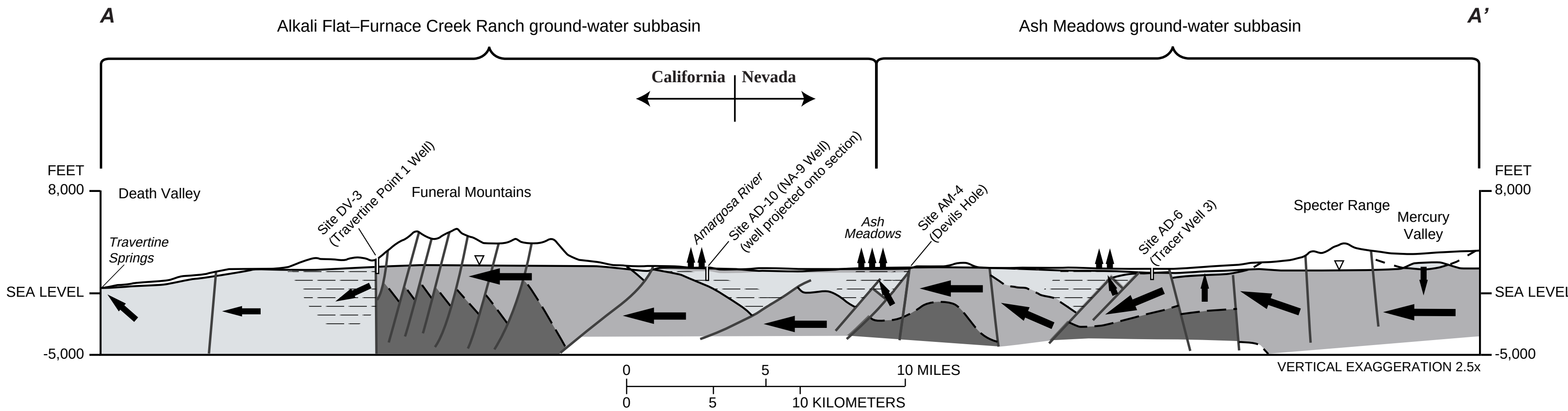



## EXPLANATION

**Hydrologic units—Units shaded only beneath water table**

**Valley-fill aquifer**—Alluvium. Dashed pattern represents area in section where fine-grained deposits act as local confining unit

**Carbonate-rock aquifer**—Dolomite and limestone

**Basement confining unit**—Quartzite and siltstone

**Contact**—Dashed where uncertain or inferred. Short dashed line shows geologic contact in unsaturated rock above water table

**Fault**

**Water table**

**General direction of regional ground-water flow**—Size of arrow indicates relative volume of ground-water flow. Multiple arrows indicate uncertain or multiple flow directions

**Monitoring well**

**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: Feet below land surface | | Open interval | | Contributing unit |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | Top | Bottom | Diameter (inches) | Type | |
| 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: Feet below land surface: Top | Open interval: Feet below land surface: Bottom | Open interval: Diameter (inches) | Open interval: Type | Contributing unit |
|---|---|---|---|---|---|---|---|---|---|
| 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: Feet below land surface: Top | Open interval: Feet below land surface: Bottom | Open interval: Diameter (inches) | Open interval: Type | Contributing unit |
|---|---|---|---|---|---|---|---|---|---|
| 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.

**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; 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<br>453 | 435<br>826 | 10<br>U | P<br>X | L | F | 19 |
| 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<br>1,900 | 1,882<br>1,950 | 10<br>9 | P<br>X | L | C | 20*C* |
| 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<br>2,199<br>1,960 | 2,199<br>2,205<br>2,020 | 7<br>11<br>3 | P<br>X<br>P | L | C | 20*B* |

**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

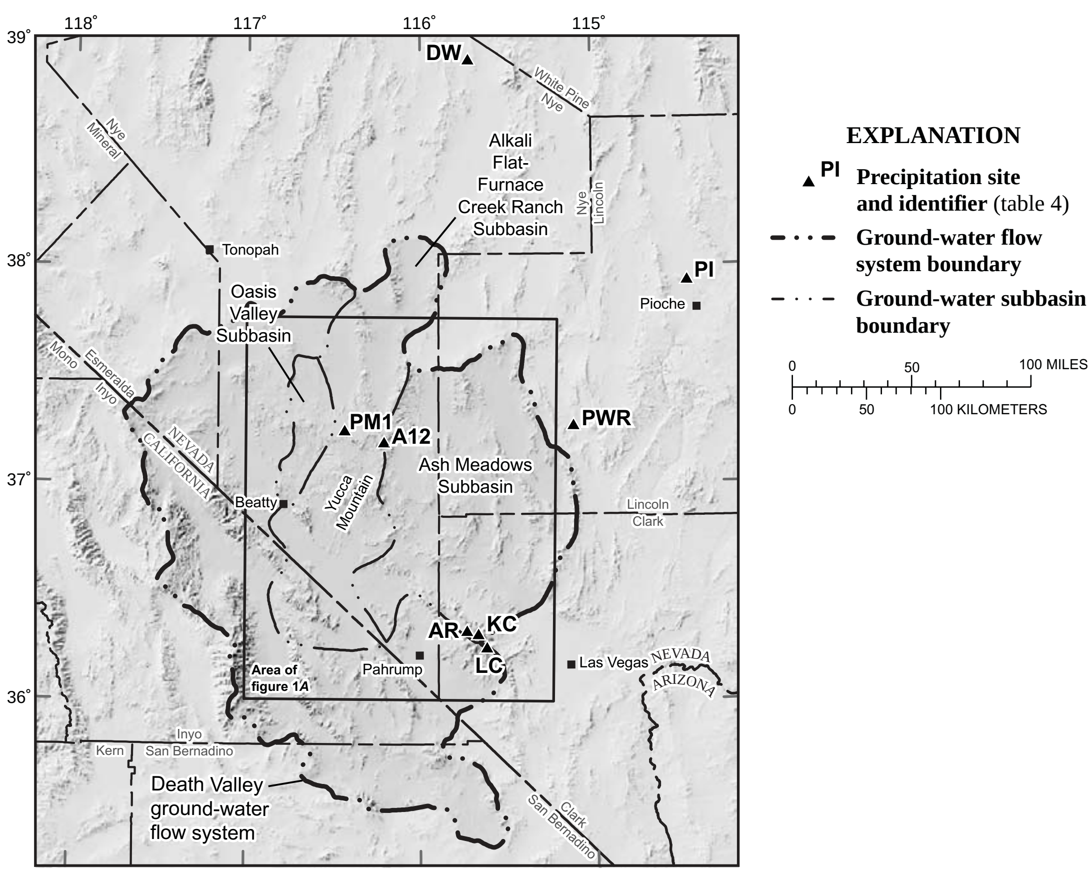
**Table 4**. Location and elevation information for precipitation sites used to create precipitation indices

**Index**: 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

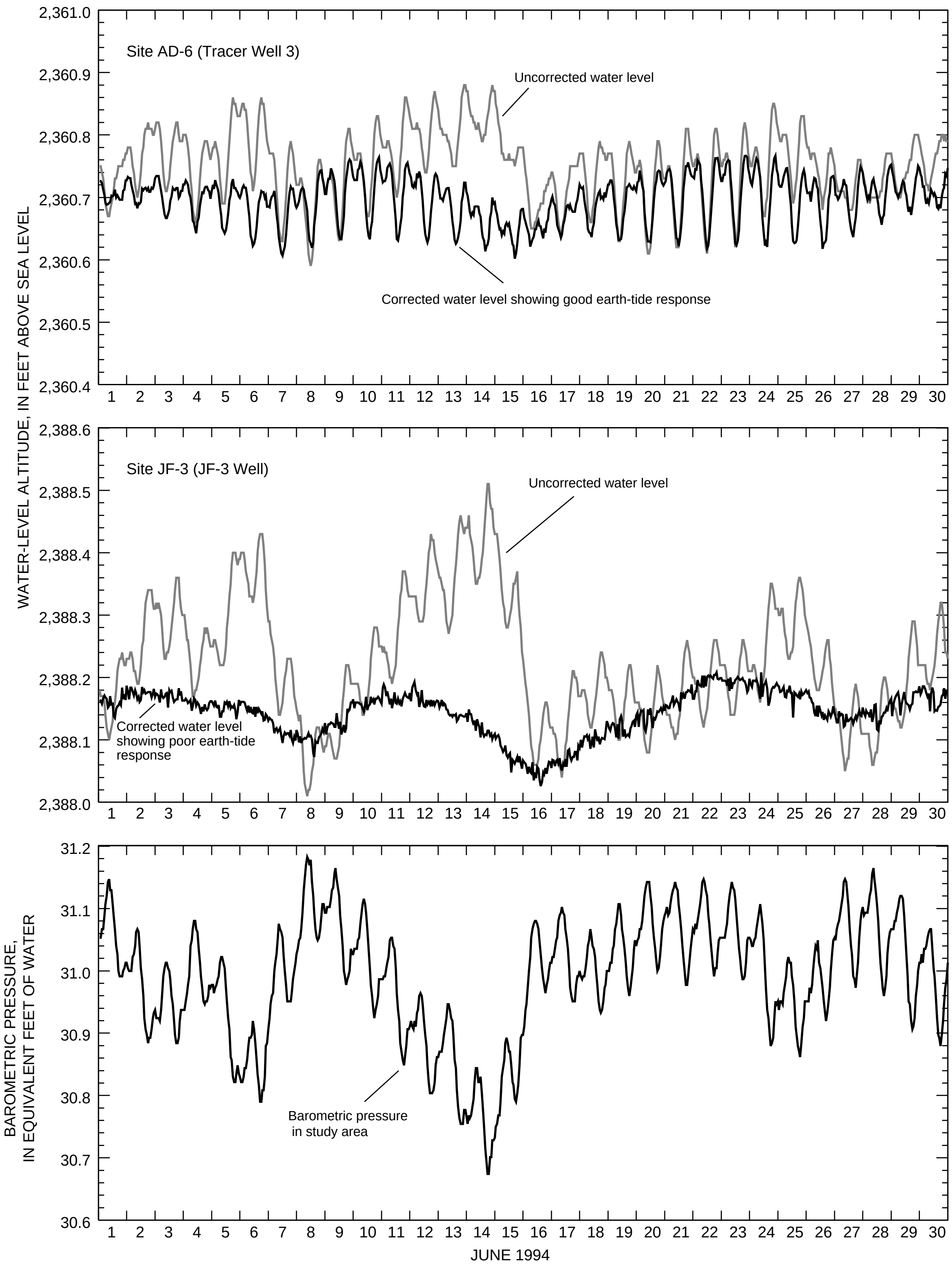



**Figure 5.** Response of water levels at sites AD-6 (Tracer Well 3) and JF-3 to barometric pressure and earth tides, June 1994. Water levels were corrected for instantaneous effects of barometric pressure.

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.

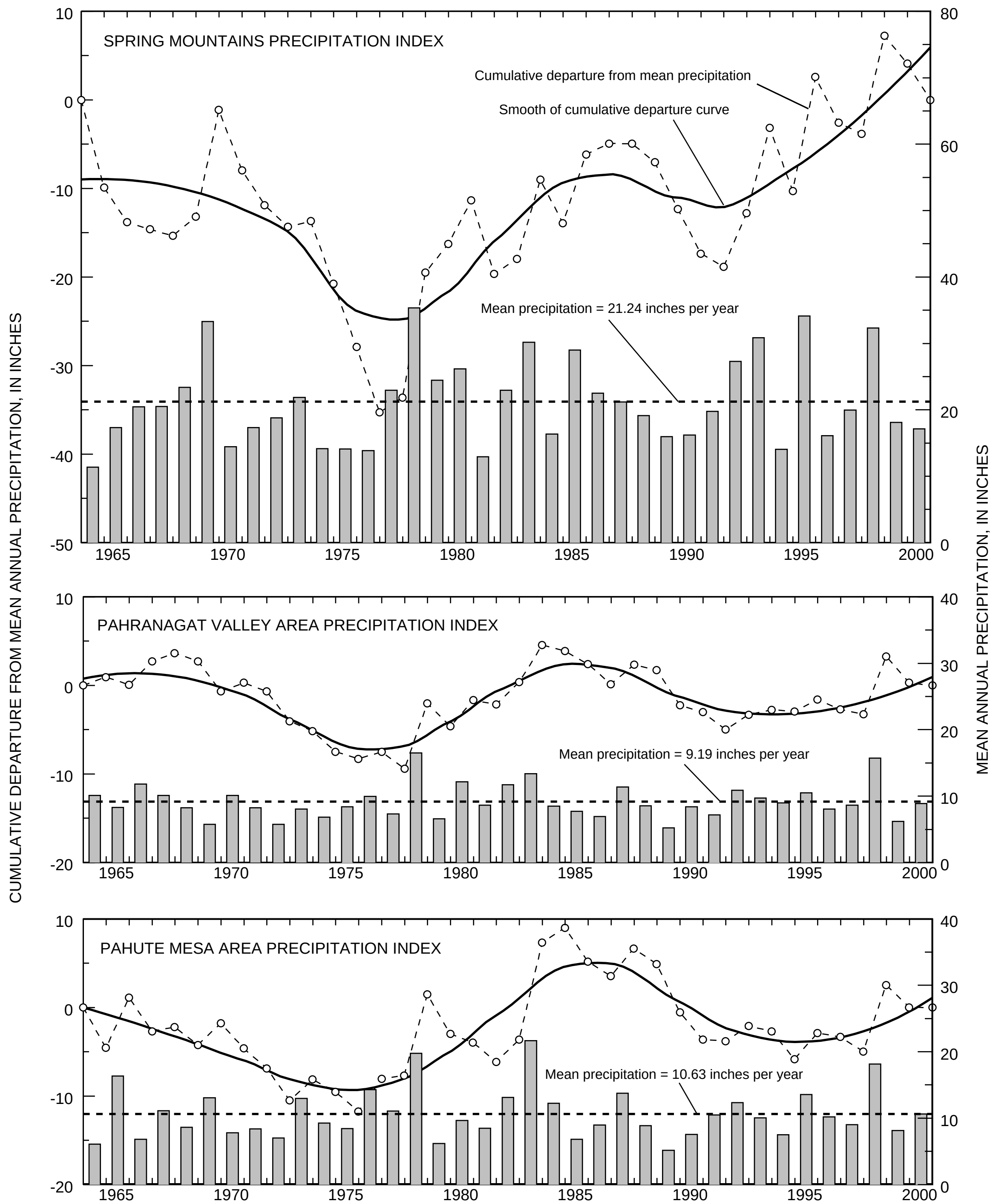



**Figure 6.** Annual precipitation and cumulative departure from mean annual precipitation at index sites in the Spring Mountains, Pahranagat Valley area, and Pahute Mesa area, 1964–2000. See figure 4 for locations of precipitation sites. Wet periods are shown by increasing slope in cumulative departure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

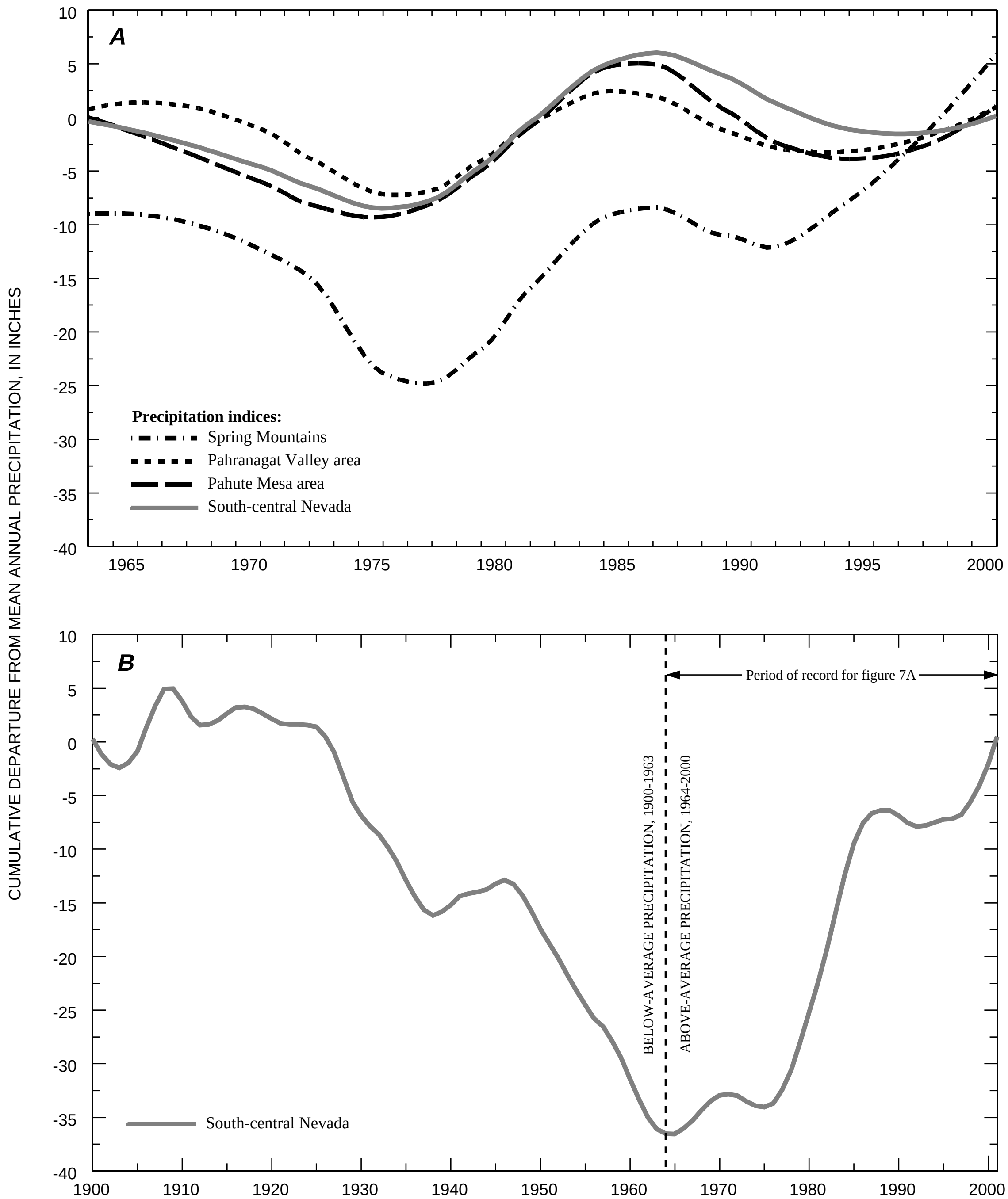



**Figure 7.** Cumulative departures from mean annual precipitation for index sites in the Spring Mountains, Pahranagat Valley area, Pahute Mesa area, and south-central Nevada: (*A*) Smoothed curves of all four indices from 1964 to 2000; (*B*) Smooth of the south-central Nevada index from 1900 to 2000.

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).

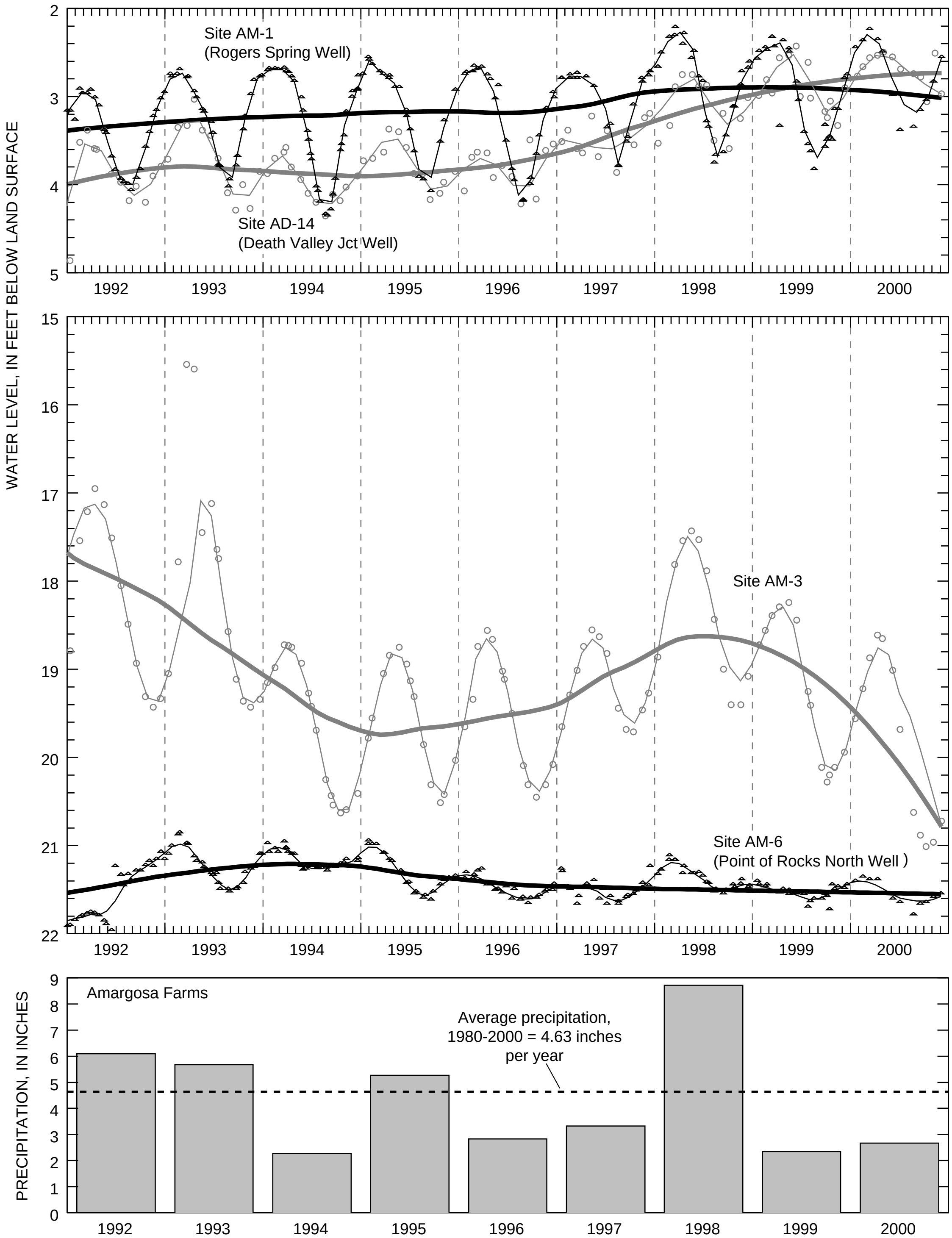



**Figure 8**. Effects of evapotranspiration on seasonal fluctuations in water levels in selected wells in the Yucca Mountain region and precipitation at Amargosa Farms, 1992–2000. For each year of record, seasonal water levels peak in the winter months and are lowest in the summer months, corresponding 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.

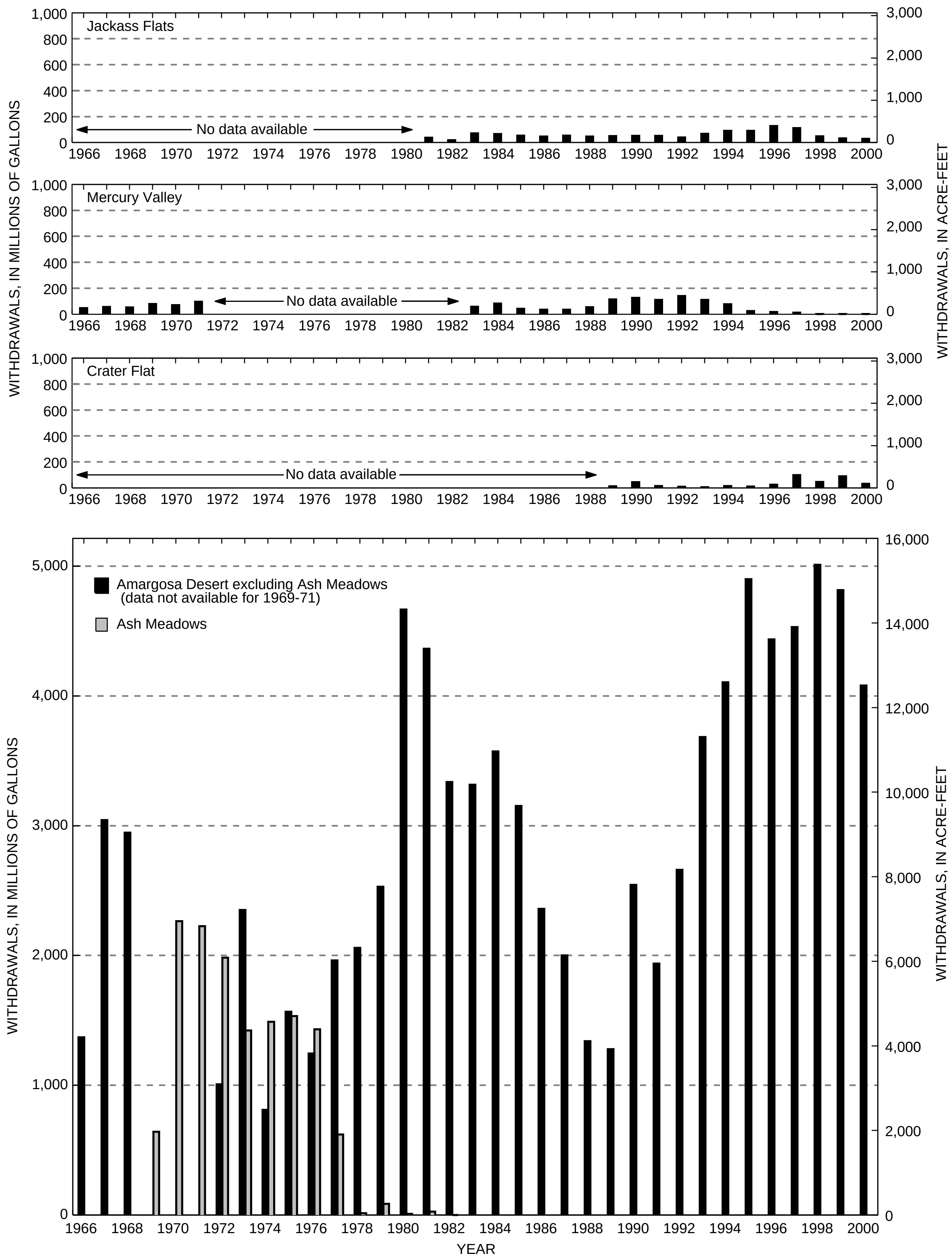



**Figure 9**. Estimates of annual ground-water withdrawals in Jackass Flats, Mercury Valley, Crater Flat, and Amargosa Desert, 1966–2000. Scales are the same for all plots.

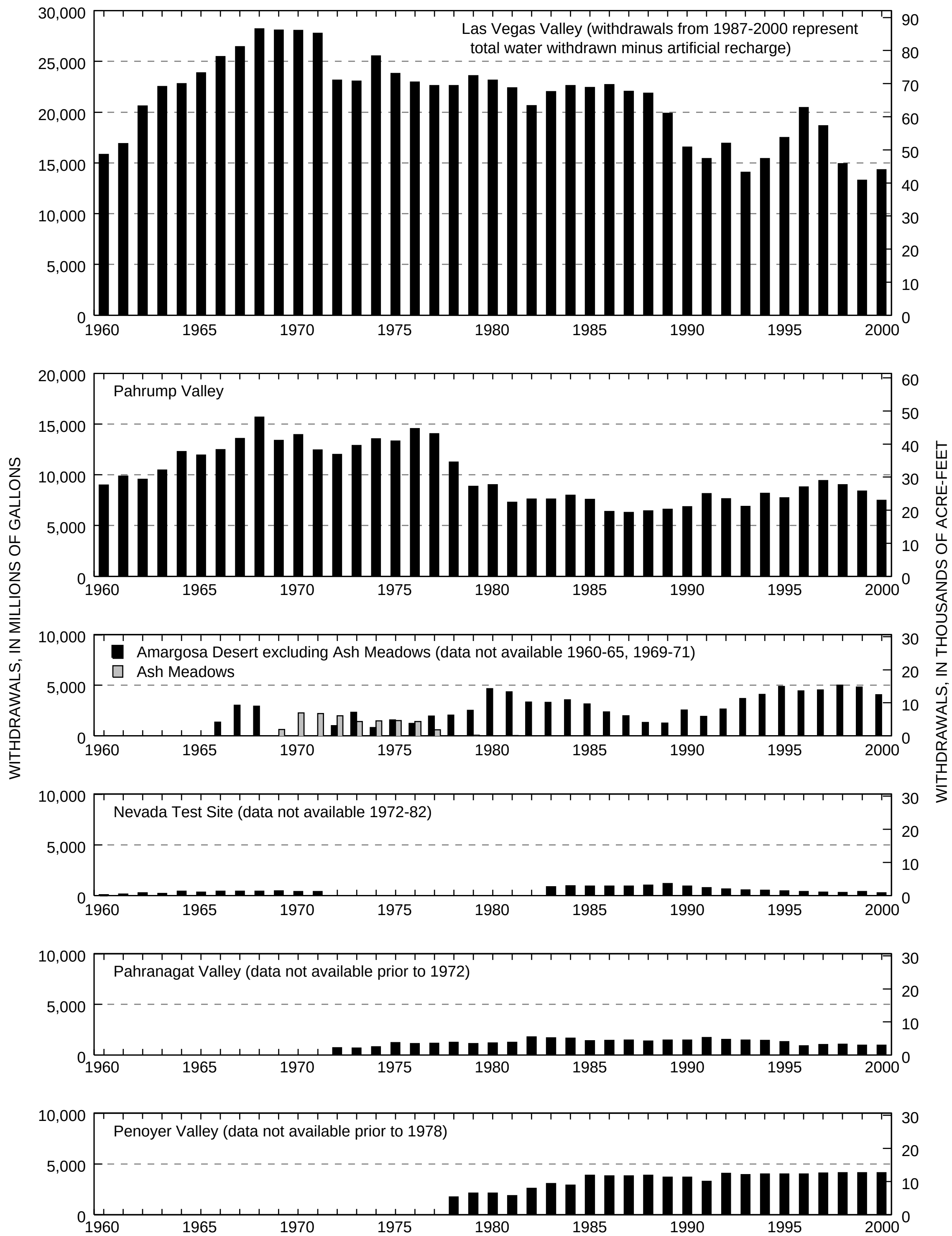



**Figure 10**. Estimates of annual ground-water withdrawals in selected major pumping centers for the Yucca Mountain region, 1960–2000. Scales are the same on all plots.

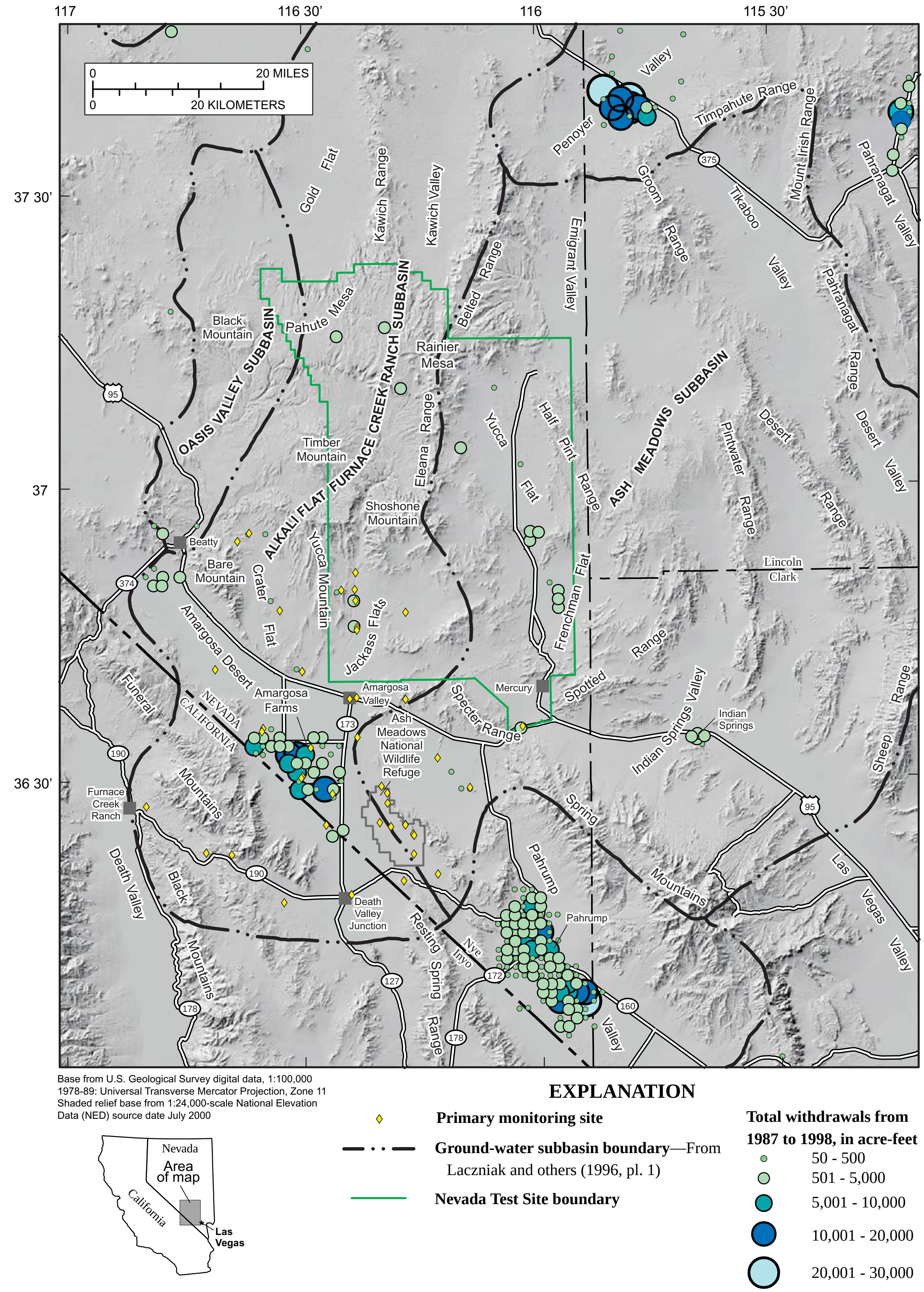



**Figure 11**. Reported regional ground-water withdrawals, totaled by square-mile section for 1987–98, in the Yucca Mountain region, southern Nevada and eastern California. (Withdrawals are not shown for Las Vegas Valley, California, or west of the Alkali Flat–Furnace Creek ground-water subbasin boundary.)

## 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

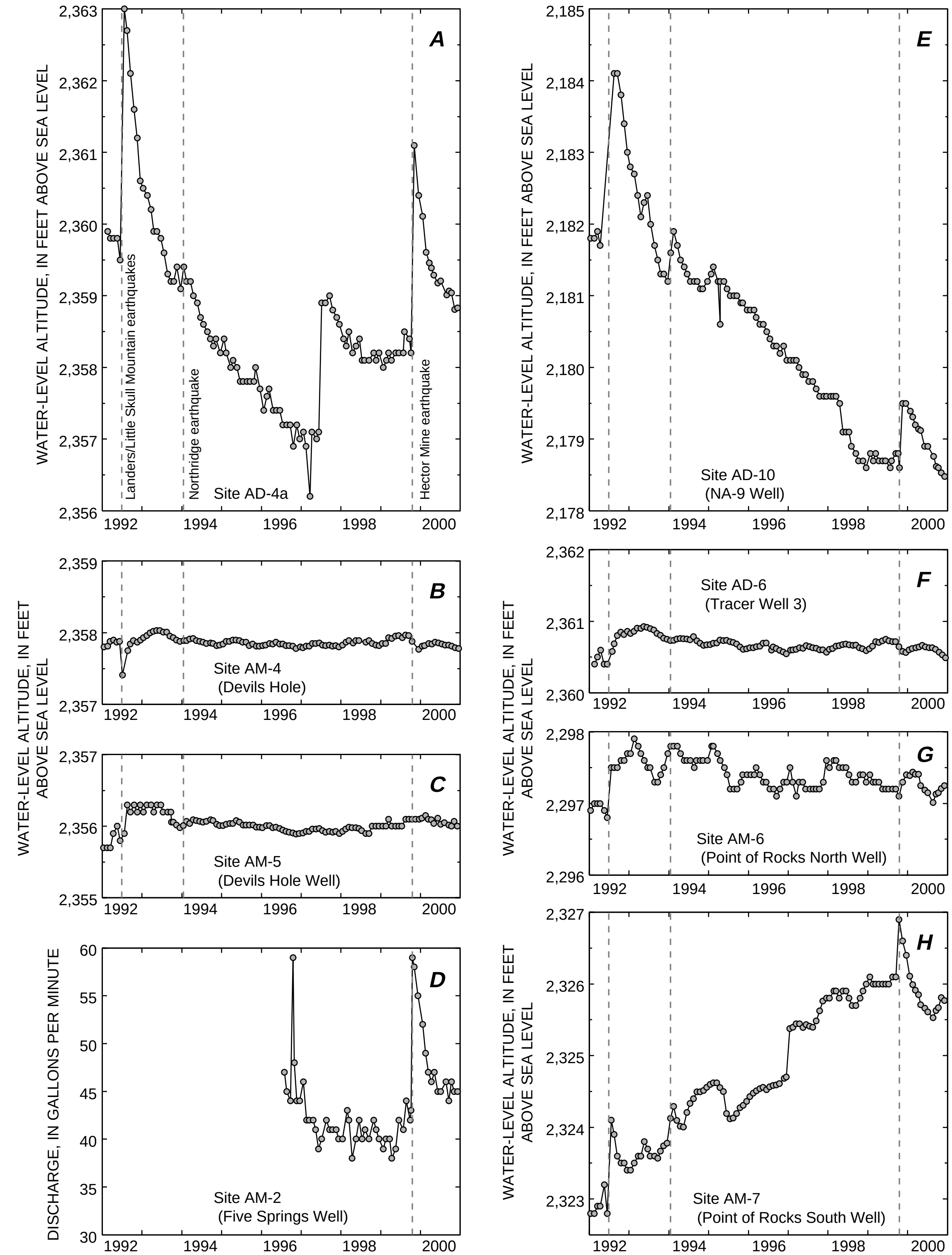



**Figure 12**. Water-level altitudes and discharge, 1992–2000, for wells and springs in the Yucca Mountain region that may have been affected by major earthquakes. Dashed lines mark Landers/Little Skull Mountain (1992), Northridge (1994), and Hector Mine (1999) earthquakes. Horizontal and vertical scales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

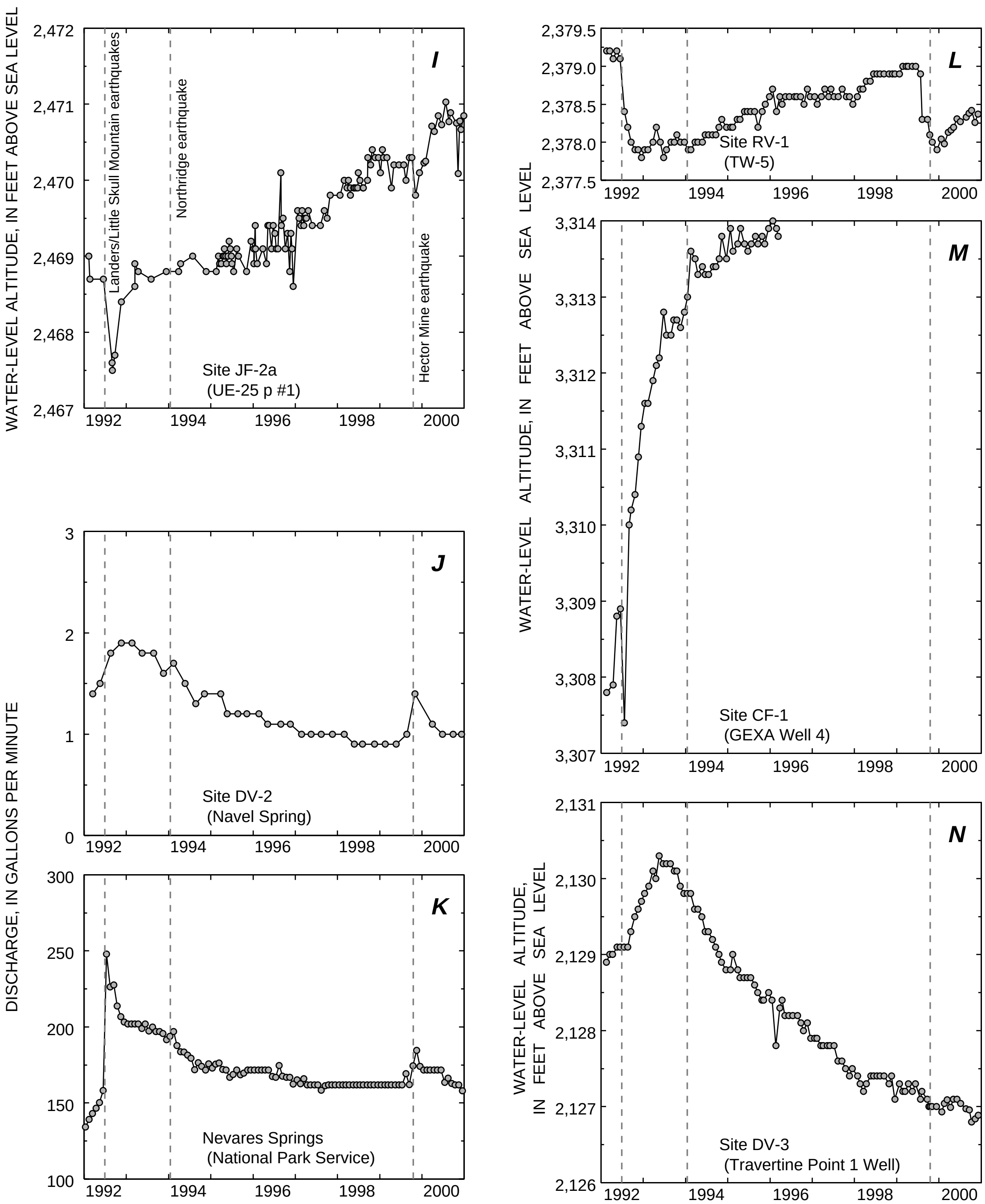



**Figure 12.** Continued.

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

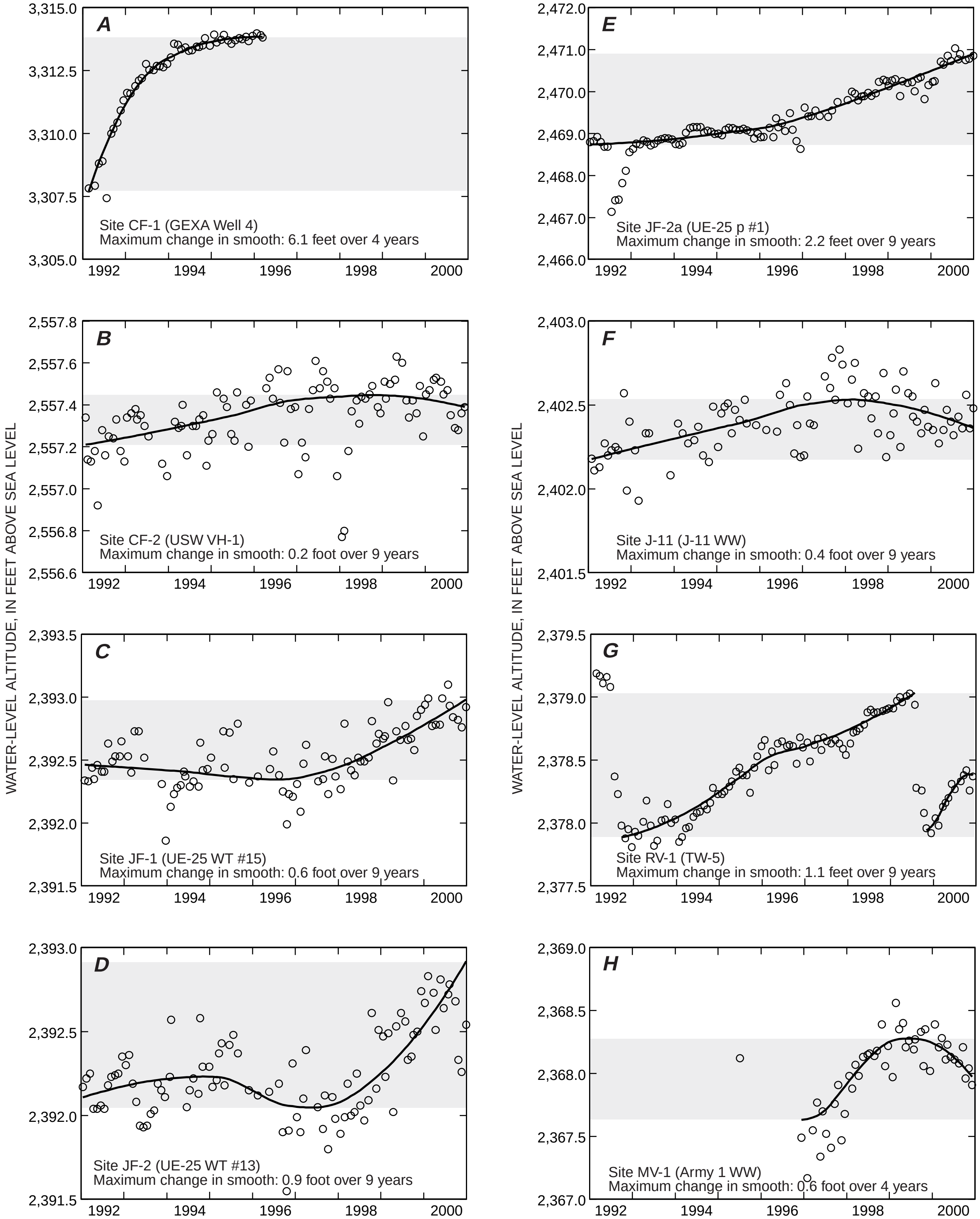



**Figure 13**. Smooths of water levels in wells with statistically significant upward trends from 1992 to 2000. Upward trends are based on Mann-Kendall trend test as presented in table 6. “Maximum change in smooth” (highlighted in gray on plots) is the change in water-level altitude from the maximum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

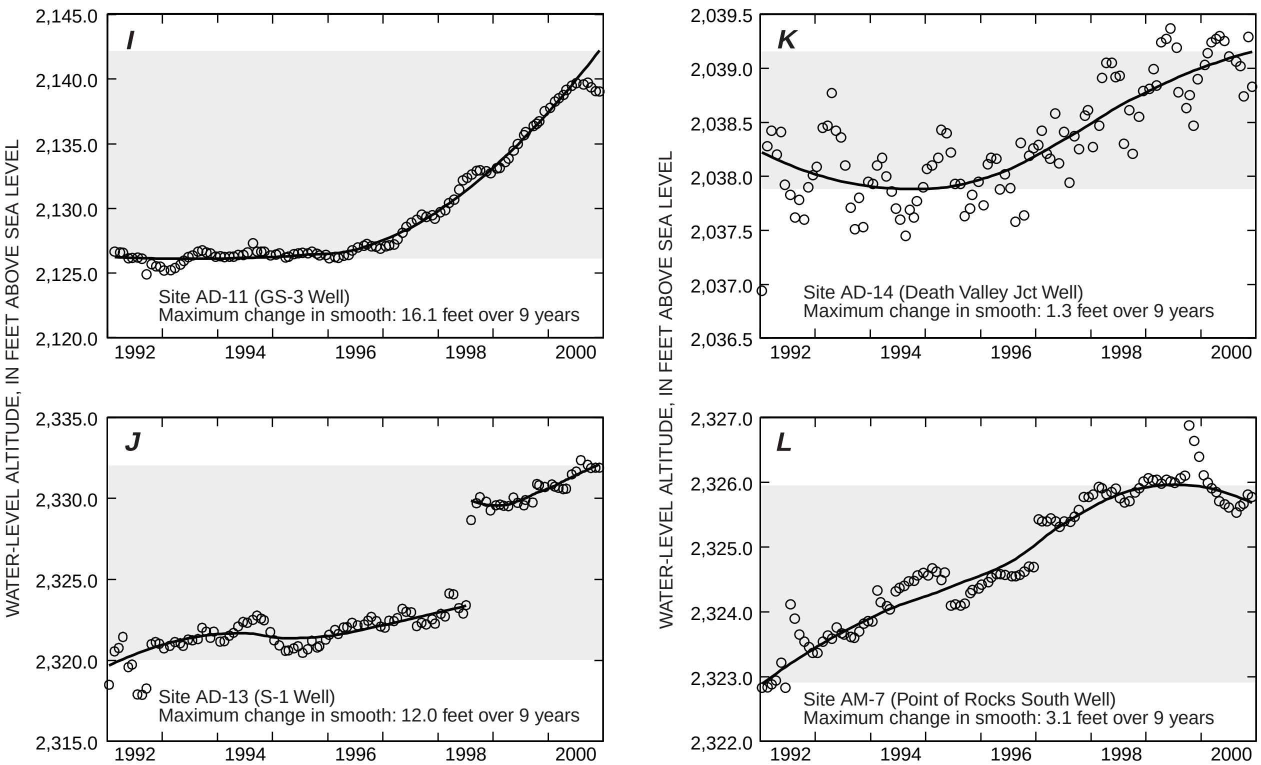



**Figure 13.** Continued.

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

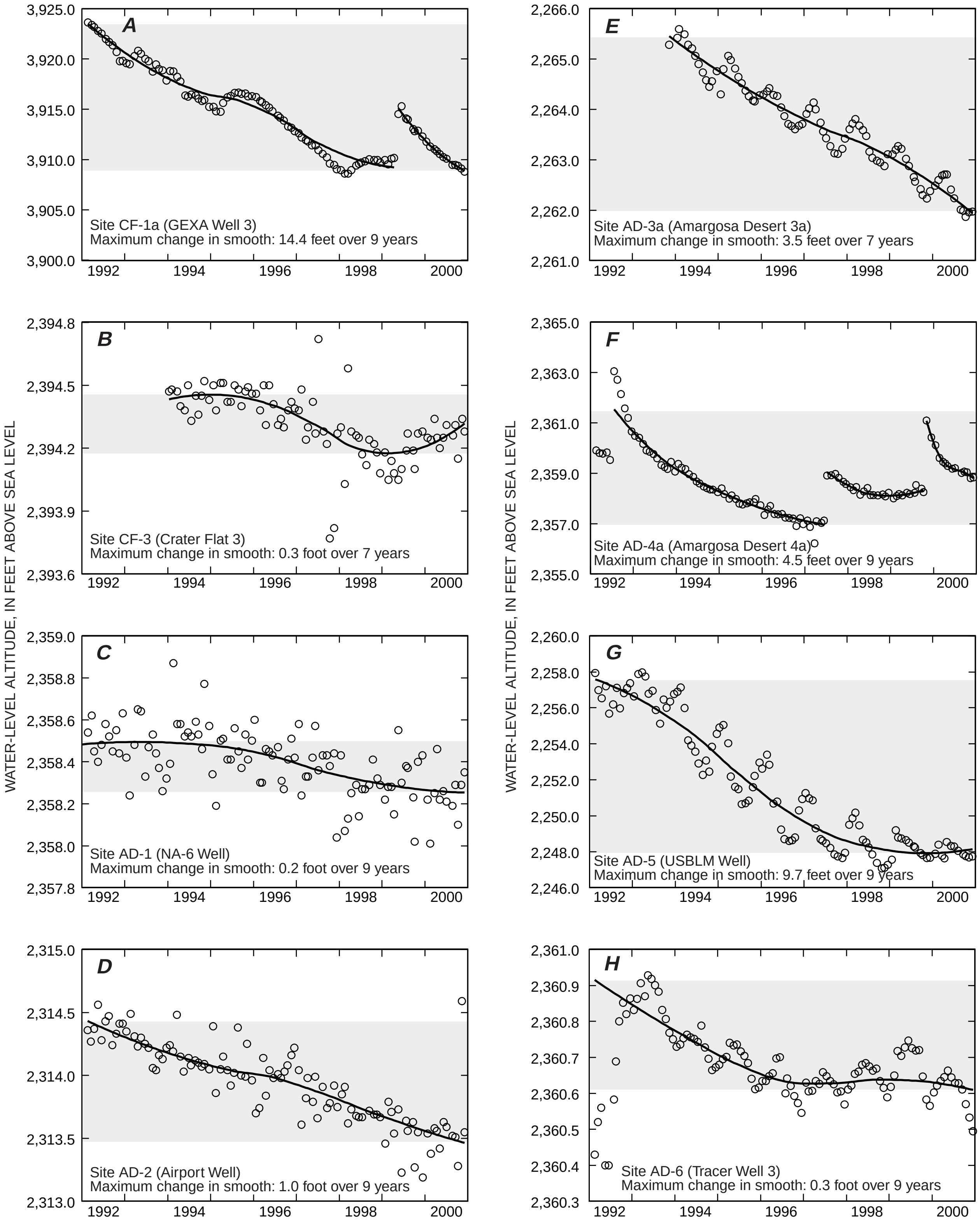
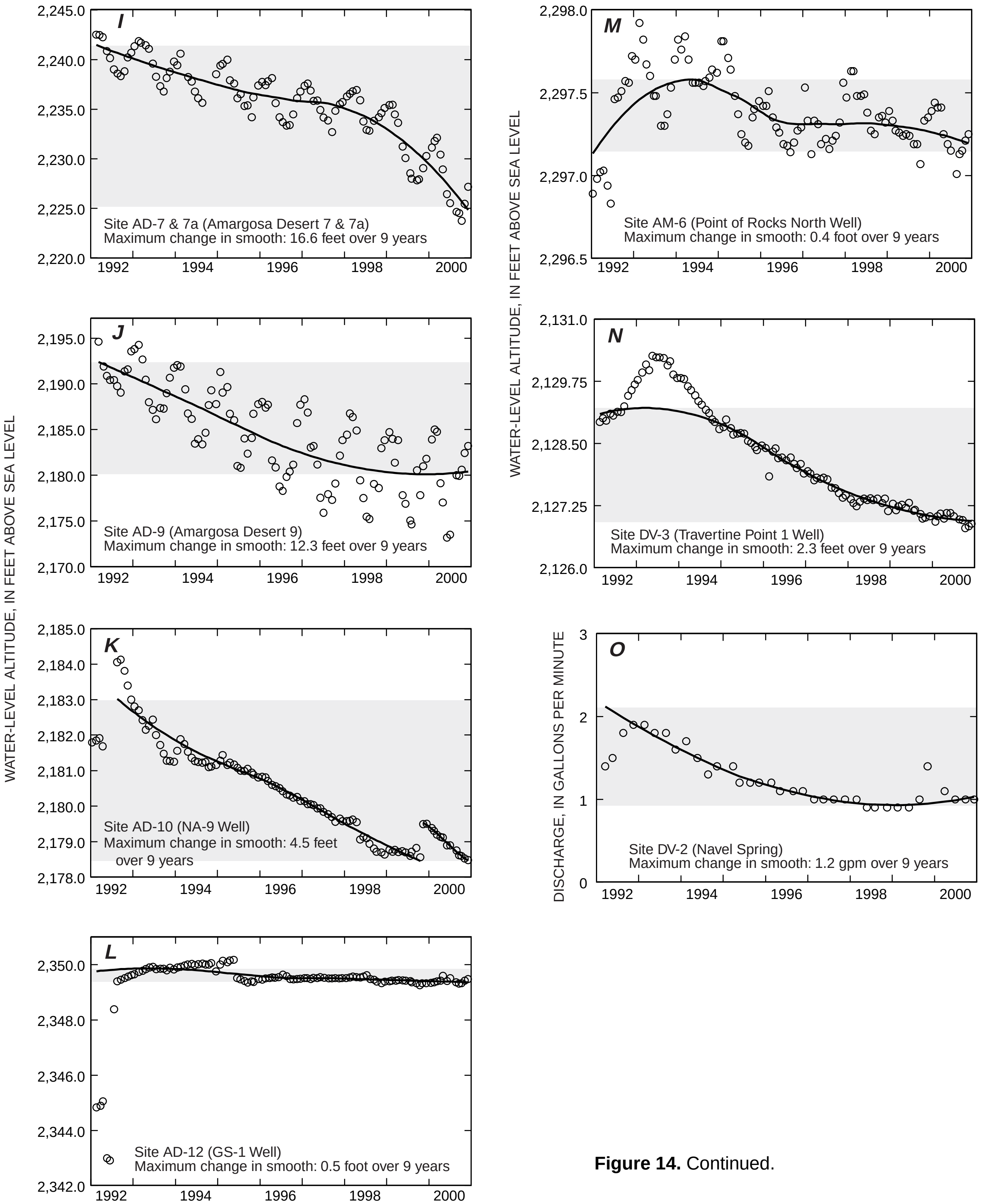



**Figure 14**. Smooths of water levels in wells and discharge from a spring with statistically significant downward trends from 1992 to 2000. Downward trends are based on Mann-Kendall trend test as presented in tables 6 and 7. “Maximum change in smooth” (highlighted in gray on plots) is the change in 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.

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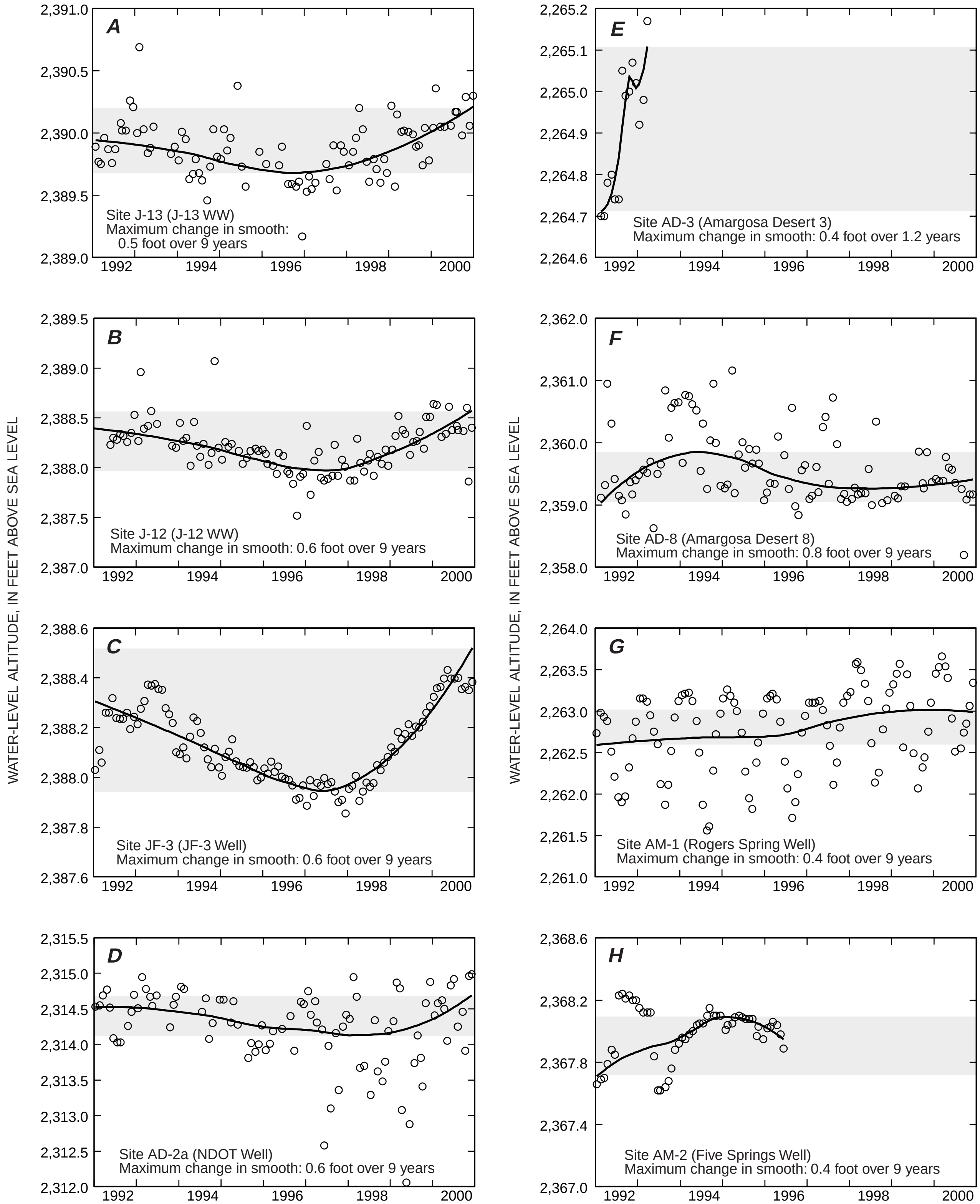


**Figure 15**. Smooths of water levels in wells (and in Devils Hole) with no statistically significant trends from 1992 to 2000. Absence of trend is based on Mann-Kendall trend test as presented in table 6. “Maximum change in smooth” (highlighted in gray on plots) is the change in water-level altitude 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.

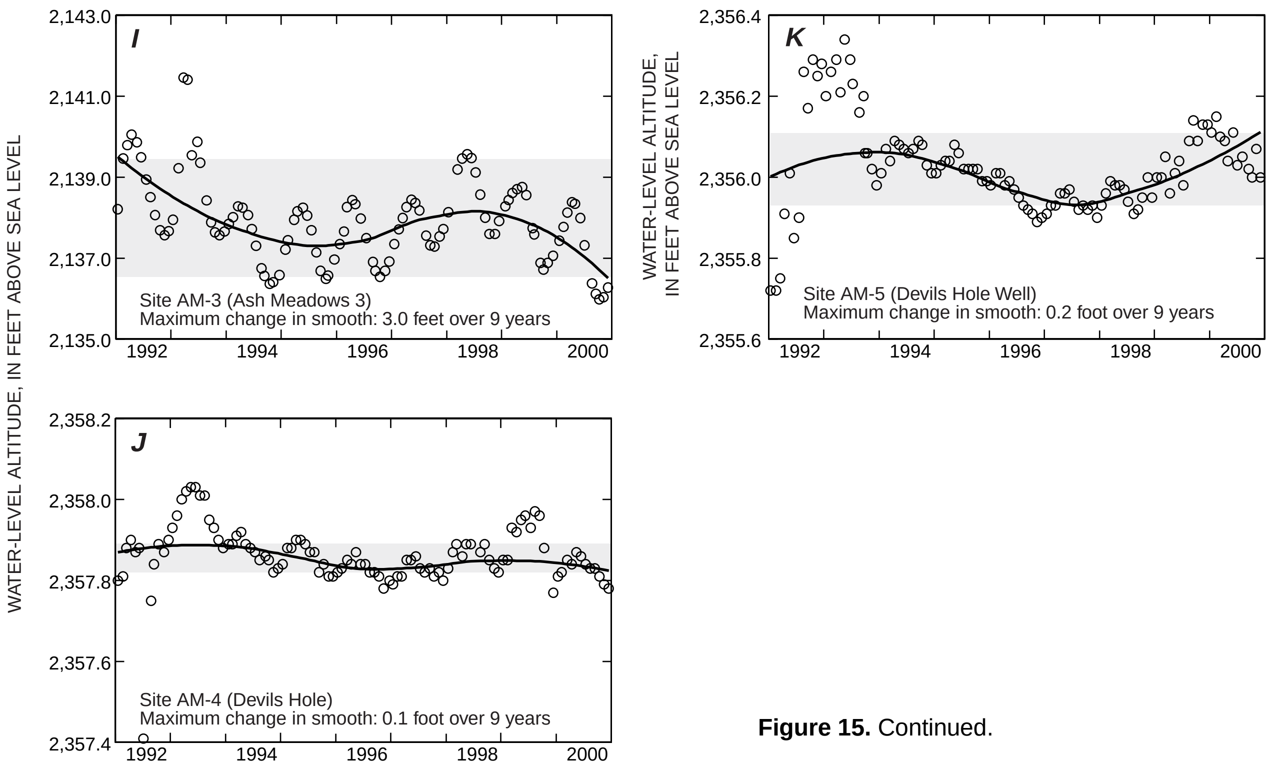


**Figure 15.** Continued.

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.

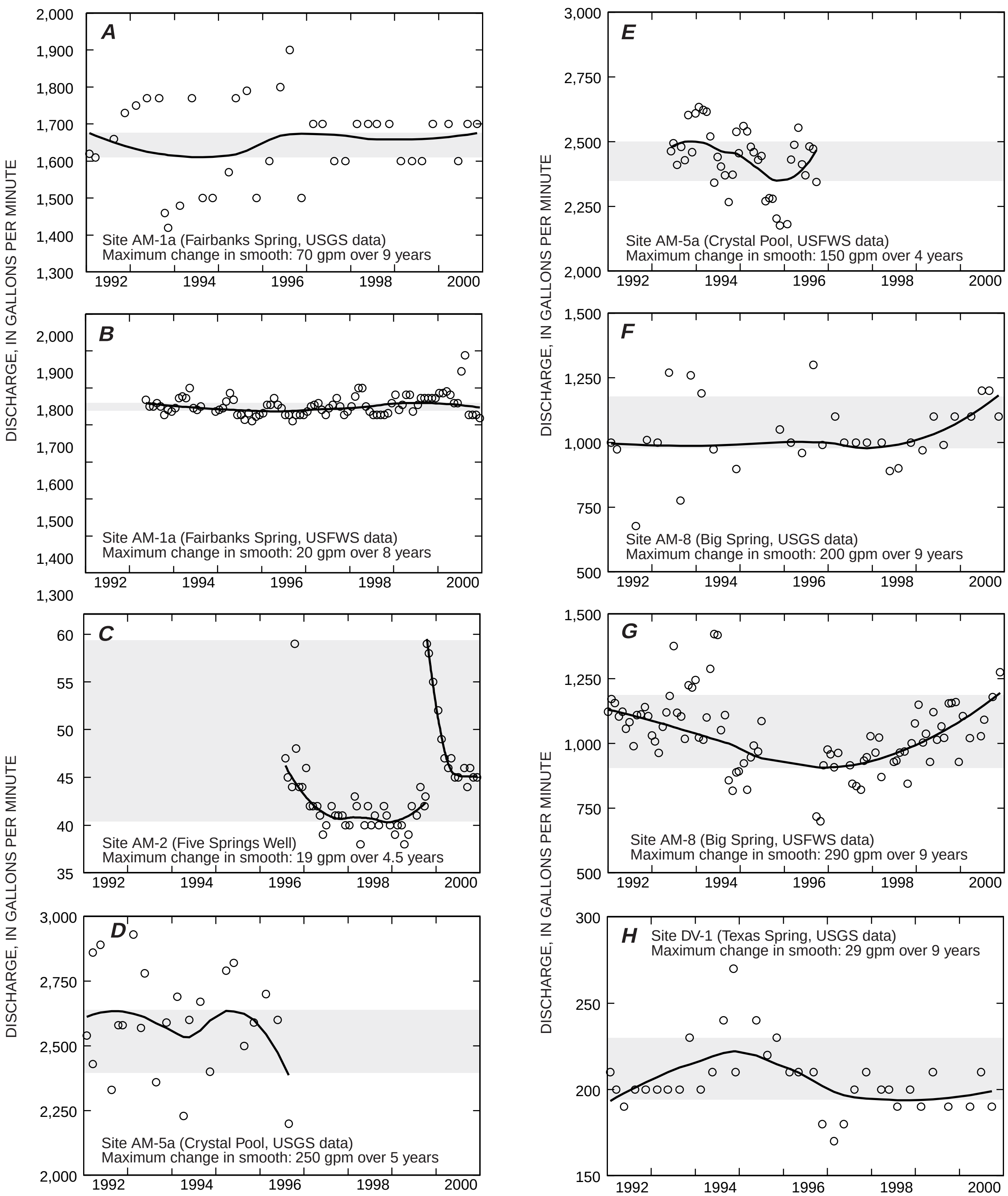


**Figure 16**. Smooths of discharge from springs and one flowing well with no statistically significant trends from 1992 to 2000. Absence of trend is based on Mann-Kendall trend test as presented in table 7. “Maximum change in smooth” (highlighted in gray on plots) is the change in discharge from the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

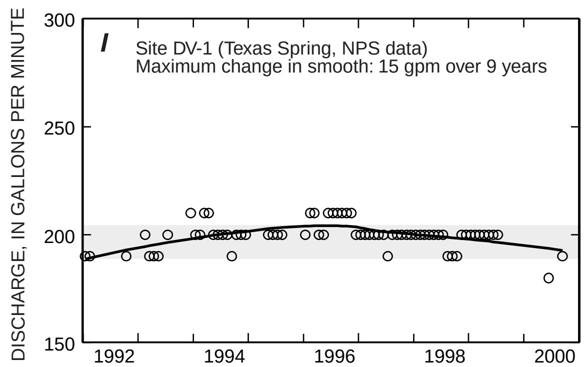


**Figure 16.** Continued.

## 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 |