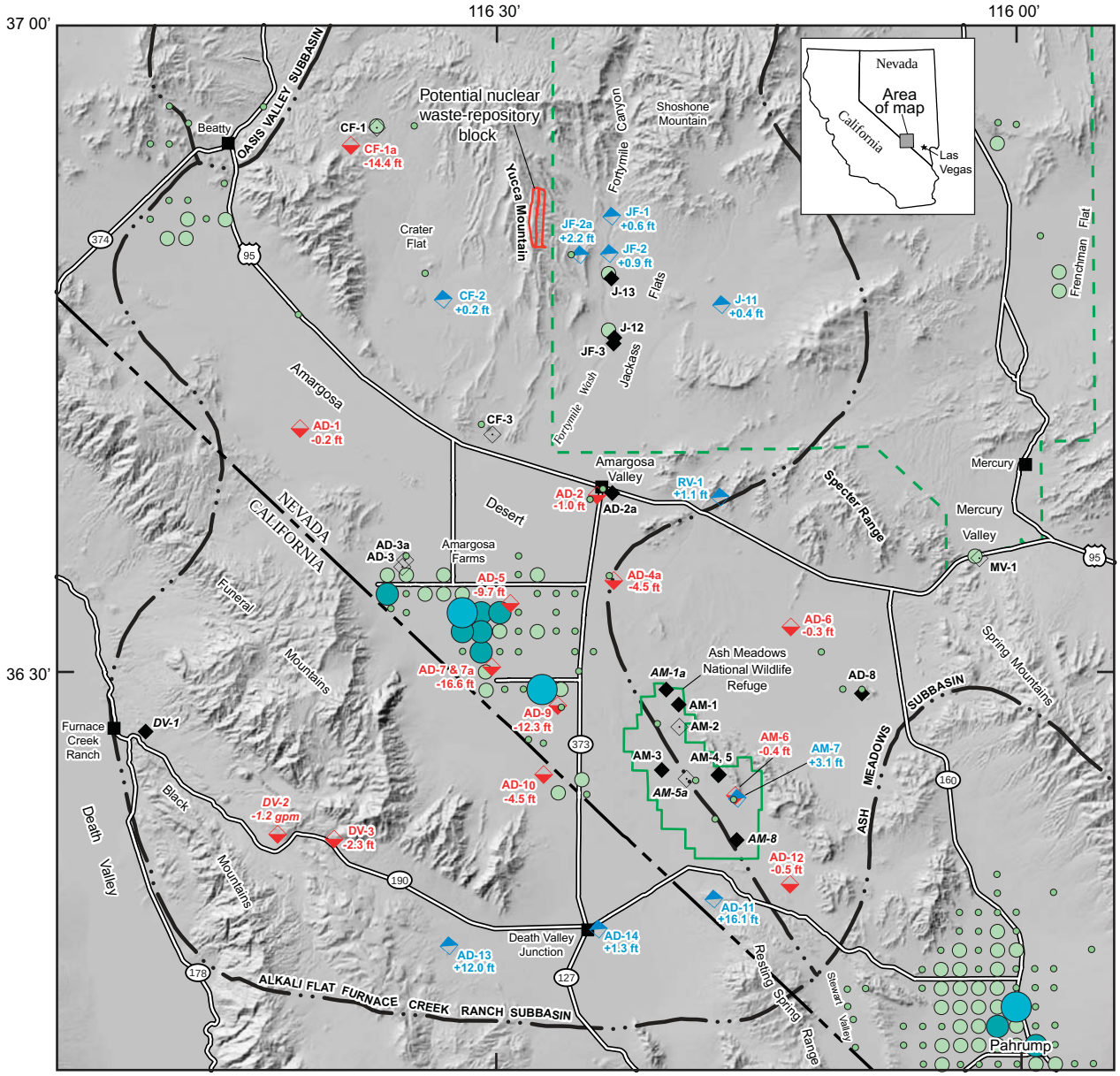

Base from U.S. Geological Survey digital data, 1:100,000 1978 89: Universal Transverse Mercator Projection, Zone 11. Shaded relief base from 1:24,000-scale National Elevation Data (NED) source date July 2000

0 5 10 15 MILES

0 5 10 15 KILOMETERS

EXPLANATION

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

AD-13 13.6 ft — Significant upward trend

CF-1a -13.6 ft — Significant downward trend

J-13 — No significant upward or downward trend

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

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

Nevada Test Site boundary

Total withdrawals from 1992 to 2000, in acre-feet

10 - 500

501 - 5,000

5,001 - 10,000

10,001 - 21,000

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

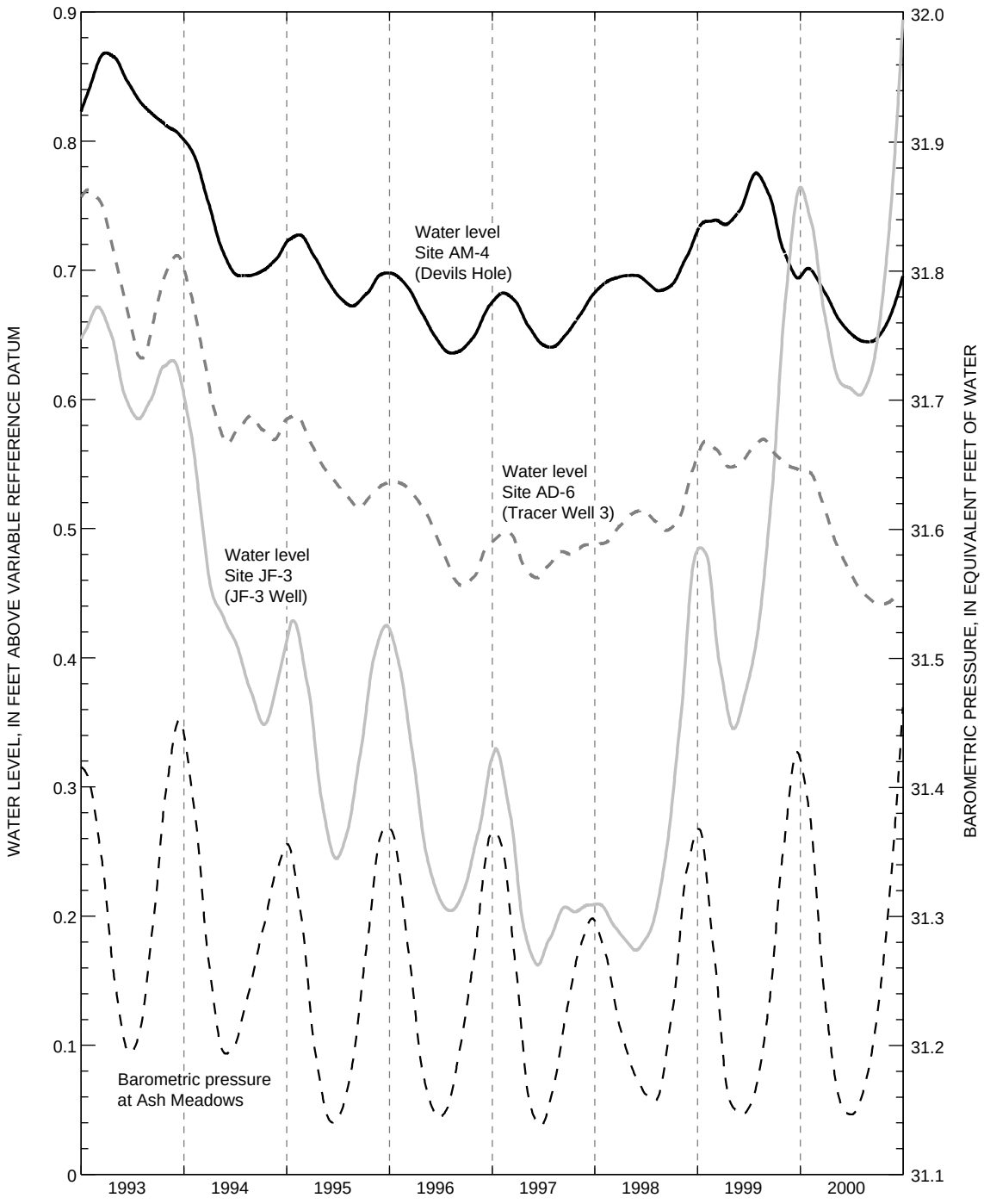

Figure 18. Relation of seasonal fluctuations in continual water levels at two sites in the regional carbonate-rock aquifer (Devils Hole and site AD-6) and one site in a volcanic-rock aquifer (site JF-3), 1993–2000. All hydrographs are smooths of daily mean water levels corrected for instantaneous effects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

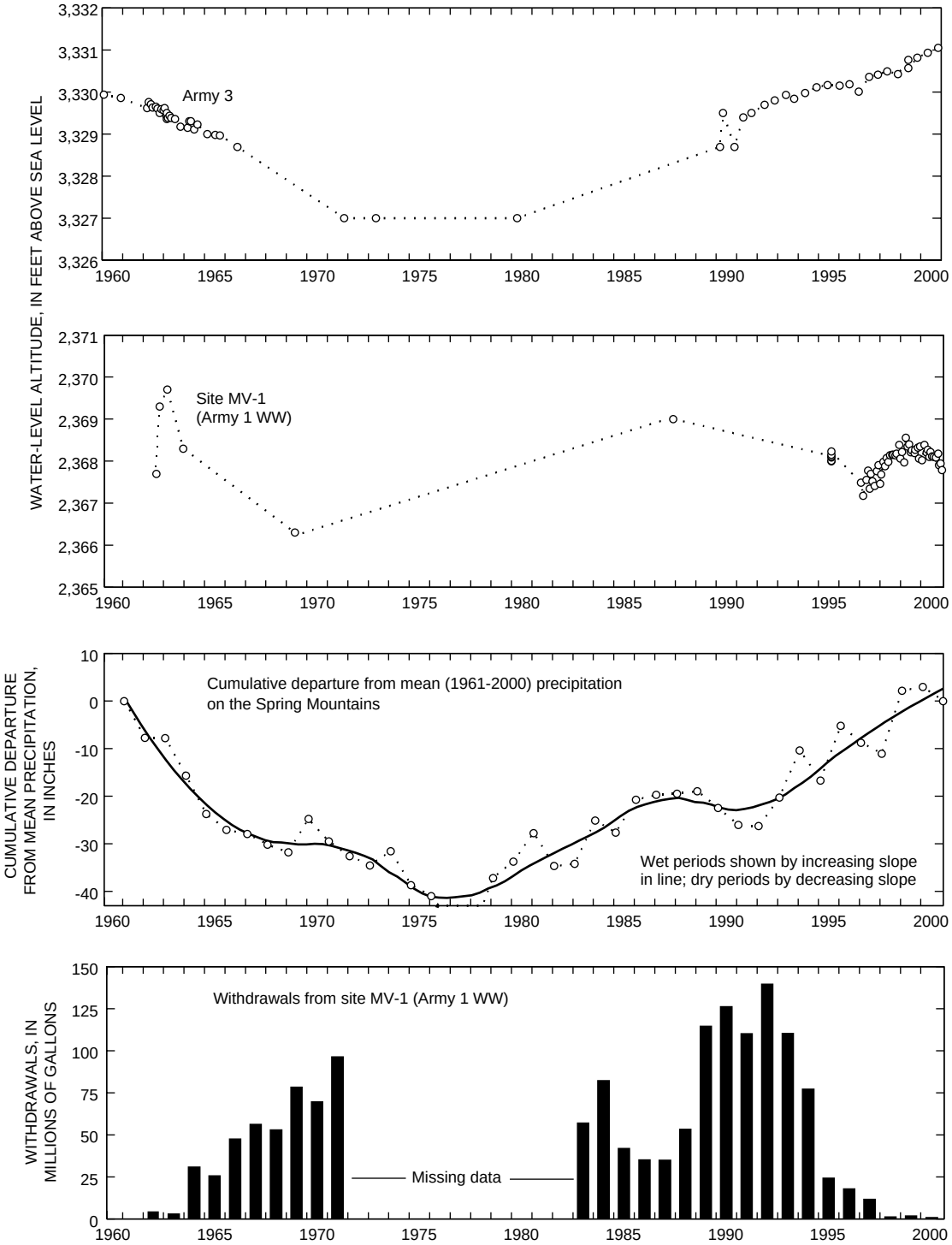

Figure 19. Relation of water levels in Army 3 and Army 1 WW to cumulative departure from mean precipitation in the Spring Mountains and annual ground-water withdrawals at Army 1 WW, 1960–2000.

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

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

Climate Change

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

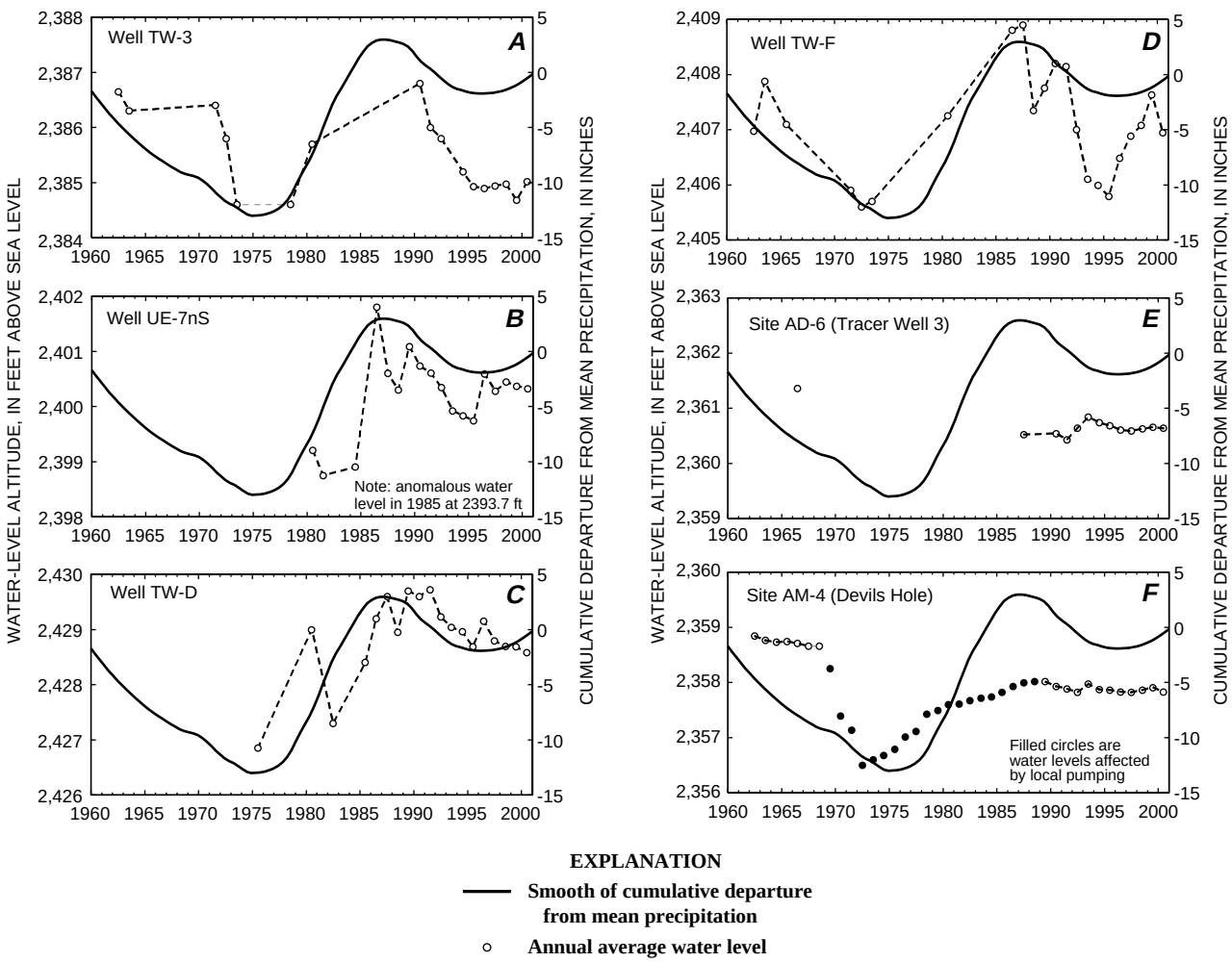

Figure 20. Relation of annual average water levels from the carbonate-rock aquifer in the Ash Meadows ground-water subbasin, and cumulative departure from mean precipitation for the south-central Nevada precipitation index, 1960–2000. Scales are the same for all plots.

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

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

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

Ground-Water Withdrawals

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

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

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

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

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

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

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

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

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

Seismic Events

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

Alkali Flat–Furnace Creek Ranch Ground-Water Subbasin

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

Jackass Flats

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

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

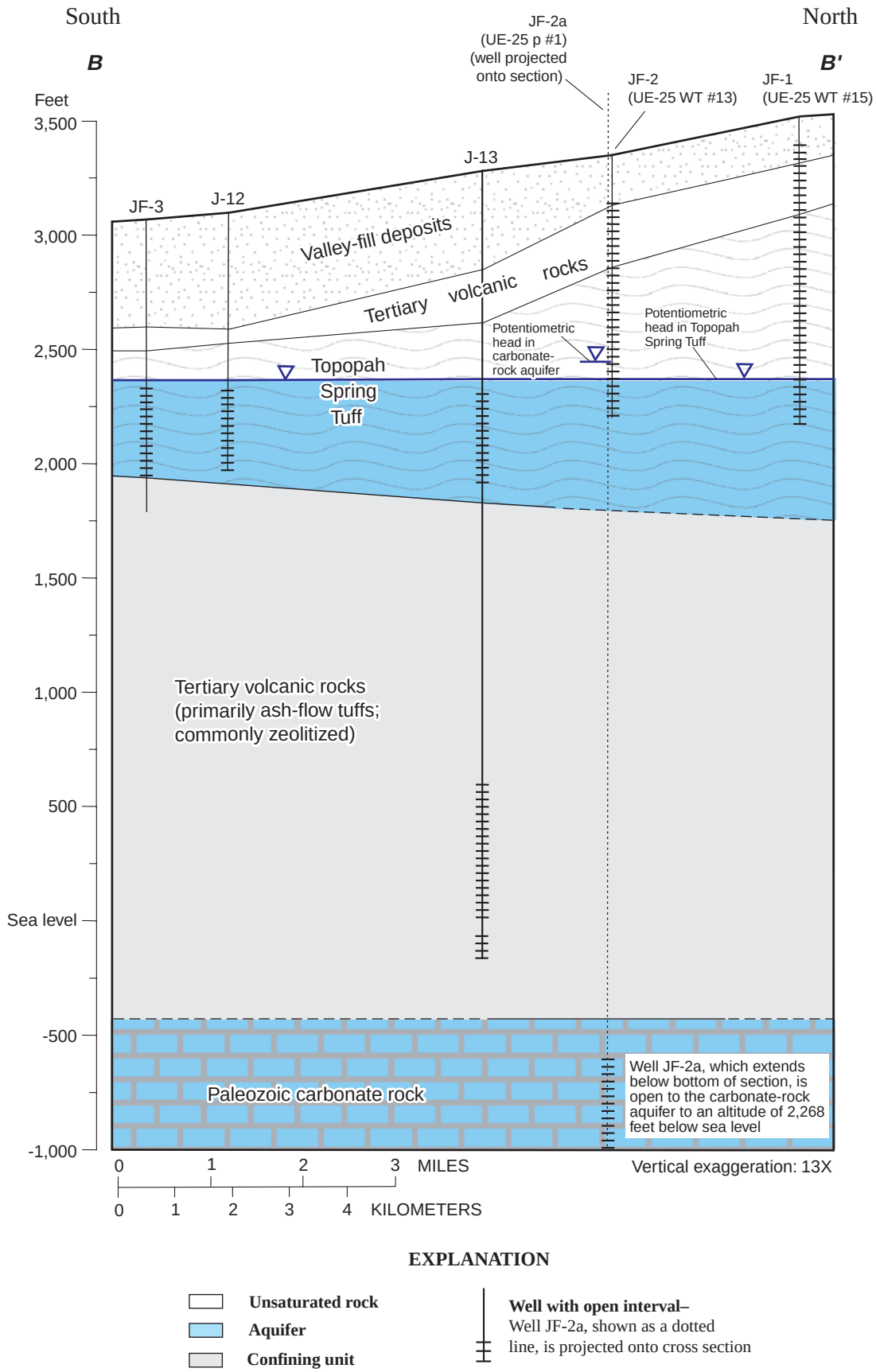

Figure 21. Hydrogeologic section along Fortymile Wash in Jackass Flats. Line of section is shown in figure 1*B*.

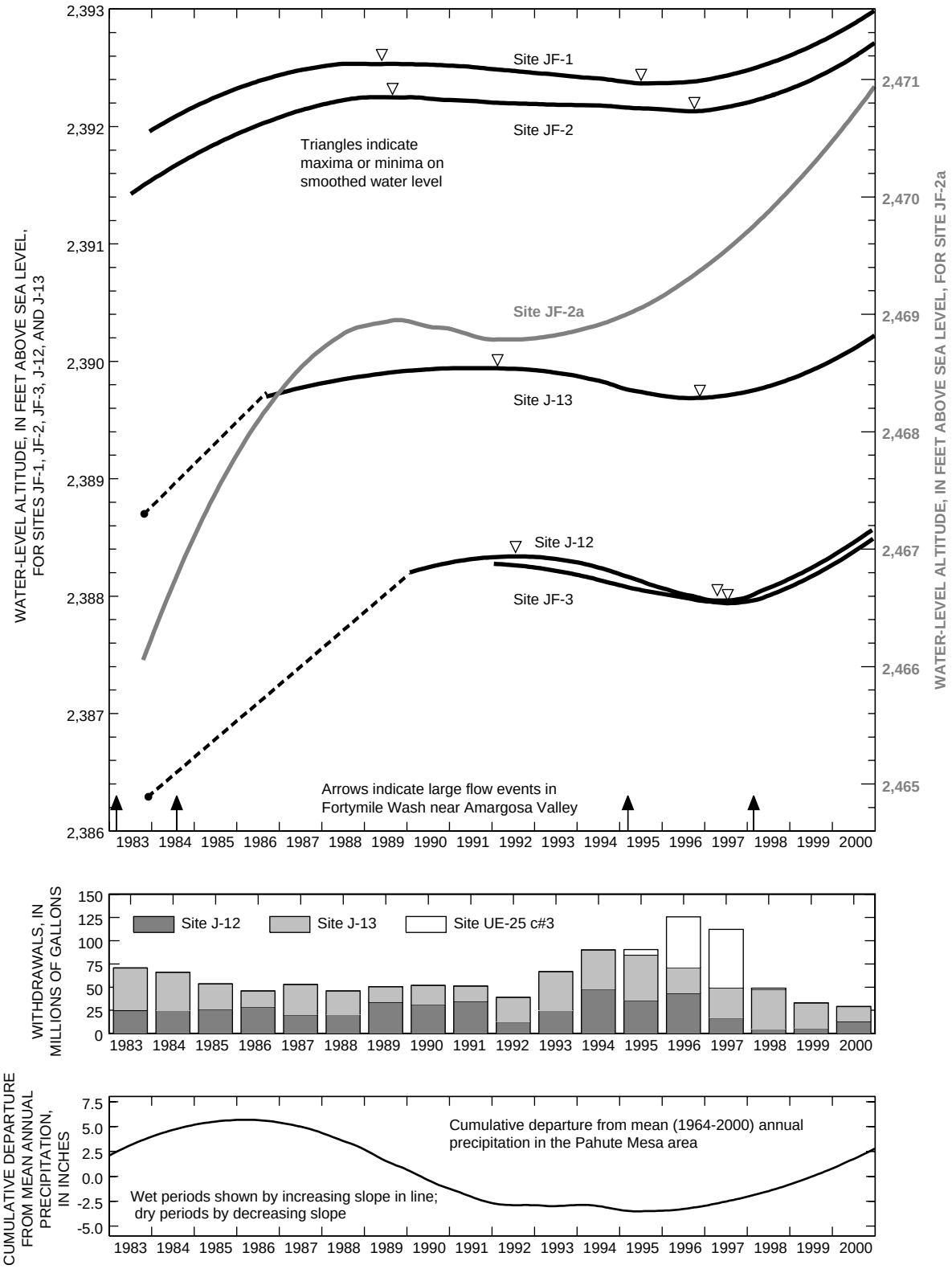

Figure 22. Relation among cumulative departure from mean annual precipitation on Pahute Mesa area, annual pumpage in Jackass Flats, and smoothed periodic or monthly mean water levels in six wells along Fortymile Wash, 1983–2000.

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

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

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

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

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

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

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

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

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

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

Amargosa Desert

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

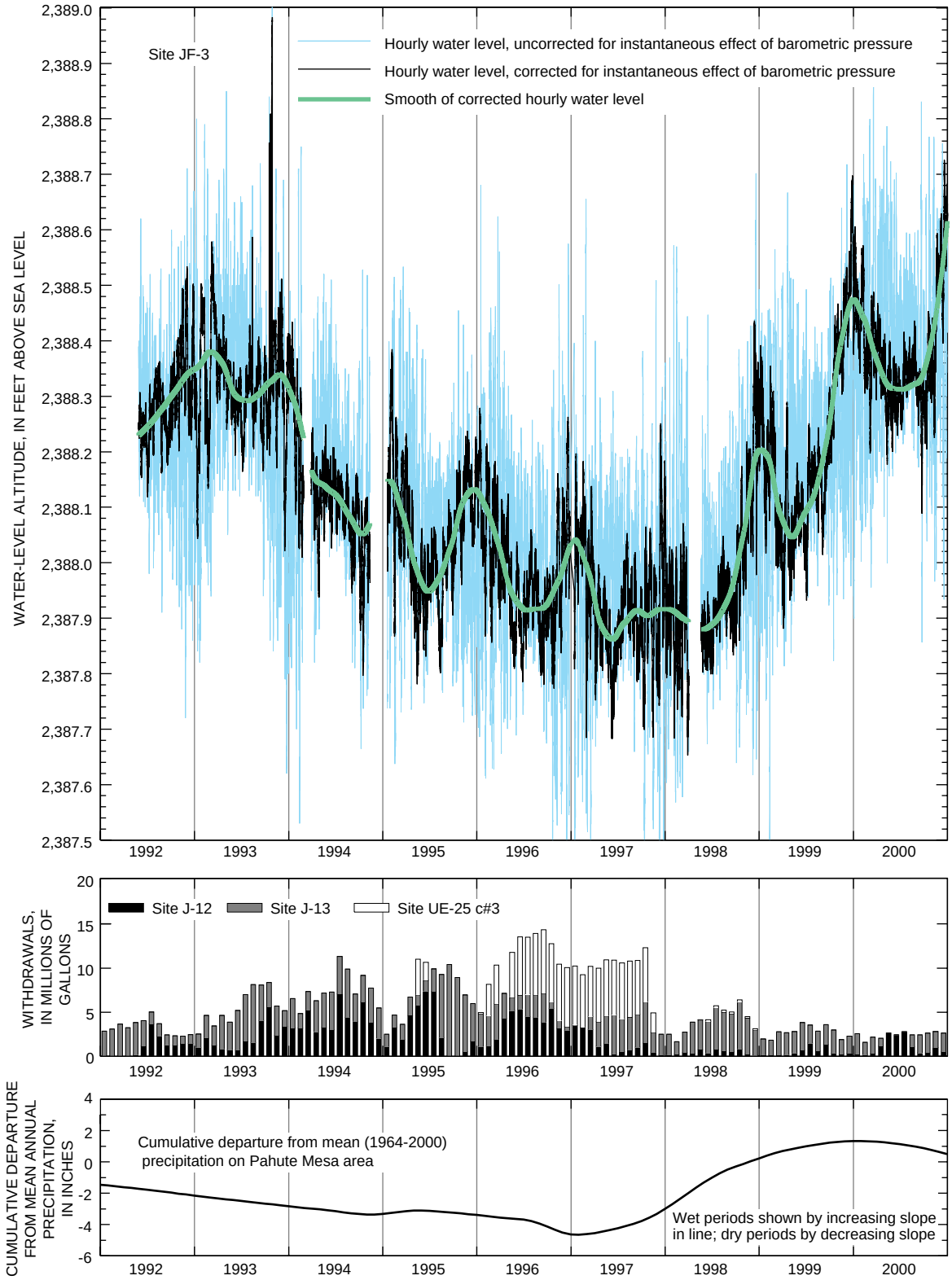

Figure 23. Relation among cumulative departure from mean annual precipitation on Pahute Mesa area, monthly pumpage in Jackass Flats, and hourly water levels in well JF-3 uncorrected and corrected for instantaneous effects of barometric pressure, 1992–2000.

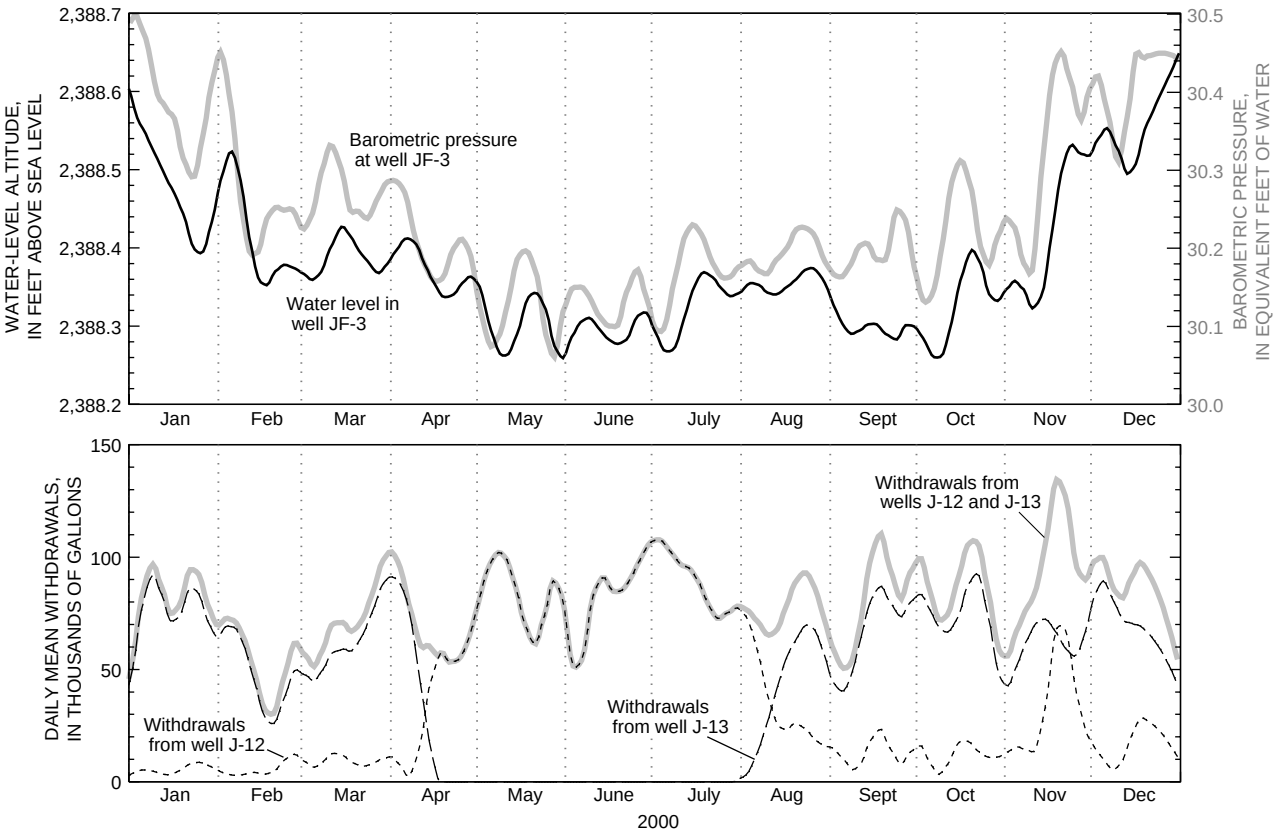

Figure 24. Relation between smooth of daily mean water levels in well JF-3 corrected for instantaneous effects of barometric pressure, barometric pressure at well JF-3, and smooths of daily mean pumpage from wells J-12 and J-13, 2000.

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

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

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

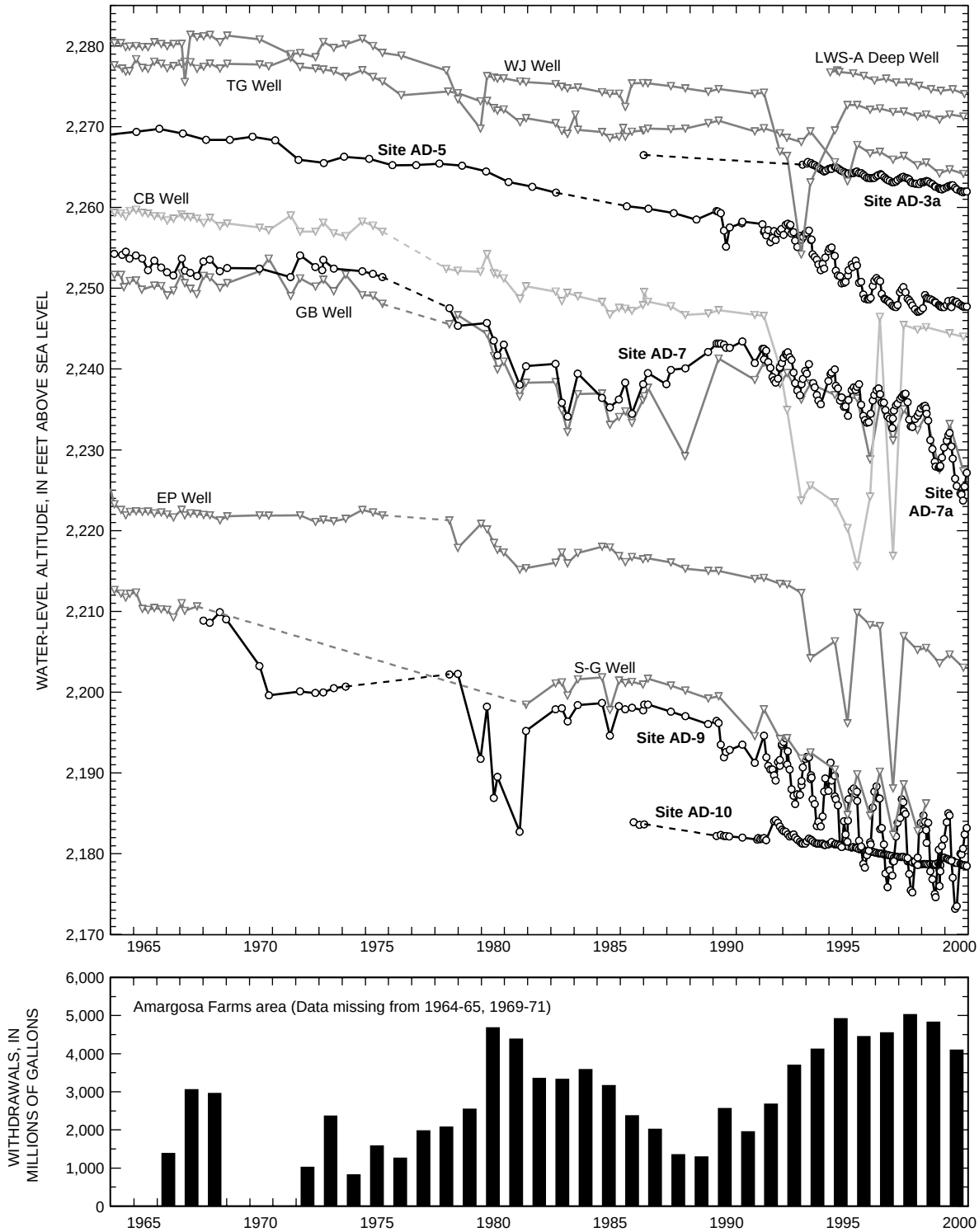

Figure 25. Relation between water levels in selected wells and estimated annual ground-water withdrawals in the Amargosa Farms area, 1964–2000. Network wells in bold.

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

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

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

Death Valley

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

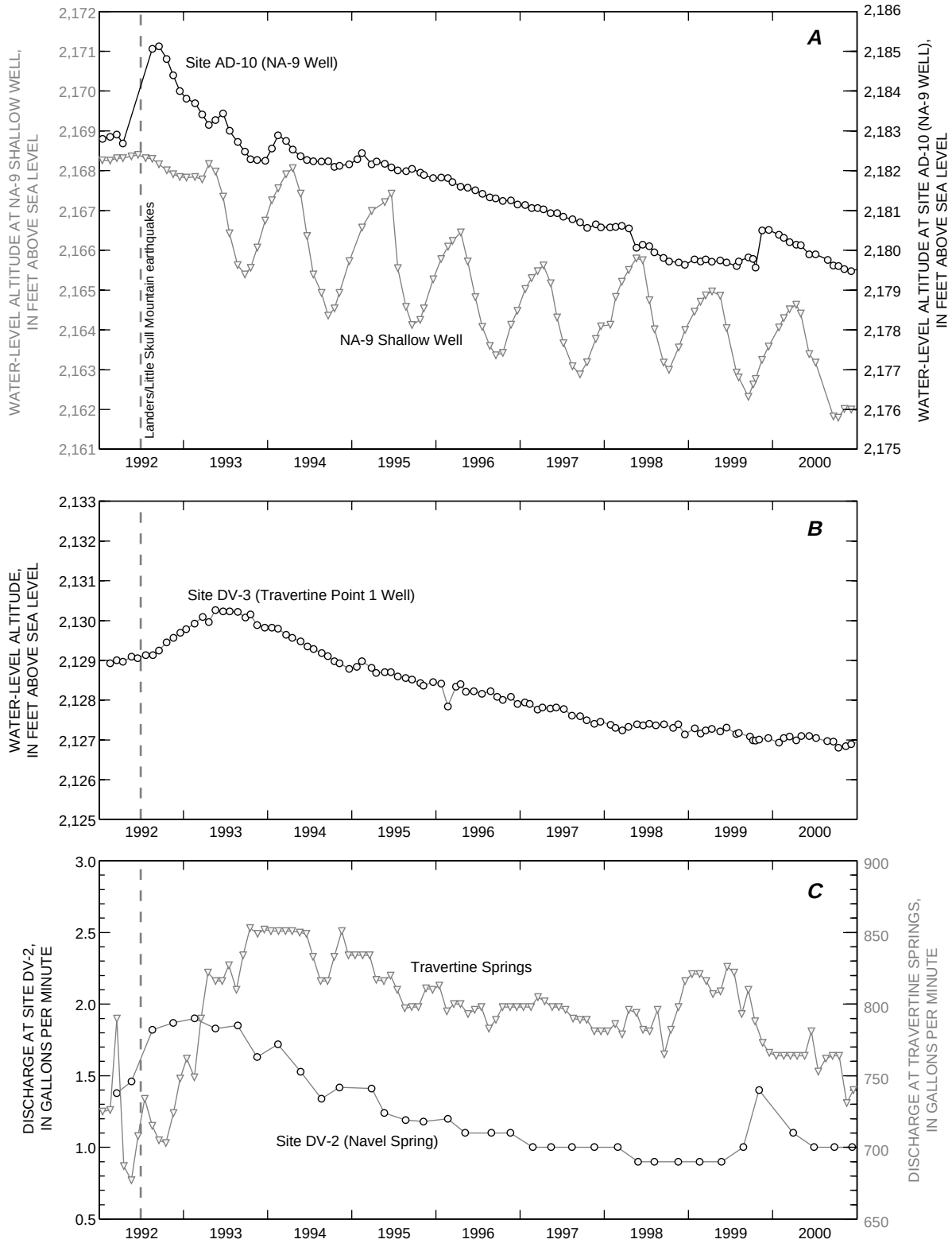

Figure 26. Relation among (A) water levels at site AD-10 (NA-9 Well) and NA-9 Shallow Well; (B) water levels at site DV-3 (Travertine Point 1 Well); and (C) discharges at site DV-2 (Navel Spring) and Travertine Springs, 1992–2000.

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

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

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

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

SUMMARY

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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APPENDIX A: BASIC DATA PLOTS

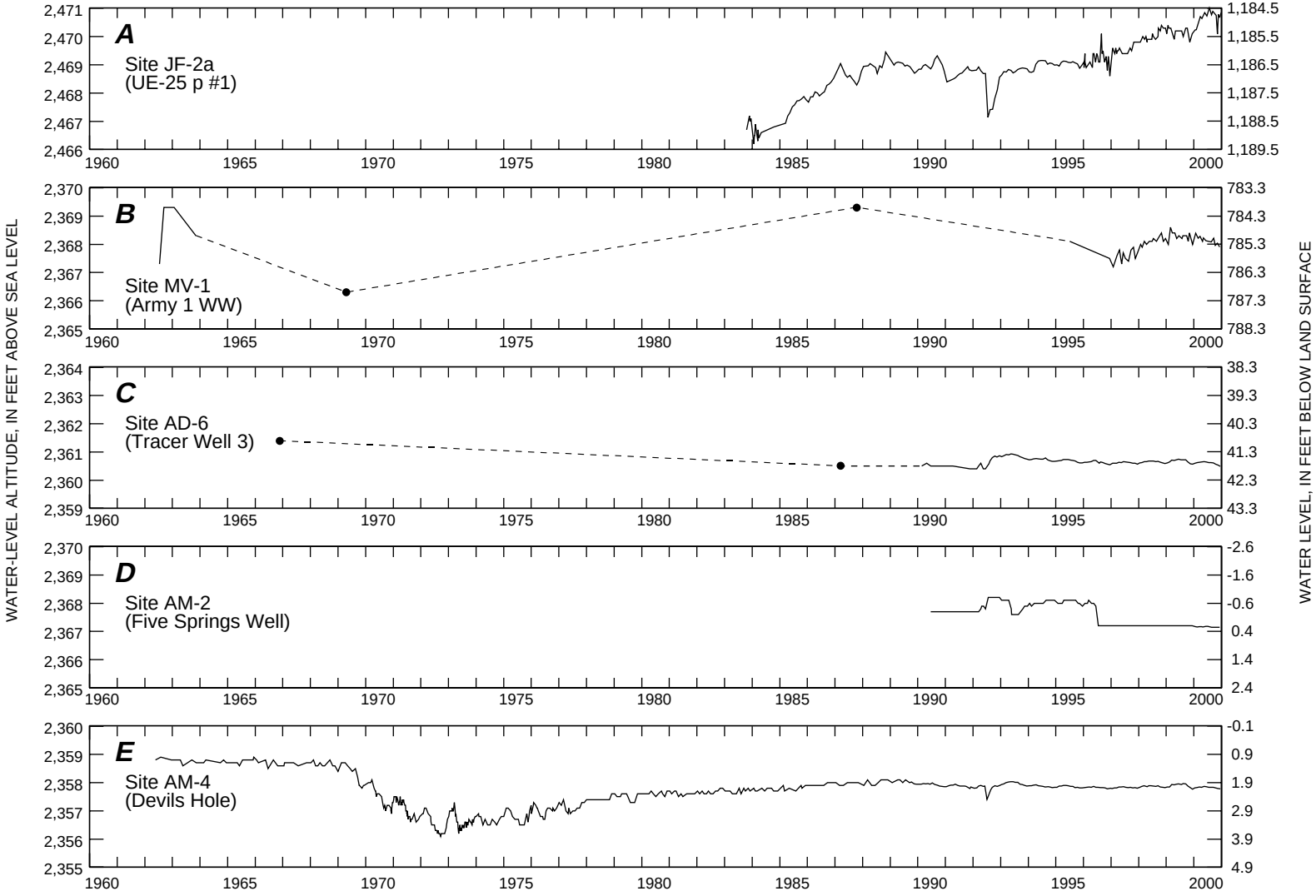
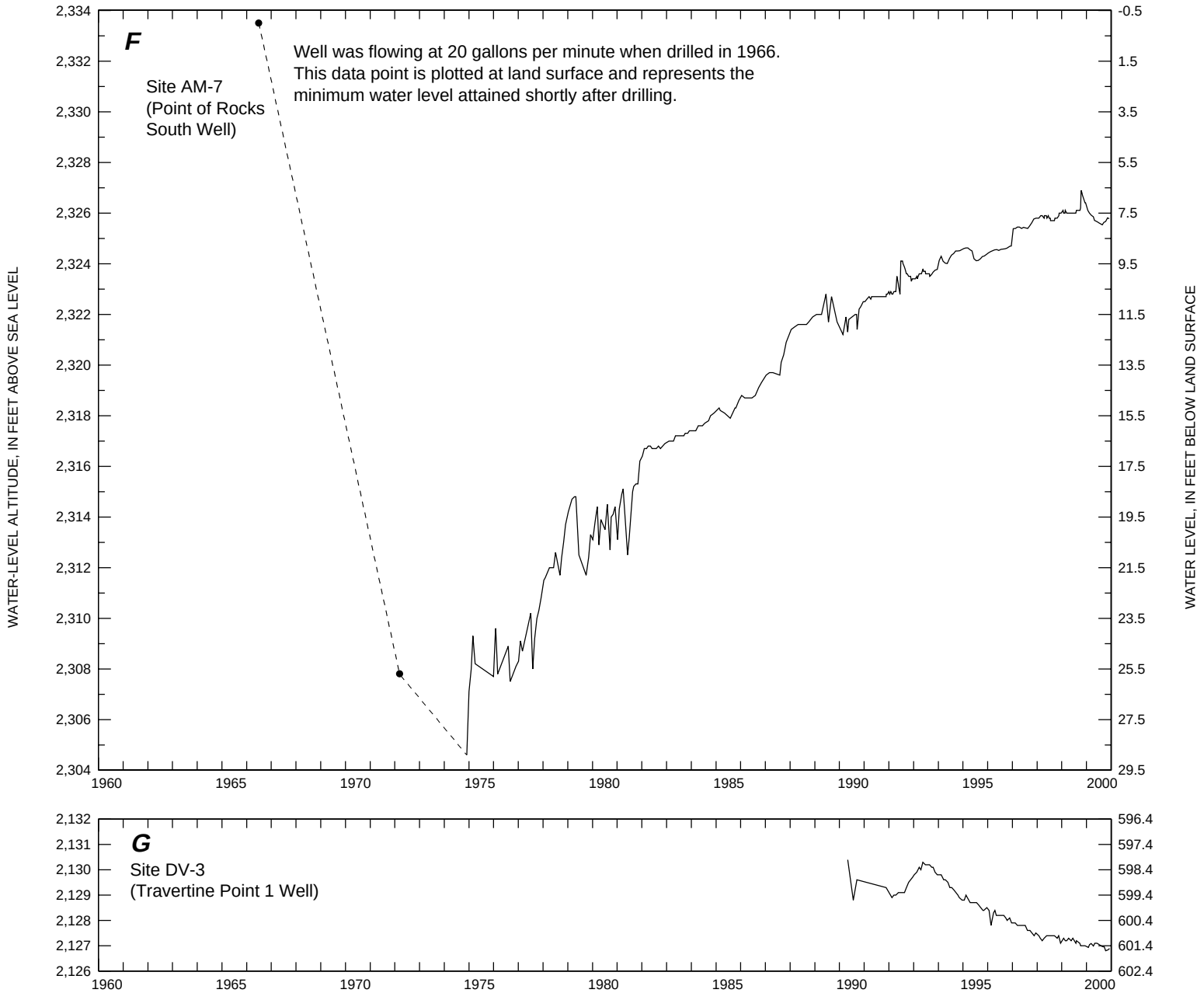


Figure 27. Water levels from 1960 to 2000 for selected sites at which primary contributing units are carbonate rock. Lines connect periodic data (or monthly mean data where continual data were available) and are dashed where measurements were not available for consecutive calendar years. Data that may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



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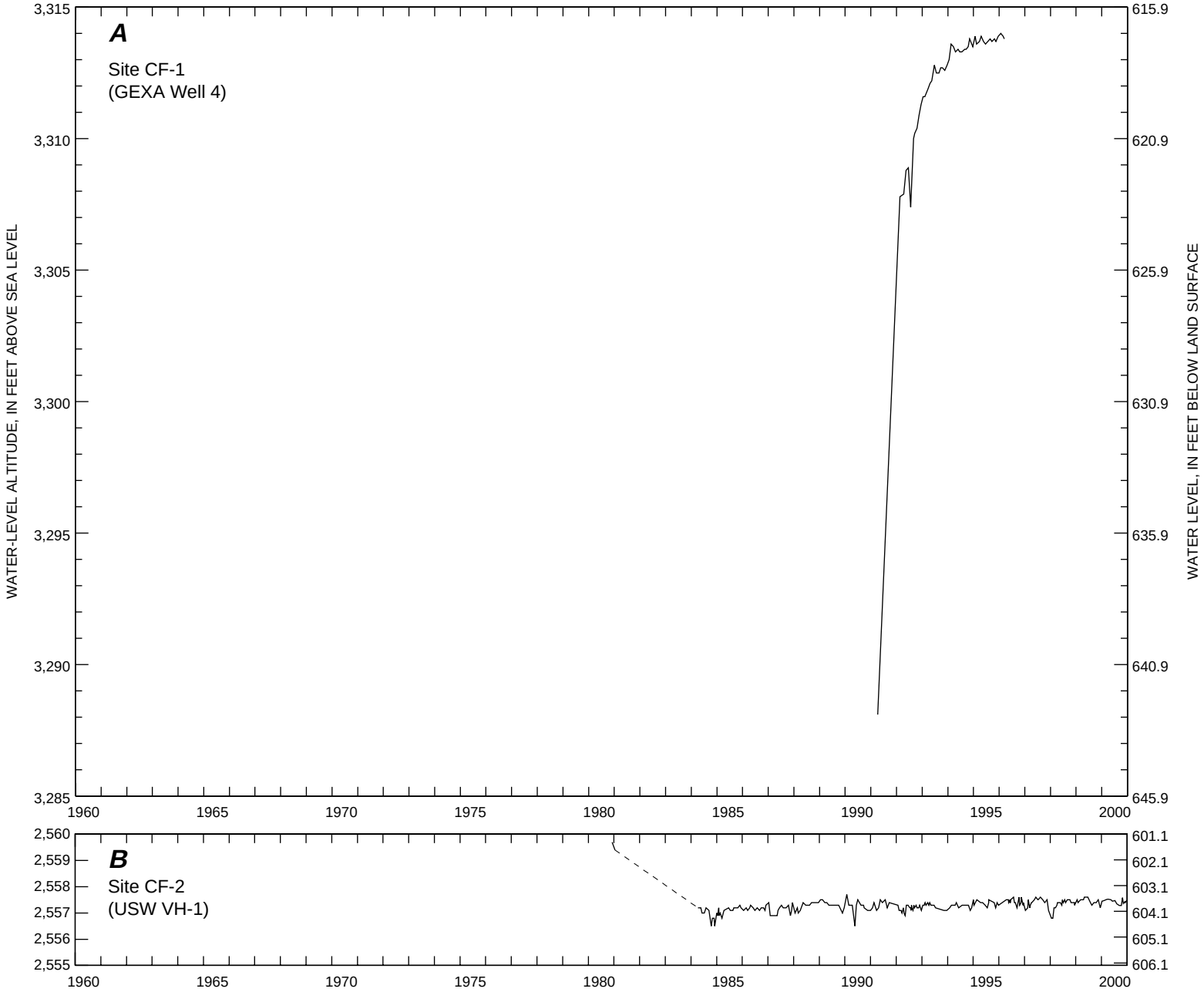
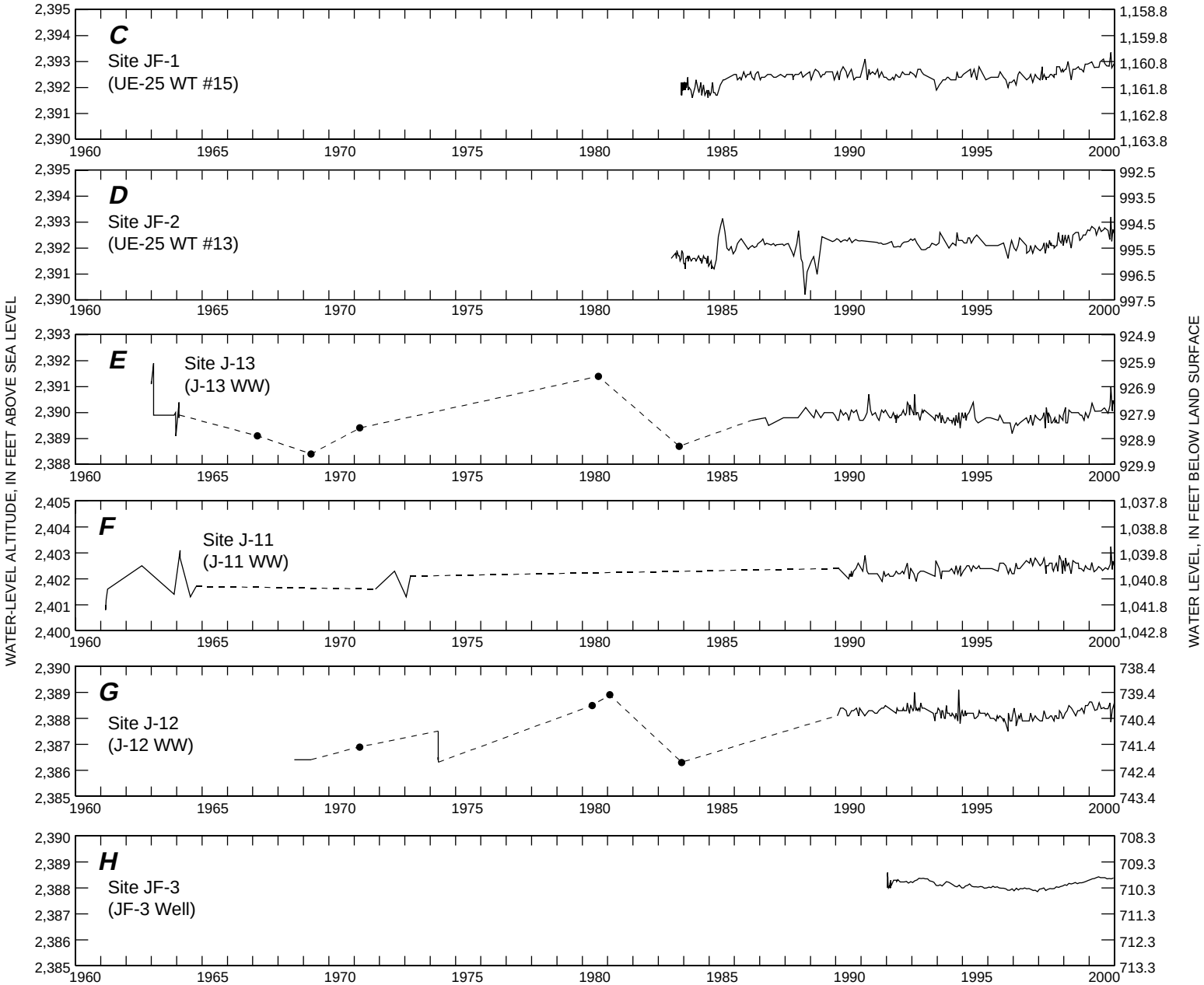


Figure 28. Water levels from 1960 to 2000 for selected sites at which primary contributing units are volcanic rock. Lines connect periodic data (or monthly mean data where continual data were available) and are dashed where measurements were not available for consecutive calendar years. Data that may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



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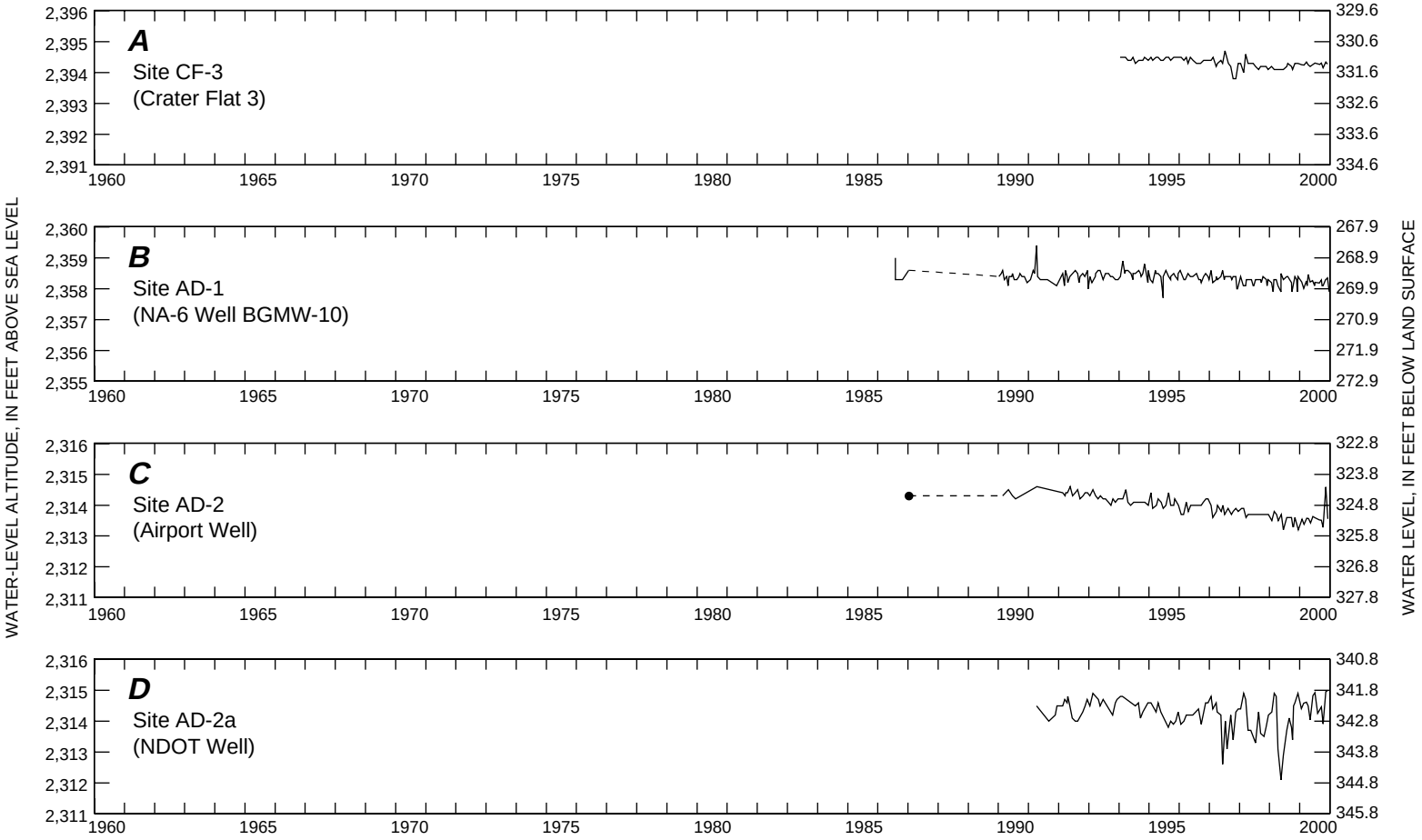
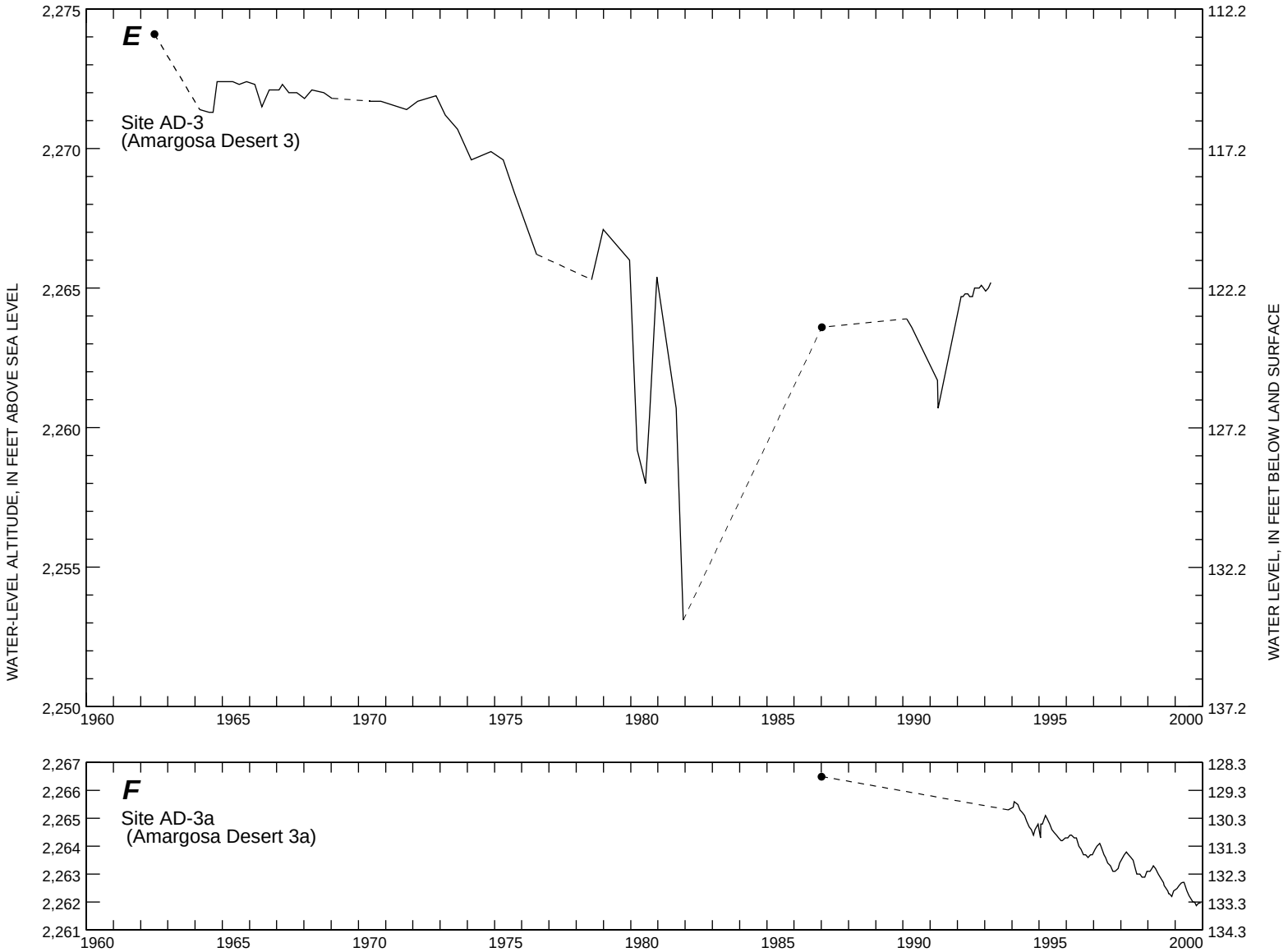


Figure 29. Water levels from 1960 to 2000 for selected sites at which primary contributing units are valley fill. Lines connect periodic data (or monthly mean data where continual data were available) and are dashed where measurements were not available for consecutive calendar years. Data that may represent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



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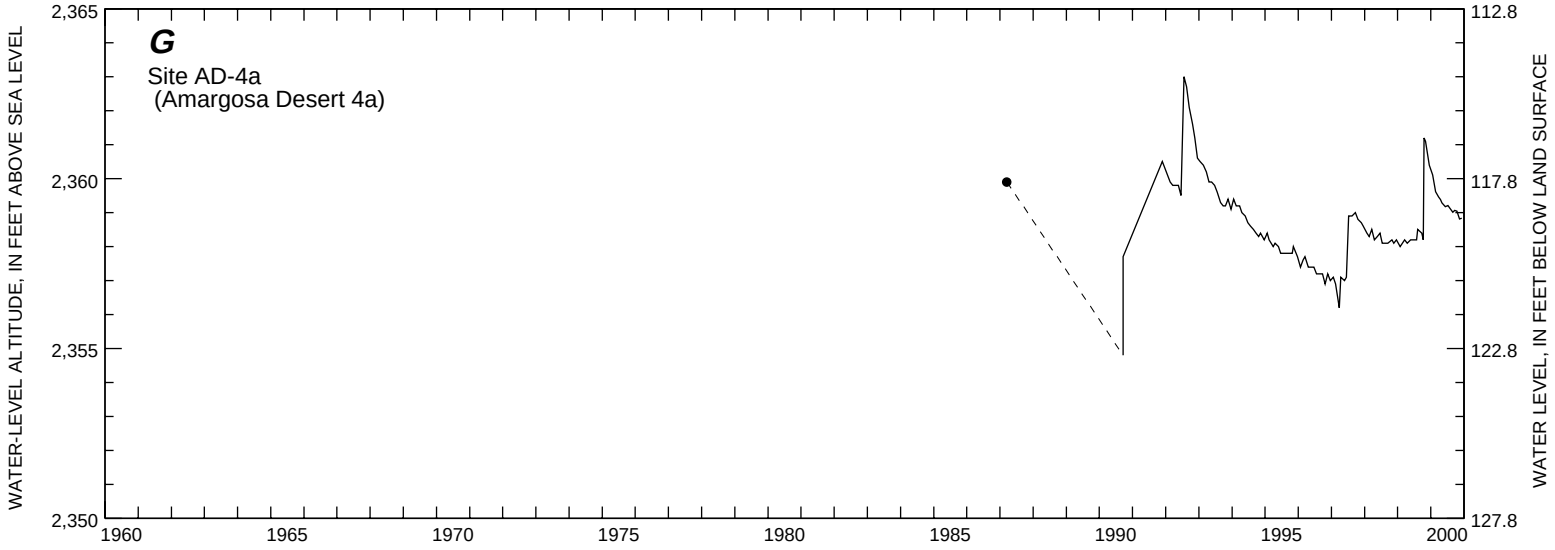

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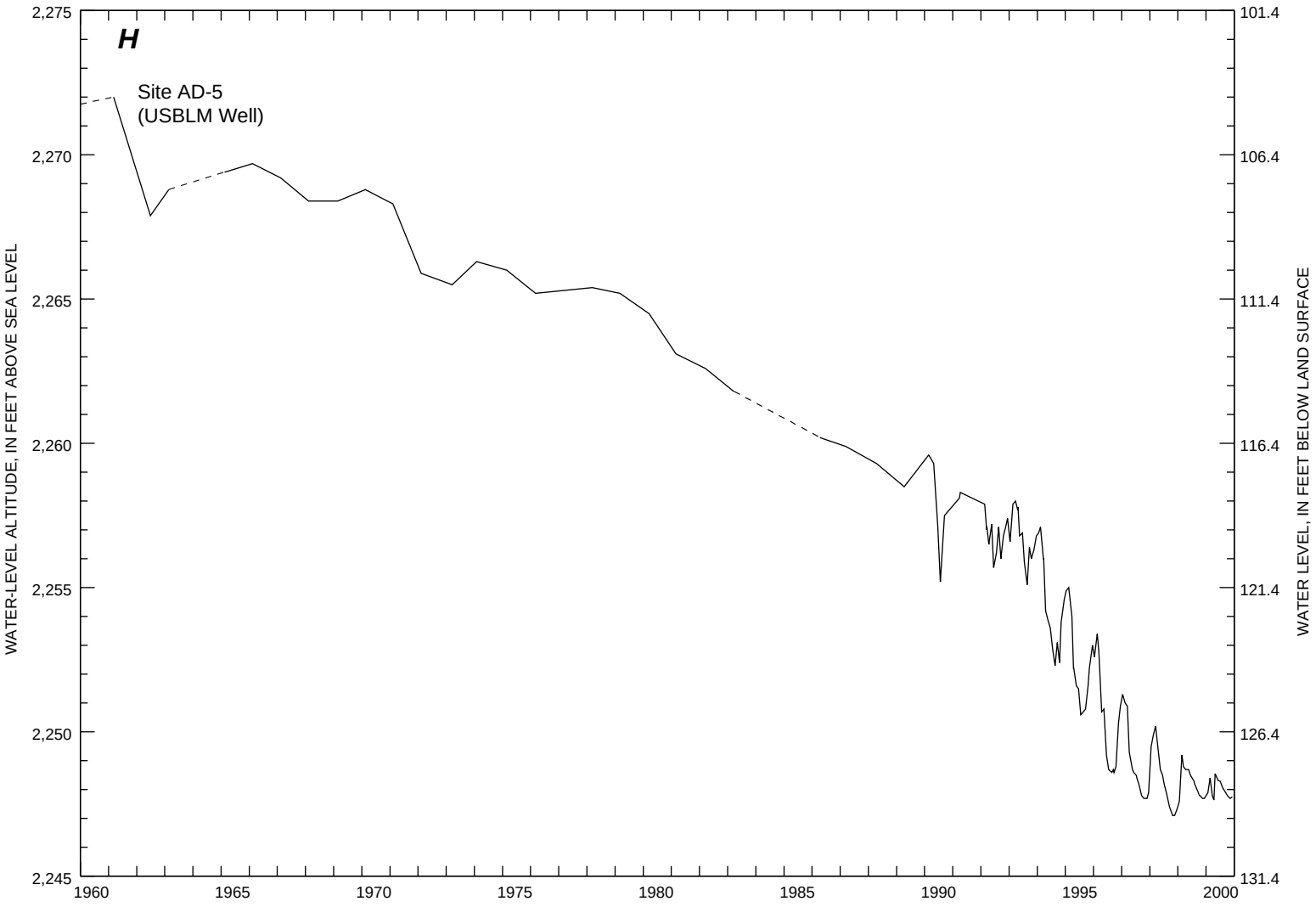

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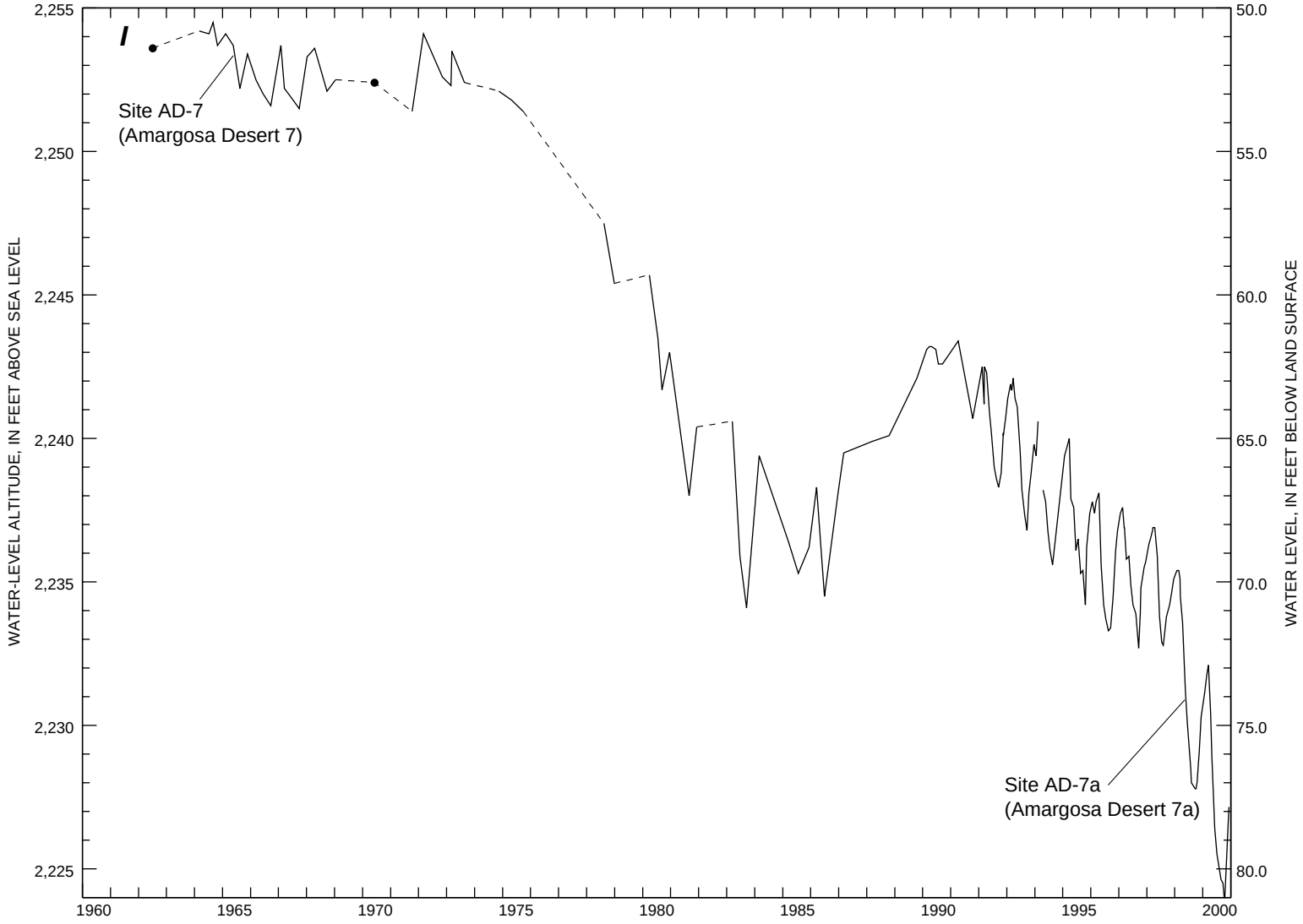

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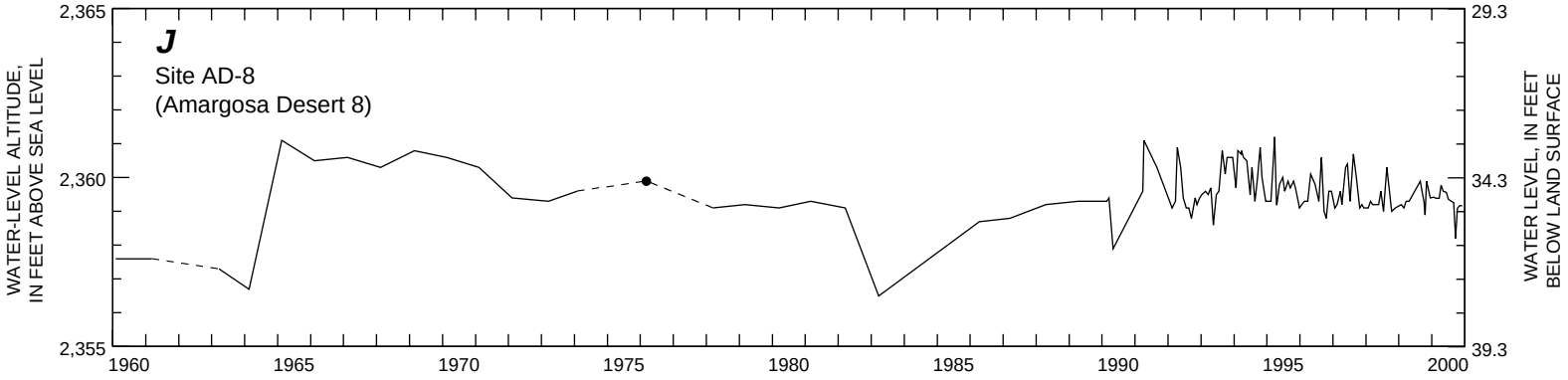

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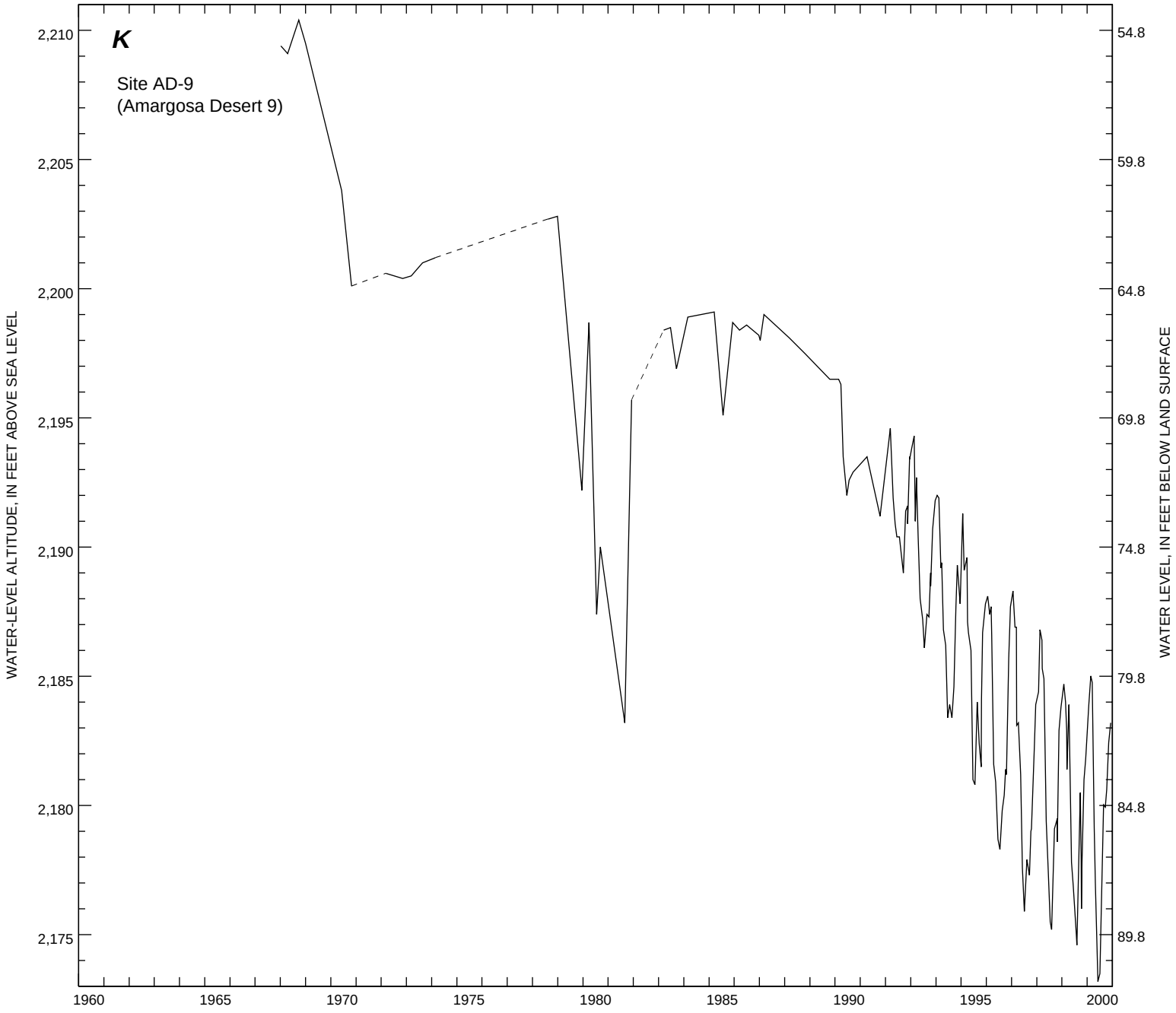

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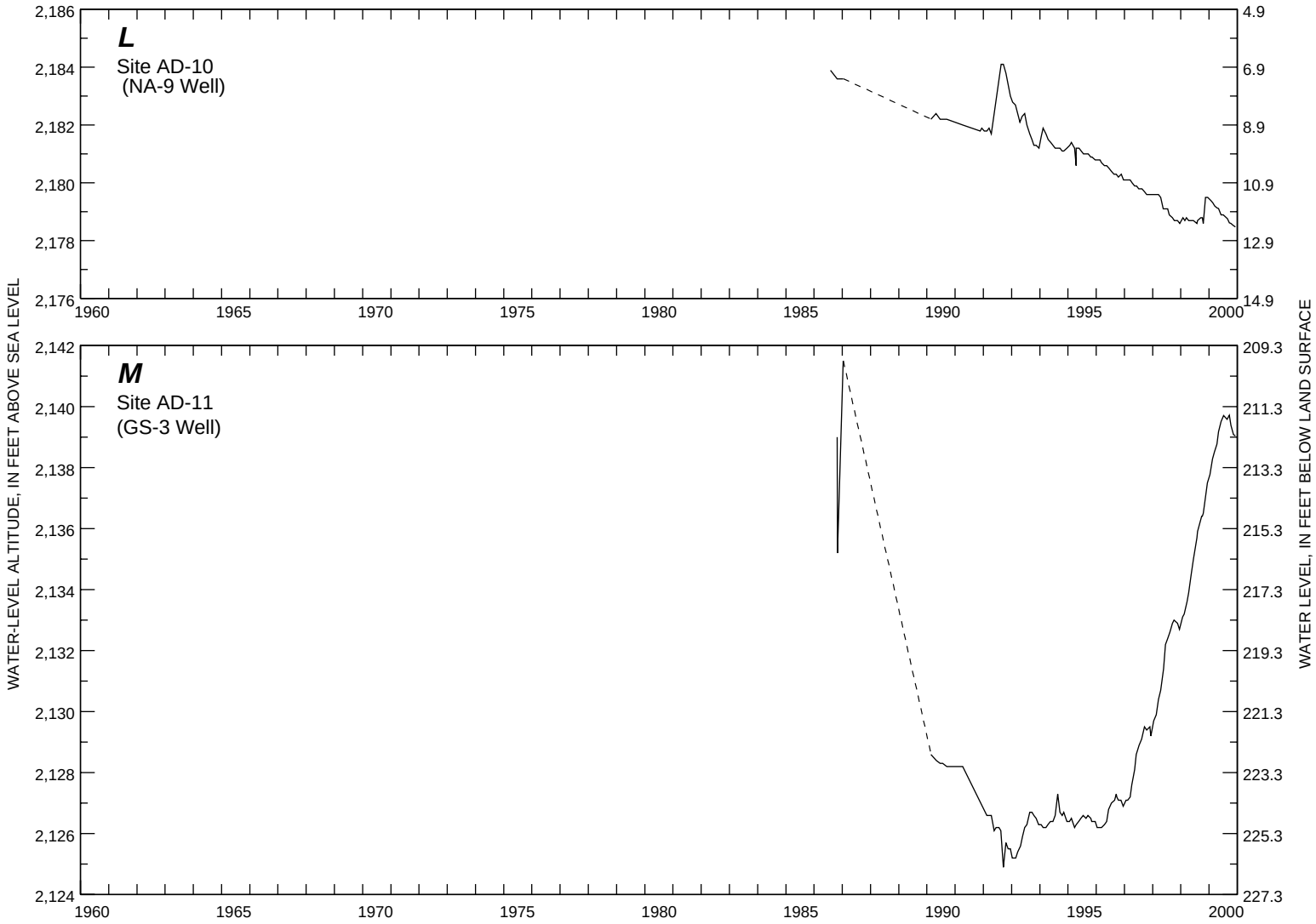

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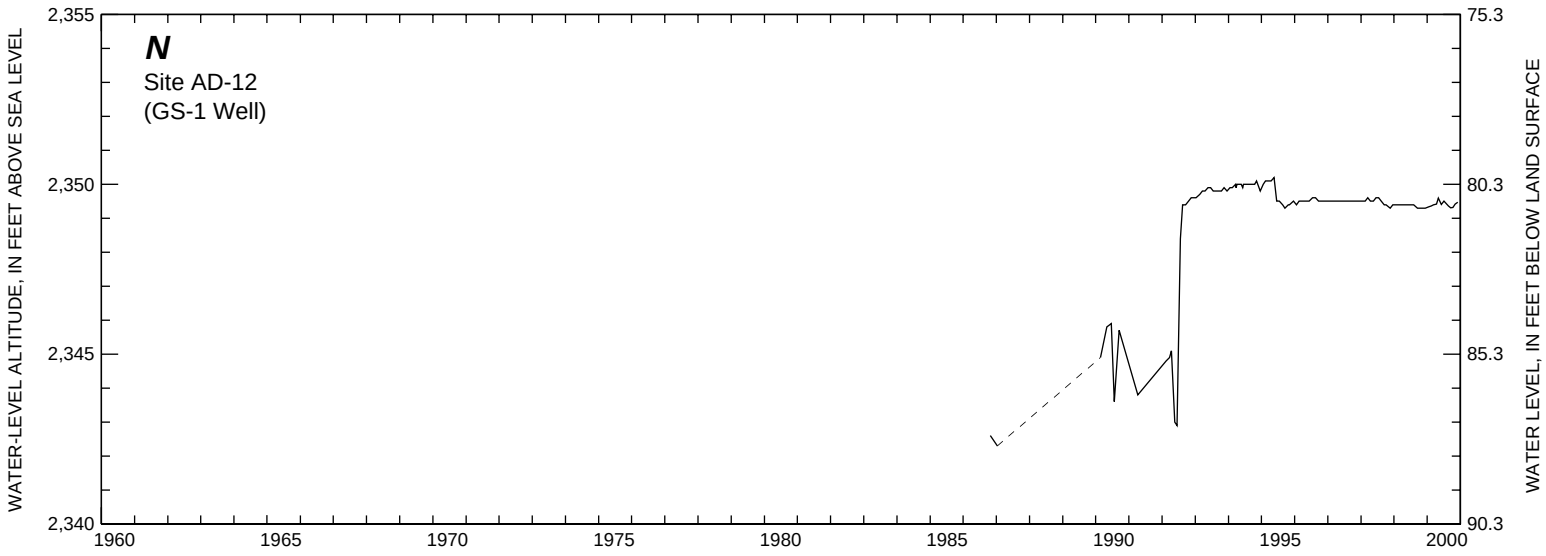

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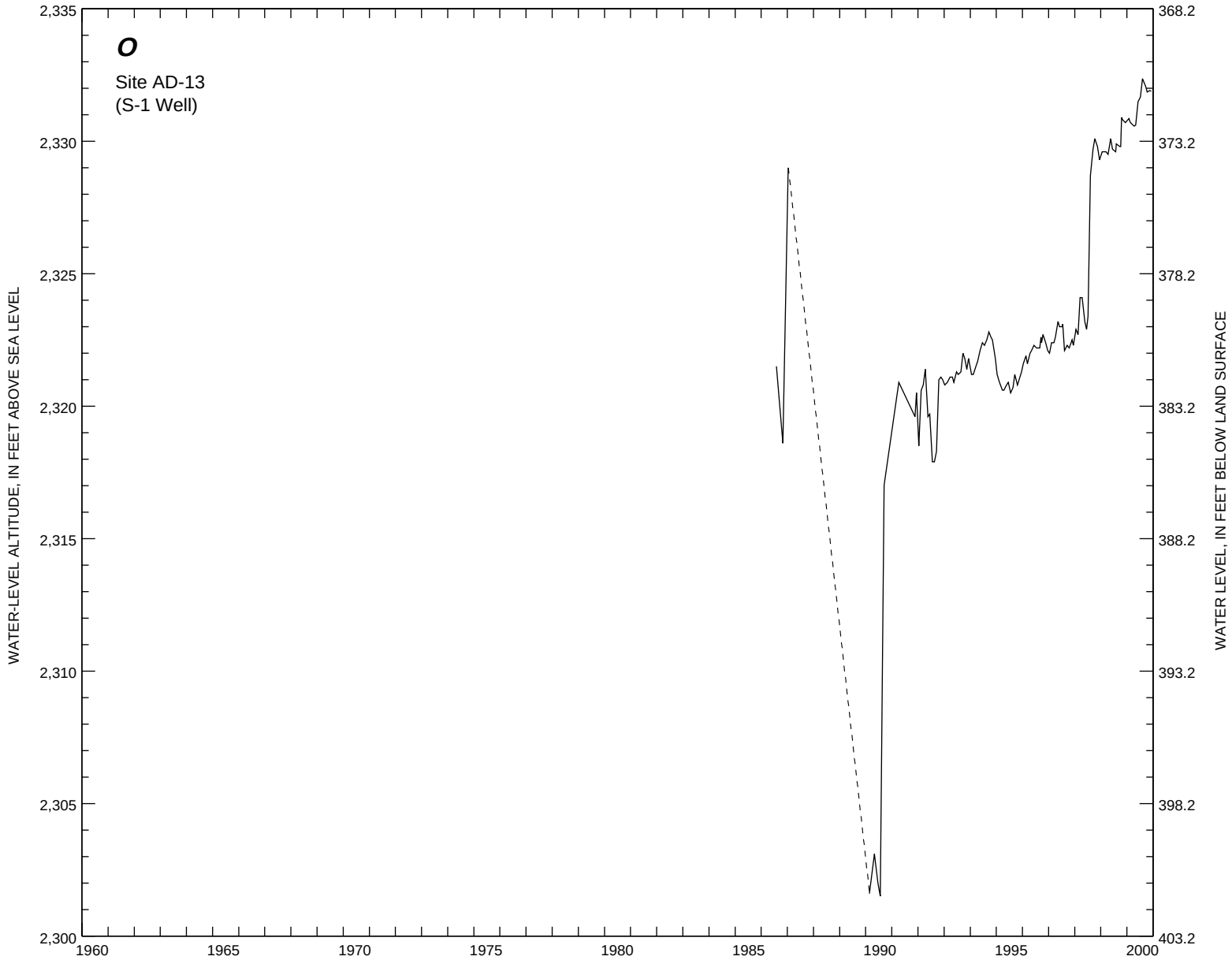

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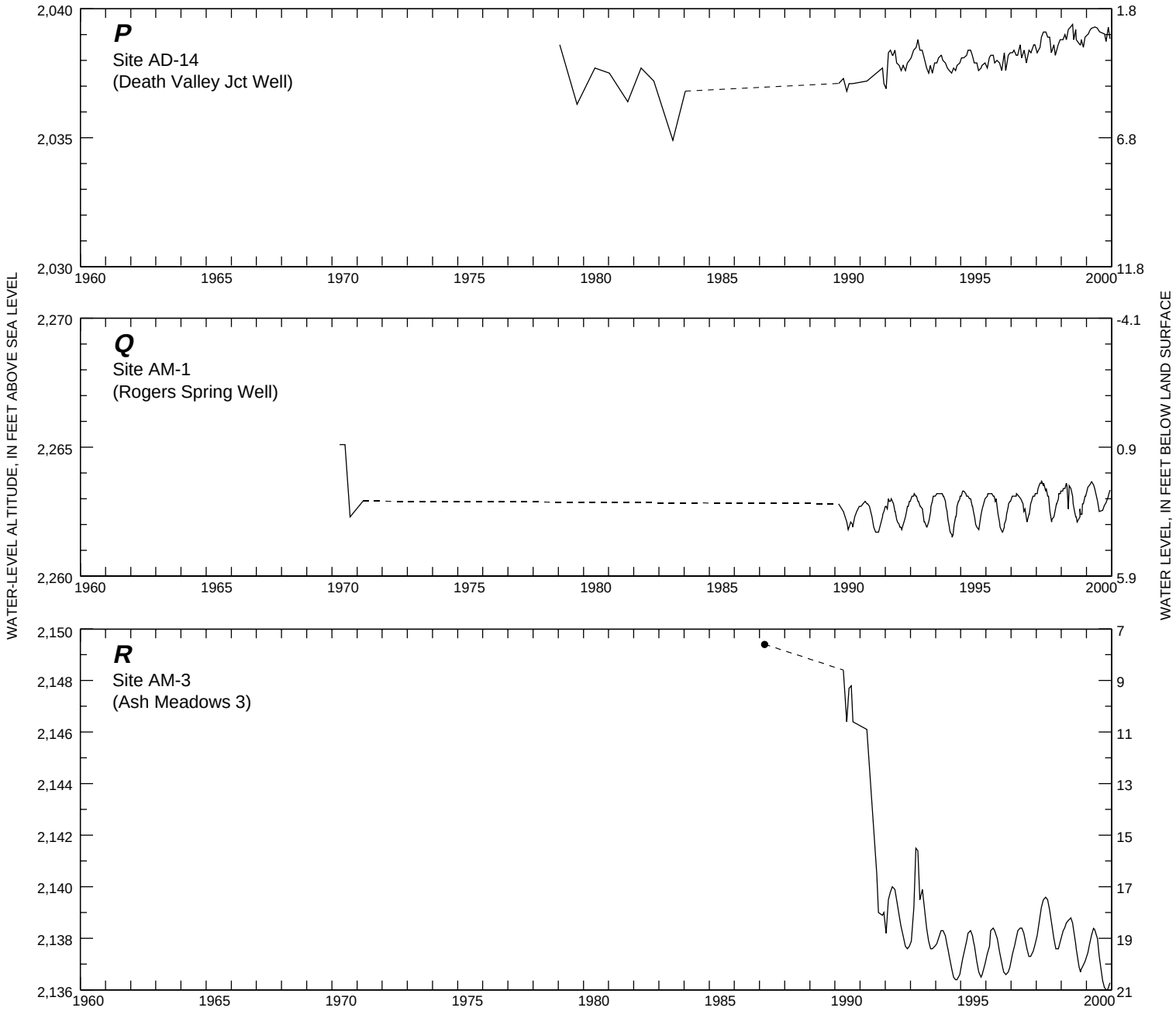

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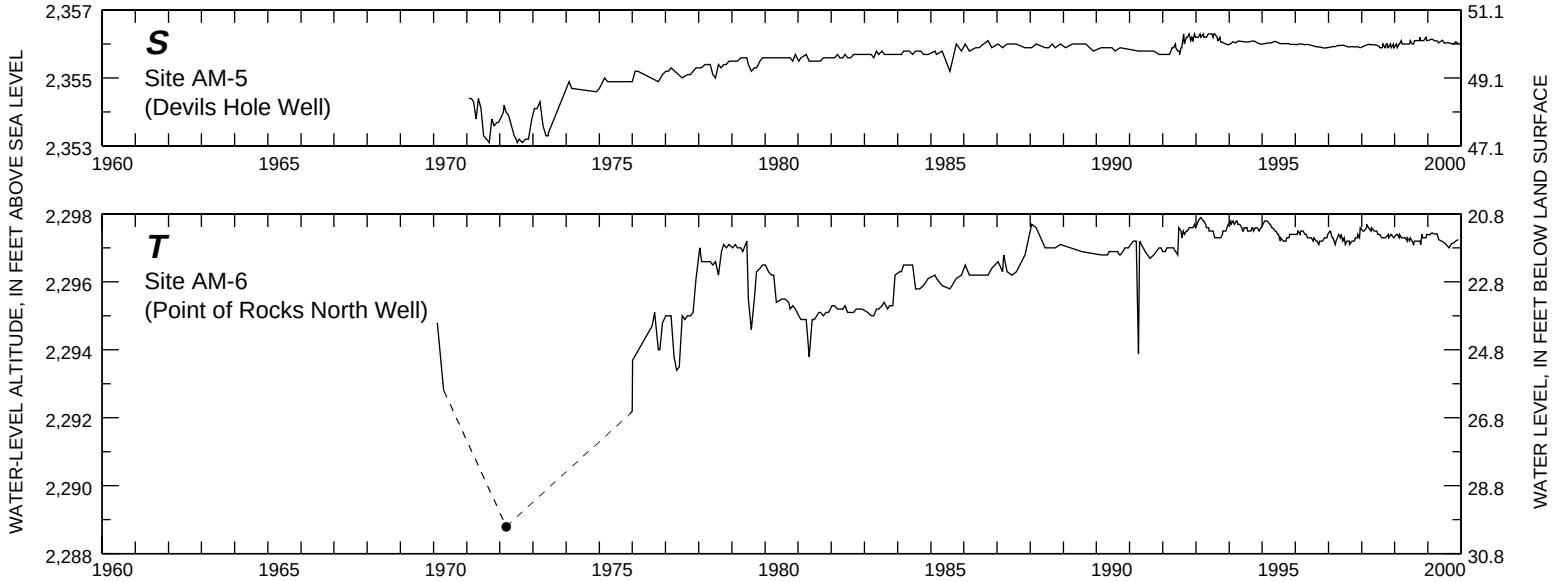

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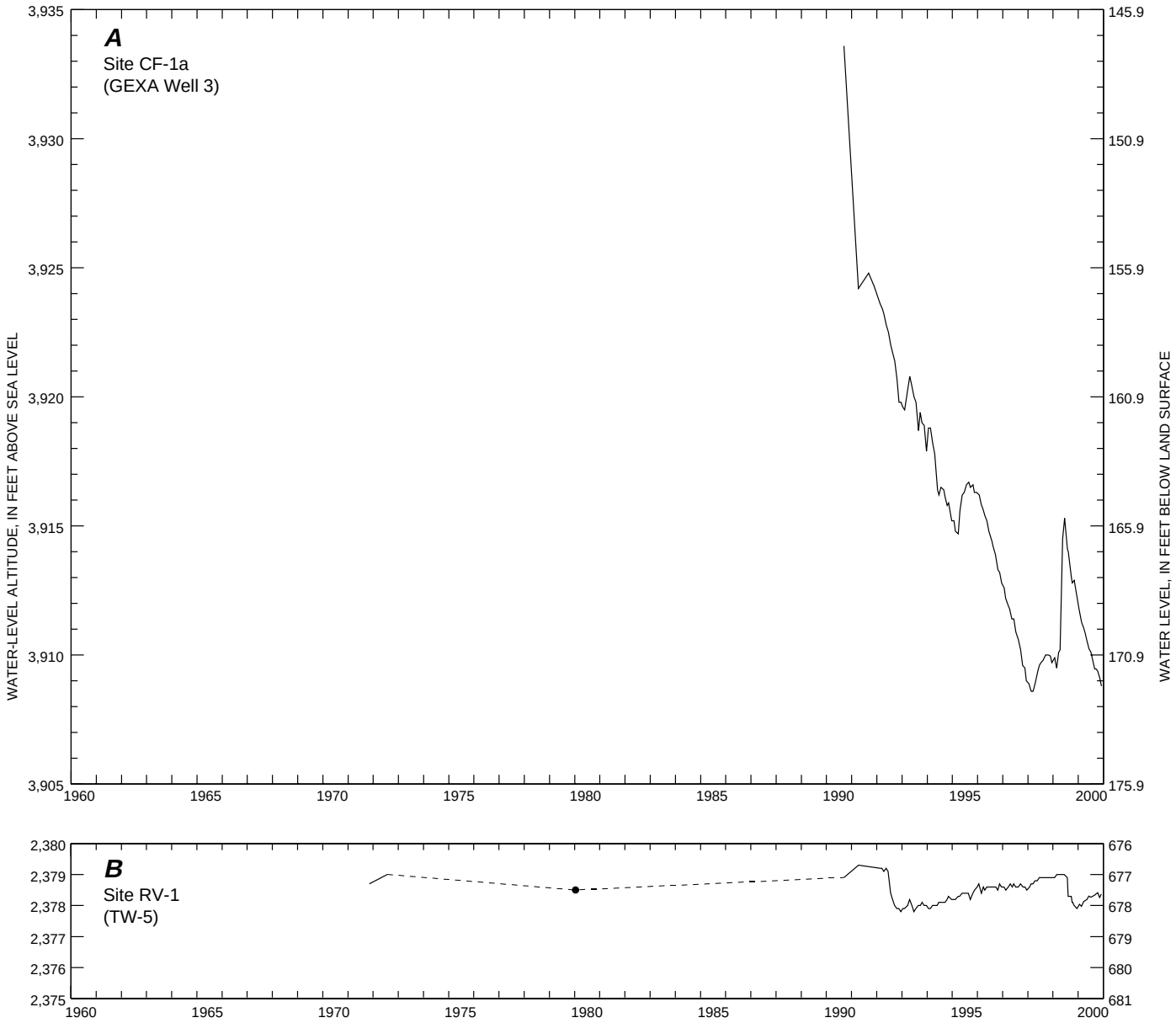

Figure 30. Water levels from 1960 to 2000 for selected sites at which primary contributing units are undifferentiated sedimentary rocks. Lines connect periodic data and are dashed where measurements were not available for consecutive calendar years. Data that may represent short-term conditions at a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

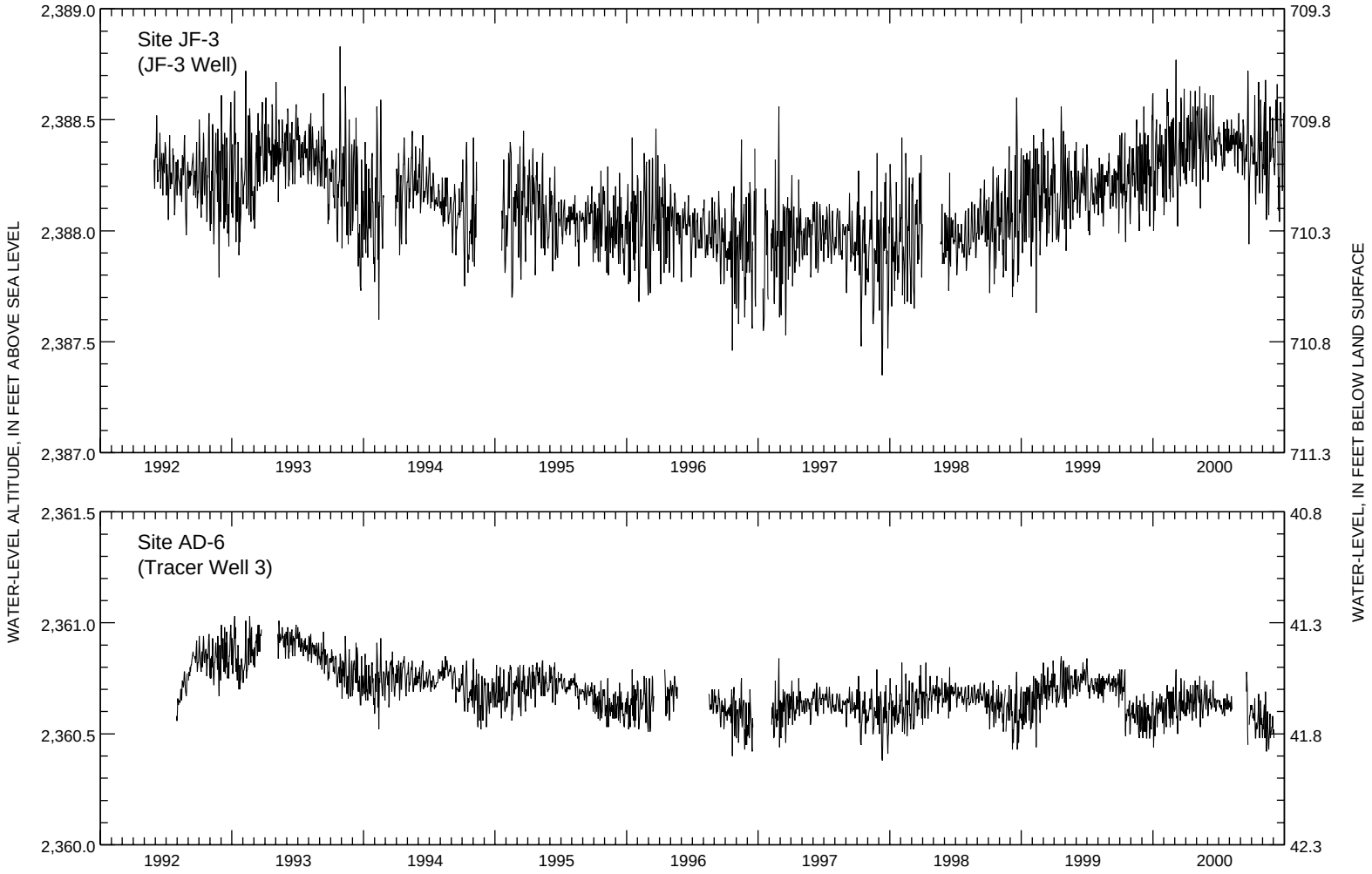

Figure 31. Daily average water levels at site JF-3, May 1992 through December 2000, and at site AD-6, July 1992 through December 2000. Vertical and horizontal scales have been expanded beyond those for figures 27–30 to show high resolution of the data.

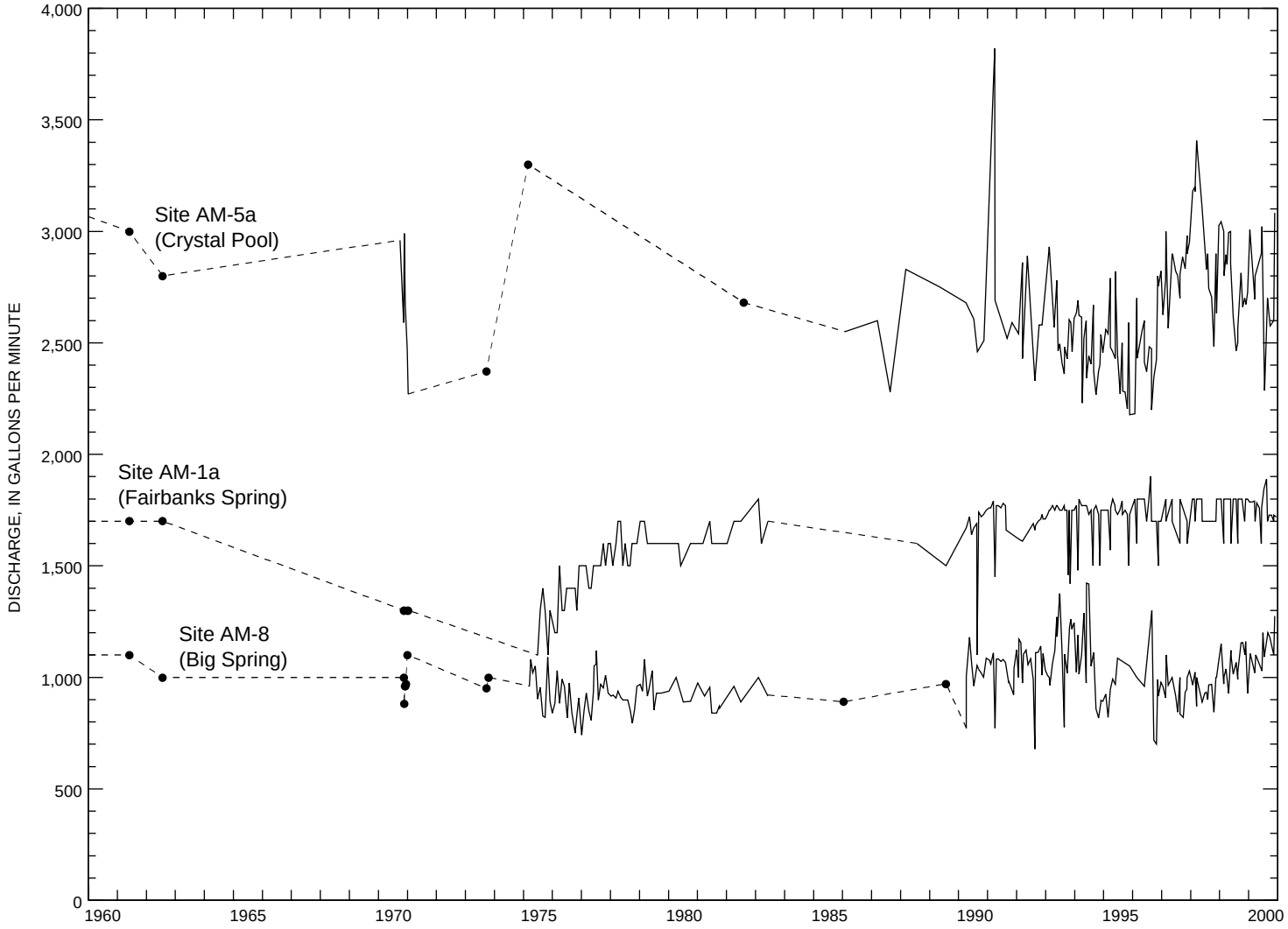

Figure 32. Discharge at sites AM-1a (Fairbanks Spring), AM-5a (Crystal Pool), and AM-8 (Big Spring), 1960–2000. Lines connect periodic measurements and are dashed where measurements were not available for consecutive calendar years.

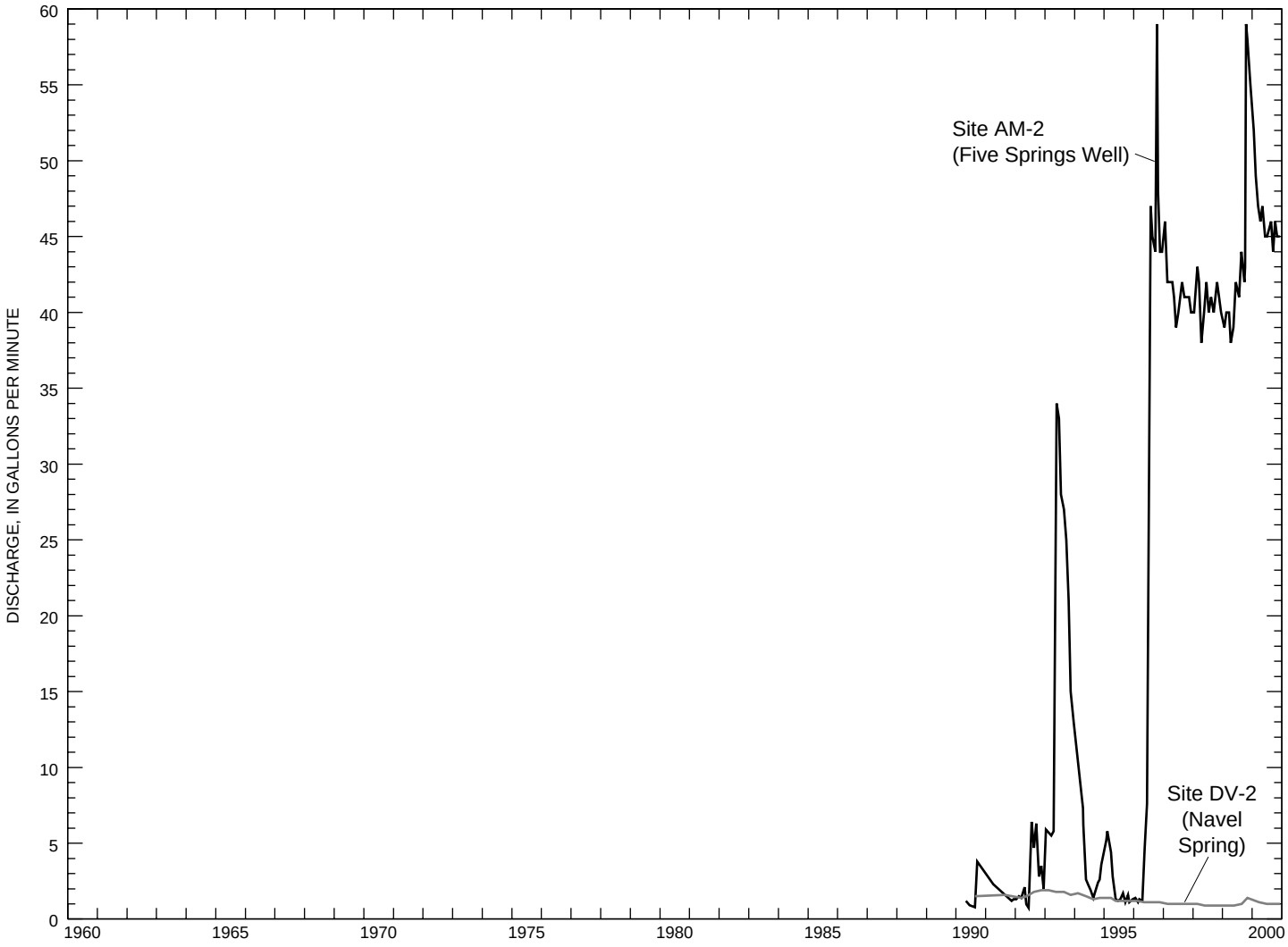

Figure 33. Discharge at sites AM-2 (Five Springs Well) and DV-2 (Navel Spring), 1990–2000. Lines connect periodic measurements.

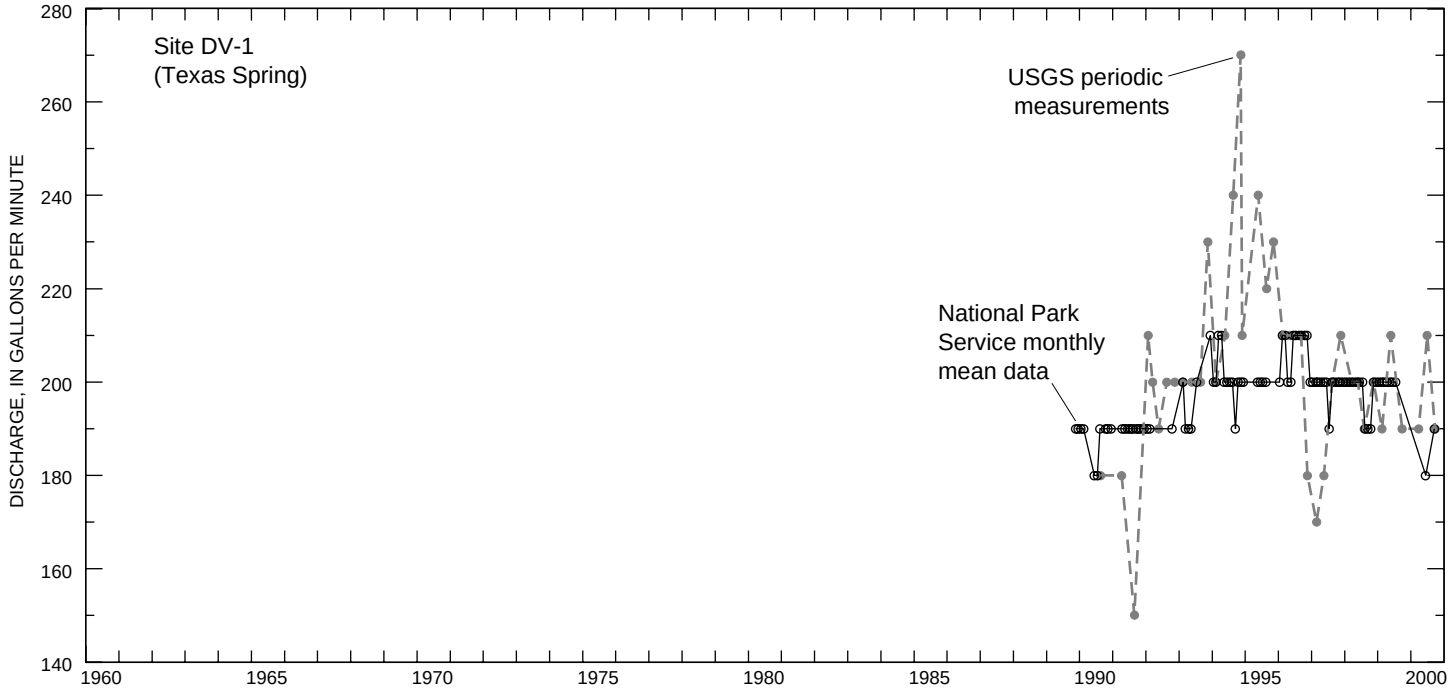

Figure 34. Discharge at site DV-1 (Texas Spring), 1989–2000. Filled gray symbols indicated periodic USGS measurements. Open black circles represent National Park Service monthly mean data.

APPENDIX B: SUPPLEMENTAL NOTES FOR SELECTED SITES

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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