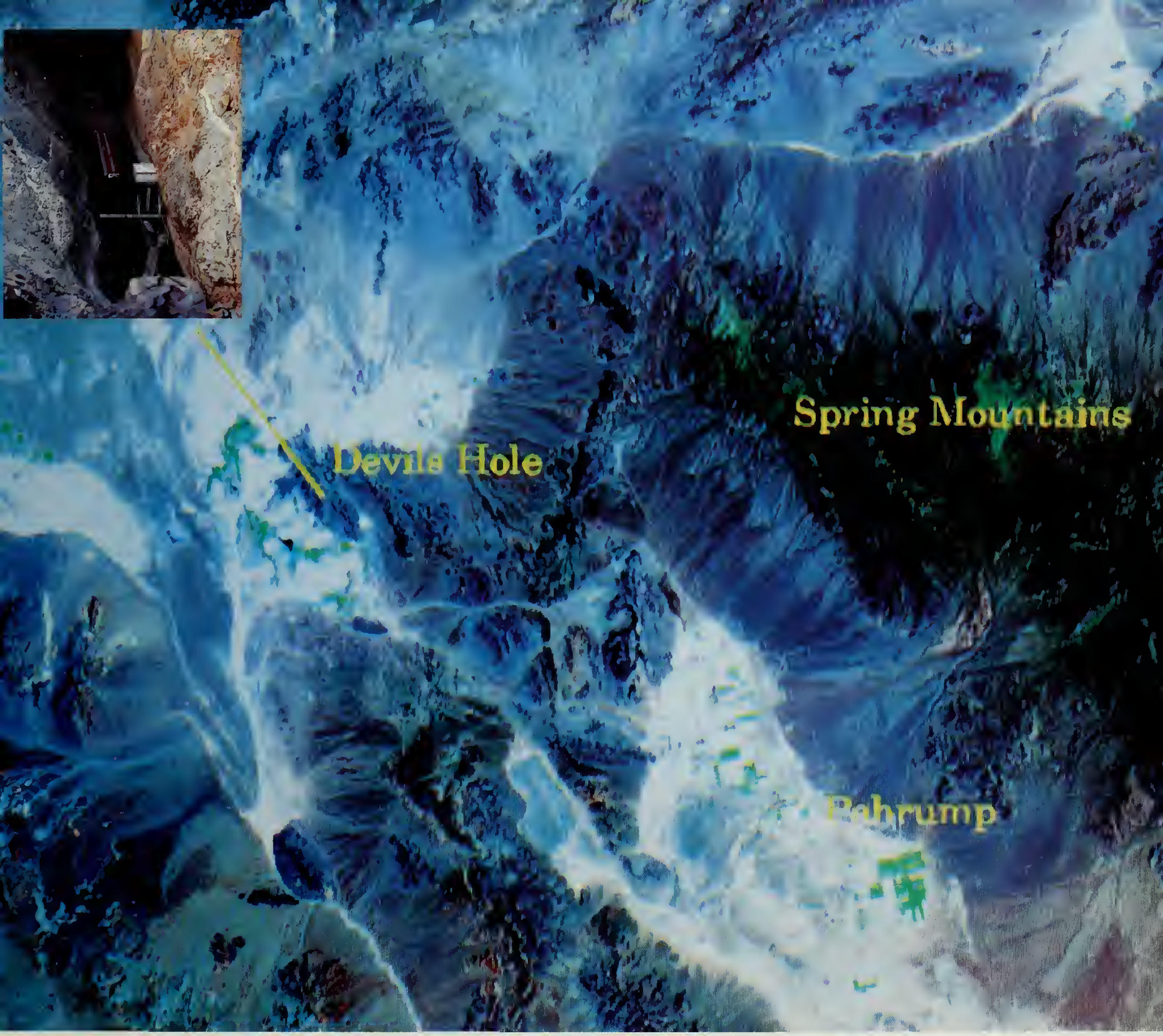

HYDROLOGIC EVALUATION OF RECENT WATER-LEVEL DECLINE AT DEVILS HOLE

1994

Las Vegas Valley Water District

COOPERATIVE WATER PROJECT
Water for Nevada's Future
Report No. 12

Cover background image is from the LANDSAT Thematic Mapper Satellite:
image shows the area surrounding Devils Hole, with a photo of Devils Hole and its water level recorder inset;
background image is enhanced using bands 7, 4, and 2

HYDROLOGIC EVALUATION OF RECENT WATER-LEVEL DECLINE AT DEVILS HOLE

By

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EXECUTIVE SUMMARY

This report evaluates possible explanations for a recent decline in water level in Devils Hole, a water-filled fissure in carbonate rock in Ash Meadows, Nevada. The water level in Devils Hole represents the potentiometric surface of the ground water within a regional carbonate aquifer that discharges at Ash Meadows. Water-level changes are of concern because Devils Hole is the sole habitat for a species of desert pupfish, *Cyprinodon diabolis*, that lives in the upper depths of the pool. The stage in Devils Hole began to decline about 1988, reversing a trend of water-level rise that had occurred for more than a decade. As of September 1992, a net decline of approximately 0.2 ft had been observed.

Physical processes that act over relatively short periods of time (several years or more) are identified as possible explanations for the stage decline. Potential explanations that are considered included short-term climatic changes (trends in precipitation), pumping in adjacent areas, and recent tectonic activity. A substantial data base was compiled in order to investigate these potential explanations. The data include water-level measurements throughout the regional ground-water flow system, precipitation data in southern Nevada, ground-water pumping records, spring discharge data, and recent seismic events.

Analysis of precipitation data was limited to high-elevation precipitation in areas that supply ground-water recharge to Ash Meadows. Using linear regression, a significant relationship was established between precipitation in the Spring Mountains and stage in Devils Hole, with a one-year lag in the effect of precipitation on stage. The linear relationship, which was based on the period of stage data from 1979-1992, produced a coefficient of determination (r^2) of 0.85. Precipitation data from Pahute Mesa, in the western part of the Nevada Test Site, were then added to the analysis. A multiple linear regression was developed using two independent variables: precipitation in the Spring Mountains, and precipitation on Pahute Mesa. The regression used stage data from 1979-1992 and lag times of one year for Spring Mountains precipitation and five years for Pahute Mesa precipitation. The addition of Pahute Mesa precipitation to the regression increased r^2 to 0.90, which indicates that the linear relationship explains 90 percent of the variation in the stage data. The statistical significance of these results was verified using hypothesis testing.

Ground-water pumping from Amargosa Valley, Pahrump Valley, and the Nevada Test Site (NTS) was analyzed as a potential cause of the decline in stage at Devils Hole. No statistically significant relationships were found between Devils Hole stage and pumping in either Amargosa Valley or Pahrump Valley, using linear correlation and regression. This result is consistent with the observation that neither area shows a trend of increased pumping in recent years. Pumping records at the Nevada Test Site were not of sufficient length to allow quantitative analysis such as linear regression, so these data were evaluated qualitatively. Total pumping at the NTS in the years 1983-1988 does not show any pronounced increase, suggesting that this pumping is an implausible explanation for the stage decline that began in 1988. Analysis of NTS pumping also considered potential impacts from Army 1 WW, the NTS water-supply well that is closest to

Devils Hole. If pumping from this well affects Devils Hole stage, the impacts would most likely appear in monitoring wells located between Army 1 WW and Devils Hole. Hydrographs from two such wells monitored by the U.S. Geological Survey (AD-7 and AD-8) do not show any significant decline in water level. It is therefore unlikely that pumping in Army 1 WW has caused the observed stage decline.

Tectonic processes that are typically associated with seismicity are considered as possible explanations for the stage decline. The water level in Devils Hole clearly responds to seismic events, such as the Landers-Big Bear earthquakes of June 1992, which caused a drop in water level that persisted for weeks. Dynamic ground motion associated with an earthquake could alter the local flow system at Ash Meadows by changing the permeability of one of the flow paths that leads to a spring orifice. This, in turn, could result in increased spring discharge and thereby lower the water level in Devils Hole. The report also considers the potential effects of preseismic and aseismic strain. Preseismic strain, which may have been associated with stress build-up preceding the Landers-Big Bear earthquakes, could produce precursory water-level changes in Devils Hole by changing the porosity of the carbonate aquifer. Seismic activity on local faults in Ash Meadows may also have affected water levels in Devils Hole. Several small earthquakes have been reported since 1987 within one to three miles from Devils Hole. These events could cause a decrease in water level in two ways: (1) by dropping land surface in the ground-water discharge area, resulting in increased discharge by springs or by evapotranspiration from phreatophytes, or (2) by altering the permeability of a flow path that conducts flow to a spring orifice, which could also increase discharge, in the same manner as ground motion from a more distant earthquake.

Underground nuclear testing on the Nevada Test Site may have affected Devils Hole. A nuclear detonation could produce seismic energy that might alter the local flow system at Ash Meadows, resulting in increased spring discharge and a decrease in water level in Devils Hole. Underground nuclear tests may also affect hydrologic conditions indirectly by triggering increased seismic activity across the southern Great Basin.

This report concludes that precipitation trends are the most likely explanation for the decline in stage at Devils Hole observed since 1988, as demonstrated by a quantitative relationship. Ground-water pumping does not appear to be a possible cause because no statistically significant relationships were found between ground-water pumping and Devils Hole stage. Finally, tectonic activity cannot be ruled out as a contributing factor to the recent stage decline at Devils Hole, possibly acting simultaneously with precipitation effects.

1.0 INTRODUCTION

Devils Hole is a small pool in a limestone fissure that is located in Ash Meadows, an area within the southeastern part of the Amargosa Desert in southwestern Nevada (Fig. 1). The water level of the pool represents the potentiometric surface of the ground water in the carbonate rock of the region. These Paleozoic carbonate rocks comprise the primary aquifer of a regional interbasin ground-water flow system, whose discharge area is at Ash Meadows. Ground-water discharge at Ash Meadows occurs mainly through a northwest-trending linear belt of large springs less than one mile to the southwest of Devils Hole.

Devils Hole is the sole habitat for a species of desert pupfish, *Cyprinodon diabolis*, that lives in the upper depths of the pool. The Devils Hole pupfish feeds and spawns on a slightly submerged rock shelf in the pond, and a sufficient water level in Devils Hole is therefore required to maintain the pupfish's habitat.

This study was motivated by a decline in the water level, or stage, in Devils Hole that began about 1988. A net decline of about 0.2 feet (ft) has been observed since that time, according to data collected by the National Park Service (NPS). The stage in Devils Hole has been monitored almost continuously for over 30 years, primarily by the U.S. Geological Survey (USGS), but in recent years by the NPS.

Fluctuations in water level at Devils Hole and concern about the pupfish habitat are not new phenomena. A dramatic decline in stage at Devils Hole occurred over 20 years ago, beginning in 1968, in response to nearby ground-water pumping for irrigation. Dudley and Larson (1976) provide a detailed review of these events. Because the drop in water level threatened to expose the submerged rock shelf, the United States filed a civil suit in 1971 to stop the ground-water pumping. A protracted series of hearings followed, resulting in a final decree issued in April 1978 (Cappaert v. United States. 375 F.Supp. 456 (1974), aff'd, 508 F.2d 313 (9th Cir. 1974), aff'd, 426 U.S. 128 (1976), on remand, 455 F.Supp. 81 (1978)). The federal court decree restricted pumping in Ash Meadows and established a minimum water level of 2.7 ft below a specified reference point, as judged necessary to preserve the Devils Hole pupfish. The water level in Devils Hole gradually recovered, due to the reduction of nearby pumping that occurred from the late 1960's to mid-1970's, until the recent decline began in about 1988.

This report presents an evaluation of the factors that could have produced the recent decline. In section 2.0, the regional and local hydrogeology of the study area are reviewed. Section 3.0 identifies the factors that might influence Devils Hole stage. Section 4.0 contains the analysis of these factors, utilizing an extensive data base that was compiled for this investigation. Conclusions of this investigation are summarized in section 5.0.

2.0 HYDROGEOLOGIC FRAMEWORK

2.1 STUDY AREA

The study area encompasses the regional carbonate ground-water system, which discharges at Ash Meadows and several other locations. This regional ground-water system includes the Amargosa Desert and areas to the north and east, as indicated on Figure 1.

2.2 PREVIOUS WORK

The most comprehensive evaluation of the hydrogeology of the study area was completed by Winograd and Thordarson (1975), and their work has been adopted by many subsequent investigators as a fundamental conceptual model of regional interbasin ground-water flow. During the 1980's, studies of the regional carbonate rock aquifer in southern Nevada have been coordinated by the USGS as part of the Great Basin Regional Aquifer-System Analysis (Great Basin RASA), and have produced numerous reports listed by Dettinger (1989). Comprehensive hydrogeologic studies that focus on the Amargosa Desert were performed by Naff (1973), and Pexton (1984). Dudley and Larson (1976) evaluated the hydrogeology at Ash Meadows. Numerical models of ground-water flow within the area have been published by Bateman and others (1972), Waddell (1982), and Czarnecki and Waddell (1984).

Many geologic, geophysical, and geochemical studies have been performed within the southern Great Basin over the last 40 years, and are too numerous to list here. The geology of the region is covered in the geologic map of Nevada (Stewart and Carlson, 1978), and discussed in a corresponding report by Stewart (1980). In recent years, much work has centered on understanding the geology of the Yucca Mountain area, to the northwest of Devils Hole (for example, Carr and Yount, eds., 1988). A geologic map of a nine-quadrangle area north of Ash Meadows (the south-central portion of the Nevada Test Site) was compiled by Maldonado (1985). Geologic investigations in the vicinity of Devils Hole have been published by Denny and Drewes (1965), who mapped the geology of the Ash Meadows quadrangle, and Carr (1988), who mapped the Devils Hole area.

Numerous reports on the hydrology of the region have been prepared. A list, compiled by Waddell (1982), includes: Amargosa Desert area (Walker and Eakin, 1963; Claassen, 1985); Death Valley (Hunt and others, 1966; Pistrang and Kunkel, 1964; Miller, 1977); Ash Meadows flow system (Winograd and Thordarson, 1975; Winograd and Pearson, 1976; Dudley and Larson, 1976; Naff, Maxey, and Kaufmann, 1974); Oasis Valley (Malmberg and Eakin, 1962; White, 1979); and Nevada Test Site area (Rush, 1970). Regional hydrologic data for the Great Basin are summarized by Thomas and others (1986).

2.3 REGIONAL GEOLOGIC SETTING

Most of the study area lies within a structural-physiographic subsection of the southern Great Basin referred to as the Walker Lane Belt. The Walker Lane Belt is a northwest-trending lateral shear zone about 50 to 75 miles (mi) wide that is believed to be a continental-scale lineament extending from Texas to Oregon (Carr, 1984). In southwestern Nevada, this complex zone has been interpreted as dividing the southern Great Basin into two regions: an area to the northeast dominated by extensional faulting that trends generally north-south, and an area to the southwest in which both strike-slip faulting and extensional faulting occur in a predominantly northwest direction (Brocher and others, 1993; Carr, 1990; Fox and Carr, 1989). Two major strike-slip faults that are part of the Walker Lane Belt border the Amargosa basin (Pexton, 1984). On the northeastern end of the valley is the termination of the right-lateral Las Vegas Valley shear zone, which extends eastward to Las Vegas. On the southeastern end of the valley near Death Valley Junction is the termination of the right-lateral Furnace Creek-Death Valley fault, which runs through Death Valley.

The study area has undergone a complex geologic history that includes various periods of deposition, deformation and faulting, erosion, and volcanism, producing a complex distribution of rocks (Fig. 1). As a result, there is not full agreement on the tectonic evolution of the area and various conceptual models have been posed (for example, Carr, 1984, 1990; Wernicke, 1985; Hamilton, 1988).

Following is a simplified chronology of geologic and tectonic events, taken mainly from Winograd and Thordarson (1975), Stewart (1980), Plume and Carlton (1988), and Waddell (1982). Major stratigraphic and hydrologic units corresponding to the discussion are summarized in Table 1.

From the late Precambrian through the Paleozoic, the continental margin of western North America was located in what is now central Nevada. During this period, deposition of thick sediments occurred along the continental shelf and slope in a wedge-shaped prism, the Cordilleran miogeosyncline. This deposition was characterized by two major sequences of clastic and carbonate sedimentation. The Precambrian to mid-Cambrian sand and clay muds of the miogeosyncline are now primarily siltstones, quartzites and shales, and constitute an aquitard (the lower clastic aquitard). The overlying carbonate deposits of the mid-Cambrian to late Devonian now constitute a widespread, but discontinuous, regional aquifer (the lower carbonate aquifer). A shift to clastic deposition caused by the Antler orogeny occurred around the Late Devonian to Mississippian, resulting in deposition of argillite, with some quartzite and limestone. This unit, called the Eleana formation, comprises the upper clastic aquitard. Subsequent erosion of the Antler Highlands shifted the depositional environment back to carbonates, forming the Tippipah Limestone of Pennsylvanian and Permian age. This unit is referred to as the upper carbonate aquifer, and is of minor hydrologic significance because it is unsaturated in most areas, or is not separable from the lower carbonate aquifer in areas where the Eleana formation is absent (Waddell, 1982).

During the Mesozoic, these sediments were horizontally compressed into a major system of folds and west-dipping thrust faults. Two northeast-trending Mesozoic thrust faults are located in the vicinity of Ash Meadows: the Specter Range thrust fault to the northwest of Devils Hole, and the Montgomery thrust to the southeast of Devils Hole (Winograd and Thordarson, 1975, p. C75). Ash Meadows itself lies on the upper plate of the Montgomery thrust fault. The

Mesozoic thrust faults laterally displaced rocks over large distances. Wernicke and others (1988) estimate that the total shortening of the prism between Las Vegas and the Sierra Nevada was likely greater than 100 km (60 mi). In the westernmost part of the sedimentary wedge, the Sierra Nevada batholith was emplaced during this time. The compression and igneous activity of the Mesozoic were probably related to subduction of the ancient Pacific plate beneath western North America. Rocks of Mesozoic age are largely absent from the area.

A geologically quiet period began in the late Mesozoic and lasted through the mid-Cenozoic. Then about 30 million years ago, major tectonic and igneous activity began, and continues to the present. Crustal extension resulted in normal block faulting, which produced the Basin and Range topography. Hamilton (1988) states that the width of the Basin and Range province has almost doubled as a result of this crustal extension. In addition, major displacements occurred along strike-slip faults. During the Tertiary, volcanic activity resulted in thicknesses of over 13,000 ft of extrusive rocks. The volcanic rocks of this period have varying hydrologic properties and range from confining beds to aquifers. During the Tertiary and Quaternary, stream and alluvial deposits have filled most of the valleys in the area.

2.4 LOCAL GEOLOGY AND STRUCTURE

The geology of the Ash Meadows quadrangle was mapped by Denny and Drewes (1965). This work delineated the stratigraphy and geomorphology of the area, but did not include structure in detail. Dudley and Larson (1976) offered an interpretation of the faults and lineaments in the area. Carr (1988) mapped the structural geology of the Devils Hole area.

The predominant structural features in the Ash Meadows area are northwest-trending faults and folds, discussed in detail by Carr (1988). Carr (1988) also noted that the area contains many small faults and fractures with a northeast strike. This subordinate structural orientation has hydrologic significance because the northeast direction appears to be one of increased permeability. According to Carr (1974), the orientation of minimum principal stress in the region is about N 50 W, so that northwest-striking faults are under compression, and northeaststriking faults are under tension and will tend to open. A Rose diagram summarizing the orientations of lineations and faults was constructed by Rojstaczer (1987).

One of most important local features is a major normal fault first inferred from a gravity survey (Healey and Miller, 1971) that strikes north to northwest and is downthrown on the west side. This structure, shown on Figure 2, has been referred to as "the gravity fault" of Winograd and Thordarson (1975). These authors presented evidence that the high-angle fault forms a hydraulic barrier that creates the spring discharge zone of the Ash Meadows ground-water basin. Their explanation is that the lower carbonate aquifer is dammed by downfaulted low-permeability sedimentary and tuffaceous rocks of Tertiary and Quaternary age (p. C81-C82).

Additional detail on the gravity fault (Fig. 2) is provided by a recent seismic survey in the eastern Amargosa Desert (Brocher and others, 1993). The east-west trending seismic profile crosses the north part of the gravity fault, and proceeds eastward across all or parts of three Tertiary subbasins located north of Ash Meadows. Brocher and others (1993) suggest that the gravity fault is actually a system of listric faults about 2 km (1.2 mi) wide, and estimate the total throw across the system to be about 1.0 to 1.4 km (0.6 to 0.9 mi). They also note that this feature forms the eastern boundary of an extensive structural trough that trends northward across the Great Basin, underlying Crater Flat and Yucca Mountain. Carr (1990) refers to this structural trough as the Kawich-Greenwater rift, and interprets it as an important regional tectonic boundary.

Devils Hole lies at the southeastern edge a northwest-trending ridge of Cambrian carbonate rocks, referred to informally by Carr (1988) as Devils Hole Ridge. Devils Hole Ridge is one of a series of hills (referred to by Carr as the Amargosa Ridges) that expose the Cambrian Bonanza King Formation. This limestone and dolomite formation constitutes the bedrock of the area, and is also the base of the lower carbonate aquifer of Winograd and Thordarson (1975). The surrounding basin fill in Ash Meadows consists primarily of Tertiary and Quaternary fine-grained sediments.

Structurally, Devils Hole is a collapse depression that lies along a local northeast-trending, high-angle reverse fault of Cenozoic age. In plan view, Devils Hole is approximately 75 ft by 25 ft at the land surface, with a depth to the water surface of about 50 ft below the rim (Carr, 1988). Below the water surface, the fissure is extensive in a northeast-to-southwest direction, but its average width is less than six ft. The maximum depth of Devils Hole is unknown, but greater than 436 ft (Riggs, 1992). The geologic evolution of this feature remains an area of varying opinions. Some investigators suggest Devils Hole is primarily a dissolution feature. For example, Dudley and Larson (1976) stated that Devils Hole resulted from solution enlargement of a fault zone in Cambrian limestone, followed by collapse of the roof and walls into the cavern. Other investigators believe Devils Hole is primarily a tectonic feature that resulted from extension along the local northeast-trending fault (Carr, 1988; Riggs, 1992).

2.5 GROUND-WATER FLOW SYSTEM

Ash Meadows is located within a large multibasin ground-water flow system that covers approximately 15,800 mi^2 in southern Nevada and is designated as the Death Valley ground-water flow system by Harrill and others (1988). The system is characterized by regional interbasin flow, primarily through fractured and structurally deformed carbonates and volcanics, and includes about 27 distinct hydrographic areas. Ground-water movement is generally toward the south and southeast toward Death Valley, the terminus of the system.

Several subsystems have been defined within the Death Valley system based on ground-water discharge at intermediate points. Winograd and Thordarson (1975) observed that ground water discharges at three intermediate areas in the region: (1) Ash Meadows, (2) Alkali Flat, near Death Valley Junction, and (3) Oasis Valley. Based on this, the authors defined two ground-water subbasins: (1) the Ash Meadows ground-water basin, which includes the area that discharges ground water to the springs at Ash Meadows, and (2) the Oasis Valley-Fortymile Canyon ground-water basin, which includes the western half of the Nevada Test Site and appears to discharge to Oasis Valley and Alkali Flat. Winograd and Thordarson (1975) were tentative in defining the boundaries of this second subsystem. They were also uncertain about the origin of the discharge at Furnace Creek Ranch, in east-central Death Valley, which occurs mainly at Travertine Springs, Texas Springs, and Nevares Springs. The authors hypothesized that discharge to the springs of the Furnace Creek Ranch area comes at least partly from the valley fill of the central Amargosa Desert. However, they stated that discharge may also come from the lower carbonate aquifer. Regional flow to the Furnace Creek Ranch area is possible because the southern part of the Funeral Mountains northwest of Death Valley Junction is composed of Paleozoic carbonate rocks.

Waddell (1982) adopted Winograd and Thordarson's basic conceptual model, but divided the area into three ground-water basins, named for their discharge areas: (1) Ash Meadows, (2) Oasis Valley, and (3) Alkali Flat-Furnace Creek Ranch. Each basin includes the area that contributes to its discharge zone. Waddell essentially divided Winograd and Thordarson's Oasis Valley-Fortymile Canyon ground-water basin into two basins. In Waddell's conceptual model, the Ash Meadows and Oasis Valley ground-water basins are actually subbasins within the Alkali Flat-Furnace Creek Ranch basin. This is the case because discharge at Ash Meadows and Oasis Valley is structurally controlled. The presence of low-permeability rocks in both areas dams the regional aquifer, creating high water levels which result in springs and evapotranspiration by phreatophytes. However, the carbonate aquifer is not completely dammed, and some water flows over or through the hydraulic barriers into the Alkali Flat-Furnace Creek Ranch ground-water basin. Discharge at the springs near Furnace Creek Ranch is probably a mixture of ground water from all three basins (Waddell, 1982).

This report adopts the division of ground-water basins used by Waddell (1982). The dashed line on Figure 1 outlines the area contained within the three subbasins discussed above. This area includes roughly half of the hydrographic areas within the Death Valley ground-water flow system. It excludes hydrographic areas to the northwest, such as Sarcobatus Flat and Gold Flat, and also areas farther downgradient in the system, such as Lower Amargosa Valley and Death Valley, the ultimate discharge zone for the system.

2.5.1 Ash Meadows Ground-Water Basin

The Ash Meadows subbasin, which comprises the eastern half of the study area shown in Figure 1, is characterized by regional flow in the Paleozoic carbonates that moves generally from the northeast to the southwest. High transmissivities and low hydraulic gradients exist throughout much of the basin, due to the fractured and faulted nature of the carbonate aquifer. Winograd and Thordarson (1975) noted the particularly high transmissivity of the aquifer between the Specter Range on the northeast border of the Amargosa Desert and the Ash Meadows discharge area, and suggested that this is a result of intense fracturing of the upper plate of the Specter Range thrust fault.

In Ash Meadows, the regional aquifer (the lower carbonate aquifer) is overlain by Tertiary and Quaternary valley fill consisting principally of alluvial and lacustrine deposits. This material constitutes a local aquifer that is probably recharged by upward flow from the underlying lower carbonate aquifer.

The Ash Meadows discharge zone is a northwest-trending linear belt of springs located within one mile downgradient of Devils Hole (Fig. 2). Some discharge also occurs from a playa in an unnamed valley northeast of the spring line. Walker and Eakin (1963) estimated the average discharge from the springs at Ash Meadows to be 17,000 acre-ft/year. Hydrologic and geochemical evidence that this spring discharge represents discharge from the regional carbonate aquifer was presented by Winograd and Thordarson (1975).

According to Winograd and Thordarson (1975), recharge to the Ash Meadows ground-water basin is derived principally from precipitation falling on the Spring Mountains and the Sheep and Pahranagat Ranges, and from underflow from Pahranagat Valley. Minor amounts of recharge may result from precipitation on the Timpahute, Desert, Pintwater, and Spotted Ranges (Fig. 1). There is much uncertainty in the relative amounts of recharge from these locations, due to uncertainty in ground-water flow paths and in the boundaries of the Ash Meadows subbasin itself.

Estimates of recharge to ground water in Nevada are often based on precipitation isohyetals. The principal amounts of average annual precipitation within the Ash Meadows basin are: about 320,000 acre-ft on the Sheep Range, about 100,000 acre-ft on the Spring Mountains, and about 90,000 acre-ft on the southern Pahranagat Range (Winograd and Thordarson, 1975, p. C92). A fraction of the total precipitation volume becomes ground-water recharge. Waddell's numerical model (1982) of steady-state ground-water flow in the Ash Meadows basin used annual recharge values of about 11,000 acre-ft from the Sheep Range, and about 5,000 acre-ft each from the Spring Mountains and the Pahranagat Range. However, Winograd and Thordarson (1975) postulated that up to 35 percent of the ground-water discharge at Ash Meadows is from Pahranagat Valley, based on an analysis of the deuterium content of the ground water in Pahranagat Valley and at Ash Meadows. Waddell's model (1982) did not test this hypothesis due to lack of potentiometric data in this region. Consequently, Waddell (1982) noted that if the hypothesis is correct, his estimates of recharge from the Sheep Range and the Pahranagat Range are too large.

The eastern boundary of the Ash Meadows ground-water basin has always been particularly uncertain. Investigators have suggested recently that the boundary should be moved in, from its current location within the Sheep Range to a location within Desert Valley to the west (for example, Winograd and others, 1992, Fig. 1). If this alternative eastern boundary is correct, recharge from the Sheep Range may not be a significant source of the discharge at Ash Meadows.

3.0 POTENTIAL INFLUENCES ON DEVILS HOLE STAGE

Because of the Devils Hole pupfish, concern about potential declines in the stage at Devils Hole has existed for over 30 years. In 1963, the NPS requested that the USGS evaluate potential effects of increasing ground-water development in the area on Devils Hole stage. Worts (1963) reviewed the geology and hydrology of the area and raised the possibility of pumping impacts on Devils Hole stage. Climate was also recognized by Worts (1963) as a potential factor in stage changes. He suggested that a prolonged drought could cause a decline in stage, in much the same manner as pumping.

In this investigation, physical processes that might affect stage in Devils Hole are divided into two types: processes that are expected to act over a relatively short time period, and those that act over the long term. Short-term processes, acting over periods of several years or more, may include the following:

- Relatively short-term changes in climate, such as wet or dry trends in precipitation,
- Ground-water pumping in areas surrounding Devils Hole, and
- Tectonic activity of a relatively sudden nature, such as seismicity that could alter either the height of the land surface near Devils Hole or the permeability of a flow path leading to a spring orifice, or preseismic strain that could change the porosity of the carbonate rocks.

Longer-term processes, acting over periods of decades or more, may include the following:

- Long-term climatic changes, and
- Tectonic changes that occur slowly and gradually over a long period of time.

The nature of the expected response of the stage in Devils Hole is different for these two types of processes. Short-term processes are expected to produce rather abrupt changes in stage, while long-term processes would produce gradual, progressive changes in stage.

The decline in stage that has been observed since about 1988 represents an abrupt departure from the trend of increasing stage that had been observed from the late 1970's to 1988. For this reason, a short-term process is the most likely explanation for the recent decline, and this report will focus on the short-term processes cited above. However, one or both of the long-term processes mentioned above may also be occurring, but these low-frequency, long-period effects would be masked by higher-frequency, shorter-period effects. Because it is unlikely that they explain recent events at Devils Hole, long-term climatic and tectonic changes are not treated in this report, with the exception of the following comments on paleohydrology.

A brief review of the literature on paleo-climate and paleohydrology suggests that water-levels in the southern Great Basin of Nevada have been declining throughout the Quaternary. This conclusion was reached by Winograd and Szabo (1988), who evaluated paleo-ground-water discharge by dating features such as calcite veins and travertine deposits. They concluded that the regional water table has lowered progressively throughout southern Nevada during the Quaternary, and is likely to continue to decline for at least another 100,000 years. Winograd and Szabo (1988) estimated the apparent rate of decline of the water level at Ash Meadows as 0.02 to 0.08 meters per thousand years, which is about 7×10^{-5} to 3×10^{-4} ft/yr. A panel appointed by the National Research Council (1992) to evaluate the potential for ground-water rise at Yucca Mountain also agreed with these conclusions regarding paleo-water levels. At Devils Hole itself, various types of calcium carbonate deposits indicate former higher water levels (Mehringer and Haynes, 1972). Evidence suggests that the water level in Devils Hole has not exceeded 9 meters (about 30 ft) above its present level in the last 45,000 years (Winograd and others, 1989) and has probably been below land surface at Devils Hole for hundreds of thousands of years.

A long-term decline in water levels during the Quaternary is consistent with the generally-held supposition that the climate in the Amargosa Desert was substantially wetter and cooler during the Pliocene than today. Evidence for this wetter climate in the Ash Meadows area was discussed by Pexton (1984), Hay and others (1986), and Winograd and Thordarson (1975, p. C82-C83). A number of investigators, notably Winograd and others (1985), have postulated an explanation for the change in climate. They suggested that uplift of the Sierra Nevada during the last several million years led to a progressive decrease in Pacific moisture reaching the Amargosa Desert. Pexton (1984) stated that, by the late Pleistocene, the shift to a dry climate had likely occurred.

Winograd and Szabo (1988) pointed out that climate change is not the only explanation for the gradual lowering of water levels in the southern Great Basin. Erosion of highlands onto the valley floors may have apparently lowered the water table, they hypothesized. In addition, tectonics may play a role in three ways.

First, tectonic uplift of the land surface at Devils Hole may have increased the depth to the water table, although not actually changing the water-table altitude. Since Devils Hole is on the upthrown side of the gravity fault of Winograd and Thordarson (1975), it is plausible that this area may have been uplifted gradually. Winograd and Doty (1980, p. 73) estimate about 15 m (49 ft) of uplift over a period of a few tens of thousands to 100,000 years. In addition, the authors present evidence of possible upwarping of the Ash Meadows area during the Pleistocene.

Second, tectonic depression of adjacent areas, such as the Death Valley ground-water discharge area, may have resulted in a decline in water levels throughout the ground-water system in response. Winograd and Szabo (1988) note that the floor of Death Valley has probably moved downward during the Pliocene and Pleistocene, and suggest that the regional ground-water flow system present today developed in response to the lowering of the discharge area at Death Valley.

Third, extensional fracturing caused by tectonic activity may create or widen spring orifices, increasing ground-water discharge and thereby lowering ground-water levels in response. Winograd and Doty (1980) cite this hypothesis as a plausible explanation for a long-term decline in water level in Devils Hole, especially given that the land surface at the major springs of Ash Meadows (Crystal Pool and Big Spring) is 120 to 160 ft lower than the water-level elevation in Devils Hole. Finally, an extensional tectonic regime generally exists in the Basin and Range, which has experienced an average extension rate of about 10 mm/yr (0.25 inch/yr) over the last five million years (Wernicke and others, 1988).

These long-term changes occur too slowly to produce the recent water-level decline at Devils Hole. The occurrence of any of these long-term, progressive changes in water levels does not preclude relatively rapid fluctuations in water levels in response to shorter-term phenomena. These shorter-term processes are the subject of the remainder of this report.

4.0 DATA ANALYSIS

In this study, a substantial data base was compiled in order to investigate the short-term factors discussed above that might influence Devils Hole stage. Existing published and unpublished data were obtained and compiled into useable formats, and a summary of these data is given in Table 2. The data include Devils Hole stage measurements, water-level measurements throughout the regional ground-water flow system, precipitation data in southern Nevada, pumping data for the Nevada Test Site, Pahrump Valley, and Amargosa Valley, and discharge data for springs in Ash Meadows and Death Valley.

The following sections of the report present an evaluation of the processes that are most likely to influence Devils Hole stage. These processes include trends in precipitation in areas that are sources of ground-water recharge, pumping in several regions, and tectonic activity. The analyses presented herein utilized the data in Table 2 that are most relevant to these processes. Other data were evaluated in a qualitative manner and are not discussed in this report, but are nonetheless included in Table 2 for completeness.

4.1 DEVILS HOLE STAGE DATA

Water-level data from Devils Hole has been collected by the U.S. Geological Survey (USGS) intermittently from 1953 to 1962 (Hoffman, 1988) and almost continuously from 1962 to August 1989. In August 1989, the National Park Service (NPS) took over monitoring activities from the USGS and has been collecting continuous stage data at Devils Hole since that time.

The USGS has provided on diskette a provisional record of stage data collected at Devils Hole from May 1962 through September 1989. The data consist of daily mean values of stage. Some of the pre-1968 record was revised to correct the data to a standard reference datum (J.R. Harrill, written commun., 1992). A report documenting the data collected by the USGS at Devils Hole through 1988 is currently being prepared by the USGS (J.R. Harrill, oral commun., 1993). Some hydrologic data at Devils Hole were previously published by the USGS in a series of annual reports covering the period July 1972 through June 1978, given by Larson (1974a, 1974b, 1975), Hanes (1976), and Carson (1979, 1980). These published data include measurements of water levels in Devils Hole and several nearby wells, spring discharge data, and records of electrical power consumption for nearby pumping wells.

Provisional data from the NPS was provided on diskette for the period August 30, 1989 through September 30, 1992. The data include daily mean, daily high, and daily low stage in Devils Hole. The NPS has collected continuous data at Devils Hole since August 30, 1989 using a Stevens A-71 Chart Recorder and a Stevens A/F Data Logger, both of which are connected to the same float mechanism. In July 1992, the NPS added a redundant data collection system consisting of an Enmos pressure transducer connected to an Omnidata Data Logger. The NPS is preparing the data for release in a report, which will assign accuracy ranges to the record (O.R. Williams, written commun., 1992). According to the NPS, accuracy of the record has ranged from ± 0.01 to ± 0.1 ft, but 67 percent of the data is within ± 0.02 ft (O.R. Williams, written commun., 1992).

A complete record of daily mean stage in Devils Hole from May 1962 through September 1992 was created by joining the two sets of data. Both agencies provided data for the month of September 1989, a period of apparently overlapping instrumentation. A comparison of the USGS and the NPS data during this month shows the two records agree to within a maximum difference of 0.04 ft. The absence of an abrupt offset between the two records apparently indicates that no changes in the reference datum occurred when data collection shifted from the USGS to the NPS.

However, verification that a standard datum has consistently been used in measuring stage in Devils Hole is not straightforward. The reference point for measuring stage in Devils Hole has a complicated history. In brief, the arbitrary datum was originally marked by a copper washer, which was lost sometime after 1976. By 1979, a brass screw was inserted into the hole that previously contained the washer. In May 1992, the NPS noted that the brass screw was loose

(O.R. Williams, written commun., 1992), and a more stable reference point (a steel bolt) was installed in the rock wall near the brass screw.

In ensuring a consistent datum, a problem at the site has been the lack of elevation surveys that are referenced to a regional, stable benchmark. Various surveys have been performed to determine the elevation of the datum marker, but local benchmarks were referenced, and different local benchmarks may have been used in the surveys. The current datum marker (steel bolt) was surveyed at the time of installation (O.R. Williams, written commun., 1992). The elevation was referenced to a local benchmark, with the result that the present staff plate 0.00 mark was 0.05 ft higher than the datum marker (brass screw) elevation previously measured by the USGS. To our knowledge, this discrepancy remains unresolved. There has been speculation that the land-surface elevation at Devils Hole may have changed as a result of tectonic activity, and recent seismic events in particular. This possibility will be discussed further in section 4.4 of the report. Nevertheless, the month of overlapping data collected by both agencies indicates no change in the datum resulting from the transfer of monitoring from the USGS to the NPS. Consequently, the data of the USGS and the NPS together most likely form a consistent record of Devils Hole stage.

Figure 3 shows the composite record of raw data (daily mean stage) collected by the USGS and the NPS. Gaps in the records from both agencies exist, presumably as a result of instrument failure, including failure induced by seismic events. The gaps range in length from one day to over seven months, in 1964. However, gaps in the data since the early 1980's are typically less than one month in length.

In order to better see recent trends, the composite stage record for the last 10 years only is shown in Figure 4. In this plot, data gaps were filled using linear interpolation, and the data were smoothed using an 11-day centered moving average. The decline in water level from late 1988 to 1992 is about 0.2 ft. The sharp drop in water level in June 1992 is due to the Landers and Big Bear earthquakes on June 28, 1992. As the graph shows, the stage has recovered from these seismic events to approximately its pre-earthquake level.

Periodic measurements of Devils Hole stage are currently collected by the USGS as part of its Water-Resources Monitoring Program. Figure 5 shows these data, which begin about 1984. A comparison between Figures 4 and 5 indicates that these periodic measurements generally match the continuous data. Of particular interest in Figure 5 are the last two periodic measurements, taken after September 30, 1992 (the date of most recent NPS data). These two data points, in November 1992 and February 1993, indicate recovery of the stage to approximately its 1988 level. As more recent NPS data becomes available, it will be possible to check this apparent trend against the continuous stage record.

4.1.1 Previous Stage Decline

A distinctive feature of the composite stage record (Fig. 3) is the pronounced trough caused by local pumping in Ash Meadows during the late 1960's to mid-1970's. Dudley and Larson (1976) provide a thorough discussion of the observed effects of pumping in Ash Meadows on Devils Hole stage and also on spring discharge. They showed qualitative correlations between gross pumping from nearby wells (see Fig. 2 for location) and water levels in Devils Hole, and generally concluded that pumping from these wells caused the 2.5-ft decline in stage observed between 1968 and 1972.

Dudley and Larson (1976) evaluated the local hydrogeology in detail, noting that only one of the irrigation wells (Well 7) produced water directly from the Paleozoic carbonate aquifer. The other wells drew water from what they called the local aquifer system, i.e., travertine and continental limestones. Apparently, this local aquifer system has some degree of hydraulic connection with the regional carbonate aquifer, whose water level is represented by Devils Hole. However, the nature of the hydraulic connection between the wells themselves and between the wells and Devils Hole is complex, the authors concluded.

Rojstaczer (1987) attempted to quantitatively evaluate the degree of hydraulic connection between Devils Hole and the Ash Meadows production wells. He used well hydraulics theory to model the drawdown at Devils Hole (assuming it behaves as an observation well) due to pumping in nine irrigation wells during the period June 1969 through January 1972. Rojstaczer's analysis (1987) was based on the relation, developed by Theis (1935), between water-level decline and pumping discharge, radial distance from the pumping well, time, and aquifer properties of transmissivity (T) and storativity (S). In the simplest of three models posed by Rojstaczer, it was assumed that the irrigation wells tap one equivalent, homogeneous, isotropic, areally extensive aquifer. Rojstaczer then computed the best-fit values of T and S using a least-squares approach by solving the following minimization problem:

$$min \sum_{t} \left[s_c(T,S) - s_{obs}\right]^2 \tag{1}$$

where, at the end of each month t, s_{obs} is the observed stage decline and s_c is the computed stage decline. Using this procedure, Rojstaczer obtained reasonably good agreement between observed and computed stage declines.

4.1.2 Use of Stage Record in this Analysis

In this investigation, relationships are considered between trends in Devils Hole stage and trends in other phenomena such as precipitation, ground-water pumping, and seismic activity. The effects of these processes may be more subtle than the effects of local pumping in Ash Meadows due to: the low-magnitude nature of an effect itself, or to the distance from Devils Hole, which may attenuate an effect. In order to identify such subtle effects, the large-magnitude "local disturbances" in the stage record must be filtered out before correlations are sought between stage and processes whose effects are more subtle.

An attempt was made to filter out the effects of local irrigation pumping from the stage record. The objective was to repeat and extend in time (beyond 1972) the analysis of Rojstaczer (1987), and to then filter the observed stage data by subtracting the computed stage. However, the analysis could not be extended in time due to a lack of accurate pumping data for Ash Meadows after 1972. Records of electrical power consumption exist for the period 1972-1977, but the meter readings for these records are in doubt. Therefore, the only alternative in this investigation was to exclude that period of the stage record affected by local pumping. Accordingly, the period from 1969 to about 1978, which visibly represents a "trough" in the stage data, was excluded from the analysis.

4.2 ANALYSIS OF PRECIPITATION DATA

This section of the report evaluates the potential impact of short-term climatic trends on Devils Hole stage. Trends in precipitation will cause variations in amounts of ground-water recharge, which in turn will affect ground-water levels. Precipitation isohyetals have long been used in Nevada to estimate ground-water recharge, typically using the Maxey-Eakin method or some variation of this empirical technique (Avon and Durbin, 1992).

Previous analyses of precipitation data in southern Nevada have been published by French (1983, 1989). In the first paper, French (1983) analyzed the distribution in time and space of precipitation data collected at 64 stations through 1979. Half of the stations (32) were on the Nevada Test Site. French (1983) concluded that the data supported the division by Quiring (1965) of southern Nevada into three climatological zones (excess, deficit, and transition), characterized by the amount and type of precipitation received. In the analysis, however, French used only years in which there were no missing daily precipitation data, resulting in the elimination of many years of data.

A subsequent analysis by French (1989) focused on precipitation data for 11 stations on the Nevada Test Site that had relatively long periods of record. Missing daily data were estimated and inserted wherever possible. In addition, the data base was extended by six years, from 1979 through 1985. By adding six years to the record, French (1989) found significant increases in the mean values of annual precipitation at all 11 stations. This positive trend in the data with time was demonstrated to be statistically significant.

In this investigation, a data base of precipitation data was compiled by requesting available records from the Western Regional Climate Center, the U.S. Geological Survey, the Nevada State Engineer, and the Nevada State Climatologist (see Table 2). Subsequent analysis was limited to high-elevation precipitation in areas that contribute the majority of ground-water recharge to Ash Meadows. As discussed previously, recharge to the Ash Meadows ground-water basin is probably derived primarily from precipitation on the Spring Mountains, the Sheep Range, and the Pahranagat Range. No precipitation stations were located in the Pahranagat Range. Two stations in the Sheep Range are operated by the USGS; however, the period of record is short, from about 1986 to the present, and therefore a meaningful analysis could not be performed. Long-term records of precipitation in the Spring Mountains do exist, however, and are analyzed in the following section. In addition, high-elevation precipitation on Pahute Mesa, on the western half of the Nevada Test Site, is analyzed (section 4.2.2). Based on the boundaries of ground-water flow systems by Winograd and Thordarson (1975) and Waddell (1982), Pahute Mesa lies just outside the western boundary of the Ash Meadows basin, and within the Alkali Flat-Furnace Creek Ranch ground-water basin. However, because these boundaries are uncertain and because data exist for Pahute Mesa, the data are evaluated.

4.2.1 <u>Spring Mountains Precipitation</u>

Annual precipitation data collected by the Nevada State Engineer's Office were obtained for eight stations in the Spring Mountains. Table 3 lists the stations, their locations, and elevations. Because these stations are storage gages that are serviced in the summer, the annual data represent climate year values, i.e., from June 30 of the previous year to July 1 of the current year. The period of record for these data is generally from 1961 to the present; however, numerous gaps exist in the raw data (Table 4).

The USGS also maintains a small network of high-altitude storage gages. Three stations are located in the Spring Mountains, but only seven years of data exist, from 1986 through 1992. For this reason, comprehensive analysis was limited to the State Engineer's data. However, a general consistency check was made between the USGS data and the State Engineer's data to verify that the two data sets exhibited similar trends at nearby stations.

The first step in the analysis was to fill the gaps in the raw data. This was done using multiple linear regression, where a relationship was developed between a station having a data gap (the dependent variable), and two to three other stations having record during that period (the independent variables). Table 5 summarizes this process by listing, for each data gap, the stations and corresponding regression coefficients used to develop a relationship for that station. Also listed for each relationship are the standard error of the estimate and the coefficient of variation for the annual estimate. The regressions were then used to estimate the missing data, and the filled records are given in Table 6.

In order to check the consistency of the precipitation record at each station, double mass analyses were performed. The accumulated precipitation at each station was plotted against the accumulated mean precipitation, where the mean of all eight stations was used. As shown by Figures 6a and 6b, the double-mass plots at stations 1, 2, 5, and 7 (Adams Ranch, Cold Creek, Roberts Ranch, and Williams Ranch) exhibit good straight-line relationships. The double-mass plots for the other four stations show more pronounced changes in slope that may indicate inconsistencies in the records. Accordingly, further analysis was limited to the four stations having straight-line double-mass plots.

Plots of annual precipitation and cumulative departure from the mean for the eight Spring Mountains stations are given in Figures 7a - 7h. The records generally show a wet period from the late 1970's through the mid-1980's, followed by a dry period from the late 1980's to 1991, although variability at individual stations exists.

The next step in the analysis was to determine whether a relationship exists between precipitation in the Spring Mountains and stage in Devils Hole. If such a relationship exists, it would be between cumulative departure from mean precipitation and stage, with the possibility that the effect on stage is lagged in time. Accordingly, the cumulative departure from the mean precipitation at stations 1, 2, 5, and 7 (referred to herein as "precipitation index") was compared to mean annual stage in Devils Hole. The mean annual stage was computed based on the climate year, for consistency with the precipitation records. Figure 8 shows a comparison of these two data sets. The "trough" in the stage data discussed earlier is evident here, from 1969 to about 1979.

Initially, linear correlations were computed between the two data sets using lag times ranging from zero to 10 years. The lag times represent the delayed effect upon the stage of changes in the precipitation index. The correlations, shown in Table 7, were performed using the same stage data (1979-1992) in all cases, and the period of precipitation data was shifted backward in time by the indicated lag. This permitted correlations with lags ranging from zero to 10 years.

The results of the linear correlations are best evaluated by two factors: the coefficient of determination, and the level of significance. While the correlation coefficient (r) is a measure of the strength of the correlation, the coefficient of determination (r^2) is easier to interpret because it represents the proportion of the total variation in the stage data that is explained by the linear relationship between the two variables, precipitation index and stage. Table 7 show that the highest correlation ($r^2 = 0.85$) occurs with a one-year lag, but that some degree of correlation exists for other lags as well. It is also important to evaluate the level of significance of the correlation, which is determined by hypothesis testing. This can be understood as the probability that there is in fact no correlation between the two variables. At a one-percent level of significance (which is very conservative), Table 7 indicates that correlations with lags of six or more years are rejected as having an unacceptably high risk of no correlation.

Having identified the best correlation between Spring Mountains precipitation index and Devils Hole stage, linear regressions were next performed using the one-year lag. Regression differs from correlation in that one variable (the independent variable) is assumed to explain, or predict, values of the other variable (the dependent variable). Correlation, on the other hand, makes no assumptions about the nature of the relationship, only examining its strength. In the regressions, the precipitation index was taken as the independent variable, and the mean annual stage in Devils Hole was used as the dependent variable.

The linear regressions excluded the period from 1969 to 1979, when the Devils Hole stage was influenced strongly by nearby pumping in the Ash Meadows area. Any relationship between precipitation index and stage would be masked during this period by the greater impacts of the local pumping upon the stage. Consequently, regression was performed for three cases (Table 8): (1) the recent period of stage data, 1979-1992, (2) the early period of stage data, 1963-1969, and (3) both periods of data together. In the third regression, a dummy variable was used to allow determination of two parallel best-fit lines, corresponding to the two periods of data, that are separated by an offset. This technique is appropriate for representing the offset between the early and recent data, which is a result of the more-or-less permanent dewatering of the valley-fill aquifer due to intensive pumping. The offset can be seen clearly in Figure 9, which shows the scatter of the stage versus the precipitation index for the early and recent period. The use of a dummy variable maintains the same slope for the two regression lines, which corresponds to the assumption that the nature of the relationship between precipitation and stage has remained constant over time.

The best-fit lines resulting from the three regressions are shown on Figure 9. The highest coefficient of determination (r^2 = 0.85) occurs for the recent-period regression, while the dummy-variable regression and the early-period regression produce r^2 = 0.69 and 0.61, respectively.

As with linear correlation, in linear regression the degree of relationship between the two variables is evaluated by both the coefficient of determination (r^2) and the level of significance.

Table 8 summarizes information on the significance of the regressions. Hypothesis testing was performed by computing the t-statistic for the slope of each regression line, to test if the slope is statistically different from zero. The null hypothesis, which is that the slope of the line is zero, is rejected at a one-percent level of significance for two of the regressions. For the early-period regression however, the null hypothesis of zero slope is not rejected at a one-percent level of significance (rejection occurs only at a higher level of significance, approximately two percent). This indicates that, at a one-percent significance level, there is an unacceptably high risk that the slope of the early-period regression is zero and there is no relationship.

To summarize the analysis, a quantitative relationship was found between precipitation in the Spring Mountains and stage in Devils Hole, using the period of stage data from 1979-1992, with stage lagged behind precipitation index by one year. The resulting linear regression between precipitation and stage explains 85 percent of the variation in the stage data, and is statistically significant.

As a final point, there is a plausible physical explanation for the different slopes obtained for the early and recent period regressions. The explanation is related to the damping effect of evapotranspiration (ET) on changes in ground-water levels produced by changes in recharge to ground water. This damping effect, due to the springs and phreatophytes at Ash Meadows, is dependent upon the depth to the water table. As the depth to the water table increases, the effectiveness of the damping is reduced, until at some critical depth ET ceases, and so does the damping. Between the early and recent periods of data, dewatering resulted in lowered water levels in Amargosa Valley especially to the north and west of Ash Meadows area. This likely caused a decrease in ET by phreatophytes and playas in the recent period (1979-1992) relative to early period. Therefore, variations in recharge to ground water during the recent period, when water levels are lower, will produce a greater effect on water levels. This is demonstrated by the larger slope for the regression of the recent period of data.

4.2.2 Nevada Test Site Precipitation

A data base of daily precipitation values for approximately 52 stations, many of which are on the Nevada Test Site, is currently maintained by the Desert Research Institute, University of Nevada (DRI). These data are from two sources: National Weather Service precipitation gages and gages operated by DRI for the Department of Energy (DOE).

An analysis similar to that of the Spring Mountains precipitation data was performed on precipitation data for the Nevada Test Site. The approach was to limit the analysis to high-elevation stations, which would contribute the majority of the recharge from precipitation to the ground-water system. Table 9 lists the precipitation stations above 6,000 ft elevation. All of these stations are located on Pahute Mesa, approximately 55 to 60 miles from Devils Hole. As the table shows, only three of the ten stations have records after 1973. Of those three stations, one (Station 96) has numerous gaps in the data. For this reason, the remaining two stations (84 and 86) were selected for the analysis.

As a first step, monthly total precipitation was computed for Stations 84 and 86. The record for Station 84 is free of missing data; however, the record for Station 86 contains 22 months of missing data, where any month lacking more than two daily values was considered missing.

The monthly gaps in the record for Station 86 were filled using linear regression, with Station 84 as the independent variable. To determine the appropriate period of data from Station 84 to use, a double-mass plot of accumulated monthly precipitation at Station 86 vs. Station 84 was prepared (Fig. 10). The 22 months for which precipitation values were missing at Station 86 were excluded from the accumulated values for both stations. The plot shows a pronounced break in slope at January 1969. Accordingly, the early part of the record (January 1964 to January 1969) was excluded. Several other slight breaks in slope are noted on Figure 10, but they are less abrupt than the January 1969 break, and no additional data were excluded. The regression was performed using all months of data for Station 84 from January 1969 to November 1992. Table 10 gives the resulting regression coefficients, with the standard error of a monthly estimate.

For comparison with the Spring Mountains precipitation regressions, the standard error of an annual estimate of precipitation was computed. The standard error of an estimate for a given year depends on how many months of missing data occur in that year. Accordingly, Table 11 lists the standard errors for individual years of record for Station 86. These values are somewhat lower than those for the Spring Mountains precipitation regressions, which is expected since only part of a year is being estimated.

The missing months of record at Station 86 were estimated using the regression relationship. Annual climate-year totals were then computed for both stations for the period 1969-1992. Figures 11 and 12 show annual precipitation and cumulative departure from the mean for Stations 84 and 86. Comparing the cumulative departures from the mean, it can be seen that the two stations exhibit similar trends, with the exception of the first few years of data (1965 to about 1969). Therefore, the cumulative departure from the mean of the two stations was selected as an index of precipitation on Pahute Mesa. Figure 13 is a comparison between this index of precipitation on Pahute Mesa and the annual average stage in Devils Hole.

Next, linear correlations were computed between annual stage in Devils Hole and the index of precipitation on Pahute Mesa. Using 14 years of stage data for the period 1979-1992, correlations could be calculated for various lags of precipitation with respect to stage ranging from zero to 14 years. Table 12 shows that between lags of two and about nine years, the correlation coefficients form a generally bell-shaped curve, with the highest correlation occurring at a five-year lag. At a five-year lag, the coefficient of determination ($r^2 = 0.53$) indicates that 53 percent of the variation in the stage data is explained by the linear relationship between Pahute Mesa precipitation and stage. In addition, all of the correlations pass a t-test at a one-percent level of significance.

The results of these correlations with Devils Hole stage are reasonable, especially when compared to the Spring Mountains precipitation analysis. The distance from the northwestern part of the Spring Mountains to Ash Meadows is less than 20 mi, while the distance from Pahute Mesa to Ash Meadows is about 60 mi. Therefore, a longer lag time is expected between precipitation trends at Pahute Mesa and their effects at Devils Hole. Furthermore, a weaker correlation between Pahute Mesa precipitation index and Devils Hole stage is anticipated, given that the longer flow path to Ash Meadows likely means greater attenuation of the effects of trends in recharge.

The next step was to assume a cause-and-effect relationship between index of precipitation on Pahute Mesa and Devils Hole stage, and to perform linear regressions using the five-year lag. Figure 14 shows the scatter of stage vs. precipitation index at the five-year lag. Unlike the Spring Mountains data analysis, the data set for regression could not be expanded from the period used for correlation (1979-1992) to include earlier data. This was because the Pahute Mesa precipitation data before January 1969 were rejected based on a break in slope in the double-mass plot. Therefore, the regression strength ($r^2 = 0.53$) and slope significance (one-percent level) are equivalent to those obtained from correlation, because the same data period was used. The regression coefficients are given in Table 13, which is discussed further in the following section.

4.2.3 Synthesis of Precipitation Data

The results of the preceding two sections indicate that precipitation on both the Spring Mountains and Pahute Mesa has an effect on stage in Devils Hole. This suggests that a multiple linear regression can be developed using as independent variables the precipitation indices for (1) Spring Mountains and (2) Pahute Mesa, and using Devils Hole stage as the dependent variable. This process can also be considered as stepwise regression, where a second independent variable (Pahute Mesa precipitation index) is added to the existing regression that used the Spring Mountains precipitation index. Such a regression was performed using the best lag times identified from the correlations, i.e., one year for the Spring Mountains precipitation index, and five years for the Pahute Mesa precipitation index.

Table 13 compares the multiple linear regression using Spring Mountains and Pahute Mesa precipitation with the individual simple linear regression for each variable. The multiple linear regression shows that the slope for the Spring Mountains precipitation index is almost twice the slope for the Pahute Mesa precipitation index, indicating that its influence on Devils Hole stage is almost twice as great. With regard to the overall strength of the multiple regression, the coefficient of determination (r^2) is 0.90, indicating that 90 percent of the variation in the stage data is explained by the linear relationship. With regard to the significance of the multiple regression, two hypothesis tests were performed. First, both regression slopes were tested using an F-test for multiple linear regression at a one-percent level of significance. The null hypothesis that both slopes are zero is rejected, with 99 percent confidence, which establishes that the independent variables as a whole are useful in explaining the dependent variable. The second hypothesis test, the partial F-test, was performed to evaluate the improvement in r^2 that results from adding Pahute Mesa precipitation index (a second independent variable) to the simple regression that used Spring Mountains precipitation. By including this additional variable, there is apparent improvement in the ability to explain the variation in the stage, with r^2 increasing from 0.85 to 0.90. However, the statistical significance of this result must be verified. The partial F-test is used to determine whether it is worthwhile to include Pahute Mesa precipitation in the regression. The results of this test indicate that the explanatory power of this additional variable is significant, at a level of one percent.

4.3 ANALYSIS OF PUMPING DATA

Pumping data in several regions were evaluated to examine whether Devils Hole stage is being affected by such activities. Net ground-water pumping could potentially have an effect on the water level in Devils Hole, where net pumping is the gross pumping less that portion of the pumped water that is returned to the ground-water system via recharge.

4.3.1 Amargosa Valley Pumping

Amargosa Valley is the hydrographic area within which Devils Hole is located (Harrill and others, 1988). Reviews of ground-water conditions in this area have been recently conducted by Kilroy (1991), and Nichols and Akers (1985). Development of ground water within the valley has occurred since the 1950's, and maps of the water table prepared by Kilroy (1991) document the water-level change during the period 1952-1987. The greatest water-level declines were observed in the Amargosa Farms area, where ground-water pumping for irrigation is concentrated. In this region, located about 15 miles northeast of Devils Hole, ground-water levels have declined more than 30 ft since the 1950's. Kilroy (1991) notes that much of the decline occurred during the 1970's, and the rate of decline decreased during the 1980's. Areas distant from Amargosa Farms showed little change in water levels. In the Ash Meadows area, water levels have declined by less than 10 ft since the 1950's, according to Kilroy (1991).

Hydrographs showing water levels for 11 wells in the Amargosa Valley are contained in Appendix A. Most of the measurements were made since the 1980's by the USGS as part of the Water-Resources Monitoring Program for the DOE. With the exception of wells AD-4, AD-15, and AM-3, the hydrographs for these wells in the Amargosa Valley do not show significant declines since the 1980's.

As was discussed previously, pumping for irrigation in the Ash Meadows area of the Amargosa Valley occurred from 1968 until approximately 1977, and had a marked effect upon Devils Hole stage. The correlation between local pumping and stage decline was reported by Dudley and Larson (1976); Rojstaczer (1987) simulated the stage decline due to pumping using a Theis model.

Since about 1977, no significant pumping has occurred in the Ash Meadows area. However, pumping from other parts of the Amargosa Valley continues. Since the mid-1980's, the majority of the pumping has occurred within the Amargosa Farms area. The possibility of a relationship between this pumping and Devils Hole stage can be examined using linear regression. The procedure is analogous to the precipitation regressions previously performed, except that the independent variable is cumulative pumping, while the dependent variable is stage.

Cumulative pumping is the proper independent variable to use in the regression, rather than annual pumping. This can be understood by considering the expected relationship between annual pumping and stage if pumping were constant from year to year, and that pumping caused the stage to gradually decline. Linear regression would indicate no relationship between constant annual pumping and declining stage, when in fact there is a relationship. However, linear regression of cumulative pumping and stage would correctly identify an inverse relationship between these two quantities.

An inventory of ground-water pumping in Amargosa Valley was obtained from the Nevada State Engineer's office. The records consist of annual estimates of ground-water pumping that are based primarily on irrigated acreage. Virtually all of the pumping occurs within the area bounded by townships T16S and T17S and ranges R48E and R49E. This area is at least five miles away from Devils Hole and to the west of the gravity fault noted by Winograd and Thordarson (1975).

Annual data for Amargosa Valley pumping were available for six years only, 1985-1989 and 1991. In order to construct a continuous record for the analysis, total pumping for 1990 was estimated as 5,000 acre-ft (K. Brothers, Las Vegas Valley Water District, oral commun., 1993). Figure 15 shows the annual and cumulative pumping in Amargosa Valley.

A comparison between mean annual stage in Devils Hole and cumulative pumping in Amargosa Valley is given in Figure 16. In this case, Devils Hole stage was averaged by calendar year to correspond to the pumping data. In the precipitation analysis, linear correlations were performed to identify the lag time that led to the best relationship. In this analysis, where pumping occurs from the same ground-water basin in which Devils Hole is located, a significant lag time in effect upon the stage is not expected. Furthermore, with only seven years of data, each year of lag that is introduced eliminates one year of data. For these conceptual and practical reasons, linear regressions were performed using only these lags: a zero-year and a one-year lag of stage with respect to cumulative pumping.

Table 14 lists the results of the regressions of Amargosa Valley cumulative pumping and Devils Hole stage. In the case of a zero-year lag, the regression slope fails to pass a t-test at a one-percent level of significance. This indicates that the slope is not significantly different from zero, and therefore there is no relationship between cumulative pumping and stage at a zero-year lag. In addition, the positive regression slope makes no sense physically, for it represents a positive correlation between cumulative pumping and stage. In the case of a one-year lag, the regression slope is negative and consequently indicates a physically plausible relationship, i.e., a negative correlation between cumulative pumping and stage. However, the slope of this regression also fails to pass the t-test at a one-percent level of significance. Therefore, there is also no relationship between cumulative pumping in Amargosa Valley and stage at a one-year lag.

4.3.2 Pahrump Valley Pumping

Pahrump Valley, which lies to the east of Amargosa Valley (Fig. 1), is a hydrographic area within the Death Valley regional ground-water flow system (Harrill and others, 1988). This hydrographic area includes Pahrump Valley and Stewart Valley, a small area in the west. The basin receives virtually all of its recharge from precipitation in the Spring Mountains, which form the northeast border of the area. Using the Maxey-Eakin method, Harrill (1986) estimated ground-water recharge as 26,000 acre-ft/yr, but obtained a value of 37,000 acre-ft/yr using a numerical ground-water flow model. Ground water flows from the recharge area across the valley to the southwest. Discharge of ground water from the basin occurs as ET by springs and phreatophytes (10,000-13,000 acre-ft/yr under natural conditions) and as subsurface outflow to the southwest (6,000-19,000 acre-ft/yr under natural conditions). It is believed that the outflow moves under the Nopah Range, which lies along the southwest border of Pahrump Valley, and enters the ground-water basins to the southwest (Chicago Valley and California Valley), from which interbasin flow continues until discharge in Death Valley (Harrill and others, 1988). However, some investigators have raised the possibility of a relation between the Pahrump Valley ground-water basin and the Ash Meadows discharge area to the north and west.

A hydraulic differential exists from Pahrump Valley toward Ash Meadows, and the degree of hydraulic connection between these two ground-water basins has long been the subject of controversy. Winograd and Thordarson (1975) provide a thorough review of this matter, and conclude that significant flow from Pahrump Valley to Ash Meadows is unlikely. Their conclusions are based on three observations: (1) Rocks assigned to the lower clastic aquitard outcrop in a nearly continuous band between Pahrump Valley and Ash Meadows, suggesting that an impermeable boundary exists between Ash Meadows and Pahrump Valley. (2) Further evidence for a hydraulic barrier is provided by differences in water-level elevations between western Pahrump Valley and Ash Meadows. The water levels in northwestern Pahrump Valley are almost 200 ft higher than the water level in the lower carbonate aquifer at Devils Hole, suggesting that the ground water in Pahrump Valley is ponded by a relatively impermeable barrier. (3) Geochemical differences exist between the ground waters in Pahrump Valley and Ash Meadows. Previous studies had noted similarities in high calcium, magnesium, and bicarbonate, but had not recognized that ground water at Ash Meadows contains greater amounts of sodium, potassium, sulfate, chloride and dissolved solids. Winograd and Thordarson (1975) address the possibility that ground water from western Pahrump Valley changes chemically during movement to Ash Meadows. They fail to find any progressive westward increase in the above-mentioned constituents, and conclude that at most only a small percentage of the Ash Meadows ground-water discharge could be derived from either Pahrump or Stewart Valleys.

Ground-water pumping in Pahrump Valley increased significantly beginning in the early 1960's, which subsequently altered components of the predevelopment water budget. Under development conditions, virtually all of the spring discharge was captured and ET by phreatophytes decreased, so that by 1976, total discharge by ET was about 2,800 acre-ft/yr (Harrill, 1986). This discharge could be captured because pumping centers were located near areas of discharge by springs and phreatophytes. However, almost none of the subsurface outflow to the southwest (estimated as 18,000 acre-ft/yr in 1976) can be captured by pumping. The pumping has resulted in significant water-level declines and depletion of ground-water storage. During the period 1962-1975, Harrill (1986) reports maximum water-level declines of about 60 ft, and total storage depletion of about 219,000 acre-ft, which is about 40 percent of the total pumpage. Hydrographs of three wells in northwestern Pahrump Valley (see Fig. A-1 for location) are shown in Appendix A, Figures A-17, A-18, and A-19. In two of the wells (P-1 and P-2), water levels measured since the 1980's show some recovery from the long-term decline of the previous several decades. In the third well (P-3), water levels apparently continue to decline, without much change in rate of decline.

Estimates of annual pumping in Pahrump Valley were assembled from two sources: Harrill (1986), and the Nevada State Engineer's Office. Annual and cumulative pumping for the period

1962-1991 are shown in Figure 17. However, no data were available for 1979-1982 and 1990. The annual records show that the amount of pumping in Pahrump Valley during recent years has declined relative to the 1960's and 1970's.

The possibility of a relationship between cumulative pumping in Pahrump Valley and Devils Hole stage was investigated using linear regression, following the same procedure as described previously for Amargosa Valley. Figure 18 shows a comparison of the two data sets. Because of several years of missing pumping data, cumulative pumping was computed for two distinct periods, 1962-1978 and 1983-1989. Regressions were performed for the two periods of data separately, and then for both periods together using a dummy variable. Lag times of zero, one, and two years were used to represent a delay in the effect of pumping upon stage. Again, because of the relatively short periods of data, longer lag times were not feasible because they would reduce the number of observations available for regression. The results of the regressions are presented in Table 15. Interpretation of the strength and significance of the regressions is made in a manner identical to that previously discussed for Amargosa Valley. Therefore, Table 15 is not discussed in detail here. In summary, the regressions fail to identify any relationship between pumping in Pahrump Valley and Devils Hole stage that is both physically meaningful (i.e., negative correlation) and statistically significant (i.e., non-zero regression slope). This result is consistent with the determination of Winograd and Thordarson (1975) that there is little or no hydraulic connection between Pahrump Valley and Ash Meadows.

4.3.3 Nevada Test Site Pumping

Ground-water pumping occurs at the Nevada Test Site (NTS) and is used primarily for water supply and dust control. Records of annual pumping from 22 water-supply wells on the Nevada Test Site were obtained from the Nevada State Engineer's Office. The data, which are compiled by the USGS for the Department of Energy (DOE), were contained in Exhibit No. 111 filed in October 1991 during a water-rights hearing for DOE. The data are presented in Table 16 and include the period 1951-1990. However, no records were kept during the period 1972-1982, according to the exhibit.

Figure 19 shows the locations of the 22 water-supply wells on the Nevada Test Site. In this report, the wells are grouped into five geographic regions to aid in interpretation: Pahute Mesa, Yucca Flat and vicinity, Frenchman Flat, Fortymile Wash, and Mercury Valley. Figure 20 illustrates the total pumping at the Nevada Test Site, and Figures 21a - 21e show the annual pumping distributed in each of the five geographic regions.

It is possible that net pumping from the Nevada Test Site wells could have an impact on the stage in Devils Hole. Following the conceptual model of Waddell (1982), which is based largely upon that of Winograd and Thordarson (1975), the wells in Mercury Valley, Frenchman Flat, and the Yucca Flat vicinity are within the Ash Meadows ground-water basin. The wells in Fortymile Wash and the Pahute Mesa area are in the Alkali Flat-Furnace Creek Ranch ground-water basin. However, the boundaries between these two basins are not well-known, and the Ash Meadows ground-water basin is actually a subbasin of the Alkali Flat-Furnace Creek Ranch ground-water basin. Accordingly, potential impacts from any of the wells should not be immediately ruled out.

An appropriate approach to evaluate the potential impact of NTS pumping would be to perform regressions in a manner similar to the analysis of pumping in Amargosa and Pahrump Valleys. However, the lack of data for NTS pumping during the period 1972-1982, and after 1990, presents a limitation.

Alternate approaches to analyze NTS pumping were considered, such as the use of analytic solutions to represent the drawdown expected as a result of pumping. Given the complexity of the regional ground-water flow system, which is controlled by hydraulic barriers caused by faulted and folded low-permeability rocks, it is difficult to determine ground-water flow paths between individual NTS wells and the Ash Meadows area. Therefore, there is great uncertainty in the degree of hydraulic connection between individual NTS wells and Devils Hole. This suggests it is not appropriate to try to evaluate impacts of NTS pumping using analytic solutions such as the Theis method. More appropriately, an assessment of the cumulative impact of net

NTS pumping upon Devils Hole could be performed using a numerical ground-water flow model, if a reasonable representation of the regional flow system were agreed upon.

Instead, a qualitative evaluation of the potential cumulative impact of NTS pumping was performed. The graph of annual total pumping at the Nevada Test Site (Fig. 20) shows no abrupt or significant trends of increasing pumping during the years 1983-1988. The data do show that pumping in 1989 was somewhat greater than in the previous several years. The increase in pumping in 1989 represents about 40 percent above the average pumping for 1983-1988. However, this cannot be the cause of the stage decline in Devils Hole because the increased pumping (in 1989) occurred after the decline in Devils Hole stage began (in 1988). Furthermore, the majority of recent NTS pumping (and the 1989 increase) occurs in areas that are large distances from Devils Hole: Pahute Mesa and the Yucca Flat area. Assuming that increased pumping in these areas might affect Devils Hole, the effects would likely require a period from a few up to about five years to reach Devils Hole. (The five-year estimate is based on the correlations of Pahute Mesa precipitation and Devils Hole stage presented in section 4.2.2.)

Aside from cumulative impacts that may result from NTS pumping, it is worthwhile to consider potential impacts from the pumping location closest to Devils Hole. The well nearest to Devils Hole is Army 1 WW (about 18 miles away), which comprises the Mercury Valley pumping shown in Figure 21a. Army WW 1 is completed in Paleozoic carbonate rocks (Meyer and Smith, 1964), with open intervals at depths of 800 to 1050 ft and 1360 to 1946 ft (USGS, 1991). Annual pumping from Army 1 WW is less than 400 acre-ft, and has averaged about 200 acre-ft/yr over the period 1983-1990. If pumping at Army 1 WW has affected Devils Hole stage, one would expect to see the effect in monitoring wells located between Army 1 WW and Devils Hole. Monitoring wells AD-7 and AD-8 lie in the northeastern part of the Amargosa Desert, between Army 1 WW near Mercury, and Devils Hole (App. A, Fig. A-1).

Monitoring well AD-7, also known as Tracer Hole 3, penetrates the regional carbonate aquifer about seven miles northeast (upgradient) from the spring discharge area in Ash Meadows (Fig.

A-1). Well AD-7 was drilled by the USGS in 1966 to provide geologic and hydrologic information on the carbonates as part of a tracer study in the northeastern part of the Amargosa Desert (Johnston, 1968). The lithologic log shows that Paleozoic rocks of the Bonanza King formation were first encountered at 610 ft depth, and are overlain by Quaternary and Tertiary lacustrine deposits, alluvium, and basalt. The borehole was originally drilled to 807 ft depth, but bridged at 665 ft. Casing was installed to 620 ft depth, and the borehole is open below that depth. The USGS (1991) reports the total depth of the well as 678 ft in its description of the Water-Resources Monitoring Program, and states that this well is intended to detect changes in ground-water levels in the regional carbonate aquifer due to activities upgradient from Ash Meadows.

Monitoring well AD-8, also known as the Cherry Patch well, is located about 10 miles east-northeast of the springs at Ash Meadows. This well is completed to a depth of 215 ft in the valley-fill material, and is intended to monitor changes in the valley-fill aquifer (USGS, 1991).

The hydrographs for wells AD-7 and AD-8 are shown in Appendix A (Figs. A-5 and A-6). The hydrographs indicate that no significant decline in water levels has occurred in either of these wells, particularly during the period corresponding to the recent decline in Devils Hole stage (1988-1992). Therefore, it is unlikely that pumping at Army 1 WW could have caused the observed decline in stage at Devils Hole without the impacts being seen at either of these intermediate wells, especially well AD-7 in the carbonate aquifer.

4.4 TECTONICS

Tectonic activity may influence the stage in Devils Hole, either gradually over long periods of time, or more abruptly, over shorter periods of time. Tectonic processes that act over long periods of time were discussed briefly in section 3.0. In this section of the report, tectonic processes that act over shorter periods of time and are typically associated with seismicity are considered as possible explanations for the decline in Devils Hole stage that began around 1988.

4.4.1 Response of Water Levels to Strain

Changes in water levels in wells due to seismic events, earth tides, and atmospheric loading are well-known phenomena. They demonstrate that water wells can be sensitive indicators of crustal strain. Numerous investigators have noted that water levels in Devils Hole fluctuate in response to seismic events, earth tides, and barometric pressure (for example, Dudley and Larson, 1976). To understand the dynamics of this process, one must consider the nature of the strain event, the nature of the response of the aquifer, and the nature of the well-aquifer system.

The type of strain event considered here is tectonic strain occurring over periods of up to several years. This type of tectonic activity is usually associated with slip on a fault plane. (This is a common theoretical model, although some investigators believe that preseismic tectonic strains produce dilatancy, which is an increase in volume due to the opening of fresh microfractures, which in turn causes a drop in pore pressure.) This slip may occur in several ways: (1) preseismic or precursory slip, which is movement on the same fault plane as a future earthquake, (2) coseismic slip, which is slip on a fault plane during an earthquake, and (3) aseismic slip, or fault creep, which is steadily propagating movement unaccompanied by seismicity.

All three types of slip are believed to produce deformation, or crustal strain, which may cause a hydrologic response in the ground-water system. There are generally two types of responses of a ground-water system to slip on a fault plane: (1) a dynamic response, which is associated with the passage of earthquake waves through the ground surface, and (2) a response that accompanies the volume strain, or dilatation, which is the fractional change in volume of the rocks that results from deformation.

Dynamic responses are usually transient, short-lived phenomena, with the exception that dynamic ground motion may produce increases in formation permeability. In Devils Hole, dynamic ground motion from an earthquake could produce this effect, but because Devils Hole is part of a system of water-filled fissures and not a porous medium, it is useful to describe the effect using an analogy to pipe flow. The dynamic shaking accompanying an earthquake could alter the "plumbing" of the system by changing the aperture of one of the "pipes" that conducts flow locally in Ash Meadows from the carbonate rock to a spring orifice. In hydraulic terms, a change in the aperture of one of the pipes will change the resistance to flow from the carbonate rock to the spring orifice. Devils Hole can be considered as a piezometer measuring the hydraulic head in the carbonate aquifer just upgradient of its discharge area. The water level of the pool in Devils Hole is at least 100 ft above the elevation of the major springs at Ash Meadows, which means the hydraulic differential is great, and even a small decrease in the resistance to flow could produce an important increase in springflow, which in turn could produce a decrease in water level in Devils Hole.

Volume strain or dilatation results from slip on a fault plane, but is also produced by earth tides and atmospheric loading. The response of an aquifer to dilatation occurs primarily as a change in porosity and a corresponding change in the volume of the pore fluid, because the change in volume of the solid material is assumed to be relatively small (Bredehoeft, 1967). Thus the dilatation of the aquifer causes a change in pressure head in the aquifer. The amplitude of the response of the water level in a well is generally different from the amplitude of the pressure head disturbance in the aquifer. The response of the water level in a well to the disturbance is dependent upon (1) the frequency of the pressure head disturbance, (2) the aquifer properties, (3) the radius of the well casing, and (4) the inertial effects of water in the well. For example, a water well filters out high-frequency strain events. There is also a time lag, or phase shift, between the dilatation of the aquifer and the water-level response in the well, due to the time required for water to flow into and out of the well. The theory of water-level changes in wells due to seismic events, earth tides, and atmospheric loading has been discussed in detail (for example, Cooper and others, 1965; Bredehoeft, 1967; Hsieh and others, 1987; Rojstaczer, 1988a, 1988b, Rojstaczer and Agnew, 1989; and Rojstaczer and Riley, 1990).

The response of rocks of the regional carbonate aquifer to strain has been studied by Galloway and Rojstaczer (1988). These authors analyzed the frequency response of four wells in Yucca Mountain to strains from earth tides and barometric pressure. One of the wells is in the upper part of the lower carbonate aquifer. Galloway and Rojstaczer (1988) used the response of the water level to earth tides to calibrate the well's sensitivity to strain. They found that the areal strain sensitivity (expressed in cm of water per areal nanostrain) was relatively high for the well in the regional carbonate aquifer when compared to the other three wells, which are completed in Tertiary volcanics.

4.4.2 Preseismic Strain

Preseismic, or precursory, strain may cause hydrologic responses in the ground-water system as a result of volume strain of the aquifer. Such responses, which typically consist of anomalous flow rates or pressures of ground water, are referred to as hydrologic precursors. A review of water-level changes documented world-wide that have been attributed to preseismic slip is given by Roeloffs (1988). Hydrologic precursors have been observed at distances of up to several hundred miles from future earthquake epicenters, and precursor times have ranged from less than one day to more than one year. According to Roeloffs (1988), many investigators believe that precursory water-level declines occur more commonly than water-level rises.

This theory of precursory water-level changes as a result of preseismic deformation offers a plausible explanation for the water-level decline at Devils Hole, given a recent increase in regional seismic activity. A hypothesis would be that there was a regional build-up of stress for several years preceding the Landers-Big Bear earthquakes that occurred on June 28, 1992. The Landers earthquake (Ms 7.5), which occurred along the Mohave Shear Zone in southern California (about 150 miles from Devils Hole), was the largest earthquake in the western United States in the past 40 years (Mori and others, 1992). Three hours later, an earthquake (Ms 6.5) occurred near Big Bear Lake in the San Bernardino Mountains, about 25 miles west of the first earthquake. These two earthquakes are associated with, and possibly the cause of, increased seismicity in many regions of the western U.S., including the Yucca Mountain area, about 30 miles northwest of Devils Hole. On June 29, 1992, a 5.6-magnitude earthquake occurred at Little Skull Mountain, about 20 miles north of Devils Hole.

4.4.3 Coseismic Strain

Evidence of hydrologic changes associated with coseismic strain, such as changes in springflow, streamflow, and ground-water levels, is reviewed by the National Research Council (1992, p. 109). The coseismic strain associated with the Landers-Big Bear earthquakes produced a persistent water-level change in Devils Hole. The Devils Hole stage dropped by about 0.5 ft, but gradually recovered in the following weeks (Fig. 3). A persistent decrease in water level of about 0.5 m (1.6 ft) was also observed in a well monitoring the carbonate aquifer beneath Yucca Mountain (O'Brien and Tucci, 1992). These coseismic water-level fluctuations appear to be transient phenomena.

However, another hypothesis involving coseismic strain can be developed to possibly explain the decline in Devils Hole stage that began about 1988. Since 1987, at least four small earthquakes have been recorded on normal faults in Ash Meadows, in areas about one to three miles west-southwest from Devils Hole. These earthquakes are as follows: magnitude 1.64 on November 6, 1987 (Harmsen and Bufe, 1992), magnitude 1.41 on September 3, 1989 (Harmsen and Bufe, 1992), magnitude 1.13 on June 16, 1990 (Harmsen, 1991), and magnitude 1.06 on February 7, 1991 (J.R. Harrill, oral commun., 1993). Harrill (oral commun., 1992) noted that the first earthquake occurred several months before the beginning of the downward trend in Devils Hole stage. While it is unlikely that these earthquakes were large enough to cause a visible coseismic response in water level, they could affect water levels in two ways. The first possibility is a slight drop in land-surface elevation where the springs are, which would produce an increase in discharge by springs or by evapotranspiration due to phreatophytes, gradually lowering ground-water levels in response. Second, local faulting may have opened new fractures or increased existing fractures, producing the same effect as potentially attributable to dynamic ground motion from more distant earthquakes: increased spring discharge and lowered water level at Devils Hole. In either case, even a subtle increase in ground-water discharge may be sufficient to gradually lower ground-water levels.

4.4.4 Fault Creep

Fault creep, or aseismic slip, has produced both transient and persistent water-level changes in numerous locations, as reviewed by Roeloffs and others (1989). This phenomenon is particularly well-documented in the Parkfield, California area, where researchers study water-level changes as indicators of crustal strain with the hope of predicting the next earthquake on this segment of the San Andreas Fault. There is no reported fault creep occurring in the Devils Hole area, so aseismic strain is not a likely cause of the observed water-level decline.

4.4.5 Underground Nuclear Tests

Announced underground nuclear tests conducted in recent years at the Nevada Test Site are reviewed by Harmsen (1991) and Harmsen and Bufe (1992). The detonations were located in the vicinity of Pahute Mesa and Yucca Flat, in the northern and northeastern part of the NTS, at distances of about 40 to 60 miles from Devils Hole. Local seismic magnitudes of the detonations were estimated by the Berkeley Seismographic Laboratory or by the National Earthquake Information Center in Golden, Colorado. These organizations reported local magnitudes of up to 5.6 for the announced tests conducted during the period 1987-1990.

Underground nuclear tests at the Nevada Test Site have likely altered the hydrologic regime in the vicinity of the tests by increasing permeability. More importantly, it is possible that the detonations could produce hydrologic changes at more distant locations in the same manner as earthquakes: by altering the resistance to flow in one of the "pipes" of the Devils Hole fissure system, leading to increased spring discharge and thereby lowering the water level in Devils Hole.

Aside from direct hydrologic effects, underground nuclear testing may indirectly affect conditions by triggering increased seismic activity. Harmsen (1992, p. 152) reports that the nuclear tests induce heightened levels of low-frequency seismicity in the northern NTS for periods ranging from hours to days following tests. In addition, Harmsen (1992) raises the possibility that NTS tests may increase the natural seismicity rate across the southern Great Basin for several days. He suggests that earthquakes might be triggered at distances up to 100 km (60 mi), particularly if the time between tests is several months. This hypothesis is an area of current research, and as Carr (1984, p. 40) notes, attempts to understand the seismotectonics of the region are complicated by the overprint of seismicity triggered by underground nuclear explosions.

5.0 CONCLUSIONS

This investigation has evaluated possible explanations for the decline of about 0.2 ft in stage at Devils Hole that has been observed since 1988. Potential explanations that were considered included short-term climatic changes (that is, trends in precipitation), pumping in adjacent areas, and recent tectonic activity. Principal methods of evaluation included linear correlation and regression, where all statistical results were subjected to hypothesis-testing to verify their statistical significance.

The results of this study indicate that recent trends in precipitation are the most likely explanation for the decline in stage. Evidence for this conclusion was derived primarily from linear regressions of Devils Hole stage and an index of precipitation in the Spring Mountains, a source area for recharge to the regional carbonate aquifer. The highest correlation was found to occur with a one-year lag of stage with respect to index of precipitation. Regression using stage data from 1979-1992 produced a coefficient of determination (r^2) of 0.85, which indicates that 85 percent of the variation in the stage data is explained by the linear relationship.

The precipitation analysis also included a multiple linear regression that was developed using two independent variables: the index of precipitation in the Spring Mountains and a similar index of precipitation on Pahute Mesa. The regression used stage data from 1979-92 and the respective lag times that were identified previously from correlations (one year for the Spring Mountains precipitation index, five years for Pahute Mesa precipitation index). The results indicated that the addition of Pahute Mesa precipitation as a second independent variable in the regression increased r^2 to 0.90. However, the slopes of the regression coefficients demonstrate that the influence on Devils Hole stage of Spring Mountains precipitation is almost twice that of Pahute Mesa precipitation.

Ground-water pumping from Amargosa Valley, Pahrump Valley, and the Nevada Test Site was evaluated as a possible cause of the stage decline. Linear regressions of Devils Hole stage and cumulative pumping from Amargosa Valley and Pahrump Valley did not identify any relationship between cumulative pumping in these areas and stage. This result is consistent with the observation that neither area shows a trend of increased pumping in recent years. The record at the Nevada Test Site was not of sufficient length to allow quantitative analysis such as linear regression, so these data were evaluated qualitatively. Total pumping at the NTS in the years 1983-1988 does not show any pronounced increase that could plausibly explain the stage decline that began in 1988. In addition, potential impacts from the individual NTS water-supply well that is closest to Devils Hole (Army 1 WW) were considered. No significant decline in water levels was observed in two monitoring wells located between Army 1 WW and Devils Hole, which suggests that the stage decline at Devils Hole is not related to water-supply pumping at Army 1 WW.

Tectonic activity may have contributed to the stage decline in Devils Hole, acting simultaneously with precipitation effects. A quantitative relationship between tectonics and stage decline since 1988 has not been established; however, water levels in Devils Hole clearly respond to seismic events. Recent tectonic activity (the Landers-Big Bear earthquakes) has caused water-level changes that persisted for weeks. The dynamic ground motion associated with earthquakes could alter the permeability, or the resistance to flow, of a flow path leading to a spring orifice in Ash Meadows, resulting in increased spring discharge and thereby lowering the water level in Devils Hole. Devils Hole may also be sensitive to preseismic strain, which could change the porosity of the carbonate aquifer and produce precursory water-level changes. It is plausible that a regional build-up of stress may have occurred for several years preceding the Landers-Big Bear earthquakes, and that this stress caused volume strain of the carbonate aquifer. Volume strain, in turn, may have contributed to the observed decline in stage.

Local seismic activity on normal faults in Ash Meadows may also have affected water levels in Devils Hole. Since 1987, four small earthquakes, ranging in magnitude up to 1.64, have been reported within one to three miles from Devils Hole. These events could produce a decline in water level in two ways: (1) a slight drop in land surface would result in increased discharge by springs or by evapotranspiration due to phyreatophytes, thereby lowering ground-water levels, or (2) local faulting could open new fractures or increase existing fractures, also resulting in increased ground-water discharge and lowered water levels in the same manner as potentially produced by dynamic ground motion from more distant earthquakes.

Finally, Devils Hole is within about 60 miles of portions of the Nevada Test Site where underground nuclear tests have been conducted in recent years. Analogous to an earthquake, a nuclear detonation could produce seismic energy that might alter permeability, or resistance to flow, in a flow path that leads to a spring orifice in Ash Meadows. This in turn, could increase ground-water discharge and lower the water level in Devils Hole. In addition, underground nuclear tests trigger increased seismic activity and might thereby indirectly affect water levels at Devils Hole.

This report establishes a quantitative link between precipitation trends and changes in stage at Devils Hole. The linear regression developed in this study demonstrates statistically that the water level in Devils Hole fluctuates in response to trends in precipitation in areas of recharge to the regional carbonate aquifer. Conversely, a statistically significant relationship does not exist between nearby ground-water pumping and stage in Devils Hole. Tectonic activity remains a possible factor in the recent stage decline at Devils Hole.

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TABLES

Table 1.--Major hydrostratigraphic units.

HYDROLOGIC UNIT	GEOLOGIC UNIT	AGE	TECTONIC/ SEDIMENTARY SETTING	APPROXIMATE TRANSMISSIVITY (ft^2/day)
Alluvial aquifer	Numerous stream and alluvial fan gravels	Quaternary and Tertiary	Filling of basins created by basin-and-range and strike-slip faulting	9×10^1 to 5×10^3
Lacustrine confining beds	Various lake bed deposits of silts and clays	Quaternary and Tertiary	Playa lakes	$<9 \times 10^1$
Tuffaceous aquifers and confining beds	Numerous units. Important aquifers include Paintbrush and Timber Mountain Tuffs, and basalts and rhyolitic flows	Tertiary	Oligocene and Miocene volcanism resulted from subduction of plate. Later activity associated with the overriding of oceanic ridge systems	6×10^1 to 9×10^3
Minor confining bed	Granitic stocks	Cretaceous through Permian	Magmatic activity caused by subduction of oceanic rocks beneath North American plate	(Not regionally significant)
Upper carbonate aquifer	Tippipah Limestone	Permian and Pennsylvanian	Shelf-and-slope environment following erosion of Antler Highland	(Not regionally significant)
Upper clastic aquitard	Eleana Formation (argillite, quartzite, limestone)	Mississippian and Late Devonian	Deep-water (?) deposition of sediments off Antler Highland, within the back-arc basin	$<9 \times 10^1$
Lower carbonate aquifer	Devils Gate Limestone, Nevada Formation, Pogonip Group, Nopah Formation, Bonanza King Formation, and Carrara Formation (limestones and dolomites)	Middle Cambrian to Late(?) Devonian	Shelf-and-slope environment, east side of back-arc basin	9×10^1 to 5×10^5
Lower clastic aquitard	Carrara Formation, Zabriskie Quartzite, Wood Canyon Formation, Stirling Quartzite, and Johnnie Formation (siltstones, quartzites, and shales)	Early Cambrian and Precambrian	Rift zone	$<9 \times 10^1$

SOURCES: Waddell (1982), and Winograd and Thordarson (1975)

Table 2.--Data for investigation of Devils Hole (Page 1 of 2).

Data[1]	Location	Source	Period of Record	Frequency	Format
WL	Devils Hole	USGS Carson City, NV	5/23/62 - 5/31/91	Mean daily values	ASCII file
WL	Devils Hole	NPS Fort Collins, CO	8/30/89 - 9/30/92	Daily mean, high, and low values	ASCII file
WL	Nevada Test Site (72 wells or test holes)	USGS, for DOE's Hydrology/Radionuclide Monitoring Program[2]	1988 - 1989 plus existing historic data	Varies	ASCII file
WL	Nevada Test Site Monitoring Network (49 wells or test holes)	USGS, for DOE's Environmental Restoration Program	1989 - 1992	At least quarterly	ASCII file
WL	Regional Monitoring Network (approx. 36 wells)	USGS, for DOE's Environmental Restoration Program	1989 - early 1993 plus existing historic data	Quarterly	ASCII file
WL	Southern Nevada Carbonate Rock Monitoring Network (approx. 65 wells)	USGS Carson City, NV	Varies	Varies	ASCII file
WL	Yucca Mountain, Amargosa Desert, and Furnace Creek Areas (34 wells)	USGS, for DOE's Water-Resources Monitoring Program[3]	Begins 2/92, plus existing historic data	Varies	Tabular
WL	Yucca Mountain Region (28 wells)	USGS, for DOE's Nevada Nuclear Waste Storage Investigations[4]	Varies by well; 1981 - 1989	Varies	Tabular
PR	Death Valley Regional Flow System[5]	Western Regional Climate Center, Reno, NV	Varies by station; latest data is 10/92	Monthly totals	ASCII file
PR	3 storage gages in Spring Mountains and 2 in Sheep Range	USGS Carson City, NV	1986 - 1992	Yearly	ASCII file
PR	8 storage gages in Spring Mountains	Nevada State Engineer's Office (Bill Quinn)	Early 1960's - 1992	Yearly	Tabular
PR	Nevada Test Site	Desert Research Institute, Las Vegas (Dick French)	Varies by station; earliest data 1952; latest 12/92	Daily values	ASCII file
SP	Fairbanks Spring	USGS, for DOE's Water-Resources Monitoring Program[3]	1/1/1910 - 2/16/93	23 measurements	Tabular
SP	Five Springs Well	"	5/2/90 - 3/23/93	22 measurements	
SP	Crystal Pool	"	4/1/50 - 2/16/93	24 measurements	
SP	Big Spring	"	1/1/16 - 2/16/93	21 measurements	
SP	Navel Spring	"	8/23/90 - 2/18/93	7 measurements	
SP	Texas Spring	"	8/23/90 - 2/18/93	9 measurements	

Table 2.--Data for investigation of Devils Hole (Page 2 of 2).

SP	Nevares Spring	NPS Fort Collins, CO	9/1/89 - 10/9/92	Daily discharge	ASCII file
SP	Travertine Spring	"	9/1/89 - 10/9/92	Daily discharge	ASCII file
SP	Texas Spring	"	9/1/89 - 10/8/92	Daily discharge	ASCII file
SP	Fairbanks Spring	U.S. Fish & Wildlife Service	5/30/92 - 1/18/93	Daily discharge	Tabular
PU	Nevada Test Site, 22 water-supply wells	Exhibits introduced into public record (Nevada State Engineer, 10/91)	Varies by well; earliest data 1951; latest 1990[6]	Annual totals	Tabular
PU	Pahrump Valley (#162)	Nevada State Engineer's Office	1962 - 1991, with missing years: '64, '65, '79, '80, '81, '82, '90	Annual totals	Tabular
PU	Amargosa Valley (#230)	Nevada State Engineer's Office	1985 - 1989; 1991	Annual totals	Tabular

NOTES:

[1] WL = Water levels
PR = Precipitation
SP = Spring Discharge
PU = Pumping

[2] Data contained in USGS Open-File Report 92-130 (Wood, 1992).

[3] Data contained in six quarterly reports to DOE dated February 1992, May 1992, August 1992, October 1992, January 1993, and April 1993.

[4] Data contained in three USGS Open-File Reports: OFR 88-468 (Robison and others, 1988); OFR 90-113 (Gemmell, 1990); OFR 91-178 (O'Brien, 1991).

[5] 10 stations with good records that include data for the last 10 years.

[6] No records are available for period 1972-1982.

Table 3.--Precipitation stations in the Spring Mountains.

Station No.	Station Name	Township - Range - Section	Elevation (Ft)
1	Adams Ranch	19S - 56E - 06	9050
2	Cold Creek	18S - 55E - 13	7400
3	Kyle Canyon	19S - 57E - 32	7500
4	Lee Canyon	19S - 56E - 02	8400
5	Roberts Ranch	20S - 57E - 34	6000
6	Spring Mountain Ranch	21S - 58E - 03	4000
7	Williams Ranch	20S - 56E - 27	6000
8	Wheeler Pass	18S - 55E - 16	7683

Table 4.--Annual precipitation (inches) at Spring Mountains stations -- raw data (1)

Climate Year	Station No. (2)							
	1	2	3	4	5	6	7	8
1961		5.9	19.8	12.75	6.3		13	
1962	1	16.25	4	30.4	14.1	10	13.8	15
1963		6.17		15.65	8.		8.25	
1964		8.	11.5	5	5	11	14	9.2
1965	2	10.1	12.2	21.15	11.5		16.9	13.
1966		11.85	18.71	23.6	18.7	7.85	18.05	12.55
1967	18.6	13.05	18.4	24.5	15.85	14	10.	9.6
1968	23.2	14.2	22.2	24.8	13.	6.95	9.8	15
1969	31.	3	29.7	39.2	20.9	12	21.	9.1
1970	13.2		14.15	8	10.8	9.7	9.2	16
1971	17.05	17.2	16.1		11.6	10.8	10.2	10.5
1972	16.8	17.2	15.3	24.2	18.5	11	7.	13.8
1973	27.3	23.9	26.1	12.2	8		18.6	15
1974	10.3	11.1	14.5	17.7		3.6	6.8	8.8
1975	12.6	17.6	17.6	12.15	14.95	14	15.7	17.4
1976	12.	5	11.25	18.3	8.1	5.45	6.9	11.3
1977	18.	16.3	17.85	33.	10.	6.1	11.	13.8
1978	33.03	26.	34.1		8	18.3	28.5	
1979	24.46	3	22.5	7	15.95	13.6	18.45	
1980	24.85		27.3		15.6	17.7	21.9	
1981	10.8	9.2	14.2	13.75	8.	6.7	9.1	17
1982	21.9	21.1	25.5	21.4	17.05	12.7	8.1	
1983	27.15	27.35	31.25	32.1	5	18.85	13	
1984	16.2	16.3	15.9	16.9	4.8	14.	15.	
1985	28.85	3	32.25	25.85	9	14.25	24.3	19.55
1986	19.	22.2	24.35	24.2	13.35	11.7	12.9	18.1
1987	22.	18.6	18.1	23.5	15.2	8.85	15.87	17.25
1988	21.35	17.9	12.3	23.8	15.25	10.5	20.15	19.5
1989	17.7	16.45	11.55	18.65	11.85	8.6	12.95	11.95
1990	15.65	15.45	15.55	17.35	11.3	7.25	11.6	13.9
1991	16.55	19.15	19.55	23.25	15.6	10.05	15.65	15.8
1992	23.8	24.55	27.3	30.75	19.35	16.35	19.7	23.65

(1) Raw data in significant digits as reported by the Nevada State Engineer. Data gaps (shaded) are numbered for cross-reference to equation number in Table 5.

(2)
1 = Adams Ranch
2 = Cold Creek
3 = Kyle Canyon
4 = Lee Canyon
5 = Roberts Ranch
6 = Spring Mountain Ranch
7 = Williams Ranch
8 = Wheeler Pass

Table 5.--Regression coefficients for filling gaps in Spring Mountains precipitation data.

EQN. No. (1)	Station No. (2)			Regression Coefficients (3)				s_e (4)	c_v (5)
	x_1	x_2	x_3	a_0	a_1	a_2	a_3		
1	2	4	5	4.24	0.26	0.35	0.13	2.73	0.15
2	2	3	--	1.97	0.52	0.40	--	3.21	0.16
3	1	3	7	4.66	0.18	0.32	0.26	2.51	0.14
4	2	5	7	5.96	0.63	0.31	-0.21	3.61	0.20
5	2	3	--	12.29	0.40	0.13	--	5.80	0.27
6	1	5	7	2.23	1.13	0.08	-0.11	4.36	0.19
7	1	3	6	8.40	0.63	0.23	-0.21	4.32	0.19
8	2	3	--	4.18	0.41	0.14	--	3.63	0.27
9	1	3	4	2.08	0.38	0.21	0.03	3.45	0.25
10	2	4	5	2.29	0.69	-0.18	-0.01	2.16	0.22
11	2	3	--	-3.10	0.64	0.10	--	2.13	0.20
12	1	3	7	0.94	-0.06	0.27	0.39	2.36	0.22
13	3	4	--	5.15	0.38	0.07	--	4.61	0.33
14	2	3	--	3.35	0.45	0.15	--	4.71	0.34
15	2	4	5	0.95	0.76	-0.02	0.14	2.41	0.16
16	1	3	7	10.34	-0.49	0.11	0.82	3.51	0.24
17	1	3	6	2.93	0.37	0.02	0.55	2.62	0.17

(1) Numbers correspond to data gaps in Table 4, which indicates station used as dependent variable.

(2)
1 = Adams Ranch
2 = Cold Creek
3 = Kyle Canyon
4 = Lee Canyon
5 = Roberts Ranch
6 = Spring Mountain Ranch
7 = Williams Ranch
8 = Wheeler Pass

(3) Regression of form: $y = a_o + a_1 x_1 + a_2 x_2 + a_3 x_3$

(4) s_e = Standard error of the estimate for annual precipitation (in).

(5) c_v = Coefficient of variation for annual precipitation.

Table 6.--Annual precipitation (inches) at Spring Mountains stations -- filled record (1).

Climate Year	Station No. (2)							
	1	2	3	4	5	6	7	8
1961	11.06	5.90	19.80	12.75	6.30	3.95	13.58	6.06
1962	20.95	16.25	17.75	30.4	14.1	7.76	13.8	14.64
1963	12.37	6.17	10.63	15.65	8.	3.58	8.25	6.45
1964	10.76	8.	11.5	17.04	9.07	3.26	8.72	9.2
1965	12.13	10.1	12.2	21.15	11.5	4.68	16.9	13.
1966	15.67	11.85	18.71	23.6	18.7	7.85	18.05	12.55
1967	18.6	13.05	18.4	24.5	15.85	7.23	10.	9.6
1968	23.2	14.2	22.2	24.8	13.	6.95	9.8	13.04
1969	31.	25.14	29.7	39.2	20.9	15.16	21.	9.1
1970	13.2	13.93	14.15	16.96	10.8	9.7	9.2	13.03
1971	17.05	17.2	16.1	21.27	11.6	10.8	10.2	10.5
1972	16.8	17.2	15.3	24.2	18.5	9.58	7.	13.8
1973	27.3	23.9	26.1	12.2	17.64	15.03	18.6	15.19
1974	10.3	11.1	14.5	17.7	10.76	3.6	6.8	8.8
1975	12.6	17.6	17.6	12.15	14.95	10.08	15.7	17.4
1976	12.	12.19	11.25	18.3	8.1	5.45	6.9	11.3
1977	18.	16.3	17.85	33.	10.	6.1	11.	13.8
1978	33.03	26.	34.1	33.31	19.61	18.3	28.5	25.87
1979	24.46	21.02	22.5	26.2	15.95	13.6	18.45	19.9
1980	24.85	23.51	27.3	26.67	15.6	17.7	21.9	22.39
1981	10.8	9.2	14.2	13.75	8.	6.7	9.1	10.88
1982	21.9	21.1	25.5	21.4	17.05	12.7	8.1	18.51
1983	27.15	7.35	31.25	32.1	19.77	18.85	19.26	23.94
1984	16.2	16.3	15.9	16.9	4.8	14.	15.	16.94
1985	28.85	26.43	32.25	25.85	20.53	14.25	24.3	19.55
1986	19.	22.2	24.35	24.2	13.35	11.7	12.9	18.1
1987	22.	18.6	18.1	23.5	15.2	8.85	15.87	17.25
1988	21.35	17.9	12.3	23.8	15.25	10.5	20.15	19.5
1989	17.7	16.45	11.55	18.65	11.85	8.6	12.95	11.95
1990	15.65	15.45	15.55	17.35	11.3	7.25	11.6	13.9
1991	16.55	19.15	19.55	23.25	15.6	10.05	15.65	15.8
1992	23.8	24.55	27.3	30.75	19.35	16.35	19.7	23.65
MEAN	19.0	17.0	19.5	22.6	13.8	10.0	14.3	14.9

(1) Data gaps filled using multiple linear regression equations in Table 5.

(2)
1 = Adams Ranch
2 = Cold Creek
3 = Kyle Canyon
4 = Lee Canyon
5 = Roberts Ranch
6 = Spring Mountain Ranch
7 = Williams Ranch
8 = Wheeler Pass

Table 7.--Correlations of annual data for Devils Hole Stage and Spring Mountains precipitation (1).

Lag Time (Yrs) (2)	r (3)	r^2 (4)	Significance Level (%) (5)
0	0.85	0.73	1×10^{-2}
1	0.92	0.85	3×10^{-4}
2	0.87	0.76	5×10^{-3}
3	0.84	0.71	2×10^{-2}
4	0.76	0.57	2×10^{-1}
5	0.70	0.49	5×10^{-1}
6	0.53	0.28	5×10^{0}
7	0.41	0.17	1×10^{1}
8	0.35	0.12	2×10^{1}
9	0.14	0.02	6×10^{1}
10	-0.18	0.03	5×10^{1}

(1) Correlations performed using 14 years of mean annual stage data, 1979-1992.

(2) Lag of index of precipitation in Spring Mountains with respect to stage in Devils Hole.

(3) Correlation Coefficient for stage and precipitation data, 14 pairs of observations.

(4) Coefficient of Determination = square of correlation coefficient.

(5) Probability in percent from Student's T-Distribution of a Type I error, i.e., of rejecting the null hypothesis of zero correlation when the null hypothesis is in fact true.

Table 8.--Regressions of Spring Mountains precipitation and Devils Hole stage, one-year lag.

No.	State Period	Index of Precip. Period	No. Obs.	Regressions Coefficients		r^2	Is Slope Different from Zero? (1)	Is Relationship Physically Plausible? (2)
				Slope	Intercept			
1	1979-92	1978-91	14	0.021	1.83	0.85	Yes	Yes
2	1963-69	1962-68	7	0.004	1.12	0.61	No	Yes
3	1963-69, 1979-92	1962-68, 1978-91	21	0.016	0.88, 1.89 (3)	0.69	Yes	Yes

(1) Hypothesis-testing performed on the regression slope using a t-test at a 1% level of significance. Rejection of the null hypothesis that the slope is zero leads to the conclusion, with 99% confidence, that the slope is different from zero.

(2) A positive correlation between precipitation and stage is physically plausible.

(3) A dummy variable was used in the regression to relate the two periods of data, producing two parallel lines having different intercepts.

Table 9.--High-elevation precipitation stations on Pahute Mesa, Nevada Test Site (1).

Station No.	Station Name	Latitude/ Longitude	Elevation (Ft)	Data Period/Quality
84	Area 12 Mesa	37 11/116 13	7490	1960-1992/No Gaps
86	Pahute Mesa 1	37 15/116 26	6550	1964-1992/Some Gaps
87	Pahute Mesa 2	37 18/116 28	6340	to 1973 only
88	Pahute Mesa 3	37 16/116 23	6490	to 1973 only
89	Pahute Mesa 4	37 15/116 18	6900	to 1973 only
90	Pahute Mesa 5	37 20/116 18	6750	to 1973 only
96	U-20K	37 18/116 31	6070	1980-1990/Numerous Gaps
101	Area 12 Mesa S	37 11/116 12	7640	to 1964 only
102	Area 12 Mesa NW	37 13/116 14	7670	to 1964 only
103	Area 12 Mesa NE	37 12/116 12	7240	to 1964 only

(1) Stations at elevations above 6,000 ft.

Table 10.--Regression coefficients for filling gaps in Pahute Mesa precipitation data.

y (1)	x (2)	Period of Record (3)	Regression Coefficients (4)		s_e (5)
			a_0	a_1	
Station 86	Station 84	1/69 - 11/92	0.18	0.39	0.48

(1) Dependent variable used in regression.

(2) Independent variable used in regression.

(3) Period of monthly data used in regression.

(4) Regression of form: $y = a_0 + a_1 x$.

(5) Standard error of the estimate for monthly precipitation (in).

Table 11.--Standard errors of estimates of missing precipitation data, Pahute Mesa station 86.

Climate Years	No. of Missing Months	S_e (1)	C_v (2)
1970-83, 1986, 1990	0	--	--
1992	1	0.48	0.06
1985, 1987, 1988, 1991	3	0.83	0.11
1984	4	0.95	0.13
1989	5	1.07	0.14

(1) Standard error of the estimate for annual precipitation (in).

(2) Coefficient of variation for annual precipitation.

Table 12.--Correlations of annual data for Devils Hole stage and Pahute Mesa precipitation (1)

Lag Time (Yrs) (2)	r (3)	r^2 (4)	Significance Level (%) (5)
0	-0.07	0.00	8×10^{-1}
1	0.02	0.00	9×10^{-1}
2	0.36	0.13	2×10^{-1}
3	0.62	0.38	2×10^{-2}
4	0.66	0.43	1×10^{-2}
5	0.73	0.53	3×10^{-3}
6	0.63	0.40	2×10^{-2}
7	0.60	0.36	2×10^{-2}
8	0.62	0.39	2×10^{-2}
9	0.49	0.24	7×10^{-2}
10	0.28	0.08	3×10^{-2}
11	0.17	0.03	6×10^{-1}
12	0.02	0.00	9×10^{-1}
13	-0.17	0.03	6×10^{-1}
14	-0.17	0.03	6×10^{-1}

(1) Correlations performed using 14 years of mean annual stage data, 1979-1992.

(2) Lag of stage in Devils Hole with respect to index of precipitation for Pahute Mesa.

(3) Correlation Coefficient for stage and precipitation data, 14 pairs of observations.

(4) Coefficient of Determination = square of correlation coefficient.

(5) Probability in percent from Student's T-Distribution of a Type I error, i.e., of rejecting the null hypothesis of zero correlation when the null hypothesis is in fact true.

Table 13.--Summary of regressions of precipitation and Devils Hole stage.

Independent Variable(s) (1)	Stage Period	Index of Precip. Period	No. Obs.	Regression Coefficients		r^2	Are Slope(s) Different from Zero?
				Slope(s)	Intercept		
PM	1979-92	1974-87	14	0.027	2.21	0.53	Yes (2)
SP	1979-92	1978-91	14	0.021	1.83	0.85	Yes (2)
SP & PM	1979-92	1974-87 (PM) 1978-91 (SP)	14	0.010 (PM) 0.017 (SP)	1.92	0.90	Yes (3)

(1) PM = Pahute Mesa Precipitation Index
SP = Spring Mountains Precipitation Index

(2) Hypothesis-testing performed on the regression slope using a t-test at a 1% level of significance. Rejection of the null hypothesis that the slope is zero leads to the conclusion, with 99% confidence, that the slope is different from zero.

(3) Two hypothesis tests performed:

i. F-test for multiple linear regression performed on both slopes at a 1% level of significance. Rejection of the null hypothesis that both slopes are zero leads to the conclusion, with 99% confidence, that the slopes are different from zero.

ii. Partial F-test performed to evaluate statistical significance of adding independent variable PM to regression using SP only, i.e., to evaluate improvement in r^2 from 0.85 to 0.90. Rejection of the null hypothesis leads to the conclusion that the explanatory power of PM is significant, at a 1% level.

Table 14.--Regressions of Amargosa Valley cumulative pumping and Devils Hole stage.

No.	Stage Period	Pumping Period	Lag (Yrs)	No. Obs.	Regression Coefficients		r^2	Is Slope Different from Zero? (1)	Is Relationship Physically Plausible? (2)
					Slope	Intercept			
1	1985-91	1985-91	0	7	7.9×10^{-7}	1.97	0.02	No	No
2	1986-91	1985-90	1	6	-2.1×10^{-6}	1.89	0.11	No	Yes

(1) Hypothesis-testing performed on the regression slope using a t-test at a 1% level of significance. Rejection of the null hypothesis that the slope is zero leads to the conclusion, with 99% confidence, that the slope is different from zero.

(2) A negative correlation between cumulative pumping and stage is physically plausible.

Table 15.--Regressions of Pahrump Valley cumulative pumping and Devils Hole stage.

No.	Stage Period	Pumping Period	Lag (Yrs)	No. Obs.	Regression Coefficients		r^2	Is Slope Different From Zero? (1)	Is Relationship Physically Plausible? (2)
					Slope	Intercept			
1	1963-68	1963-68	0	6	-2.0×10^{-7}	1.17	0.30	No	Yes
2	1983-89	1983-89	0	6	2.3×10^{-6}	2.19	0.89	Yes	No
3	1963-68. 1983-89	1963-68, 1983-89	0	13	5.6×10^{-7}	1.29, 2.03 (3)	0.17	No	No
4	1963-68	1962-67	1	6	-2.2×10^{-7}	1.18	0.31	No	Yes
5	1983-89	1982-88	1	6	2.2×10^{-6}	2.13	0.90	Yes	No
6	1963-68, 1984-90	1962-67, 1983-89	1	13	3.0×10^{-7}	1.24, 1.99 (3)	0.15	No	No
7	1964-68, 1985-91	1962-66, 1983-89	2	12	-5.8×10^{-8}	1.20, 1.94 (3)	0.27	No	Yes

(1) Hypothesis-testing performed on the regression slope using a t-test at a 1% level of significance. Rejection of the null hypothesis that the slope is zero leads to the conclusion, with 99% confidence, that the slope is different from zero.

(2) A negative correlation between cumulative pumping and stage is physically plausible.

(3) A dummy variable was used in the regression to relate the two periods of data, producing two parallel lines having different slopes.

Table 16.-- Nevada Test Site Pumping, acre-ft/yr (Page 1 of 2)

YEAR	UE-1rWW	WW-2	WW-A	UE-5cWW	WW-5A	WW-5B	WW-5c	WW-3	WW-4	WW-C	WW-C1
1951					29.77	62.30		8.59			
1952					29.77	62.30		8.59			
1953					29.77	62.30		8.59			
1954					29.77	62.30	55.55	8.59			
1955					29.77	62.30	55.55	8.59			
1956					29.77	62.30	55.55	8.59			
1957					29.77	62.30	55.55	8.59			
1958					22.10	80.72	62.00	38.67			
1959					30.08	54.94	39.28	52.79			
1960					38.98	66.60	60.15	34.37			
1961			41.13		59.85	114.17	67.83	39.90		15.04	
1962		29.77	150.69		105.88	202.87	223.74	67.52		114.78	49.72
1963		70.90	99.13		73.04	71.51	213.30	66.91		131.97	96.68
1964		74.27	161.74		59.85	94.53	148.24	62.00		174.63	216.68
1965		107.42	141.49		30.08	71.20	178.01	49.41		94.84	120.00
1966		143.33	131.97		50.95	110.18	173.71	55.86		104.35	233.25
1967		157.75	82.56		45.12	27.62	133.81	45.73		88.70	104.35
1968		158.67	60.46		49.72	31.92	182.61	22.71		248.60	82.56
1969		216.99	96.98		17.49	20.87	122.46	20.87		293.41	111.72
1970		175.86	75.50		10.74	72.43	126.14	5.52		191.51	56.16
1971		112.02	96.37			24.86	135.65			194.58	62.61
NOTE: NO DATA AVAILABLE FOR 1972-1982											
1983		133.35	136.64	3.87		98.74	129.20		73.99	85.04	115.50
1984		147.58	126.03	7.38		177.55	180.09		148.57	95.75	71.55
1985	21.45	56.83	115.09	15.27		208.20	144.60		131.78	59.44	88.86
1986	13.52	59.69	96.22	10.86		179.54	196.30		86.48	52.96	92.24
1987	15.45	130.71	92.74	25.65		154.93	154.32		86.53	21.97	68.54
1988	14.55	74.12	63.37	26.96		176.33	208.03		143.36	53.41	76.20
1989	0.00	59.71	0.00	9.77		0.00	108.65		589.41	96.97	86.12
1990	0.00	55.83	0.00	0.00		0.00	117.81		209.24	91.07	71.64

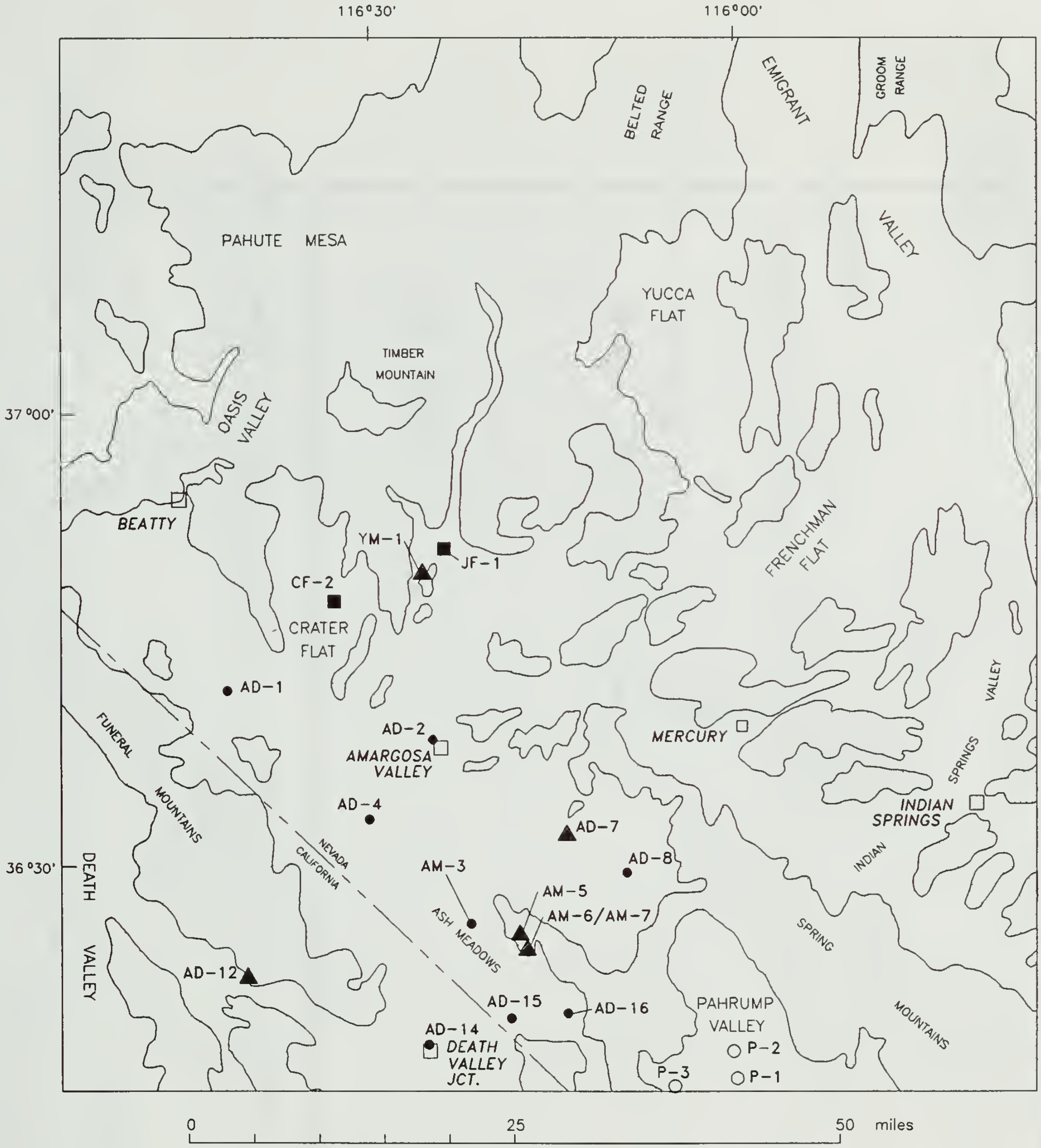
YEAR	UE-15dWW	UE-16d WW	WW-8	UE-19cWW	UE-19eWW	UE-19gSWW	U-20WW	U-20a2WW	Army1WW	J-12WW	J-13WW
1951											
1952											
1953											
1954											
1955											
1956											
1957											
1958											

Table 16.-- Nevada Test Site Pumping, acre-ft/yr (Page 2 of 2)

YEAR	UE-1rWW	WW-2	WW-A	UE-5cWW	WW-5A	WW-5B	WW-5c	WW-3	WW-4	WW-C	WW-C1
1959											
1960											
1961										92.07	
1962									12.89	184.15	
1963			16.27						8.29		
1964			343.43					52.17	94.22		
1965			99.13		34.37			27.93	77.96		
1966	52.48		111.10		19.34			19.34	145.17		
1967	114.48		176.47		31.30	64.45		69.98	172.18		
1968	123.68								161.74		
1969	115.70								239.70		
1970	114.78								213.00		
1971	8.29								294.94		
NOTE: NO DATA AVAILABLE FOR 1972-1982											
1983		13.98	180.74	128.44					174.41	75.48	141.32
1984		24.86	187.61	196.72					251.95	76.09	126.10
1985		77.87	184.88	316.80					127.71	80.31	84.18
1986		118.07	116.30	261.09			228.73		106.98	87.76	53.51
1987		104.45	209.80	156.83			210.82		106.54	62.37	100.01
1988		116.83	200.35	197.27			323.57		163.02	62.82	78.38
1989		79.83	165.37	425.50			345.48		351.26	103.04	52.09
1990		101.10	131.70	339.33			285.08		378.97	95.80	62.85

DATA SOURCE: Exhibit filed in October 1991 with Nevada State Engineer during water-rights hearing for Department of Energy (DOE).

APPENDIX A



- ● Monitoring well in valley fill
- ▲ Monitoring well in carbonate rocks
- ■ Monitoring well in valcanic rocks
- ○ Monitoring well – no information on lithology

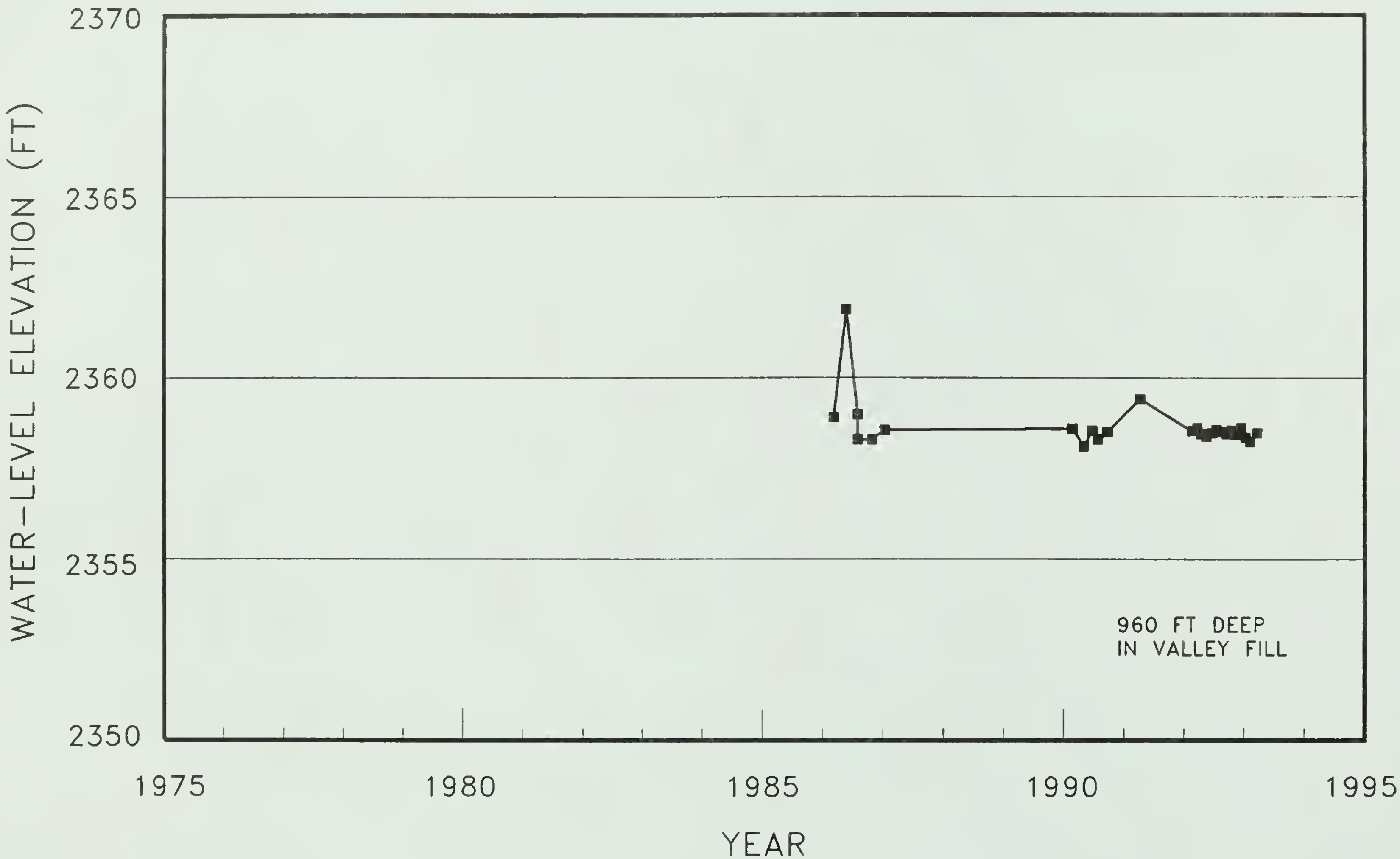
- Valley fill moterial
- Cansolidated rocks

JOB NO. 590	DATE: 5-17-93
BY: LA	DRAWN: MW
FILE: 19MONW.DWG	REV: NS

HCI HYDROLOGIC CONSULTANTS, INC.

LOCATION OF SELECTED REGIONAL MONITORING WELLS

Figure A-1



SEE FIG. A-1 FOR WELL LOCATION

DATA SOURCE:
U.S. GEOLOGICAL SURVEY
WATER-RESOURCES
MONITORING PROGRAM

HCI HYDROLOGIC CONSULTANTS, INC.	JOB NO. 590	DATE: 5-11-93	WATER-LEVEL ELEVATION IN WELL AD-1	Figure A-2
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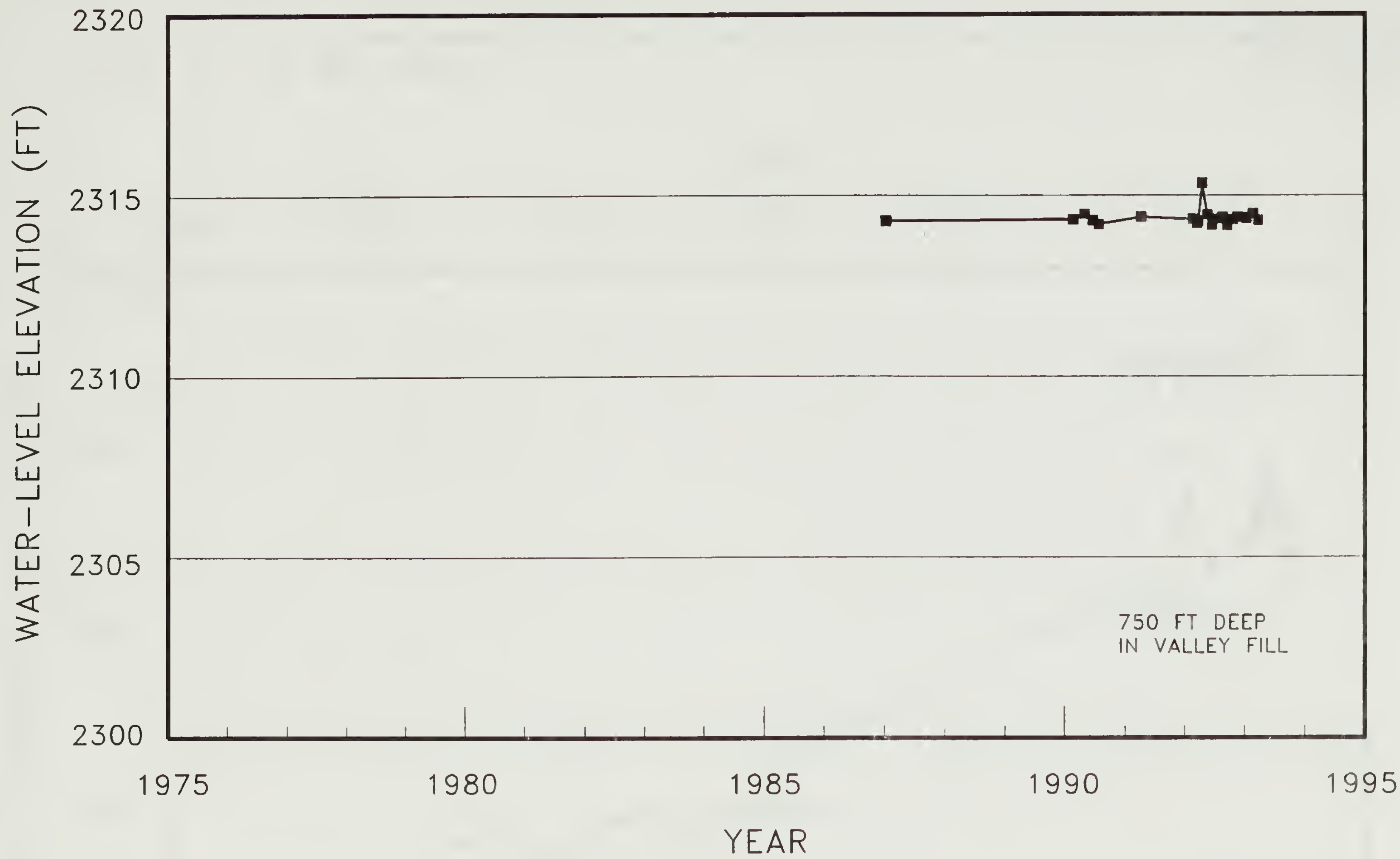

SEE FIG. A-1 FOR WELL LOCATION

DATA SOURCE:
U.S. GEOLOGICAL SURVEY
WATER-RESOURCES
MONITORING PROGRAM

HCI HYDROLOGIC CONSULTANTS, INC.	JOB NO. 590	DATE: 5-11-93	WATER-LEVEL ELEVATION IN WELL AD-2	Figure A-3
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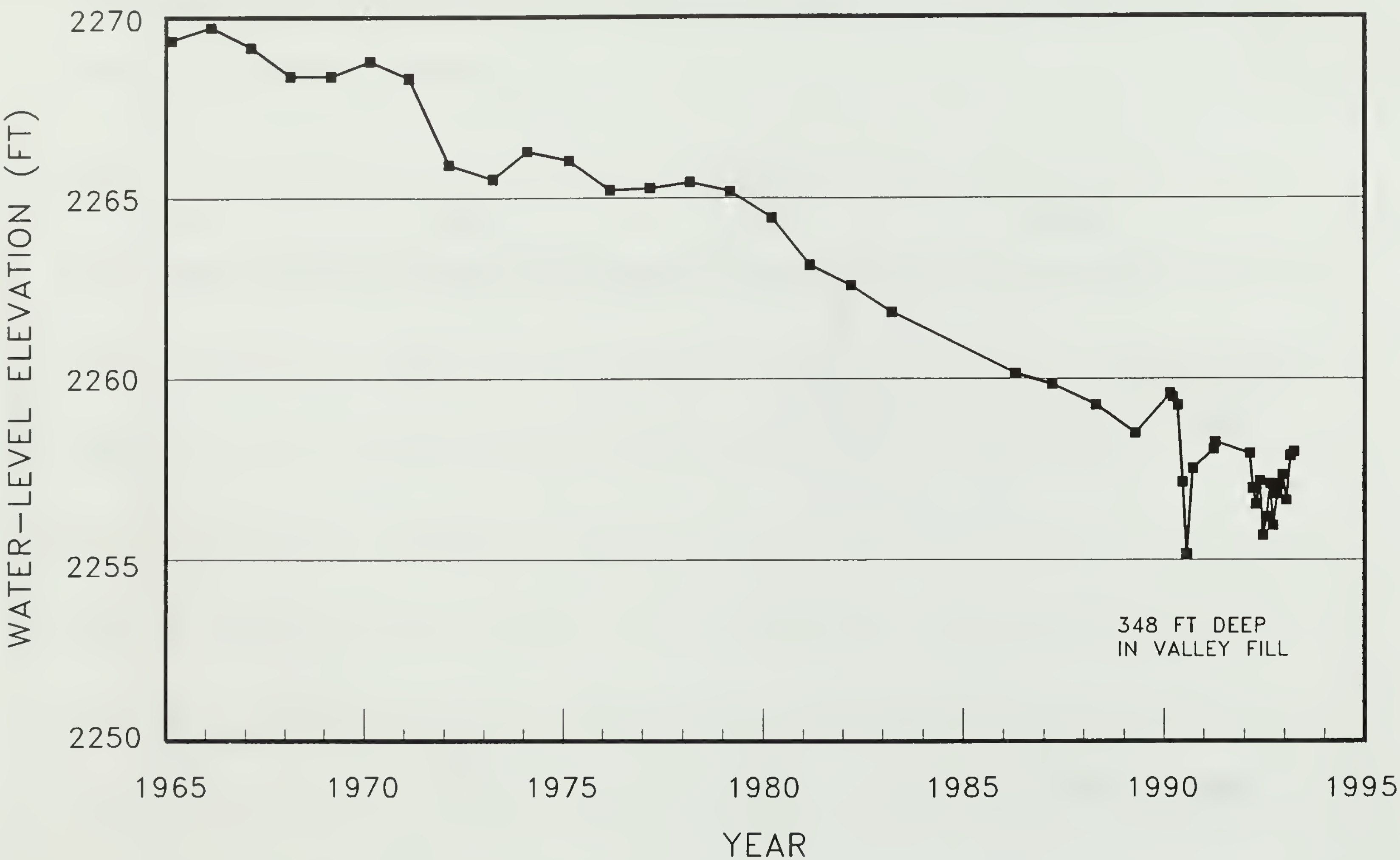

SEE FIG. A–1 FOR WELL LOCATION

DATA SOURCE:
U.S. GEOLOGICAL SURVEY
WATER–RESOURCES
MONITORING PROGRAM

HCI HYDROLOGIC CONSULTANTS, INC.	JOB NO. 590	DATE: 5–11–93	WATER–LEVEL ELEVATION IN WELL AD–4	Figure A–4
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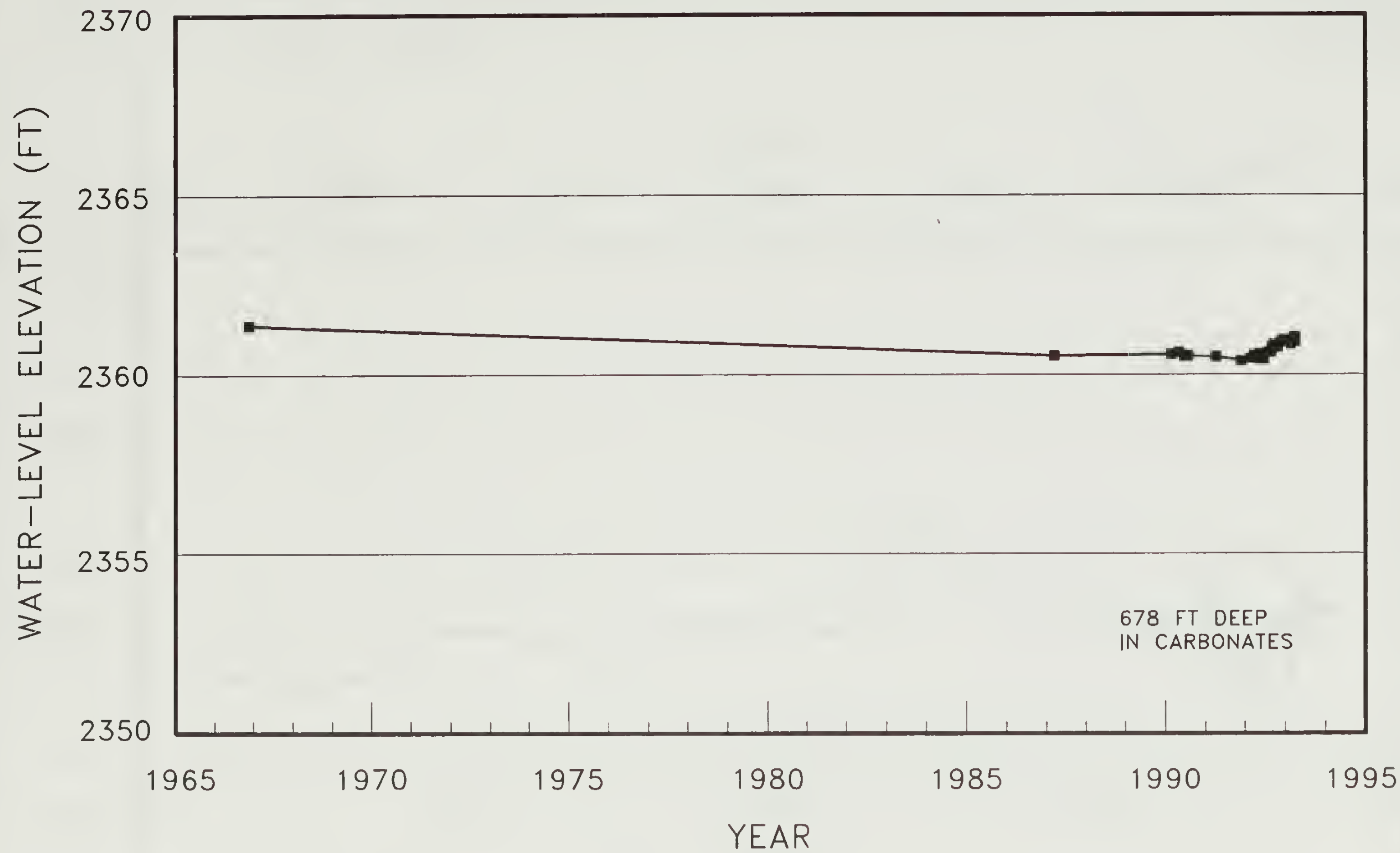

SEE FIG. A-1 FOR WELL LOCATION

DATA SOURCE:
U.S. GEOLOGICAL SURVEY
WATER-RESOURCES
MONITORING PROGRAM

HCI HYDROLOGIC CONSULTANTS, INC.	JOB NO. 590	DATE: 5-11-93	WATER-LEVEL ELEVATION IN WELL AD-7	Figure A-5
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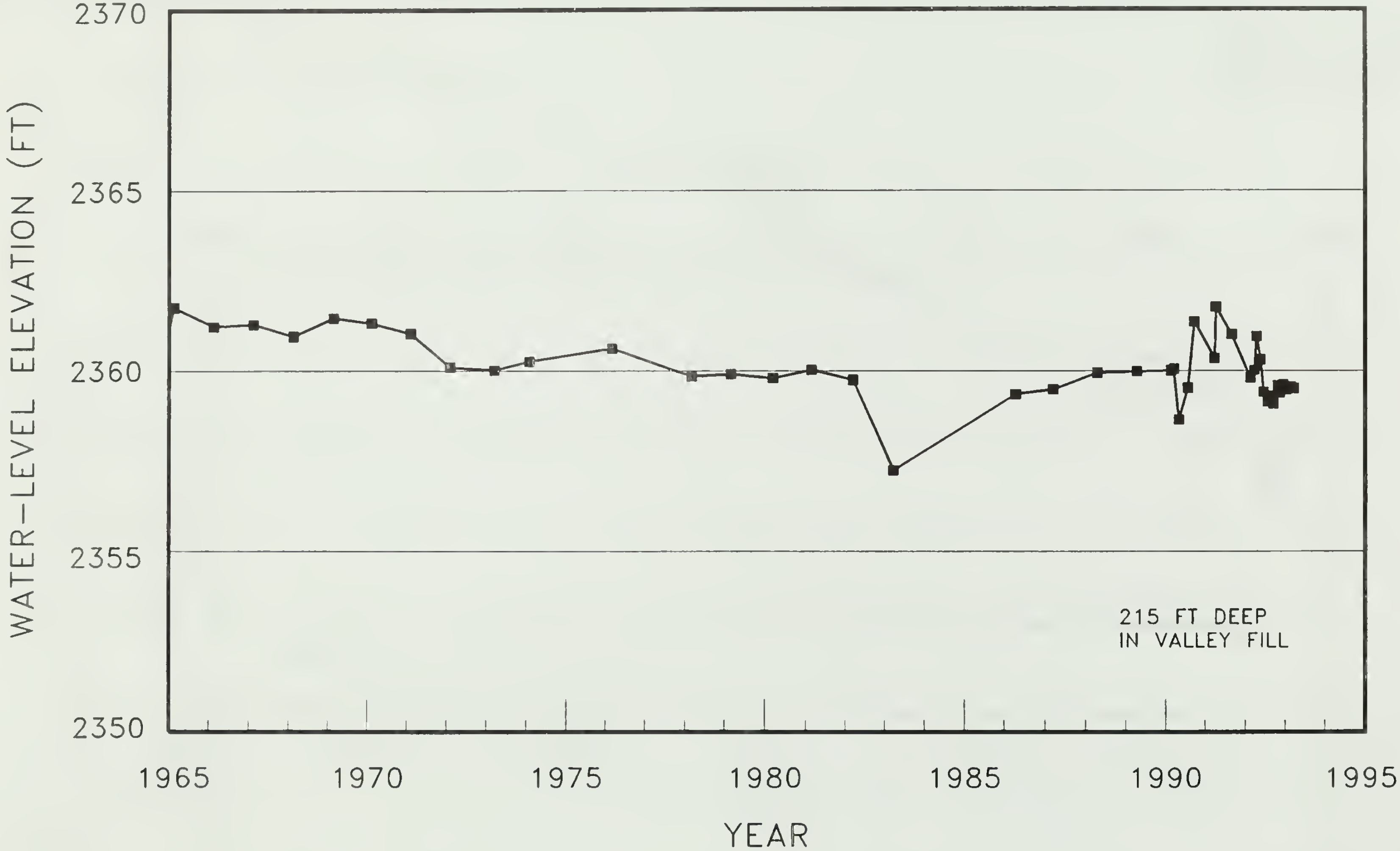
	FILE: AD-7.DWG	REV:		



SEE FIG. A-1 FOR WELL LOCATION

DATA SOURCE:
U.S. GEOLOGICAL SURVEY
WATER-RESOURCES
MONITORING PROGRAM

HCI HYDROLOGIC CONSULTANTS, INC.	JOB NO. 590	DATE: 5-11-93	WATER-LEVEL ELEVATION IN WELL AD-8	Figure A-6
	BY: LA	DRAWN: NS		
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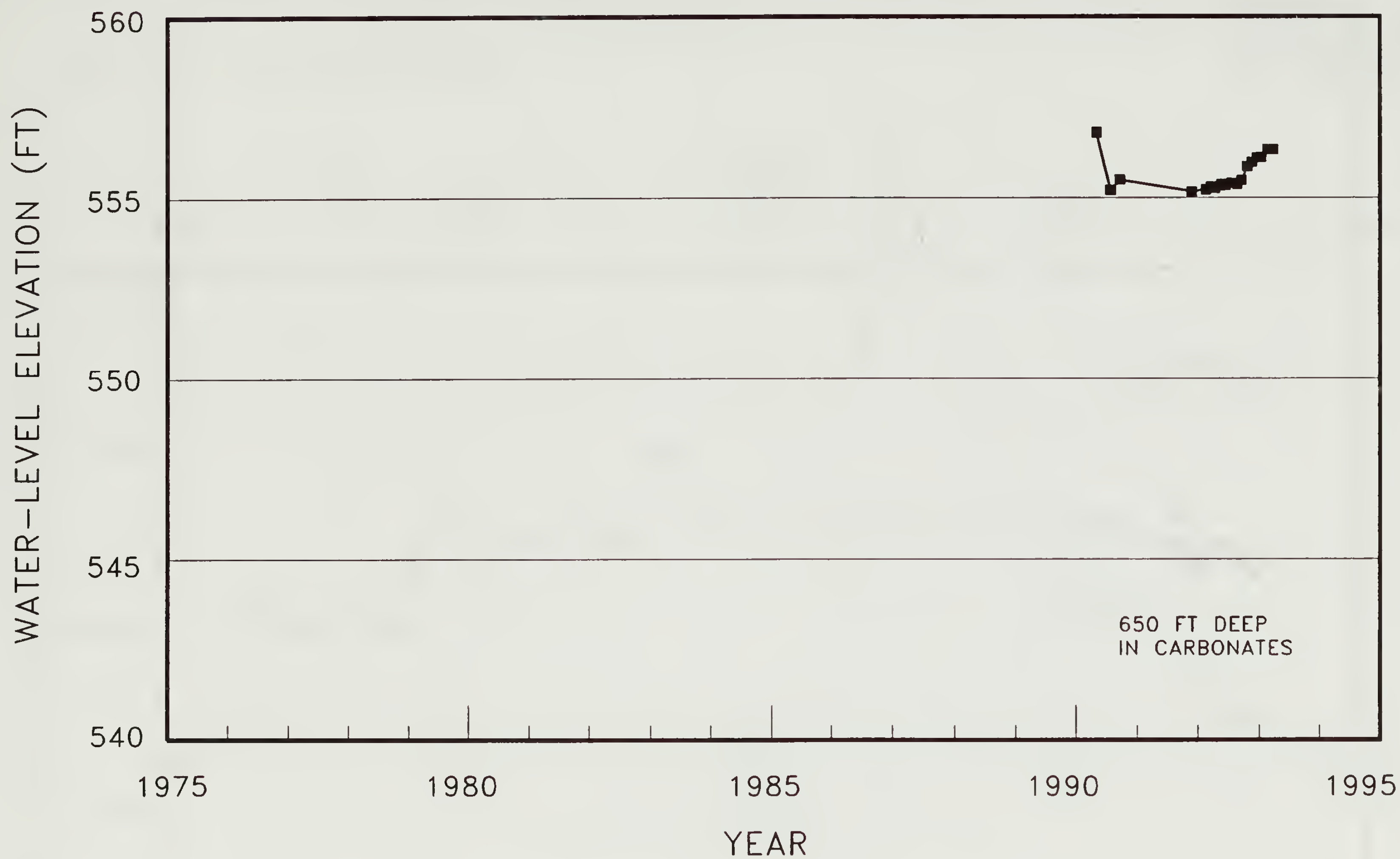

SEE FIG. A-1 FOR WELL LOCATION

DATA SOURCE:
U.S. GEOLOGICAL SURVEY
WATER-RESOURCES
MONITORING PROGRAM

HCI HYDROLOGIC CONSULTANTS, INC.	JOB NO. 590	DATE: 5-11-93	WATER-LEVEL ELEVATION IN WELL AD-12	Figure A-7
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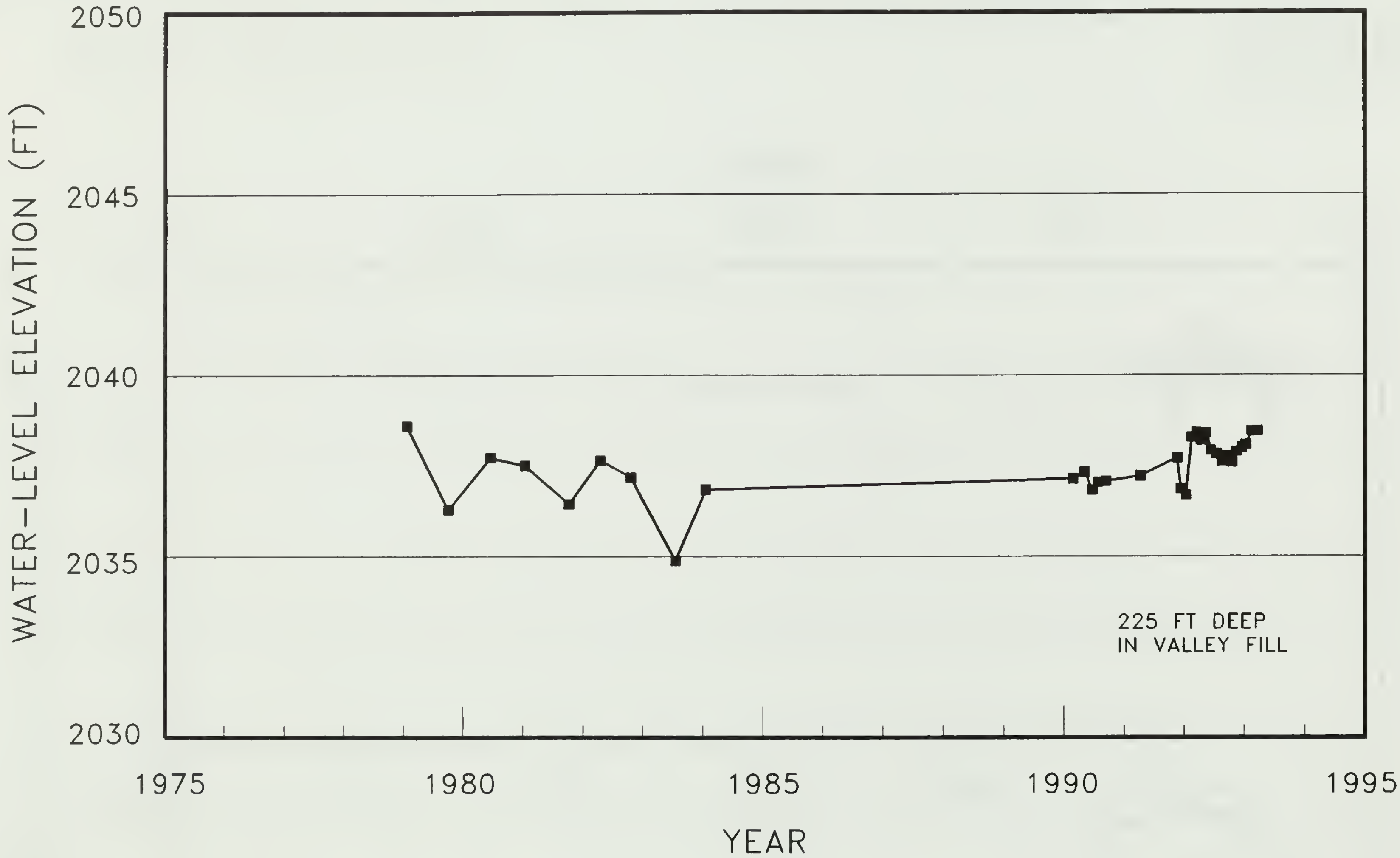

SEE FIG. A-1 FOR WELL LOCATION

DATA SOURCE:
U.S. GEOLOGICAL SURVEY
WATER-RESOURCES
MONITORING PROGRAM

HCI HYDROLOGIC CONSULTANTS, INC.	JOB NO. 590	DATE: 5-11-93	WATER-LEVEL ELEVATION IN WELL AD-14	Figure A-8
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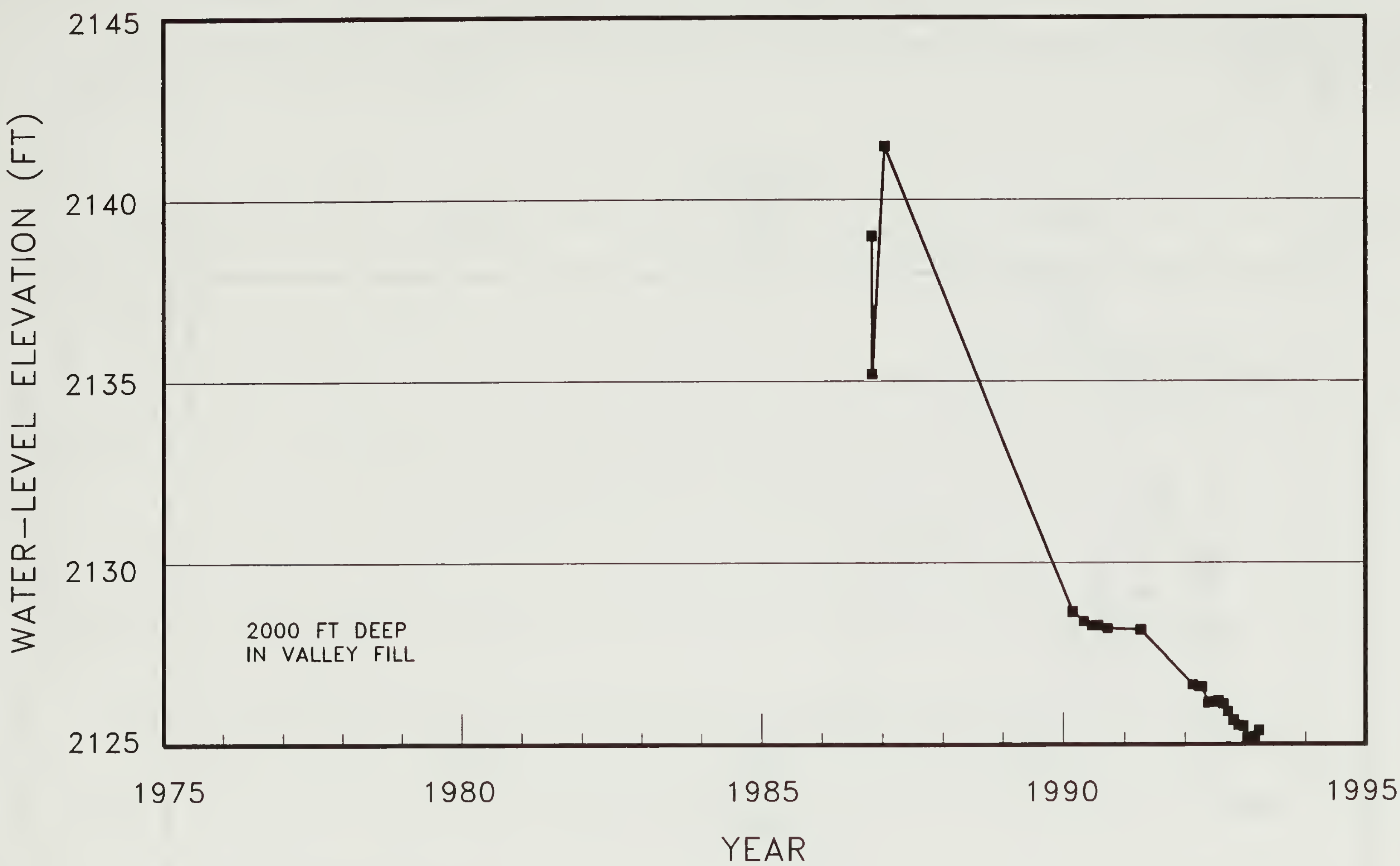

SEE FIG. A-1 FOR WELL LOCATION

DATA SOURCE:
U.S. GEOLOGICAL SURVEY
WATER-RESOURCES
MONITORING PROGRAM

HCI HYDROLOGIC CONSULTANTS, INC.	JOB NO. 590	DATE: 5-11-93	WATER-LEVEL ELEVATION IN WELL AD-15	Figure A-9
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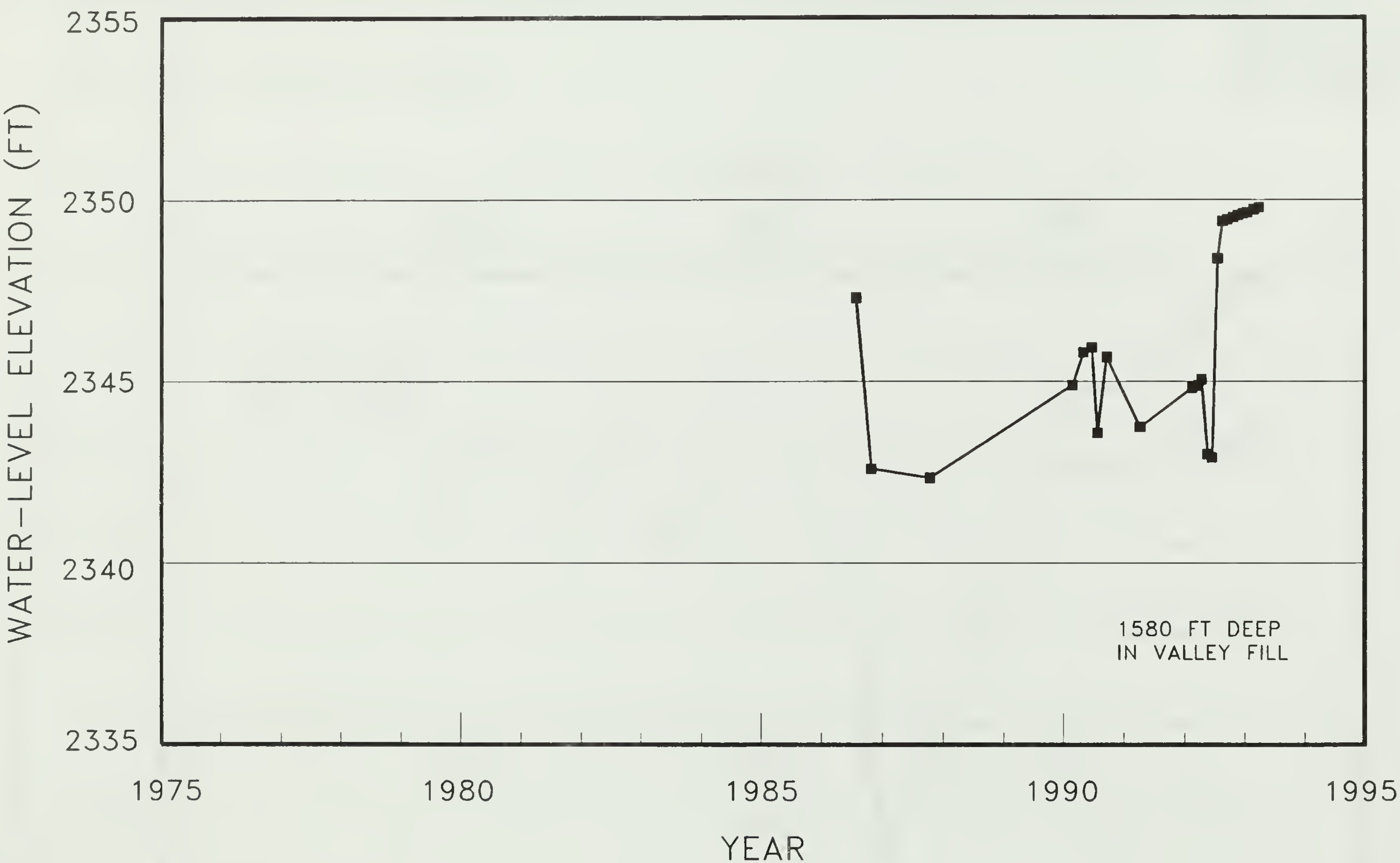

SEE FIG. A-1 FOR WELL LOCATION

DATA SOURCE:
U.S. GEOLOGICAL SURVEY
WATER-RESOURCES
MONITORING PROGRAM

HCI HYDROLOGIC CONSULTANTS, INC.	JOB NO. 590	DATE: 5-11-93	WATER-LEVEL ELEVATION IN WELL AD-16	Figure A-10
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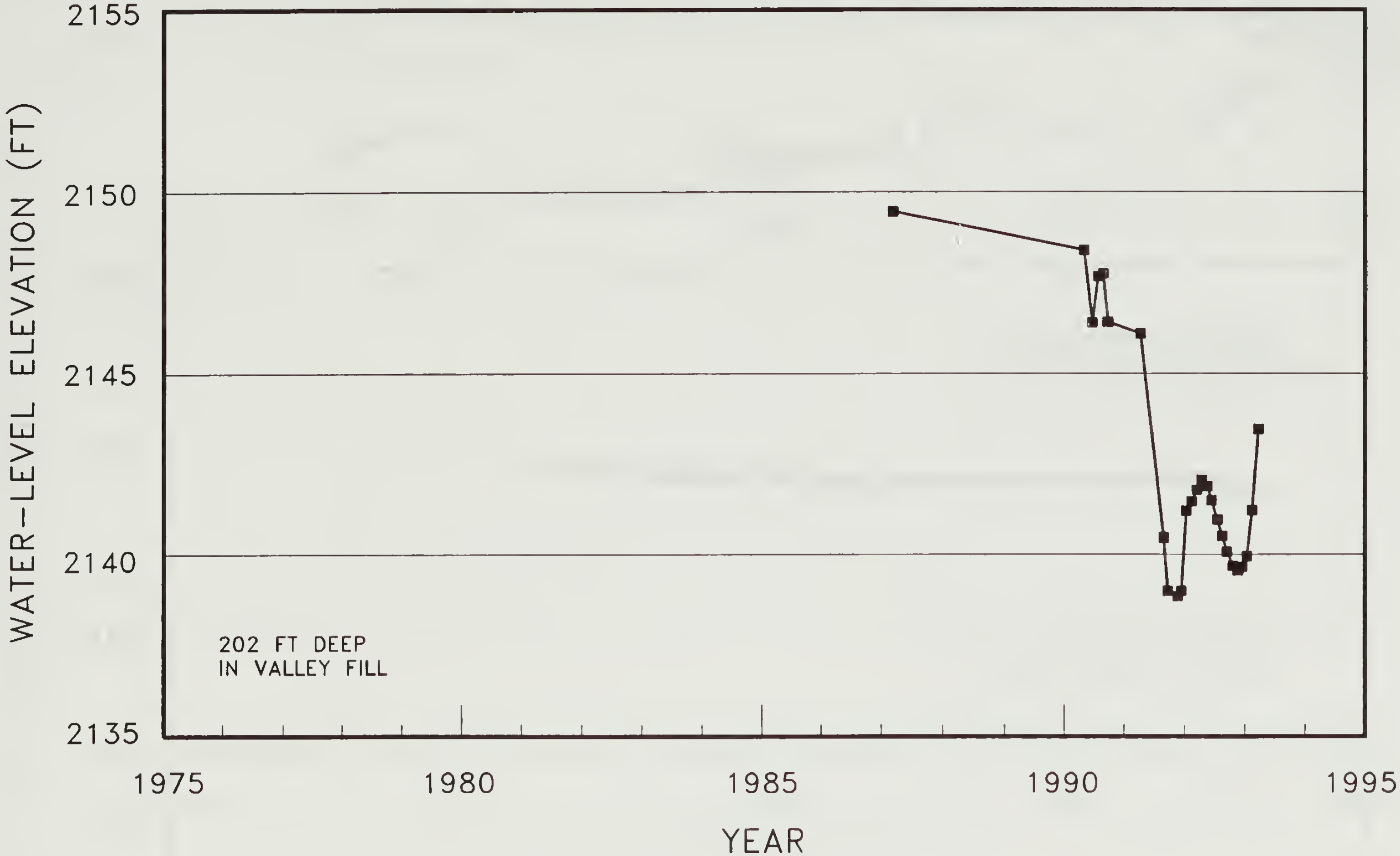
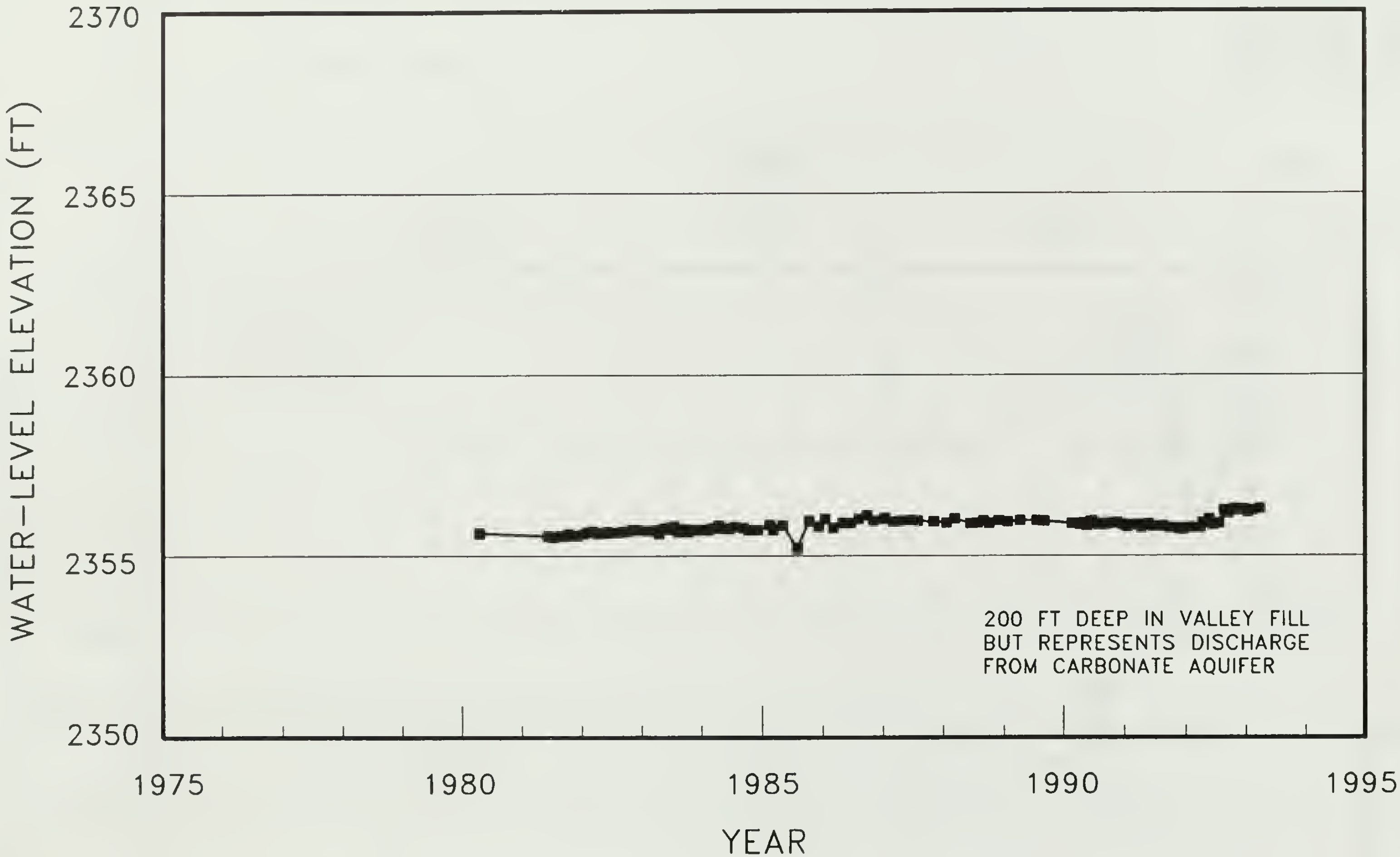


SEE FIG. A-1 FOR WELL LOCATION

DATA SOURCE:
U.S. GEOLOGICAL SURVEY
WATER-RESOURCES
MONITORING PROGRAM

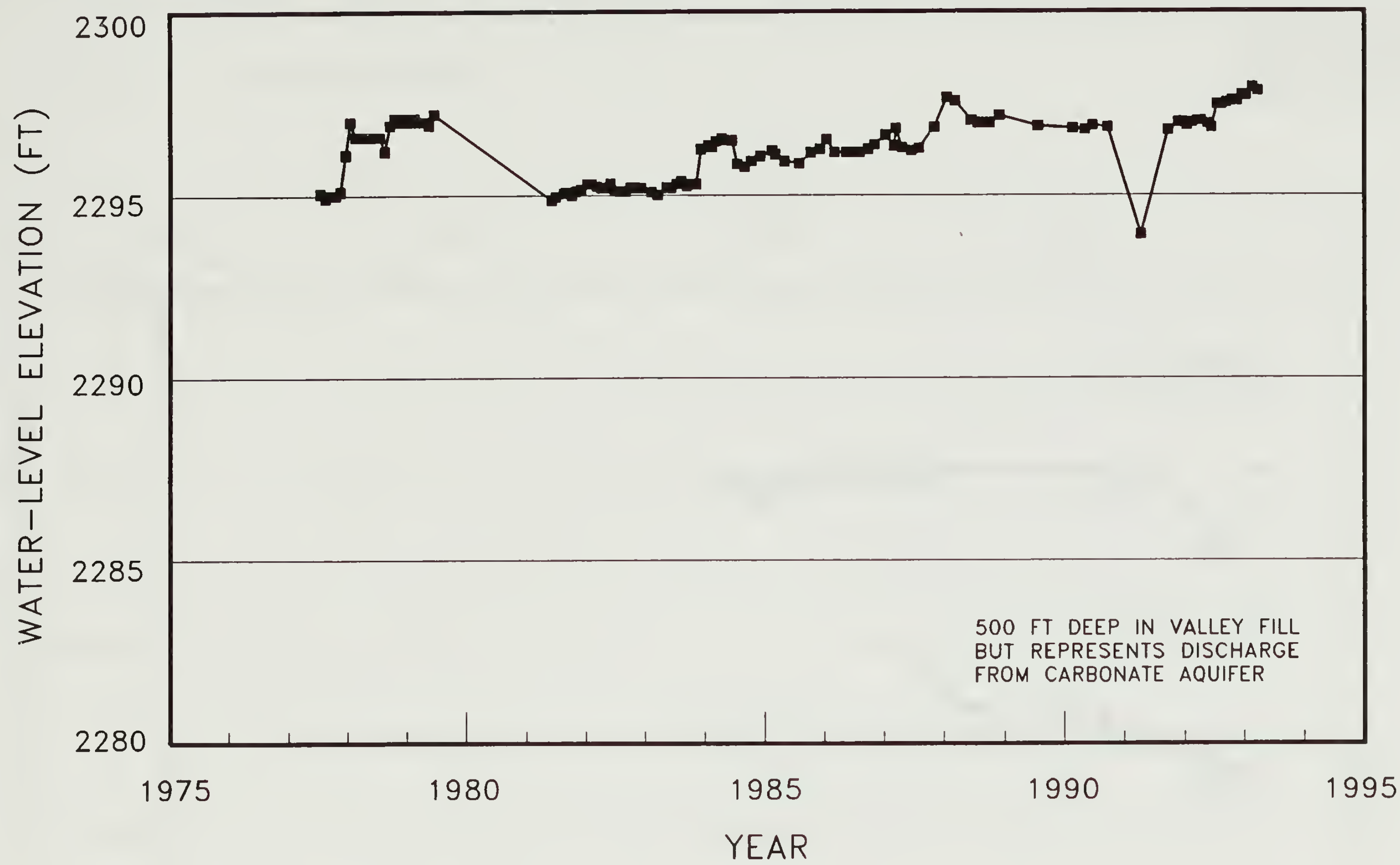
HCI HYDROLOGIC CONSULTANTS, INC.	JOB NO. 590	DATE: 5-11-93	WATER-LEVEL ELEVATION IN WELL AM-3	Figure A-11
	BY: LA	DRAWN: NS		
	FILE:AM-3_NEW.DWG	REV:		



SEE FIG. A-1 FOR WELL LOCATION

DATA SOURCE:
U.S. GEOLOGICAL SURVEY
WATER-RESOURCES
MONITORING PROGRAM

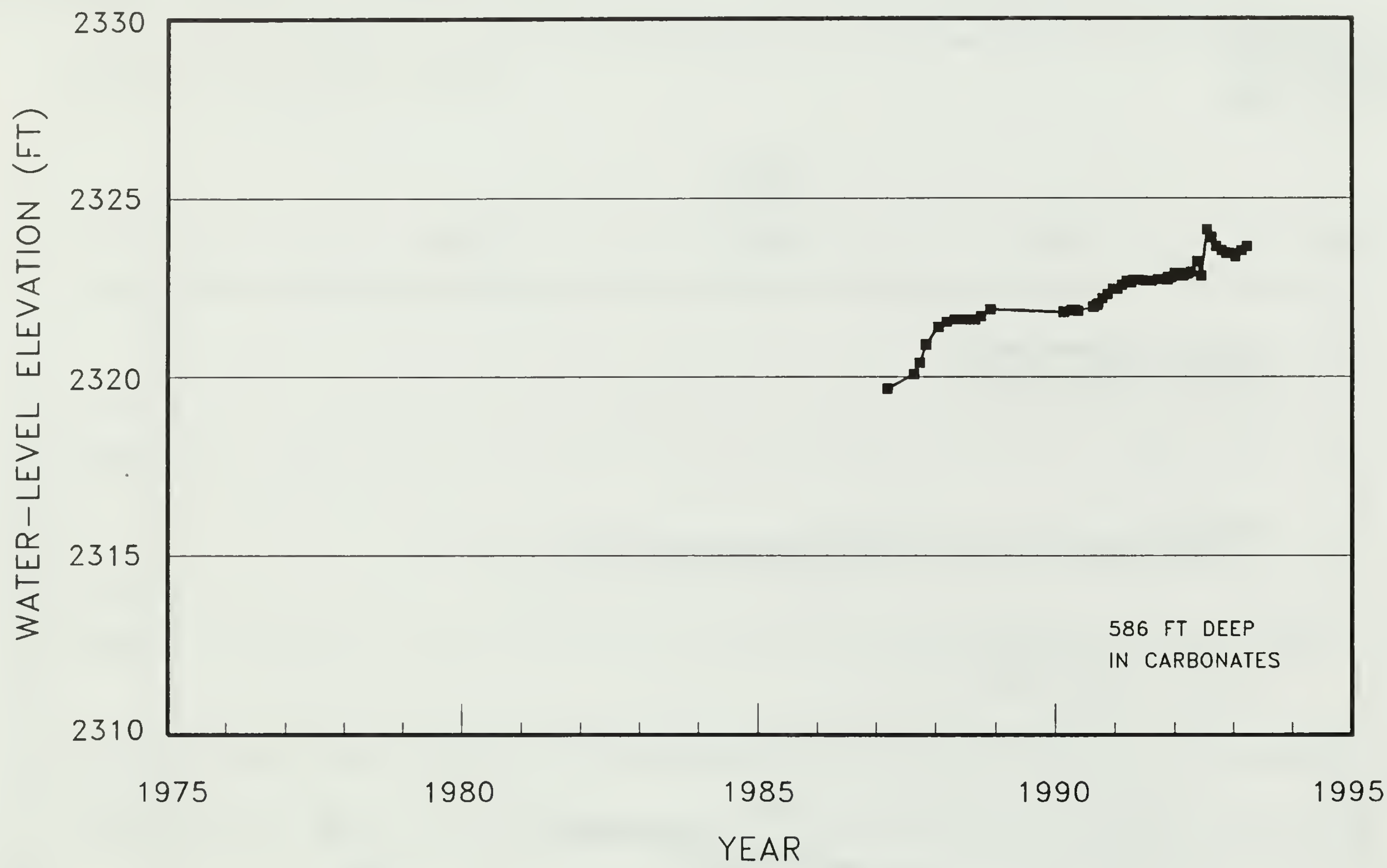
HCI HYDROLOGIC CONSULTANTS, INC.	JOB NO. 590	DATE: 5-11-93	WATER-LEVEL ELEVATION IN WELL AM-5	Figure A-12
	BY: LA	DRAWN: NS		
	FILE: AM-5.DWG	REV:		



SEE FIG. A-1 FOR WELL LOCATION

DATA SOURCE:
U.S. GEOLOGICAL SURVEY
WATER-RESOURCES
MONITORING PROGRAM

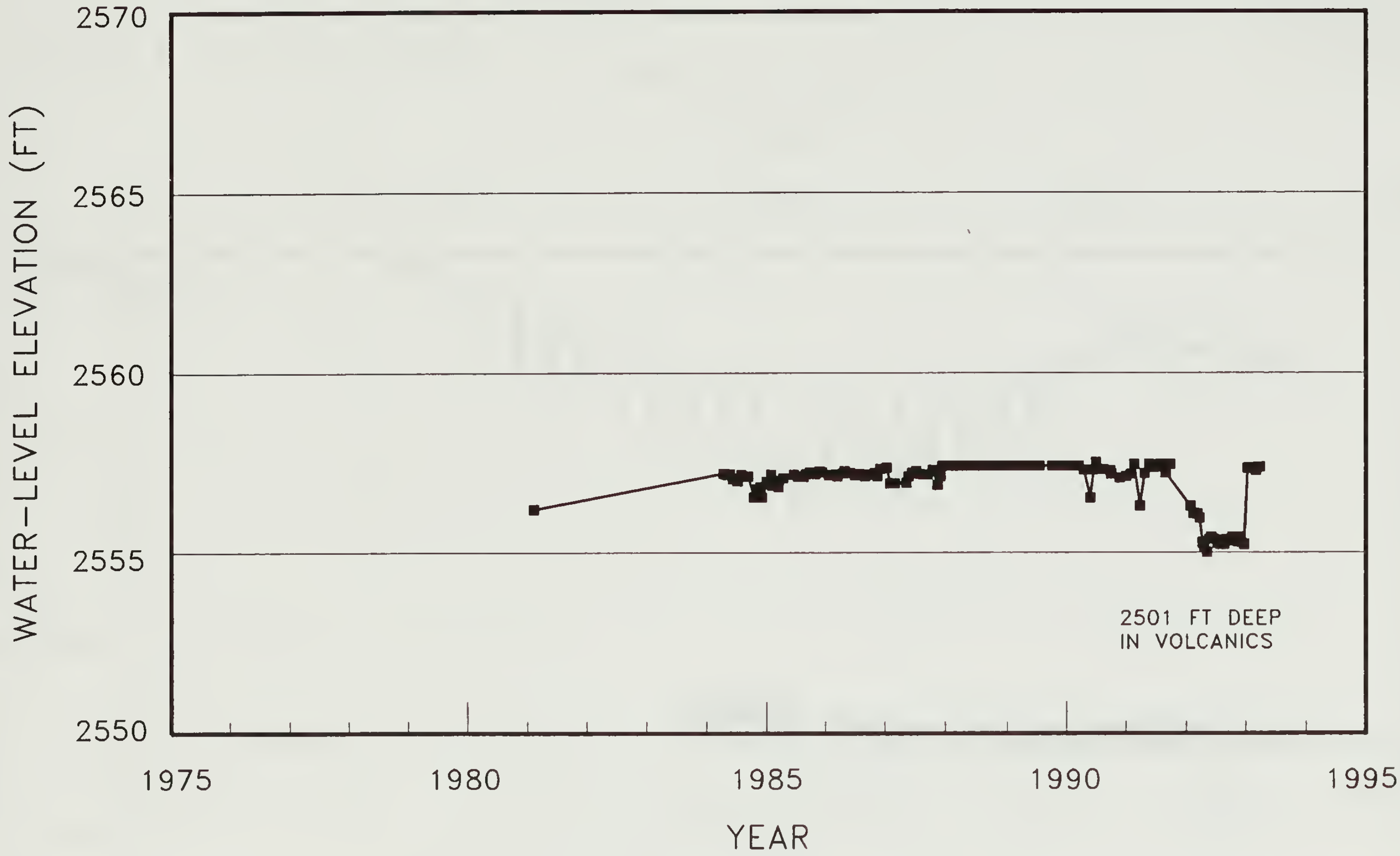
HCI HYDROLOGIC CONSULTANTS, INC.	JOB NO. 590	DATE: 5-11-93	WATER-LEVEL ELEVATION IN WELL AM-6	Figure A-13
	BY: LA	DRAWN: NS		
	FILE: AM-6.DWG	REV:		



SEE FIG. A-1 FOR WELL LOCATION

DATA SOURCE:
U.S. GEOLOGICAL SURVEY
WATER-RESOURCES
MONITORING PROGRAM

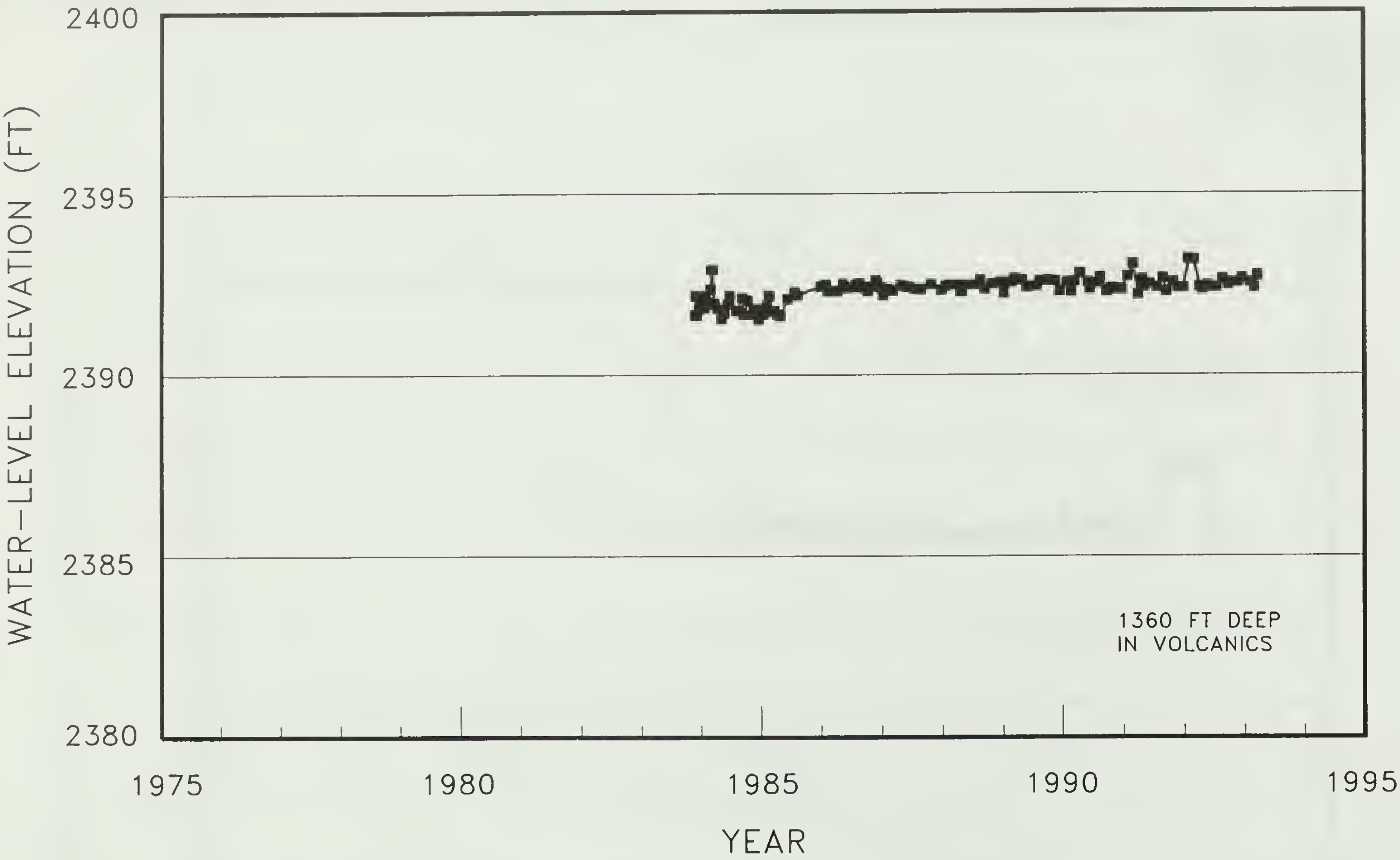
HCI HYDROLOGIC CONSULTANTS, INC.	JOB NO. 590	DATE: 5-11-93	WATER-LEVEL ELEVATION IN WELL AM-7	Figure A-14
	BY: LA	DRAWN: NS		
	FILE: AM-7.DWG	REV:		



SEE FIG. A-1 FOR WELL LOCATION

DATA SOURCE:
U.S. GEOLOGICAL SURVEY
WATER-RESOURCES
MONITORING PROGRAM

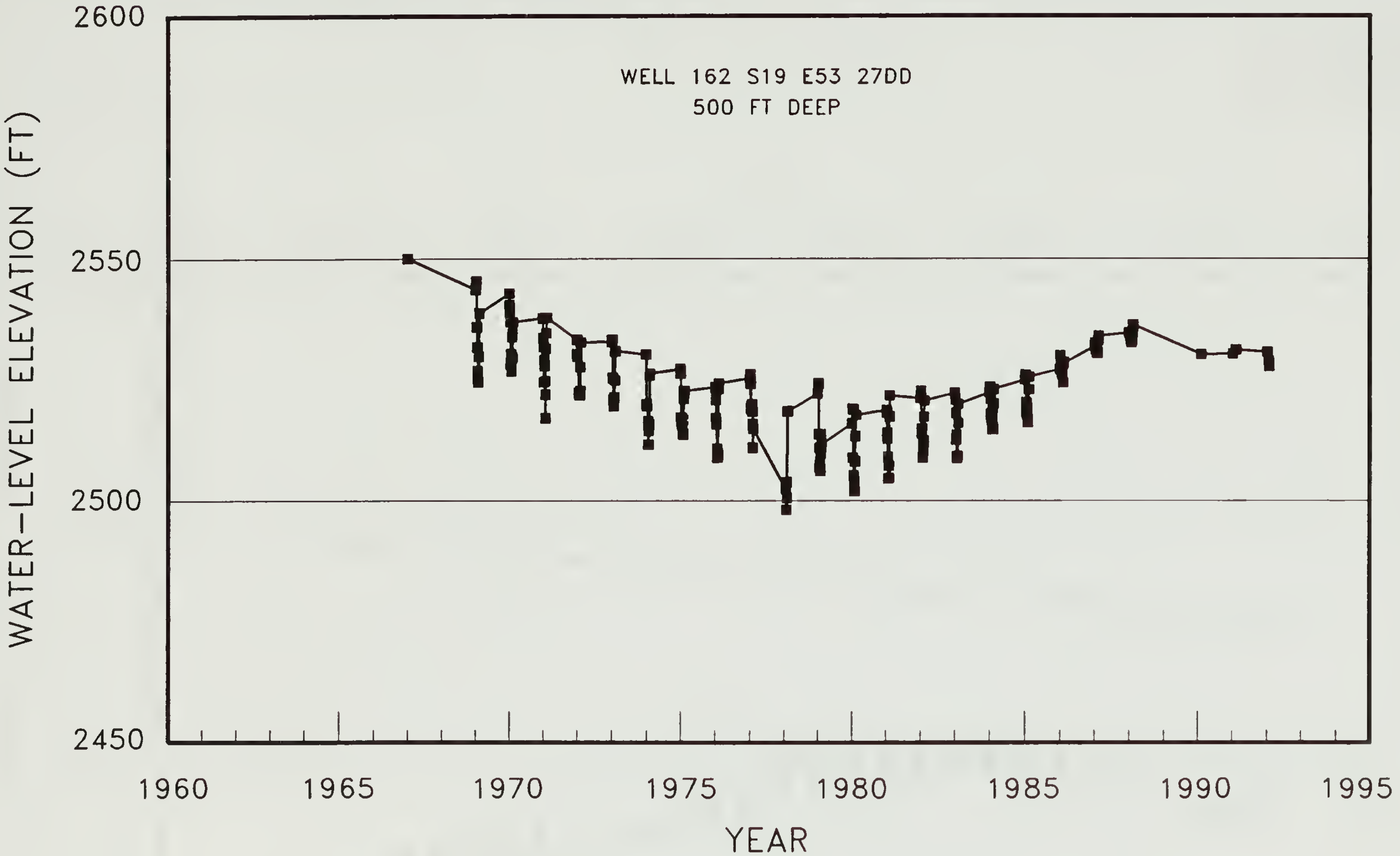
HCI HYDROLOGIC CONSULTANTS, INC.	JOB NO. 590	DATE: 5-11-93	WATER-LEVEL ELEVATION IN WELL CF-2	Figure A-15
	BY: LA	DRAWN: NS		
	FILE: CF-2.DWG	REV:		



SEE FIG. A-1 FOR WELL LOCATION

DATA SOURCE:
U.S. GEOLOGICAL SURVEY
WATER-RESOURCES
MONITORING PROGRAM

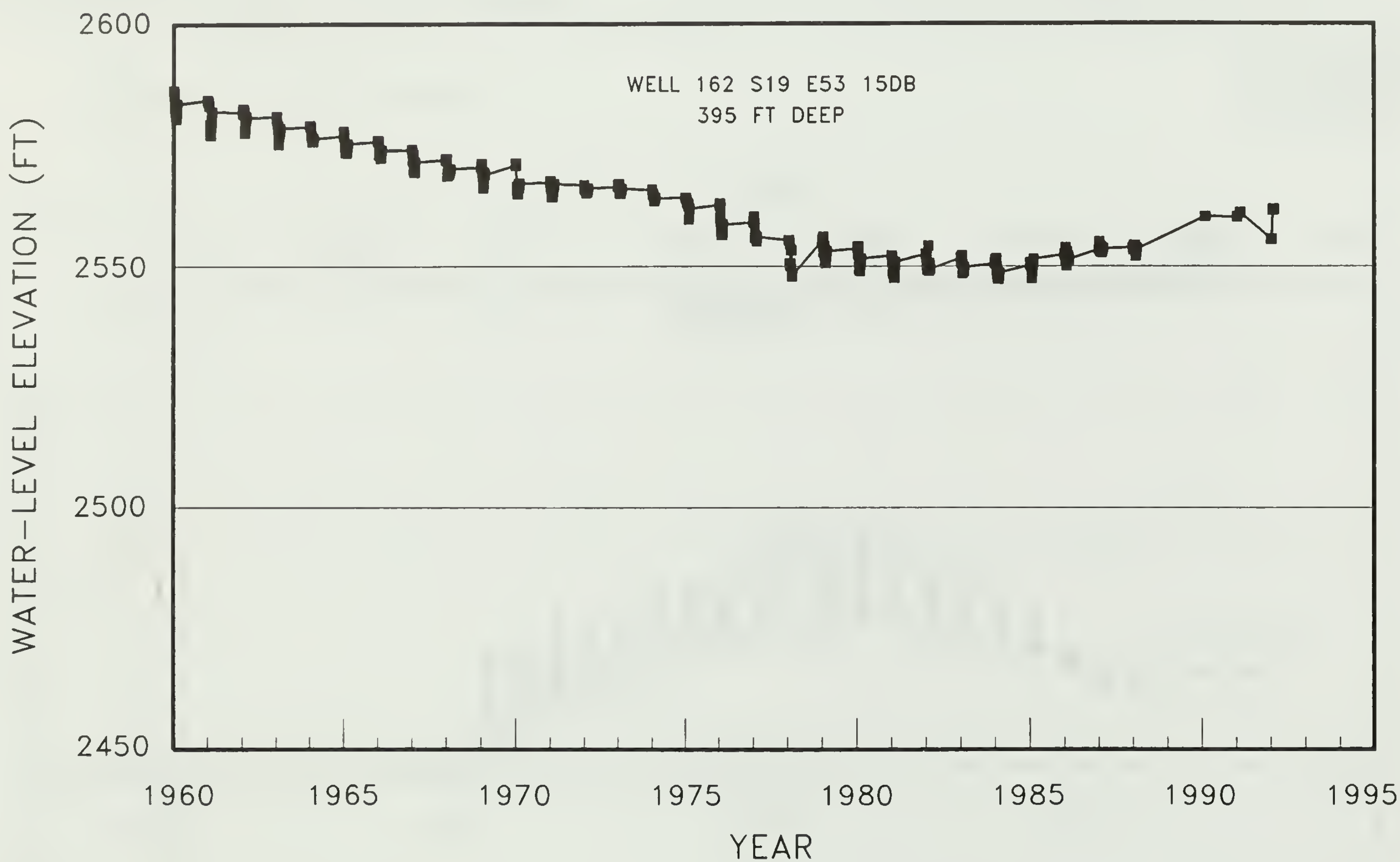
HCI HYDROLOGIC CONSULTANTS, INC.	JOB NO. 590	DATE: 5-11-93	WATER-LEVEL ELEVATION IN WELL JF-1	Figure A-16
	BY: LA	DRAWN: NS		
	FILE: JF-1.DWG	REV:		



SEE FIG. A-1 FOR WELL LOCATION

DATA SOURCE:
U.S. GEOLOGICAL SURVEY
SO. NEVADA CARBONATE
ROCK MONITORING NETWORK

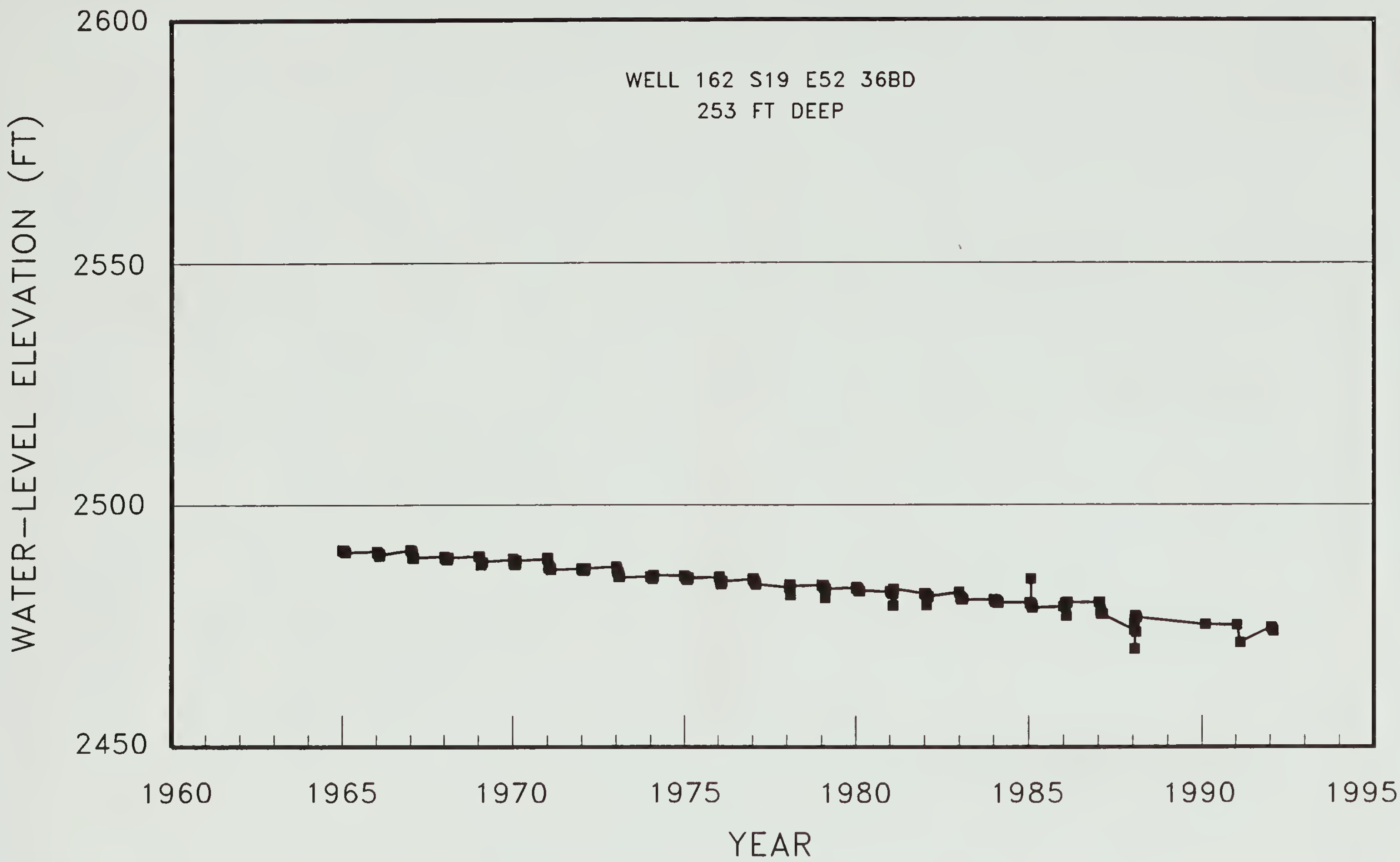
HCI HYDROLOGIC CONSULTANTS, INC.	JOB NO. 590	DATE: 5-14-93	WATER-LEVEL ELEVATION IN PAHRUMP VALLEY WELL P-1	Figure A-17
	BY: LA	DRAWN: NS		
	FILE: P-1.DWG	REV:		



SEE FIG. A-1 FOR WELL LOCATION

DATA SOURCE:
U.S. GEOLOGICAL SURVEY
SO. NEVADA CARBONATE
ROCK MONITORING NETWORK

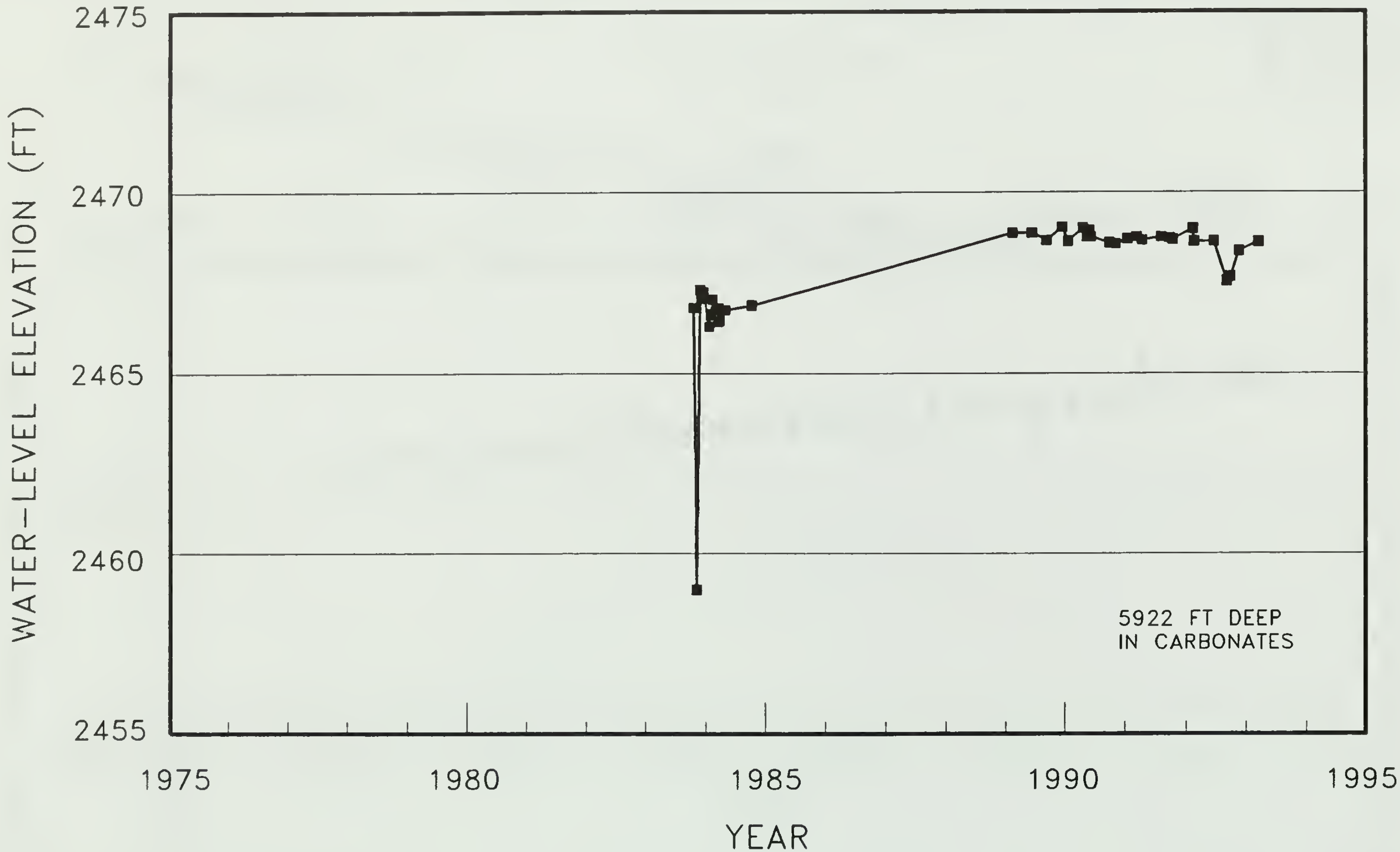
HCI HYDROLOGIC CONSULTANTS, INC.	JOB NO. 590	DATE: 5-14-93	WATER-LEVEL ELEVATION IN PAHRUMP VALLEY WELL P-2	Figure A-18
	BY: LA	DRAWN: NS		
	FILE: P-2.DWG	REV:		



SEE FIG. A-1 FOR WELL LOCATION

DATA SOURCE:
U.S. GEOLOGICAL SURVEY
SO. NEVADA CARBONATE
ROCK MONITORING NETWORK

HCI HYDROLOGIC CONSULTANTS, INC.	JOB NO. 590	DATE: 5-13-93	WATER-LEVEL ELEVATION IN PAHRUMP VALLEY WELL P-3	Figure A-19
	BY: LA	DRAWN: NS		
	FILE: P-3.DWG	REV:		

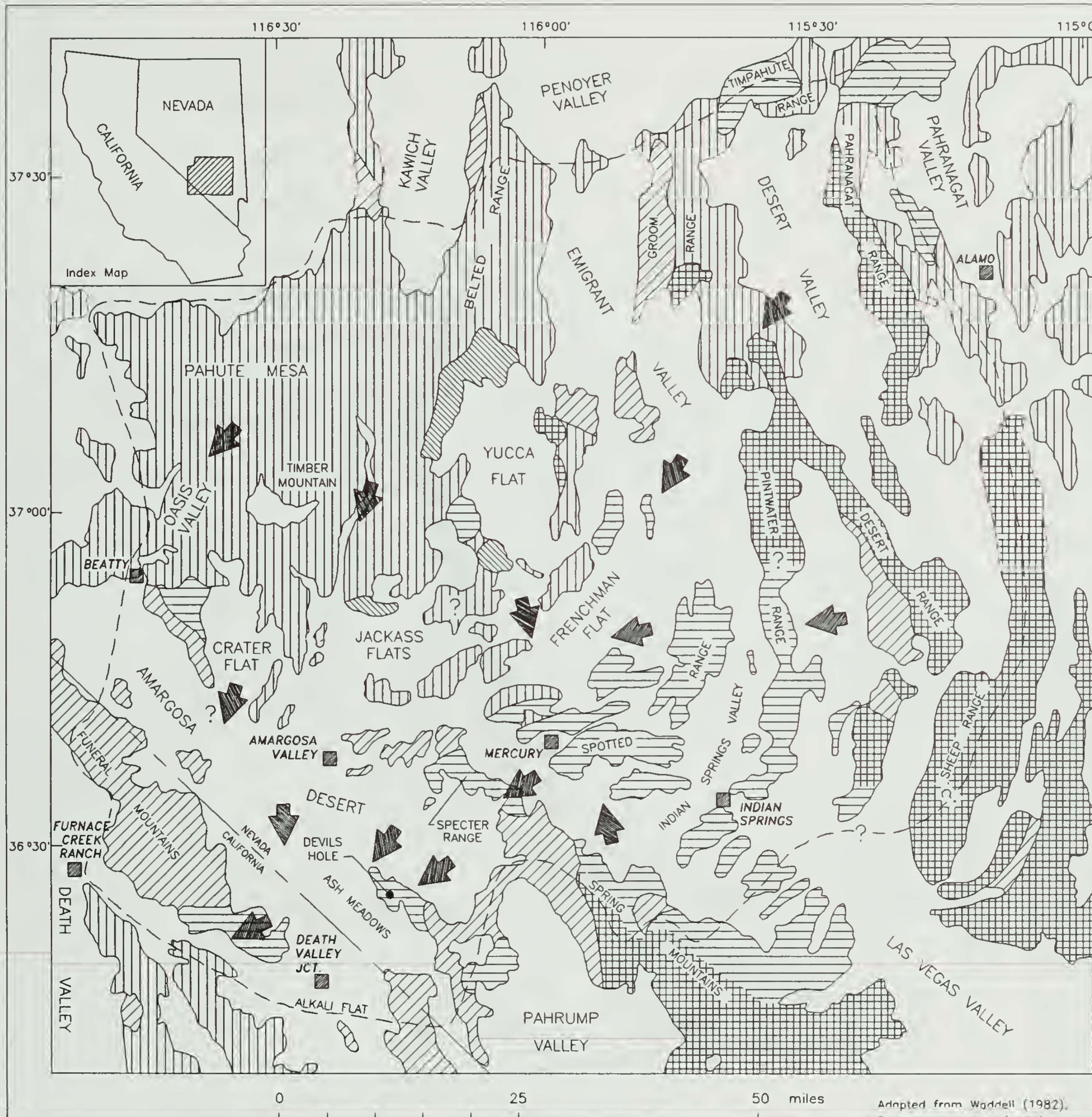


SEE FIG. A-1 FOR WELL LOCATION

DATA SOURCE:
U.S. GEOLOGICAL SURVEY
WATER-RESOURCES
MONITORING PROGRAM

HCI HYDROLOGIC CONSULTANTS, INC.	JOB NO. 590	DATE: 5-11-93	WATER-LEVEL ELEVATION IN WELL YM-1	Figure A-20
	BY: LA	DRAWN: NS		
	FILE: YM-1.DWG	REV:		

FIGURES



Adapted from Waddell (1982), Dudley and Larson (1976), Winograd and Thordarson (1975)

QUATERNARY
Alluvium, lake beds, and minor volcanic rocks

TERTIARY
Tuff, rhyolite, and associated volcanic rocks

MESOZOIC (Minor -- not shown)

PALEOZOIC
Undifferentiated rocks above lower clastic aquitard

Upper clastic aquitard

Lower carbonate aquifer

PALEOZOIC (CAMBRIAN)-PRECAMBRIAN
Lower clastic aquitard

Contact

Approximate boundary of ground-water system (after Waddell, 1982)

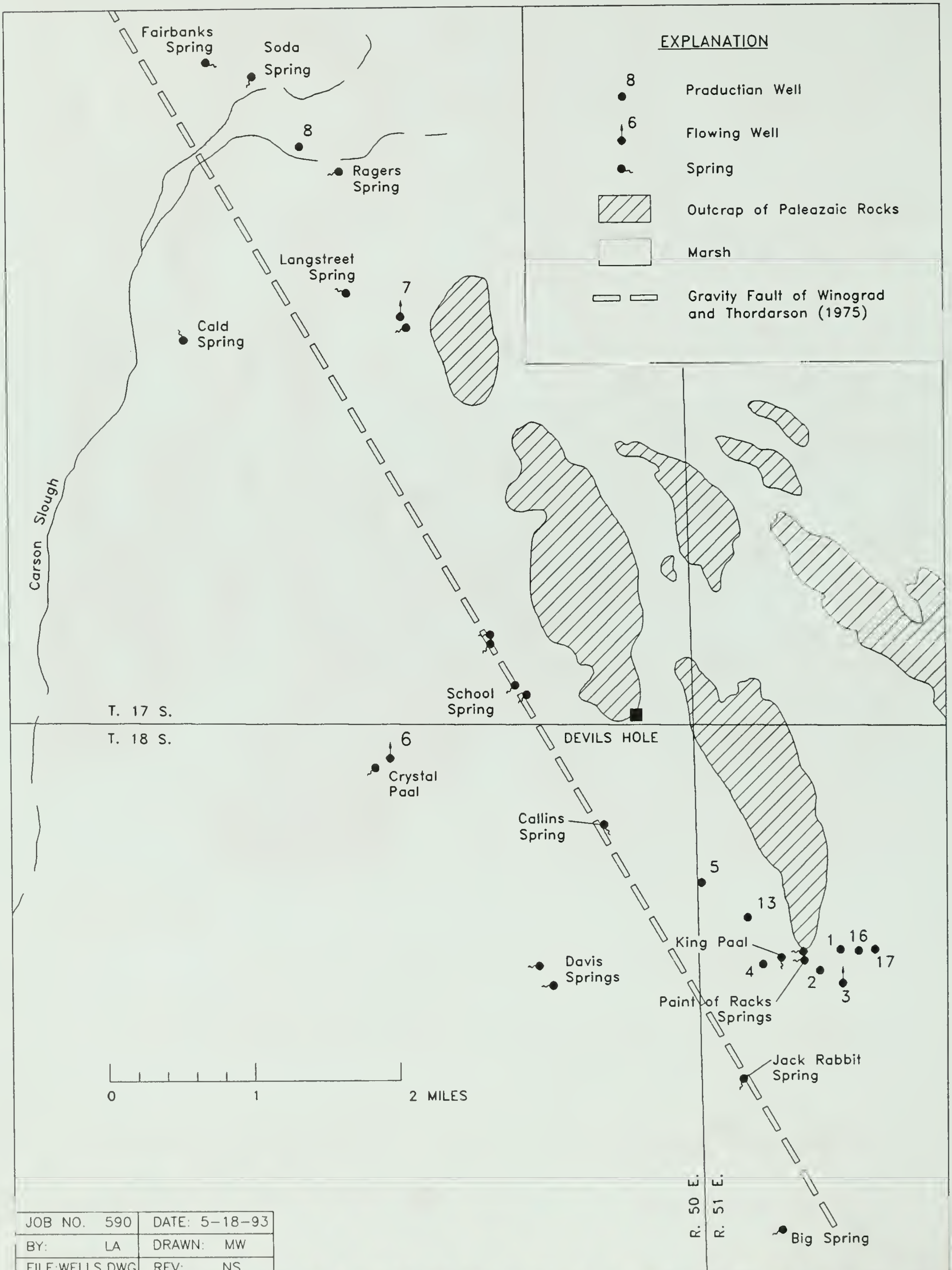
Approximate direction of ground-water flow

JOB NO. 590	DATE: 5-19-93
BY: LA	DRAWN: MW
FILE: FIG1.DWG	REV: NS

HCI HYDROLOGIC CONSULTANTS, INC.

GENERALIZED HYDROGEOLOGY OF STUDY AREA

Figure 1

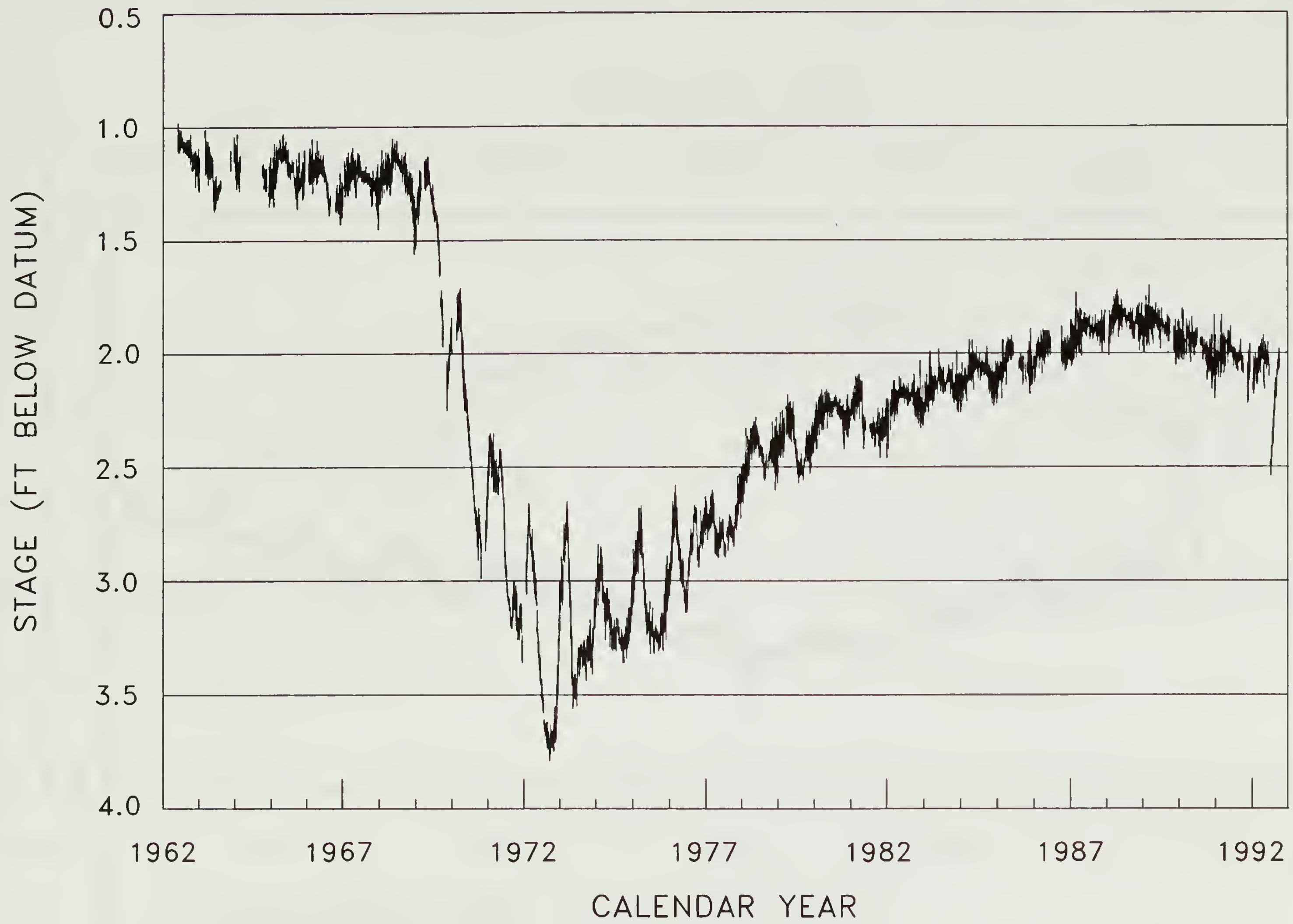


JOB NO. 590	DATE: 5-18-93
BY: LA	DRAWN: MW
FILE: WELLS.DWG	REV: NS

HCI HYDROLOGIC CONSULTANTS, INC.

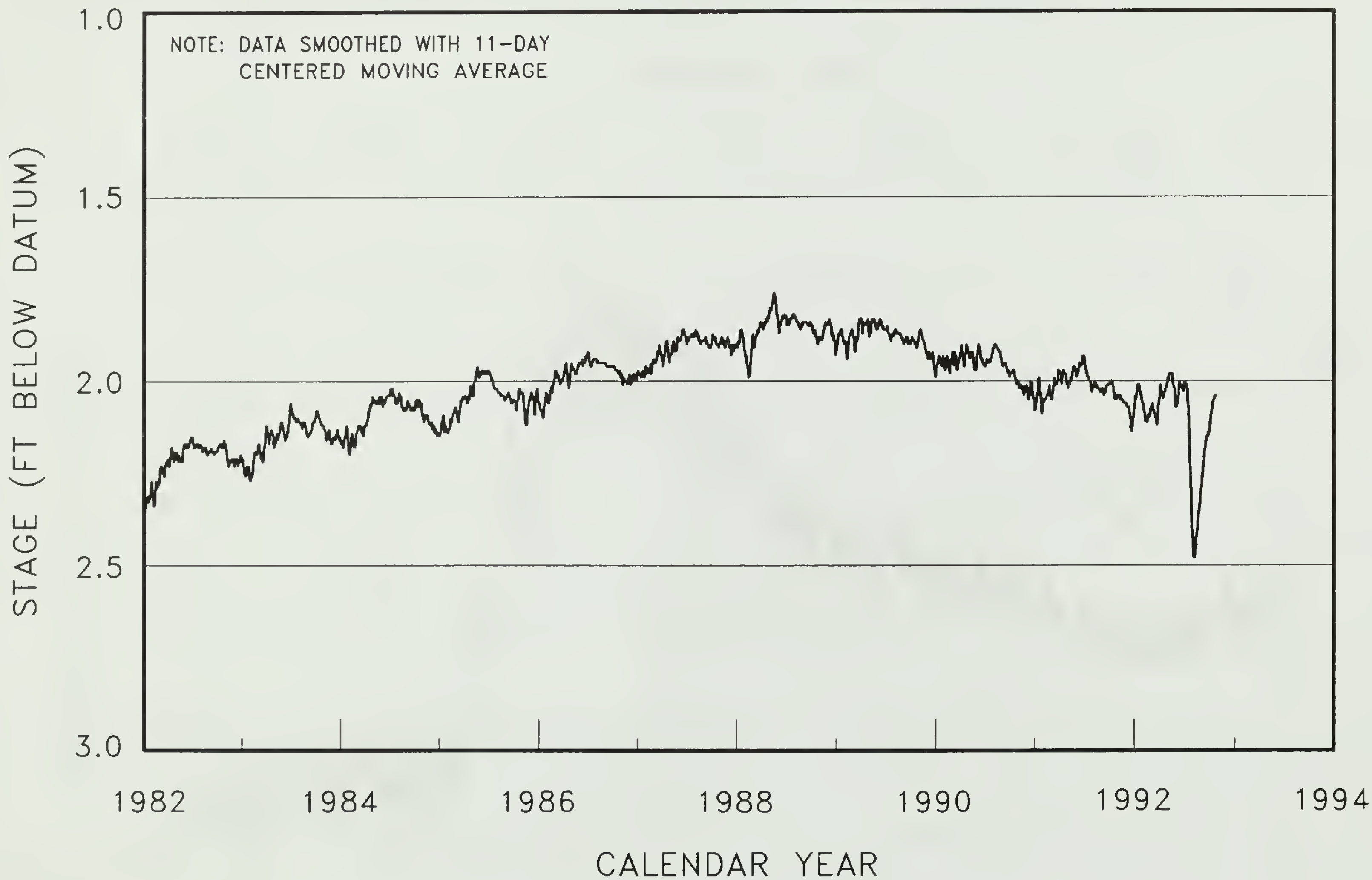
LOCATION OF SELECTED WELLS AND SPRINGS IN THE ASH MEADOWS AREA (Adapted from Dudley and Larson, 1976)

Figure 2



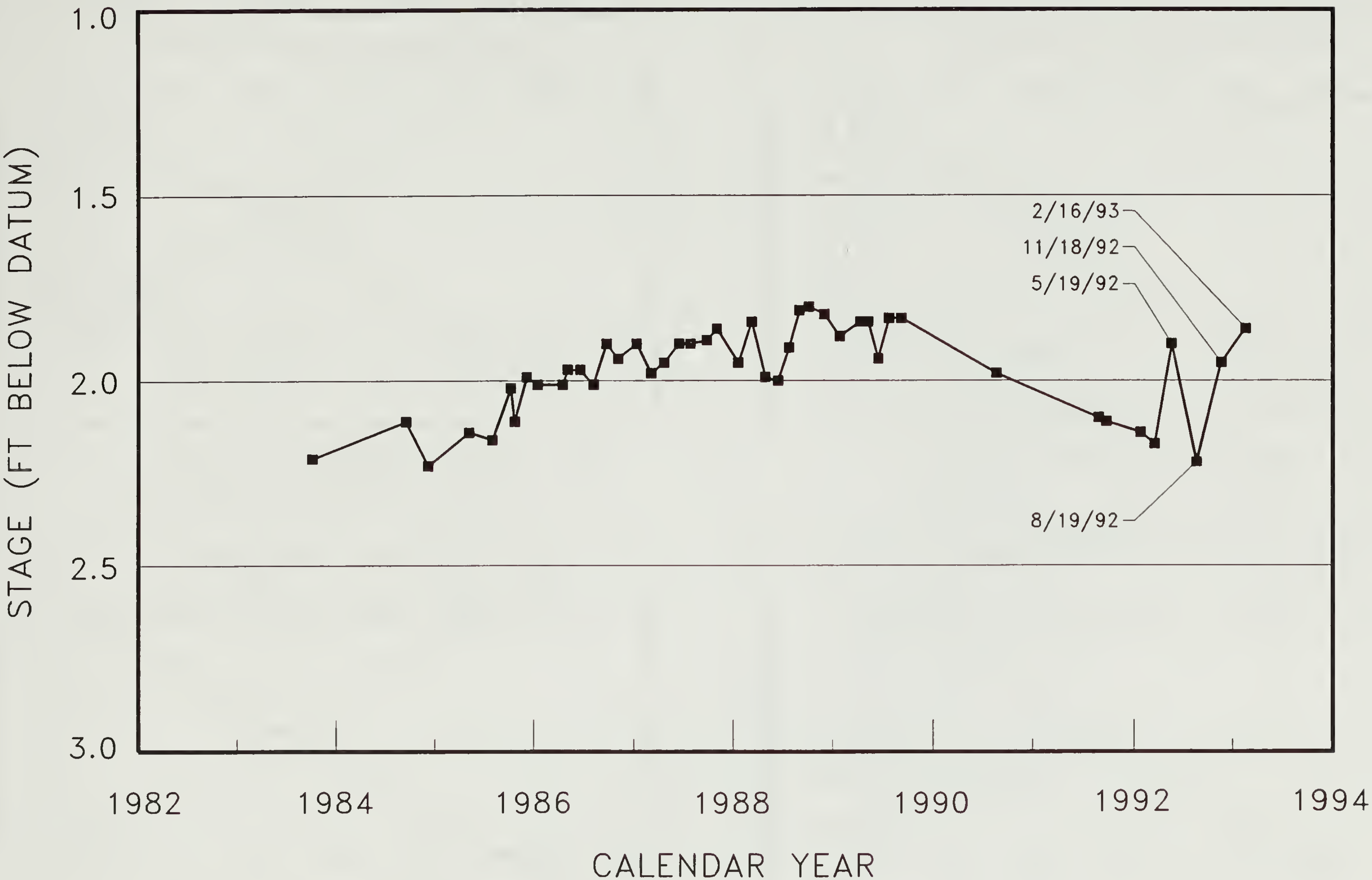
HCI HYDROLOGIC CONSULTANTS, INC.	JOB NO. 590	DATE: 5-13-93	DAILY MEAN STAGE IN DEVILS HOLE, MAY 23, 1962 THROUGH SEPTEMBER 30, 1992
	BY: LA	DRAWN: NS	
	FILE: DHGRAPH.DWG	REV:	

Figure 3

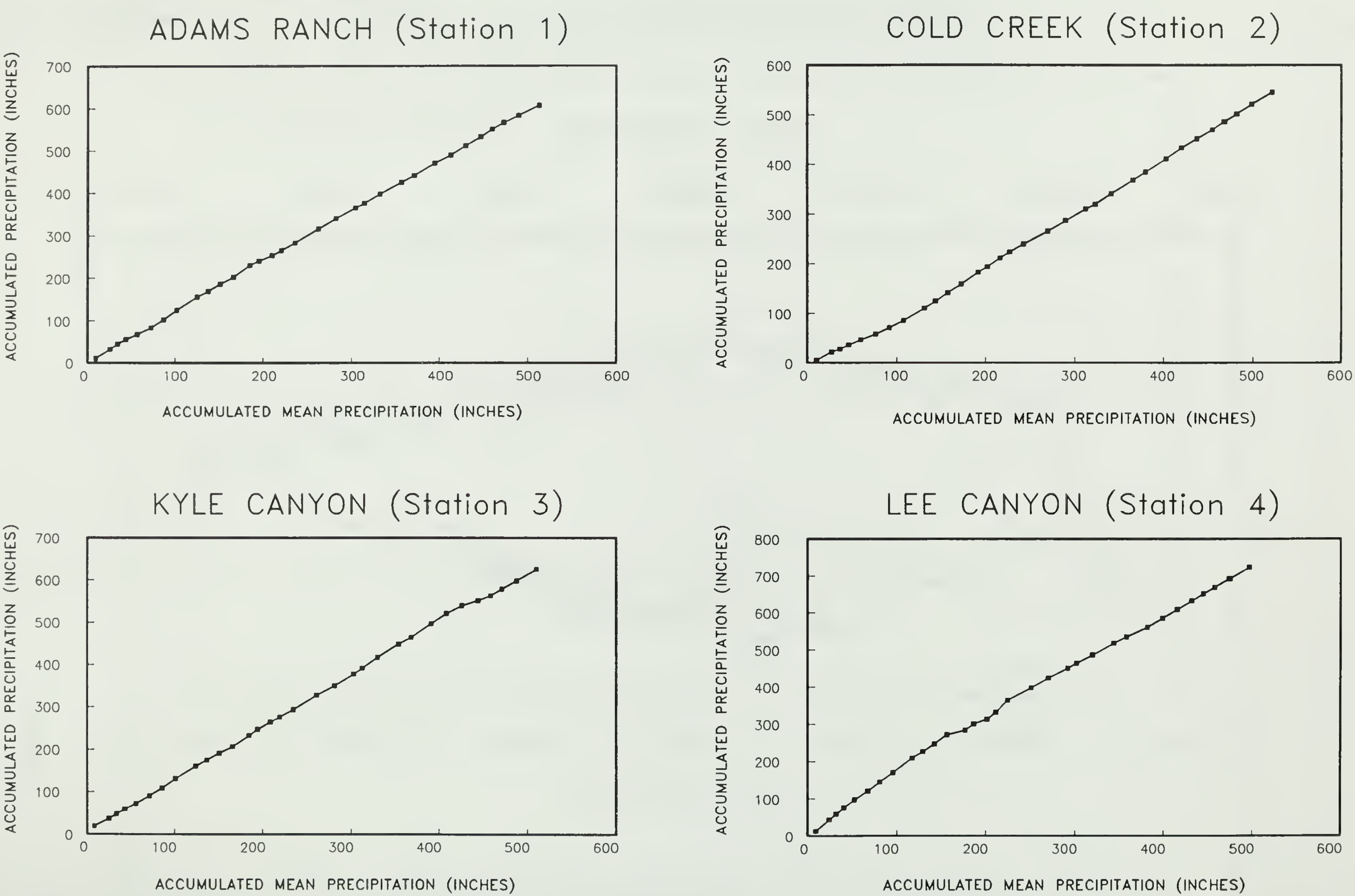


HCI HYDROLOGIC CONSULTANTS, INC.	JOB NO. 590	DATE: 5-27-93	DAILY MEAN STAGE IN DEVILS HOLE, JANUARY 1, 1982 THROUGH SEPTEMBER 30,1992
	BY: LA	DRAWN: NS	
	FILE:DH82_94A.DWG	REV:	

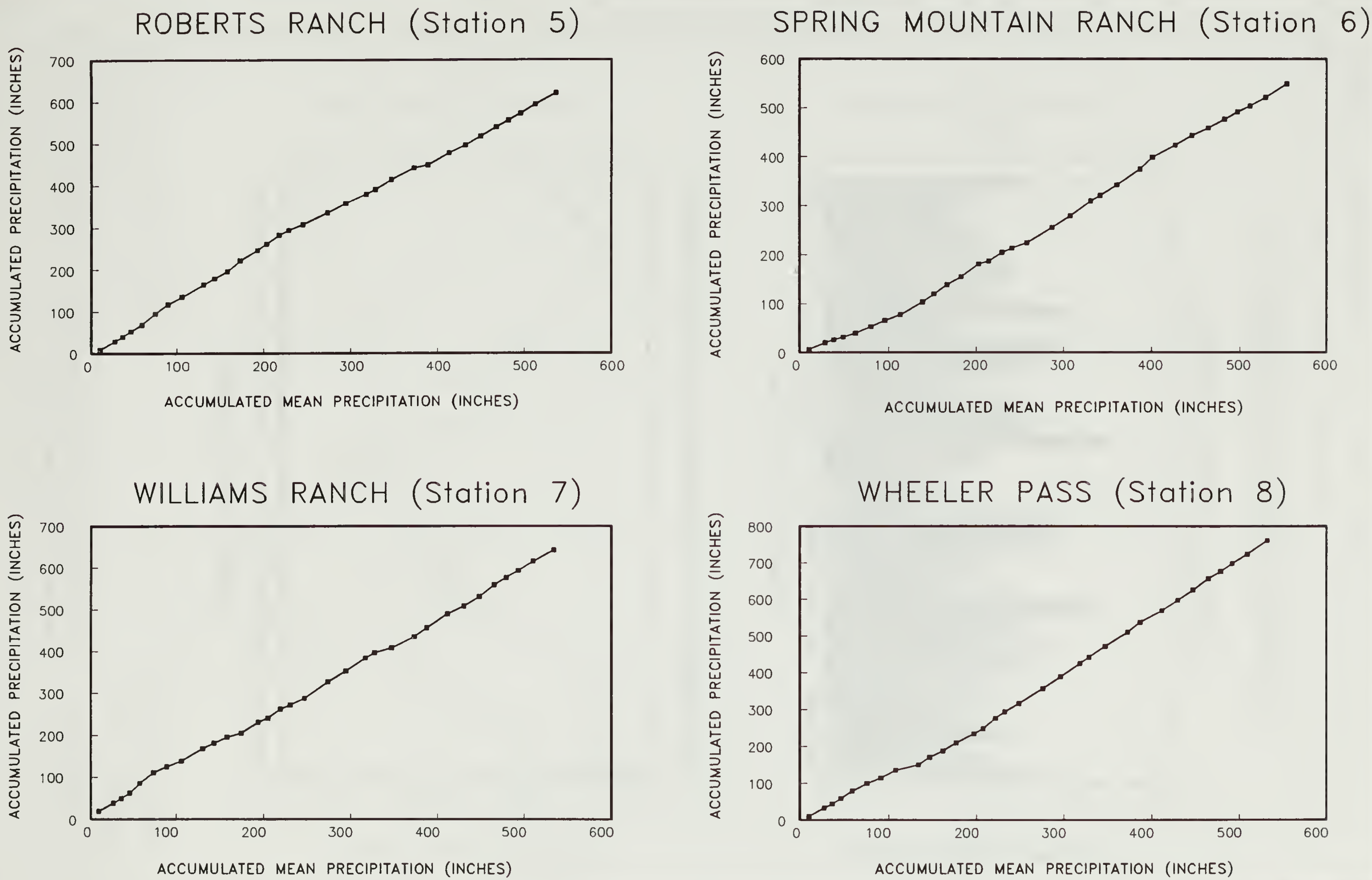
Figure 4



HCI HYDROLOGIC CONSULTANTS, INC.	JOB NO. 590	DATE: 5-24-93	PERIODIC MEASUREMENTS OF DEVILS HOLE STAGE BY USGS WATER RESOURCES MONITORING PROGRAM	Figure 5
	BY: LA	DRAWN: NS		
	FILE:DH82_94B.DWG	REV:		

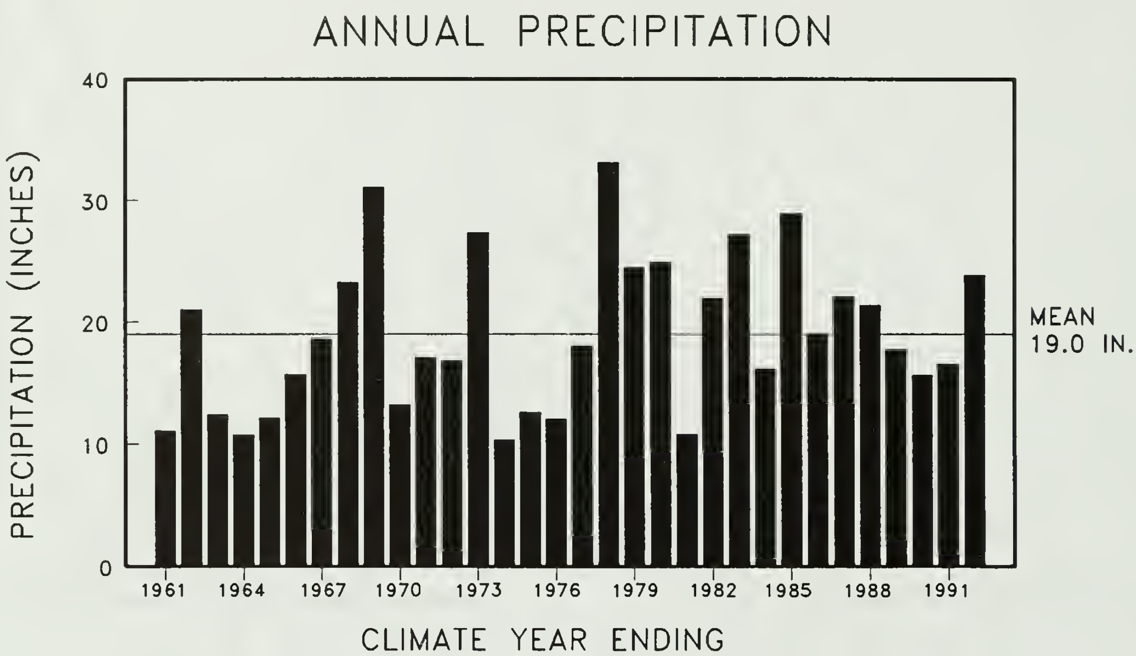


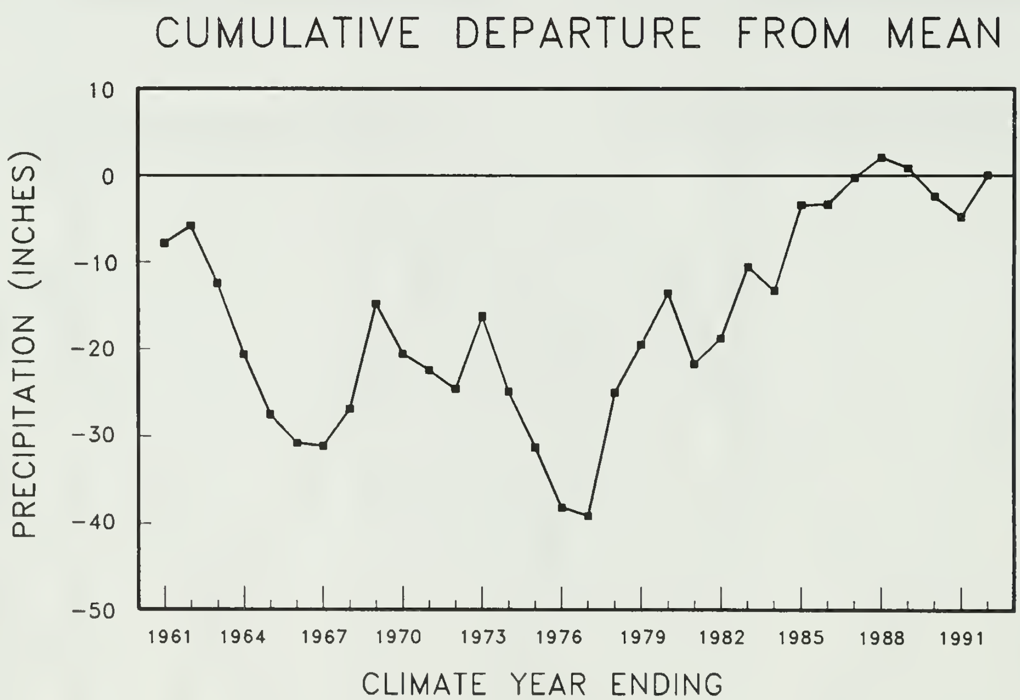
HCI HYDROLOGIC CONSULTANTS, INC.	JOB NO. 590	DATE: 5-21-93	DOUBLE-MASS ANALYSES FOR SPRING MOUNTAINS PRECIPITATION STATIONS 1 – 4	Figure 6a
	BY: LA	DRAWN: MW		
	FILE:D_MASS1.DWG	REV: NS		



HCI HYDROLOGIC CONSULTANTS, INC.	JOB NO. 590	DATE: 5-21-93	DOUBLE-MASS ANALYSES FOR SPRING MOUNTAINS PRECIPITATION STATIONS 5 – 8	Figure 6b
	BY: LA	DRAWN: MW		
	FILE:D_MASS2.DWG	REV: NS		

ADAMS RANCH (Station 1)





JOB NO. 590	DATE: 5-17-93
BY: LA	DRAWN: MW
FILE:AP_CD1.DWG	REV: NS

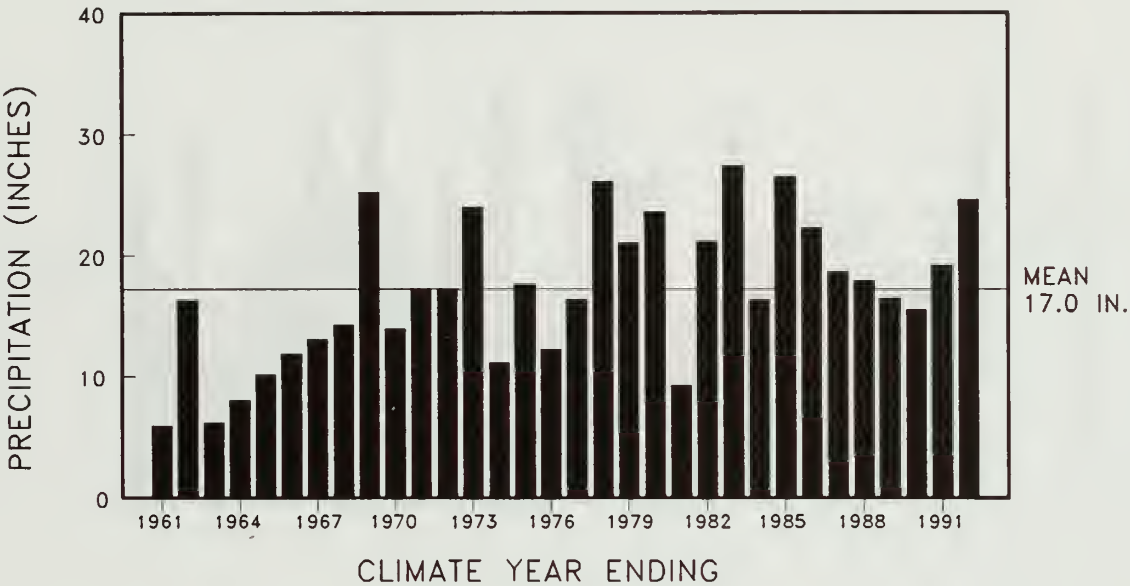
HCI HYDROLOGIC CONSULTANTS, INC.

ANNUAL PRECIPITATION AND CUMULATIVE DEPARTURE FROM MEAN FOR ADAMS RANCH

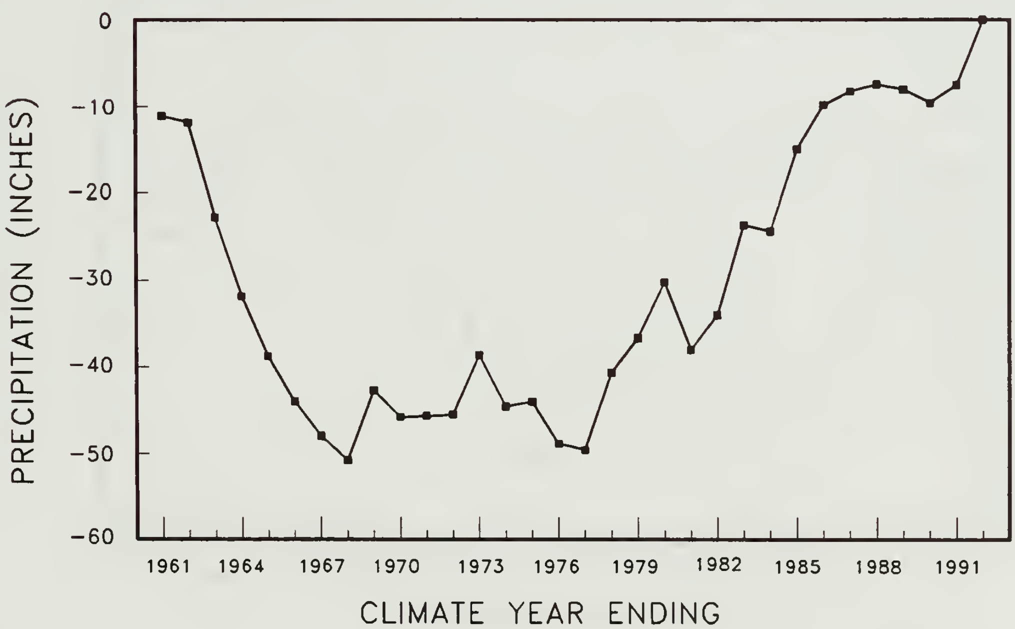
Figure 7a

COLD CREEK (Station 2)

ANNUAL PRECIPITATION



CUMULATIVE DEPARTURE FROM MEAN

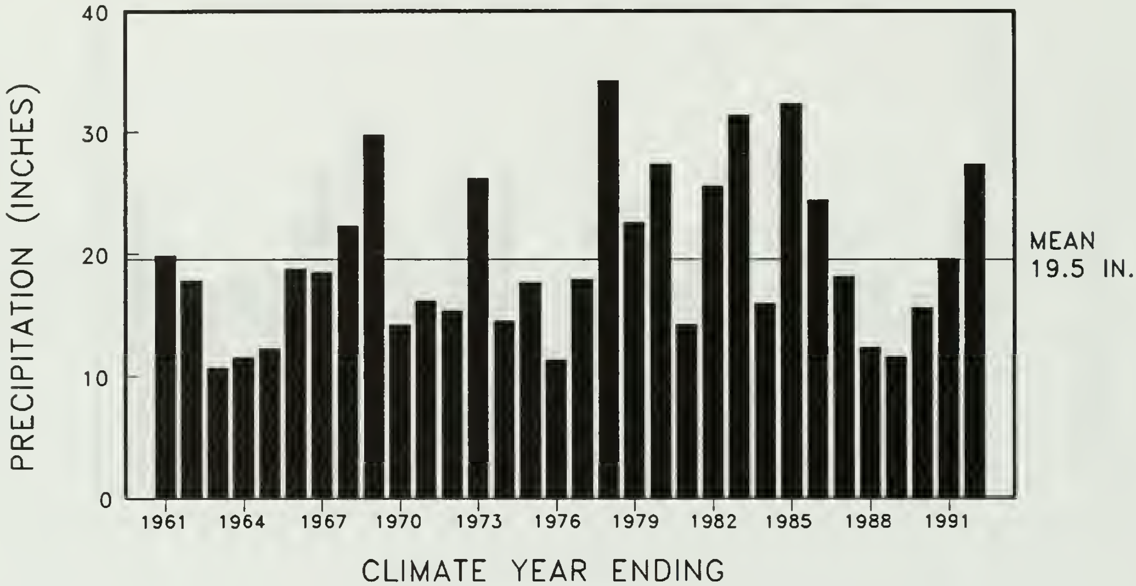


JOB NO. 590	DATE: 5-17-93
BY: LA	DRAWN: MW
FILE:AP_CD2.DWG	REV: NS

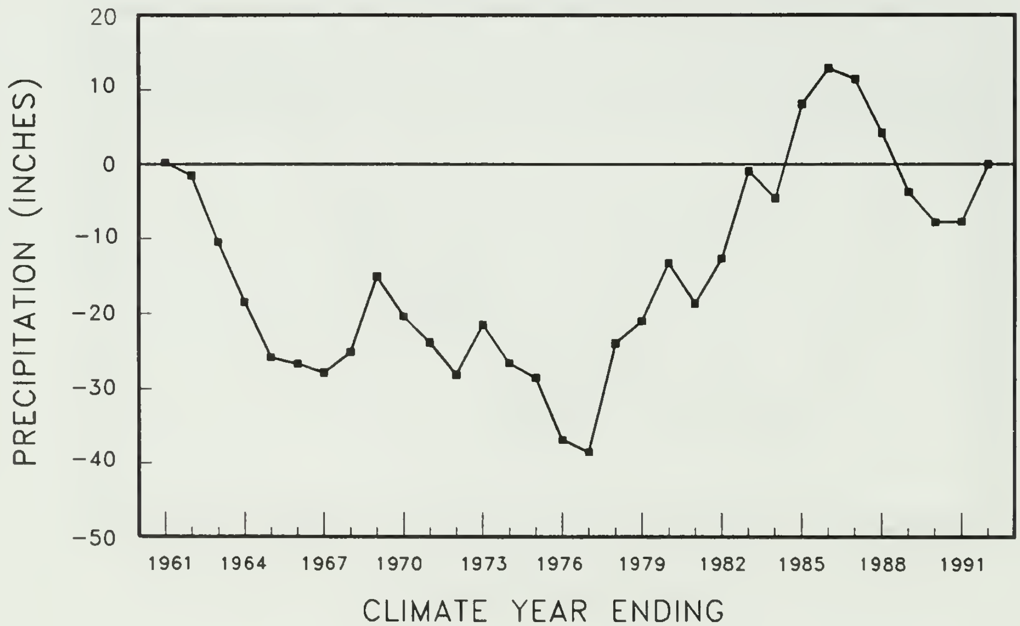
HCI HYDROLOGIC CONSULTANTS, INC.	ANNUAL PRECIPITATION AND CUMULATIVE DEPARTURE FROM MEAN FOR COLD CREEK	Figure 7b

KYLE CANYON (Station 3)

ANNUAL PRECIPITATION



CUMULATIVE DEPARTURE FROM MEAN

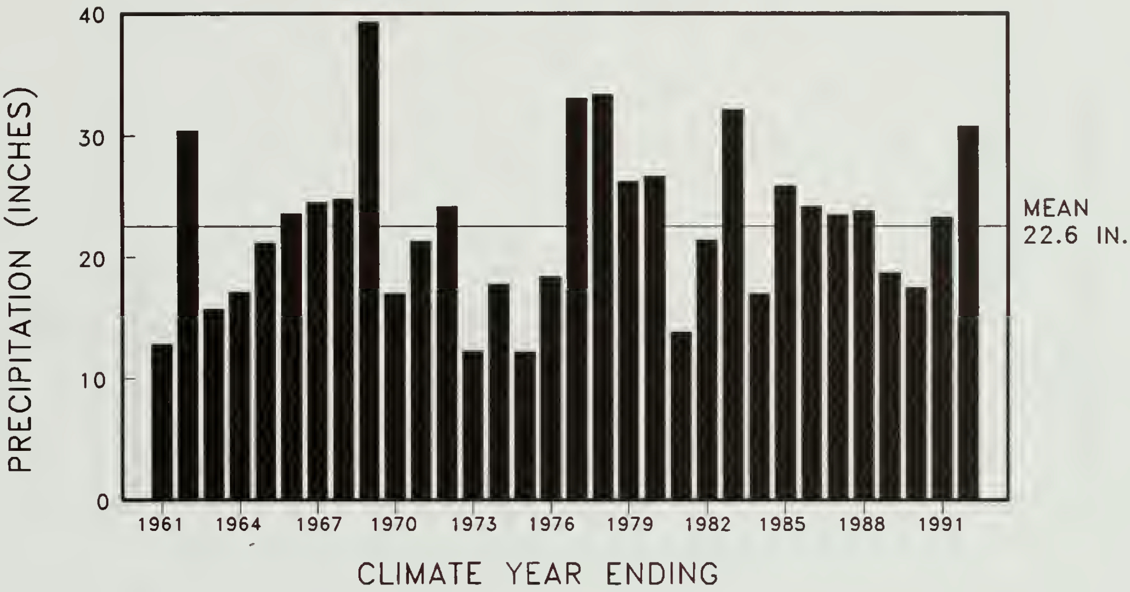


JOB NO. 590	DATE: 5-17-93
BY: LA	DRAWN: MW
FILE:AP_CD3.DWG	REV: NS

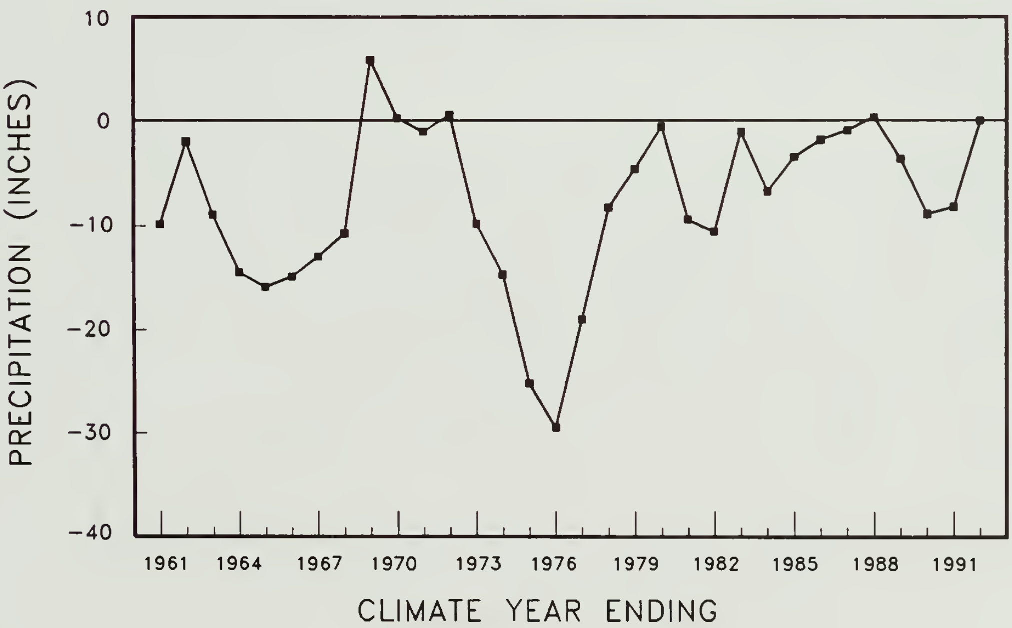
HCI HYDROLOGIC CONSULTANTS, INC.	ANNUAL PRECIPITATION AND CUMULATIVE DEPARTURE FROM MEAN FOR KYLE CANYON	Figure 7c

LEE CANYON (Station 4)

ANNUAL PRECIPITATION



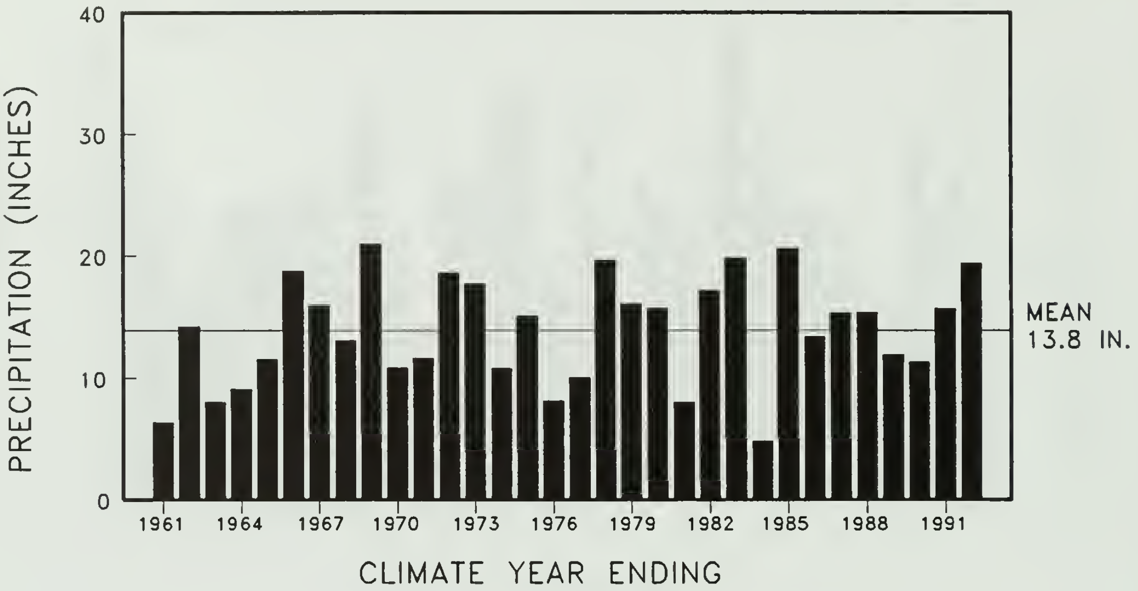
CUMULATIVE DEPARTURE FROM MEAN



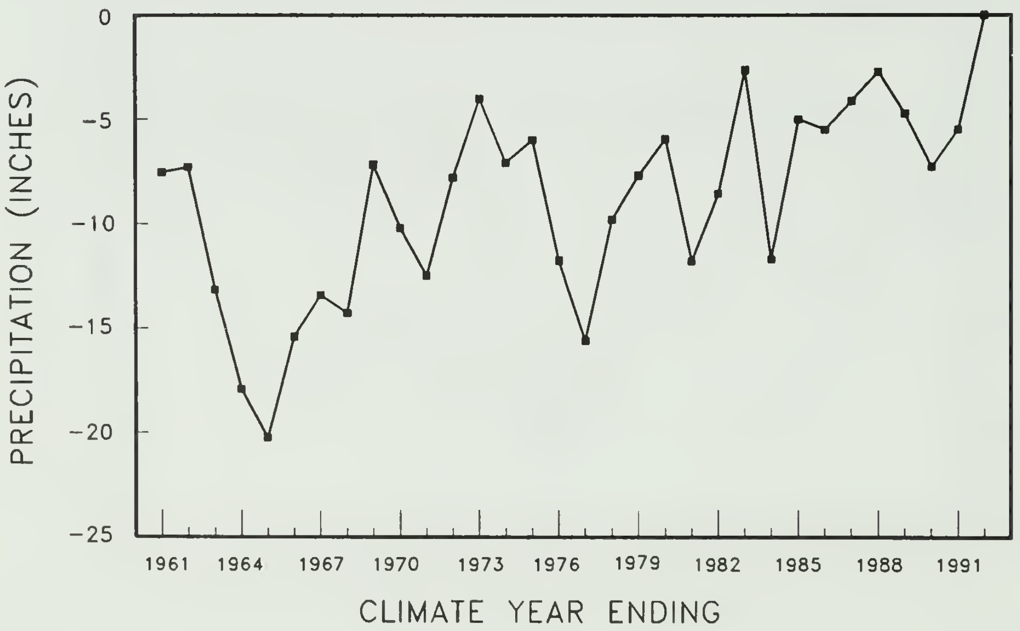
JOB NO. 59D	DATE: 5-17-93		
BY: LA	DRAWN: MW		
FILE:AP_CD4.DWG	REV: NS		
HCI HYDROLOGIC CONSULTANTS, INC.		ANNUAL PRECIPITATION AND CUMULATIVE DEPARTURE FROM MEAN FOR LEE CANYON	Figure 7d

ROBERTS RANCH (Station 5)

ANNUAL PRECIPITATION



CUMULATIVE DEPARTURE FROM MEAN



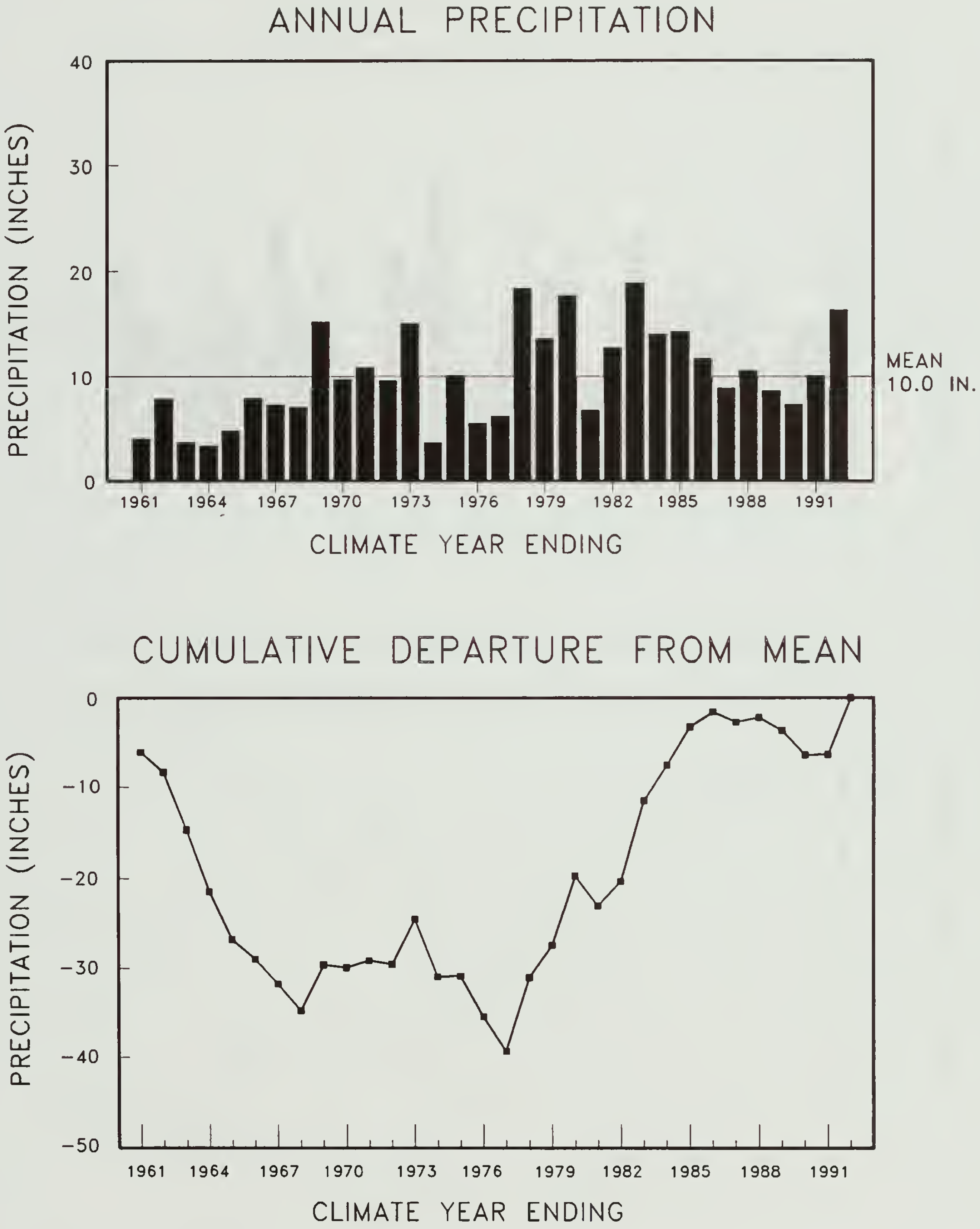
JOB NO. 590	DATE: 5-17-93
BY: LA	DRAWN: MW
FILE:AP_CD5.DWG	REV: NS

HCI HYDROLOGIC CONSULTANTS, INC.

ANNUAL PRECIPITATION AND CUMULATIVE DEPARTURE FROM MEAN FOR ROBERTS RANCH

Figure 7e

SPRING MOUNTAIN RANCH (Station 6)



JOB NO. 590	DATE: 5-17-93
BY: LA	DRAWN: MW
FILE:AP_CD6.DWG	REV: NS

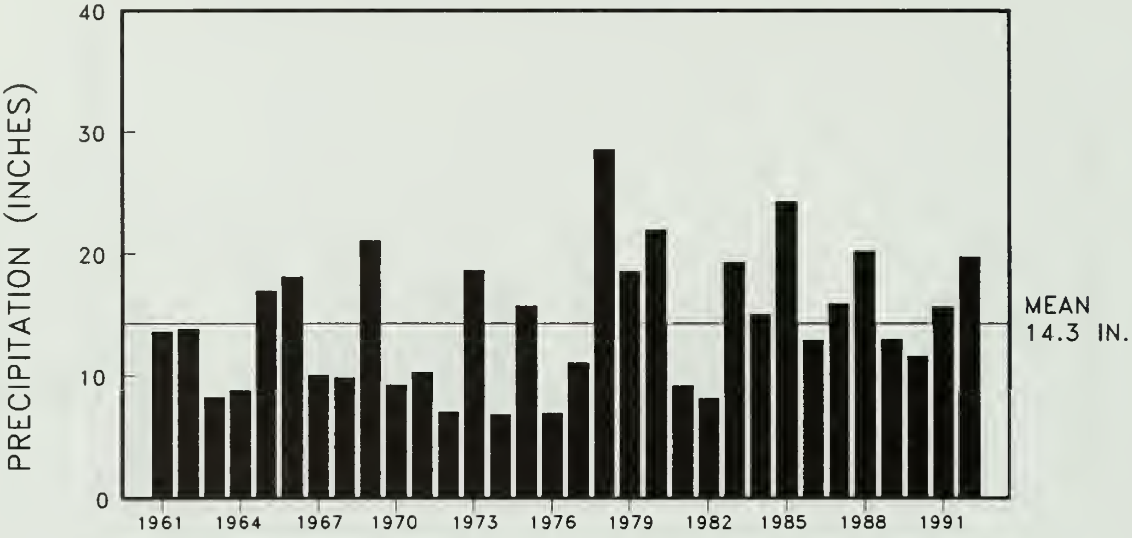
HCI HYDROLOGIC CONSULTANTS, INC.

ANNUAL PRECIPITATION AND CUMULATIVE DEPARTURE FROM MEAN FOR SPRING MOUNTAIN RANCH

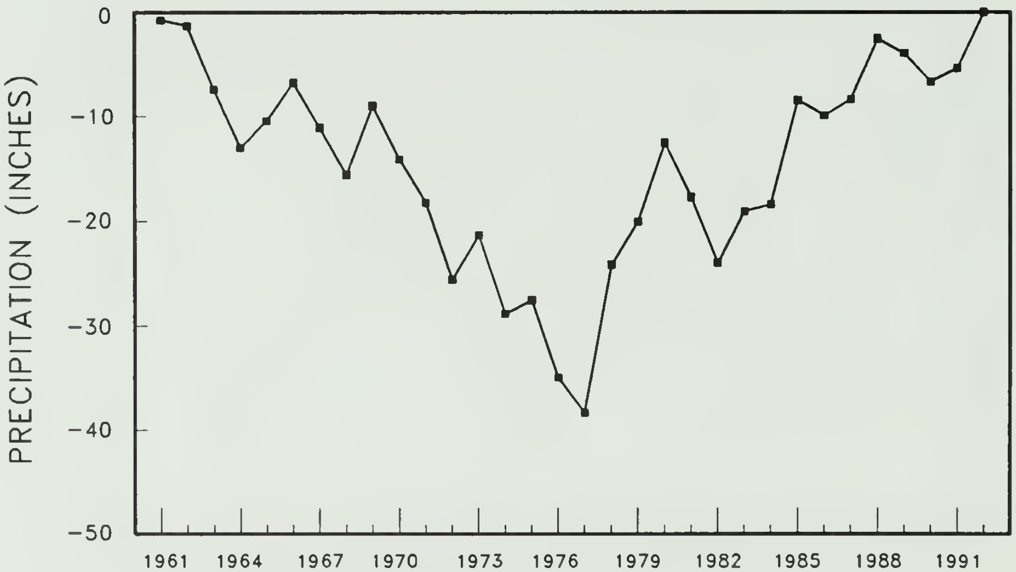
Figure 7f

WILLIAMS RANCH (Station 7)

ANNUAL PRECIPITATION



CUMULATIVE DEPARTURE FROM MEAN



JOB NO. 590	DATE: 5-17-93
BY: LA	DRAWN: MW
FILE:AP_CD7.DWG	REV: NS

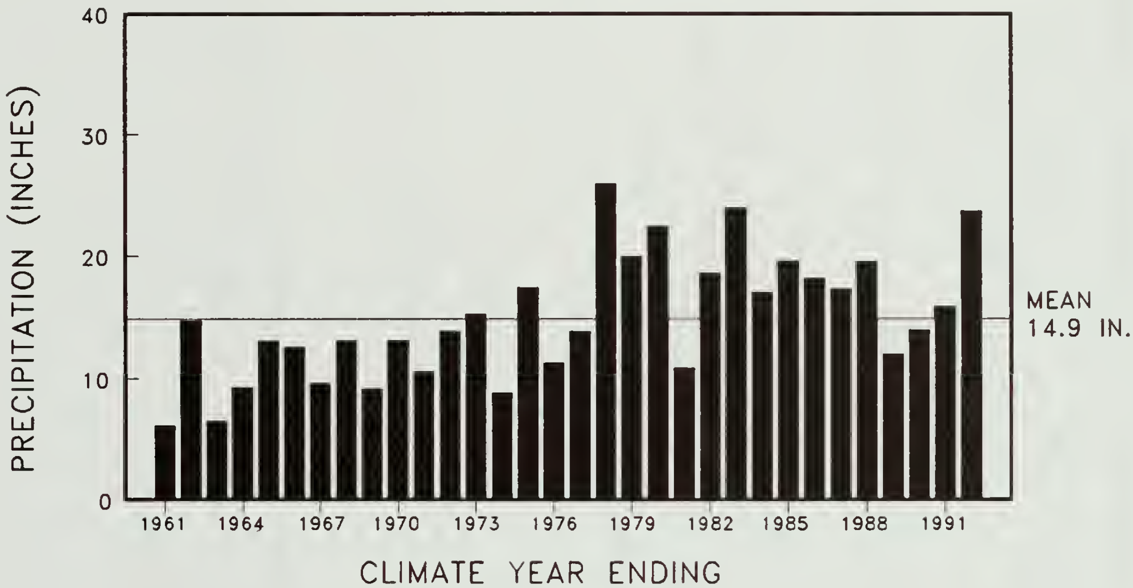
HCI HYDROLOGIC CONSULTANTS, INC.

ANNUAL PRECIPITATION AND CUMULATIVE DEPARTURE FROM MEAN FOR WILLIAMS RANCH

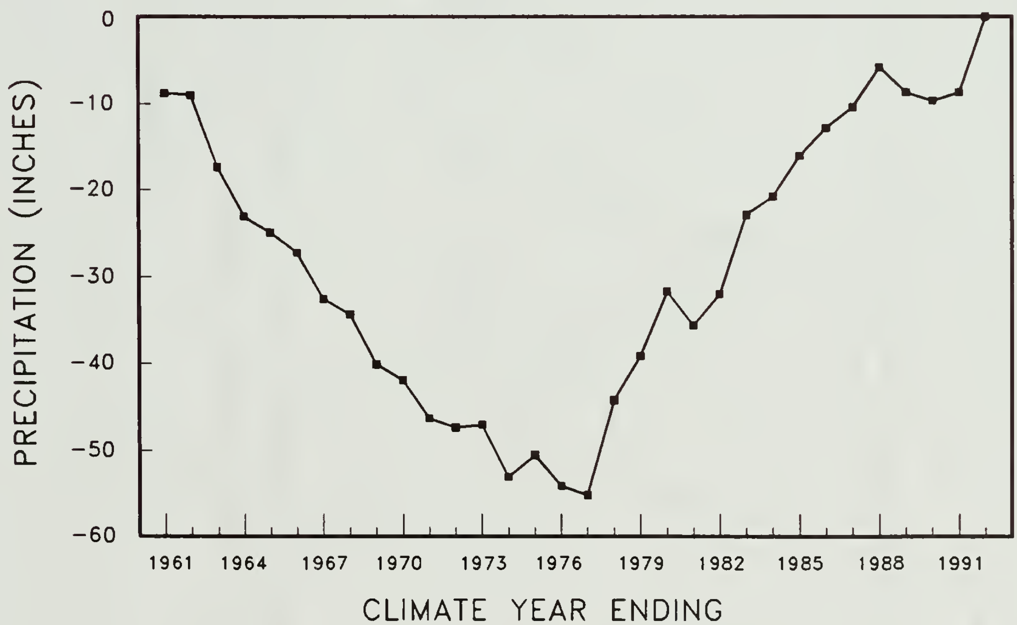
Figure 7g

WHEELER PASS (Station 8)

ANNUAL PRECIPITATION

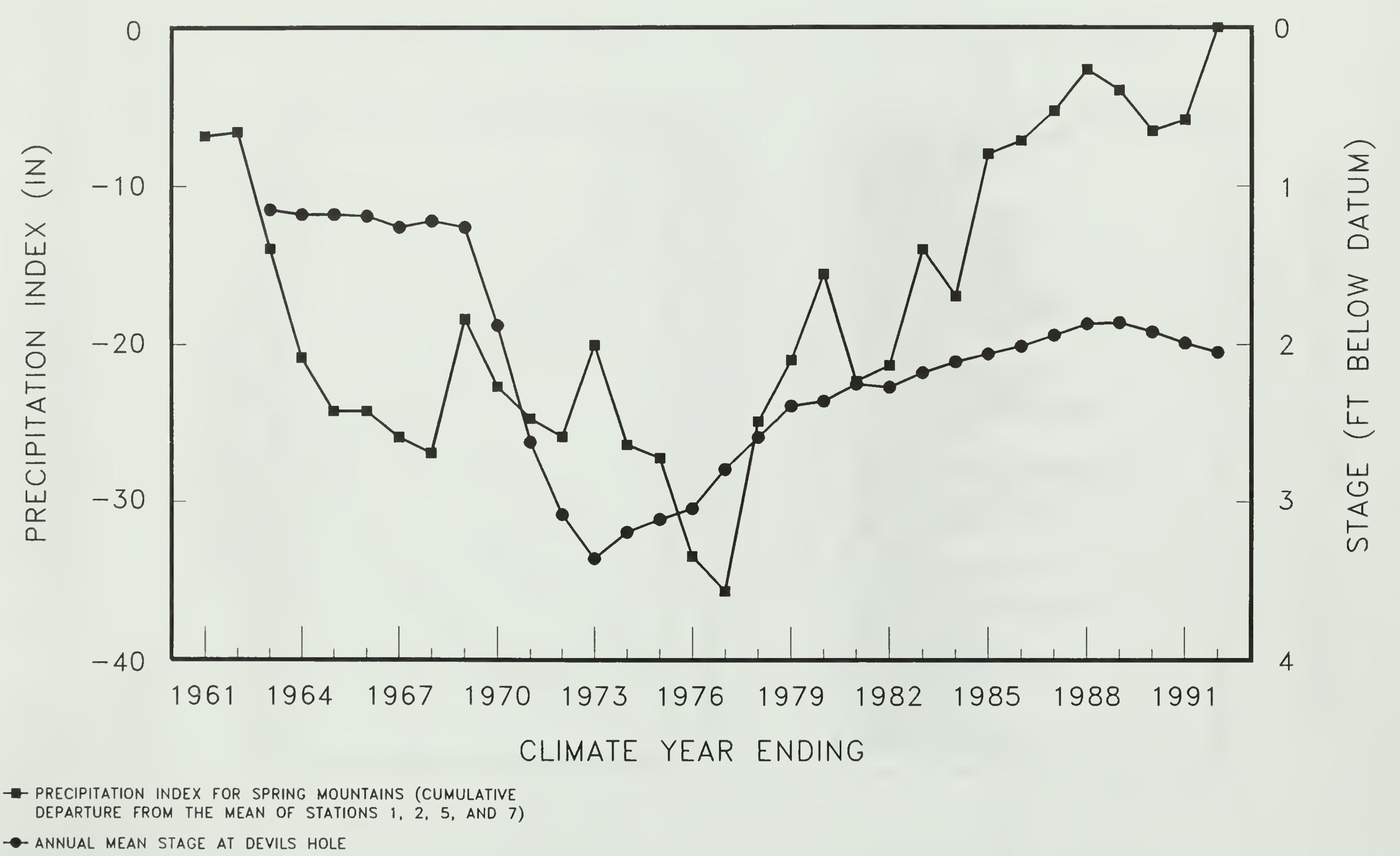


CUMULATIVE DEPARTURE FROM MEAN

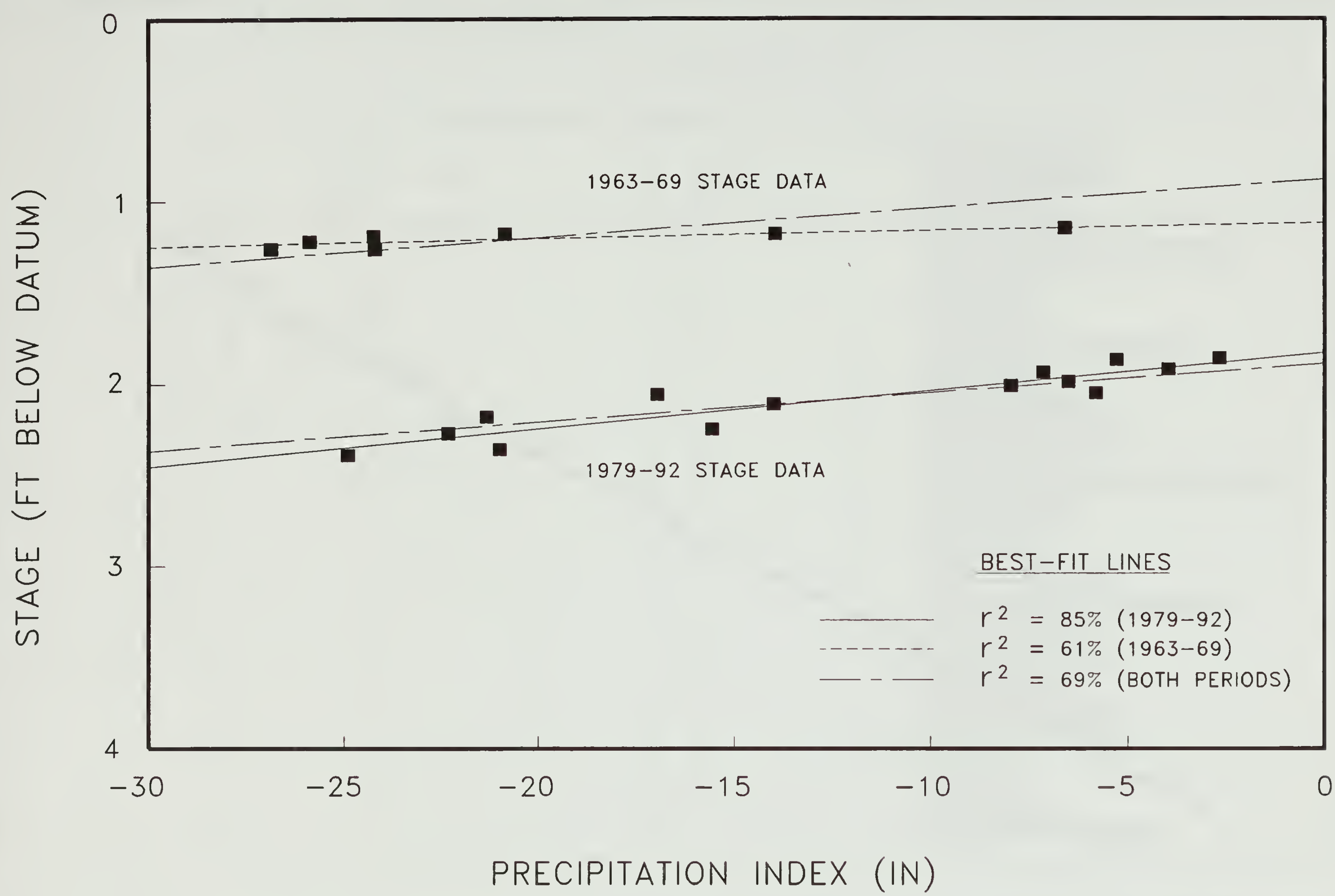


JOB NO. 590	DATE: 5-17-93
BY: LA	DRAWN: MW
FILE:AP_CD8.DWG	REV: NS

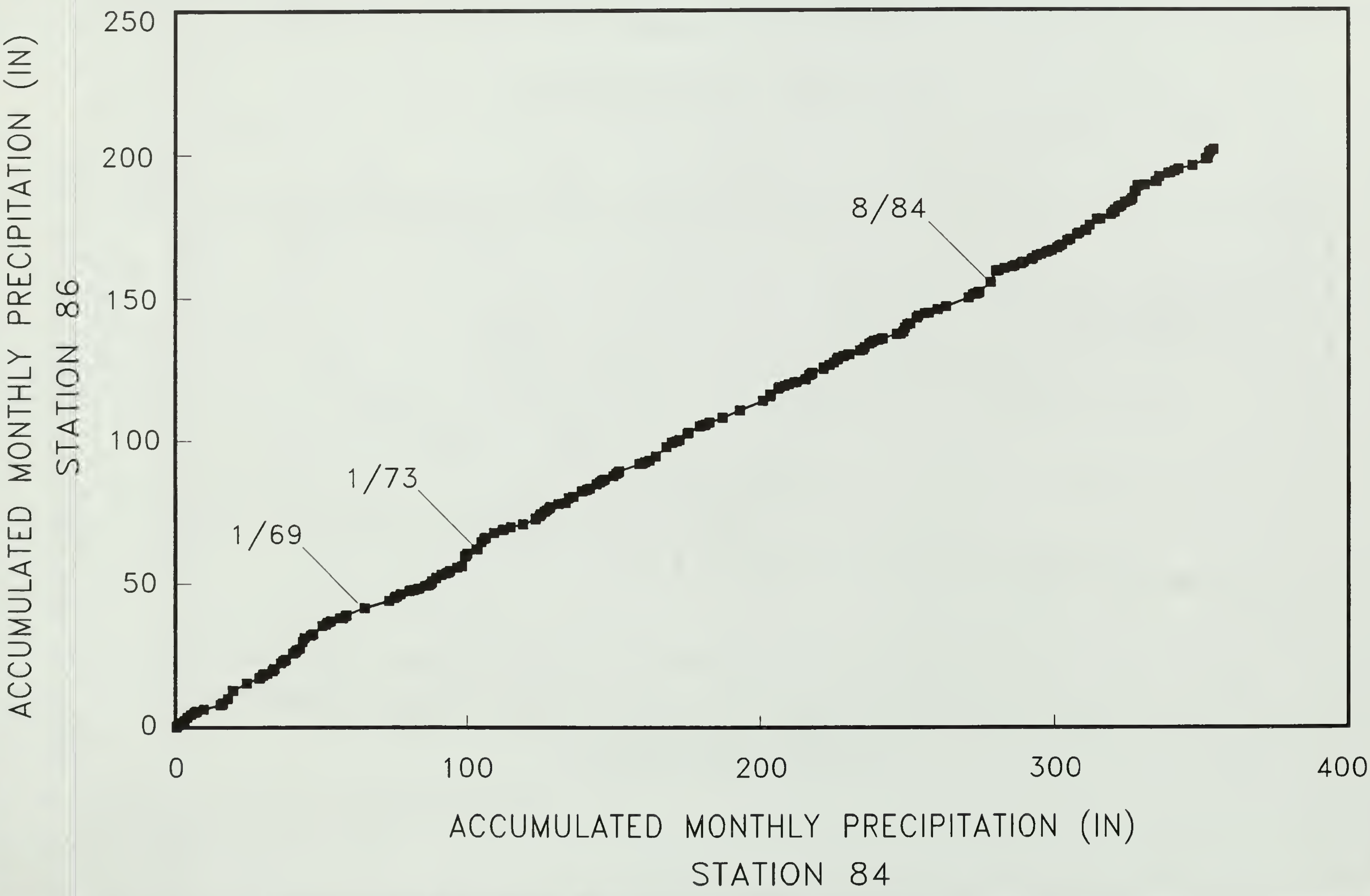
HCI HYDROLOGIC CONSULTANTS, INC.	ANNUAL PRECIPITATION AND CUMULATIVE DEPARTURE FROM MEAN FOR WHEELER PASS	Figure 7h



HCI HYDROLOGIC CONSULTANTS, INC.	JOB NO. 590	DATE: 4-16-93	COMPARISON OF DEVILS HOLE STAGE WITH INDEX OF PRECIPITATION FOR SPRING MOUNTAINS	Figure 8
	BY: LA	DRAWN: NS		
	FILE: ST_PRC.DWG	REV:		



HCI HYDROLOGIC CONSULTANTS, INC.	JOB NO. 590	DATE: 5-5-93	SCATTER DIAGRAM OF DEVILS HOLE STAGE VS. INDEX OF PRECIPITATION FOR SPRING MOUNTAINS, STAGE LAGGED BY 1 YEAR
	BY: LA	DRAWN: NS	Figure 9
	FILE: SCAT_1YR.DWG	REV:	

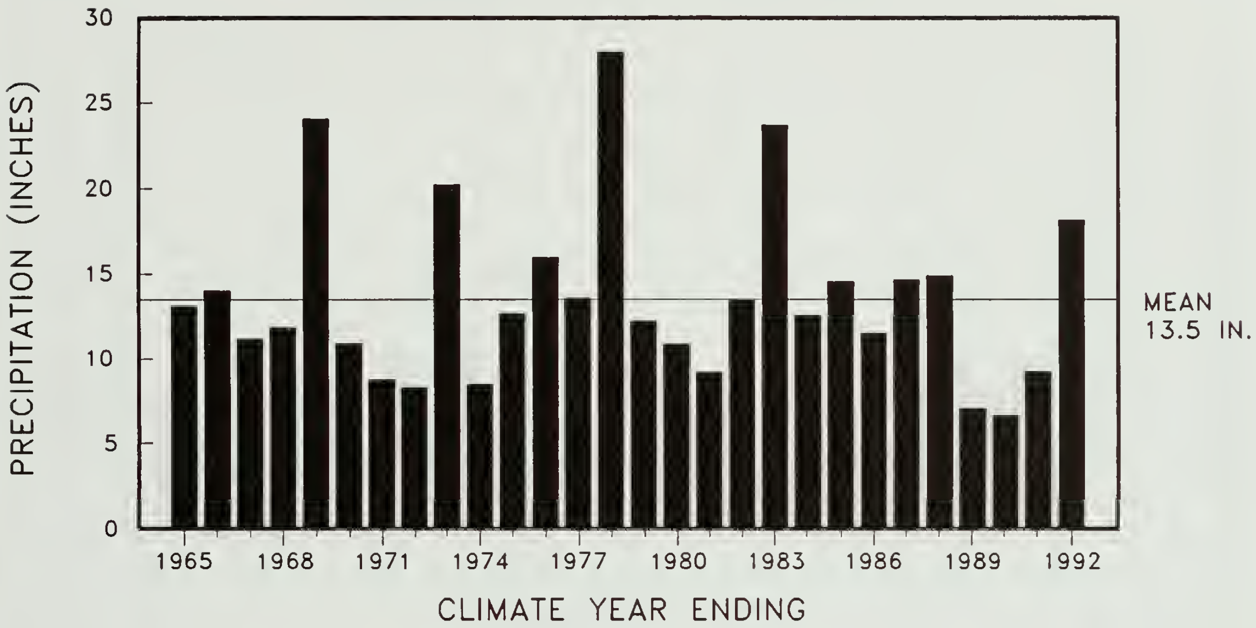


HCI HYDROLOGIC CONSULTANTS, INC.	JOB NO. 590	DATE: 4-29-93	DOUBLE-MASS ANALYSIS FOR PAHUTE MESA PRECIPITATION STATIONS
	BY: LA	DRAWN: NS	
	FILE: NTS_DOUB.DWG	REV:	

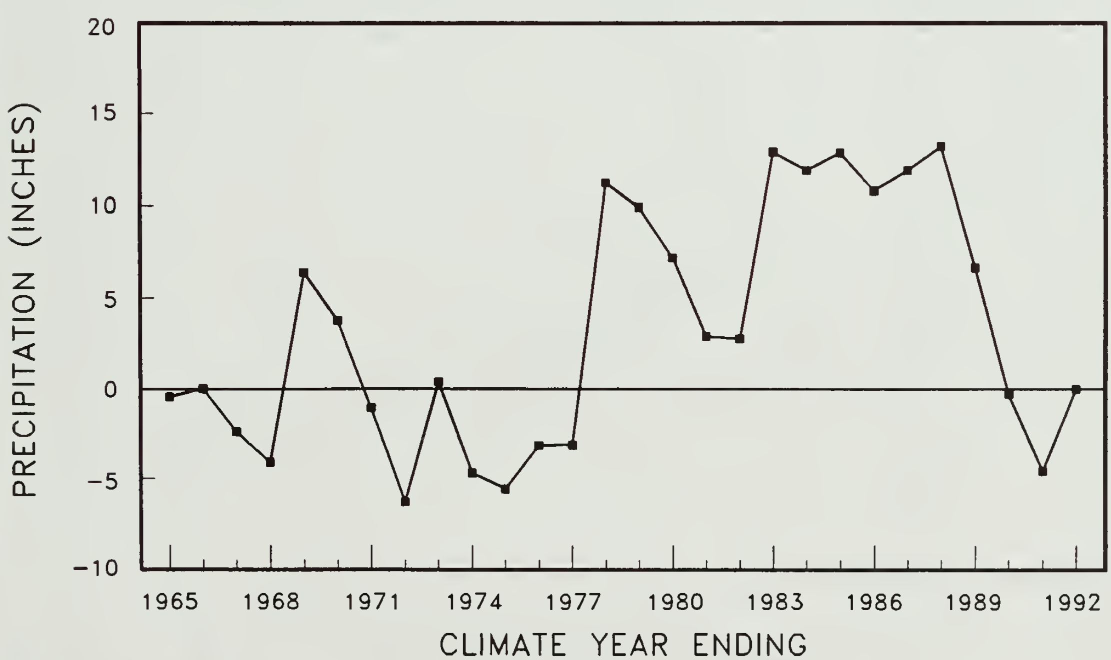
Figure 10

STATION 84

ANNUAL PRECIPITATION



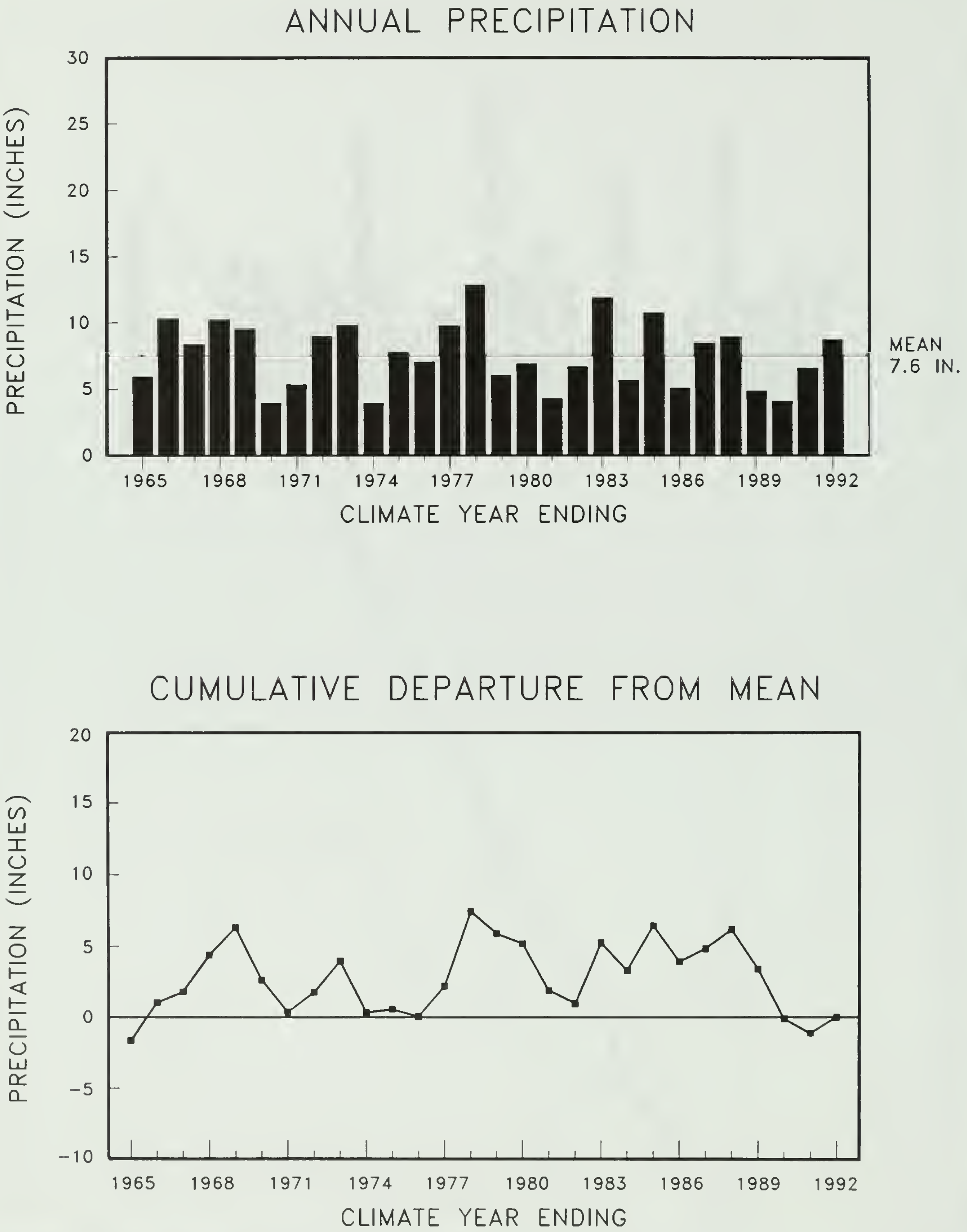
CUMULATIVE DEPARTURE FROM MEAN



JOB NO. 590	DATE: 5–3–93
BY: LA	DRAWN: NS
FILE:APCD_84.DWG	REV:

HCI HYDROLOGIC CONSULTANTS, INC.	ANNUAL PRECIPITATION AND CUMULATIVE DEPARTURE FROM MEAN FOR PAHUTE MESA STATION 84	Figure 11

STATION 86

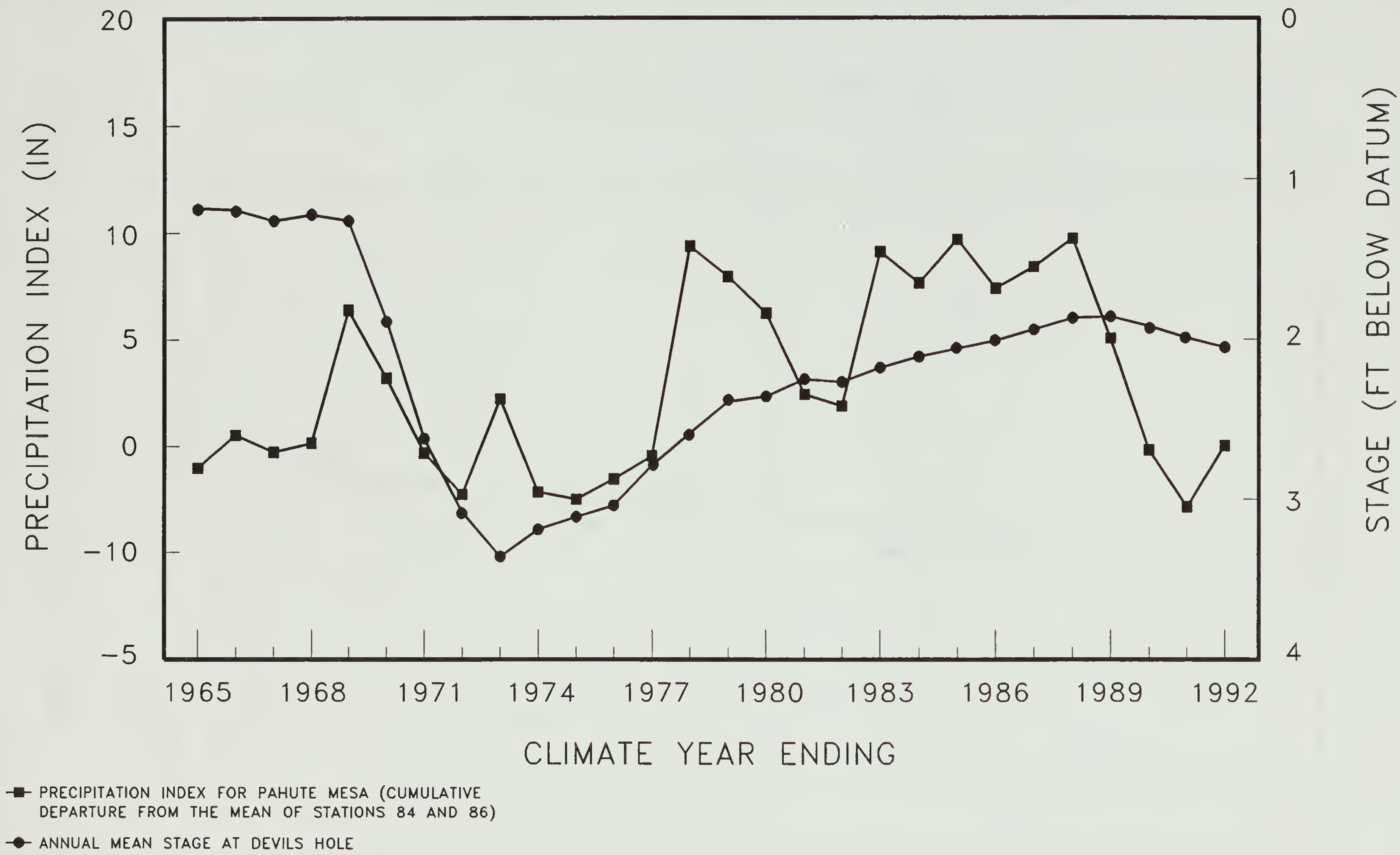


JOB NO. 590	DATE: 2-6-93
BY: LA	DRAWN: MW
FILE:APCD_86.DWG	REV:

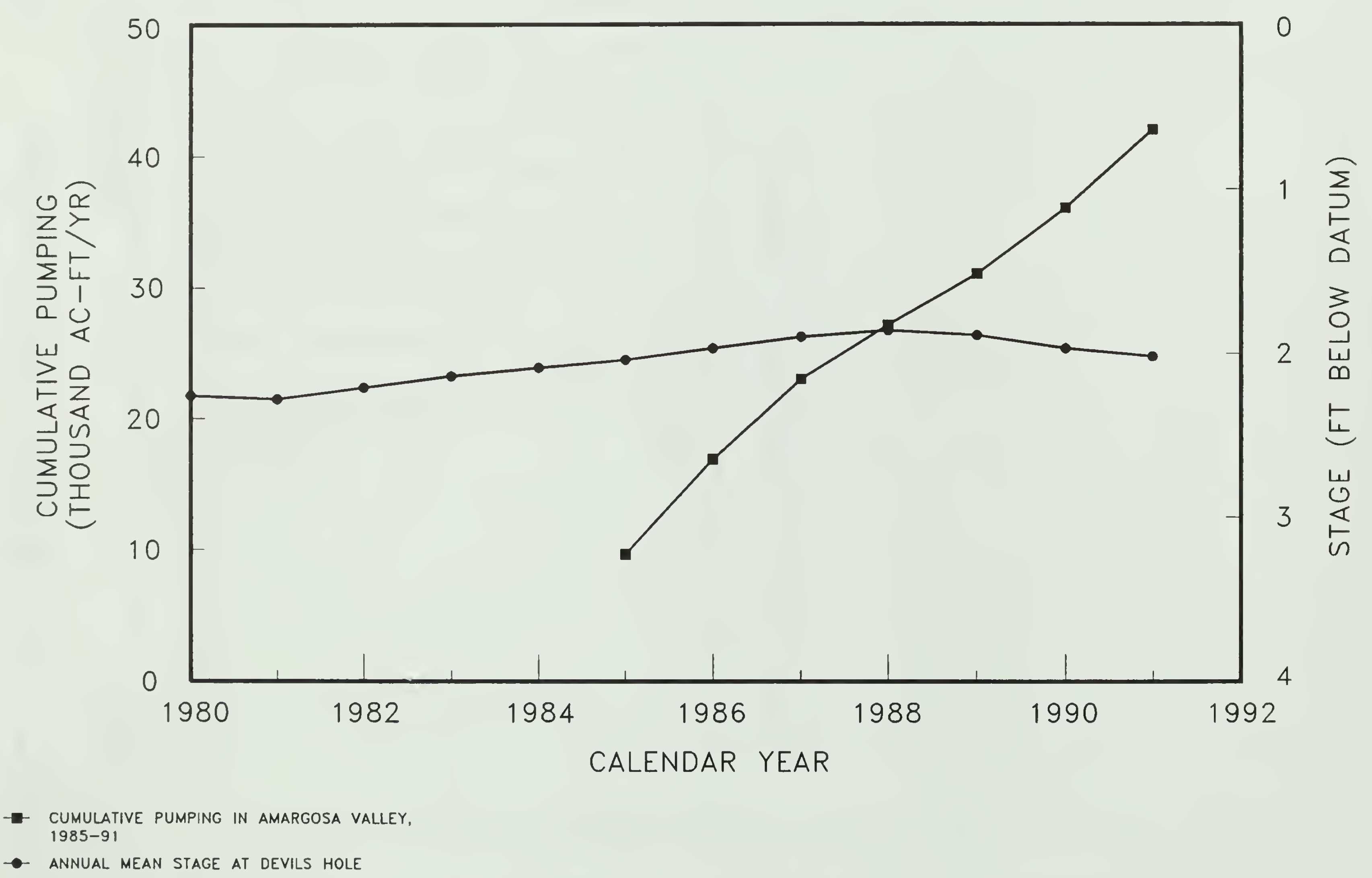
HCI HYDROLOGIC CONSULTANTS, INC.

ANNUAL PRECIPITATION AND CUMULATIVE DEPARTURE FROM MEAN FOR PAHUTE MESA STATION 86

Figure 12

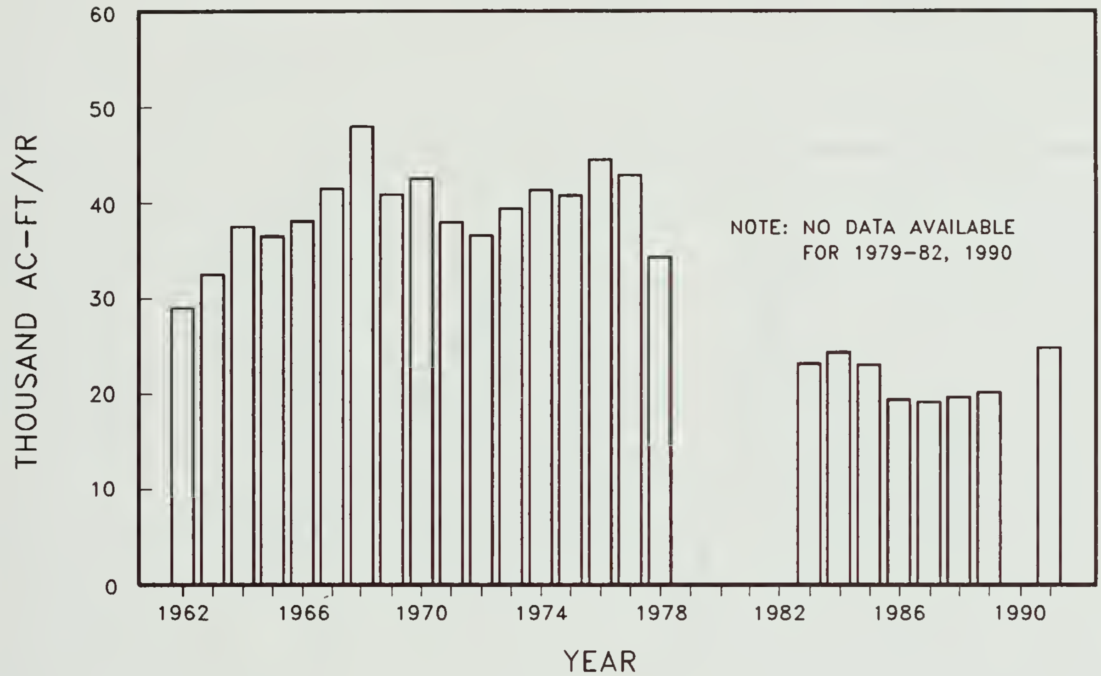


HCI HYDROLOGIC CONSULTANTS, INC.	JOB NO. 590	DATE: 4-23-93	COMPARISON OF DEVILS HOLE STAGE WITH INDEX OF PRECIPITATION FOR PAHUTE MESA	Figure 13
	BY: LA	DRAWN: NS		
	FILE:NTS_STPR.DWG	REV:		

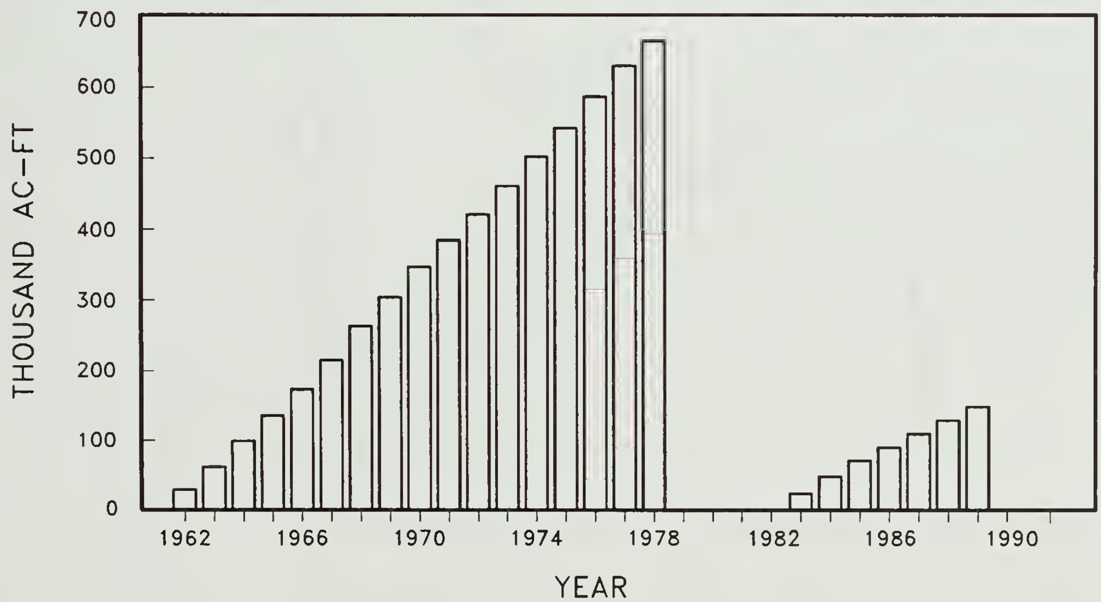


HCI HYDROLOGIC CONSULTANTS, INC.	JOB NO. 590	DATE: 4-28-93	COMPARISON OF DEVILS HOLE STAGE WITH CUMULATIVE PUMPING IN AMARGOSA VALLEY
	BY: LA	DRAWN: NS	
	FILE:AMAR_PS.DWG	REV:	Figure 16

ANNUAL PUMPING



CUMULATIVE PUMPING, 1962–78 AND 1983–89



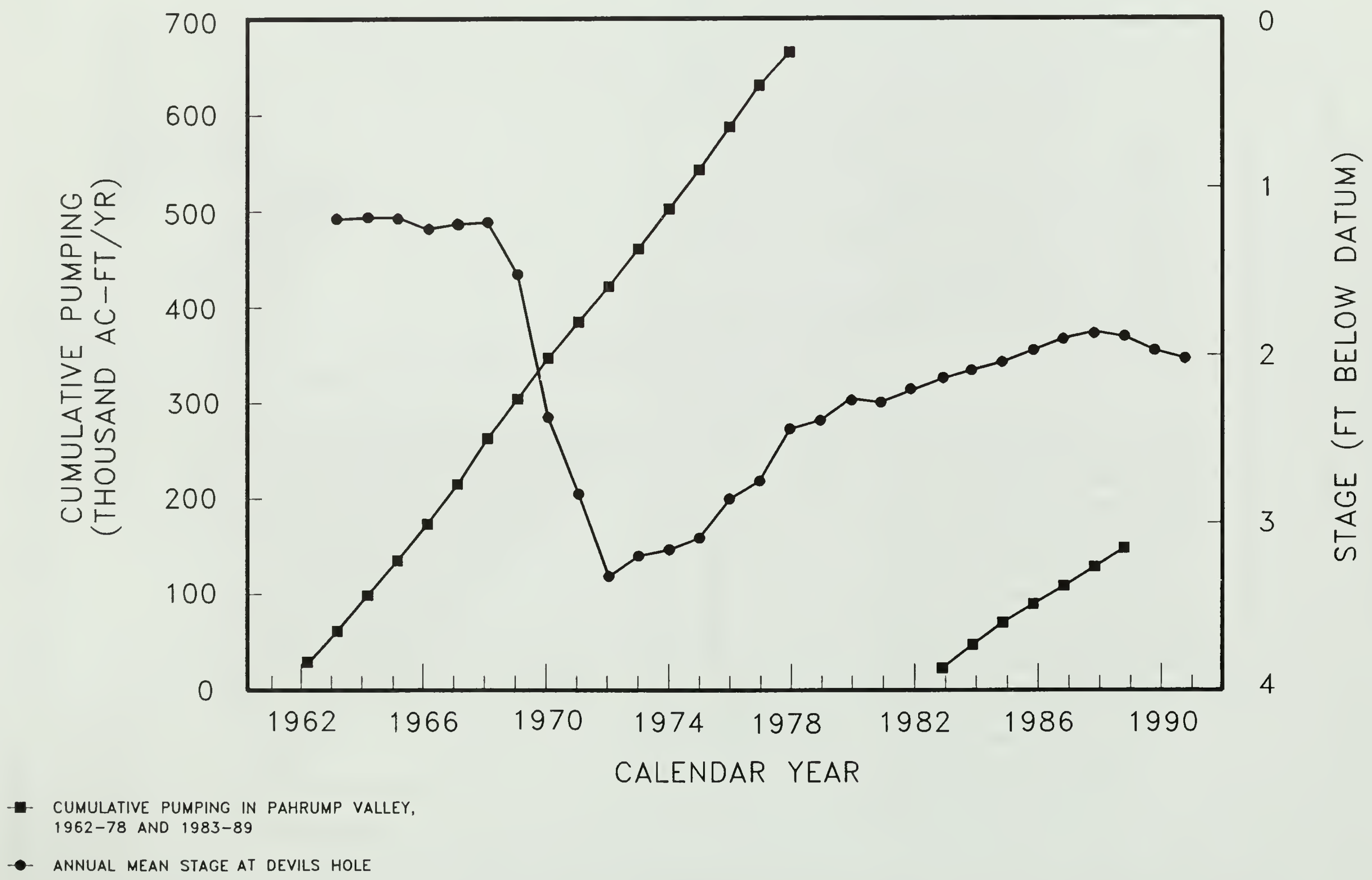
DATA SOURCES:
NEVADA STATE ENGINEER,
AND HARRILL (1986)

JOB NO. 590	DATE: 4–26–93
BY: LA	DRAWN: NS
FILE:PAHR_PMP.DWG	REV:

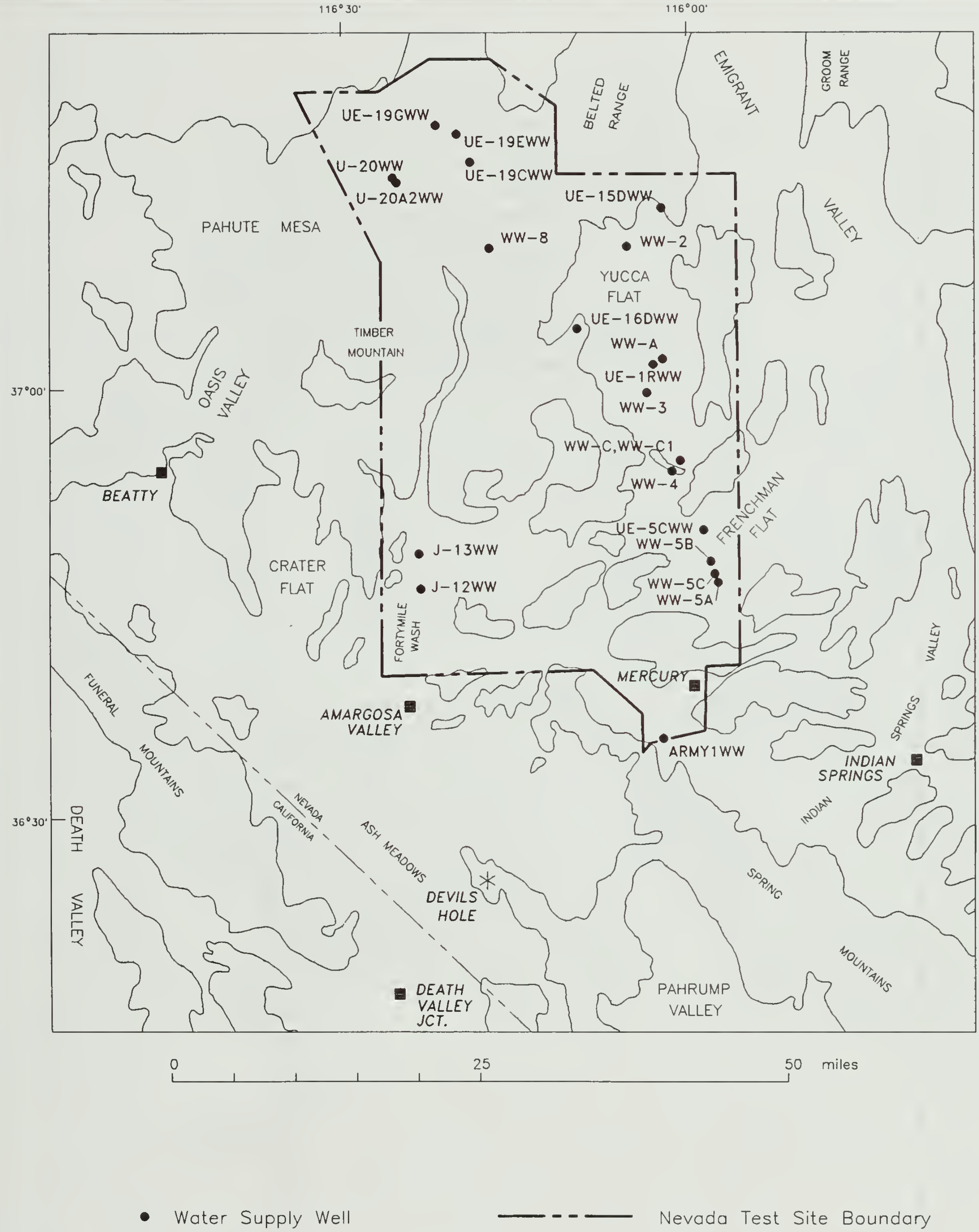
HCI HYDROLOGIC CONSULTANTS, INC.

ANNUAL AND CUMULATIVE PUMPING IN PAHRUMP VALLEY, 1962–1991

Figure 17



HCI HYDROLOGIC CONSULTANTS, INC.	JOB NO. 590	DATE: 4-28-93	COMPARISON OF DEVILS HOLE STAGE WITH CUMULATIVE PUMPING IN PAHRUMP VALLEY	Figure 18
	BY: LA	DRAWN: NS		
	FILE:PAHR_PS.DWG	REV:		

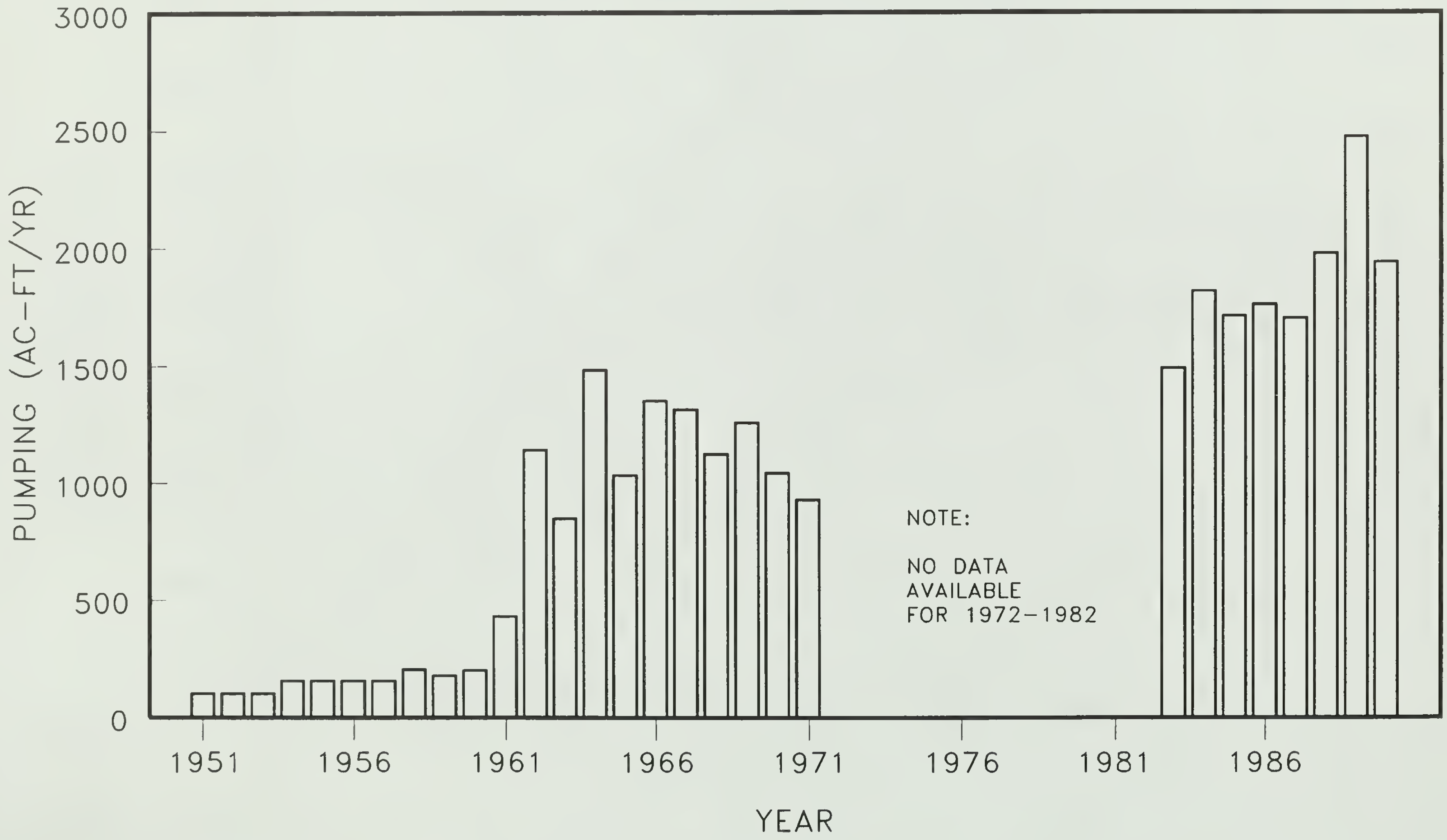


JOB NO. 590	DATE: 4-27-93
BY: LA	DRAWN: MW
FILE: NTSPUMP.DWG	REV:

HCI HYDROLOGIC CONSULTANTS, INC.

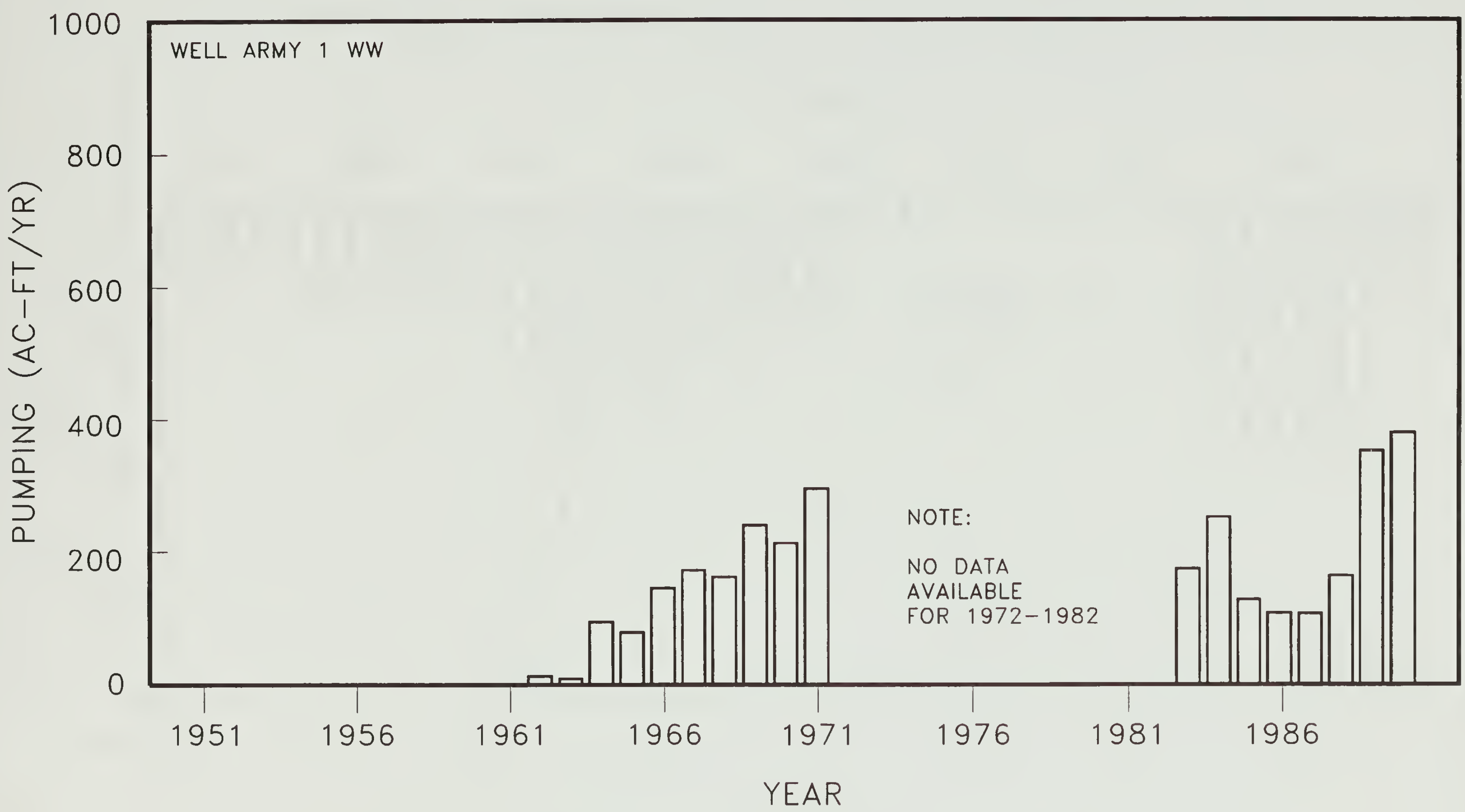
LOCATION OF WATER SUPPLY WELLS ON THE NEVADA TEST SITE

Figure 19



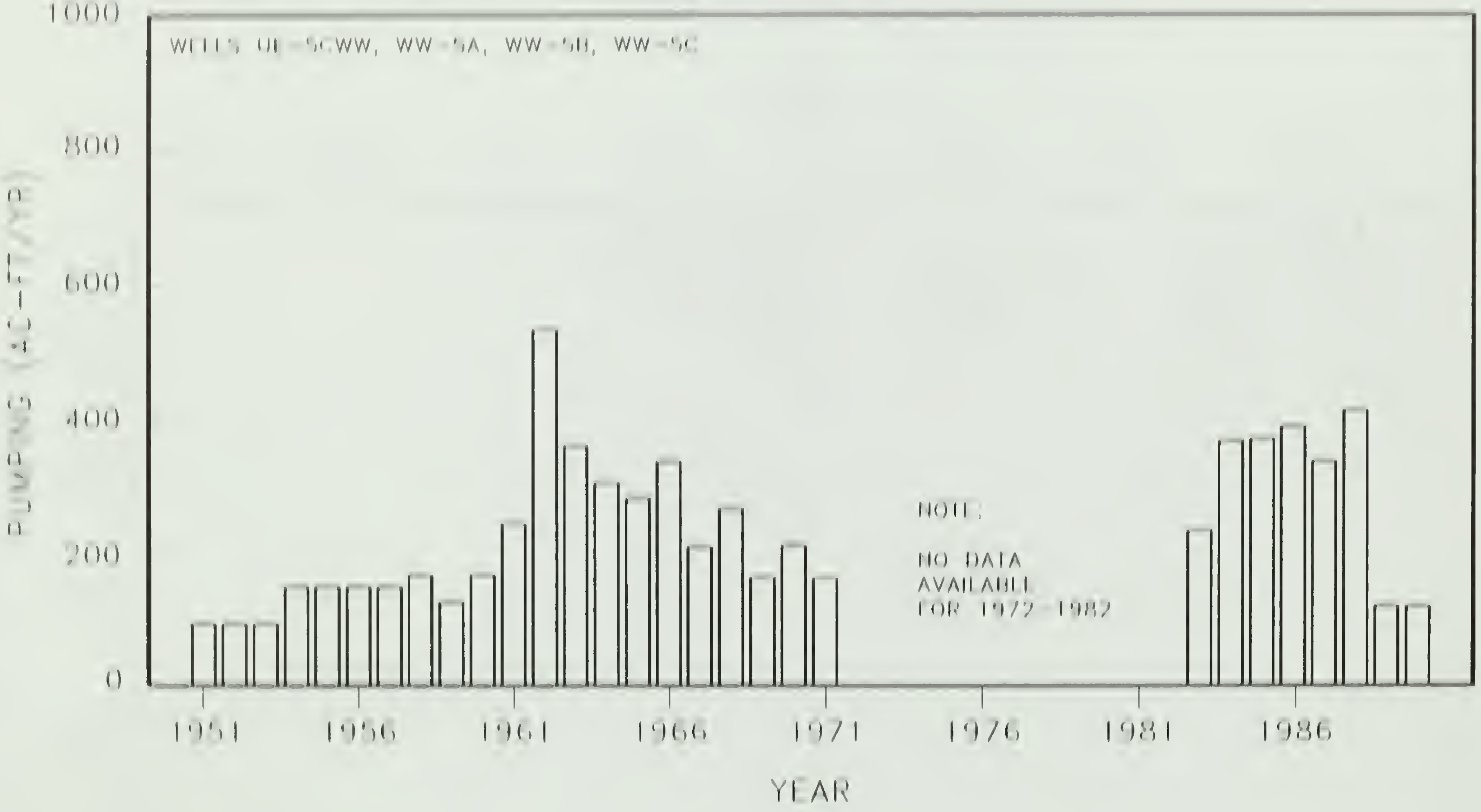
HCI HYDROLOGIC CONSULTANTS, INC.	JOB NO. 590	DATE: 4-23-93	TOTAL REPORTED PUMPING AT NEVADA TEST SITE, 1951-1990
	BY: LA	DRAWN: NS	
	FILE:NTS_TOT.DWG	REV:	

Figure 20



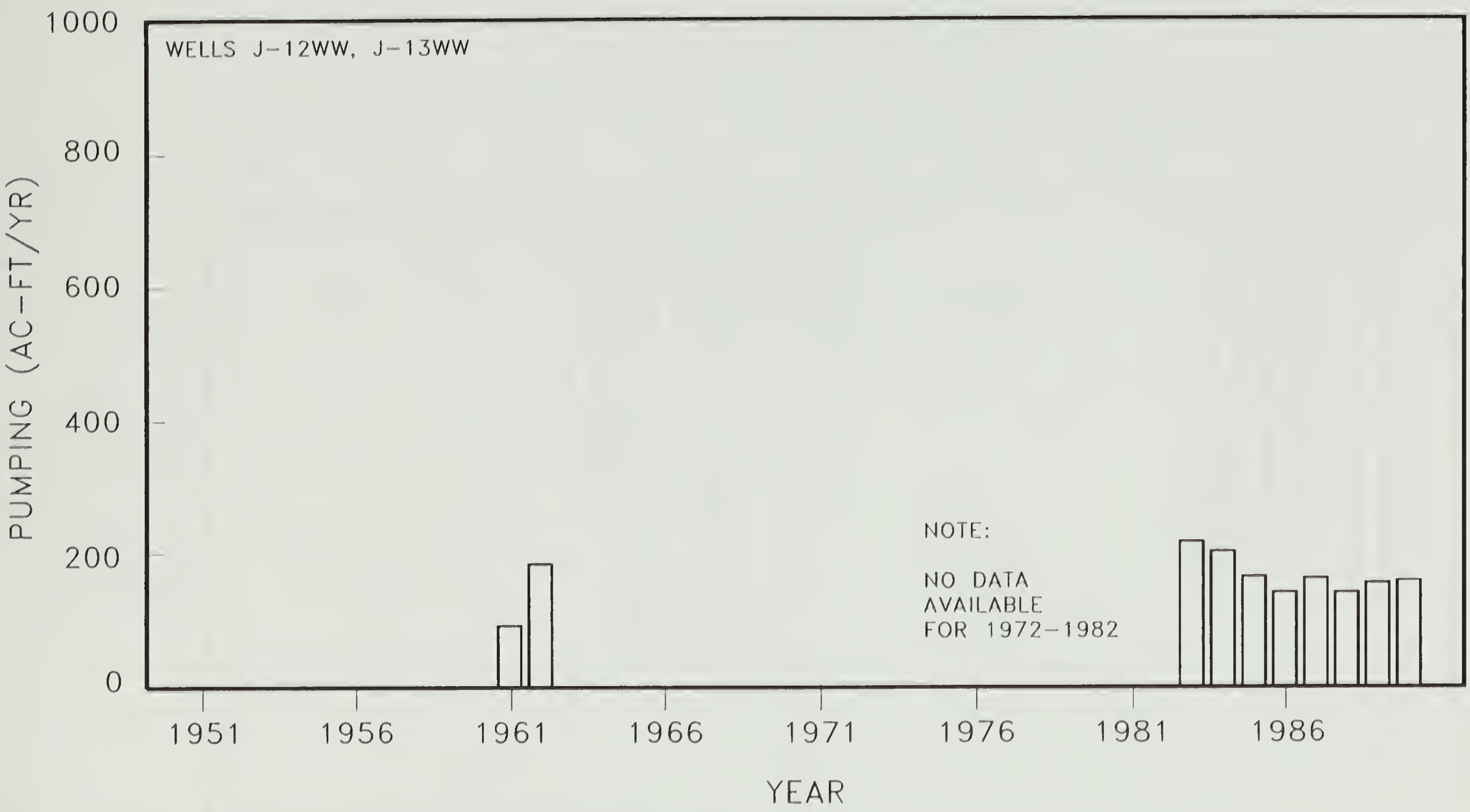
HCI HYDROLOGIC CONSULTANTS, INC.	JOB NO. 590	DATE: 4-23-93	REPORTED PUMPING IN MERCURY VALLEY, NEVADA TEST SITE, 1951-1990
	BY: LA	DRAWN: NS	
	FILE:NTS_MERC.DWG	REV:	

Figure 21a



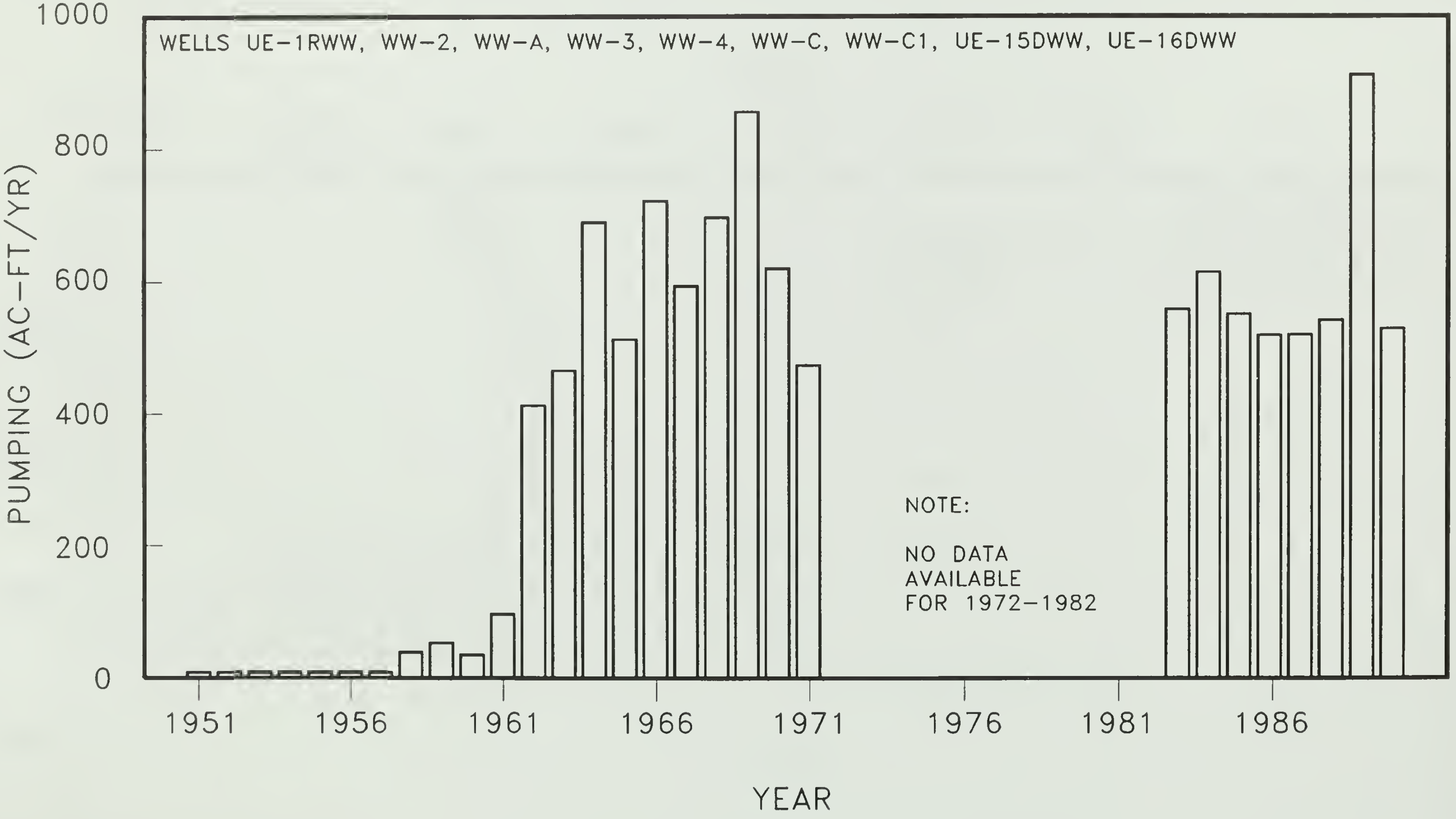
HYDROLOGIC CONSULTANTS, INC	JOB NO. 590 / BY TA / FILE NM: FRN.DWG	DATE 4-23-93 / DRAWN NS / REV	REPORTED PUMPING IN FRENCHMAN FLAT AREA, NEVADA TEST SITE, 1951-1990

Figure 21b



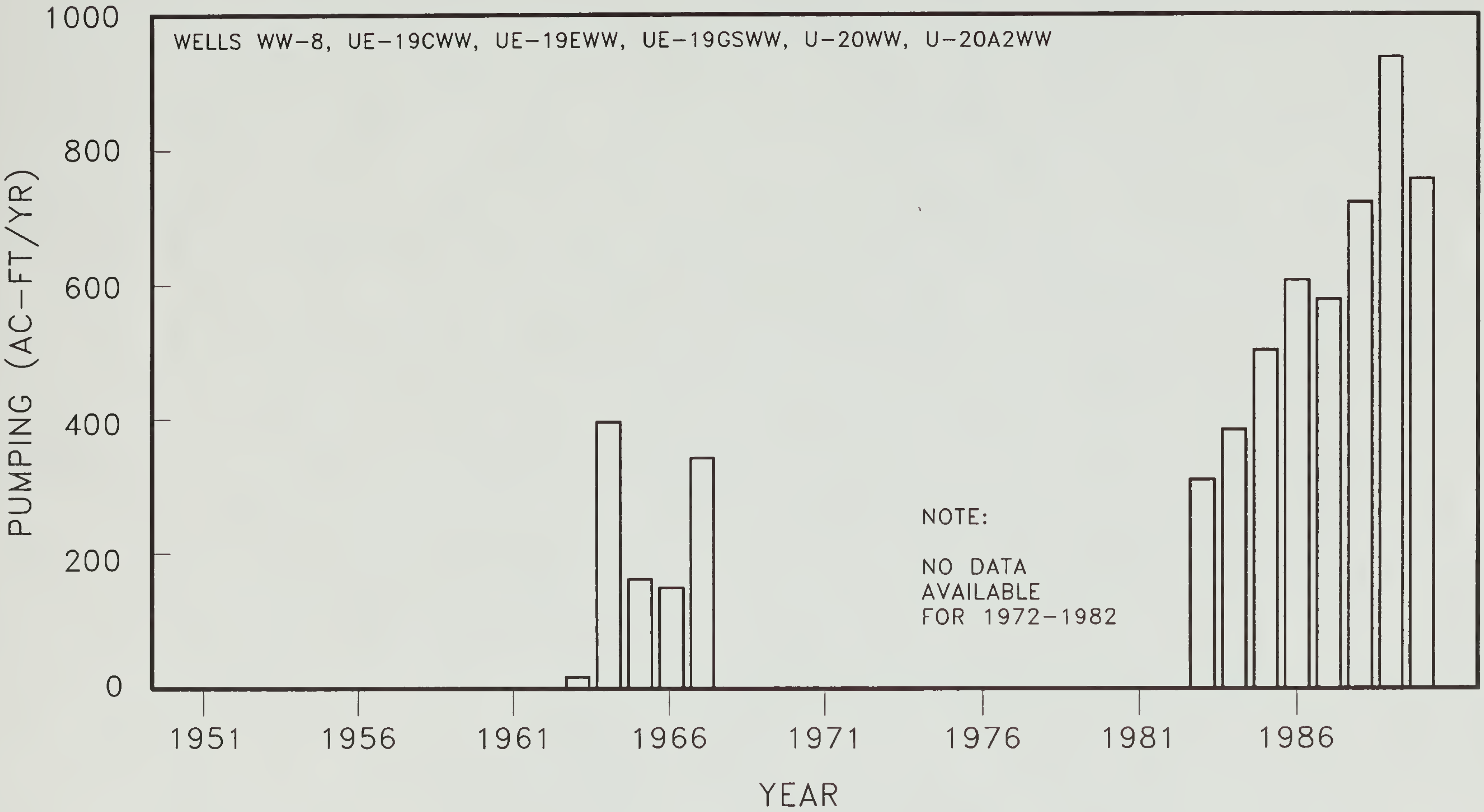
HCI HYDROLOGIC CONSULTANTS, INC.	JOB NO. 590	DATE: 4-21-93	REPORTED PUMPING IN FORTYMILE WASH, NEVEDA TEST SITE, 1951-1990
	BY: LA	DRAWN: NS	
	FILE:NTS_FORT.DWG	REV:	

Figure 21c



HCI HYDROLOGIC CONSULTANTS, INC.	JOB NO. 590	DATE: 4-23-93	REPORTED PUMPING IN YUCCA FLAT AREA, NEVADA TEST SITE, 1951-1990
	BY: LA	DRAWN: NS	
	FILE:NTS_YUK.DWG	REV:	

Figure 21d



HCI HYDROLOGIC CONSULTANTS, INC.	JOB NO. 590	DATE: 4-23-93	REPORTED PUMPING IN PAHUTE MESA AREA, NEVADA TEST SITE, 1951-1990
	BY: LA	DRAWN: NS	
	FILE:NTS_PAHU.DWG	REV:	

Figure 21e