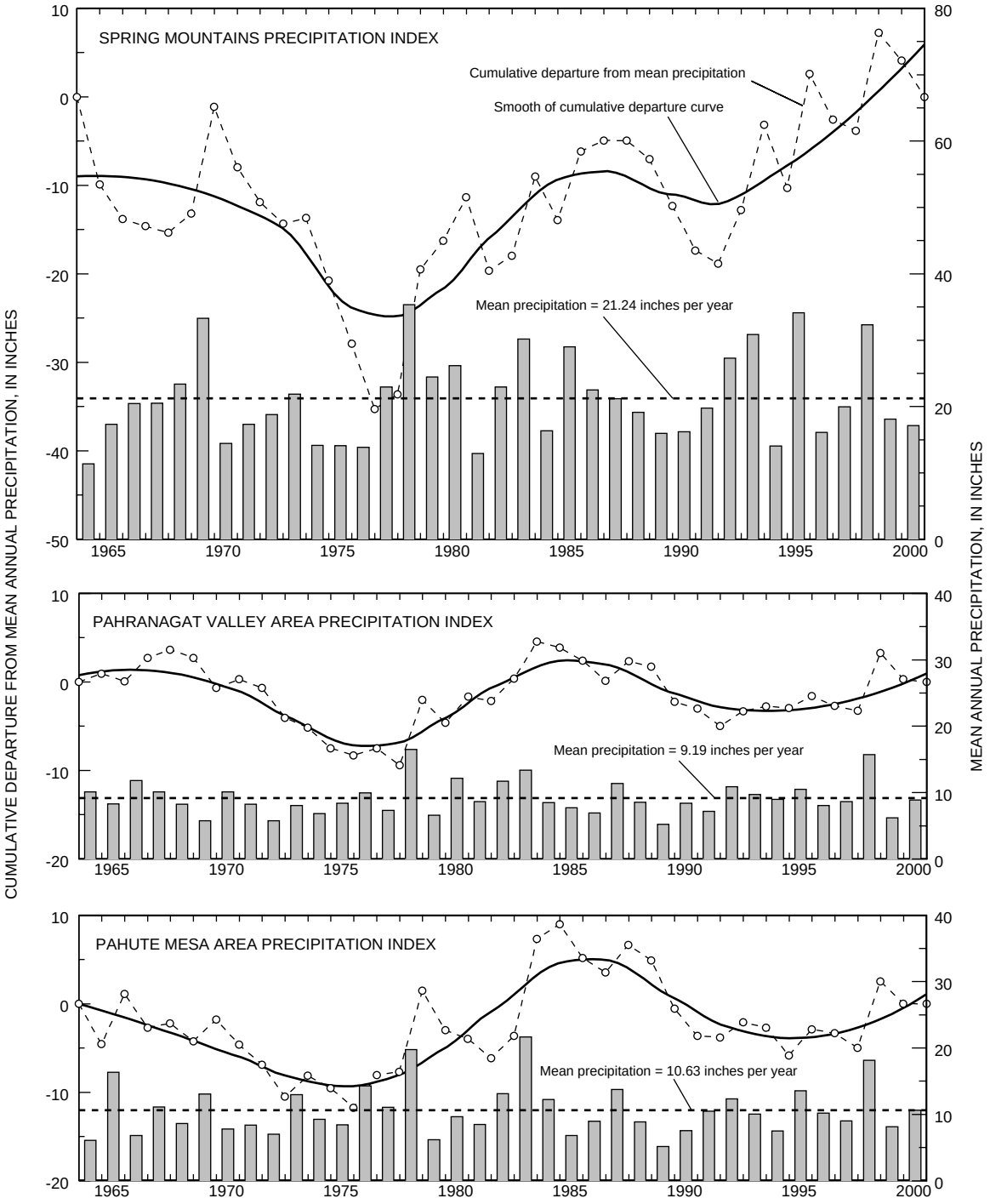


Figure 6. Annual precipitation and cumulative departure from mean annual precipitation at index sites in the Spring Mountains, Pahranagat Valley area, and Pahute Mesa area, 1964–2000. See figure 4 for locations of precipitation sites. Wet periods are shown by increasing slope in cumulative departure curve; dry periods are shown by decreasing slope. Scales on all plots are the same.

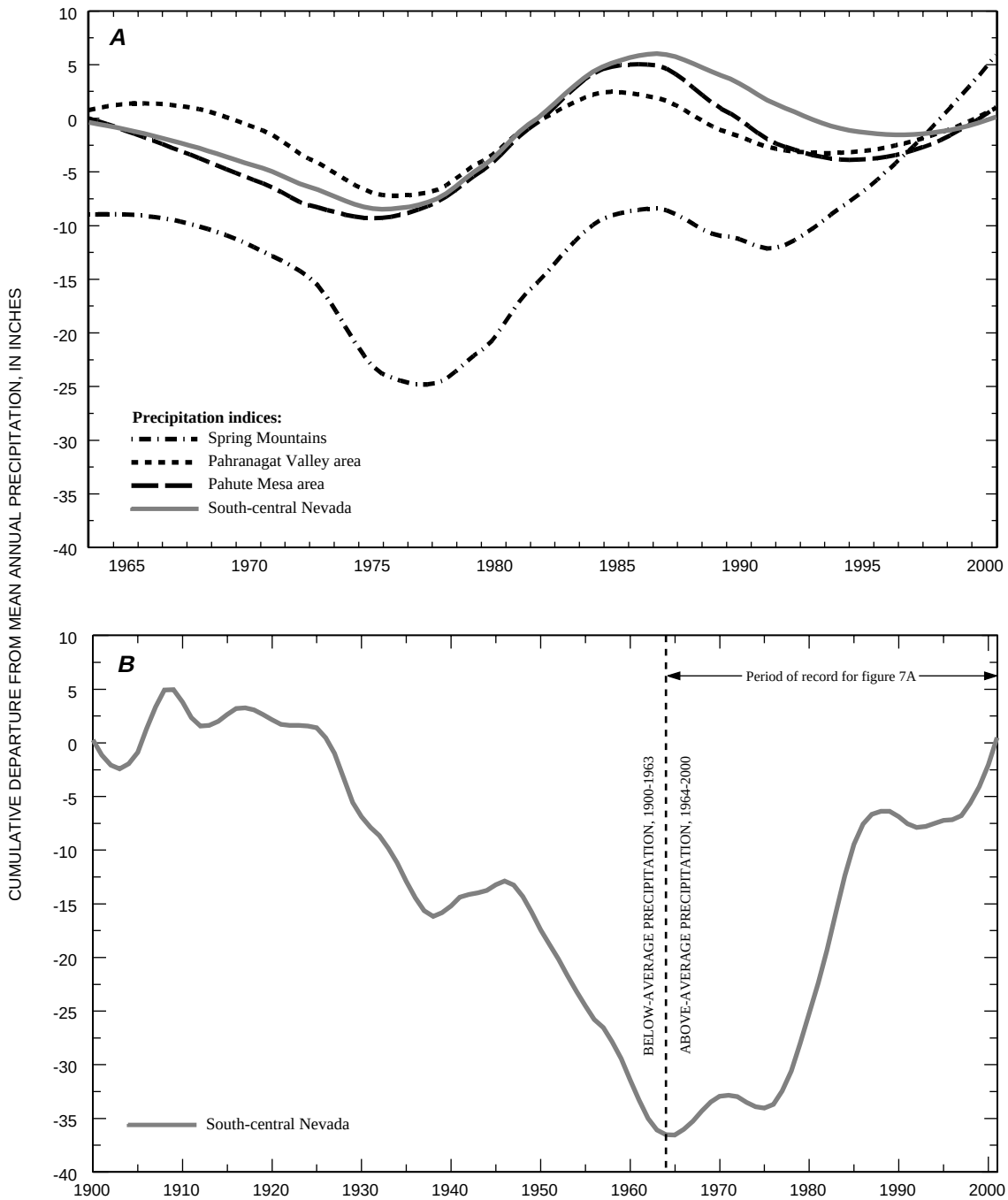


Figure 7. Cumulative departures from mean annual precipitation for index sites in the Spring Mountains, Pahranagat Valley area, Pahute Mesa area, and south-central Nevada: (*A*) Smoothed curves of all four indices from 1964 to 2000; (*B*) Smooth of the south-central Nevada index from 1900 to 2000.

The lag time between periods of excess precipitation and a response in regional water levels in some observation wells can be relatively short (a few months to a few years) given the relatively large distances (tens to hundreds of miles) from recharge areas to these wells. The apparent discrepancy between lag time and distance might be explained as follows. For precipitation falling on mountains some distance from the study area, the lag time includes two components: (1) the time necessary for precipitation to travel through the unsaturated zone and enter the ground-water system, and (2) the time necessary for changes in hydraulic head in recharge areas to be observed in a well as a pressure response in a confined aquifer system (Davis and DeWiest, 1966, p. 46). In many high-altitude areas of southern Nevada, precipitation may infiltrate rapidly through the unsaturated zone because soils are thin, bedrock is fractured, and evapotranspiration rates are low (Flint and others, 2002, p. 194). Even in high-altitude areas where the unsaturated zone is relatively thick, ground-water recharge through fractured volcanic or carbonate rocks may occur in a few years or less (Clebsch, 1961, p. 124; Winograd and others, 1998, p. 90; and Guerin, 2001). In comparison, precipitation in desert basins that typically are not recharge areas may take thousands of years to infiltrate the unsaturated zone (Tyler and others, 1996). After precipitation reaches the ground-water system, the pressure response in a confined aquifer system may propagate quickly through permeable fractured rocks or slowly through less-permeable confining units. In an unconfined aquifer system, responses from precipitation recharge are expected to be variable, with relatively quick response times in areas of local recharge to little measurable response in areas distant from a source of recharge.

Evapotranspiration

Evapotranspiration (ET) within the study area occurs primarily in discharge areas, where depths to ground water are shallow. The primary natural discharge areas in the study area (fig. 2) are Ash Meadows, Alkali Flat, and Death Valley (D'Agnese and others, 1997, p. 45–46). In these areas, evaporation from moist soils and transpiration by phreatophytes account for most of the ET.

Shallow ground-water levels can be influenced by ET. In Ash Meadows, Laczniak and others (1999) analyzed the response of water levels to ET in 27 shallow wells that were 5 to 60 ft deep, and made the following observations. Annual water-level fluctuations caused by ET ranged from about 0.4 to 10 ft. Superimposed on the annual fluctuations in many of the shallow wells were short-term responses to local precipitation events that typically attenuated in about 2 weeks or less. The annual maximum depth to water occurred in late summer or fall, shortly after the annual maximum ET rate for the area. The magnitude of the annual change in water table from the effects of ET is not proportional to the rate of ET because other factors influence water-table declines, such as depth to the water table, distance to a local surface-water source, and aquifer and soil properties. Additionally, the deeper a well is screened below the water table, the less the water level in the well will respond to ET.

Four wells in the primary monitoring network for this study had water levels that appeared to be responding to ET—three in Ash Meadows and one near Death Valley Junction (fig. 8). The open intervals in these wells are relatively deep, ranging from 100 to 500 ft below land surface. Depths to water in these wells range from about 2 to 22 ft below land surface. Annual water-level fluctuations range from about 0.3 ft at site AM-6 (Point of Rocks North Well) to 2 ft at site AM-3. The high water level at site AM-3 prior to 1994 (fig. 29*R*; app. A) was likely caused by seepage of surface water to the shallow water table from a nearby ditch. At site AM-6 (Point of Rocks North Well), much of the long-term decline in water level may be a result of equilibration from a sharp rise in water level following the 1992 Landers/Little Skull Mountain earthquakes. Water levels in the remaining two wells—site AM-1 (Rogers Spring Well) and site AD-14 (Death Valley Jct Well)—rose slightly from 1992 to 2000. Water levels in all four wells appear to respond to extremes in precipitation. The driest and wettest years at Amargosa Farms between 1992 and 2000 were 1994 and 1998, respectively. Three of the four sites (AM-1, AD-14, and AM-3) show below-average water levels during the summer or fall of 1994 (driest year). Conversely, with the exception of site AD-14, the remaining three sites show above-average water levels during the late winter or early spring of 1998 (wettest year).

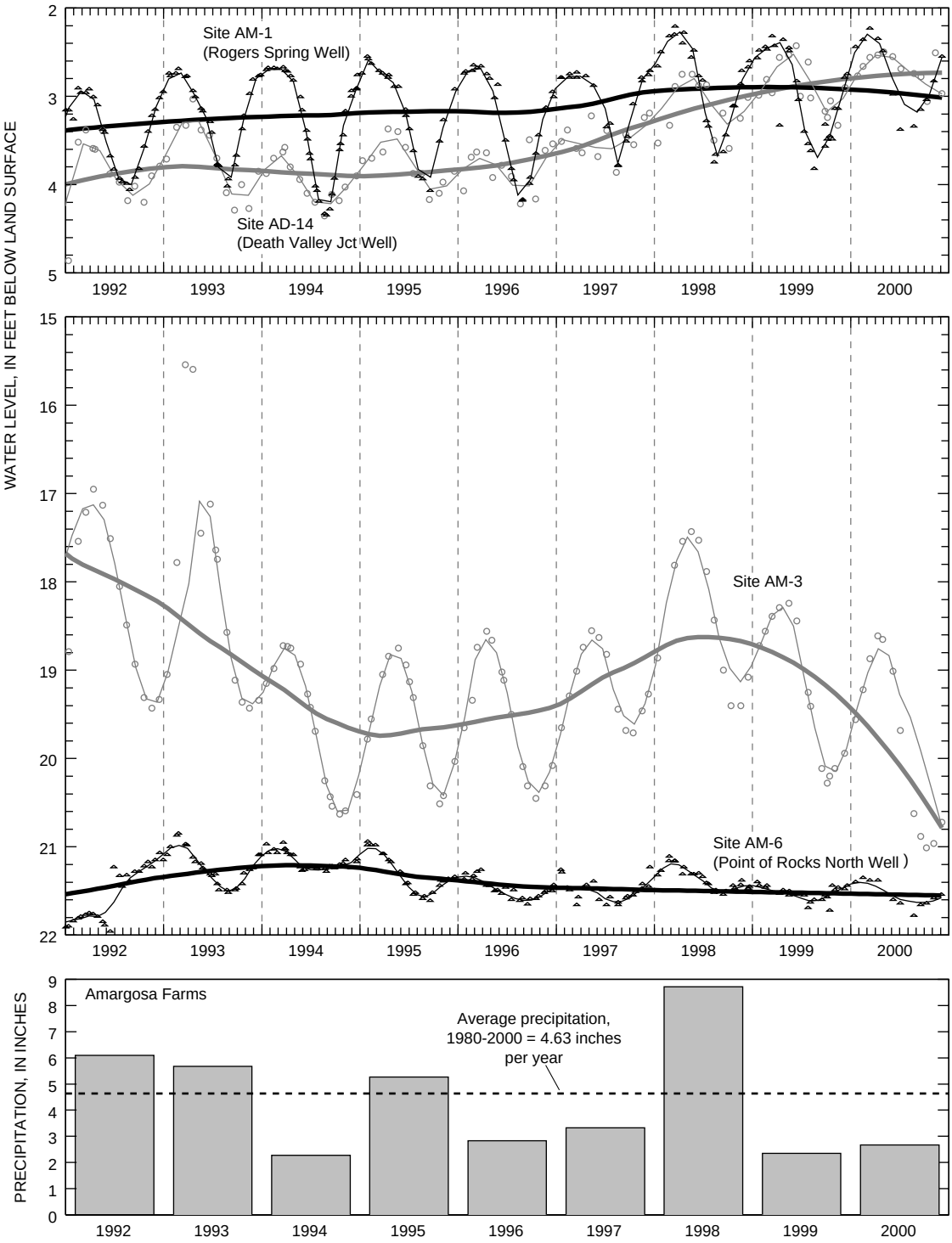


Figure 8. Effects of evapotranspiration on seasonal fluctuations in water levels in selected wells in the Yucca Mountain region and precipitation at Amargosa Farms, 1992–2000. For each year of record, seasonal water levels peak in the winter months and are lowest in the summer months, corresponding to low evapotranspiration rates in the winter and high evapotranspiration rates in the summer. Two smooth lines on each set of water levels show seasonal (thin line) and long-term (thick line) trends. Scales are the same on water-level plots.

Ground-Water Withdrawal

Ground-water withdrawals from 1966 to 2000 were compiled for all hydrographic areas within the study area (fig. 9). Also compiled were withdrawals from 1960 to 2000 for major pumping centers in and near theYucca Mountain region (fig. 10). Withdrawals for the NTS are totaled for regional comparison (fig. 10), and shown for the two hydrographic areas within the study area, Mercury Valley and Jackass Flats (fig. 9). Additionally, maps, by square-mile section of total withdrawals from 1987 to 1998 were created for the Yucca Mountain region (fig. 11). Ground-water withdrawal data are reported in millions of gallons (1 Mgal equals approximately 3.07 acre-ft).

Las Vegas Valley is the largest user of ground water in the Yucca Mountain region. Although Las Vegas Valley is not part of the Death Valley ground-water flow system, it was chosen for discussion because of its possible influence on water levels in the study area. (See “Ground-Water Withdrawals” subsection under “Devils Hole and Eastern Amargosa Desert” section.) Water was artificially injected into valley-fill aquifers in Las Vegas Valley beginning in 1987. Injected water was subtracted from total withdrawals to determine net withdrawals because only water that is permanently removed from the aquifer is likely to have an effect on long-term water levels. Figure 10 indicates that net withdrawals peaked around 1970 at about 28,000 Mgal/yr and generally declined through 2000. Net withdrawals in 2000 were about 14,000 Mgal/yr.

Major withdrawals occur to the south of the study area in Pahrump Valley (fig. 10). NDWR pumpage inventories were available for Pahrump from 1960 to 2000, with the exception of 1979 through 1981. For these 3 years, irrigation use was estimated using remote-sensing data and domestic use was estimated based on the number of domestic wells in NDWR’s well log database (R.J. La Camera, U.S. Geological Survey, written commun., 2002). Withdrawals in Pahrump Valley declined from an average of 12,400 Mgal/yr for 1960–79 to 7,500 Mgal/yr for 1981–98. This reduction coincides with a transition from agricultural to municipal water use in Pahrump Valley. Irrigation use declined from about 15,600 Mgal in 1968 to about 4,900 Mgal in 1998. Conversely, domestic and municipal use rose from 100 to 2,500 Mgal/yr in the same period.

The Amargosa Desert has large withdrawals in the center of the study area. NDWR pumpage inventories were available for the western part of the Amargosa Desert for 1966–68, 1973, 1983, and 1985–2000. Irrigation use was estimated using remote sensing data and domestic use was estimated based on the number of domestic wells in NDWR’s well-log database for 1972, 1974-82, and 1984 (R.J. La Camera, U.S. Geological Survey, written commun., 2002). Additionally, withdrawals from the Ash Meadows area were available for the years 1969–82 (R.J. La Camera, U.S. Geological Survey, written commun., 2001). These withdrawals were estimated using power-consumption records and probably are the only large withdrawals from the Ash Meadows area from 1960 to 2000. Currently (2000), approximately 1 percent of withdrawals from Amargosa Desert is from the Ash Meadows ground-water subbasin; the remaining 99 percent is from the Alkali Flat–Furnace Creek Ranch ground-water subbasin. Total withdrawals in Amargosa Desert increased from about 1,300 Mgal in 1988 to about 5,000 Mgal in 1998, but decreased to about 4,100 Mgal in 2000. From 1988 to 1998, irrigation use increased from 1,000 to 3,900 Mgal/yr, predominately in the Amargosa Farms area. During this same period, mining use, which occurs in the northwestern and southwestern parts of the Amargosa Desert, increased from 300 to 800 Mgal/yr.

Withdrawals for the NTS were compiled for the years 1960–2000, with the exception of 1972–82 when only partial records were available. Water use peaked at the NTS in 1989 at 1,100 Mgal/yr, and, in general, declined through 2000 (fig. 10). NTS withdrawals are relatively minor in comparison to withdrawals from Las Vegas Valley, Pahrump Valley, and Amargosa Desert (figs. 9 and 10). However, withdrawals in Jackass Flats and Mercury Valley may be important sources for water-level fluctuations because they are near primary monitoring sites evaluated for this study.

Withdrawals for Penoyer and Pahranagat Valleys were compiled for the years 1978–2000 and 1972–2000, respectively. Most, if not all, of the supply wells in these valleys are completed in valley-fill aquifers and are relatively far (about 100 mi) from most primary monitoring sites. Therefore, major pumping centers in Penoyer and Pahranagat Valleys are likely to have little to no observable effect on water-level trends in the Yucca Mountain region.

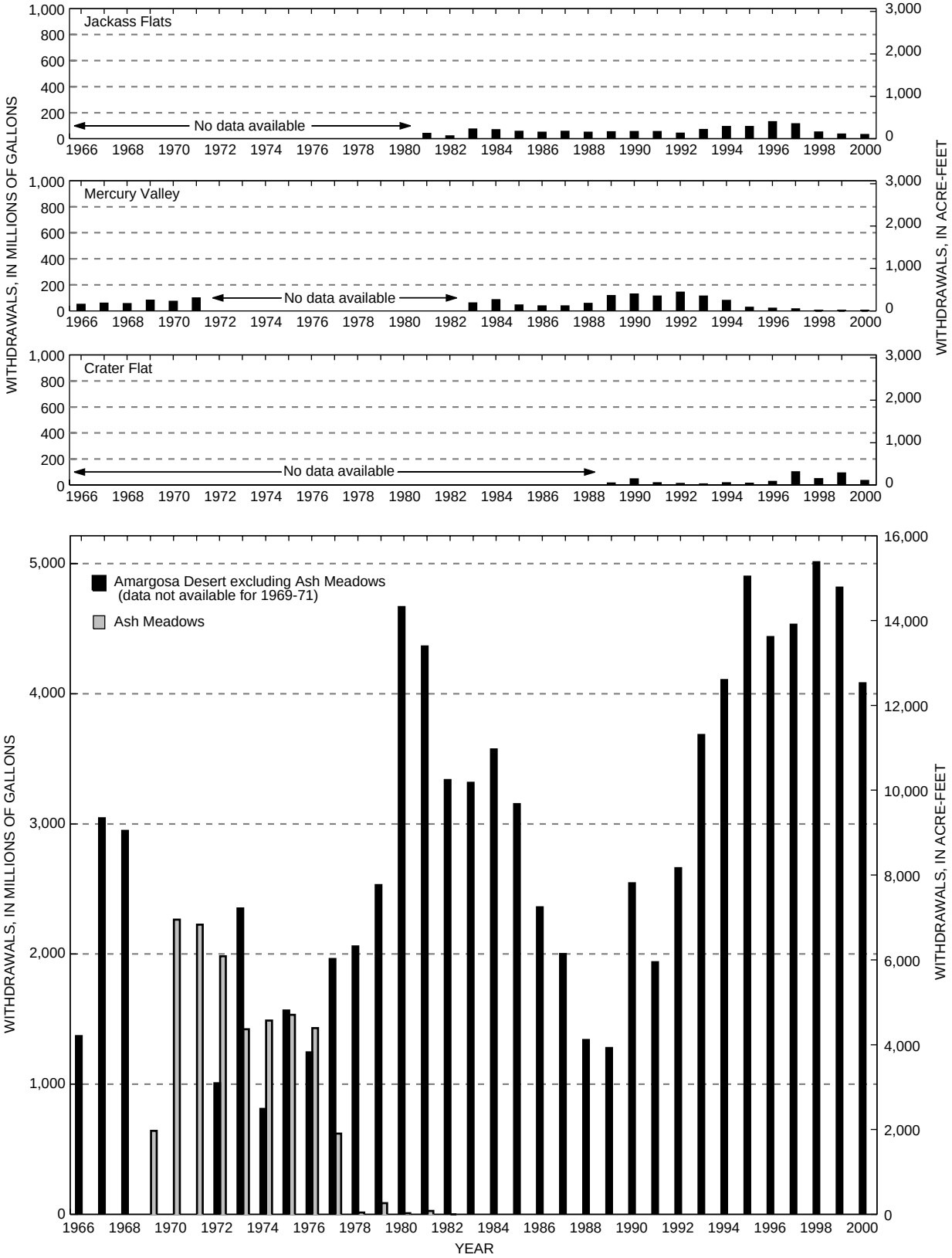


Figure 9. Estimates of annual ground-water withdrawals in Jackass Flats, Mercury Valley, Crater Flat, and Amargosa Desert, 1966–2000. Scales are the same for all plots.

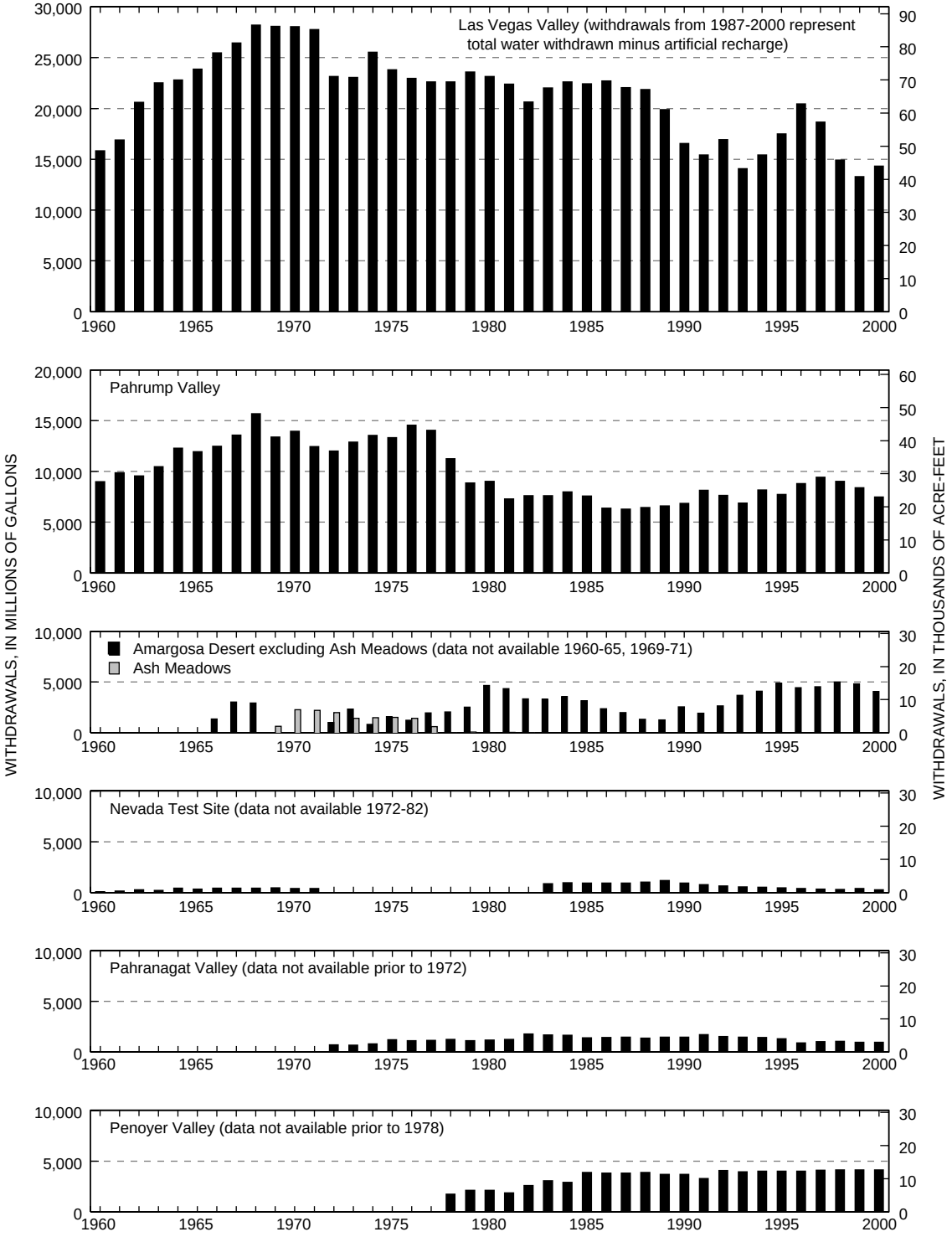
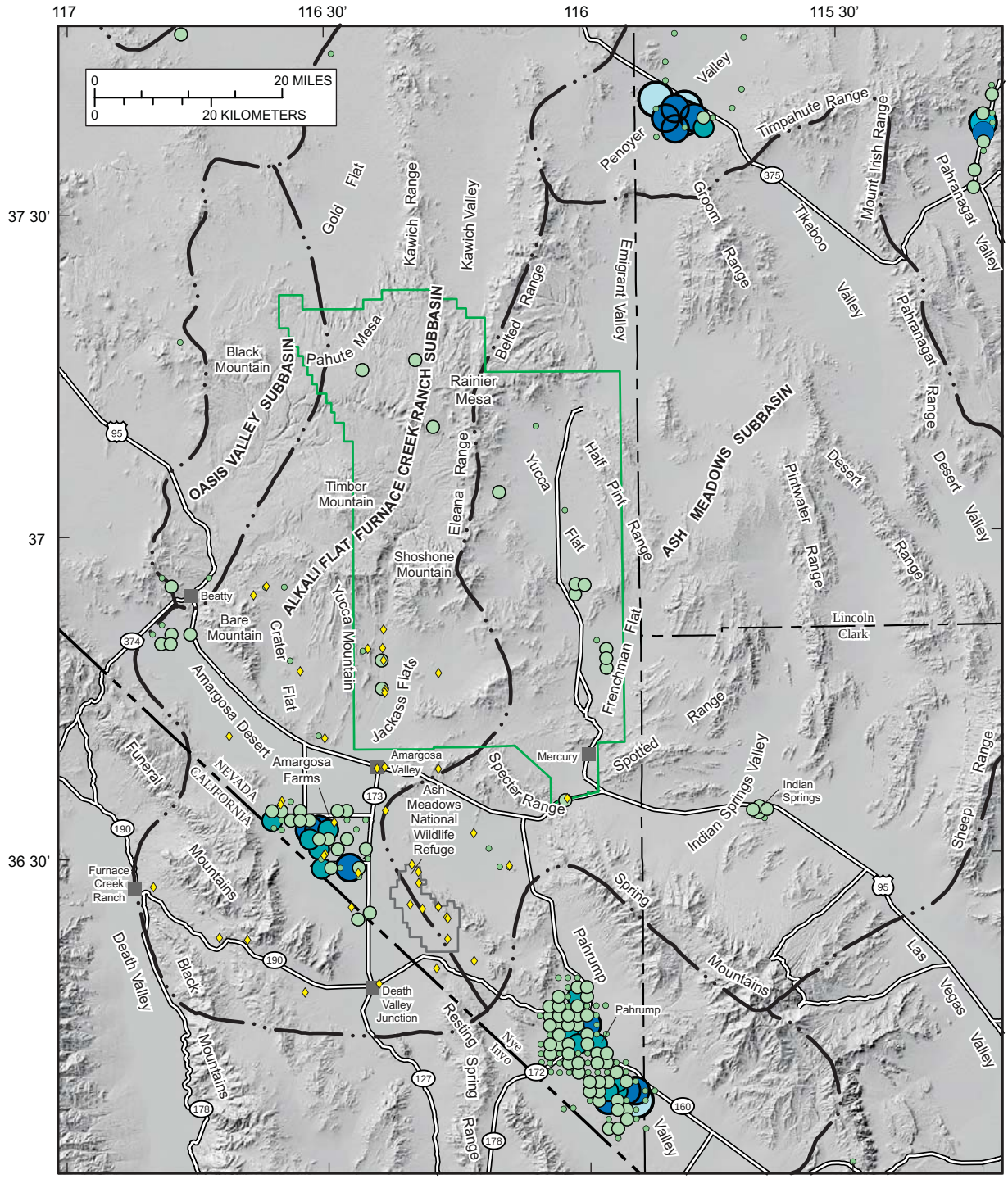


Figure 10. Estimates of annual ground-water withdrawals in selected major pumping centers for the Yucca Mountain region, 1960–2000. Scales are the same on all plots.



Base from U.S. Geological Survey digital data, 1:100,000
1978-89: Universal Transverse Mercator Projection, Zone 11
Shaded relief base from 1:24,000-scale National Elevation Data (NED) source date July 2000

EXPLANATION

Primary monitoring site

Ground-water subbasin boundary—From Laczniak and others (1996, pl. 1)

Nevada Test Site boundary

Total withdrawals from 1987 to 1998, in acre-feet

- 50 - 500
- 501 - 5,000
- 5,001 - 10,000
- 10,001 - 20,000
- 20,001 - 30,000

Figure 11. Reported regional ground-water withdrawals, totaled by square-mile section for 1987–98, in the Yucca Mountain region, southern Nevada and eastern California. (Withdrawals are not shown for Las Vegas Valley, California, or west of the Alkali Flat–Furnace Creek ground-water subbasin boundary.)

Seismic Activity

Earthquakes have affected water levels in various wells in the Yucca Mountain region (fig. 12). Several mechanisms may be responsible for these water-level changes, which are more likely to be observed in confined aquifers. Near an earthquake epicenter (within about 90 mi for the 7.6-magnitude Landers earthquake; Roeloffs and others, 1995, p. 7), water levels are affected by changes to the static strain field. Water levels will rise where the aquifer was compressed and will fall where extended. Farther from the epicenter, short-term changes in water levels (less than 10 minutes in duration) can be caused by strain-generating seismic waves that pass through the earth as compressional (P) waves followed by surface waves (Roeloffs and others, 1995, p. 6). Oscillatory water-level fluctuations in response to earthquake seismic waves are dependent on the earthquake's magnitude and distance from the well; the dimensions of the well; the transmissivity, storage coefficient, and porosity of the aquifer; and the type, period, and amplitude of the wave (Cooper and others, 1965). Longer-lasting water-level changes (several days to months) in wells at distances beyond the static strain field may be caused directly by changes in fluid pressure near the well or indirectly by changes to the hydraulic properties of the aquifer that affect fluid pressure near the well. Changes in hydraulic properties may result in permanent alterations in hydraulic conductivity, flow paths, and gradients. Over time, water levels will equilibrate to the new flow field by rising in some areas and declining in others.

Because earthquakes generally cause only small, short-term fluctuations in water levels, wells that are monitored infrequently (monthly or less often) may not show evidence of these fluctuations. Typically, the largest water-level response occurs shortly after an earthquake as the seismic waves pass through the site. Within minutes, most of the large transient changes have dissipated (O'Brien, 1992, 1993). Short-term water-level fluctuations can occur from earthquakes at large distances from the measurement location. Using an analog recorder, Dudley and Larson (1976, p. 11) showed that water levels in Devils Hole respond to earthquakes as distant as 6,900 mi. Water-level fluctuations at Devils Hole caused by distant earthquakes were up to several tenths of a foot in magnitude and lasted from 1 to 2 hours. Although short-term water-level responses to earthquakes are most common, water levels in some wells may take hours, months, or even years to recover from an earthquake.

Three major earthquakes centered in California—the Landers, Northridge, and Hector Mine—affected water levels in wells in the Yucca Mountain region between 1992 and 2000. The Landers and Hector Mine earthquakes each had a magnitude of 7.6, and the Northridge earthquake had a magnitude of 6.8. The epicenters of these three earthquakes were about 130 to 190 mi from the Ash Meadows area. Effects from at least one of the earthquakes were observed in almost one third of the primary monitoring sites (fig. 12). In general, the relative change in water levels resulting from earthquakes was small compared to effects from pumping or other factors. Most sites recorded an increase in water level or discharge following an earthquake. However, four sites recorded a drop in water level following an earthquake: three sites—AM-4 (Devils Hole), AD-6 (Tracer Well 3), and JF-2a (UE-25 p #1)—are completed in the regional carbonate-rock aquifer, and one site—RV-1 (TW-5)—is completed in the basement-confining unit.

The Landers earthquake was part of a series of related earthquakes that occurred between April 23 and June 29, 1992. Four major earthquakes (6.3–7.0 magnitude) occurred in southern or northern California from April 23–26, 1992 (O'Brien, 1992). The Landers earthquake, with an epicenter about 160 mi south of the Ash Meadows area, occurred on June 28, 1992. Following the Landers earthquake by one day was the 5.6-magnitude Little Skull Mountain earthquake on the south side of the NTS—the largest recorded earthquake within the NTS boundary (O'Brien, 1993, p. 9). Water-level changes from the four earthquakes preceding the Landers earthquake had small effects on some of the monthly water levels in the primary monitoring network. However, the Landers/Little Skull Mountain earthquakes had the greatest observed effect on water levels and discharge of any of the earthquakes during the study period. In some cases, such as at site RV-1 (fig. 12*L*), the water level took a year or more to recover. Water levels at sites AD-4a (fig. 12*A*) and AD-10 (fig. 12*E*) rose 3.5 and 2.5 ft, respectively, and recovered to pre-earthquake levels in about 1 year. Sharp upward spikes in water levels at both of these sites are superimposed on long-term declines caused by nearby pumping. For additional documentation of

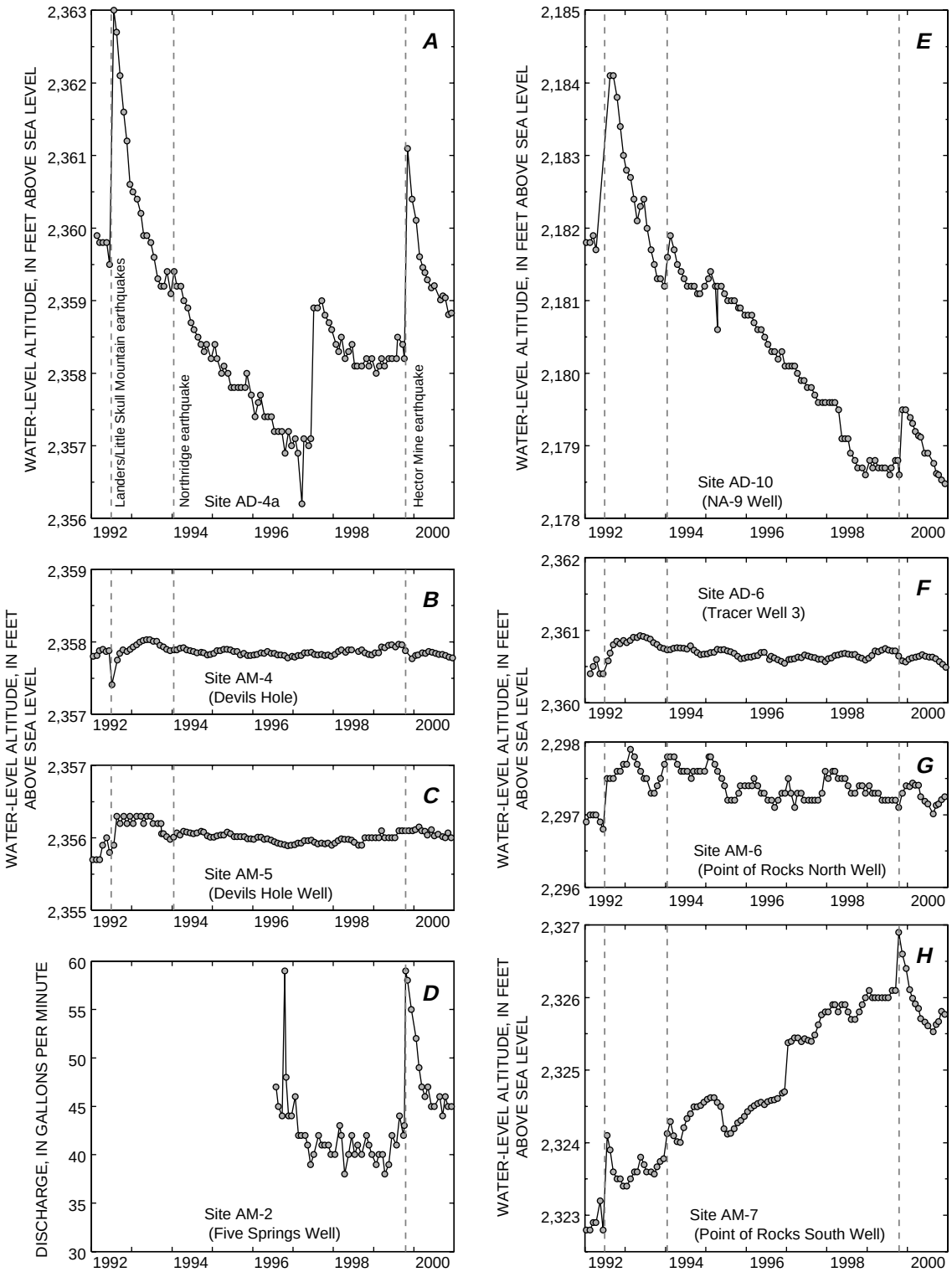


Figure 12. Water-level altitudes and discharge, 1992–2000, for wells and springs in the Yucca Mountain region that may have been affected by major earthquakes. Dashed lines mark Landers/Little Skull Mountain (1992), Northridge (1994), and Hector Mine (1999) earthquakes. Horizontal and vertical scales are the same on all water-level plots; vertical scales vary on discharge plots.

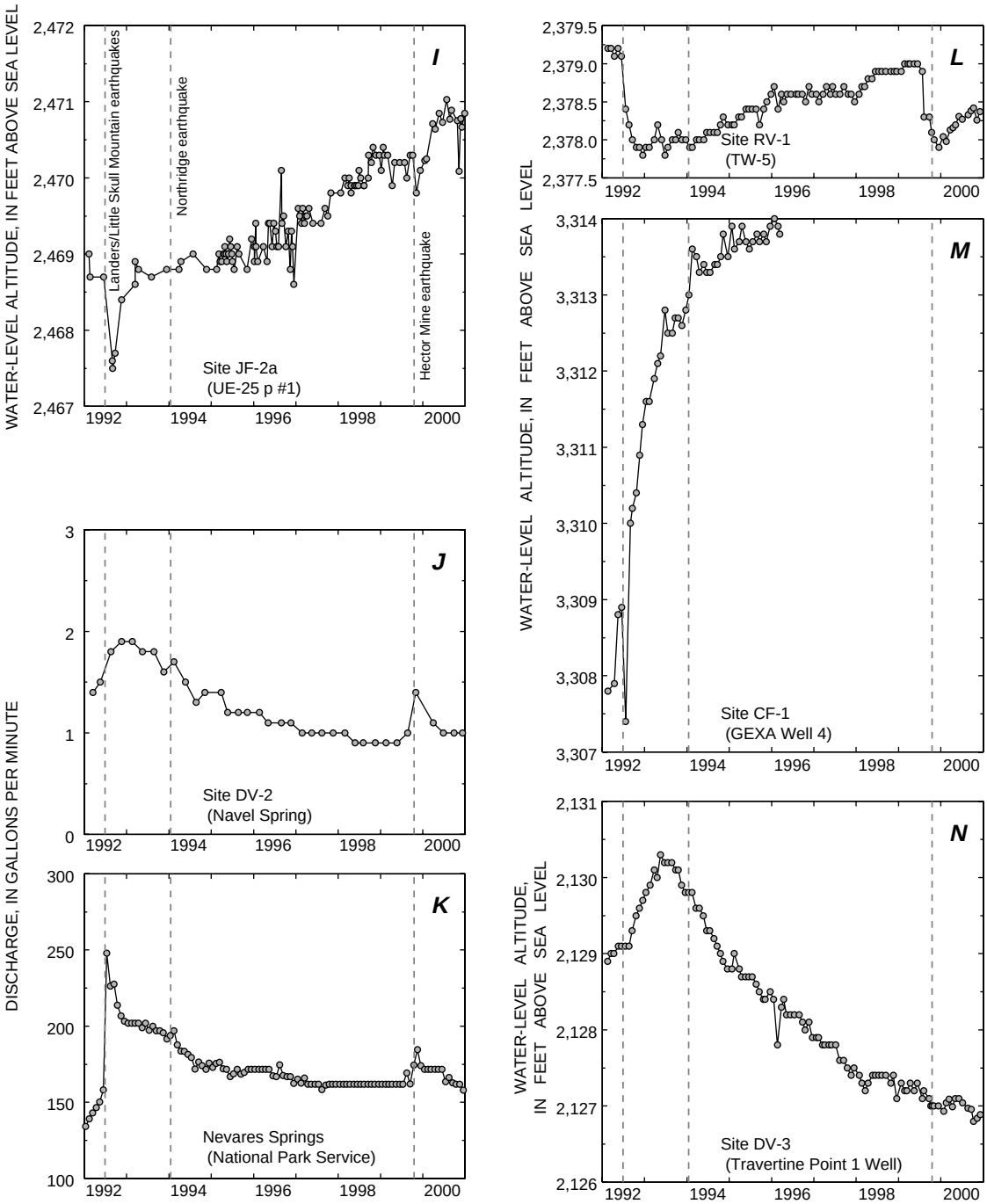


Figure 12. Continued.

water-level effects from the Landers series of earthquakes, see O'Brien (1992, 1993), Galloway and others (1994), and Roeloffs and others (1995).

The Landers/Little Skull Mountain earthquakes also affected spring discharge in the Yucca Mountain region. Nevares Springs (fig. 12*K*) and Travertine Springs (see "Death Valley" section) had discharges that were greater in 2000 than prior to the Landers/Little Skull Mountain earthquakes in 1992. Nevares Springs appears to have reached an equilibrium discharge that is 30 gal/min greater than the pre-earthquake discharge, whereas Travertine Springs appears to still be declining in 2000.

Water-level fluctuations caused by the Northridge earthquake, which occurred on January 17, 1994, were less than 1 ft in wells in the primary monitoring network. In most cases, these changes in water levels were less than changes caused by the Landers/Little Skull Mountain or Hector Mine earthquakes. For many of the sites, earthquake-induced water-level changes were not visible in the monthly measurements.

The Hector Mine earthquake occurred on October 16, 1999, and, although it was the same magnitude as the Landers earthquake, it did not have as great an effect on water levels. Recorded water-level fluctuations ranged from about 0.2 to 3 ft. Some water levels in wells returned to the pre-earthquake level within a few months. Site AD-4a recorded the largest earthquake-induced water-level fluctuation of 3 ft. The water level in this well was still returning to the pre-earthquake level at the end of 2000 (fig. 12*A*).

ANALYSIS OF TRENDS IN GROUND-WATER LEVELS AND SPRING DISCHARGE

Water levels from 37 sites and discharge from 6 sites were graphically and statistically analyzed for trends. Some of the trends were compared to potential factors causing the trends, to better understand influences on the ground-water system. In the discussion that follows, trends may be grouped by location, aquifer, or source of the trend. Seasonal, intermediate, and long-term trends are discussed where appropriate.

Long-term trends (1992–2000) were statistically analyzed using the Mann-Kendall trend test (Helsel and Hirsch, 1992, p. 326–328). The period 1992–2000 was selected for statistical trend analysis because the data sets had consistent monthly data, whereas prior to 1992 data from many wells and springs were measured sporadically. Data not used in the trend test consisted of a few isolated water levels, primarily levels affected by pumping or recent pumping of the well being monitored. Shorter periods of record at some sites occurred when a site was discontinued from the network prior to the end of 2000 or a new site was added after 1992. Two sites (AM-2 and AM-5a) had shorter periods of record analyzed because of changes near the wellhead or spring outlet that artificially affected the trend of the data.

The Mann-Kendall trend test was used to test for a monotonic change in water level or discharge with time. The Mann-Kendall method is a nonparametric trend test that determines whether a statistically significant upward or downward change in water level or discharge has occurred over the period of record. The method does not imply anything about the magnitude of the change or whether the change is linear.

Trends were graphically displayed using LOWESS smooths of the data (figs. 13–16). Smooths were used to help display the underlying trends in data, especially where the data scatter was high relative to the trend. Smooths of the data were used to display trends because fitting a straight line through the data generally is not appropriate. Most sources of water-level fluctuations do not result in a linear or monotonic trend in one direction for long periods. For example, water levels can fluctuate with time because of the cyclic nature of recharge, changing rates of pumping in water-supply wells, and earthquakes.

LOWESS smoothing was used to quantify the magnitude of the change in water level or discharge with time. The magnitude of the change was quantified using the maximum change in the smoothed data that is plotted in figures 13–16. The maximum change was calculated by subtracting the minimum value on the smooth from the maximum value. Although not perfect, this method of quantifying the magnitude of change was used because many of the trends are not linear or monotonic. Therefore, a more simplified method, such as quantifying the change in slope of a linear fit or subtracting the last water level in 2000 from the first water level in 1992, may not be appropriate. For example, because of equilibration following an earthquake at site RV-1 (fig. 13*G*), the trend is significantly upward based on the Mann-Kendall trend test. However, the beginning water level in 1992 is higher than the final water level in 2000, indicating an overall decline in water level. The maximum change in the

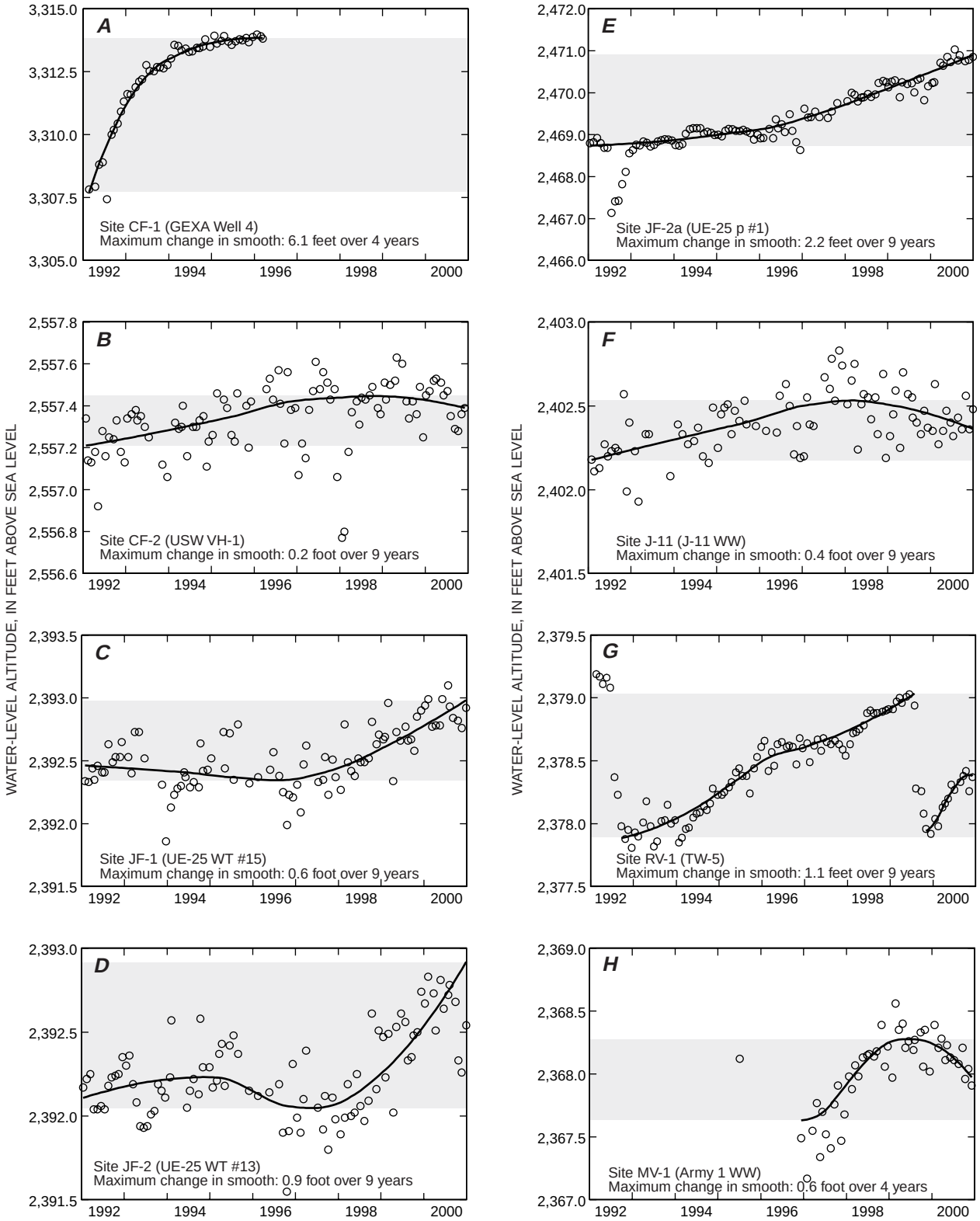


Figure 13. Smooths of water levels in wells with statistically significant upward trends from 1992 to 2000. Upward trends are based on Mann-Kendall trend test as presented in table 6. “Maximum change in smooth” (highlighted in gray on plots) is the change in water-level altitude from the maximum to the minimum part of the smooth. Vertical scales are maximized on each plot to show distribution of data and shape of trend.

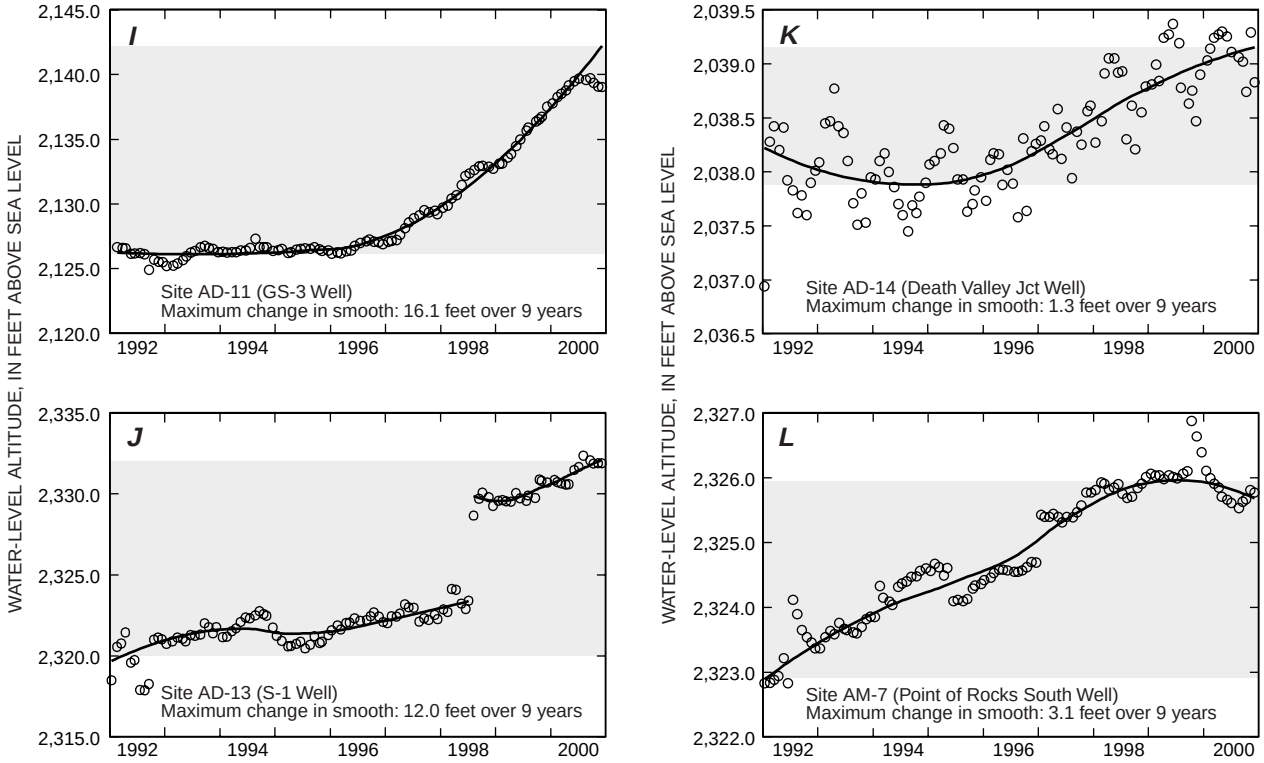


Figure 13. Continued.

smooth provides a better estimate of the magnitude of the change in water level that corresponds with the statistically significant rise in water level. The magnitude of change can be useful when comparing trends at different sites. The magnitude of the change in the smoothed water level ranged from 0.2 to 16.6 ft.

Most of the correlations of data sets in this report were analyzed graphically. Graphical analysis was used because it can provide a better indication of the overall strengths and weaknesses of a relation between two variables. In addition, many statistical correlations can be developed that are statistically significant but coincidental. Furthermore, in some cases, such as the effect of pumping on water levels, the mathematical relation is not straightforward. For example, following a sustained decrease in pumping, water levels may rise or they may continue to decline at a lesser rate. In this type of situation, the relation between pumping and water levels is difficult to analyze statistically but may be apparent in graphical form. Statistical correlations were applied only in the section “Jackass Flats.” In this section, the nonparametric Spearman rank correlation coefficient (Helsel and Hirsch, 1992, p. 217–218) was used to correlate water levels between wells.

When data from multiple sites are presented for evaluation in the figures that accompany this report, consistent horizontal and vertical scales are maintained in each figure so that sites can be compared easily. Exceptions to maintaining consistent scales are figures 13, 14, 15, and 16, in which vertical scales were maximized. The intent of these figures is to show short-term changes in the trend and the distribution of data around the trend line rather than to compare sites to one another.

Results of the statistical trend analysis are listed in tables 6 and 7 and shown in figures 13–16. An upward or downward change in water level or discharge was considered statistically significant if the Mann-Kendall trend test had a 99-percent confidence level (p-value less than 0.01), Kendall’s tau was greater than 0.2, and, for water-level trends, the maximum change in the smoothed water level was greater than or equal to 0.2 ft. Trends were upward at 12 water-level

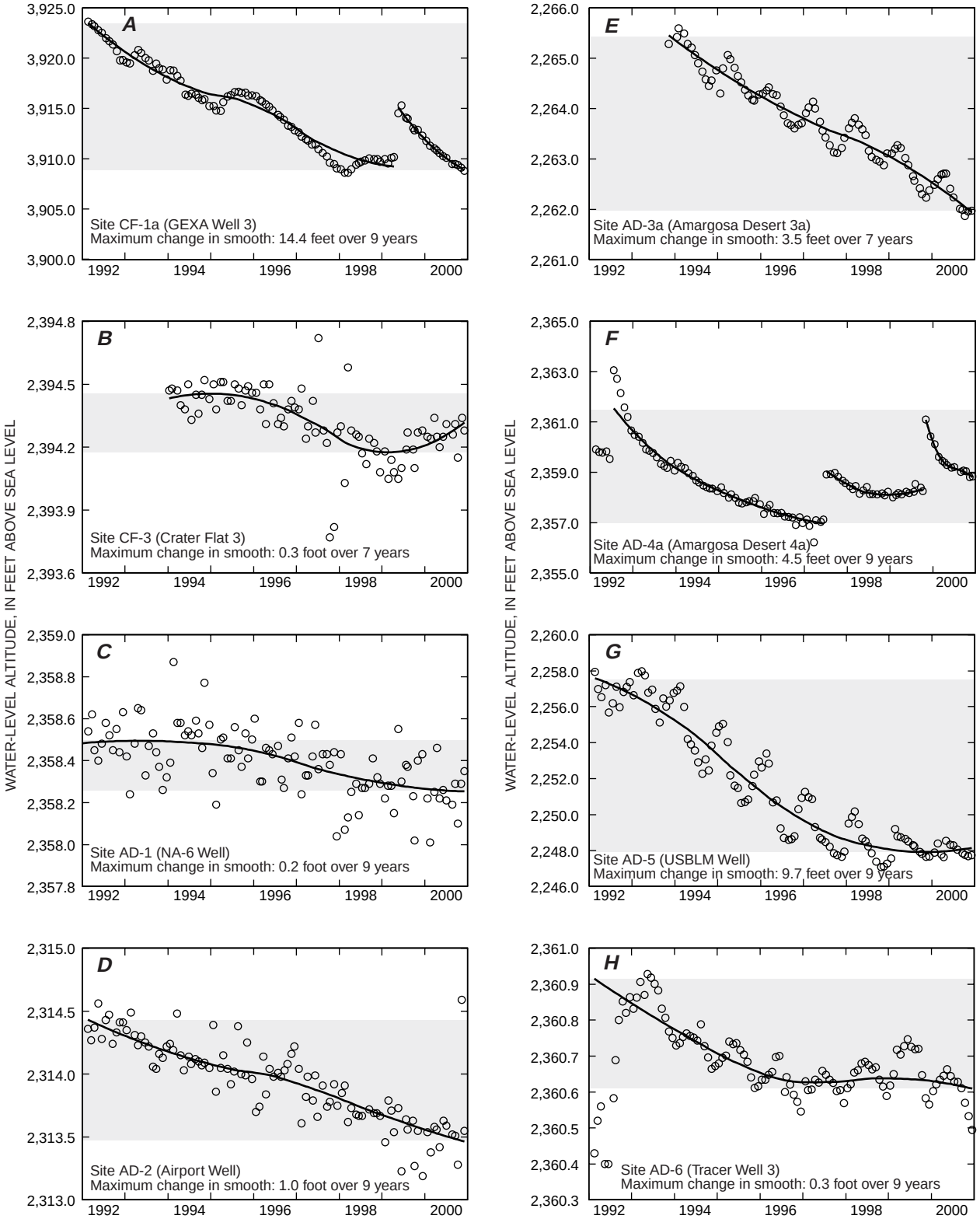


Figure 14. Smooths of water levels in wells and discharge from a spring with statistically significant downward trends from 1992 to 2000. Downward trends are based on Mann-Kendall trend test as presented in tables 6 and 7. “Maximum change in smooth” (highlighted in gray on plots) is the change in water-level altitude or discharge from the maximum to the minimum part of the smooth. Vertical scales are maximized on each plot to show distribution of data and shape of trend.

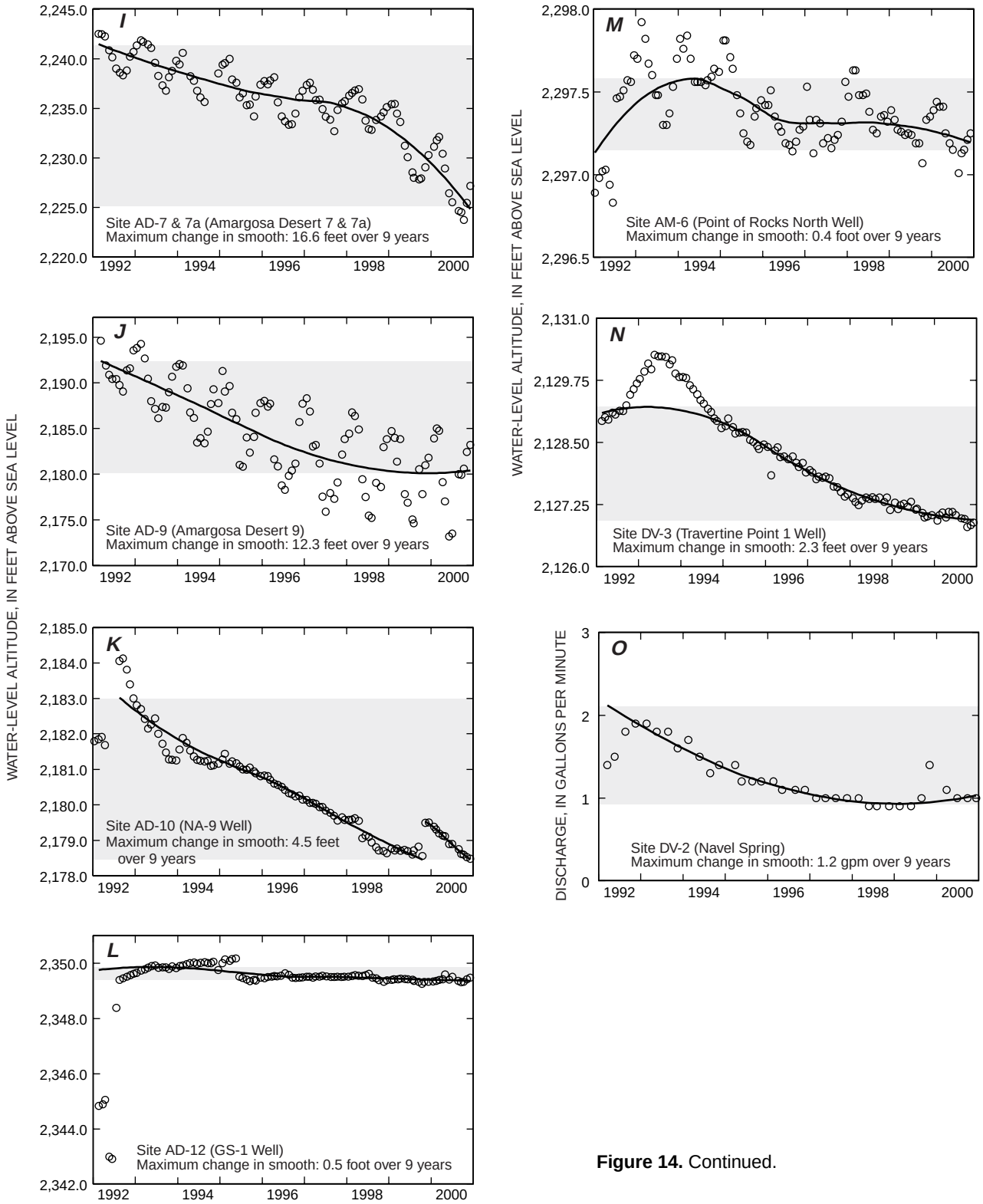


Figure 14. Continued.

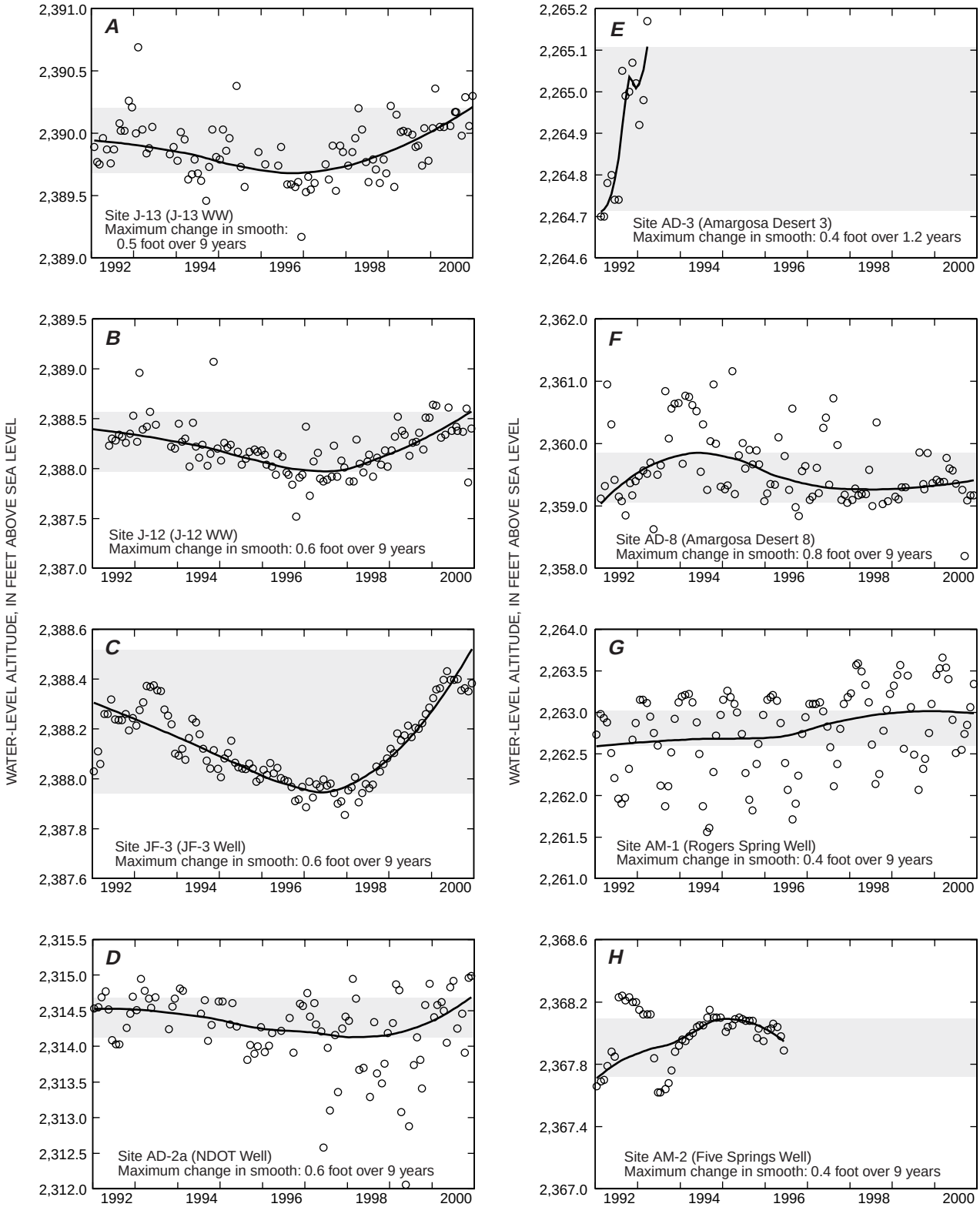


Figure 15. Smooths of water levels in wells (and in Devils Hole) with no statistically significant trends from 1992 to 2000. Absence of trend is based on Mann-Kendall trend test as presented in table 6. “Maximum change in smooth” (highlighted in gray on plots) is the change in water-level altitude from the maximum to the minimum part of the smooth. Vertical scales are maximized on each plot to show distribution of data and shape of trend.

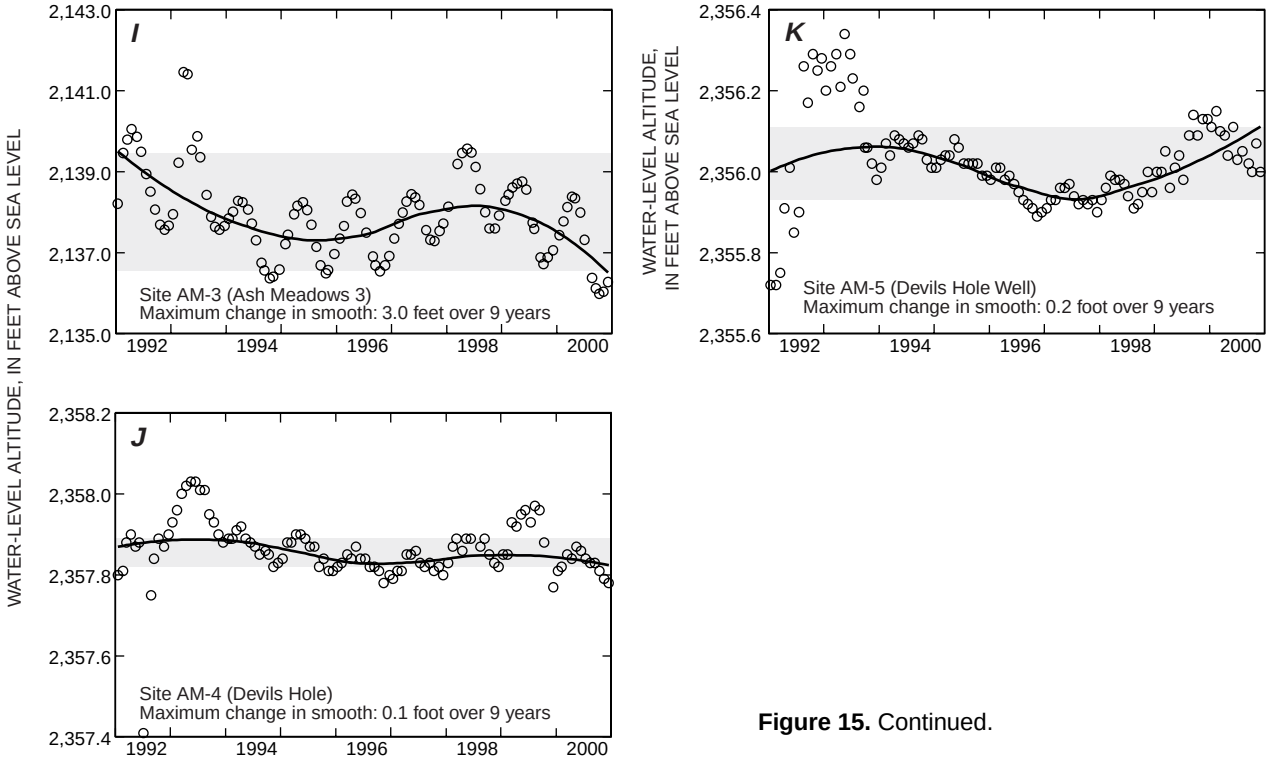


Figure 15. Continued.

sites (fig. 13) and downward at 14 water-level sites and 1 spring discharge site (fig. 14). No statistically significant upward or downward trend was observed at 11 water-level sites and 5 discharge sites (figs. 15 and 16). A data set with no statistically significant upward or downward trend can be as meaningful for understanding the ground-water system as a data set with a statistically significant trend. For example, in Jackass Flats, water levels in three wells had statistically significant upward trends and three wells showed no statistical trend. However, when data were plotted and patterns of water-level change were compared between all six wells, the influences of recharge and pumping on the ground-water system became apparent (see “Jackass Flats” section).

The distribution of trends throughout the study area is shown in figure 17. In general, the magnitude of the change in water level from 1992 to 2000 (as defined by the difference between the maximum and minimum water-level or discharge values on the LOWESS smooths in figs. 13–16) was small, except where influenced by nearby pumping or local effects (such as possible equilibration from well construction or diversion of nearby surface water).

Seasonal trends are superimposed on some of the long-term trends in water levels or discharge. Causes for seasonal trends include seasonal changes in barometric pressure, evapotranspiration, pumping, and recharge. The magnitude of seasonal change in water level can vary from as little as 0.05 ft in regional aquifers to greater than 5 ft in wells affected by evapotranspiration (Laczniak and others, 1999) or pumping. Figure 18 shows seasonal fluctuations in smoothed water levels (corrected for instantaneous effects of barometric pressure) ranging in magnitude from about 0.05 to 0.2 ft for two wells in the regional carbonate-rock aquifer in the Ash Meadows ground-water subbasin and one well in the volcanic-rock aquifer in Jackass Flats. These small seasonal water-level changes in regional aquifers probably are the result of a lagged response to barometric pressure that was not removed during the barometric correction. Patterns of high water levels in the winter and low water levels in the summer are in good agreement with patterns of high barometric pressure in the winter and low pressure in the summer (fig. 18). Any small seasonal or short-term fluctuations in water levels in these regional wells from pumping or pulses of recharge likely are masked by the influences of barometric pressure.

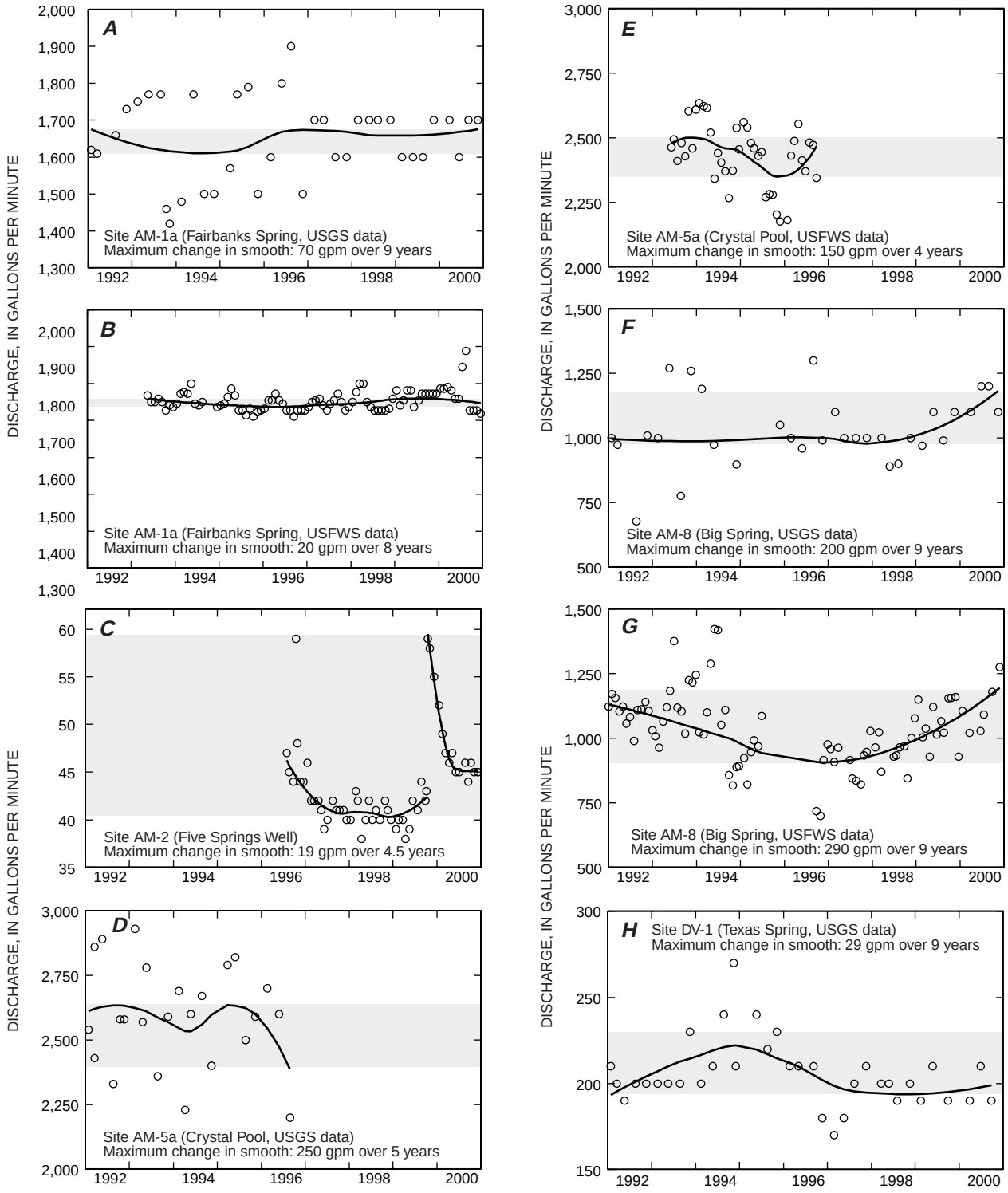


Figure 16. Smooths of discharge from springs and one flowing well with no statistically significant trends from 1992 to 2000. Absence of trend is based on Mann-Kendall trend test as presented in table 7. “Maximum change in smooth” (highlighted in gray on plots) is the change in discharge from the maximum to the minimum part of the smooth. Vertical scales are maximized on each plot to show distribution of data and shape of trend.

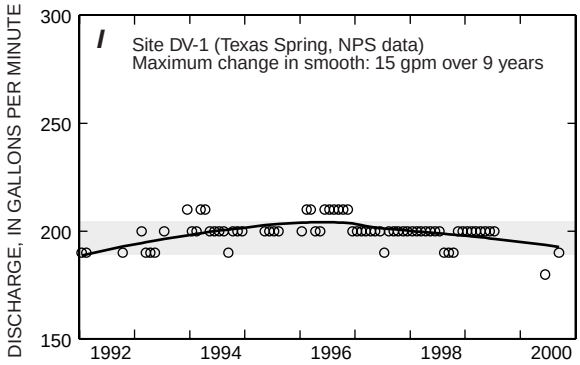


Figure 16. Continued.

Ash Meadows Ground-Water Subbasin

Fourteen sites from the primary monitoring network are within the Ash Meadows ground-water subbasin (fig. 1*B*); most are located within the Ash Meadows National Wildlife Refuge (NWR). Water levels remained relatively stable at primary sites in the Ash Meadows ground-water subbasin, with one well showing a rising trend and several wells declining slightly (fig. 17). Anomalous and/or site-specific water-level and discharge trends are discussed in appendix B for the following sites: AD-8 (Amargosa Desert 8), AD-12 (GS-1 Well), AM-2 (Five Springs Well), AM-5a (Crystal Pool), AM-6 (Point of Rocks North Well), and AM-7 (Point of Rocks South Well). Water-level trends from wells near Mercury Valley (fig. 17) and from Devils Hole and nearby wells in the eastern Amargosa Desert are discussed in the following sections.

Mercury Valley

Site MV-1 (Army 1 WW) is the farthest upgradient well in the primary monitoring network within the Ash Meadows ground-water subbasin (fig. 17). The water level in this well rose about 0.6 ft from 1997 to 2000 (fig. 13*H*). Army 1 WW, completed in the carbonate-rock aquifer, is a water-supply well used to support NTS activities in Mercury Valley. From 1992 to 2000, withdrawals decreased from 135 Mgal/yr to less than 1 Mgal/yr (fig. 19). Most of the decrease in withdrawals occurred in July 1994.

A comparison was made between (1) water levels in Army 1 WW, (2) water levels in Army 3, (3) withdrawals from Army 1 WW, and (4) cumulative departure from mean annual precipitation in the Spring Mountains (fig. 19). Water-level measurements for Army 1 WW prior to 1997 are sparse. Based on limited data for Army 1 WW, the following conclusions can be made. First, the somewhat erratic early measurements in Army 1 WW probably are caused by short-term changes in rates of pumping in the well and varying periods between the time the pump was shut off and the water level was measured. Second, pumping in Army 1 WW has had little long-term effect on static water levels in Army 1 WW. Water levels in 1962, when pumping began in Army 1 WW, are similar to water levels in 2000 (fig. 19). Third, data are insufficient to determine if water levels in Army 1 WW are responding to precipitation, as is probably the case with Army 3. Army 3 is completed in Cenozoic volcanic rock and is in southern Indian Springs Valley, 15 mi east-southeast of Army 1 WW (fig. 1*A*). The volcanic rock near Army 3 is fed by upward leakage of water from the regional carbonate-rock aquifer (Winograd and Thordarson, 1975, p. 62). Army 3 is in an ideal location to monitor recharge to the Ash Meadows ground-water subbasin from the northern Spring Mountains (figs. 1*A* and 2). Plots of water levels in Army 3 and precipitation in the Spring Mountains follow similar patterns (fig. 19).

Devils Hole and Eastern Amargosa Desert

The Ash Meadows NWR, established in 1984 and managed by USFWS, encompasses more than 22,000 acres of spring-fed wetlands. Within the refuge boundaries is a 40-acre tract of land containing Devils Hole, which is managed by NPS as part of Death Valley National Park. Four of the seven species of native fish present in the refuge are federally listed endangered species, including the Devils Hole pupfish, *Cyprinodon diabolis*. Prior to establishment as a national wildlife refuge, the Ash Meadows area was intensively farmed, particularly during the late 1960's to mid-1970's. Consequent lowering of the pool level in Devils Hole and exposure of the spawning shelf for the Devils Hole pupfish led to a U.S. Supreme Court decision in 1976 that established the minimum water level as 2.7 ft below a reference washer placed in the south wall of Devils Hole. In 1962, the average pool level was 1.1 ft below the reference washer. As of December 2000, the water level stood at 2.1 ft below the washer. The history of local withdrawals and the effect on the stage of Devils Hole are documented in Dudley and Larson (1976).

Table 6. Analysis of water-level trends, using the Mann-Kendall test, for selected wells in the Yucca Mountain region

Level of significance (p): Probability that water-level changes are due to chance rather than a trend; <, less than.

Maximum change in smoothed water level: A measure of the amount of variation in water level for the period analyzed. The change is the difference between the maximum and minimum water-level values on the LOWESS smooth (figs. 13–15).

Statistically significant trend: Considered significant if more than 3 years of data in which level of significance is less than 0.01, Kendall's tau is greater than 0.2 and maximum change in smoothed water level is greater than or equal to 0.2 foot; up, water-level rising; down, water level declining; none, no monotonic trend for period analyzed.

Site number (fig. 1*B*)	Site name	Period of record analyzed	Number of observations	Level of significance (p)	Kendall's tau	Maximum change in smoothed water level (feet)	Statistically significant trend
CF-1	GEXA Well 4	1992–1996	49	<0.001	0.85	6.1	up
CF-1a	GEXA Well 3	1992–2000	107	<.001	-.75	14.4	down
CF-2	USW VH-1	1992–2000	99	<.001	.33	.2	up
CF-3	Crater Flat 3	1994–2000	84	<.001	-.47	.3	down
JF-1	UE-25 WT #15	1992–2000	92	<.001	.40	.6	up
JF-2	UE-25 WT #13	1992–2000	95	<.001	.28	.9	up
JF-2a	UE-25 p #1	1992–2000	104	<.001	.78	2.2	up
J-13	J-13 WW	1992–2000	93	.16	.10	.5	none
J-11	J-11 WW	1992–2000	88	<.001	.28	.4	up
J-12	J-12 WW	1992–2000	100	.42	-.05	.6	none
JF-3	JF-3 Well	1992–2000	108	.2	-.08	.6	none
RV-1	TW-5	1992–2000	107	<.001	.33	1.1	up
MV-1	Army 1 WW	1995–2000	49	<.001	.38	.6	up
AD-1	NA-6 Well (BGMW-10)	1992–2000	108	<.001	-.41	.2	down
AD-2	Airport Well	1992–2000	106	<.001	-.72	1.0	down
AD-2a	NDOT Well	1992–2000	91	.08	-.13	.6	none
AD-3	Amargosa Desert 3	1992–1993	14	.004	.58	.4	none
AD-3a	Amargosa Desert 3a	1993–2000	85	<.001	-.85	3.5	down
AD-4a	Amargosa Desert 4a	1992–2000	107	<.001	-.25	4.5	down
AD-5	USBLM Well	1992–2000	107	<.001	-.75	9.7	down
AD-6	Tracer Well 3	1992–2000	107	<.001	-.34	.3	down
AD-7 and 7a [1]	Amargosa Desert 7 and 7a	1992–2000	103	<.001	-.72	16.6	down
AD-8	Amargosa Desert 8	1992–2000	101	.007	-.18	.8	none
AD-9	Amargosa Desert 9	1992–2000	106	<.001	-.55	12.3	down
AD-10	NA-9 Well	1992–2000	105	<.001	-.87	4.5	down
AD-11	GS-3 Well	1992–2000	107	<.001	.79	16.1	up
AD-12	GS-1 Well	1992–2000	107	<.001	-.28	.5	down
AD-13	S-1 Well	1992–2000	108	<.001	.75	12.0	up
AD-14	Death Valley Jct Well	1992–2000	108	<.001	.53	1.3	up
AM-1	Rogers Spring Well	1992–2000	108	.003	.20	.4	none
AM-2	Five Springs Well	1992–1996	54	.73	.03	.4	none
AM-3	Ash Meadows 3	1992–2000	107	.006	-.18	3.0	none
AM-4	Devils Hole	1992–2000	106	.002	-.20	.1	none
AM-5	Devils Hole Well	1992–2000	109	.04	-.13	.2	none
AM-6	Point of Rocks North Well	1992–2000	108	<.001	-.28	.4	down
AM-7	Point of Rocks South Well	1992–2000	108	<.001	.78	3.1	up
DV-3	Travertine Point 1 Well	1992–2000	107	<.001	-.84	2.3	down

[1] Sites AD-7 and AD-7a were combined for the statistical analysis because, based on water levels, both sites appear to be monitoring the same zone in the valley-fill aquifer (fig. 29*I*). In 1994, the well at site AD-7 was recompleted (either cleaned out and developed or deepened during recompletion), as a result, this site was renamed AD-7a.

Table 7. Analysis of trends in discharge, using the Mann-Kendall test, for selected springs and one well in the Yucca Mountain region

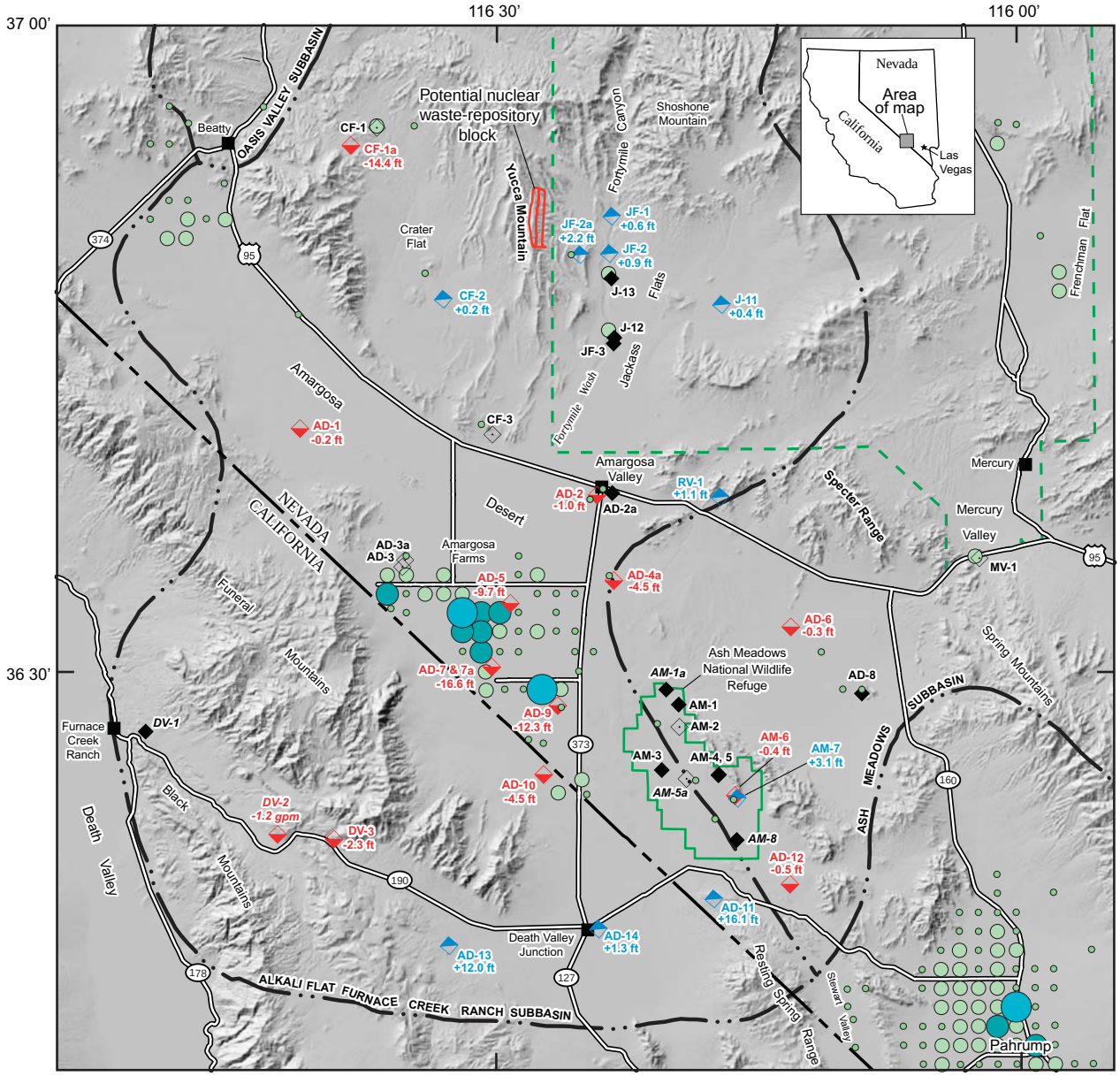
Data source: USGS, U.S. Geological Survey; USFWS, U.S. Fish and Wildlife Service; NPS, National Park Service.

Level of significance (p): Probability that changes in discharge are due to chance rather than a trend; <, less than.

Maximum change in smoothed discharge: A measure of the amount of variation in discharge for the period analyzed. The change is the difference between the maximum and minimum discharge values on the LOWESS smooth (figs. 14 and 16).

[Abbreviation: gal/min, gallons per minute]

Site number (fig. 1*B*)	Site name	Data source	Period of record analyzed	Number of observations	Level of significance (p)	Kendall's tau	Average discharge for period of record analyzed (gal/min)	Maximum change in smoothed discharge (gal/min)	Statistically significant trend
AM-1a	Fairbanks Spring	USGS	1992–2000	37	0.59	0.06	1,650	70	none
AM-1a	Fairbanks Spring	USFWS	1993–2000	89	.08	.12	1,760	20	none
AM-2	Five Springs Well	USGS	1996–2000	56	.27	.10	44	19	none
AM-5a	Crystal Pool	USGS	1992–1996	24	.96	-.01	2,600	250	none
AM-5a	Crystal Pool	USFWS	1993–1996	40	.02	-.25	2,450	150	none
AM-8	Big Spring	USGS	1992–2000	32	.18	.16	1,020	200	none
AM-8	Big Spring	USFWS	1992–2000	85	.1	-.12	1,040	290	none
DV-1	Texas Spring	USGS	1992–2000	35	.14	-.17	205	29	none
DV-1	Texas Spring	NPS	1992–2000	70	.58	-.04	200	15	none
DV-2	Navel Spring	USGS	1992–2000	36	<.001	-.67	1.3	1.2	down



Base from U.S. Geological Survey digital data, 1:100,000 1978 89: Universal Transverse Mercator Projection, Zone 11. Shaded relief base from 1:24,000-scale National Elevation Data (NED) source date July 2000

0 5 10 15 MILES

0 5 10 15 KILOMETERS

EXPLANATION

Monitoring site for which water levels or discharge from 1992 to 2000 were statistically analyzed for trends (see tables 6 and 7)—Upper number is site identification; lower number indicates maximum change in smoothed water level in feet (ft) or discharge, in gallons per minute (gpm). Discharge sites are in italic

AD-13 13.6 ft — Significant upward trend

CF-1a -13.6 ft — Significant downward trend

J-13 — No significant upward or downward trend

CF-1 — Insufficent data for determining a trend from 1992 to 2000

Ground-water subbasin boundary—From Laczniak and others (1996, pl. 1)

Nevada Test Site boundary

Total withdrawals from 1992 to 2000, in acre-feet

10 - 500

501 - 5,000

5,001 - 10,000

10,001 - 21,000

Figure 17. Trends in water levels or spring discharge and total ground-water withdrawals from each square-mile section for the study area between 1992 and 2000.

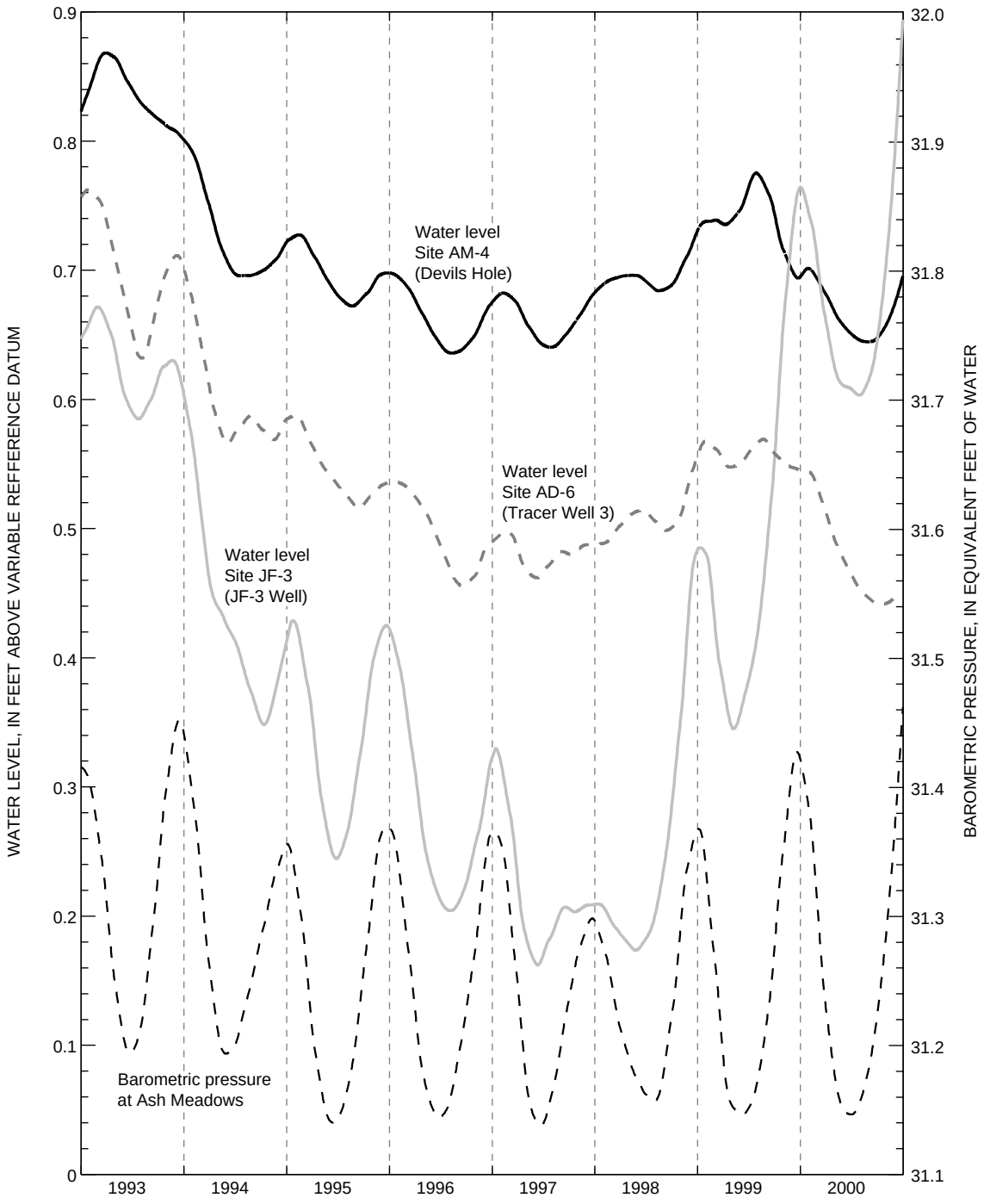


Figure 18. Relation of seasonal fluctuations in continual water levels at two sites in the regional carbonate-rock aquifer (Devils Hole and site AD-6) and one site in a volcanic-rock aquifer (site JF-3), 1993–2000. All hydrographs are smooths of daily mean water levels corrected for instantaneous effects of barometric pressure. Variable reference datum was used to put multiple sites on one plot.

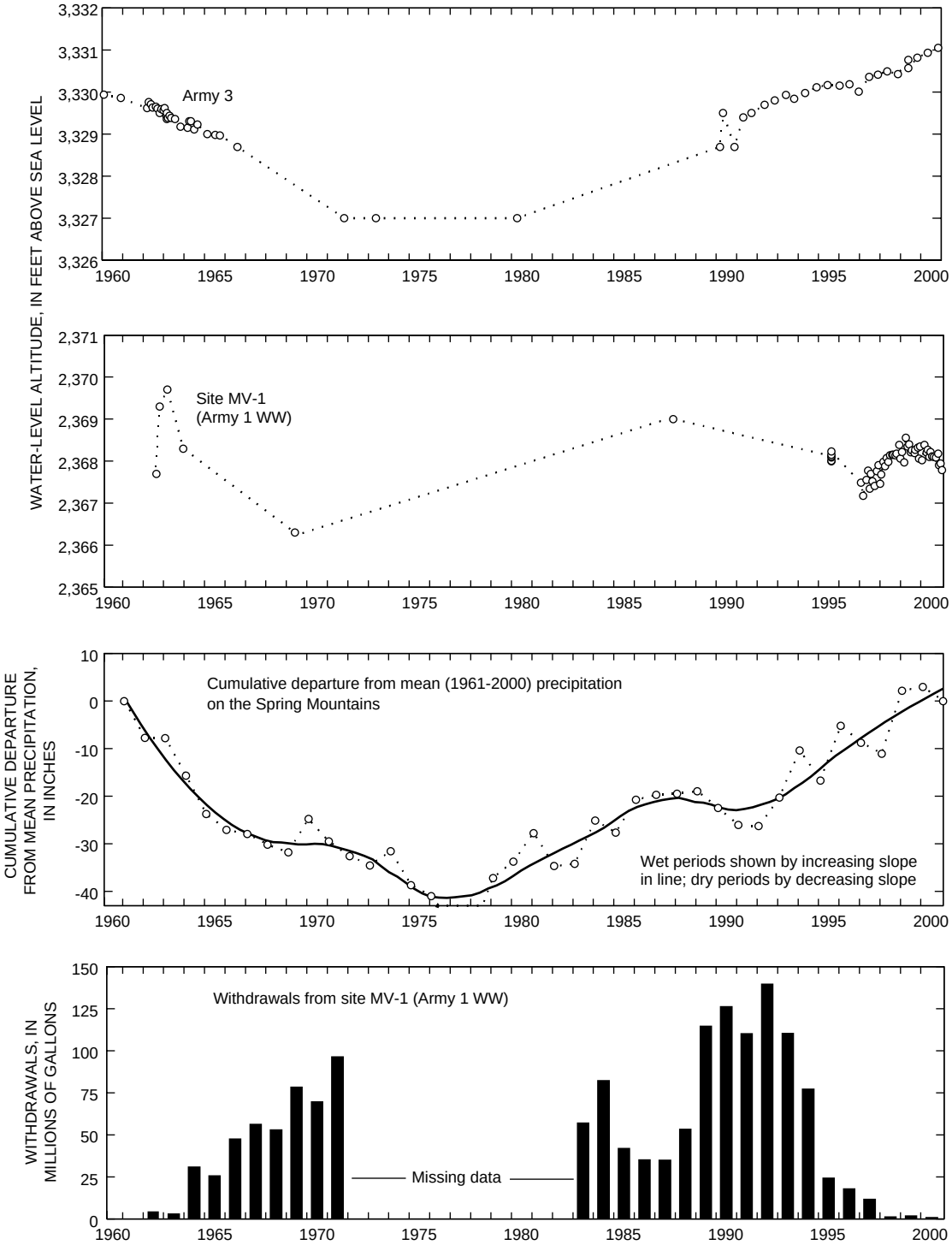


Figure 19. Relation of water levels in Army 3 and Army 1 WW to cumulative departure from mean precipitation in the Spring Mountains and annual ground-water withdrawals at Army 1 WW, 1960–2000.

The history and recovery period and factors affecting that recovery through 1999 are documented in Harrill and Bedinger (2000).

Water levels and spring discharge in Ash Meadows probably are affected by changes in climate, ground-water withdrawals, and seismic events. No conclusive evidence exists, however, to suggest how much influence each of these factors has on the area as a whole, or whether the controlling processes are different for different areas within Ash Meadows. Similar water-level fluctuations from 1960 to 2000 at sites AD-6 (Tracer Well 3), AM-4 (Devils Hole), and AM-5 (Devils Hole Well) are attributed to a combination of the above-named factors and are discussed in the following sections.

Climate Change

The relation between precipitation and water levels in Devils Hole, Tracer Well 3, and four wells in the carbonate-rock aquifer in Frenchman and Yucca Flats (upgradient from Devils Hole) is shown in figure 20. Hydrographs of annual average water levels from wells TW-3, UE-7nS, TW-D, and TW-F (fig. 1*A*) look similar to plots of cumulative departure from mean precipitation for south-central Nevada. These wells were selected for analysis based on long periods of record, remoteness from pumping, and completion in the carbonate-rock aquifer. In general, water levels at these sites declined from the early 1960's through the late 1970's, rose throughout most of the 1980's, declined

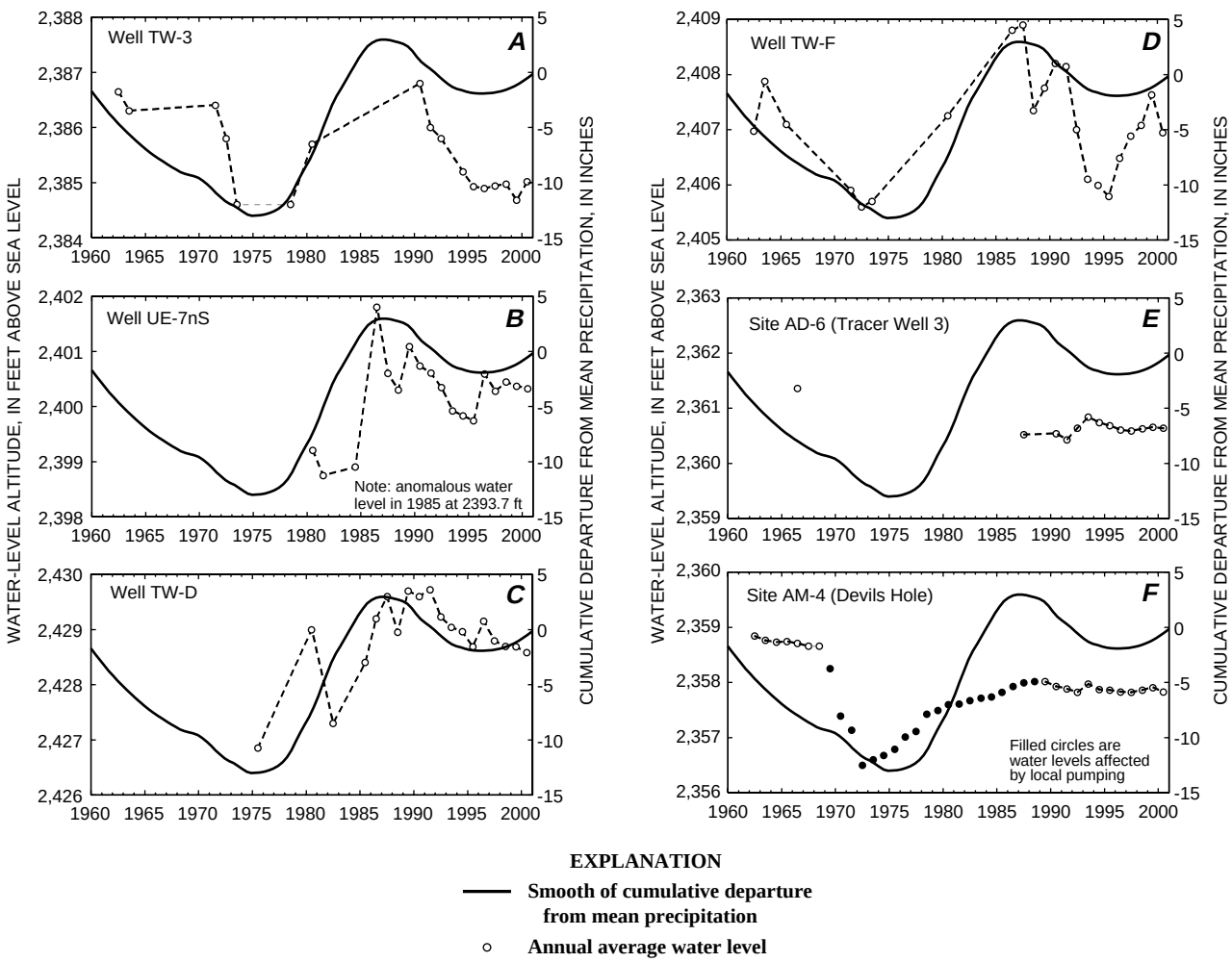


Figure 20. Relation of annual average water levels from the carbonate-rock aquifer in the Ash Meadows ground-water subbasin, and cumulative departure from mean precipitation for the south-central Nevada precipitation index, 1960–2000. Scales are the same for all plots.

from the late 1980's to the mid-1990's, and stabilized or rose through 2000 (fig. 20). Water levels at these sites were lower in 2000 than in the late 1980's, similar to water levels in Devils Hole (fig. 20). Therefore, the slight overall drop in Devils Hole water level from the late 1980's to 2000 may simply reflect a deficit in precipitation.

The magnitude of water-level fluctuation in Devils Hole is small because of its proximity to a discharge area. In the discharge area, changes in water level are dampened by springs, which are at a fixed altitude. Therefore, the magnitude of water-level fluctuations at sites located in and near Ash Meadows discharge area, such as Tracer Well 3 and Devils Hole, are less when compared to fluctuations at sites distant from this discharge area, such as wells TW-3, UE-7nS, TW-D, and TW-F (fig. 20).

Water levels in Devils Hole declined at a rate from about 0.02 to 0.03 ft/yr during the periods 1962–68 and 1989–2000. Theoretically, this rate of decline could be attributed to below-average precipitation that occurred during these periods. From 1968 (prior to pumping in Ash Meadows) to 1989 (probable post-recovery from pumping in Ash Meadows), the rate of decline of water levels in Devils Hole was about 0.03 ft/yr. This rate of decline is similar to the rate during pre-pumping and post-recovery, despite above-average precipitation during the period 1968–89. Water levels in two wells (TW-F and TW-3) upgradient from Devils Hole, which were affected primarily by precipitation, increased to their highest levels on record in the late 1980's (fig. 20). This suggests that, at least during 1968–89, processes other than recharge affected water levels in Devils Hole (and probably the eastern Amargosa Desert) and prevented water levels from rising to naturally occurring levels. Likely processes are ground-water withdrawals from pumping centers affecting regional areas or incomplete recovery from pumping in Ash Meadows.

Ground-Water Withdrawals

Ground-water levels in the Ash Meadows area may be affected by withdrawals from several pumping centers that influence regional areas (figs. 9–11), including Las Vegas Valley, Pahrump Valley, the Amargosa Farms area, and NTS. Withdrawals from Las Vegas Valley and Pahrump Valley have been considerable since the early 1900's, whereas large withdrawals from Amargosa Farms and NTS began in the mid-1950's to early 1960's. No direct correlation was found between withdrawals from any of the pumping centers listed above and water levels in Ash Meadows. However, the lack of a correlation between water levels in Ash Meadows and one of these pumping centers is not surprising because: (1) water-level data sets from Ash Meadows prior to 1989 are of poor quality or do not exist, (2) effects from distant pumping may be lagged and subtle, and (3) water-level fluctuations may be the result of multiple influences including withdrawals from more than one pumping center, changes in natural recharge, and seismic events.

Las Vegas Valley is the largest ground-water withdrawal center near the Yucca Mountain region, but also is the farthest from Ash Meadows (50 mi to the west side of the Las Vegas Valley). In the west-central part of Las Vegas Valley (southeast corner of fig. 2), where high-yield municipal-supply wells are located, ground-water levels declined more than 300 ft from about 1915 to 1990 (Burbey, 1995, p. 22). The ground-water cone of depression from this pumping intercepts the bedrock/alluvium interface near the base of the Spring Mountains on the west side of Las Vegas Valley (Burbey, 1995, p. 22; Morgan and Dettinger, 1996, p. 80). This raises the possibility that the ground-water recharge mound beneath the Spring Mountains could be shifted toward Las Vegas Valley because of a steepening potentiometric surface. If this occurred under equilibrium conditions, the amount of natural recharge from the Spring Mountains to either Pahrump or to the Ash Meadows ground-water subbasin would be reduced by an amount equal to the flux of water induced into the Las Vegas Valley by pumping. This reduced recharge could result in declining water levels near Ash Meadows or Pahrump.

Pahrump Valley, about 20 mi southeast of Ash Meadows, is the second largest ground-water withdrawal center near the Yucca Mountain region. From 1913 to 1975, water levels declined by 100 ft in some areas of Pahrump Valley; 60 ft of the decline occurred from 1962 to 1975 (Harrill, 1986, p. 36 and 40). In recent years, a decrease in overall pumping caused water levels to recover in some parts of Pahrump Valley, while water levels in other parts of the valley declined. Withdrawals from Pahrump Valley, and resulting water-level declines, might intercept natural recharge supplied by the Spring Mountains to the Ash

Meadows ground-water subbasin (fig. 2). Interception of recharge to the subbasin could result in declining water levels in the Ash Meadows area, although the effect might take years to observe depending largely on the distance from the recharge area to an observation well.

The Amargosa Farms area, about 10 mi west of Ash Meadows, is the third largest ground-water withdrawal center near the Yucca Mountain region, but the closest withdrawal center to many of the wells in the primary network. From the 1950's through 2000, water levels have declined in the Amargosa Farms area as much as 30 ft because of pumping. Interactions between the Alkali Flat–Furnace Creek Ranch (AFFCR) ground-water subbasin and the Ash Meadows ground-water subbasin have been suggested by Dudley and Larson (1976, p. 42), and Winograd and Thordarson (1975, p. 82). These interactions were investigated to determine the possibility that pumping in the Amargosa Farms area could be affecting water levels in the Ash Meadows area. Winograd and Thordarson (1975, p. 82) suggested a possible path of underflow through the relatively thick carbonate rocks in an area near Fairbanks Spring (site AM-1a; fig. 1*B*). In this area, water in the carbonate-rock aquifer may move from the Ash Meadows subbasin directly into the AFFCR subbasin. Discharge at Fairbanks Spring and water levels at nearby site AM-1 (Rogers Spring Well; fig. 1*B*), had no statistically significant upward or downward trends from 1992 to 2000 (tables 6 and 7; figs. 15*G* and 16*B*). Dudley and Larson (1976, p. 47–48) suggest a connection between the two ground-water subbasins because the chemistry of water from an area just south of Fairbanks Spring more closely resembles water from the AFFCR subbasin than from the Ash Meadows subbasin. They suggest that, in this area, water in the carbonate-rock aquifer may be moving westward into the AFFCR subbasin, whereas water in the valley fill could be moving eastward from the AFFCR subbasin. If a connection does exist between the Ash Meadows subbasin and the AFFCR subbasin, then a cone of depression from pumping in the Amargosa Farms area might be able either to draw more water across this subbasin boundary through the underlying carbonate-rock aquifer or decrease the amount of water flowing into the Ash Meadows subbasin through the valley fill. Either possibility could explain declining water levels in the Ash Meadows area. The relation between the carbonate-rock aquifer and the valley-fill aquifer in the Amargosa Farms area, and the interaction between the two subbasins require further investigation to determine whether pumping from the Amargosa Farms area has an effect on flow in the Ash Meadows subbasin.

Ground-water withdrawals from the NTS are relatively minor and the distance between NTS supply wells and Ash Meadows is relatively far (20–50 mi) compared to other withdrawal centers (figs. 9–11). The effects on water levels in Ash Meadows from withdrawals on the NTS are believed to be small to negligible. Wells in the carbonate-rock aquifer upgradient from the Specter Range and near the NTS, including Army 1 WW (site MV-1), show no evidence of declining water levels resulting from regional pumping. Water levels in wells in the carbonate-rock aquifer north of the Specter Range appear to be controlled primarily by recharge (figs. 19 and 20). In contrast, water levels in Las Vegas and Pahrump Valleys, and in the Amargosa Farms area, appear to be affected primarily by pumping and have undergone relatively large declines for many years.

Water levels in Devils Hole and site AD-6 (Tracer Well 3) show no evidence of being affected by pumping in Army 1 WW. Water levels were analyzed during a period in June 1994 when pumping in Army 1 WW was reduced abruptly. Withdrawals from Army 1 WW from 1989 to 1993 consistently averaged about 120 Mgal/yr (fig. 19). Following the abrupt reduction in pumping, withdrawals from 1995 to 1997 were relatively consistent at about 18 Mgal/yr. Water levels corrected for barometric pressure at sites AD-6 and Devils Hole, about 10 and 20 mi, downgradient of Army 1 WW, respectively, do not show a corresponding increase in water levels after June 1994 (fig. 18). During this time, water levels at these two sites were in a declining trend and continued to decline until late 1996.

Water levels in Devils Hole also may be affected by long-term recovery from local pumping in the Ash Meadows area that ceased in 1982 (Harrill and Bedinger, 2000, p. 14). Although most of the recovery from local pumping occurred prior to 1988, Harrill and Bedinger estimate that water levels in 2000 may be about 0.5 ft from complete recovery. The predicted rate of recovery for water levels in Devils Hole from local pumping was estimated to be about 0.01 ft/yr in 2000 (Harrill and Bedinger, 2000, app. 2). This small rate of recovery is likely masked by water-level changes caused by other effects. About 1.5 mi southeast of Devils Hole, at site AM-7 (Point of Rocks South Well),

water levels are still recovering from local pumping that occurred 20 years earlier (fig. 27*F* in app. A; app. B).

Seismic Events

Earthquakes are known to affect spring discharge and water levels in the Yucca Mountain region, including Ash Meadows (fig. 12). Some of these effects, observed in discharge records for the carbonate-rock aquifer, appear to last for years. For example, after an abrupt increase in discharge at Travertine Springs in Death Valley following the Landers/Little Skull Mountain earthquakes in 1992, discharge declined for about 8 years (see "Death Valley" section). Discharge from Travertine Springs at the end of 2000 was similar to discharge prior to the Landers/Little Skull Mountain earthquakes; however, it is not clear whether discharge will continue to decline. Closer to Ash Meadows, water levels at site AD-6 (Tracer Well 3) rose approximately 0.4 to 0.5 ft following the Landers/Little Skull Mountain earthquakes (fig. 14*H*). Water levels in this well declined for 4 years but did not approach pre-earthquake levels until the end of 2000. In Devils Hole and Devils Hole Well, water levels were affected by the Landers/Little Skull Mountain earthquakes for more than a year (figs. 12*B* and 12*C*). Water levels in Devils Hole abruptly dropped following the June 1992 earthquakes, then rose above pre-earthquake levels through June 1993, and finally returned to normal in 1994.

Alkali Flat–Furnace Creek Ranch Ground-Water Subbasin

Thirty monitoring sites are within the AFFCR ground-water subbasin (fig. 1*B*). Trends in water levels and spring discharge from three hydrographic areas—Jackass Flats, Amargosa Desert, and Death Valley—are discussed. Water levels in Jackass Flats were relatively stable from 1992 to 2000 (fig. 17), showing either no statistically significant trends or small rising trends. In the Amargosa Desert, water levels declined from about 3 to more than 15 ft in the Amargosa Farms area from 1992 to 2000. Three wells in the southern part of Amargosa Desert (sites AD-11, AD-13, and AD-14) showed relatively large rising trends. In the Death Valley hydrographic area, water levels and spring discharge at several sites declined from 1992 to 2000. Anomalous or site-specific water-level or discharge trends are discussed in appendix B for the following sites: CF-1 (GEXA Well 4), CF-1a (GEXA Well 3), CF-2 (USW VH-1), CF-3, RV-1 (TW-5), AD-2a (NDOT Well), AD-11 (GS-3 Well), AD-12 (GS-1 Well), AD-13 (S-1 Well), AM-3, and DV-1 (Texas Spring). Water-level trends for sites adjacent to Yucca Mountain (CF-2, JF-1, JF-2, JF-2a, J-11, J-12, and J-13) were previously analyzed for the period 1985–95 by Graves and others (1997).

Jackass Flats

Water levels in six wells adjacent to Fortymile Wash were monitored. Five of these wells—JF-1 (UE-25 WT #15), JF-2 (UE-25 WT #13), J-13, J-12, and JF-3—line up in an approximately north-south direction adjacent to Fortymile Wash (fig. 1*B*) and are open to volcanic rocks. The sixth well, JF-2a (UE-25 p #1), is about 1.5 mi west of site JF-2 and is open to the Paleozoic carbonate-rock aquifer. Correlation of hydrostratigraphic units penetrated by these wells is shown in figure 21 (section *B–B′* in fig. 1*B*). The upper unsaturated units consist of valley-fill deposits, undifferentiated Tertiary volcanic rocks (mostly the Tiva Canyon Tuff), and the top of the Topopah Spring Tuff. The Topopah Spring Tuff has a saturated thickness of about 400–600 ft in the area and is the principal source of water to wells J-12 and J-13 (Plume and La Camera, 1996, p. 11; Thordarson, 1983, p. 27). Wells JF-1, JF-2, and JF-3 are used as observation wells to monitor pumping from water-supply wells J-12 and J-13. Below the Topopah Spring Tuff are more than 2,000 ft of Tertiary volcanic rocks that are primarily ash-flow tuffs and are predominately zeolitized. These volcanic rocks separate the Topopah Spring Tuff aquifer from the Paleozoic carbonate-rock aquifer and, as a group, probably function as a confining unit because of their generally low vertical hydraulic conductivities (Thordarson, 1983, p. 23–24; Craig and Robison, 1984, p. 30–32). The water level in well JF-2a is about 80 ft higher than shallower wells completed in volcanic rocks, indicating an upward ground-water gradient from the carbonate-rock aquifer to the Topopah Spring Tuff; however, upward flux of ground water probably is small (Craig and Robison, 1984, p. 53).

Smooths of water-level altitudes for the six wells near Fortymile Wash were compared to estimated annual ground-water withdrawals from Jackass Flats, and to a smooth of cumulative departure from mean annual precipitation in the Pahute Mesa area from 1983

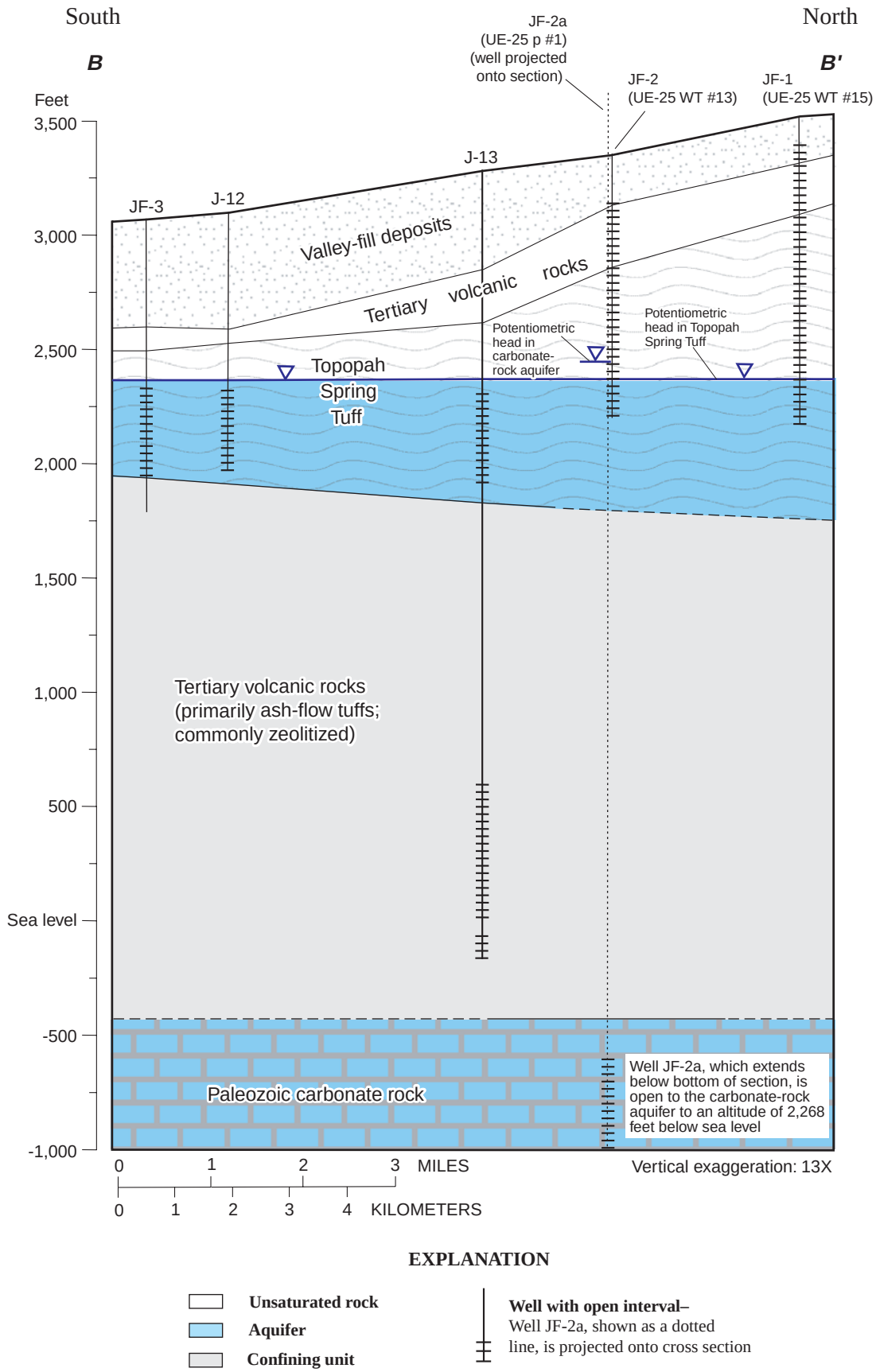


Figure 21. Hydrogeologic section along Fortymile Wash in Jackass Flats. Line of section is shown in figure 1*B*.

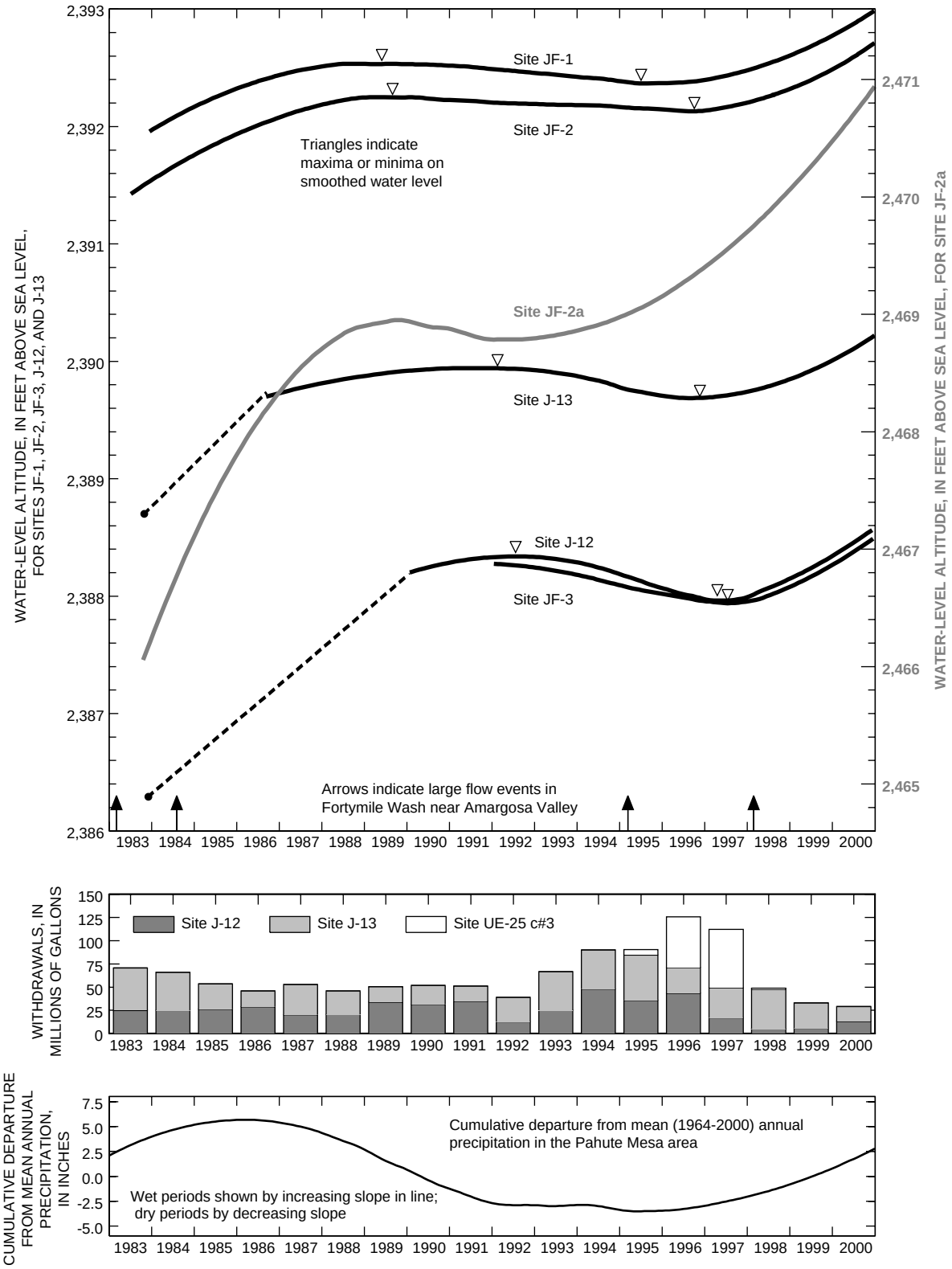


Figure 22. Relation among cumulative departure from mean annual precipitation on Pahute Mesa area, annual pumpage in Jackass Flats, and smoothed periodic or monthly mean water levels in six wells along Fortymile Wash, 1983–2000.

through 2000 (fig. 22). Smooths of the water-level altitudes were created using monthly periodic measurements or monthly mean water levels when continual data were available. When more than one periodic measurement was available for a particular month, a representative measurement near the middle of the month was used. No water levels in wells J-12 and J-13 that may have been affected by pumping or recent pumping of these wells were used for the smooths in figure 22. Ground-water withdrawals in Jackass Flats from 1983 to 2000 consisted primarily of pumpage from water-supply wells J-12 and J-13 and test well UE-25c #3 (about 2.5 mi northwest of well J-13; fig. 1*A*). Test well UE-25c #3, open to volcanic rocks underlying the Topopah Spring Tuff, was pumped for extended aquifer tests primarily from 1995 through 1997 (Geldon and others, 1997; 1998).

Comparison of trends in water levels from 1983 to 2000 for the six wells near Fortymile Wash show good correlations among all wells (fig. 22). Spearman rank correlations of water levels between each combination of well pairs from 1992 to 2000 were computed. Highly significant correlations ($p < 0.001$; Spearman's rho from 0.40 to 0.72) were determined for all pairings except the correlations of well JF-2a (in the carbonate-rock aquifer) with wells JF-3, J-12, and J-13. For these three pairs, correlations were less significant ($p < 0.015$) and less strong (Spearman's rho from 0.30 to 0.31). From 1992 to 2000, water levels in wells JF-1, JF-2, and JF-2a had statistically significant upward trends, whereas water levels in wells J-12, J-13, and JF-3 showed no statistically significant upward or downward trends (table 6; fig. 17). The maximum change in the smoothed water level from 1992 to 2000 for wells completed in volcanic-rock aquifers (JF-1, JF-2, JF-3, J-12, and J-13) ranged from 0.5 to 0.9 ft (table 6). For well JF-2a, completed in the carbonate-rock aquifer, the water level rose 2.2 ft from 1992 to 2000, based on the maximum change in the smoothed water level (table 6).

The similarity between water-level fluctuations in the wells near Fortymile Wash (fig. 22) suggests a common mechanism controlling water levels in the area. The likely controls on the system are recharge and pumping in Jackass Flats. Upon preliminary examination, a reasonable case can be made for pumping as the primary cause for the gentle rises and declines in water levels. For example, water levels generally rose from 1983 to about 1990 and pumping generally decreased over this period. Water levels declined from about 1991 to the mid-1990's while in the same period, pumping increased. Finally, from the mid-1990's through 2000, water levels once again rose, while in the same period, pumping decreased (fig. 22).

Despite the apparent relation between water levels and pumping, another, perhaps more likely explanation for the long-term gentle fluctuations in water levels is recharge from precipitation. Trends in water levels and cumulative departure from mean precipitation for the Pahute Mesa area are similar (fig. 22). Wetter periods correspond to rising water levels and drier periods correspond to declining water levels.

Several lines of evidence support precipitation as the dominant mechanism controlling water levels. First, changes in water levels lag the changes in the cumulative departure from mean precipitation curve by about 3–5 years (fig. 22). A lag is expected from the time when precipitation falls until it can infiltrate the unsaturated zone, become recharge, and affect downgradient water levels. Second, the trend in well JF-2a, in the carbonate-rock aquifer, is similar to trends in water levels in the volcanic-rock aquifer. Because these systems are poorly connected, pumping in the shallow volcanic-rock aquifer is expected to have little or no effect on water levels in the carbonate-rock aquifer. Considering the relatively short pumping history, it would be unlikely for water-level changes in well JF-2a to be two to four times greater than the changes in the pumping wells. Third, comparing the maximum water level in each well between 1989 and 1992 (fig. 22) and the minimum level in each well for the mid-1990's indicates that the peak or the trough in trend begins at the upgradient well (JF-1) first and moves southward to the downgradient well (JF-3).

For example, the maximum water level for the first rising trend was reached in well JF-1 in early 1989, whereas the water level in well J-12 peaked in mid-1992. (Well JF-3 did not have a sufficient record to show the peak of the first rising trend.) Likewise, the minimum water level for the declining trend in the 1990's was reached in well JF-1 in mid-1995 and in well JF-3 in mid-1997. This indicates a 2–3 year lag for the effect of rising water levels near well JF-1 to reach the downgradient well JF-3, which also suggests that the source for the change comes from an upgradient location. Because recharge for Jackass Flats is in the upland areas to the north (fig. 2), this is a likely source. If pumping were the primary cause of the trends in water levels, one would expect the maximum and

minimum points in the trend lines to begin near the pumping wells and progress outwards, both upgradient and downgradient.

Flow in Fortymile Canyon and Fortymile Wash has been shown to be an important mechanism for recharging the volcanic-rock aquifers in Jackass Flats and valley-fill aquifers farther south (Claassen, 1985; Savard, 1994; 1998). Estimates were made of long-term recharge from flow events, based on surface-water flow data from 1969 to 1995 (Savard, 1998, p. 24). Recharge estimates were about 7.4 Mgal/yr (28,100 m^3/yr) for sections of Fortymile Wash north of well JF-1 and about three times this volume of water for sections south of well JF-1, most of it south of the NTS. (In comparison, annual withdrawal rates from 1983 to 2000 for Jackass Flats were 62.5 Mgal/yr.) Water-level rises of more than 10 ft following a large flow event have been documented in wells screened in the upper part of the saturated zone in Fortymile Canyon, about 10 mi north of well JF-1 (Savard, 1998, p. 10–13). Water-table depths in this area are relatively shallow (50 to 90 ft below land surface). Water levels in the wells in Fortymile Canyon peaked within several weeks of the flow event and took a year or more to decline. No direct evidence was recorded of rises in water levels after a large flow event (greater than 100 ft^3/s near Amargosa Valley; fig. 22) at the six sites near Fortymile Wash, where depths to water are relatively deep (700–1,200 ft). Although large flow events typically correspond with rising water levels in these six wells, it is difficult to separate the effect of direct but long-term increases in recharge through Fortymile Wash from more regional recharge that infiltrates into the highlands north of Jackass Flats.

Continual water-level data in well JF-3 show no noticeable effects from pumping in Jackass Flats. Well JF-3 was drilled as a monitoring well to provide an early indication of possible water-level declines resulting from pumping in wells J-12 and J-13 (Plume and La Camera, 1996, p. 2). Data scatter in well JF-3 for any single year from the effects of barometric pressure (uncorrected hourly water level in fig. 23) is greater than the maximum change in water level from 1992 to 2000 (smooth of corrected water level in fig. 23). Water levels uncorrected for barometric pressure typically are highest in spring and lowest in early winter (uncorrected hourly water level in fig. 23). When the instantaneous effects of barometric pressure are removed from the water levels, the data scatter decreases and the seasonal trend shows water levels peaking in early winter and at their lowest in early summer (smooth of corrected water level in fig. 23). This seasonal trend probably is caused by a lagged response to barometric pressure that was not removed during the barometric correction (fig. 18). Pumping in Jackass Flats, which is generally lowest in early winter and highest in the summer (fig. 23), probably would cause a similar seasonal trend. However, any effects on water levels in well JF-3 from pumping probably are minimal (less than 0.1 ft/yr) and are masked by the seasonal effects of the lagged response to barometric pressure. A hydraulic connection between wells J-12 and J-13 was demonstrated in a pumping test in 1964 (Thordarson, 1983, p. 50), but a 1-day pumping test in 1992 showed no connection between wells JF-3 and J-12 (Plume and La Camera, 1996, p. 15–17). However, the apparent lack of a connection between wells JF-3 and J-12 in 1992 may result from the relatively short duration of the test.

A smooth of water levels in well JF-3, corrected for the instantaneous effects of barometric pressure, was compared to smooths of barometric pressure at well JF-3 and daily mean withdrawals from wells J-12 and J-13 for 2000 (fig. 24). Daily mean withdrawals were computed from hourly withdrawal data collected with data loggers connected to the water-use meters on these wells. No apparent correlation appears between water level in well JF-3 and withdrawals from well J-12, well J-13, or the combined withdrawals from these two wells. Almost all of the cyclic fluctuations in well JF-3 that occur several times per month and have an amplitude of about 0.05 to 0.1 ft can be explained by a lagged response to barometric pressure that was not removed during the barometric correction. Any possible short-term changes in water level in well JF-3 from pumping are masked by the effects of barometric pressure.

Amargosa Desert

The Amargosa Farms area (referred to as “the Farms area”) is a major pumping center in the Yucca Mountain region (figs. 11 and 17). Water levels in some parts of the Farms area have been declining since the mid- to late 1950’s, about the same time as large-scale pumping began in the area (Walker and Eakin, 1963, p. 17 and 37). Ground-water conditions in the Farms area through the mid-1980’s are discussed in Nichols and Akers (1985) and Kilroy (1991). In general, water

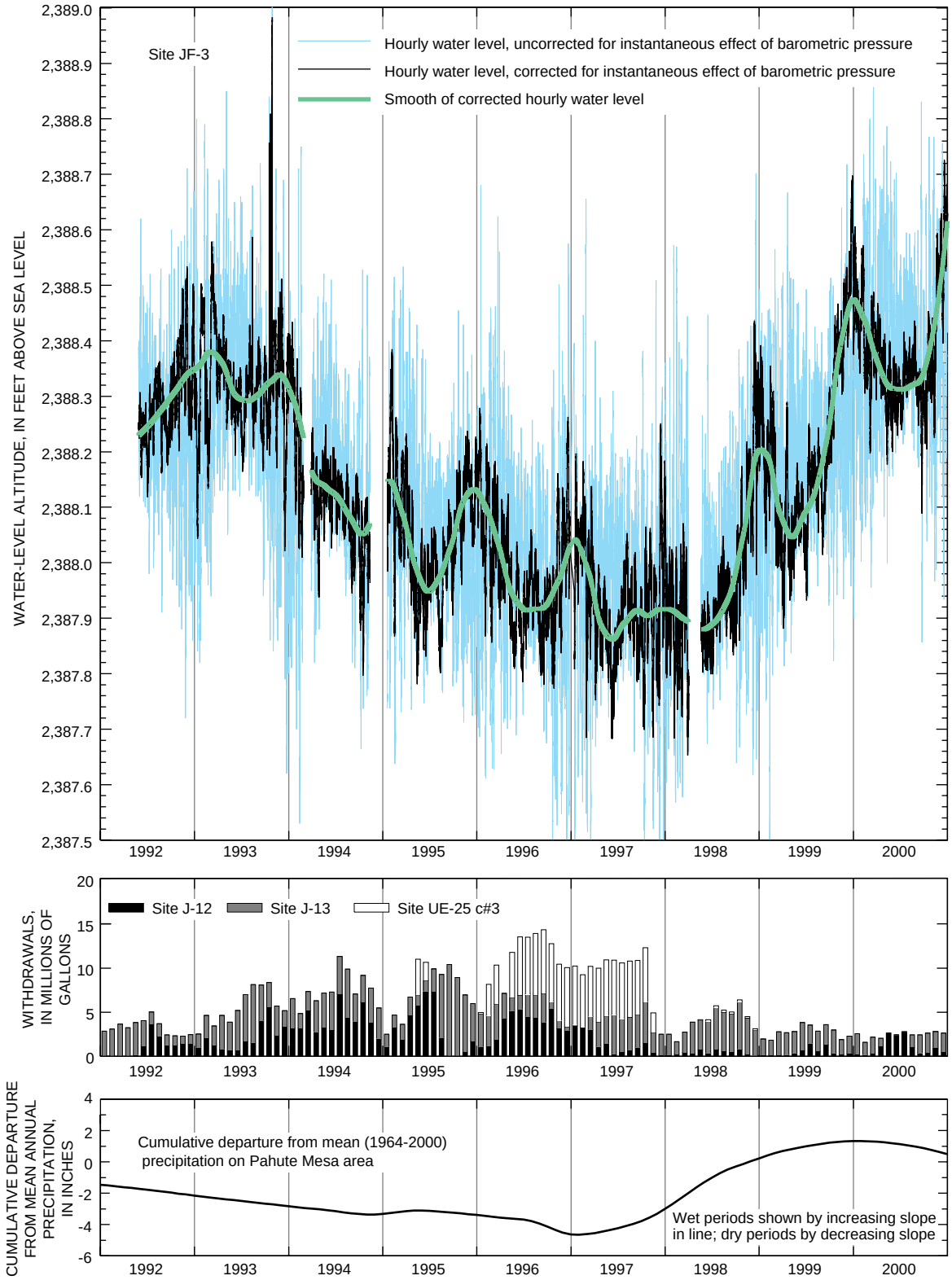


Figure 23. Relation among cumulative departure from mean annual precipitation on Pahute Mesa area, monthly pumpage in Jackass Flats, and hourly water levels in well JF-3 uncorrected and corrected for instantaneous effects of barometric pressure, 1992–2000.

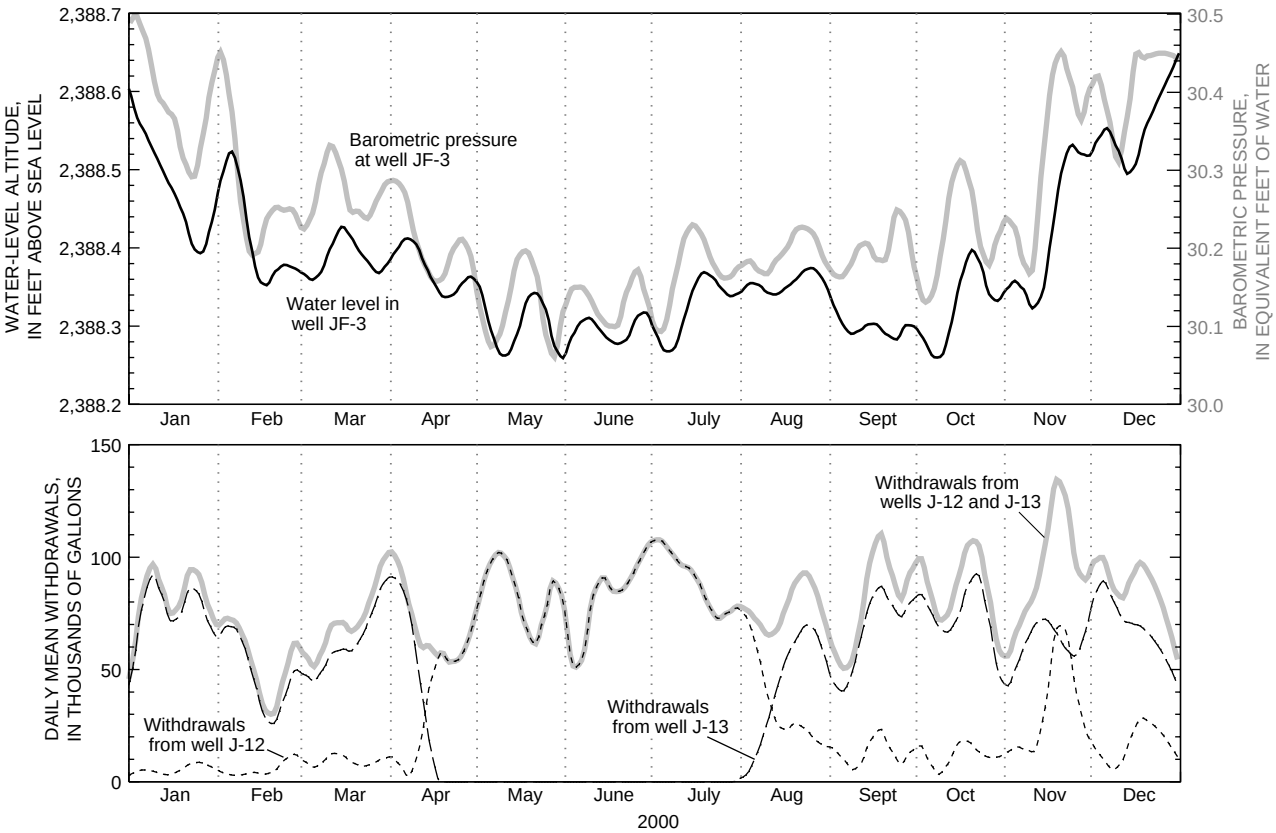


Figure 24. Relation between smooth of daily mean water levels in well JF-3 corrected for instantaneous effects of barometric pressure, barometric pressure at well JF-3, and smooths of daily mean pumpage from wells J-12 and J-13, 2000.

levels declined 10–30 ft in about a 100-mi^2 area around the Farms area from the 1950's to 1987 (Kilroy, 1991, p. 14).

Figure 25 shows water-level declines in the Farms area from 1964 to 2000. Wells are plotted by water-level altitude, with the higher altitudes (at the top of the plot) in the northern part of the Farms area and the lower altitudes in the southern part. Water levels in most wells in figure 25 were declining by 1975 and show declines from 1964 to 2000 of about 10–30 ft. Water-level declines accelerated in the early 1990's as pumping rates more than doubled from 2,160 Mgal/yr for the period 1985–92 to 4,450 Mgal/yr for the period 1993–2000 (fig. 25). Water levels from all wells in the primary monitoring network within the Farms area with data from 1992 to 2000 had statistically significant downward trends (table 6; figs. 14*E*, 14*G*, 14*I*, 14*J*, and 14*K*). Because of the large influence of pumping on water levels in observation wells in the Farms area, water-level changes caused by factors other than pumping are masked.

Walker and Eakin (1963) estimated that perennial yield, which they defined as the maximum amount of water that can be withdrawn from a ground-water system without causing a permanent loss in storage or a change in water quality, is 24,000 acre-ft/yr (7,800 Mgal/yr) for Amargosa Desert. Of this total, about 17,000 acre-ft/yr (5,500 Mgal/yr) discharges from springs in Ash Meadows (Winograd and Thordarson, 1975). The remaining amount, about 7,000 acre-ft/yr (2,300 Mgal/yr), theoretically can be withdrawn without affecting water levels in the Amargosa Desert. Withdrawals in 2000, at a rate of about 13,000 acre-ft/yr (4,100 Mgal/yr), are almost twice the available perennial-yield amount. More than 99 percent of these withdrawals are from the AFFCR ground-water subbasin. Continued high rates of pumping in the AFFCR subbasin will cause water levels to decline until the subbasin captures additional natural discharge or recharge.

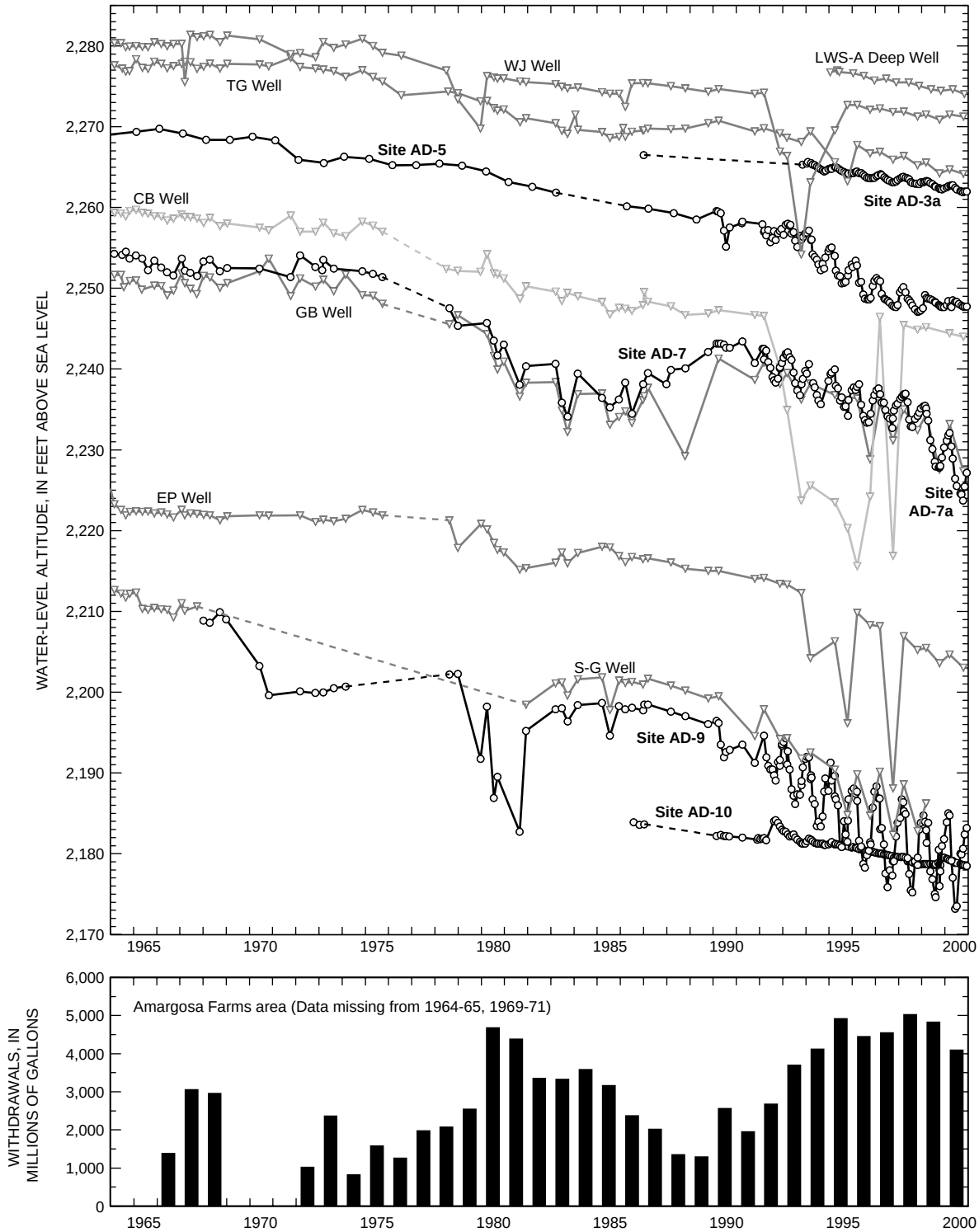


Figure 25. Relation between water levels in selected wells and estimated annual ground-water withdrawals in the Amargosa Farms area, 1964–2000. Network wells in bold.

Water levels in some wells several miles from the Farms area (fig. 17) probably are affected by pumping in the Farms area. Site AD-1 (NA-6 Well or BGMW-10) had a statistically significant water-level decline of about 0.2 ft from 1992 to 2000 (table 6; fig. 14*C*). Withdrawals from the Farms area are more likely the primary cause of water-level declines at site AD-1 rather than pumping from an area south of Beatty. The distance from the Farms area to site AD-1 is shorter (9 mi to the Farms area compared to about 11 mi to the area near Beatty) and withdrawals from the Farms area are greater (3,700 Mgal/yr compared to 500 Mgal/yr for 1992–2000; fig. 17). Site AD-2 (Airport Well), about 8 mi to the northeast of the Farms area, had a statistically significant water-level decline of about 1 ft from 1992 to 2000 (fig. 14*D*). Site AD-2 supplies a relatively small quantity of water for domestic use that is not likely the cause of the long-term water-level declines in this well. Site AD-4a, about 6 mi east of the main pumping wells in the northern part of the Farms area, had a statistically significant downward water-level trend. The maximum change in the smoothed water level was about 4.5 ft from 1992 to 2000. However, because part of this change is the result of upward adjustments by earthquakes that steepen the smooth line, the net change from the beginning of 1992 to the end of 2000 was approximately 2 ft (fig. 14*F*). Water levels at site DV-3 (Travertine Point 1 Well) and discharge at site DV-2 (Navel Spring), about 11–14 mi southwest of the Farms area, had statistically significant downward trends (figs. 14*N* and 14*O*) that possibly are attributable to withdrawals in the Farms area (see “Death Valley” section).

Sites AD-11 (GS-3 Well), AD-13 (S-1 Well), and AD-14 (Death Valley Jct Well), in the southern part of the AFFCR ground-water subbasin, have statistically significant rising water-level trends from 1992 to 2000 (figs. 13*I*, 13*J*, and 13*K*). Rising trends may have been caused by increased regional recharge in the Spring Mountains from 1992 to 2000 (fig. 6) or anomalous or local conditions (such as well-construction effects) near some or all of the well sites. Increased regional recharge along separate flow paths could explain why water levels rose in the southern part of the AFFCR subbasin while declining during the same period in the Farms area to the north. Two flow paths are possible for movement of increased recharge in the southern part of the subbasin: one path is along the southern end of the Ash Meadows and AFFCR ground-water subbasins from recharge areas in the northwest Spring Mountains to discharge areas in Alkali Flat and Death Valley (fig. 2), and a second flow path is from Pahrump Valley through the clastic confining unit to southern Ash Meadows (Walker and Eakin, 1963, p. 21; Naff and others, 1974, p. 22–23; Winograd and Thordarson, 1975, p. 90–92). The plausibility of these flow paths may be supported by strontium isotope (^{87}Sr) concentrations in water from springs and wells in the southern part of the study area (Forester and others, 1999, p. 39, 53–55). Strontium isotope concentrations in water may become elevated through interaction with Precambrian siliciclastic rocks (Forester and others, 1999, p. 55), which are located in the northwestern Spring Mountains, and between Pahrump Valley and Ash Meadows.

Water-level fluctuations in monitoring wells at sites AD-11 and AD-13 in the AFFCR subbasin and site AD-12 in the Ash Meadows subbasin (figs. 29*M*, 29*O*, and 29*N*, respectively) are anomalously large compared to typical water-level fluctuations in the regional ground-water system throughout the Yucca Mountain region. The monitoring wells were installed by the USGS in 1986 by casing existing boreholes that had been drilled for mineral exploration. The primary monitoring well at each of the sites has a short (10 ft) open interval completed in valley-fill materials composed of finely laminated calcareous mudstones, which probably function as confining units. Further investigations are needed to determine if the anomalously large water-level changes at these three sites result from regional water-level changes, local aquifer conditions near the well site, slow equilibration from well construction, or poor well completion (see app. B for additional information on these wells).

Death Valley

Statistically significant downward trends for 1992–2000 were observed for water levels at sites AD-10 (NA-9 Well) and DV-3 (Travertine Point 1 Well) and for discharge from site DV-2 (Navel Spring) and Travertine Springs (tables 6 and 7). In addition, the pattern of fluctuations in water level and discharge are similar for these sites (fig. 26). The cause of these downward trends may be linked to earthquakes, withdrawals in the Amargosa Farms area, or both. The general hydrogeologic setting for these wells and springs is shown on the California side of cross section *A–A′* (fig. 3) from about the Amargosa River on the east to Travertine Springs on the west.

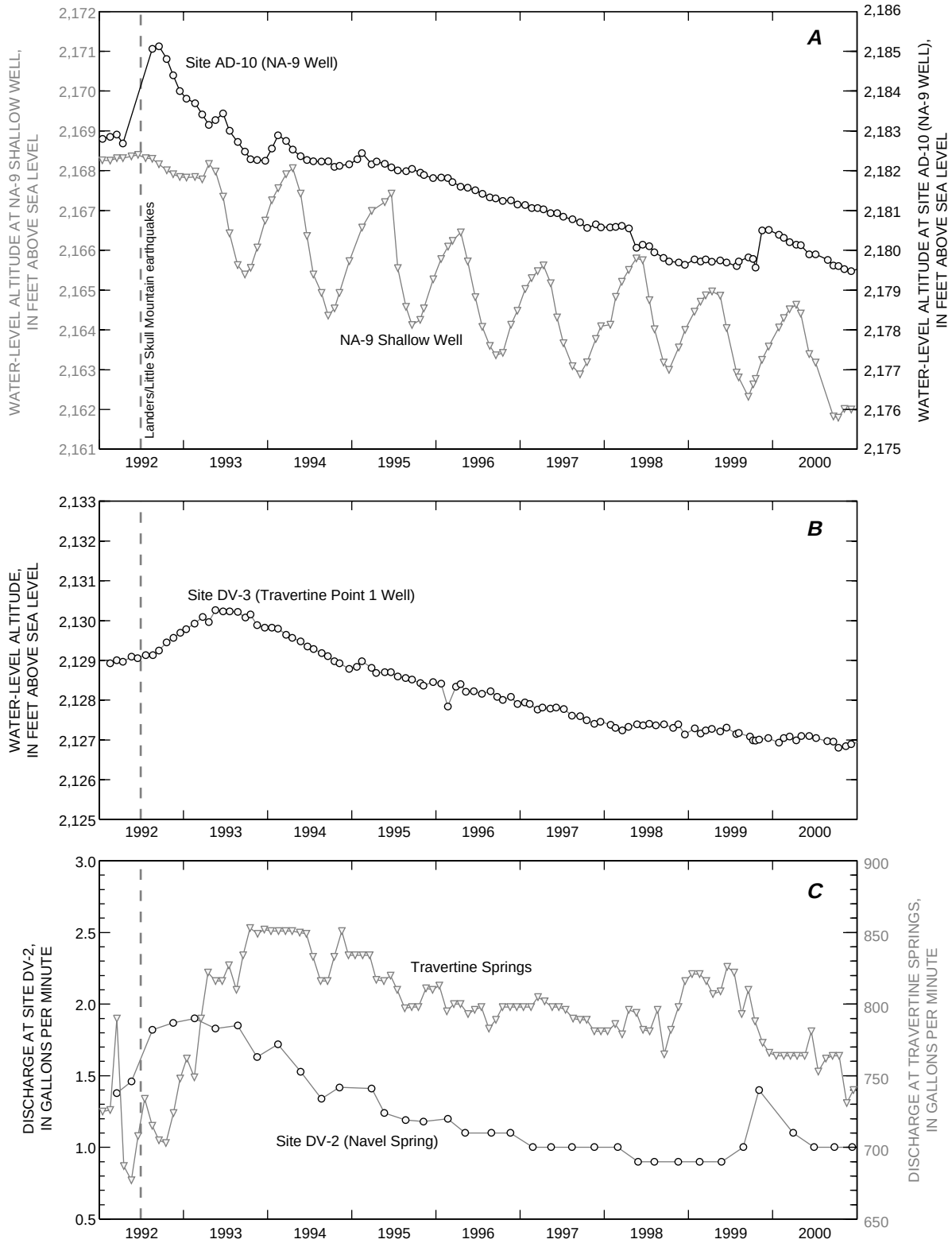


Figure 26. Relation among (A) water levels at site AD-10 (NA-9 Well) and NA-9 Shallow Well; (B) water levels at site DV-3 (Travertine Point 1 Well); and (C) discharges at site DV-2 (Navel Spring) and Travertine Springs, 1992–2000.

Water levels in NA-9 Well declined from 1992 to 2000 because of nearby pumping for irrigation in the Amargosa Farms area (fig. 26). Water levels in a shallow well (NA-9 Shallow Well), finished in the same borehole with NA-9 Well, fluctuated about 3 ft/yr beginning in 1993. The long-term rate of water-level decline is slightly greater in the shallow well (about 0.6 ft/yr) than in the deep well (about 0.4 ft/yr). The potential for water to flow upward is indicated by a 16-ft higher head in the deep well than in the shallow well. The cyclic water-level fluctuations in NA-9 Shallow Well and the long-term declines in both wells reflect seasonal pumping from the shallow aquifer in the Amargosa Farms area.

Water-level measurements for Travertine Point 1 Well from 1992 to 2000 show a similar decline to NA-9 Well but at a lesser rate (about 0.2 ft/yr). In addition, water-level fluctuations for this well have a lagged response to the Landers/Little Skull Mountain earthquakes in 1992, in contrast to the quick response time in NA-9 Well. Travertine Point 1 Well is completed within the Paleozoic carbonate-rock aquifer on the west side of the Funeral Mountains and NA-9 Well is completed in valley fill. Differences in rates of water-level decline and response time between these two wells may be related to well completion and distance from Amargosa Farms pumping.

Discharge measurements for Navel and Travertine Springs show declining trends that are similar to the water-level trend in Travertine Point 1 Well; that is, a short-term increase in discharge after the Landers/Little Skull Mountain earthquakes followed by a long-term decrease in discharge. Discharge from Navel Spring, which discharges about 1–2 gal/min from a shallow layer in the valley fill (Naff and others, 1974, p. 12), decreased about 0.5 gal/min from 1992 to 2000. However, discharge from Travertine Springs, which discharges water from the regional carbonate-rock aquifer through the valley fill, was greater in 2000 than in 1992 (fig. 26). Therefore, most of the decline in discharge at this spring may be long-term equilibration from the Landers/Little Skull Mountain earthquakes, which caused an overall increase in discharge from 1992 to 2000.

It is unclear if the decrease in discharge at Travertine Springs (and also Nevares Springs, fig. 12*K*) is caused, in part, by pumping from irrigation-supply wells in the Amargosa Farms area, about 17 mi to the northeast. Possibly, the regional carbonate-rock aquifer that supplies water to Travertine and Nevares Springs is part of a deep flow system that has little hydraulic connection to either the valley fill in the Farms area or the carbonate-rock aquifer in which Travertine Point 1 Well is completed. If a shallow flow system is present beneath western Amargosa Desert and the Funeral Mountains, as suggested in Czarnecki and Wilson (1989) and Czarnecki (1987), then water levels and discharge in Travertine Point 1 Well and Navel Spring might be affected by pumping in the Farms area while discharge from Travertine and Nevares Springs might remain unaffected.

SUMMARY

In April 1989, the USGS began a cooperative program with DOE to develop a ground-water-resources monitoring program in the Yucca Mountain region of southern Nevada and eastern California. The purposes of the monitoring program are to: (1) document the historical and current conditions of ground-water resources, (2) detect changes in the resources during investigations of Yucca Mountain, and (3) provide a basis for analyzing and identifying potential adverse effects on ground-water resources resulting from these investigations.

This report analyzes ground-water data collected or compiled as part of the cooperative USGS/DOE Environmental Monitoring Program for Yucca Mountain. Data collected for the monitoring program include water levels at 37 wells and a fissure (Devils Hole), and discharge at 5 springs and a flowing well. Total reported ground-water withdrawals within the study area (Crater Flat, Jackass Flats, Mercury Valley, and Amargosa Desert) and from the surrounding regional area (Las Vegas, Pahrump, NTS, Penoyer Valley and Pahranagat Valley) were compiled. Also compiled were precipitation data from major recharge areas in the Spring Mountains, Pahute Mesa area, and Pahranagat Valley area.

The principal emphasis in this report is to explain various trends in data collected or compiled as part of the Environmental Monitoring Program. The report provides a basis for comparing water levels and discharge between primary monitoring sites and determining how the data fit into a regional understanding of the ground-water flow system. Anomalous trends in water levels or discharge for individual wells or springs that do not appear to be caused by regional effects are identified and explained, if possible.

Water levels and spring discharge were analyzed for variability and for upward, downward, or cyclic trends with an emphasis on the period 1992–2000, a period in which water levels were measured monthly. Trends were analyzed statistically to detect significant upward or downward changes (using the Mann-Kendall trend test) and graphically to compare trends among sites. For many of the wells and springs with trends, an attempt was made to identify the cause. Potential causes of change in water levels and spring discharge include local and regional effects. Local effects include possible long-term equilibration from well construction, nearby diversions of surface water, and nearby ground-water pumping. Regional effects include ground-water pumping, recharge from precipitation, earthquakes, evapotranspiration, barometric pressure, and earth tides.

From 1992 to 2000, statistically significant upward trends were determined for 12 water-level sites and statistically significant downward trends were determined for 14 water-level sites and 1 spring-discharge site. No statistically significant upward or downward trend was observed at the remaining sites. In general, the magnitude of change in water levels from 1992 to 2000 was small (less than 2 ft), except where influenced by pumping or affected by local aquifer conditions near a well site.

Seasonal trends are superimposed on some of the long-term trends in water levels and spring discharge. Causes for seasonal trends include seasonal changes in barometric pressure, evapotranspiration, and pumping. The magnitude of seasonal change in water level can vary from as little as a 0.05 ft in regional aquifers to greater than 5 ft in monitoring wells near large supply wells in the Amargosa Farms area. Seasonal fluctuations in water levels (corrected for instantaneous effects of barometric pressure), ranging in magnitude from about 0.05 to 0.2 ft, were observed in several wells in the carbonate- or volcanic-rock aquifers. These small seasonal fluctuations are attributed to the effects of a lagged response to barometric pressure that was not removed during the barometric correction.

Evapotranspiration within the study area occurs primarily in discharge areas, where depths to ground water are shallow. The primary natural discharge areas in the study area are Ash Meadows, Alkali Flat, and Death Valley. Four wells in the network for this study had water levels that appeared to be responding to evapotranspiration—three in Ash Meadows and one near Death Valley Junction.

Three major episodes of earthquakes affected water levels in wells in the Yucca Mountain region between 1992 and 2000: the Landers/Little Skull Mountain, Northridge, and Hector Mine earthquakes. The Landers/Little Skull Mountain earthquakes had the greatest observed effect on water levels and discharge of any earthquake during the study period. Based on monthly measurements of wells in the study network, earthquakes affected water levels from a few tenths of a foot to 3.5 ft. Monthly water levels measured at 11 sites showed a response to earthquakes; water levels at 6 sites rose following an earthquake, water levels at 3 sites dropped, and at 2 sites, the water-level response was mixed. Increases in discharge following an earthquake were observed at two sites in the study network.

Fourteen sites from the primary monitoring network are located within the Ash Meadows ground-water subbasin, most are within the Ash Meadows NWR. Water levels remained relatively stable in the Ash Meadows subbasin from 1992 to 2000, with one well showing a rising trend and several declining slightly. Sites AD-6 (Tracer Well 3), AM-5 (Devils Hole Well), and AM-4 (Devils Hole) had similar water-level fluctuations from 1960 to 2000, which may be caused by regional changes in climate, ground-water withdrawals, or seismic events. Part of the change in water levels at Devils Hole and site AD-6 might be explained by changes in precipitation patterns; however, from 1960 to 2000, these sites have declined more than would be expected if precipitation were the dominant factor affecting water levels. Ground-water withdrawals from several regional sources, including Las Vegas Valley, Pahrump Valley, the Amargosa Farms area, and NTS, may account for long-term water-level declines in the Ash Meadows area. Withdrawals from Las Vegas Valley and Pahrump Valley have been considerable since the early 1900's, whereas large withdrawals from Amargosa Farms and NTS began in the mid-1950's to early 1960's. Additionally, incomplete recovery from local pumping in the Ash Meadows area that ended in 1982 may account for some of the long-term decline in water levels at Devils Hole and site AD-6.

Water levels in six wells adjacent to Fortymile Wash in Jackass Flats were monitored. Five of these wells are completed in volcanic rocks and one well is completed in the Paleozoic carbonate-rock aquifer. Ground water is withdrawn from Jackass Flats to support several DOE activities, including Yucca Mountain site characterization. From 1992 to 2000, water levels

in wells JF-1, JF-2, and JF-2a had statistically significant upward trends, whereas water levels in wells J-12, J-13, and JF-3 showed no statistically significant upward or downward trends. (Wells J-12 and J-13 are water-supply wells.) The maximum change in smoothed water level from 1992 to 2000 for wells in the volcanic-rock aquifers ranged from 0.5 to 0.9 ft, whereas for well JF-2a (the carbonate-rock well), the water level rose about 2.2 ft.

Comparison of trends in water levels from 1983 to 2000 for the six wells near Fortymile Wash show good correlations among all wells. The similarity between water-level fluctuations in these wells suggests a common mechanism controlling water levels in the area. The likely controls on the system are recharge from precipitation and pumping in Jackass Flats. Recharge appears to be the dominant factor affecting water levels near Fortymile Wash for the following reasons: First, wetter periods on Pahute Mesa (representing recharge areas upgradient of the well sites) correspond with rising water levels, whereas drier periods on Pahute Mesa correspond with declining water levels. Second, the trend in well JF-2a, in the carbonate-rock aquifer, is similar to trends in water levels in the volcanic-rock aquifer. Because these systems are poorly connected, recharge is more likely to cause water-level fluctuations in well JF-2a than is pumping from the shallow volcanic-rock aquifer. Third, a rising or declining water-level trend begins in the most upgradient well first (closer to the recharge source) and progresses downgradient. A 2- to 3-year lag time is necessary for the effect of rising water levels in the most upgradient well to reach the most downgradient well. This suggests that the source for the change comes from an upgradient location, where recharge occurs.

The largest area of consistent trends in the study area is in the Amargosa Farms area, where water levels declined from about 3 ft to more than 15 ft from 1992 to 2000 and 10–30 ft from 1964 to 2000. The Amargosa Farms area is the largest center of pumping in the study area and one of the major regional pumping centers. Water levels in some parts of the Amargosa Farms area have declined since the mid- to late 1950's, about the same time as large-scale pumping began in the area. Water-level declines accelerated in the early 1990's as pumping rates more than doubled. Pumping in the Amargosa Farms area may affect water levels in some wells as far away as 5 to 14 mi.

The water level at Travertine Point 1 Well and discharge at Navel Spring, both in the Death Valley hydrographic area, had statistically significant downward trends from 1992 to 2000. The cause of these downward trends may be linked to earthquakes, pumping in the Amargosa Farms area, or both.

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APPENDIX A: BASIC DATA PLOTS

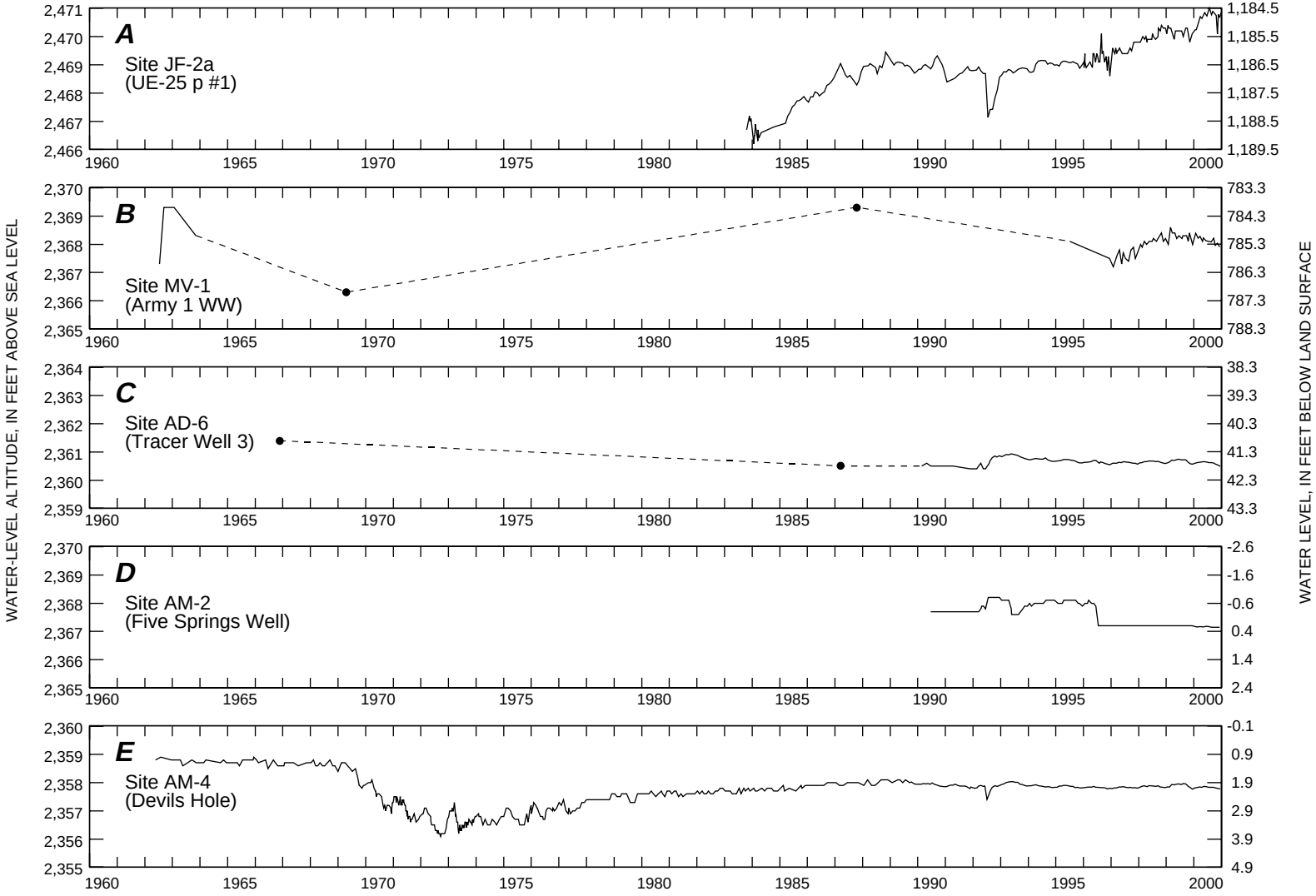
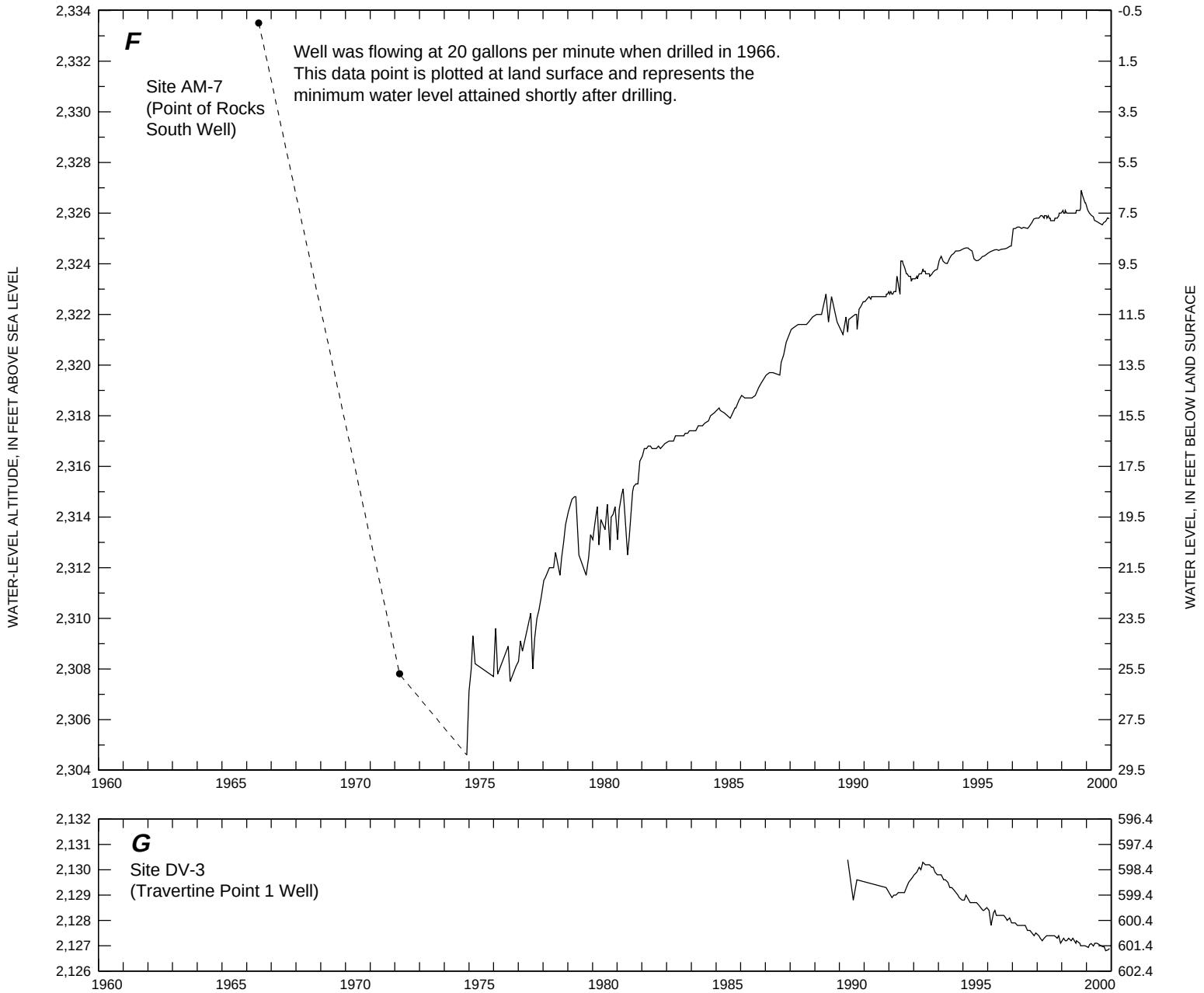


Figure 27. Water levels from 1960 to 2000 for selected sites at which primary contributing units are carbonate rock. Lines connect periodic data (or monthly mean data where continual data were available) and are dashed where measurements were not available for consecutive calendar years. Data that may represent short-term conditions at a site have been excluded (see section “Periodic Water-Level Data”).



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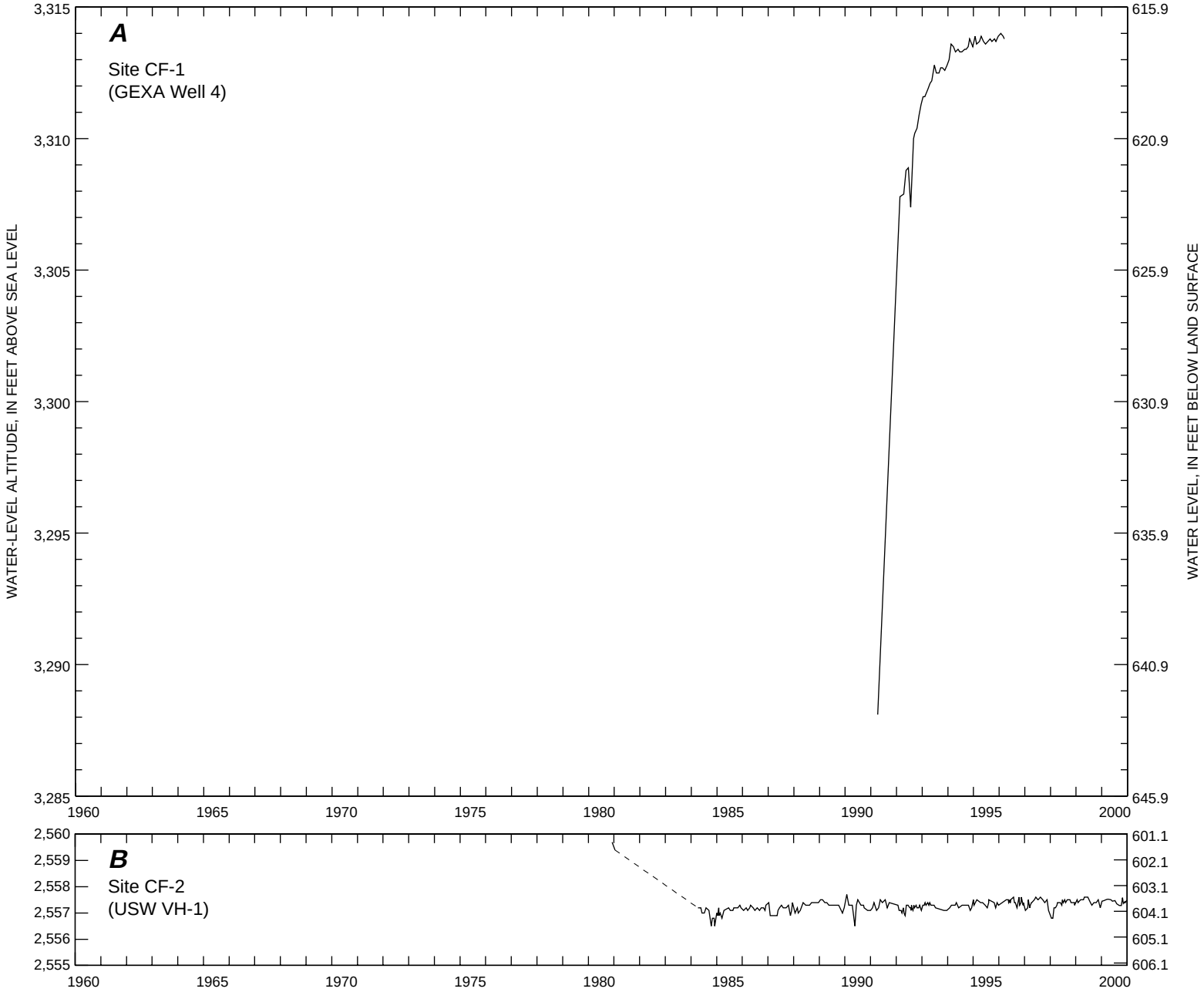
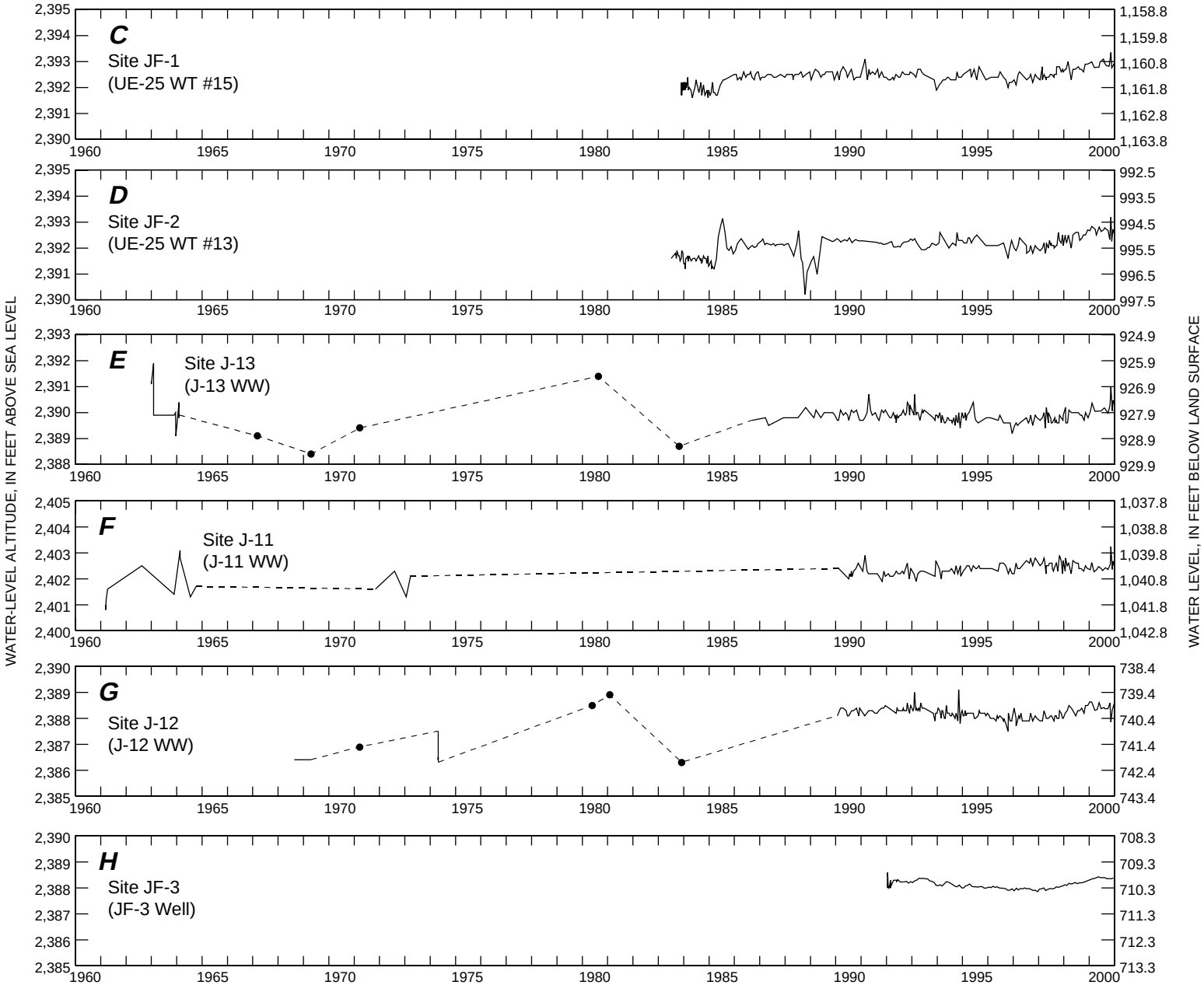


Figure 28. Water levels from 1960 to 2000 for selected sites at which primary contributing units are volcanic rock. Lines connect periodic data (or monthly mean data where continual data were available) and are dashed where measurements were not available for consecutive calendar years. Data that may represent short-term conditions at a site have been excluded (see section “Periodic Water-Level Data”).



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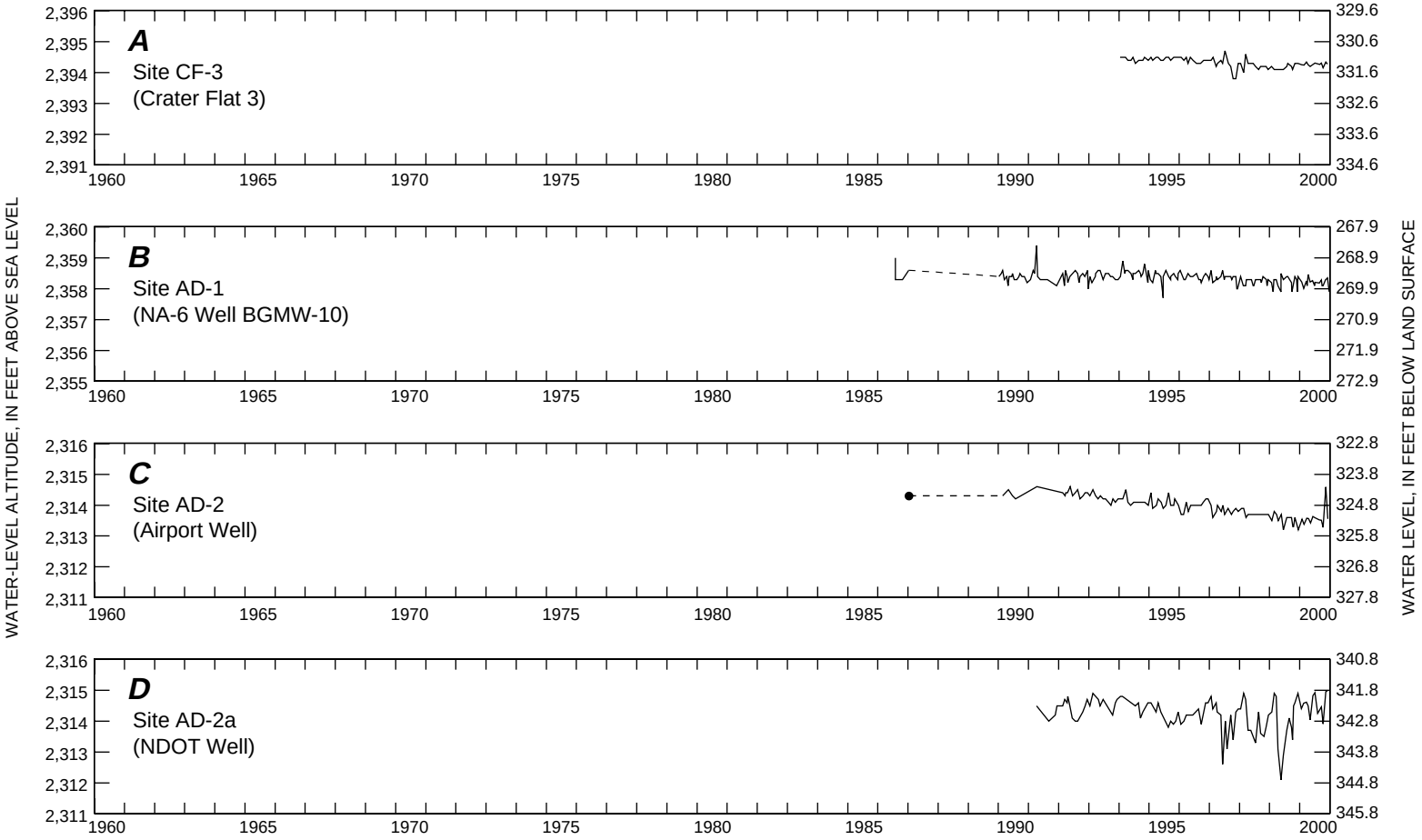
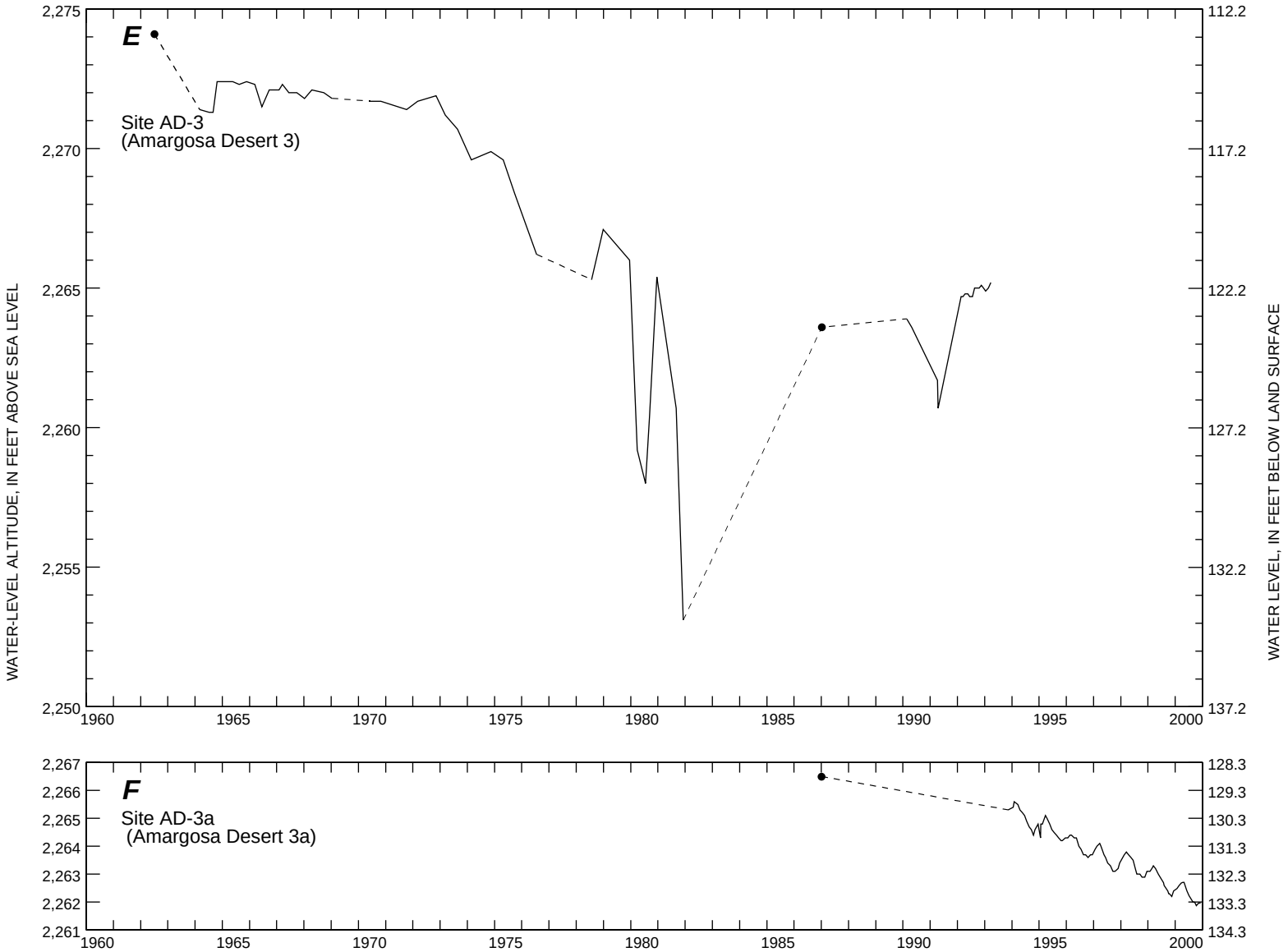


Figure 29. Water levels from 1960 to 2000 for selected sites at which primary contributing units are valley fill. Lines connect periodic data (or monthly mean data where continual data were available) and are dashed where measurements were not available for consecutive calendar years. Data that may represent short-term conditions at a site have been excluded (see section “Periodic Water-Level Data”).



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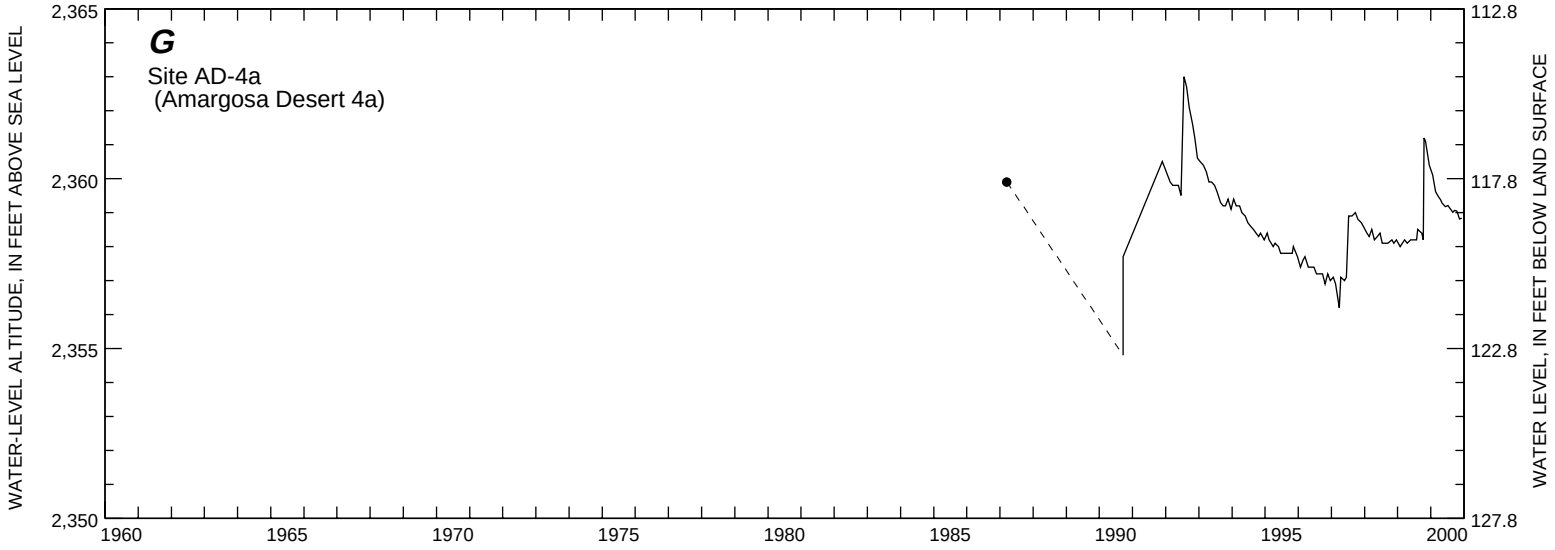

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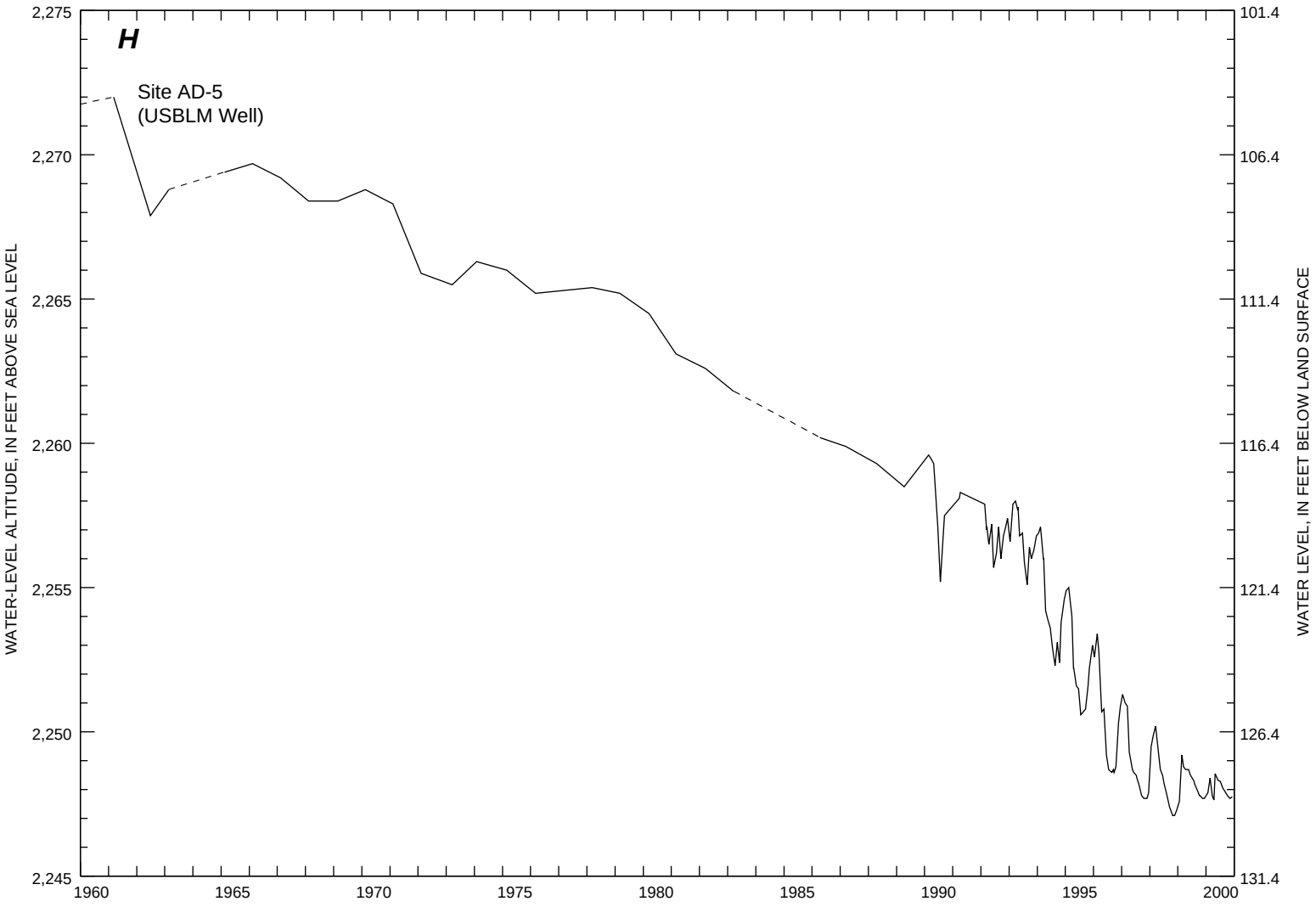

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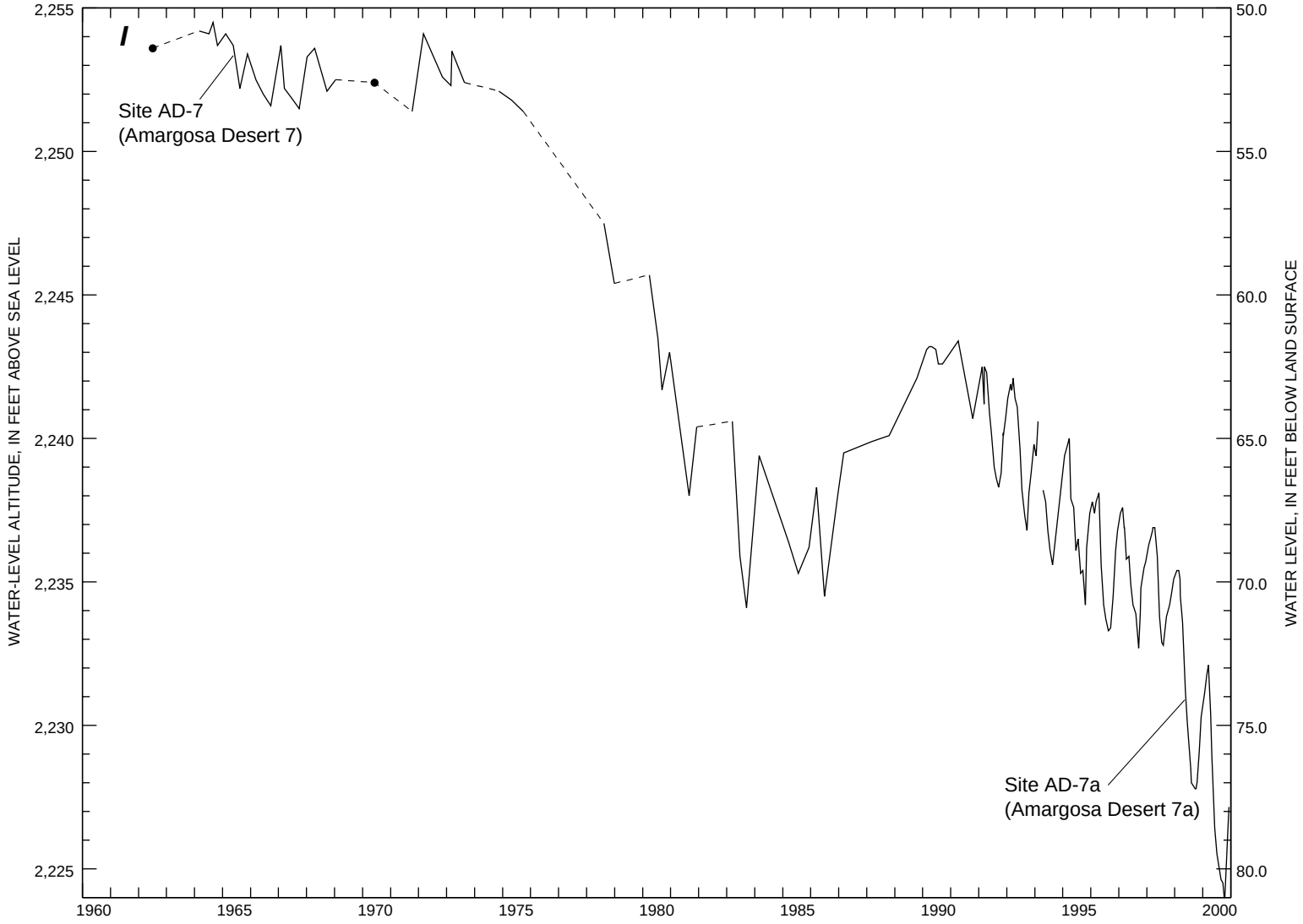

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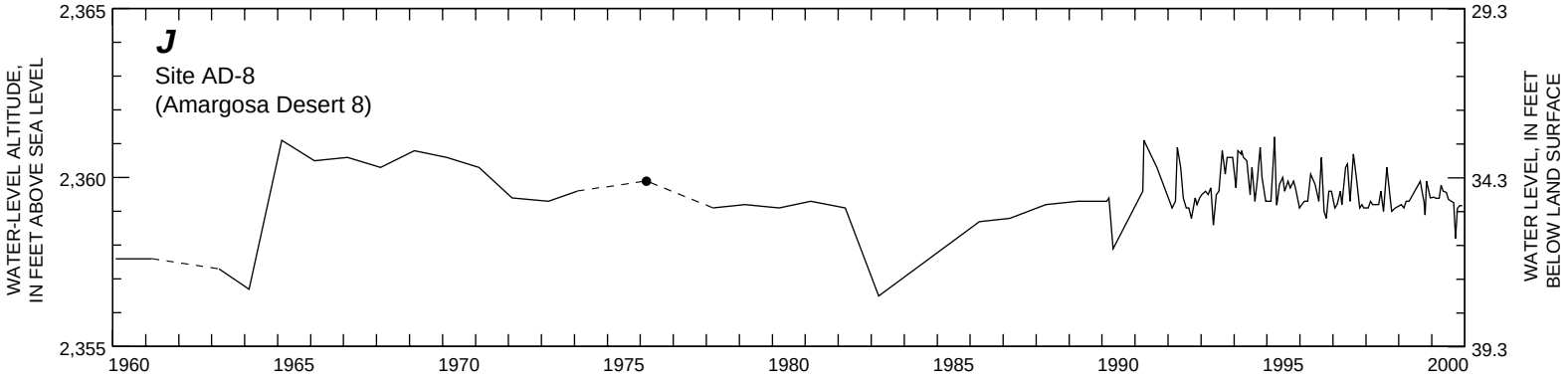

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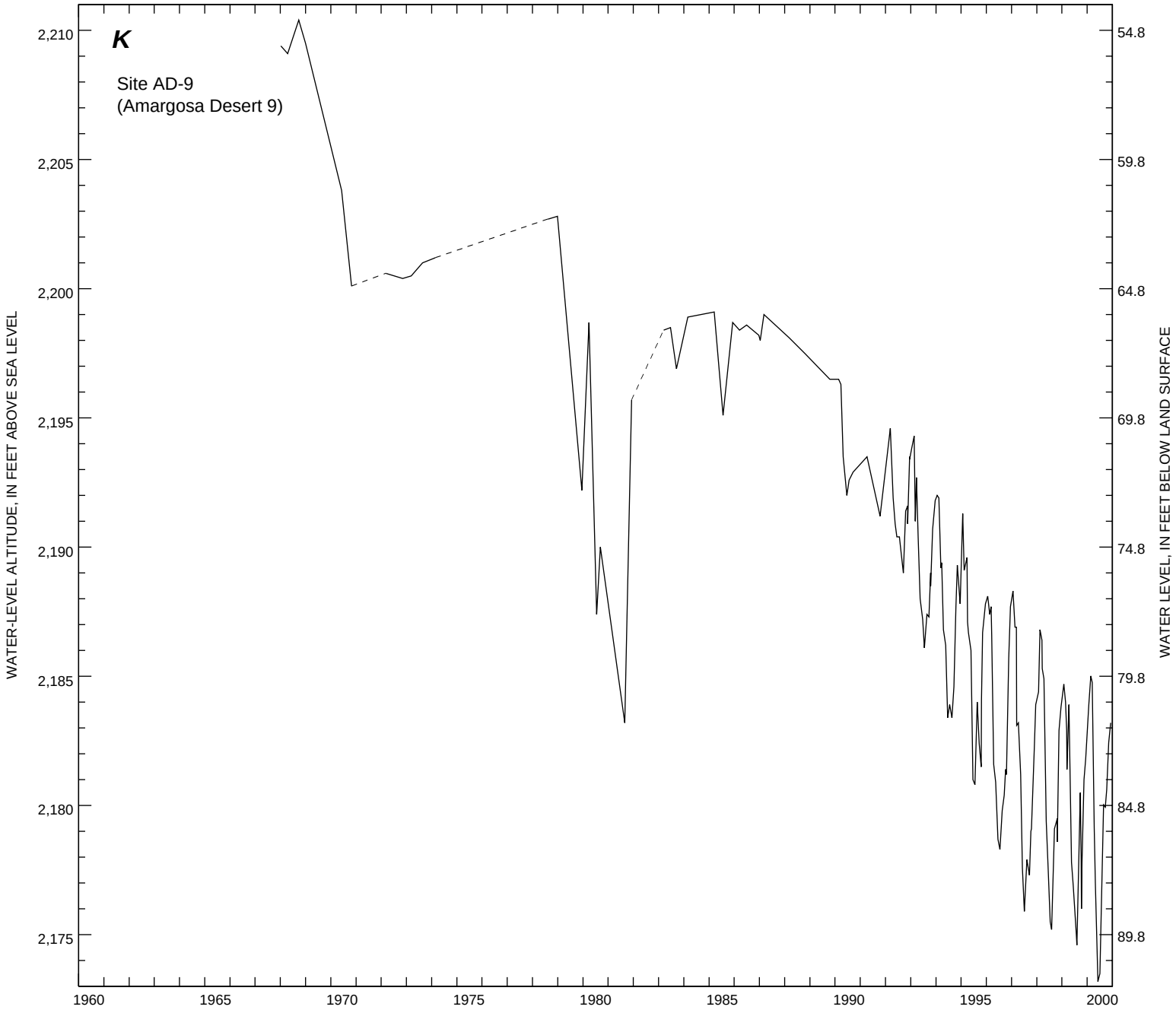

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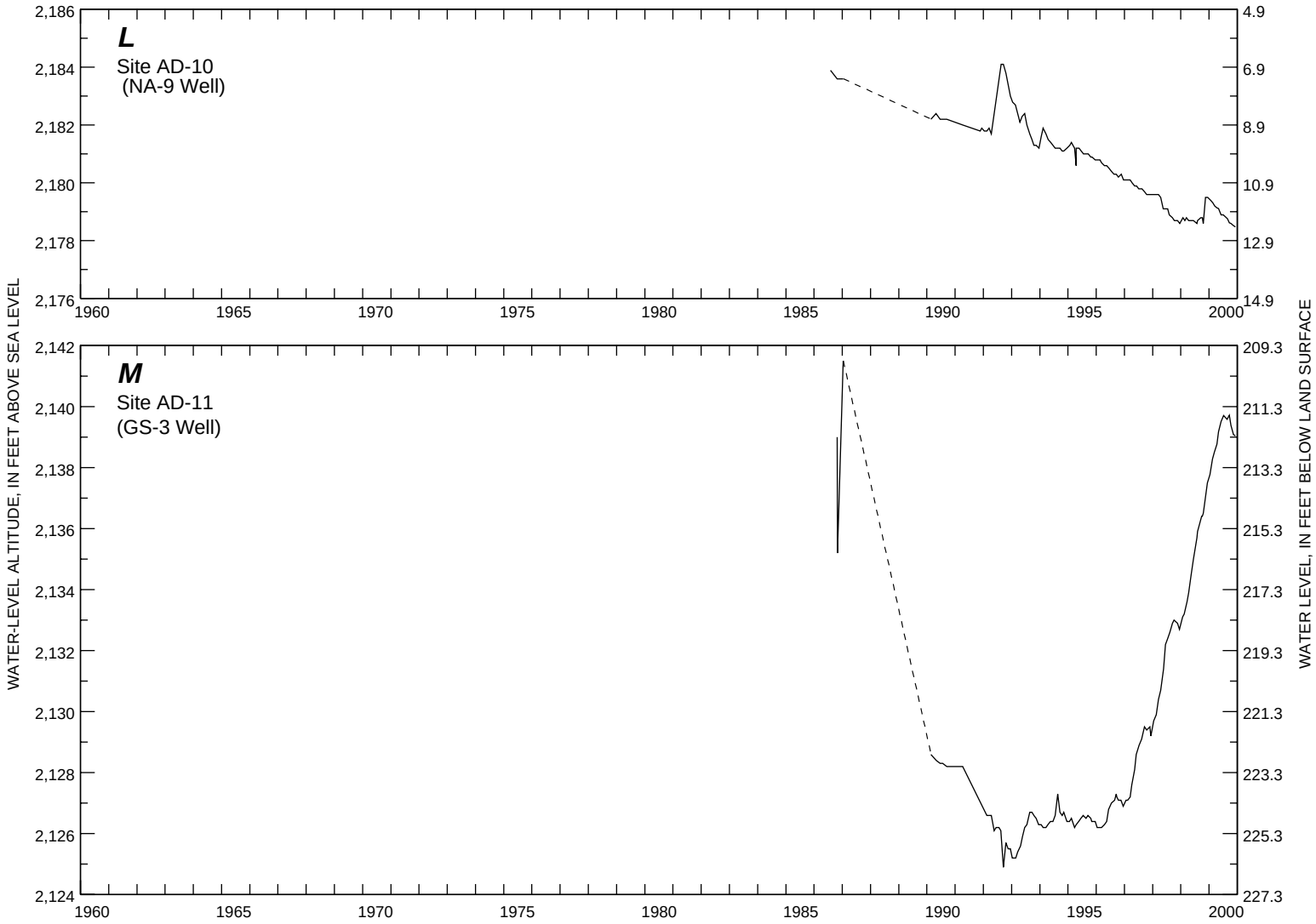

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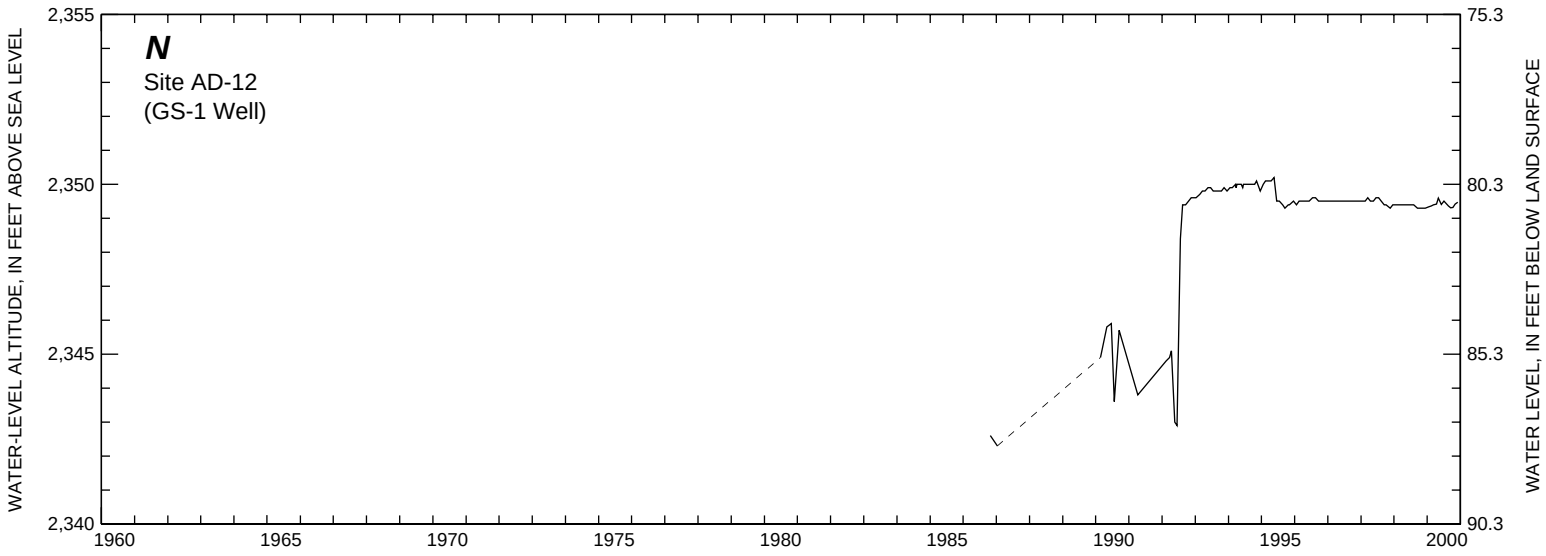

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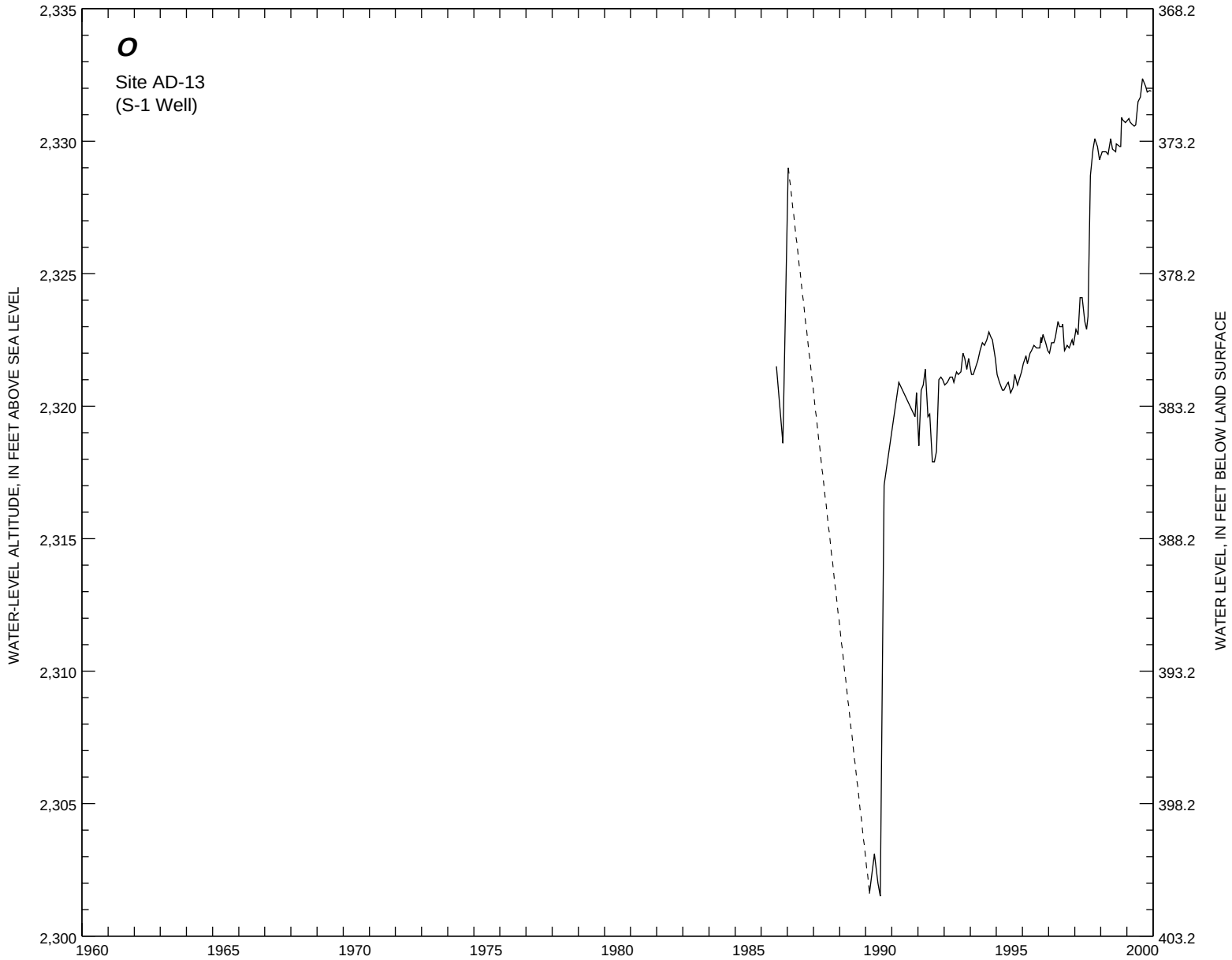

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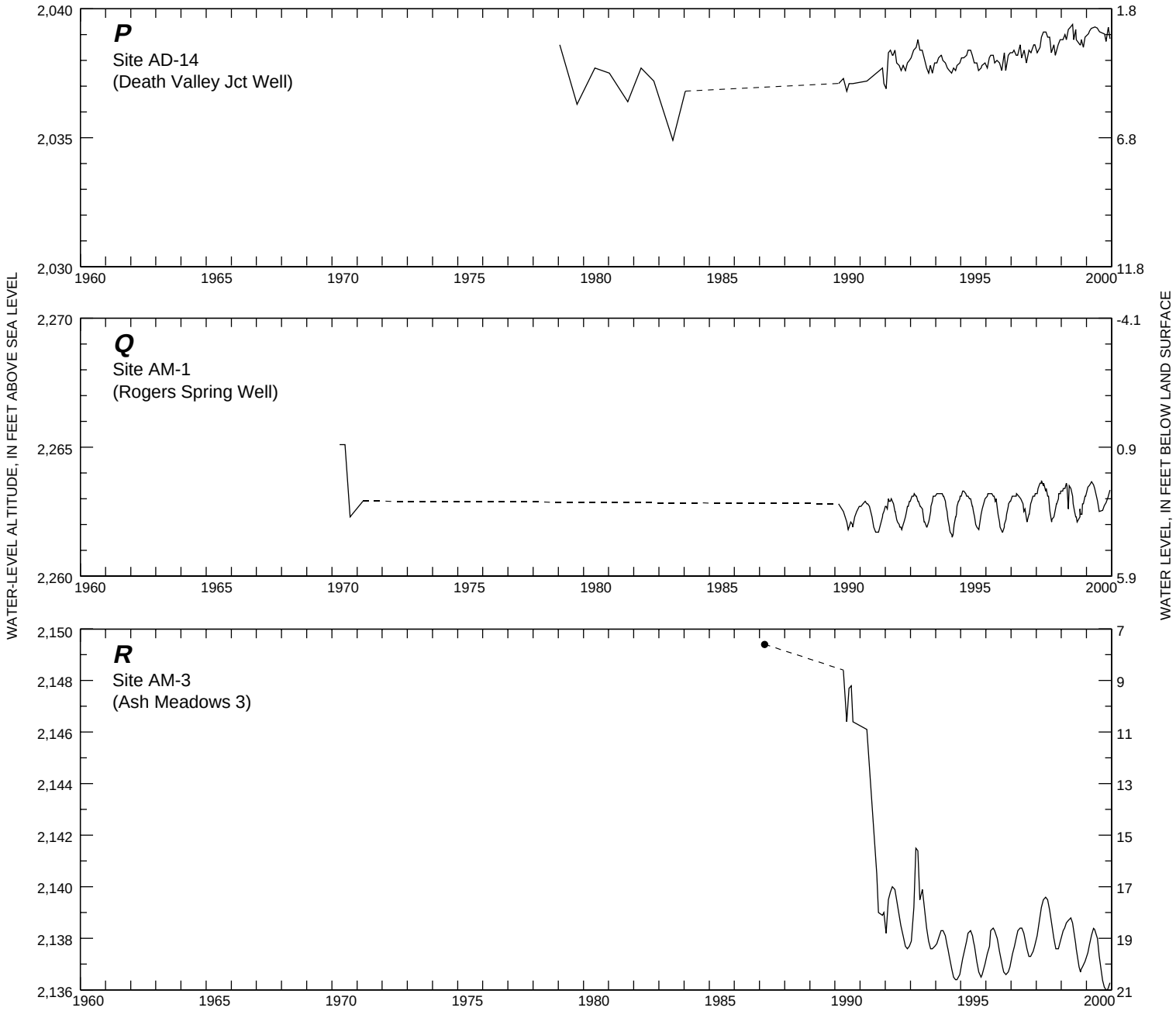

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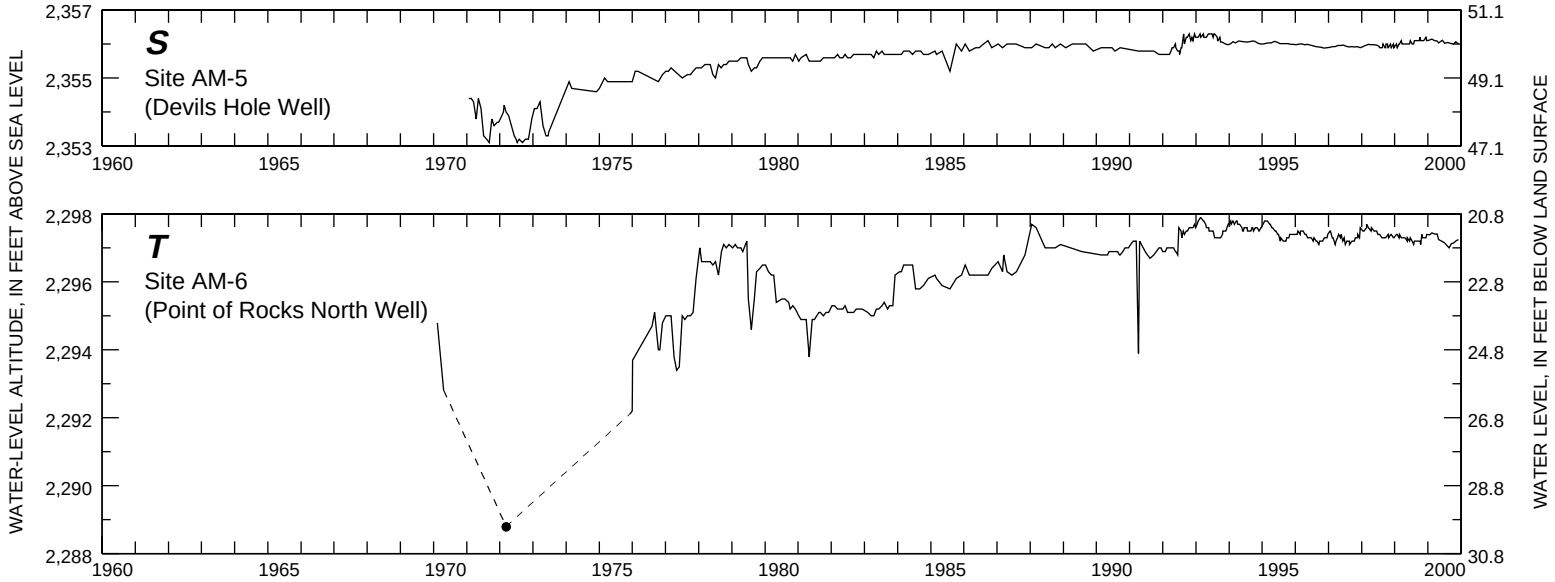

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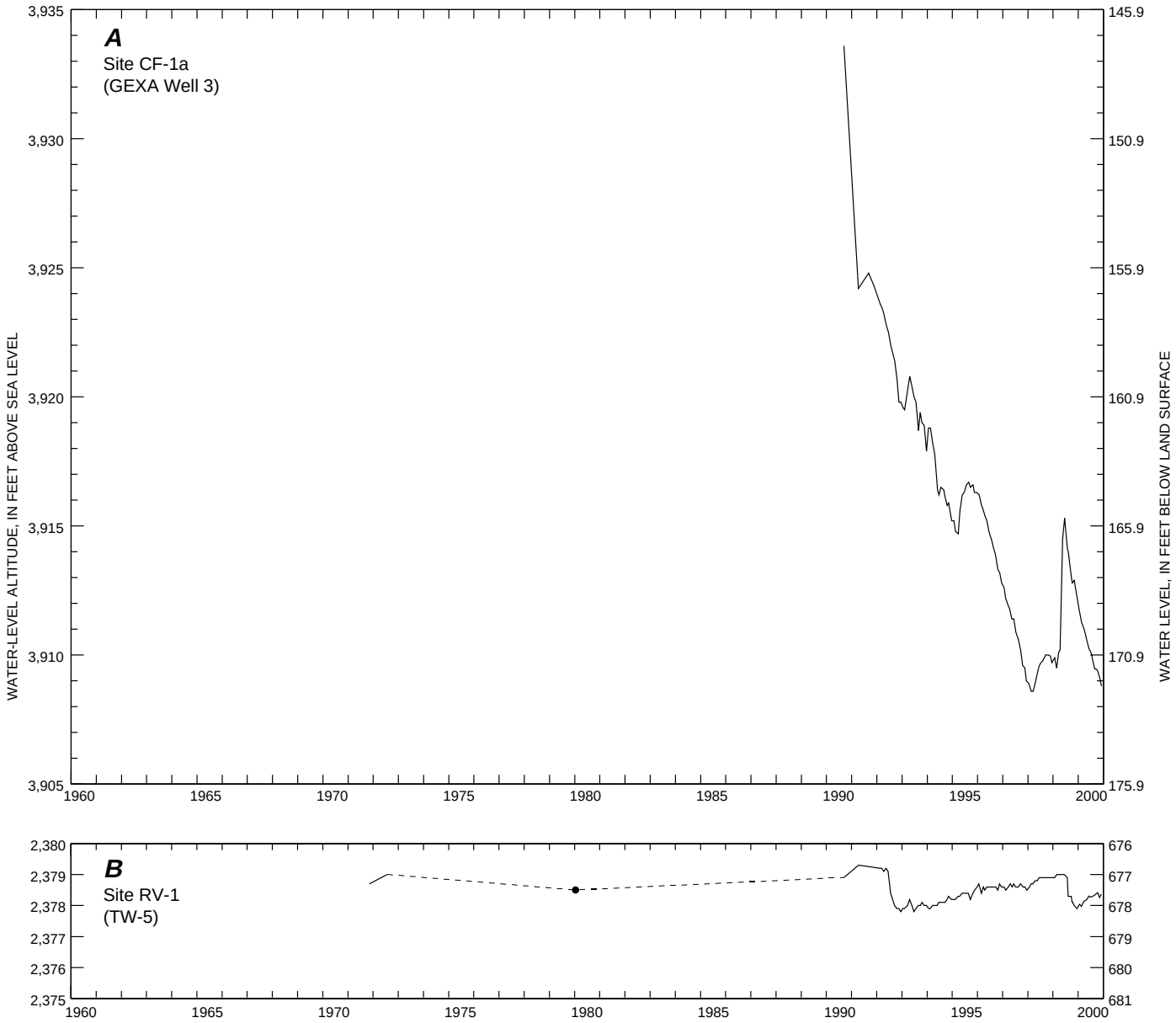

Figure 30. Water levels from 1960 to 2000 for selected sites at which primary contributing units are undifferentiated sedimentary rocks. Lines connect periodic data and are dashed where measurements were not available for consecutive calendar years. Data that may represent short-term conditions at a site have been excluded (see section “Periodic Water-Level Data”).

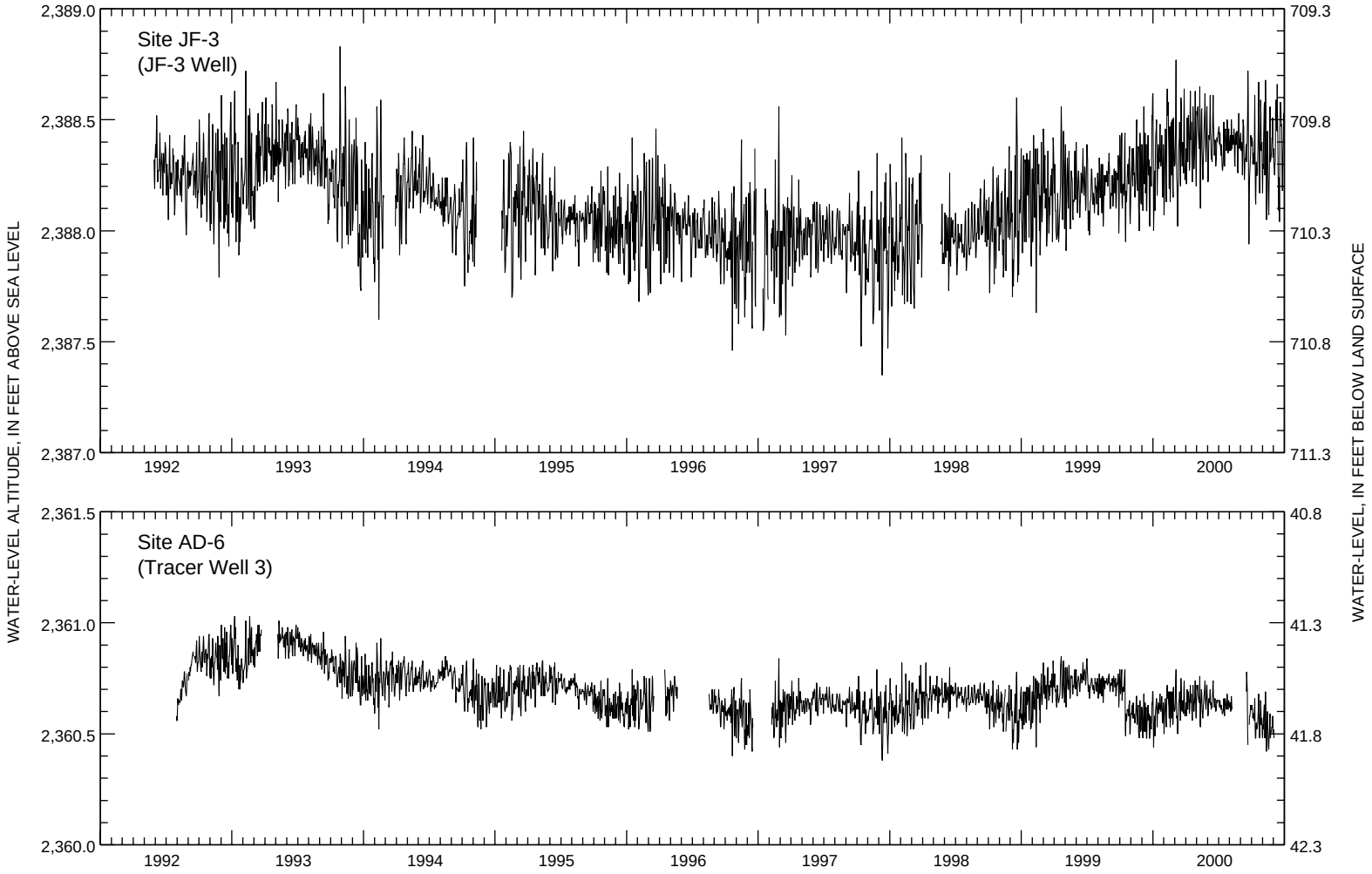

Figure 31. Daily average water levels at site JF-3, May 1992 through December 2000, and at site AD-6, July 1992 through December 2000. Vertical and horizontal scales have been expanded beyond those for figures 27–30 to show high resolution of the data.

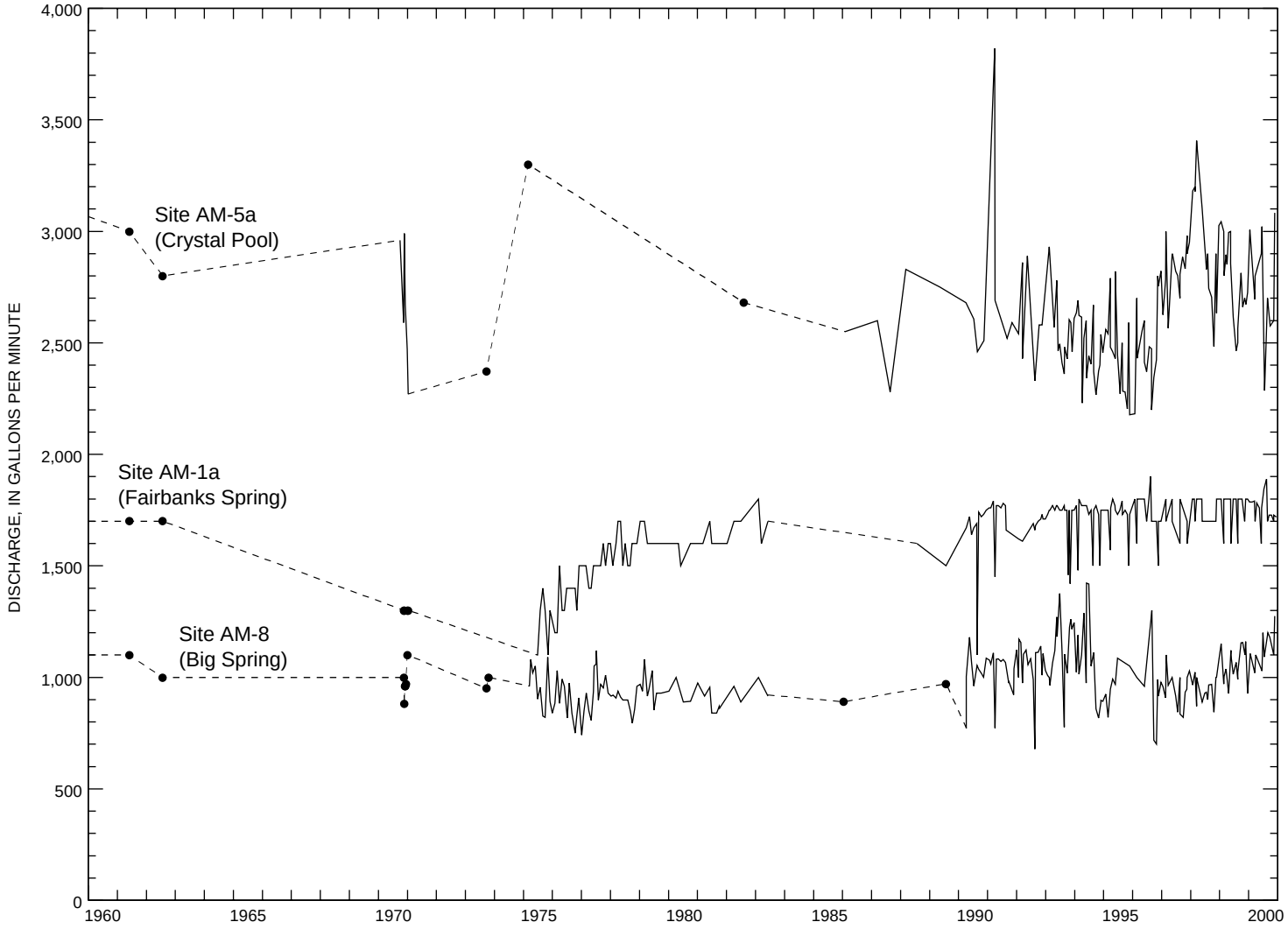

Figure 32. Discharge at sites AM-1a (Fairbanks Spring), AM-5a (Crystal Pool), and AM-8 (Big Spring), 1960–2000. Lines connect periodic measurements and are dashed where measurements were not available for consecutive calendar years.

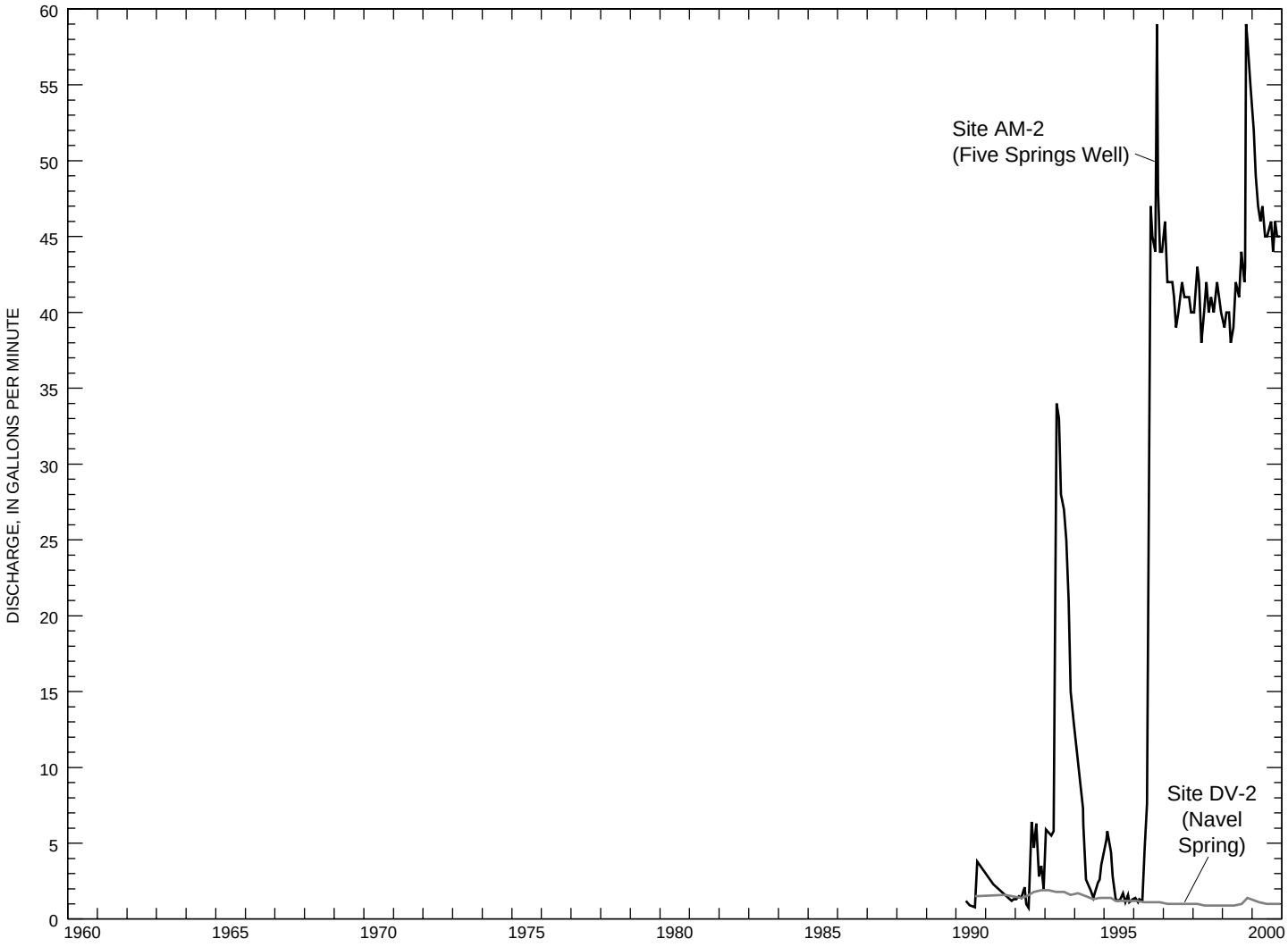

Figure 33. Discharge at sites AM-2 (Five Springs Well) and DV-2 (Navel Spring), 1990–2000. Lines connect periodic measurements.

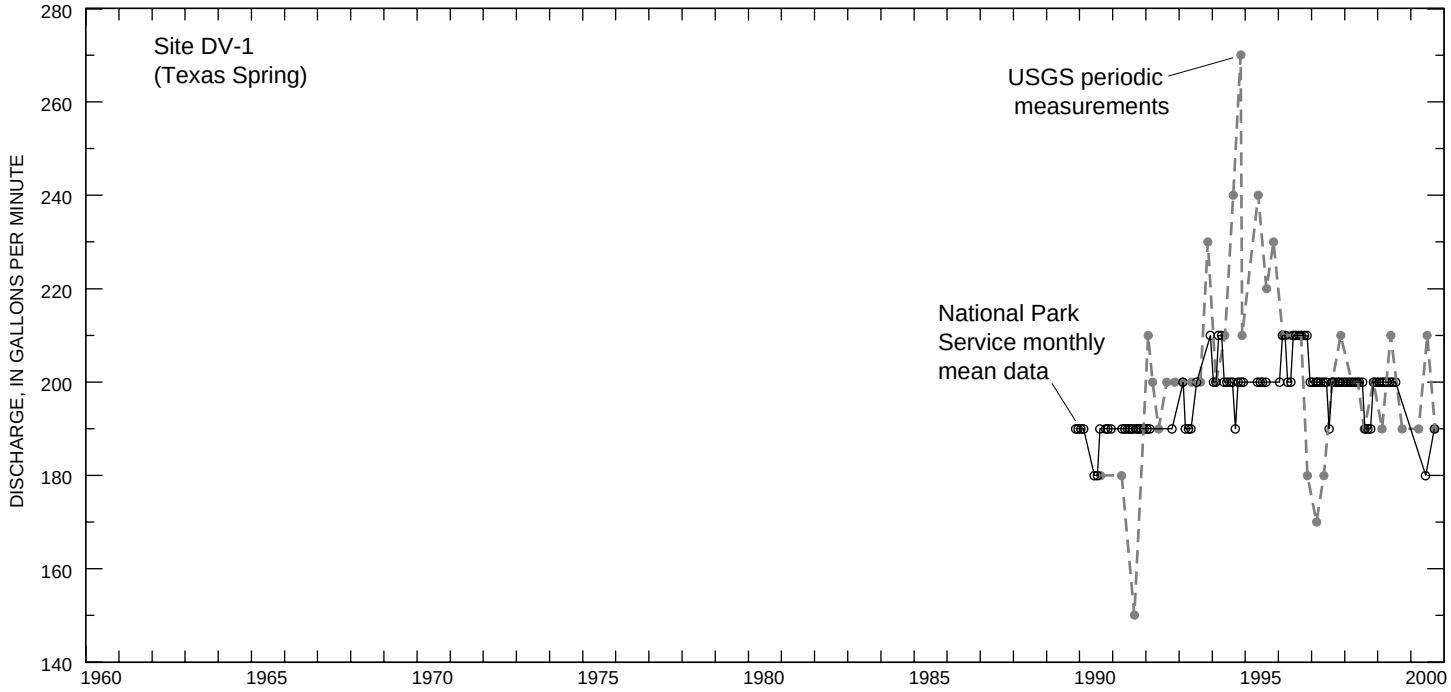

Figure 34. Discharge at site DV-1 (Texas Spring), 1989–2000. Filled gray symbols indicated periodic USGS measurements. Open black circles represent National Park Service monthly mean data.

APPENDIX B: SUPPLEMENTAL NOTES FOR SELECTED SITES

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Site CF-1 (GEXA Well 4)—Water was pumped, when needed, from site CF-1 from 1989 to 2000 for mining operations. Water levels measured in the well from 1992 to early 1996 (fig. 13*A*), a period when the well was not pumping or withdrawals were small, show a recovery from pre-1992 pumping in this well.

Site CF-1a (GEXA Well 3)— The cause of the water-level decline at site CF-1a is unclear (fig. 14*A*). Small amounts of water (1.2–2.3 Mgal/yr) were withdrawn from site CF-1a in 1989 and 1990. However, the decline in water level at site CF-1a does not seem to correlate with withdrawals from sites CF-1 or CF-1a. The well is screened at a relatively shallow depth (208–700 ft below land surface) and the water level, about 600 ft higher in altitude than at site CF-1, is probably perched or represents a shallow, localized flow system. Water may be draining through the well bore from this shallow system to a deeper system, or possibly some unknown but localized effect from nearby mining may be affecting water levels at site CF-1a.

Site CF-2 (USW VH-1)—Water levels at site CF-2 had a slight upward trend from 1992 to 2000 (fig. 13*B*). Minor pumpage at site CF-2 from 1991 to 1994 (about 0.7 Mgal/yr or less) and at a nearby well from 1991 to 2000 (about 6 Mgal/yr or less) do not appear to affect the water level at site CF-2.

Site CF-3 (Crater Flat 3)—Although site CF-3 is used for water supply for nearby mining operations, the small (0.3 ft) fluctuations in water level from 1993 to 2000 (fig. 14*B*) are not attributed to pumping. This is because the water level rose in 1999 and 2000, which happened to be the years of greatest pumping in the well (about 6 Mgal/yr as compared to 2.5–5.5 Mgal/yr from 1994 to 1998).

Site RV-1 (TW-5)—Site RV-1 is probably open to rocks at the top of the basement-confining unit that consist of shale and argillite, with lesser amounts of limestone, dolomite, and sandstone (West and Garber, 1962, p. 5–7). The well has a low yield (less than 5 gal/min), indicating the influence of the basement-confining unit (West and Garber, 1962, p. 4). The water-level trend at site RV-1 from 1992 to 2000 appears to be controlled primarily by earthquakes (figs. 12*L* and 13*G*). Water levels recovered for 7 years following the Landers/Little Skull Mountain earthquakes but dropped sharply about two months before the Hector Mine earthquake (mid-1999). Whether this drop was a precursor to the Hector Mine earthquake or the timing was coincidental is unclear.

Site AD-2a (NDOT Well)—Site AD-2a is a water-supply well. The quality of water-level measurements in this well is poor, resulting in data scatter (fig. 15*D*). The poor quality is a result of the well being recently pumped prior to many of the measurements, and a leaky pump seal that allows water to leak down the well casing, making measurement difficult.

Site AD-8 (Amargosa Desert 8)—Water levels at site AD-8, which is used as a domestic- and irrigation-supply well, have considerable data scatter (fig. 15*F*). The high degree of data scatter is probably caused by recent pumping of this well prior to many of the measurements.

Site AD-11 (GS-3 Well)—Site AD-11 is about 0.5 mi east-northeast of Grapevine Springs, which is at the base of the Resting Spring Range. The site includes a deep monitoring well (about 2,000 ft deep), which is part of the primary monitoring network, and a nested shallow piezometer (about 160 ft deep). Water levels in the deep well had a statistically significant rise of about 16.1 ft from 1992 to 2000 (table 6; fig. 13*I*), while water levels in the shallow piezometer rose about 1.1 ft during the same period. The hydraulic head in the shallow piezometer is about 140 ft higher than the head in the deep well, indicating a downward hydraulic gradient. A downward gradient is typically expected in a recharge area and seems anomalous in an area adjacent to a spring (Grapevine Springs) and distant from a major recharge source. Grapevine Springs, a series of seeps that support grapevines, may be fed by a perched system which follows an erosional contact of early Pleistocene(?) gravels and Tertiary playa lake sediments (Naff and others, 1974, p. 12). Water for the perched system may come from local recharge in the Resting Spring Range. The cause of the large rise in water level in the deep well is uncertain but could result from slow equilibration following well construction or downward leakage of water through the well annulus from the shallow perched system to the deep system.

Site AD-12 (GS-1 Well)—Water levels at site AD-12 had a statistically significant decline between 1992 and 2000 (fig. 14*L*). However, because of the anomalously large (5–7 ft) jump in water levels in 1992 followed by an anomalous 0.7 ft drop in water levels in June 1995, the trend in this well is suspect (see “Amargosa Desert” section). The 5- to 7-ft water-level rise in 1992 coincides with the Landers/Little Skull Mountain

earthquakes (fig. 29*N)*. However, the water level at site AD-12 did not return to pre-earthquake level but remained about 5 ft higher. The cause of these anomalous changes in water level are not known.

Site AD-13 (S-1 Well)—Site AD-13 includes a deep monitoring well (about 2,000 ft deep), which is part of the primary monitoring network, and a nested shallow piezometer (about 440 ft deep). Hydraulic head is higher in the deep well than in the shallow piezometer, indicating an upward hydraulic gradient. Water levels in the deep well had a statistically significant rise of about 12.0 ft from 1992 to 2000 (table 6). The somewhat steady rise in water levels in the deep well was punctuated by a large 5-ft jump in water level in 1998 and several smaller jumps from 1999 to 2000 (fig. 13*J*). Water levels in the shallow well had a pattern similar to the deep well. The cause of the large rises in water level is uncertain but could be a well-construction effect.

Site AM-2 (Five Springs Well)—Water levels and discharge at site AM-2 had no statistically significant upward or downward trends for the periods analyzed. However, interpretations based on data from this site should be viewed with caution. Site AM-2 is a flowing well located in an area of a ground-water seep. The well casing is perforated to land surface. In 1996, the topsoil around the well was removed and a diversion was created, 0.25 ft below the existing land surface, to allow flow to be measured more accurately. The diversion allows water to flow from the well bore to a nearby location where monthly volumetric discharge measurements can be made. In 1996, water levels at site AM-2 dropped sharply (fig. 27*D*), whereas discharge rose sharply (fig. 33), coinciding with the time that the diversion was created. Discharge measurements at site AM-2 prior to 1996 are biased low because much of the water was not captured prior to measurement. More recent discharge measurements represent a combination of flow directly through slotted casing near land surface and leakage from the casing's annular space. Water levels at site AM-2 prior to 1996 probably better represented the natural hydraulic head in the aquifer; measurements after the diversion are very stable but simply represent the altitude of the point of diversion from the well. Because of the complications with this well, statistical trend tests were computed on discharge data collected after the diversion and water-level data collected prior to the diversion.

Site AM-3 (Ash Meadow 3)—The high water levels at site AM-3 prior to 1994 (fig. 29*R*) are likely caused by seepage of surface water to the shallow water table from a nearby ditch that channeled water from Crystal Pool (site AM-5a; fig. 1*B*). About 1991, flow from this ditch was diverted by USFWS to a natural channel, causing the ditch to dry up and water levels to decline almost 10 ft at site AM-3 over the next 3 years (Craig Westenburg, U.S. Geological Survey, oral commun., 2001).

Site AM-5a (Crystal Pool)—Crystal Pool is the largest spring in Ash Meadows. In fall 1996, USFWS restored the spring outflow to its original channel. This restoration lowered the pool level by 8 in. and may have artificially increased flow (Tim Mayer, U.S. Fish and Wildlife Service, written commun., 1997). Discharge increased for approximately 2 years and then declined from mid-1998 to 2000 (fig. 32). Because of the effects on discharge from spring restoration, it is unclear whether the more recent decrease in discharge is a continuation of a decrease that occurred from 1993 to 1996. One indication that the decreasing trends in Crystal Pool may be part of a long-term trend is the relatively recent change in the temperature of Crystal Pool. The temperature historically was about 91° F (Winograd and Thordarson, 1975, p. 79–81) and had been constant from the 1930's to 1990. In 1990, the measured temperature was 89° F (Tim Mayer, U.S. Fish and Wildlife Service, written commun., 1997). From 1997 to 1999 several more measurements taken by USFWS ranged from 85 to 86° F, which is about 5 to 6° F cooler than prior long-term temperatures. A decrease in temperature in the spring may indicate a decrease in discharge, because the smaller the discharge, the larger the percentage of heat in the water that is lost to surrounding soils (Winograd and Thordarson, 1975, p. 80–81).

Site AM-6 (Point of Rocks North Well) and site AM-7 (Point of Rocks South Well)—Water levels at Point of Rocks North Well (POR North), which is completed in valley fill, had a statistically significant, but small, downward trend from 1992 to 2000 (table 6; fig. 14*M*). Much of the decline in this well during this period is attributed to recovery from the 1992 Landers/Little Skull Mountain earthquakes. In contrast, water levels at Point of Rocks South Well (POR South), completed in valley fill and carbonate rock, had a statistically significant upward trend of about 3.1 ft from 1992 to 2000 (table 6; fig. 13*L*). Although the trends for these two wells from 1992 to 2000 are in

opposite directions, an inspection of the hydrographs for the entire period of record indicates some similarities.

POR North was pumped from 1970 through 1976, resulting in a drawdown during periods of nonpumping of at least 6 ft. By 1979, water levels were similar to levels in 2000 (fig. 29*T*). A second period of drawdown from nearby pumping occurred in POR North in the early 1980's. Recovery was probably complete by 1988. The relatively large transmissivity (6,000 ft^2/d) of the valley fill at POR North (Dudley and Larson, 1976, p. 20) enabled water levels in the well to recover from pumping in only a few years.

POR South, originally a flowing well in 1966, was pumped from 1970 to 1972 but produced only small amounts of water. By 1972, the water level was about 25 ft below land surface. Following the cessation of pumping, water levels steadily rose through 2000, to about 8 ft below land surface (fig. 27*F*). The relatively small transmissivity (82 ft^2/d) of the saturated units at POR South (Dudley and Larson, 1976, p. 20) is probably the reason why water levels are still recovering from pumping almost 20 years after the last major pumping in Ash Meadows.

Site DV-1 (Texas Spring)—Discharge from Texas Spring had no statistically significant upward or downward trend from 1992 to 2000. Trend analysis for Texas Spring was performed using periodic data collected by the USGS and monthly means of continual data collected by the NPS. The NPS data are less variable than periodic discharge data collected by the USGS (figs. 16*H* and 16*I*). Differences between periodic measurements and monthly means may be due to site-specific conditions that affect the accuracy of the measurement methods used. Accuracy of periodic measurements is limited by unmeasurable flow near the walls of the flume, an unequal distribution of velocities in the limited width of the measurement section, and the small number of measurements (each accounting for a large percentage of total flow) made across the limited width of the measurement section.