HYDROGEOLOGY AND LAND SUBSIDENCE, EDWARDS AIR FORCE BASE, ANTELOPE VALLEY, CALIFORNIA, JANUARY 1989-DECEMBER 1991

By C.J. Londquist, D.L. Rewis, D.L. Galloway, and W.F. McCaffrey

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Conversion Factors

Multiply	By	To obtain
acre-foot (acre-ft)	1,233	cubic meter
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per year
acre-foot per square mile (acre-ft/mi^2)	476	cubic meter per square kilometer
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot per second (ft/s)	0.3048	meter per second
foot per year (ft/yr)	0.3048	meter per year
foot square per day (ft^2/d)	0.0929	meter squared per day
inch (in.)	25.4	millimeter
mile (mi)	1.609	kilometer
mile per hour (mi/h)	1.609	kilometer per hour
square mile (mi^2)	2.590	square kilometer

Temperature is given in degrees Fahrenheit (°F), which can be converted to degrees Celsius (°C) by the following equation:

$$°F=1.8(°C)+32.$$

Vertical Datum

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929--a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

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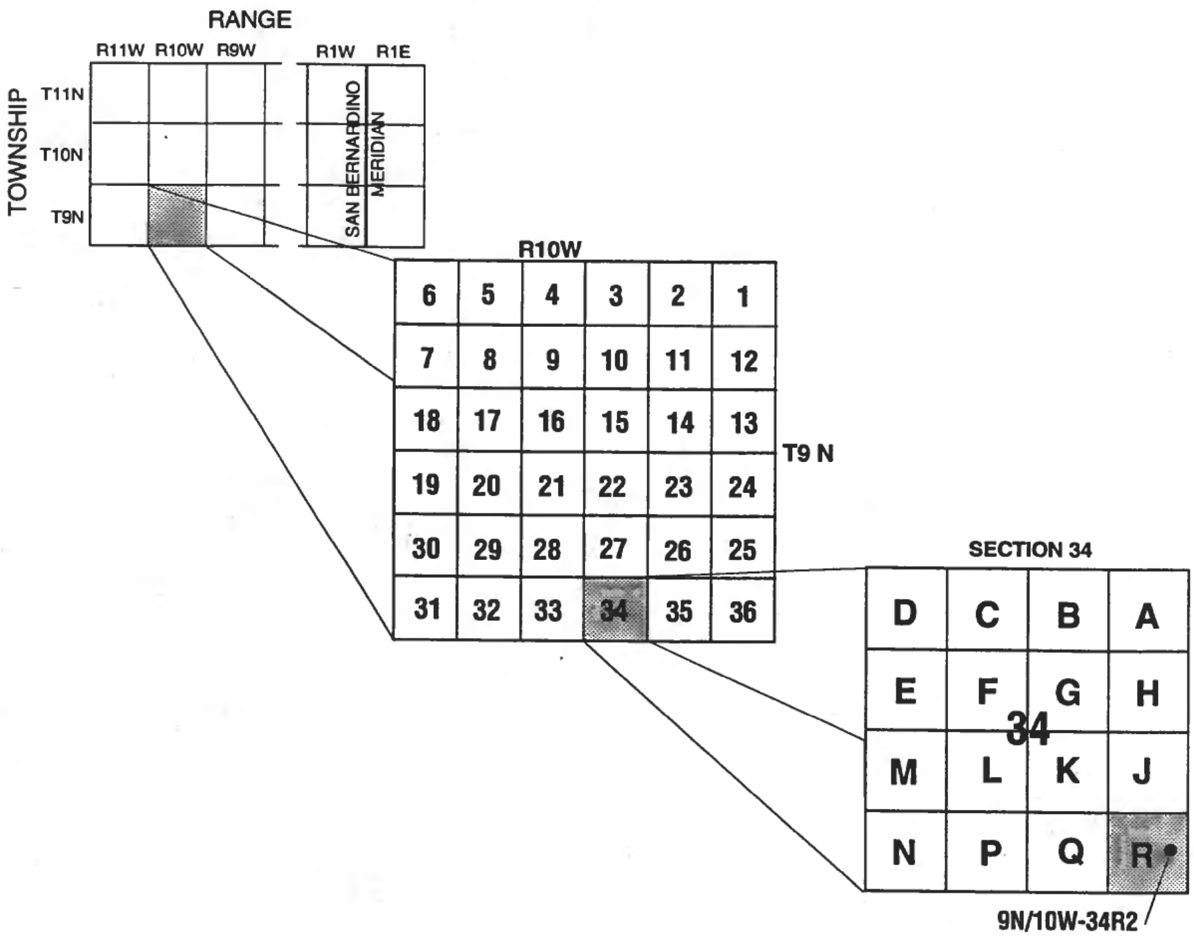
Well-Numbering System

Wells are identified and numbered according to their location in the rectangular system for the subdivision of public lands. Identification consists of the township number, north or south; the range number, east or west; and the section number. Each section is divided into sixteen 40-acre tracts lettered consecutively (except I and O), beginning with "A" in the northeast corner of the section and progressing in a sinusoidal manner to "R" in the southeast corner. Within the 40-acre tract, wells are sequentially numbered in the order they are inventoried. The final letter refers to the base line and meridian. In California, there are three base lines and meridians; Humboldt (H), Mount Diablo (M), and San Bernardino (S). All wells in the study area are referenced to the San Bernardino base line and meridian (S). Well numbers consist of 15 characters and follow the format 009N010W34R002S. In this report, well numbers are abbreviated and written 9N/10W-34R2. Wells in the same township and range are referred to only by their section designation, 34R2. The following diagram shows how the number for well 9N/10W-34R2 is derived.



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HYDROGEOLOGY AND LAND SUBSIDENCE, EDWARDS AIR FORCE BASE, ANTELOPE VALLEY, CALIFORNIA, JANUARY 1989-DECEMBER 1991

By C.J. Londquist, D.L. Rewis, D.L. Galloway, and W.F. McCaffrey

Abstract

Land subsidence has long been recognized as a problem in some parts of the Antelope Valley area of California. In 1988, the effects of subsidence were noted on Rogers Lake at Edwards Air Force Base in the form of sinklike depressions, fissures, and cracks, which have adversely affected the lakebed for landing airplanes and space shuttles. The land subsidence has been attributed to the pumping of ground water around the margins of the lakebed.

EAFB overlies two structural basins, East Antelope and Kramer, which have been filled to depths of more than 5,000 and 2,000 feet, respectively, with unconsolidated alluvium interbedded with lacustrine deposits. Lithologic and geophysical data indicate that these deposits become more consolidated with depth. Surface-geophysical information defines the East Antelope structural basin as a narrow northeast-trending trough, and indicates a possible fault zone that encompasses the Graham Ranch area.

Two alluvial aquifers are present in the Lancaster ground-water subbasin in Antelope Valley: the principal aquifer, which overlies the lacustrine deposits, is the major source of ground water for offbase users; and the deep aquifer is the major source of water at EAFB. Ground water in the Antelope Valley originates from the infiltration of surface-water runoff from the surrounding mountains. Estimates of the average annual recharge to the valley range from 40,200 to 81,400 acre-feet. In 1988, estimated pumpage in the valley was about 62,000 acre-feet and in 1990 the pumpage at Edwards Air Force Base was about 6,000 acre-feet. The long-term water-level trend at EAFB generally has been downward, and the greatest measured declines, as much as 90 feet, have occurred in the South Base well field. At the Holly site near the South Track well field, south of Rogers Lake, the hydraulic head in the overlying principal aquifer is about 100 feet higher than in the deep aquifer. The quality of ground water near Rogers Lake and in the Graham Ranch area ranges from soft to moderately hard, and commonly has a high dissolved-solids concentration. At the Buckhorn site, west of Rogers Lake, the water is characterized as very hard and slightly saline.

More than 1 foot of land subsidence has occurred since 1961 over the southern part of EAFB. The maximum measured subsidence for this period was 3.3 feet at benchmark P1155 near the South Track well field. Aquifer-system compaction measured at the Holly site showed a current average annual rate of compaction of 5.57×10^{-2} feet from May 1990 to November 1991.

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INTRODUCTION

Land subsidence has long been recognized as a problem in some parts of the Antelope Valley area of California. In 1988, its effects were noted on Rogers Lake at Edwards Air Force Base (EAFB, fig. 1) in the form of sinklike depressions, fissures, and cracks, which have adversely affected the lakebed for landing airplanes and space shuttles. In 1988, the U.S. Geological Survey (USGS), in cooperation with the U.S. Department of the Air Force, began a study at EAFB to determine the causes of land subsidence and lakebed deformation on EAFB. During the early stages of the study, the distribution of land subsidence near Rogers Lake was correlated with the distribution of ground-water level declines resulting primarily from ground-water withdrawals from base production wells. In late 1989, the USGS began a second study to determine the relation between ground-water withdrawals and land-surface deformation near Rogers Lake and to explore other potential ground-water resources whose development would minimally affect the lakebed. In 1991, the two studies were merged.

The purpose of this report is to describe geologic and hydrologic data collected by the USGS during 1989-91 and to document the results and interpretations of the hydrogeologic investigation through December 1991. The report briefly summarizes the regional hydrogeologic setting of Antelope Valley, relying mainly on previously published reports, and also describes the specific hydrogeologic data that were collected: geologic logs, borehole and surface geophysics, and ground-water levels and quality. This report includes interpretations regarding land subsidence and aquifer-system compaction. Data presented in this report are interpreted in the context of previously published findings and discussed in terms of the characterization of the aquifer system at EAFB.

The investigations reported on here focus on the area of EAFB; however, because the hydrologic processes under study are governed by physical, hydrologic, and geologic boundaries that occur at the scale of Antelope Valley, the investigations necessarily include areas of Antelope Valley outside of the boundaries of EAFB (fig. 1).

LOCATION AND GEOGRAPHIC DESCRIPTION

Edwards Air Force Base is in Antelope Valley in the western part of the Mojave Desert of southern California about 60 mi north-northeast of the city of Los Angeles, astride the Los Angeles, Kern, and San Bernardino County lines (fig. 1). The Mojave Desert is part of the Basin and Range province of the Western United States which, in this area, is characterized by faulted mountain blocks separating basins of internal drainage. Antelope Valley is a closed topographic basin with its lowest point at Rogers Lake (fig. 1). This lake, like others in the Mojave Desert, is a dry lake or playa and forms a prominent desert feature. The term playa, as used in this report, refers only to the dry lakebed surface as defined by Motts (1970, p. 9).

Antelope Valley covers about 2,200 mi^2; the alluvial fans, valley floor, interior mountain, and foothill altitudes range from about 2,270 to 3,500 ft above sea level. Altitudes of the San Gabriel and Tehachapi Mountains rise to about 10,064 and 9,731 ft above sea level, respectively. In addition to Rogers Lake, Antelope Valley contains two other dry lakes, Rosamond and Buckhorn Lakes, which also are within the boundaries of EAFB (fig. 1).

Lancaster and Palmdale are the largest population centers in Antelope Valley, having a combined population of about 128,000 in 1989 (Lancaster Chamber of Commerce, oral commun., February 1991) and about 156,000 in 1990 (U.S. Department of Commerce, Bureau of the Census, 1990). Rosamond, located west of EAFB, had a population of about 12,000 in 1989 and about 18,000 in 1990 (Rosamond Chamber of Commerce, oral commun., 1991). The 1990 census figures for the unincorporated community of Boron is 2,101. The military resident population of EAFB is 7,423 (U.S. Department of Commerce, Bureau of the Census, 1990). The employed population of EAFB was about 15,100 during 1989 and 1990 (Cost and Business Management Division of Edwards Air Force Base, written commun., 1990).

The boundaries of EAFB encompass about 470 mi^2. EAFB is operated by the U.S. Air Force Flight Test Center, whose primary mission is to train

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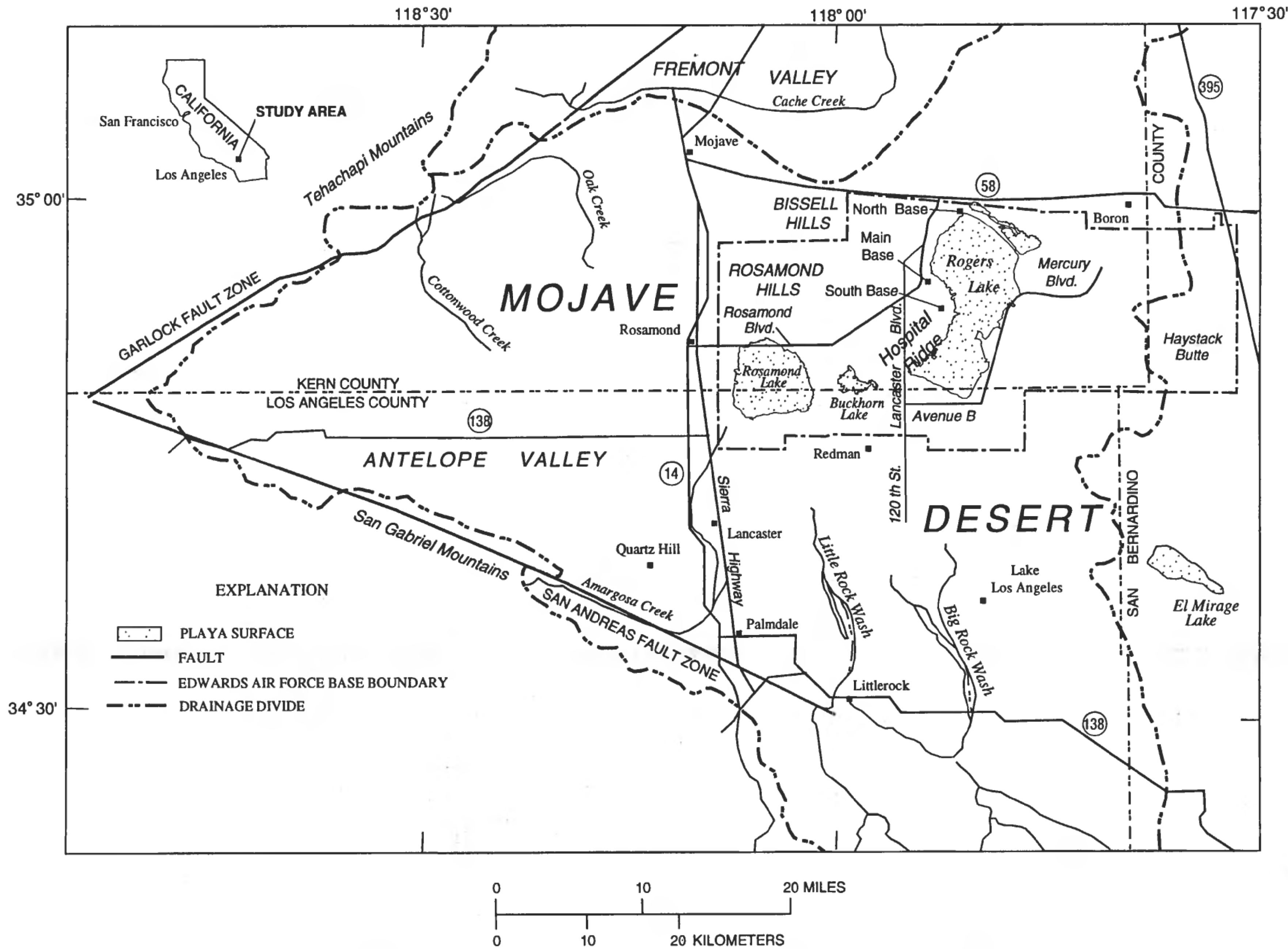

Figure 1. Location of study area.

Air Force flight test personnel and to conduct aviation development through experimental and test flight activities. EAFB is host to several tenant organizations. The National Aeronautics and Space Administration (NASA) operates the Ames-Dryden Flight Research facility at EAFB. Test facilities for the Jet Propulsion Laboratory, the Phillips Laboratory, formerly the Astronautics Laboratory, and the U.S. Air Force Rocket Propulsion Laboratory also are on EAFB. Runways on Rogers Lake are used to stage flight tests and land NASA's space shuttles; the entire lakebed surfaces of Rogers and Rosamond Lakes are designated as emergency landing surfaces.

CLIMATE AND VEGETATION

Antelope Valley is in the rainshadow of the Tehachapi and San Gabriel Mountains (fig. 1) and has a semiarid to arid climate. The average annual precipitation at EAFB is 4.8 in. for the 1933-89 period of record (Larry Plews, Project Manager, Edwards Air Force Base, oral commun., 1990). The total precipitation measured at the Lancaster Flight Service Station was 2.43 in. in 1989 and 1.85 in. in 1990 (National Oceanic and Atmospheric Administration, 1989, 1990). Most of the precipitation in Antelope Valley is in the late autumn and early winter months as a result of low-pressure frontal systems that move inland from the Pacific Ocean. Winter temperatures often cause precipitation to occur in the form of snow. Occasional summer storms occur in the area as a result of warm humid air masses moving northward from the Gulf of California or the Pacific Ocean. However, summer precipitation does not occur in significant quantities to impart a bimodal distribution to the precipitation pattern at EAFB.

Temperature variations at EAFB are characteristic of a desert climate with wide seasonal temperature extremes. During 1989 through 1990, temperatures ranged from the maximum summer high of 110°F to the minimum winter low of 3°F. The average annual temperatures were 62.7°F for 1989 and 61.0°F for 1990 (National Oceanic and Atmospheric Administration, 1989, 1990). Prevailing winds are from the west and southwest and are sustained at times as high as 30 to 40 mi/h, with occasional gusts of 60 to 70 mi/h or more.

The native vegetation throughout EAFB area is dominated by a sparse cover of xerophytes, plants whose root systems normally do not extend to the water table or capillary fringe. The most common of these are creosote bush (*Larrea tridentata*) and big sagebrush (*Artemisia tridentata*), with occasional Joshua trees (*Yucca brevifolia*) and prickly pear cacti (genus *Opuntia*). Vegetation changes at the transition between the coarse bedrock grus of the low-lying interior hills and the finer alluvial fill of the valley floor. Creosote bush generally does not occur below this area; whereas the more alkali tolerant big sagebrush (Meinzer, 1927) is abundant.

There also are some phreatophytes, plants whose roots usually penetrate the water table, such as mesquite (genus *Prosopis*), tamarisk (genus *Tamarix*), saltbush (genus *Atriplex*), and rabbitbrush (genus *Chrysothamnus*). These plants are in areas where the water table is or was near land surface in recent years, in areas of shallow perched water zones, and at dry springs. Playa surfaces and smaller clay pans are devoid of vegetation except where earth fissures and sinklike depressions provide intermittent sources of water by pooling rainfall and runoff.

PREVIOUS STUDIES

The earliest hydrogeologic reconnaissances of Antelope Valley were by Johnson (1911) and subsequently by Thompson (1929). These surveys focused on mapping ground-water resources of Antelope Valley. Their observations of the ground-water levels and the areal extent of flowing wells in Antelope Valley provide a snapshot of the ground-water conditions in Antelope Valley during the early period of ground-water development.

Thayer (1946) mapped the Antelope Valley ground-water-flow system into specific ground-water subbasins based on postulated lateral ground-water-flow boundaries. From 1947 to 1967, additional studies describing the ground-water resources of Antelope Valley and specifically the ground-water resources of EAFB were made by the State of California and the USGS. These studies have been summarized in reports by the California Department of Water Resources (1947), California Department of Public Works, (1955), Snyder (1955), Dutcher and Worts (1963), and Bloyd (1967). The number, size, and boundary locations of the ground-water subbasins originally described by Thayer (1946) were redefined using these studies by the State of California and the USGS.

The general geologic structure of the Antelope Valley was inferred on the basis of a gravity survey of the western Mojave Desert (Mabey, 1960). Geologic mapping of sections of the Antelope Valley was done by Dibblee (1952, 1957, 1958a, 1958b, 1959a, 1959b, 1959c, 1959d, 1960a) and Noble (1953). Dibblee (1960b, 1963) described the surface geology in the area of EAFB and later summarized the geology of Antelope Valley (Dibblee, 1967, 1981).

The USGS studies at EAFB between 1953 and 1969 produced eight data reports documenting ground-water conditions: Moyle (1960), Weir (1962, 1963, 1965), Giessner and Robson (1965), Giessner and Westphal (1966), Tyley (1967), and Koehler (1969). The objectives of these studies at EAFB were to (1) provide for periodic water-level measurements, (2) provide for periodic ground-water-quality analyses to monitor water-quality trends and to determine ground-water circulation patterns, and (3) provide technical advice on ground-water supply to EAFB.

Hughes (1975) evaluated the hydrogeology of the Haystack Butte area on EAFB for the U.S. Air Force Rocket Propulsion Laboratory. The previous studies in Antelope Valley formed the basis for the development and calibration of a mathematical model of the ground-water-flow system (Durbin, 1978). Duell (1987) reviewed the available ground-water-quality data for the Antelope Valley for the purpose of designing a water-quality monitoring network. Land subsidence in the Antelope Valley resulting from ground-water withdrawals for agricultural, municipal, and industrial water use was reported by Lewis and Miller (1968), McMillan (1973), Thomas and Phoenix (1976), Holzer (1984), and Blodgett and Williams (1992). As early as 1947, the California Department of Water Resources (1947), California Department of Public Works (1955) and Snyder (1955) documented that the annual ground-water pumpage in Antelope Valley exceeded the estimated average annual ground-water recharge.

REGIONAL HYDROGEOLOGIC SETTING

GEOLOGY

The Mojave Desert is a wedge-shaped block bounded by the San Andreas Fault Zone and San Gabriel Mountains to the southwest, the Garlock Fault Zone and Tehachapi Mountains to the northwest (fig. 1), and the Colorado River on the east (Hewett, 1954). Uplifts of the San Gabriel and Tehachapi Mountains isolated the Mojave Desert from the Pacific coast and created the interior or closed drainage basins of the western Mojave Desert.

Antelope Valley overlies three large sediment filled structural basins, which are separated by areas of extensively faulted, elevated bedrock (Dibblee, 1967) (fig. 2). These basins are the result of two periods of deformation (Burchfiel and Davis, 1981; Dibblee, 1981). The first of these was a period of crustal extension that occurred about 32 million years ago during the Tertiary Period and created structurally closed basins. The second period of deformation superimposed predominantly northwest-trending right-lateral faulting over the northeast-trending faults of the Basin and Range topography (Dokka, 1986, 1989; Glazner and others, 1989; Bartley and others, 1990) and ended about 700,000 years ago (Bortugno and Spittler, 1986).

EAFB overlies parts of two of these structural basins, the East Antelope basin and the Kramer basin (fig. 2). These basins have been filled to depths of more than 5,000 and 2,000 ft, respectively, with Tertiary and Quaternary sediments eroded from the adjacent bedrock highlands (Benda and others, 1960; Mabey, 1960). Borehole and gravity data indicate that the depth of fill in the East Antelope Basin could be as much as 10,000 ft (Mabey, 1960).

FAULTS

Strike-slip and normal faults are the major structures in the western part of the Mojave block with some minor, localized folding. The San Andreas and Garlock Faults are currently active, strike-slip faults. The San Andreas is a 1-mile wide, right-lateral, northwest-trending fault zone separating the Mojave Desert and the San Gabriel Mountains. The Garlock is a 1- to 2-mile wide, high-angle, left-lateral, northeast-trending fault zone, extending to the northeast about 250 mi from its junction with the San Andreas Fault (fig. 2).

Major fault traces of the Mojave Desert that extend into EAFB area include the Willow Springs, El Mirage, Blake Ranch, Spring, Kramer Hills, and Muroc Faults, an unnamed fault separating the Rosamond and Bissell Hills, and an unnamed inferred fault beneath Rosamond Lake (fig. 2). All the faults at some location along their trace display evidence of

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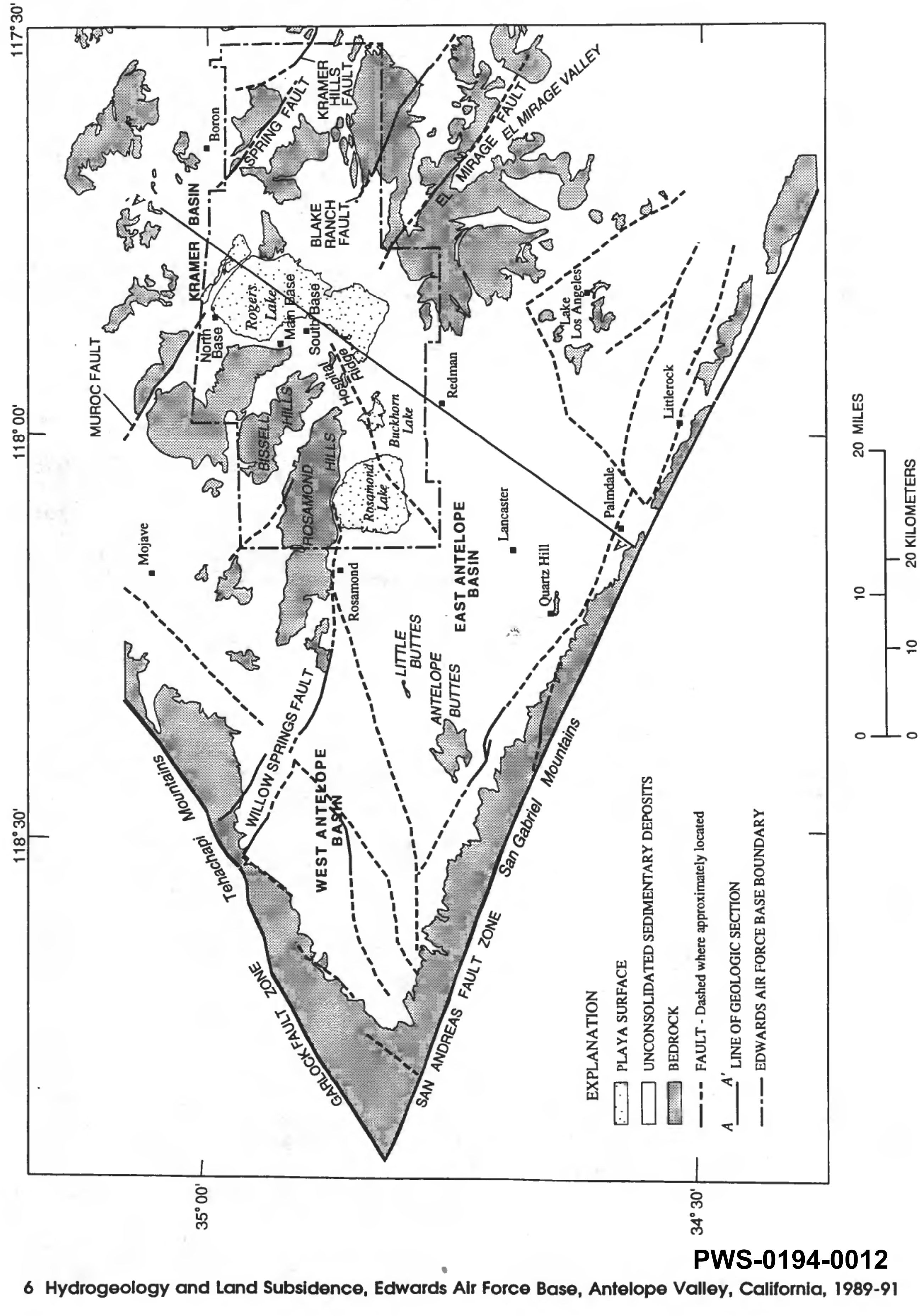

Figure 2. Generalized surficial geology and major faults in Antelope Valley. Modified from Mabey (1960) and Bloyd (1967).

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Quaternary displacement. The Willow Springs Fault, also known as the Rosamond Fault, is described by Dibblee (1963) as an east-west-trending, normal fault, much of which is buried under alluvium along the southern edge of the Rosamond Hills. The El Mirage, Blake Ranch, Spring, Kramer Hills, and Muroc Faults are northwest-trending, right-lateral faults. The El Mirage Fault crosses the hills southeast of Rogers Lake and extends into the upper limits of the alluvial fan above the lake (Dibblee, 1960b). The Blake Ranch Fault is northeast of and subparallel to the El Mirage Fault (Dibblee, 1960b). The Spring and Kramer Hills Faults are in the northeast section of EAFB (Dibblee, 1960b). The Muroc Fault is northwest of Rogers Lake (Dutcher and Worts, 1963). Movement on the Kramer Hills, Spring, and Blake Ranch Faults has occurred within the past 2 million years, and on the El Mirage Fault within the past 700,000 years (Bortugno and Spittler, 1986). The existence of an unnamed fault buried beneath Rosamond Lake along the northwest flank of the East Antelope structural basin was inferred by Mabey (1960) on the basis of gravity and borehole data. A northeast extension of the fault (fig. 2), as originally mapped, is inferred on the basis of additional surface-geophysical data, and hydrogeologic information.

STRATIGRAPHY

The bedrock complex on and near EAFB consists of pre-Cenozoic igneous rocks and consolidated Tertiary sedimentary rocks (Hewett, 1954; Dibblee, 1963). Quartz monzonite is the predominant igneous rock type exposed in the hills at EAFB (Dibblee, 1960b, 1963). The sedimentary series of rocks of Tertiary age generally consists of well-indurated volcano-clastic flows and fluvial-lacustrine sediments (Dibblee, 1963). In the few local outcrops, the Tertiary sediments form very resistant hills or ridges. The existence of Tertiary sedimentary rocks in the subsurface in the basins has been interpreted from seismic-reflection data (Cheadle and others, 1986).

A series of unconsolidated deposits of Quaternary age overlie the consolidated rocks. These deposits are the result of rapid uplift and erosion of the San Gabriel and Tehachapi Mountains during a wet, pluvial climate. Dutcher and Worts (1963) mapped these deposits as either alluvial or lacustrine, based on the mode of deposition. The alluvium is composed of unconsolidated to moderately indurated, poorly sorted gravel, sand, silt, and clay. Older units within the alluvium are typically more compacted and indurated than the younger units (Dutcher and Worts, 1963; Durbin, 1978). The lacustrine deposits are composed of fine-grained sands, silts, and clays that accumulated in a relatively large lake or marsh that at times covered large parts of the Antelope Valley (Dibblee, 1967). These lacustrine deposits consist primarily of thick layers of blue-green silty clay and a brown clay containing interbedded sand and silty sand layers. The brown clay generally overlies the blue-green clay. The transition from blue-green to brown clay may represent a change in the depositional environment from relatively deep water to shallow, intermittent submergence (Dutcher and Worts, 1963). Individual clay beds are locally as much as 100 ft thick and are interbedded with lenses of coarser material as much as 20 ft thick. The lacustrine deposits are believed to be transgressive from south to north, across Antelope Valley, lapping northward onto the older alluvium and in turn being overlapped from the south by younger alluvium (Dutcher and Worts, 1963) (fig. 3). Near the southern limit of the valley, the lacustrine deposits are buried beneath as much as 800 ft of alluvium, but near the northern limit the lacustrine deposits are exposed at land surface.

The most prominent surface features on EAFB are the lacustrine deposits that form the playa surfaces of Rogers, Rosamond, and Buckhorn Lakes. Rogers Lake is the largest of the three playas covering an area of about 46 mi^2 near the geographic center of EAFB. The playa surfaces consist of very fine-grained lacustrine sediments. Particle-size analysis of material obtained from the surface of Rogers Lake indicates that 85 percent of the particles are finer than 7.9×10^{-5} in., which is in the range of clay-sized particles. Montmorillonite and illite clays are predominant in the near surface of Rogers and Rosamond Lakes (Droste, 1961; Neal and others, 1968). Motts and Carpenter (1970) reported that surface clay deposits extend more than 75 ft beneath the southern part of the lake and 45 ft beneath the northern part of the lake on the basis of data from 14 test holes drilled on Rogers Lake. Near the center of Rogers Lake, the clay beds thin to a depth of 25 ft. According to Motts and Carpenter (1970), the relatively thin surface clay layer overlies a thick sequence of sand, which overlies a fanglomerate.

Motts and Carpenter (1970) reported a 200-foot thick sequence of clay beneath Rosamond Lake. The thickening of the clay from Rogers to Rosamond Lake is accompanied by an increase in the amount of

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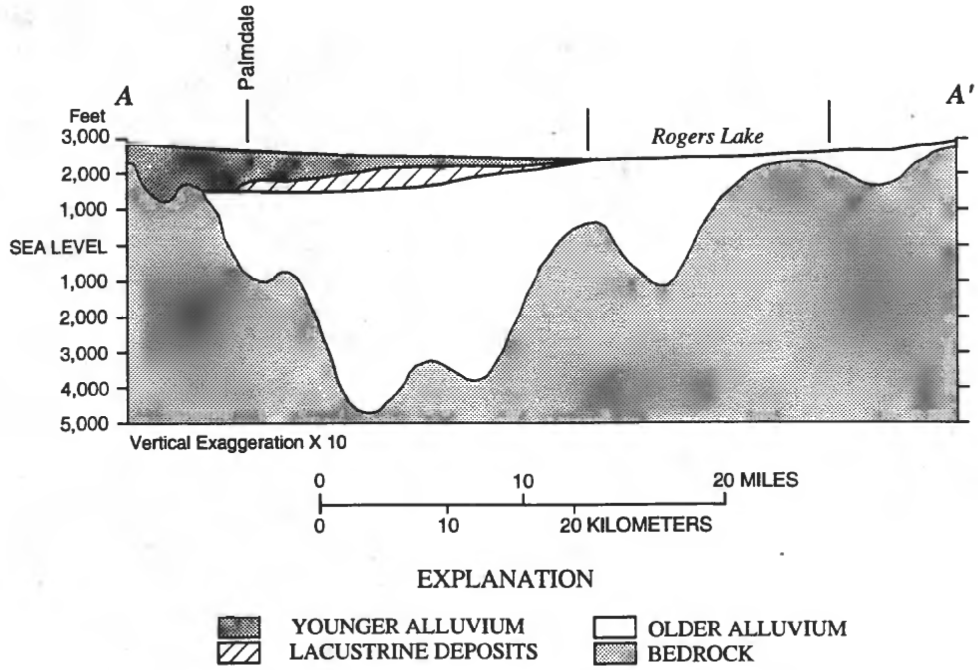

Figure 3. Generalized geologic section showing relation of lacustrine deposits to younger and older alluvium. Line of section is shown on figure 2.

blue-green clay. Motts and Carpenter (1970) attribute the increase in blue-green clay and the preservation of unaltered pollen samples to deposition under deep-water reducing conditions in the area of Rosamond Lake. Depths of the playa and lacustrine clays of Buckhorn Lake are unknown, and neither clay mineralogical information or pollen analysis are available.

Coarser grained alluvial deposits of sand, gravel, and cobbles and some silt form bajadas that skirt all the highlands near the playas. South of Buckhorn and Rosamond Lakes is a broad, sandy alluvial plain that grades gradually into the alluvial fans extending from the San Gabriel Mountains 18 mi to the south. To the west of Rosamond Lake, this plain extends 20 mi to EAFB of the Tehachapi Mountains.

AQUIFER SYSTEM

Previous investigators have defined two major ground-water-flow systems in the western Mojave Desert associated with Antelope Valley and Fremont Valley. Thayer (1946) mapped the Antelope Valley area into a series of ground-water subbasins bounded laterally by faults, consolidated rock, ground-water divides, and in some instances by arbitrary boundaries. Bloyd (1967) refined Thayer's subbasin maps on the basis of additional information, retaining the original names of the subbasins wherever possible (fig. 4). Bloyd's boundaries are the boundaries referred to in this report. EAFB overlies the Lancaster and North Muroc ground-water subbasins. The Lancaster subbasin is the largest and currently the most developed ground-water resource in Antelope Valley.

The aquifer system in the Lancaster subbasin consists of two alluvial aquifers known as the principal aquifer and the deep aquifer (Dutcher and Worts, 1963; Bloyd, 1967; Durbin, 1978). Both aquifers consist of interbedded heterogeneous mixtures of silt, sand, and gravel. The principal aquifer is unconfined and overlies lacustrine clay deposits within the sediments. This aquifer extends over most of the Lancaster subbasin south and southwest of Rogers Lake and provides most of the ground water pumped in Antelope Valley. The deep aquifer underlies the lacustrine clay beds and extends beneath Rogers Lake to the North Muroc subbasin. This aquifer is confined where overlain by the lacustrine deposits and unconfined elsewhere. Where unconfined, the deep aquifer grades upwards into the alluvium of the principal aquifer. The grading of the two aquifers provides a direct hydraulic connection between the two aquifers along the southern, western, and northeastern margins of the Lancaster subbasin

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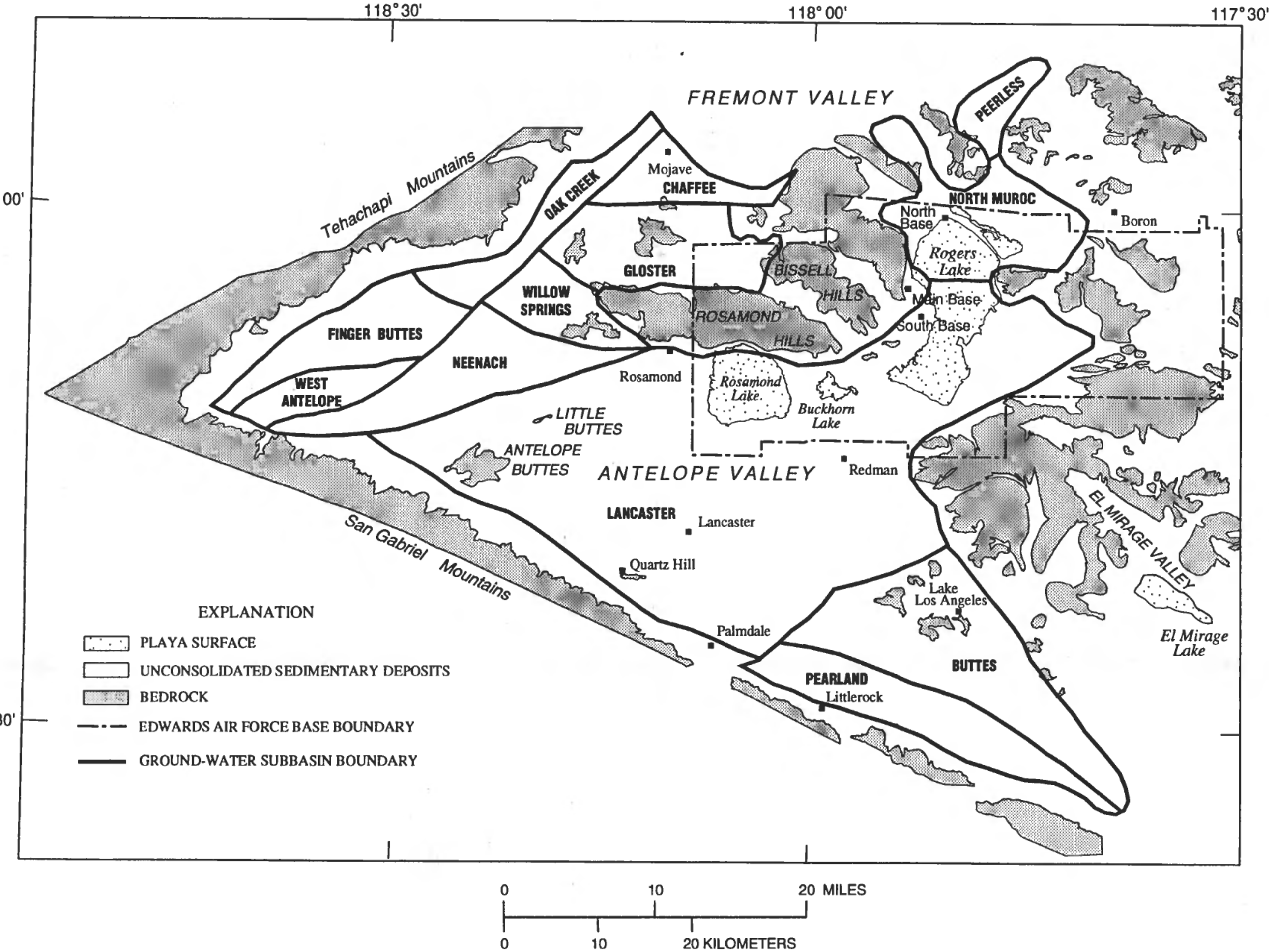

EXPLANATION

- PLAYA SURFACE
- UNCONSOLIDATED SEDIMENTARY DEPOSITS
- BEDROCK
- EDWARDS AIR FORCE BASE BOUNDARY
- GROUND-WATER SUBBASIN BOUNDARY

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Figure 4. Ground-water subbasins in Antelope Valley (from Bloyd, 1967).

(Thompson, 1929). The deep aquifer is presumed to be underlain by low-permeability, consolidated sedimentary, and igneous rocks.

Ground water in the Antelope Valley area originates primarily from precipitation in the San Gabriel and Tehachapi Mountains. A portion of the surface runoff from precipitation infiltrates into the aquifer system at EAFB of the mountains and along the courses of the major stream channels extending onto the valley floor. Estimates of natural average annual recharge to the Antelope Valley ground-water basin range from 40,280 to 81,400 acre-ft (table 1) and are based on estimates of surface-water discharge from the surrounding mountains. The more recent estimates of Bloyd (1967) and Durbin (1978) probably are more representative of the actual recharge because they are based on longer term discharge and climatological data. Bloyd (1967) estimated the annual recharge rate for all ground-water subbasins in the Antelope Valley to be 58,000 acre-ft (fig. 4), however, Durbin (1978) only included those subbasins south and east of the Rosamond Hills (fig. 4) in his estimate of 40,700 acre-ft. Duell (1987) showed that most of the ground water north of the Rosamond Hills discharges northward from the Antelope Valley directly into the Fremont Valley and, therefore, is not available for use in either the Lancaster or North Muroc subbasins.

Prior to extensive ground-water development in Antelope Valley, ground water in the principal aquifer moved from the recharge areas near the mountain fronts toward the north central part of the valley where it was discharged by springs and evapotranspiration. Before the 1940's, ground water in the deep aquifer moved northward under the lacustrine deposits and Rogers Lake, and eventually was discharged from the Lancaster subbasin into the North Muroc subbasin (Durbin, 1978) (fig. 4). Data from recent gravity studies indicate the presence of a notch within the bedrock buried beneath the lakebed sediments at the north end of Rogers Lake. This feature may have provided the pass by which ground water, circulating within the Lancaster subbasin, moved into the North Muroc subbasin and then into the Fremont Valley as suggested by Thompson (1929).

With the extensive development of the ground-water system in the valley during the 1950's and 1960's, water levels in the principal aquifer declined to below the threshold level where evapotranspiration losses become significant. Ground-water pumpage became the primary source of discharge from the principal aquifer. This extensive ground-water development also caused changes in the flow patterns of the deep aquifer. Durbin (1978) estimated that by 1961, the direction of ground-water flow out of the northern Lancaster subbasin had been reversed, and that ground water in the deep aquifer flowed toward the major pumping centers in the central part of the subbasin. Movement of ground water between the two aquifers also occurs as leakage through the lacustrine beds and is dependent on the heads in the two aquifers. The water moves from the aquifer with the higher hydraulic head into the aquifer with the lower hydraulic head. Durbin's mathematical model indicated that the direction of leakage was downward from the principal aquifer into the deep aquifer along the western and southern periphery of the lacustrine deposits and upward from the deep aquifer to the principal aquifer in the north-central part of the Lancaster subbasin.

Table 1. Estimates of average annual recharge to Antelope Valley ground-water basin based on estimates of surface-water discharge from the surrounding mountains

[acre-ft, acre-foot; acre-ft/mi^2, acre-foot per square mile; mi^2, square mile]

Average annual recharge (acre-ft)	Surface-water drainage area (mi^2)	Recharge per unit discharge area (acre-ft/mi^2)	Source
81,400	558	146	Wright (1924)
68,800	483	142	Backman (1928)
50,000	558	90	Thompson (1929)
63,000	558	113	California Department of Water Resources (1947)
40,280	497	81	Snyder (1955)
58,000	558	104	Bloyd (1967)
40,700	385	106	Durbin (1978)

The potentiometric surfaces in the spring of 1990 for the Lancaster and North Muroc subbasins are shown in figure 5. Water-level data were collected by the USGS during the spring of 1990 as part of the the Antelope Valley-East Kern Water Agency (AVEK) monitoring program. The wells in figure 5 are shown in table 2 with their respective water-level altitudes. The potentiometric depressions north and east of Little Buttes and south of Redman are similar to those shown by Bloyd (1967) and Duell (1987),

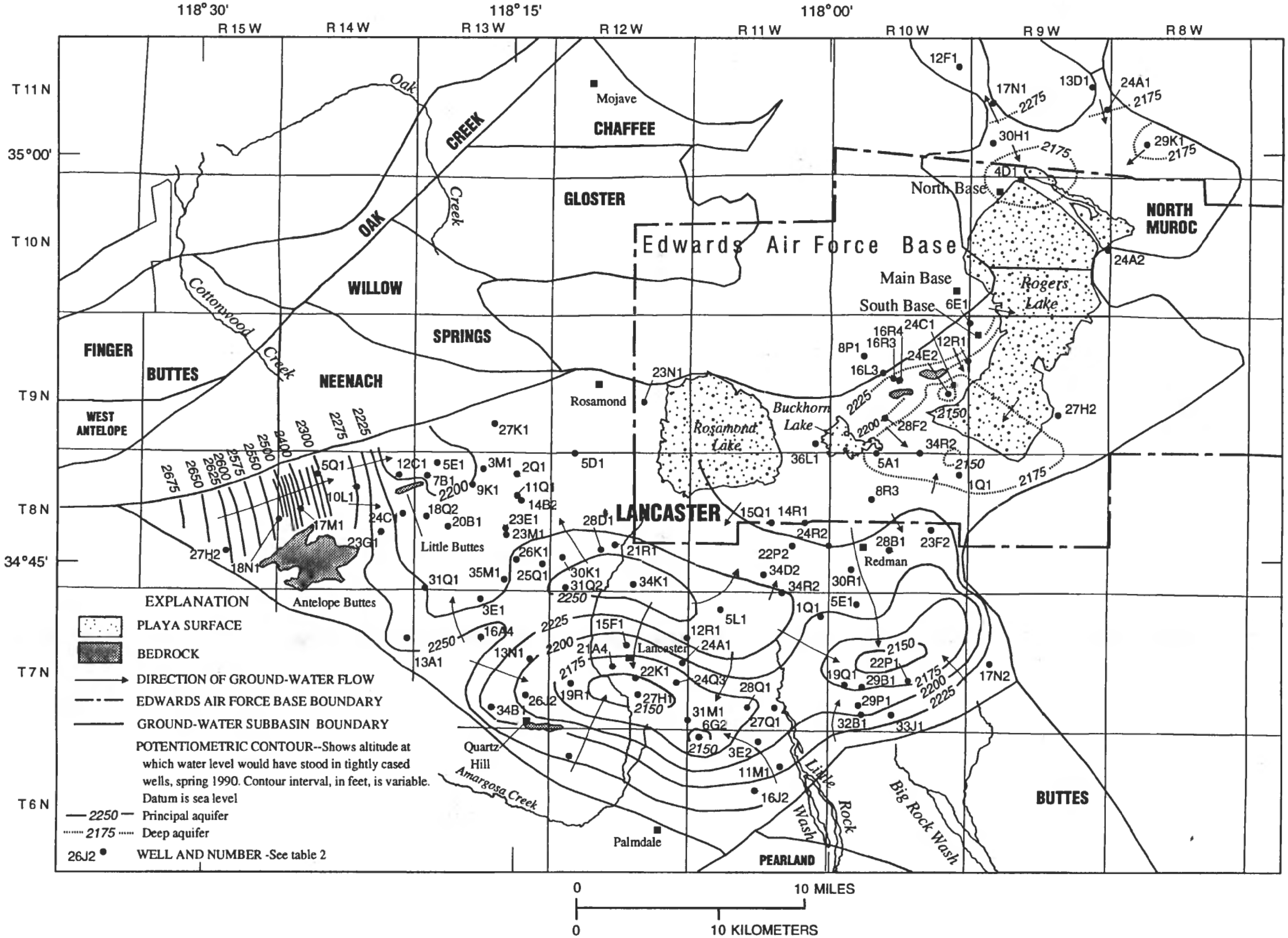

Figure 5. Potentiometric surfaces for the principal and deep aquifers of Lancaster and North Muroc ground-water subbasins spring 1990.

Table 2. Water-level altitudes for selected wells in the Lancaster and North Muroc ground-water subbasins, spring 1990

[Water-level altitudes, rounded to the nearest foot, are calculated from interpolated land-surface altitude from USGS topographic maps in feet above sea level, minus depth to water measured in hundredths of a foot]

State well No.	Water-level altitude	State well No.	Water-level altitude	State well No.	Water-level altitude
6N/11W- 3E2	2,195	8N/10W- 1Q1	2,157	8N/13W- 35M1	2,224
6G2	2,139	5A1	2,159	8N/14W- 5Q1	2,303
11M1	2,222	8R3	2,231	10L1	2,274
16J1	2,233	23F2	2,213	12C1	2,196
6N/12W- 7A1	2,250	28B1	2,207	17M1	2,419
7N/9W- 17N2	2,248	30R1	2,213	18N1	2,531
7N/10W- 5E1	2,217	8N/11W- 14R1	2,231	23G1	2,235
19Q1	2,169	15Q1	2,228	24C1	2,222
22P1	2,161	22P2	2,223	8N/15W- 27H2	2,639
29B1	2,175	24R2	2,229	9N/9W- 6E1	2,241
29P1	2,180	24R3	2,225	27H2	2,190
32B1	2,197	34D2	2,217	9N/10W- 8P1	2,290
33J1	2,217	34R2	2,227	12R1	2,182
7N/11W- 1Q1	2,196	8N/12W- 5D1	2,216	16L1	2,215
5L1	2,232	21R1	2,227	16R3	2,211
27Q1	2,178	28D1	2,249	16R4	2,219
28Q1	2,170	30K1	2,246	24C1	2,173
31M1	2,155	31Q2	2,253	24E2	2,130
33N1	2,175	34K1	2,261	28F2	2,201
7N/12W- 12R1	2,244	8N/13W- 2Q1	2,207	34R2	2,156
15F1	2,166	3M1	2,203	9N/11W- 36L1	2,186
19R1	2,158	5E1	2,198	9N/12W- 23N1	2,223
21A4	2,179	7B1	2,194	9N/13W- 27K1	2,220
22K1	2,149	9K1	2,202	10N/9W- 4D1	2,180
24A1	2,179	11Q1	2,206	24A2	2,210
24Q3	2,165	14B2	2,225	11N/8W- 29K1	2,168
27H1	2,127	18Q2	2,212	11N/9W- 13D1	2,172
7N/13W- 3E1	2,223	20B1	2,207	17N1	2,165
13N1	2,204	23E1	2,208	24A1	2,175
16A4	2,260	23M1	2,218	30H1	2,181
26J2	2,188	25Q1	2,247	36R1	2,192
34B1	2,214	26K1	2,230	11N/10W- 12F1	2,165
7N/14W- 13A1	2,229	31Q1	2,225		

but differ from those of Durbin (1978). Compared to Duell (1987), the more recent data show a steepening cone of depression between Lancaster and Palmdale (fig. 5). A potentiometric high, similar to that shown by Durbin (1978) and Duell (1987), is north of Lancaster at the terminus of Amargosa Creek. This probably is an area of recharge from surface runoff when amounts are significant enough to reach the valley floor. The recent trend of water levels in the area around Redman, an area of historically intensive ground-water pumping for agriculture irrigation, indicates slight recoveries in water levels. In this area, ground water in the principal aquifer flows southward toward an area where ground water is being pumped to supply agriculture irrigation; ground water in the deep aquifer flows northward toward EAFB water-supply wells (fig. 5).

GROUND-WATER USE

Ground-water use in Antelope Valley began in the 1880's (Thompson, 1929; Snyder, 1955) with only a few widely scattered shallow, small-diameter wells. Drilling of large-diameter production wells did not begin until about 1915. Several estimates of ground-water pumpage for Antelope Valley have been made using various indirect techniques (fig. 6). The only systematically measured and recorded pumpage data for the valley has been for EAFB; consequently, records of ground-water pumpage for Antelope Valley are incomplete. In addition, differences in estimates are significant where periods of different indirect techniques or investigators overlap.

Snyder (1955) estimated annual ground-water pumpage for Antelope Valley from 1924 through 1951 on the basis of electric-power consumption. He showed a very rapid increase in pumpage from about 55,000 to 173,000 acre-ft between 1924 and 1930. During the early 1930's, pumpage decreased somewhat and then began to increase rapidly into the 1950's (fig. 6). By 1951, the last year for which he made an estimate, the pumpage had increased to about 401,000 acre-ft. The California Department of Public Works (1955) estimated that ground-water pumpage in 1953 was about 480,000 acre-ft (fig. 6).

Investigators working during the 1970's estimated pumpage on the basis of land use and reported totals for various periods from 1950 to 1975 (fig. 6). The California State Water Resources Control Board (1974) estimated annual pumpage from 1950 through 1971. Their estimates for the early 1950's are considerably less than those of Snyder (1955) and California Department of Public Works (1955) and show a declining trend in pumpage as opposed to the rapidly increasing pumpage estimated by previous investigators. The California Department of Water Resources (K.W. Mido, written commun., 1973) estimated pumpage for 1958 through 1971. These estimates agree somewhat with those of the California State Water Resources Control Board for this period but show a more rapid decline in the annual pumpage. The Antelope Valley-East Kern Water Agency (W.G. Spinarski, written commun., 1976) estimated pumpage for 1974 and 1975. Their estimates were much higher than what would be expected from projecting the estimates of the California State Water Resources Control Board and the California Department of Water Resources. In 1988, pumpage estimates reported to the California Department of Water Resources by Antelope Valley water purveyors was about 62,000 acre-ft (Zettlemoyer, 1990; W.E. Templin, U.S. Geological Survey, written commun., 1991). The decrease in pumpage in Antelope Valley primarily is due to the decrease in irrigated agricultural land use and the import of about 41,000 acre-ft of water from the State Water Project (Zettlemoyer, 1990).

Records of pumpage for EAFB have been kept since 1947 and are documented and analyzed in various reports. Pumpage increased steadily from less than 1,000 acre-ft in 1947 to a high of 6,700 acre-ft in 1965 (fig. 7). From 1966 through 1988, annual pumpage ranged between 3,600 and 6,300 acre-ft/yr (Roy F. Weston, Inc., 1988; fig. 7). Estimates of pumpage data for 1989 and 1990 are about 5,950 and 6,150 acre-ft, respectively (Sergeant Thomison, Edwards Air Force Base, written commun., 1991; Technical Sergeant Swanigan, Edwards Air Force Base, written commun., 1991).

Durbin (1978) estimated that the annual average recharge of ground water to the Antelope Valley aquifers was about 40,700 acre-ft (table 1, fig. 6). On the basis of estimates of ground-water pumpage shown in figure 6, pumpage has exceeded recharge every year since the early 1920's. This imbalance is indicated by the declining water levels that have been recorded in wells throughout the valley. Furthermore, natural springs and a large area of flowing wells in Antelope Valley mapped by Johnson (1911) are not known to exist today.

HYDROGEOLOGIC ASSESSMENT AT EDWARDS AIR FORCE BASE

WELL DRILLING AND CONSTRUCTION

The criteria for selecting sites for the collection of borehole data and the installation of wells were based on the need for information on subsidence, subsurface geology, ground-water levels, and ground-water quality. A total of eight boreholes were drilled using mud-rotary methods during 1989-90, at four cluster sites on EAFB (fig. 8). Lithologic logs were made of the drill cuttings for one borehole at each site and bottom-hole cores were taken from seven of the boreholes. In addition to the drilling at these four sites, EAFB drilled three production wells, using mud-rotary methods, during this period, two in the Graham Ranch well field and one in the South Base well field (fig. 8) to replace production wells that had recently failed due to collapsed well casings. These wells were drilled in locations readily accessible to existing water-supply pipelines.

Construction data for wells completed in 1989 and 1990 on EAFB are summarized in table 3. Single and clustered wells were completed in boreholes at the Buckhorn, Branch Park, Holly, and Graham Ranch sites (fig. 8). Each well was screened and gravel packed; at cluster sites, wells were isolated

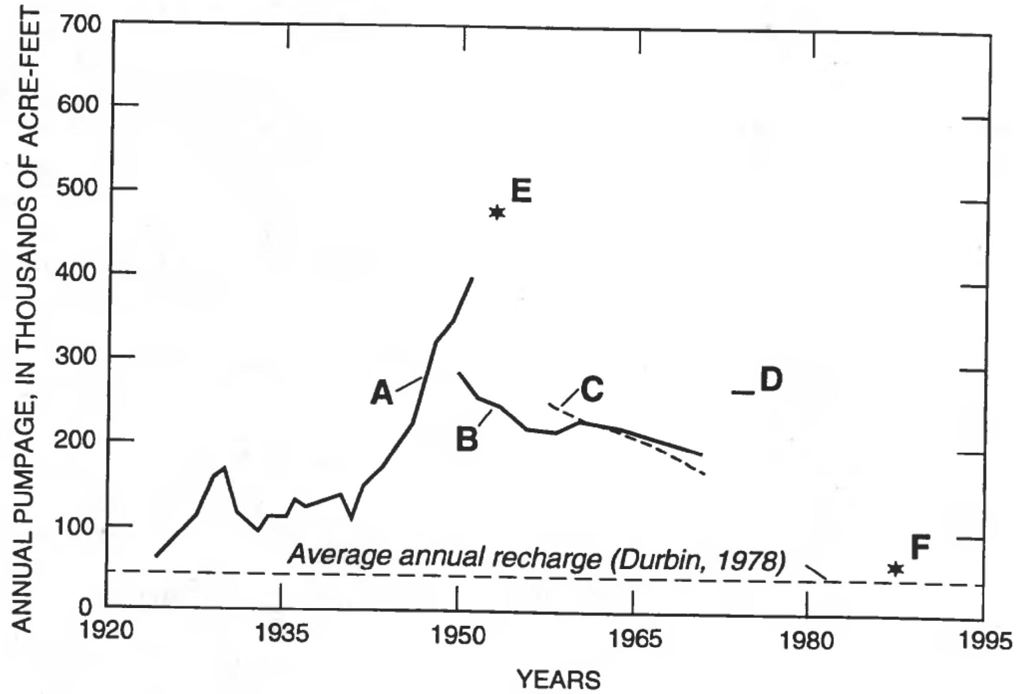

Figure 6. Estimated annual pumpage and average annual recharge for Antelope Valley, 1924-88. *A,* Snyder (1955; *B,* California State Water Resources Control Board (1974); *C,* California Department of Water Resources (K.W. Mido, written commun, 1973); *D,* Antelope Valley-East Kern Water Agency (AVEK) (W.G. Spinarski, written commun., 1976); *E,* California Department of Public Works (1955); *F,* Zettlemoyer (1990). Graph modified from Durbin (1978).

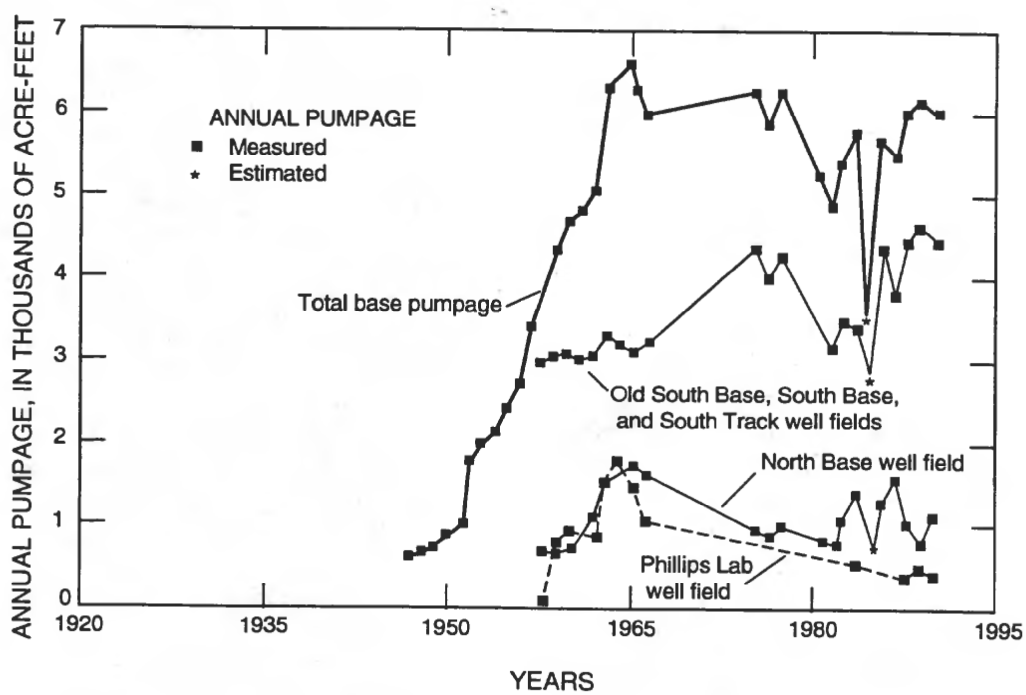

Figure 7. Annual pumpage at Edwards Air Force Base, 1947-90. Modified from Roy F. Weston, Inc. (1988).

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