sounding 56 (fig. 13), penetrate weathered quartz monzonite at an altitude of about 1,000 ft above sea level. Because of the proximity of the alluvium/weathered basement contact to the bottom of the hole, the borehole resistivity survey could not measure the contact. The interpreted geoelectric section indicates that the deep boreholes at the Holly site should have bottomed in the 70 to 100 ohm-m material, which may be consistent with the lithology depending on the interpreted resistivity of weathered quartz monzonite. However, the thick section of low resistivity (less than 15 ohm-m material interpreted in the cross section above an altitude of 1,600 ft) near sounding 56 (fig. 15*D*) does not agree well with the borehole logs, which show a homogeneous clay interval from 2,214 to 2,092 ft above sea level underlain by sands, gravels, and interbedded clays (fig. 9*C*).

The boundary between the granitic bedrock and the overlying sediments is mantled with 70 to 100 ohm-m material suggesting a gradual transition from the more competent, unweathered bedrock through a section of weathered bedrock to the overlying unconsolidated sediments. Other 70 to 100 ohm-m and greater than 100 ohm-m material is near the surface, beneath soundings 30, 43, 44, 17, 27, and 52 (figs. 15*A*, 15*B*, and 15*C*), and is underlain by lower resistivity, 30 to 70 ohm-m material. This gives the appearance that the granitic rock exposed in outcrops on Hospital Ridge do not connect with the bedrock underlying the basin, and supports the inference made from the resistivity profiles that the three northeast-trending topographic ridges, collectively referred to as Hospital Ridge, may be floating blocks of weathered quartz monzonite (Zohdy and Bisdorf, 1990). The 70 to 100 ohm-m material beneath soundings 15 and 28 (fig. 15*C*) may represent buried stream channels (Zohdy and Bisdorf, 1990).

Cross section *E-E′* (fig. 15*D*) also shows a thick section of low resistivity, material (less than 15 ohm-m) extending from west to east up the bedrock slope of the East Antelope structural basin. This is spatially correlated with the less than 15 ohm-m material occurring in cross sections *B-B′* and *C-C′* (figs. 15*A* and 15*B*). The resistivity cross sections, *B-B′* and *C-C′*, delineate the northern part of a lenticular zone of low resistivity, which is between 1,500 and 2,000 ft thick in this section of the basin. The termination of the northern boundary of the zone (fig. 15*A*) suggests that the associated deposits may be related to the inferred fault (fig. 2) or faults striking about N. 50° to 60° E. forming the northern boundary of the East Antelope structural basin in this area. Zohdy and Bisdorf (1990) suggest two possibilities for this zone: (1) the zone predominantly consists of clay beds with some clean sand and gravels interbedded within the clays or (2) the zone may consist of a number of sand and gravel beds containing brackish to saline ground water. An overlying, 15 to 30 ohm-m material thins eastward beyond sounding 58, and extends northward as far as sounding 41 (figs. 15*B* and 15*D*). The 30 to 70 ohm-m material, indicative of coarse-grained material and a potential ground-water resource, is widely distributed at depths less than 700 ft. A 4,000-foot thick section of these sediments is near soundings 51 and 42 (figs. 15*A* and 15*B*).

WATER-LEVEL MEASUREMENTS

Ground-water levels are routinely measured on an annual or semiannual basis in 19 wells (fig. 16) on EAFB as part of the Antelope Valley-East Kern Water Agency (AVEK) ground-water monitoring program. Long-term hydrographs for 16 of these wells (figs. 16, 17*A-B*, 17*E-H*, 17*J-S*) show a general long-term downward water-level trend from 1947 to 1990. The rates and amounts of these declines vary greatly for the area of EAFB. The largest documented declines were in well 9N/10W-24C1 (figs. 16 and 17*K*), where short-term declines of as much as 180 ft have been recorded and there has been a general long-term decline of about 90 ft (fig. 17*K*). Hydrographs for two of the wells, 8N/11W-14R1 and 8N/11W-15Q1 (figs. 16, 17*C*, and 17*D*), show a slight long-term increase in water levels. The water table in these wells is perched from the deeper water table by a thick sequence of clay (Dutcher and others, 1962). The hydrograph for well 9N/10W-8P1 (figs. 16 and 17*I*) shows very little water-level change over the period of record and may be isolated from the rest of the basin.

At the Holly site (fig. 8), two distinct potentiometric surfaces are separated by a thick lacustrine unit. The water level in well 8N/10W-1Q4, which is completed above the lacustrine unit, is at an altitude of about 2,249 ft and shows very little fluctuation, except for a slight downward trend from May 1990 to November 1991 (fig. 18*A*). In wells 8N/10W-1Q1, 1Q2, and 1Q3, which are completed below the lacustrine unit, the water-level altitudes fluctuated from a low of about 2,152 ft to a high of about 2,164 ft during this same period (fig. 18*B*).

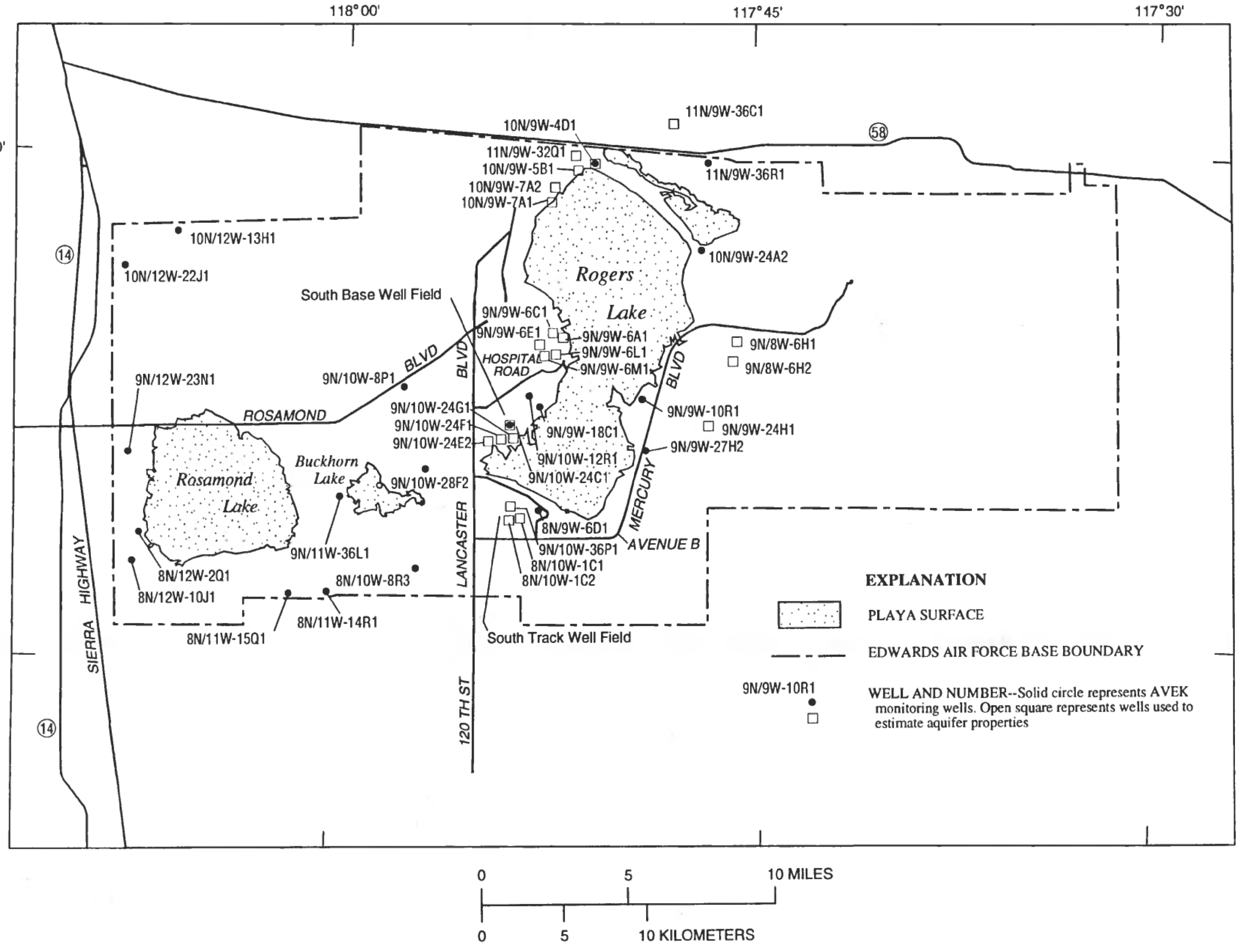

Figure 16. Location of wells routinely monitored by the U.S. Geological Survey as part of the Antelope Valley-East Kern Water Agency (AVEK) monitoring program and location of wells used to estimate aquifer properties on Edwards Air Force Base.

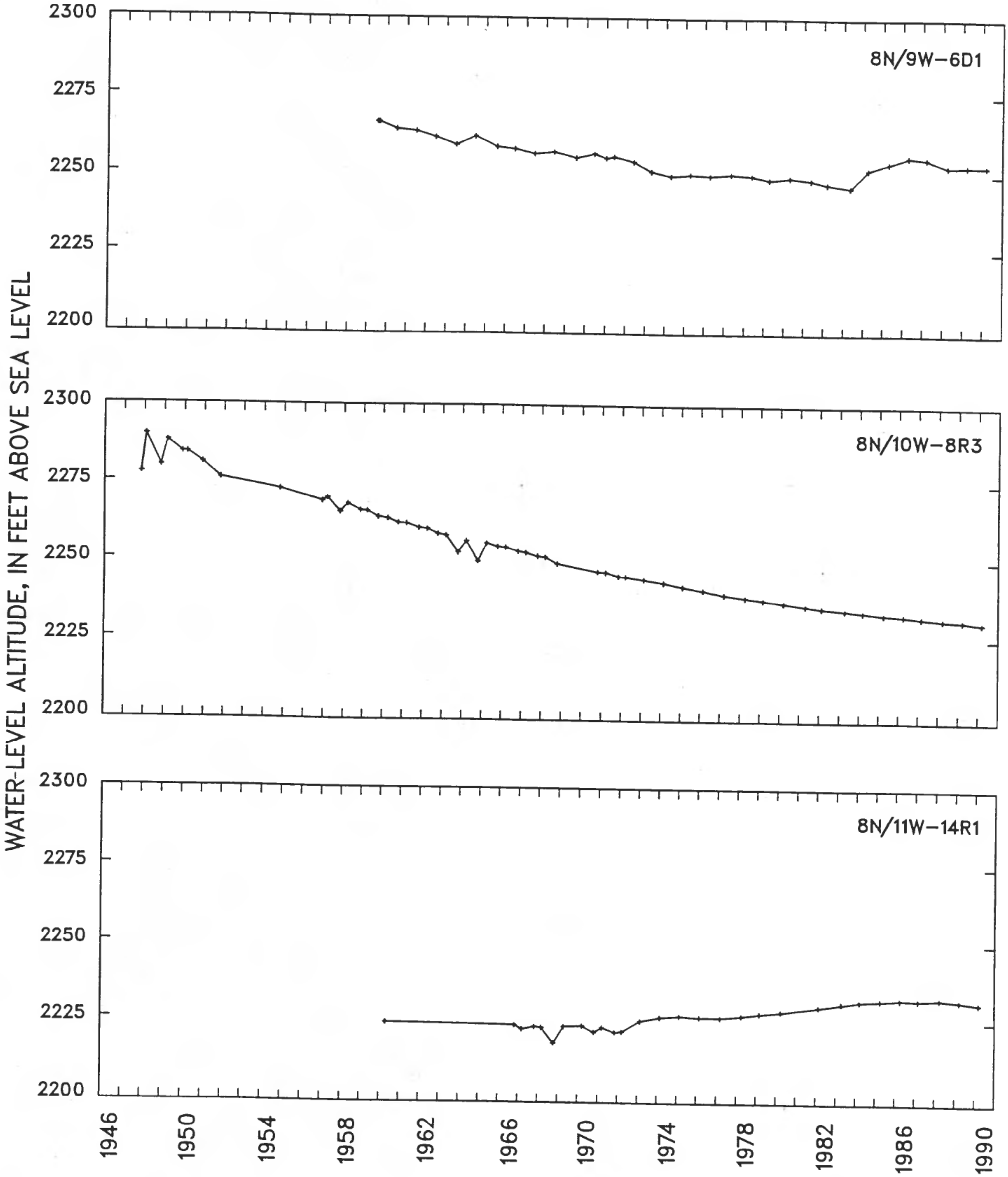

Figure 17. Water levels monitored by U.S. Geological Survey as part of the Antelope Valley-East Kern Water Agency (AVEK) monitoring program for wells on Edwards Air Force Base, 1947-90. Location of wells are shown on figure 16.

PWS-0194-0058

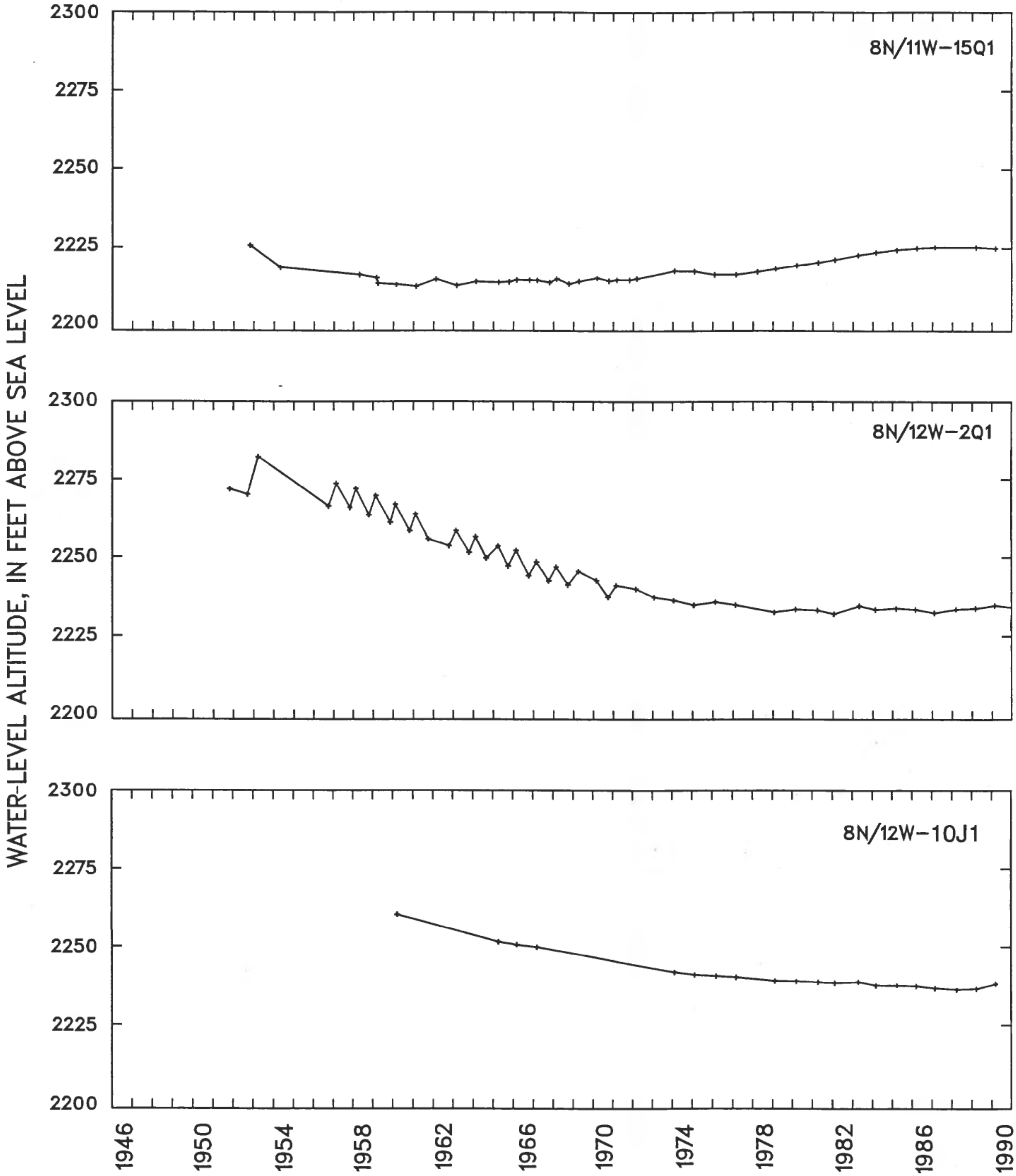

Figure 17. Water levels monitored by U.S. Geological Survey as part of the Antelope Valley-East Kern Water Agency (AVEK) monitoring program for wells on Edwards Air Force Base, 1947-90--*Continued.*

PWS-0194-0059

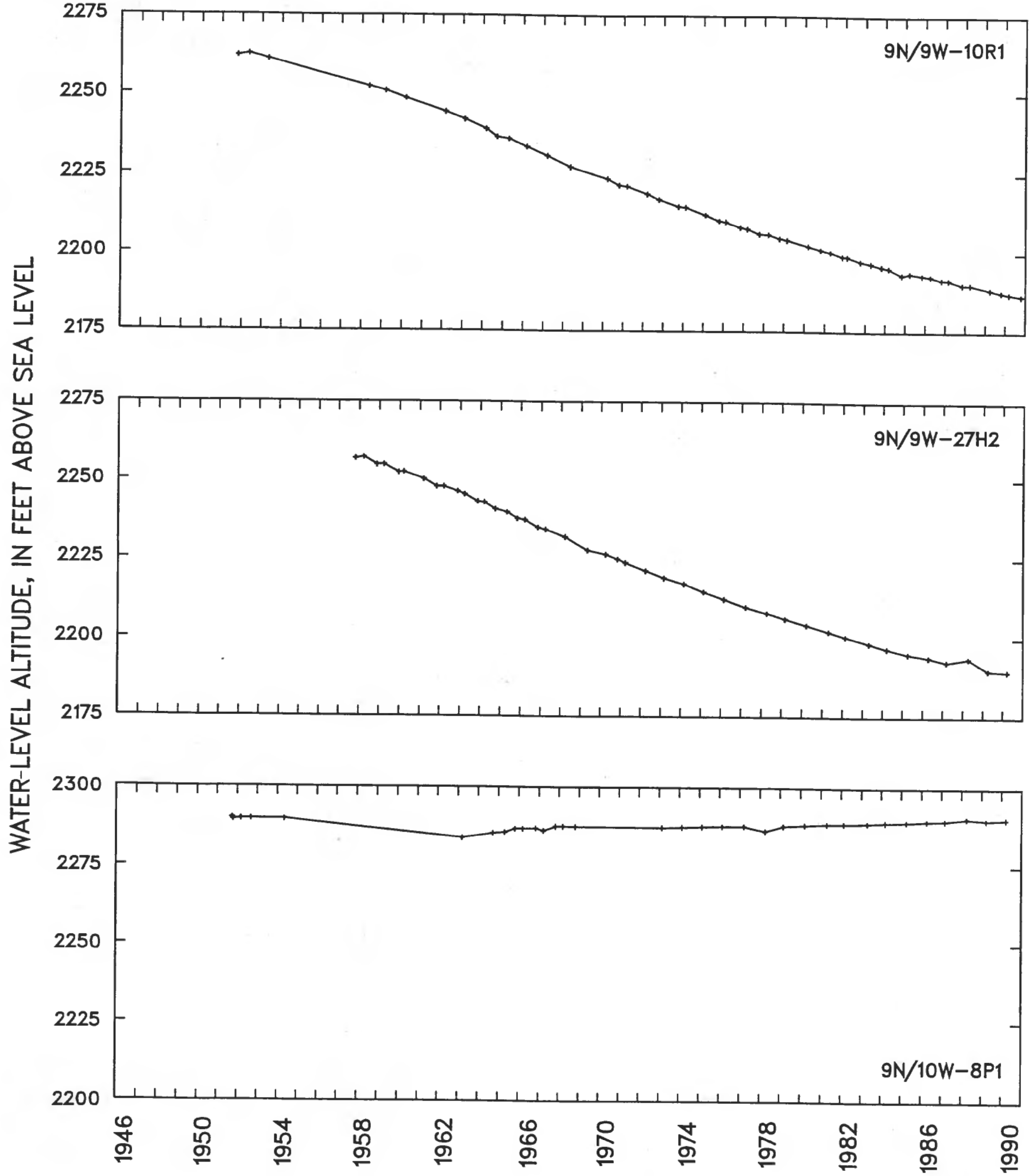

Figure 17. Water levels monitored by U.S. Geological Survey as part of the Antelope Valley-East Kern Water Agency (AVEK) monitoring program for wells on Edwards Air Force Base, 1947-90--*Continued.*

PWS-0194-0060

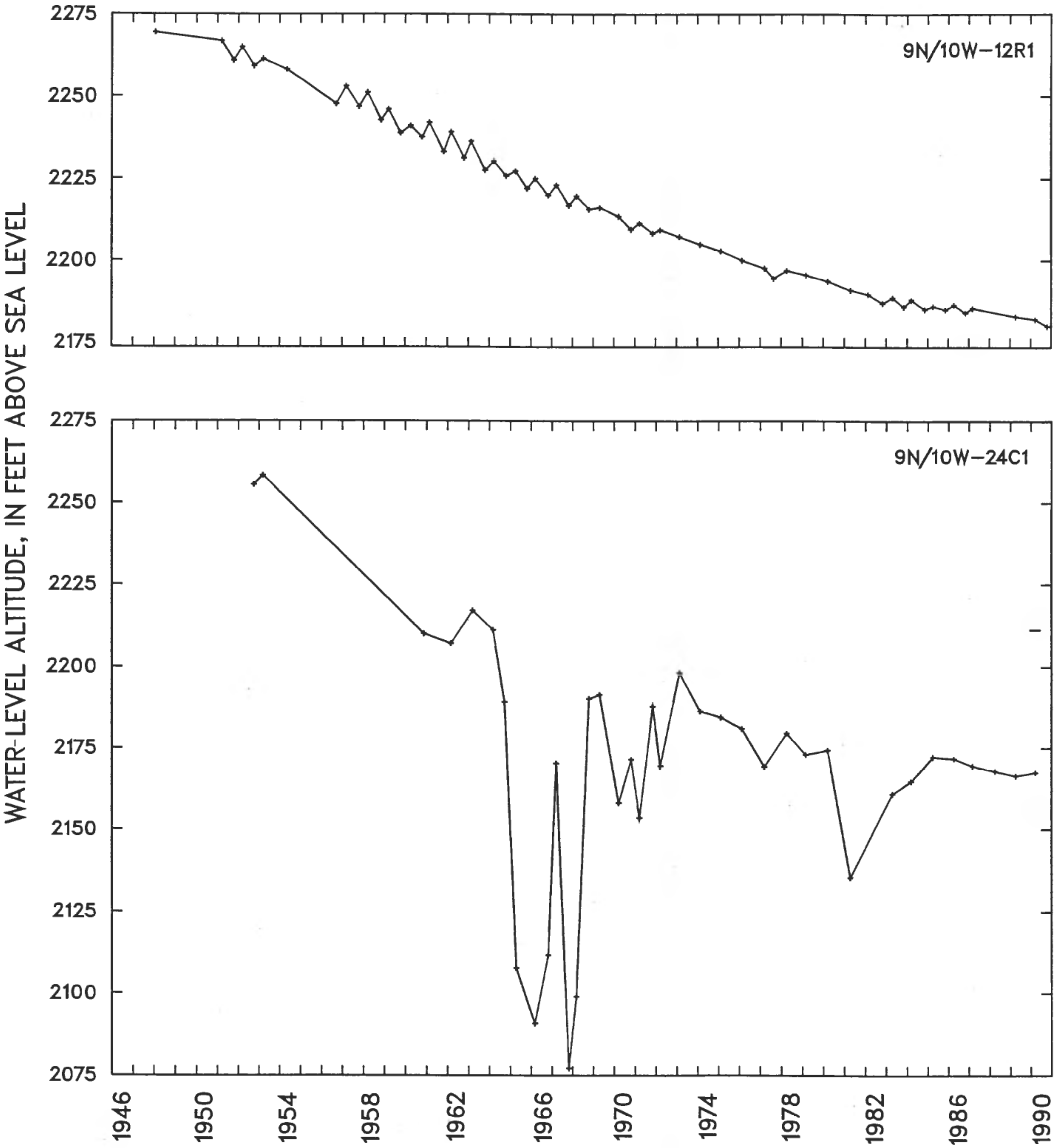

Figure 17. Water levels monitored by U.S. Geological Survey as part of the Antelope Valley-East Kern Water Agency (AVEK) monitoring program for wells on Edwards Air Force Base, 1947-90--*Continued.*

PWS-0194-0061

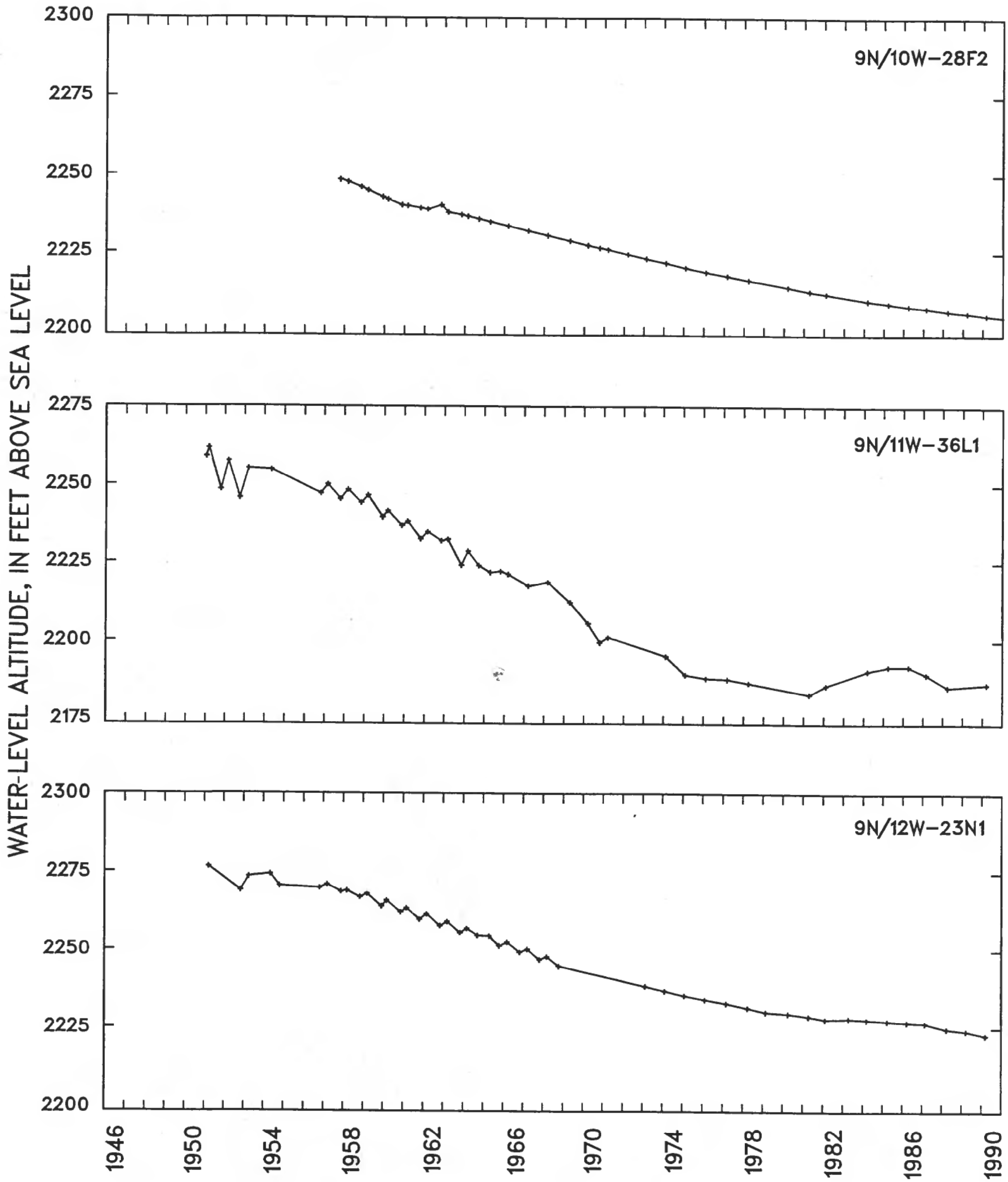

Figure 17. Water levels monitored by U.S. Geological Survey as part of the Antelope Valley-East Kern Water Agency (AVEK) monitoring program for wells on Edwards Air Force Base, 1947-90--*Continued.*

PWS-0194-0062

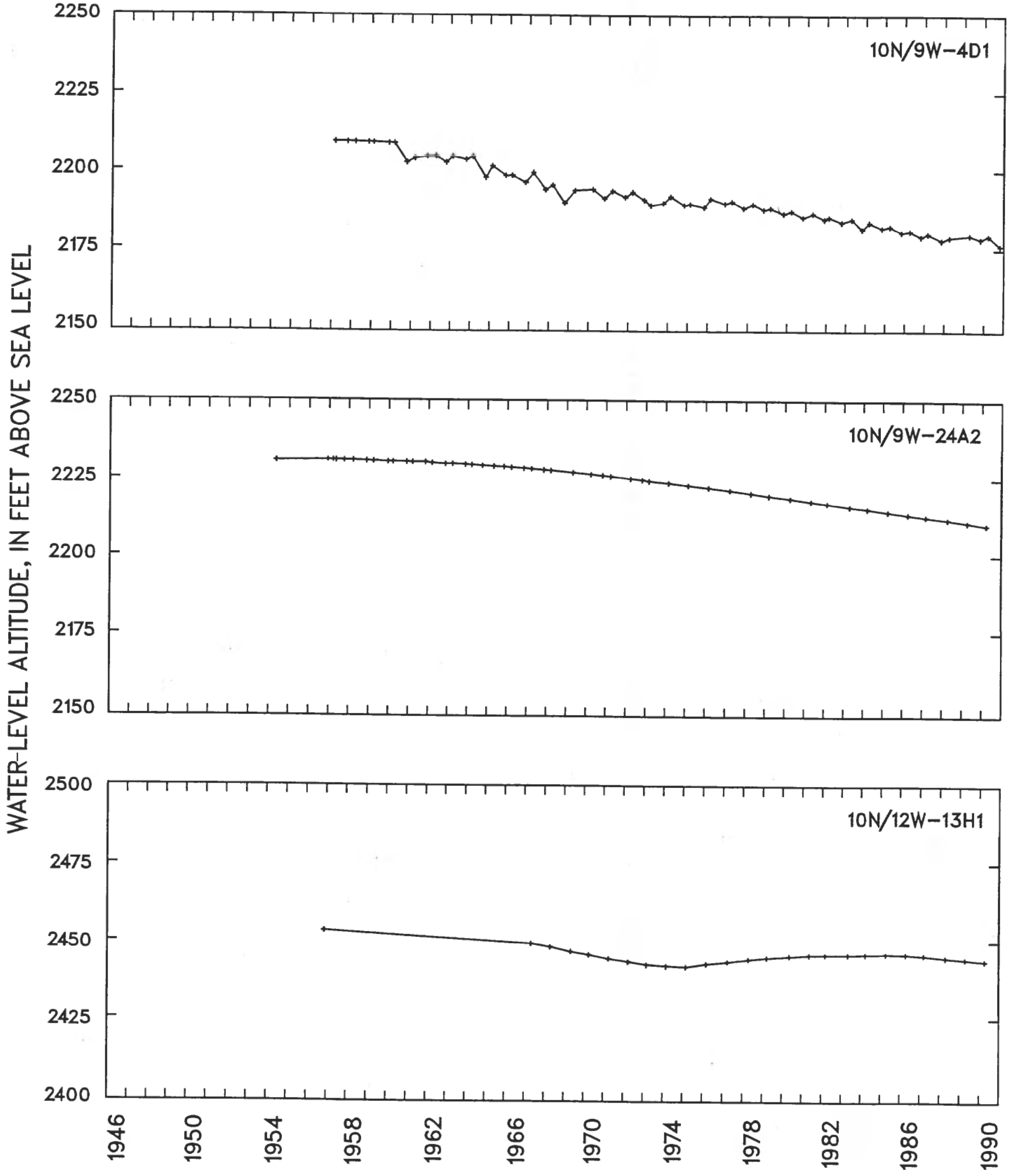

Figure 17. Water levels monitored by U.S. Geological Survey as part of the Antelope Valley-East Kern Water Agency (AVEK) monitoring program for wells on Edwards Air Force Base, 1947-90--*Continued.*

PWS-0194-0063

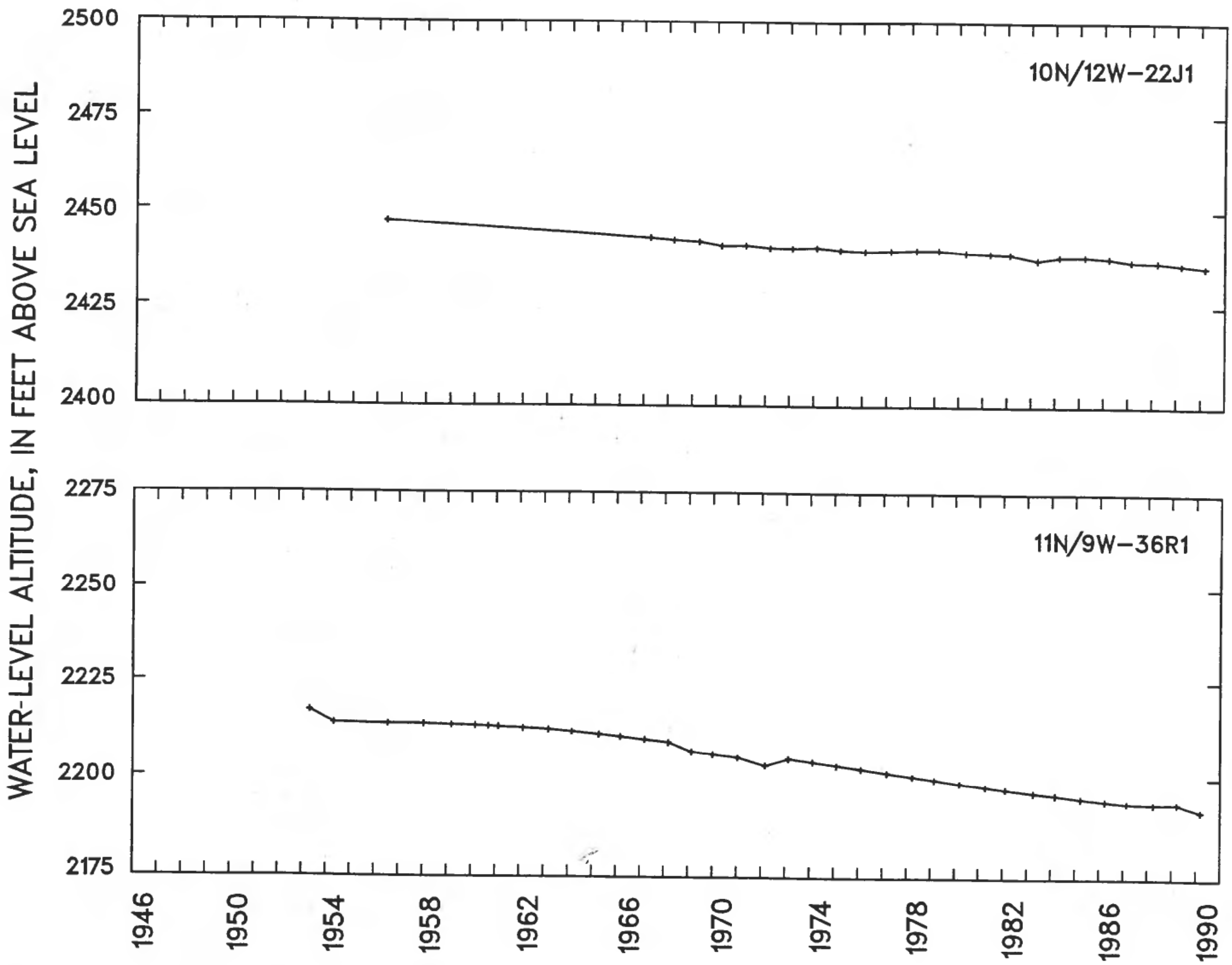

Figure 17. Water levels monitored by U.S. Geological Survey as part of the Antelope Valley-East Kern Water Agency (AVEK) monitoring program for wells on Edwards Air Force Base, 1947-90--*Continued.*

Water-level differences in the deeper wells (fig. 18*B*) show fluctuating responses to seasonal pumping stresses associated with production from the South Track well field (fig. 8). Monthly water-level changes in wells 8N/10W-1Q2 and 1Q3 are coincident, but 1Q3 has a slightly higher level, suggesting a hydraulic connection with high vertical connection within the 425- to 640-foot interval. Water-level changes in well 8N/10W-1Q1 generally are smaller than those of 8N/10W-1Q3. This may be due to the increased consolidation of the deeper alluvium and consequent decreased ground-water yield to the production wells with depth.

GROUND-WATER CHEMISTRY

During the spring of 1990, 14 ground-water samples were collected in the Rogers Lake area to determine concentrations of major ions and trace elements. These samples were collected from 10 of the new test wells drilled during 1989 and 1990 and from four base supply wells around the perimeter of the lake (fig. 19). The results of these analyses (table 6) indicate that the ground water near Rogers Lake ranges from soft to moderately hard (Hem, 1985, p. 159), and commonly has a high dissolved-solids concentration (greater than 500 mg/L). These

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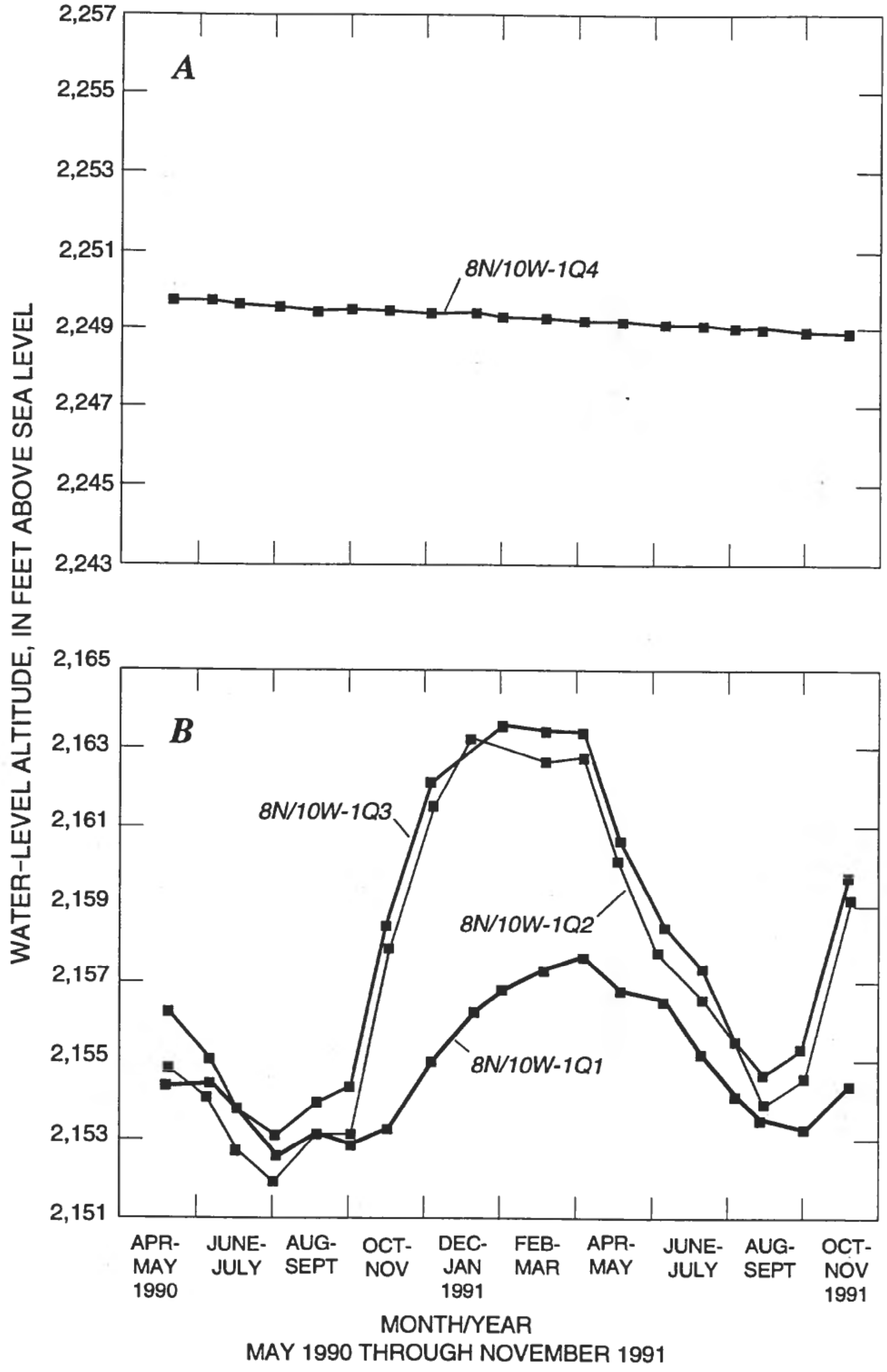

Figure 18. Water levels for wells at the Holly site on Edwards Air Force Base. *A.* Well 8N/10W-1Q4. *B.* Wells 8N/10W-1Q1-3.

analyses also indicate that, except for well 8N/10W-5A1 at the Buckhorn site (fig. 19), the concentrations of most determined constituents are less than the U.S. Environmental Protection Agency (EPA) primary and secondary drinking-water regulations for maximum contaminant levels (table 6). The only other exception was the high concentrations of fluoride in samples from the two deeper wells at the

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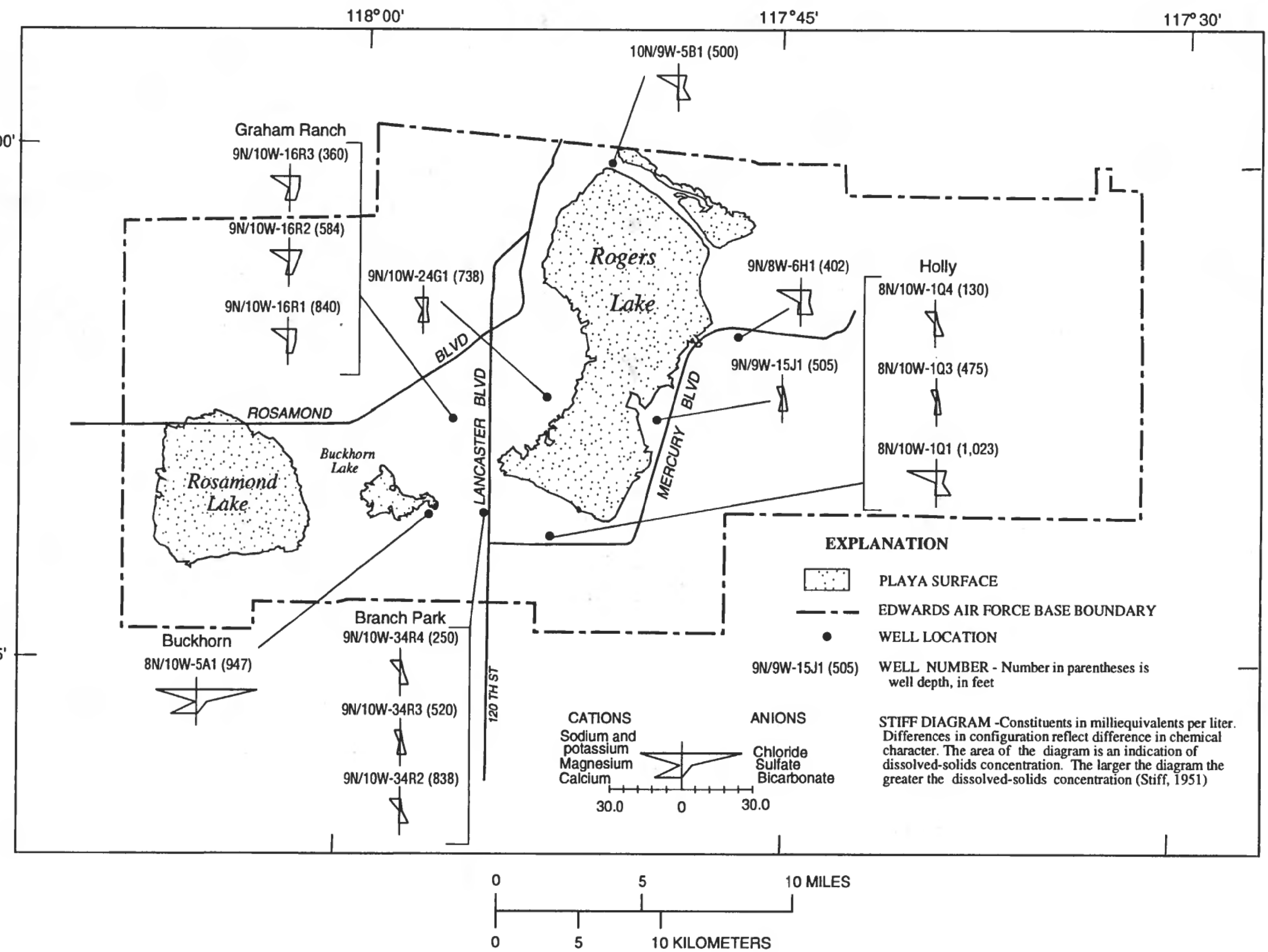

Figure 19. Ground-water quality for the Rogers Lake area on Edwards Air Force Base.

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Table 6. Summary of water quality for selected wells on Edwards Air Force Base

[State well No.: See Well-Numbering System in text. USGS, U.S. Geological Survey. USGS site identification No.: Unique number for each site based on the latitude and longitude of the site. First six digits are latitude, next seven digits are longitude, and final two digits are a sequence number to uniquely identify each site. Depth of well: Depth is in feet below land surface. Altitude of land surface in feet above sea level, rounded to nearest foot. ft, foot; mg/L, milligram per liter; --, no data; µg/L, microgram per liter; µS/cm, microsiemen per centimeter (at 25 degrees Celsius); °C, degree Celsius; <, actual value is less than value shown]

State well No.		Local well name	USGS site identification No.	Date	Time	Depth of well	Altitude of land surface	Specific conductance (µS/cm)	pH (standard units)	Temperature, water (°C)
EPA drinking-water regulations								--	[1]6.5-8.5	--
8N/10W-	1Q1	HO1	344835117531301	5-14-90	0930	1,023	2,302	1,350	9.0	22.0
	1Q3	HO3	344835117531303	5-08-90	1630	475	2,302	324	8.0	24.5
	1Q4	HO4	344835117531304	5-08-90	1440	130	2,302	486	8.3	22.5
	5A1	BH1	344921117570601	5-12-90	1830	947	2,287	2,960	8.0	24.0
9N/8W-	6H1	EC2	345420117452901	5-10-90	1145	402	2,389	1,190	7.8	22.5
9N/9W-	15J1	PLA	345214117483701	5-10-90	1230	505	2,297	364	7.9	22.5
9N/10W-	16R1	GR1	345212117561801	5-13-90	1530	840	2,315	863	8.4	25.0
	16R2	GR2	345212117561802	5-13-90	1230	584	2,315	1,120	8.3	24.0
	16R3	GR3	345212117561803	5-13-90	1000	360	2,315	1,130	8.2	22.0
	24G1	S-2	345142117531201	5-10-90	0915	738	2,280	572	8.0	20.5
	34R2	BP1	344923117550301	5-08-90	1220	838	2,290	477	7.8	26.5
	34R3	BP2	344923117550302	5-12-90	1445	520	2,290	365	8.2	26.0
	34R4	BP3	344923117550303	5-11-90	1200	250	2,290	455	8.7	22.0
10N/9W-	5B1	NB5	345949117510501	5-10-90	1400	500	2,290	972	8.0	22.5

State well No.		Local well name	Hardness, total (mg/L as $(CaCO_3)$	Hardness, noncarbonate, dissolved (mg/L as $CaCO_3$	Calcium, dissolved (mg/L)	Magnesium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Sodium (percent)	Potassium, dissolved (mg/L)	Alkalinity, water dissolved total field (mg/L as $CaCO_3$)
EPA drinking-water regulations			--	--	--	--	--	--	--	--
8N/10W-	1Q1	HO1	29	0	9.9	1.0	280	95	1.5	303
	1Q3	HO3	52	0	19	1.2	51	67	1.7	83
	1Q4	HO4	37	0	9.2	3.3	100	85	1.2	156
	5A1	BH1	570	540	220	3.8	390	60	4.0	20
9N/8W-	6H1	EC2	100	0	25	9.9	230	83	2.1	246
9N/9W-	15J1	PLA	86	0	29	3.3	48	54	2.1	106
9N/10W-	16R1	GR1	33	0	12	.77	160	91	1.7	72
	16R2	GR2	74	9	27	1.6	190	84	2.0	65
	16R3	GR3	120	12	40	5.3	190	77	2.3	110
	24G1	S-2	110	0	41	2.9	78	59	2.4	116
	34R2	BP1	20	0	6.9	.63	100	91	1.4	168
	34R3	BP2	75	0	24	3.6	52	59	2.4	106
	34R4	BP3	19	0	6.2	.75	97	91	1.2	140
10N/9W-	5B1	NB5	48	0	14	3.2	210	90	1.3	230

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Table 6. Summary of water quality for selected wells on Edwards Air Force Base--*Continued*

State well No.		Local well name	Bicarbonate, water dissolved field (mg/L as HCO_3)	Sulfate, dissolved (mg/L)	Chloride, dissolved (mg/L)	Fluoride, dissolved (mg/L)	Silica, dissolved (mg/L)	Solids, residue at 180 °C, dissolved (mg/L)	Solids, sum of constituents, dissolved (mg/L)	Nitrogen, nitrite' dissolved (mg/L as N)
EPA drinking-water regulations			--	[1]250	[1]250	[1]2.0 [2]4.0	--	[1]500	--	--
8N/10W-	1Q1	HO1	289	130	140	3.3	31	813	783	<0.010
	1Q3	HO3	101	54	5.4	.30	28	192	212	<.010
	1Q4	HO4	190	63	7.8	1.5	15	289	295	<.010
	5A1	BH1	25	220	900	.30	19	1,830	1,770	<.010
9N/8W-	6H1	EC2	300	160	140	1.4	36	760	765	<.010
9N/9W-	15J1	PLA	129	62	11	.30	30	242	251	<.010
9N/10W-	16R1	GR1	88	150	100	9.7	22	510	500	<.010
	16R2	GR2	79	160	180	5.5	21	663	628	<.010
	16R3	GR3	134	190	150	.50	24	697	680	.020
	24G1	S-2	142	71	63	.30	27	362	357	<.010
	34R2	BP1	205	45	10	.60	51	309	317	<.010
	34R3	BP2	129	50	7.5	.20	25	239	230	<.010
	34R4	BP3	171	66	9.2	.70	30	311	298	<.010
10N/9W-	5B1	NB5	281	95	110	1.0	28	608	603	<.010

State well No.		Local well name	Nitrogen, NO_2+NO_3, dissolved (mg/L as N)	Aluminum, dissolved (µg/L)	Arsenic, dissolved (µg/L)	Boron, dissolved (µg/L)	Iron, dissolved, (µg/L)	Manganese, dissolved (µg/L)	Selenium, dissolved (µg/L)
EPA drinking-water regulations			--	--	[2]50	--	[1]300	[1]50	[2]10
8N/10W-	1Q1	HO1	0.600	40	11	1,300	18	3	1
	1Q3	HO3	.400	10	17	80	7	2	<1
	1Q4	HO4	<.100	50	18	390	47	8	<1
	5A1	BH1	<.100	<10	33	190	30	440	<1
9N/8W-	6H1	EC2	2.70	<10	20	990	7	<1	1
9N/9W-	15J1	PLA	.400	<10	7	70	7	10	<1
9N/10W-	16R1	GR1	<.100	80	12	300	38	33	<1
	16R2	GR2	.300	<10	39	210	<3	23	<1
	16R3	GR3	2.70	<10	2	270	<3	2	2
	24G1	S-2	.300	<10	9	130	7	<1	<1
	34R2	BP1	<.100	20	24	540	6	7	<1
	34R3	BP2	.300	<10	14	100	<3	<1	<1
	34R4	BP3	.500	250	17	190	180	6	<1
10N/9W-	5B1	NB5	.300	<10	39	800	24	<1	<1

[1]Secondary maximum contaminant level: Contaminants that affect the esthetic quality of drinking water. At high concentrations or values, health implications as well as esthetic degradation may also exist. Secondary levels are not Federally enforceable but are intended as guidelines.

[2]Maximum contaminant level: Enforceable health based regulations.

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Graham Ranch site, 9N/10W-16R1 and 16R2, and from the deep well 8N/10W-1Q1 at the Holly site. The pH levels in samples from well 9N/10W-34R4 at Branch Park and well 8N/10W-1Q1 at Holly are slightly greater than EPA recommended secondary maximum contaminant levels (table 6).

Analysis of the sample from well 8N/10W-5A1 at the Buckhorn site (fig. 19), indicates that the water from this well exceeds EPA recommended maximum contaminant levels for chloride, dissolved solids, and manganese (table 6) and would be characterized as a very hard and slightly saline type of water (Hem, 1985, p. 157 and p. 159). The sample from this test well is from the 884- to 947-foot depth, and the poor quality of the water from this depth and location may not be representative of the water at shallower depths or of the surrounding area. At the Branch Park site, 2 mi east (fig. 19), the deepest well, 9N/10W-34R2, is open to the aquifer from 782 to 940 ft, and all determined constituents were within EPA recommended maximum contaminant levels.

The quality of the ground water in the Rogers Lake area, as characterized by major-ion concentrations, varies both areally and with depth (fig. 19). Water from the shallower wells, those wells less than 900 ft deep at the south end of Rogers Lake, generally is classified as a sodium bicarbonate type; however, the ground water at the north end of the lake and from the deep well at the Holly site (fig. 19), 8N/10W-1Q1 is classified as a sodium chloride bicarbonate type. At the Graham Ranch site (fig. 19), the ground water generally is a sodium chloride sulfate type and water from the deep test well at the Buckhorn site (fig. 19), 8N/10W-5A1 is classified as a sodium carbonate chloride type.

AQUIFER SYSTEM AT EDWARDS AIR FORCE BASE

HYDROGEOLOGIC BOUNDARIES

Two aquifers, termed "deep" and "principal", are present at EAFB. The deep aquifer underlies the entire base in the Lancaster subbasin and extends northward beneath Rogers Lake into the North Muroc subbasin. The principal aquifer underlies the southern part of EAFB as far north as the Rosamond Hills and the southern end of Rogers Lake (Durbin, 1978, pl. 1). The lateral and bottom boundaries of the deep aquifer in the area of EAFB are the contacts between the saturated alluvium and the bedrock. The upper boundary of the deep aquifer is the bottom of the lacustrine deposits, where present, and the water table elsewhere. The lateral boundaries of the principal aquifer are the contacts between the saturated alluvium and the bedrock, and between the saturated alluvium and top of the lacustrine deposits in areas where the lacustrine deposits extend above the water table. The bottom boundary is the top of the lacustrine deposits and the top boundary is the water table.

Dutcher and Worts (1963) included the Graham Ranch area as part of the main aquifer system in the Lancaster subbasin but do not indicate whether it is part of the deep or principal aquifer. Durbin (1978, pl. 1) does not include the Graham Ranch area as part of the aquifer system within the subbasin. The potentiometric surface (fig. 5) indicates that the Graham Ranch area may be weakly hydraulically connected to the deep aquifer. Lithologic and borehole geophysical logs of the wells drilled in the Graham Ranch area (figs. 9*D-F*) do not indicate the presence of any lacustrine deposits in this area. The aquifer material in this area is similar to that in the older alluvium in the lower part of the deep aquifer. The quality of the water in the Graham Ranch area is more similar to that of the water from wells on the north and east sides of Rogers Lake and deep well 8N/10W-1Q1 at the Holly site than to that of the water in the shallower wells at the Holly and Branch Park sites (fig. 19 and table 6). This similarity in water quality and lithologic data indicates that the Graham Ranch area may be part of the deep aquifer system.

Logs of boreholes drilled at the Buckhorn, Branch Park, and Holly sites indicate that the top of the lacustrine deposits is very shallow in these areas--40, 100, and 90 ft below land surface, respectively. At the Holly site, the depth to water in shallow well 8N/10W-1Q4 completed above the lacustrine deposits was about 50 ft below land surface. This shallow water level would indicate that the principal aquifer is only about 40 ft thick in this area. Land-surface altitudes at the Buckhorn and Branch Park sites are lower than at the Holly site and therefore, the principal aquifer may be even thinner at these locations. In the area of these wells and probably to the north, the principal aquifer is too thin to yield a significant volume of water. South of these sites, the principal aquifer becomes a major source of water as it thickens considerably because of the underlying southward dipping lacustrine beds (Durbin, 1978, pl. 1) and the increasing land-surface altitude.

Most of the ground water currently pumped at EAFB is presumed to come from the deep aquifer. Near EAFB well fields, the principal aquifer is either very thin or nonexistent and therefore is assumed to contribute very little water to the pumping wells. Ground water moving within the lacustrine deposits through sand stringers and interbeds also may contribute significantly to the ground-water supply at EAFB.

HYDRAULIC PROPERTIES

Aquifer hydraulic tests to determine the transmissive and storage properties of the ground-water flow system were not conducted as part of the initial phase of this study. However, several past investigations have provided estimates of aquifer properties based on pumping tests and specific capacity tests. These estimates are summarized in table 7 for the pumping tests and in table 8 for the specific capacity tests. Estimates of aquifer properties based on pumping tests range from 4,600 to 26,800 ft^2/d for transmissivity, 0.00036 to 0.13 for storage coefficient and 0.017 to 0.13 ft^2/d for vertical hydraulic conductivity of the confining unit between the principal and deep aquifers (table 7). Estimates of transmissivities based on specific capacity tests range from 600 to 32,000 ft^2/d (table 8).

Durbin (1978) estimated the aquifer properties for both the principal and deep aquifers within the area of EAFB for the purposes of modeling the ground-water flow of the entire Antelope Valley. The estimates of transmissivity were largely based on specific capacity measurements collected by McClelland (1963) and Bloyd (1967) and shown in table 8. These estimates range from 800 to 9,000 ft^2/d for the principal aquifer (Durbin, 1978, pl. 7) and from 1,700 to 14,000 ft^2/d for the deep aquifer (Durbin, 1978, pl. 8). Durbin (1978) also estimated the storage coefficient of the principal and deep aquifers based on values of the specific yield of deposits determined by Dutcher and Worts (1963). The estimates of the storage coefficient of the principal aquifer ranged from 0.05 to 0.10 (Durbin, 1978, pl. 11) and the estimate of the storage coefficient of the deep aquifer in the North Muroc ground-water subbasin and the area east of Rogers Lake was 0.15 (Durbin, 1978, pl. 12). Durbin (1978) estimated a constant storage coefficient value of 0.001 for the confined area of the deep aquifer and a constant vertical hydraulic conductivity of 0.01 ft/d for the confining bed between the two aquifers.

Table 7. Summary of pumping tests results for selected wells completed in the deep aquifer in vicinity of Edwards Air Force Base

[Well locations shown in figure 16. Type of test: MW, multiple well; SW, single well. ft/d, foot per day; ft^2/d, foot squared per day; h, hour. --, no data]

State well No.		Date	Duration (hours)	Transmissivity (ft^2/d)	Storage coefficient	Vertical hydraulic conductivity of confining unit (ft/d)	Type of test	Source
8N/10W-	1C1	8-17-61	12	[1]4,600	--	--	SW	McClelland (1963)
	1C2	5-27-85	30	[2,4]25,900/14,600	0.0023/0.00036	0.092/0.017	MW	Weston (1986)
9N/10W-	24G1	5-30-85	49	[2,4]8,300/7,200	0.0013/0.0028	0.078/0.13	MW	Do.
10N/9W-	5B1	5-24-85	55	[3]20,800	[5]0.0006	--	MW	Do.
11N/9W-	36C1	8-14-55	262	[1]12,000/26,800	[1]0.13	--	MW	McClelland (1963)

[1]Analyzed using the Theis nonequilibrium method (Theis, 1935).
[2]Analyzed using the Hantush-Jacob, Leaky Aquifer Method (Hantush and Jacob, 1955).
[3]Analyzed using the Boulton, Delayed Yield from Storage Method (Boulton, 1963).
[4]Values for transmissivity, storage coefficient, and vertical hydraulic conductivity of confining unit were computed for two monitoring wells.
[5]Storage coefficient computed from a match of the theoretical solution to the measured early-time response.

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Table 8. Summary of estimated transmissivities based on specific capacity tests for selected wells in the vicinity of Edwards Air Force Base

[Well locations shown in figure 16; ft^2/d, foot squared per day]

State well No.		Transmissivity (ft^2/d)	Source
8N10W-	1C1	3,500	McClelland (1963)
	1C2	11,100	Weston (1986)
9N/8W-	6H1	25,700	McClelland (1963)
	6H2	32,000	Do.
9N/9W-	6A1	5,400	Do.
	6C1	3,800	Bloyd (1967)
	6E1	800	McClelland (1963)
	6L1	2,900	Do.
	6M1	600	Do.
	18C1	1,900/1,900	Do.
	24H1	600	Do.
9N/10W-	24C1	800	Weston (1986)
	24E2	1,000	Do.
	24F1	15,000	Do.
	24G1	2,500/3,100	McClelland (1963)
	36P1	12,000	Weston (1986)
10N/9W-	4D1	5,800	Bloyd (1967)
	5B1	7,900	Weston (1986)
	7A1	1,200	McClelland (1963)
	7A2	2,300	Do.
11N/9W-	32Q1	6,700	Weston (1986)
	36C1	6,300	McClelland (1963)

GROUND-WATER FLOW

The general direction of ground-water flow in the deep aquifer beneath EAFB is toward a pumping depression centered beneath the South Track well field (figs. 5 and 8). The direction of ground-water movement across the reported buried bedrock ridge under the north end of Rogers Lake (fig. 10) is uncertain at this time. Durbin (1978, p. 6) reported that prior to the extensive ground-water development in the Lancaster subbasin, the flow beneath Rogers Lake was toward the north into the North Muroc subbasin but that by 1961, as pumpage increased in the Lancaster subbasin, the flow direction had reversed and was from north to south. As a result of this reversal of flow direction, ground water may be flowing from the North Muroc subbasin into the Lancaster subbasin, depending on the location and depth to the buried bedrock ridge reportedly separating the two subbasins. If the buried ridge is near the surface and extends across the lake as suggested by Dutcher and Worts (1963), then it could be acting as a partial barrier to flow creating a ground-water divide between Lancaster and North Muroc subbasins. If the ridge is deeply buried beneath the lake bed as inferred by the gravity map of the area (fig. 10), then water could now be flowing from the North Muroc subbasin into the Lancaster subbasin. Additional geophysical surveys and exploratory drilling would provide more information about this buried ridge and its effect on ground water in the area.

The direction of ground-water movement in the principal aquifer beneath EAFB is uncertain at this time. Along the southern boundary of EAFB, it is probably flowing toward the large pumping depressions south of EAFB (fig. 5) and possibly toward the pumping depression at the South Track well field near the southern end of Rogers Lake.

Several faults are known to exist within the boundaries of EAFB (fig. 2). These faults have been mapped in the bedrock hills and in some instances they have been projected into the margins of the alluvial basins. Surface evidence provides no indication that these faults have disturbed the unconsolidated material nor does available water-level data indicate that faulting is affecting the flow of ground water within the unconsolidated material. The line of old dry springs that is in the Buckhorn Lake area corresponds very closely to the N. 50° to 60° E. striking faults inferred from the geophysical data. These old springs may be the result of the inferred faulting in the area or they may have occurred at this location because it is near the northern edge of the lacustrine deposits within the unconsolidated materials filling the basin. Additional deep observation wells, installed across this old spring line, would help to determine what effect, if any, the inferred fault has on the flow of ground water in the area.

CONCEPTUALIZATION OF AQUIFER SYSTEM AT HOLLY SITE

Hydraulic heads of the Holly site wells (fig. 8) were used to develop a conceptual model of the aquifer(s) for a localized part of the hydrologic basin (fig. 20). The large contrast in hydraulic heads between 8N/10W-1Q4 and the deeper wells (figs. 18*A* and 18*B*), combined with the lack of seasonal fluctuations in well 8N/10W-1Q4 (fig. 18*A*), due to

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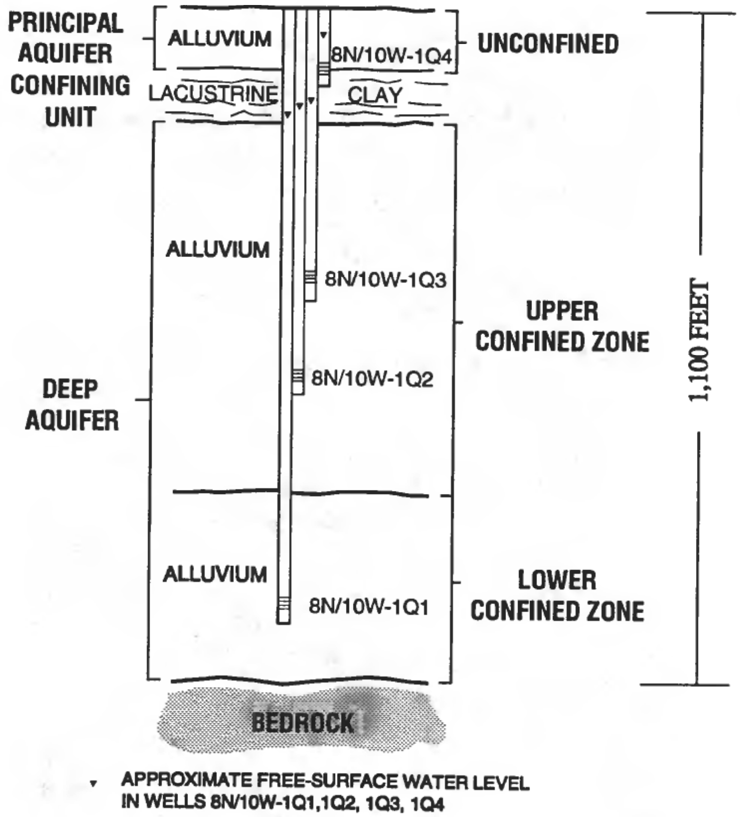

Figure 20. Conceptual model of the aquifer system at the Holly site on Edwards Air Force Base.

pumping stresses from the South Track well field (fig. 8) evident in the other Holly site wells, suggest at least two aquifers in the Holly area. The shallow aquifer monitored in well 8N/10W-1Q4 probably is an unconfined aquifer that is separated from the deeper zones by the fine-grained lacustrine sediments, evident on the resistivity logs and lithologic logs (fig. 9*C*), which act as a confining unit. The two aquifers are correlative to the previously defined principal and deep aquifers of the Lancaster groundwater subbasin.

Hydraulic heads measured in the deeper wells 8N/10W-1Q1, 1Q2, and 1Q3 indicate that formation fluid pressures are confined by the lacustrine sediments above. Seasonal fluctuations measured in wells 8N/10W-1Q2 and 1Q3 track each other closely and indicate that the aquifer thickness monitored by these wells is hydraulically well connected. However, the seasonal fluctuations measured in well 8N/10W-1Q1 are attenuated with respect to those in 1Q2 and 1Q3, indicating a poor hydraulic connection between the upper and lower zones of the deep aquifer.

Further evidence for a change in aquifer properties at the 970- to 1,075-foot depth in well 1Q1 is (1) the change in lithology from a fine- to coarse-grained material to a siltier, more indurated material and a shift to lower resistivity at about 837.5 ft; and (2) the change in water chemistry, reflected in the higher dissolved-solids concentration. On this basis, an upper and a lower zone may exist in the confined aquifer near the Holly site. The two zones may be poorly connected, with flow occurring from the upper to the lower zone, especially during the autumn and winter months of minimum pumping stress in the upper zone. The weathered bedrock in the core from the 1,097 to 1,107 ft interval (table 4) defines the lower limit of the lower zone in the confined aquifer.

The depth to water in well 8N/10W-1Q4 corresponds closely with the water level in well 8N/9W-6D1, about 1 mi to the northeast (fig. 16); however, the water levels in the deeper wells correspond closely to initial water levels measured in the newly constructed wells at Branch Park (9N/10W-34R2, 34R3, and 34R4) and Buckhorn (8N/10W-5A1) sites, about 2 and 4 mi to the west (table 3, fig. 8).

LAND SUBSIDENCE AND AQUIFER-SYSTEM COMPACTION

Subsidence of the land surface, related to groundwater withdrawal in the Antelope Valley, has been previously reported (Lofgren, 1965; Lewis and Miller, 1968; Poland, 1984). The subsidence is attributed to the compaction of fine-grained sediments in the aquifer system due to long-term pumping, lowering of aquifer hydraulic head, and increasing effective stress. In 1988, some of the effects of land subsidence were observed at EAFB with the occurrence of surface deformation features associated with land subsidence such as sinklike depressions and earth fissures. Other indications of land subsidence at EAFB include failure of production wells caused by collapsed well casings, and the protrusion above land surface of well casings, pump platforms, and survey benchmarks. In 1989-91, the USGS conducted vertical and horizontal control surveys to measure the extent and magnitude of land subsidence in the area and to establish a network of benchmarks to monitor future land subsidence (Blodgett and Williams, 1992).

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Figure 21 shows measurements of land subsidence at selected benchmarks in the area. The measurements are based on a comparison of surveys made in 1961 and 1989-91. Land subsidence greater than 1 ft affects more than 100 mi^2 of EAFB (fig. 21). The largest amount of measured subsidence on EAFB is 3.3 ft, at benchmark P1155 near the intersection of Lancaster Boulevard and Avenue B, near the South Track well field. Subsidence near other base well fields is less than 1 ft. Subsidence in the areas of Main Base, North Base, and along the eastern side of Rogers Lake also is less than 1 ft. Four feet of subsidence was measured at benchmark J1147 (fig. 21) near Avenue I and Sierra Highway in the city of Lancaster. Lines of equal land subsidence magnitudes (fig. 21) show a large area between the southern edge of Rogers Lake and the city of Lancaster where 2 or more feet of subsidence has occurred. The shape of this area south of Rogers Lake is elongated along a northeast-southwest axis, consistent with the orientation of other structural and depositional trends of the East Antelope structural basin.

In May 1990, an extensometer was installed at the Holly site to measure vertical compaction of the aquifer system. The Holly site is near the South Track well field, and near benchmarks M1155 and P1155, where the maximum amount of land subsidence has been measured on EAFB. The extensometer is anchored at a depth of about 840 ft and provides a measure of the vertical compaction of the sediments between land surface and the 840-foot depth. Extensometer data and details of the extensometer design and construction are given by Blodgett and Williams (1992).

Figure 22 shows a graph of cumulative vertical compaction measured at the Holly extensometer from May 11, 1990 through November 6, 1991. Water-level altitudes measured in well 8N/10W-1Q3 also are shown for the same period. Two distinct slopes of the compaction curve are evident: one corresponding to the spring and summer declines in water level, and another corresponding to the autumn and winter water-level recoveries. During the spring and summer months, when ground-water production from the South Track well field and other production wells is largest, the rate of vertical compaction is about 1.93×10^{-4} ft/d. During the autumn and winter months, the aquifer system continues to compact, but the rate of vertical compaction decreases to about 1.12×10^{-4} ft/d. Because the two periods of compaction are each about 6 months in duration, an average annual rate of compaction, 5.57×10^{-2} ft/yr, can be estimated from the average of the two seasonal rates or one cycle of pumping and recovery. For the period of record, 544 days, 8.16×10^{-2} ft of vertical compaction has been measured at the Holly extensometer.

The measurements of aquifer-system compaction and water-level fluctuations at the Holly site (fig. 22) can be analyzed to gain insight to the vertical compaction occurring during successive cycles of ground-water level declines. Depending on the nature of the sediments, compaction may be elastic or inelastic. In general, coarse-grained deposits such as sand and gravel compact elastically, and the compaction is small and reversible, whereas fine-grained deposits such as clays compact largely inelastically, and the compaction is much greater and chiefly irreversible. For a saturated porous medium, the vertical deformation is controlled by the effective stress and the relation can be expressed in the equation given by Terzaghi (1943):

$$\sigma_z' = \sigma_z - p,$$

where the vertical effective stress, σ_z', represents the grain-to-grain load borne by the aquifer particles, and is the difference between the overburden stress of the saturated and unsaturated rocks and soil, σ_z, and the buoyant stress imparted by the aquifer fluid pressure, p. A decline in head (fluid pressure) causes a corresponding increase in the grain-to-grain load in the aquifer system, and the sediments compact. When the head decline is areally extensive relative to the location of interest in the aquifer, the horizontal components of stress can be neglected and the vertical effective stress represents the grain-to-grain load.

The vertical effective stresses were calculated for the Holly site for the stress periods shown in figure 22, and follow the technique summarized by Poland (1984). Ground-water levels measured in the four wells provide values of aquifer fluid pressure. All calculated stresses are expressed in terms of an equivalent height of water (hydraulic head) in feet. For the stress calculations, average values were assumed for the porosity, 0.40, specific retention of moisture contained above the water table, 0.20, and for the specific gravity of individual grains, 2.7 (Bear, 1979, and Todd, 1980). Stresses were

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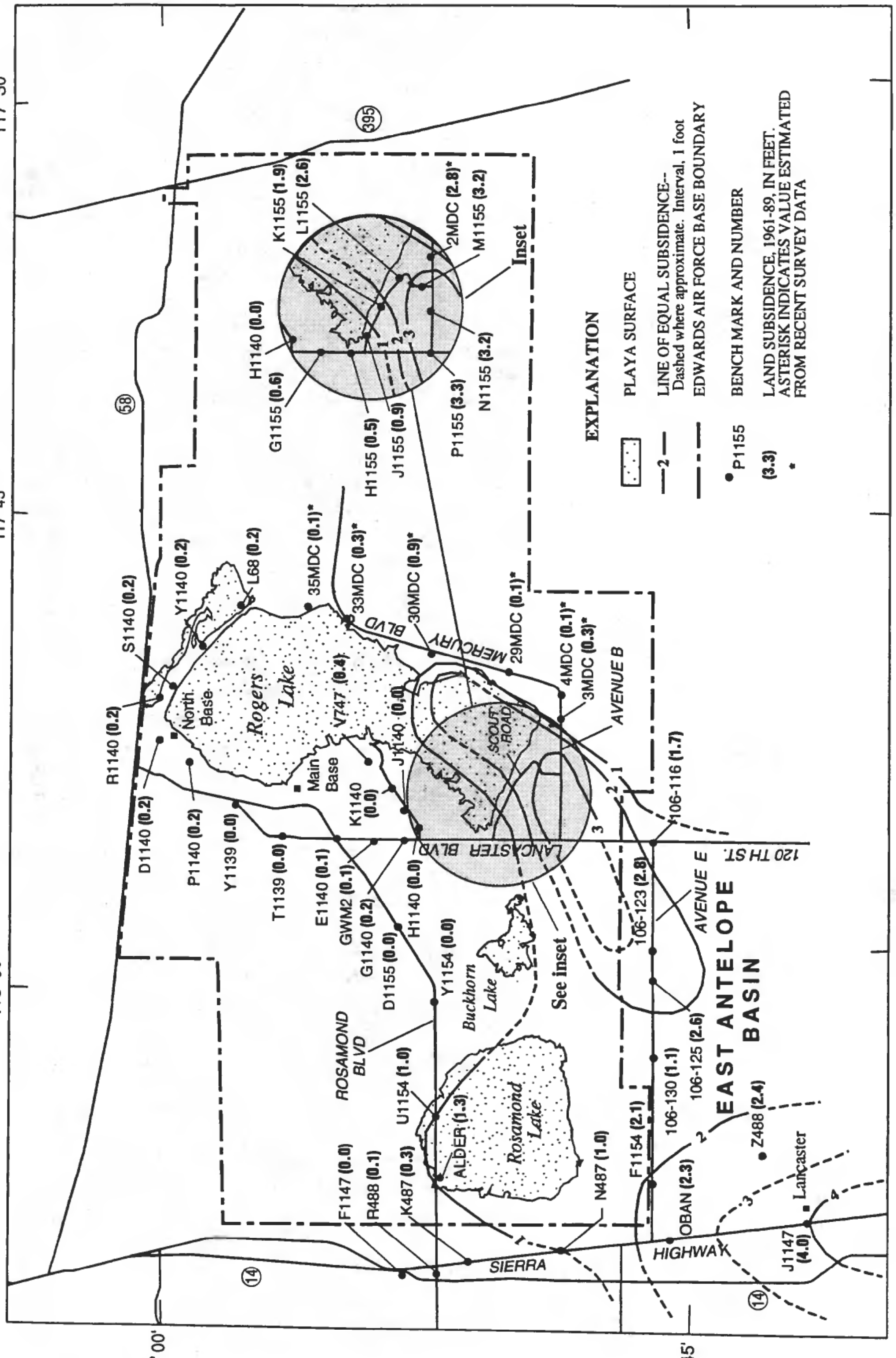

Figure 21. Magnitude of subsidence between 1961 and 1989 at selected benchmarks on Edwards Air Force Base and vicinity. Modified from Blodgett and Williams (1992).

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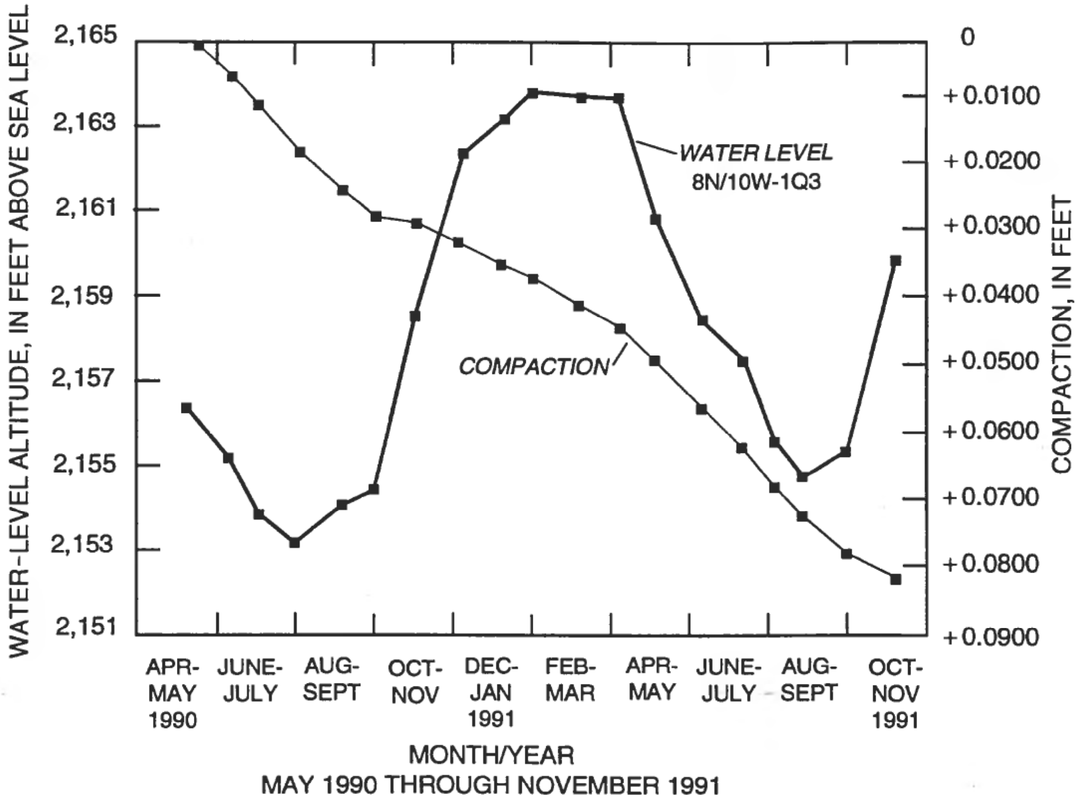

Figure 22. Water levels for well 8N/10W-1Q3 and cumulative vertical compaction at the Holly site on Edwards Air Force Base.

calculated at aquifer boundaries, according to the conceptual model of the local aquifer system (fig. 20) and at the midpoint of gravel-packed intervals. For the period of record, the maximum and minimum effective stresses in the upper zone of the confined aquifer correspond to the maximum and minimum water-level declines in 8N/10W-1Q2 and 1Q3. The change in effective stress is the difference between the effective stress, and the minimum value of effective stress computed for the selected depth in the aquifer profile. The change in effective stress represents the applied stress to the aquifer due to fluctuations of aquifer hydraulic head.

Figure 23 illustrates the change in effective stress at depth in the aquifer-system profile. The graph is based on water-level measurements made in wells 8N/10W-1Q1, 1Q2, 1Q3, and 1Q4, at the Holly site on August 3, 1990 (figs. 18*A* and 18*B*). This date corresponds to the minimum water level and maximum effective stress computed for well 8N/10W-1Q2 for the period of record. The graph shows that the upper zone of the confined aquifer, where the magnitude of hydraulic head fluctuations is greatest, experiences the greatest change in effective stress, about 10 to 11 ft expressed as an equivalent height of water. The unconfined aquifer shows little change and reflects the lack of seasonal water-level fluctuation evident in well 8N/10W-1Q4 (fig. 18*A*). The lower zone of the confined aquifer exhibits about a 5-foot change in effective stress, about one-half the amount computed for the upper zone, and also reflects the relative amplitude of the seasonal aquifer hydraulic heads measured in well 8N/10W-1Q1 (fig. 18*B*). The stress graph indicates that aquifer system compaction would be greatest in the upper zone of the confined aquifer, depending on the distribution and thickness of compressible, unconsolidated fine-grained clay units. Stresses in the lower zone also may cause compaction, but the small amounts of clay, and the degree of induration of the sediments logged in the lower zone may render the lower zone sediments less compressible than the nonindurated interbedded sediments in the upper zone.

The distribution and thickness of clay units in the upper zone of the confined aquifer (figs. 9*C* and 20) highlights the interbedded nature of the sediments

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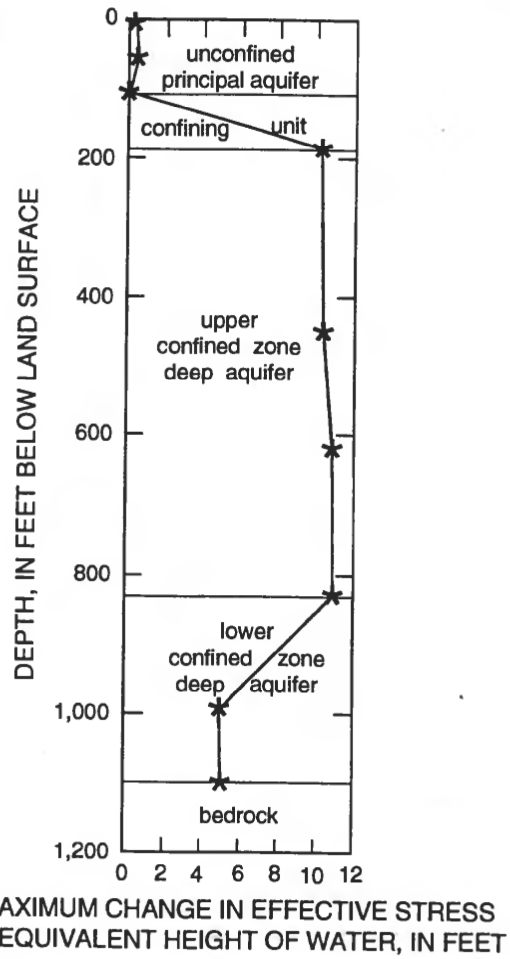

Figure 23. Maximum change in effective stress with depth at the Holly site on Edwards Air Base, for May 11, 1990 through November 6, 1991. Asterisks are the calculated change in effective stress; solid line connecting the asterisks is the inferred change in effective stress; horizontal lines are the aquifer boundaries.

that constitute the upper zone. Many 5- to 20-foot thick zones of low resistivity (fine-grained deposits) constitute the 400 to 600-foot depth interval. A thick, 90-foot interval of clayey material, constitutes the 300 to 400-foot section. Because of the large thickness, low hydraulic conductivity and relatively large compressibility of the interbedded clay layers, the compaction of the aquifer system, in response to an increased effective stress, is a time-dependent process. The lower hydraulic conductivity of the interbedded clay layers delay equilibration of hydraulic heads between the coarse-grained aquifer materials and the interbeds. Transient heads in the interbedded clays may result. These heads may be larger than the heads in the adjacent coarse-grained aquifer material, and the corresponding effective stress in the interbedded clays may be smaller due to the larger residual hydraulic heads in the clays. For a particular stress cycle, where aquifer hydraulic heads are equilibrated throughout the interbedded aquifer system, the aquifer will become 100 percent compacted for that level of stress. However, where the interbeds have not attained hydraulic-head equilibration, only a part of the ultimate compaction is realized for that stress cycle.

Figure 24 shows the relation between the change in effective stress in the upper zone of the confined aquifer to vertical compaction measured at the Holly site for the period May 11, 1990 through November 6, 1991. Most of the aquifer system compaction occurs during the two periods of largest change in effective stress. These periods are coincident with the two periods of increased rate of compaction evident in figure 22. When the change in effective stress decreases to 0 (fig. 24), the aquifer system continues to compact, albeit at a smaller rate. No expansion of the aquifer system is evident as a result of the cycling of effective stress to its smallest magnitude. A possible explanation is that any expansion of the compacted sediments is masked by the continuous compaction of clay horizons, where residual hydraulic heads are slowly equilibrating to the present day aquifer hydraulic heads. Johnson (1911) indicates that near the beginning of this century aquifer hydraulic heads in the upper zone were at altitudes higher than land surface near the Holly site and south Rogers Lake. Residual heads in some of the thicker and less permeable clay horizons in the upper zone and confining unit may not have yet equilibrated with the long-term decline in aquifer heads.

The rate of compaction, 5.57×10^{-2} ft/yr, computed for one cycle of aquifer hydraulic head decline and recovery during 1990-91 does not explain the approximately 3.2 ft of subsidence measured at nearby benchmark, M1155 since 1961 (fig. 21). At the 1990-91 rate, only 1.67 ft of subsidence would result, leaving about 1.5 ft of unaccounted land subsidence in this area. Two possible explanations are that the rate of compaction has decreased since 1961; or compaction is occurring in the sediments of the lower zone of the confined aquifer near the Holly site that are not being measured by the Holly extensometer. The latter explanation is least likely due to the reasons previously stated regarding the nature of the deposits in the lower zone. Hydrographs for two of the Antelope Valley-East Kern Water Agency wells (figs. 17*B* and 17*H*) monitored prior to 1961 show a fairly constant rate of water-level decline in

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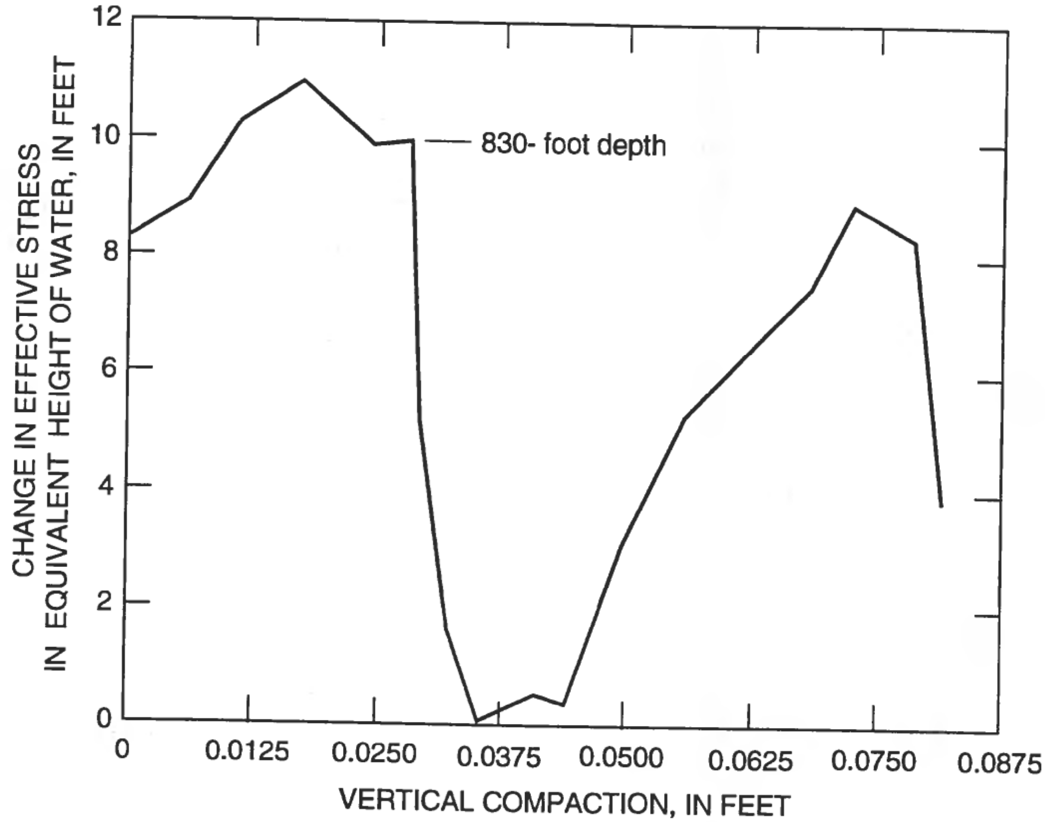

Figure 24. Relation between the change in effective stress to vertical compaction measured in the upper zone of the confined aquifer at the Holly site on Edwards Air Force Base.

early years, with a gradually decreasing rate of decline in the past 20 years. The two wells are about 4 mi west-southwest (fig. 17*B*) and 5 mi northeast (fig. 17*H*) of the Holly site on EAFB. If these trends in aquifer head declines are representative of the long-term trend at the Holly site, annual change in effective stress probably was greater at the Holly site during the decade of the 1960's, and the annual rate of compaction has been decreasing near south Rogers Lake since the early 1970's.

SUMMARY AND CONCLUSIONS

Edwards Air Force Base overlies two structural basins in the western Mojave desert; the East Antelope and the Kramer, which have been filled to depths of more than 5,000 and 2,000 ft, respectively, with Tertiary and Quaternary sediments. These sediments consist of a series of unconsolidated alluvial deposits interbedded with lacustrine deposits. Near the southern limit of the valley, the lacustrine deposits are buried beneath as much as 800 ft of alluvium, but are exposed at land surface near the northern limit.

The aquifer system in the Antelope Valley consists of two alluvial aquifers known as the principal aquifer and the deep aquifer. The principal aquifer is considered to be unconfined and overlies lacustrine deposits. This aquifer extends over most of the valley south and southwest of Rogers Lake and is the major source of ground water pumped in Antelope Valley. The deep alluvial aquifer underlies the lacustrine beds and extends to the north beneath Rogers Lake and beyond. This deep aquifer is the major source of ground water at EAFB.

Ground water in the Antelope Valley area originates primarily from precipitation in the San Gabriel and Tehachapi Mountains. Estimates of the average annual recharge to the aquifer system in the Antelope Valley range from 40,280 to 81,400 acre-ft.

Ground-water use in the Antelope Valley peaked in the early 1950's and estimates of annual pumpage for this period range from about 280,000 to 480,000 acre-ft. The estimated pumpage for 1988 was about 62,000 acre-ft. Since 1947, pumpage at EAFB has ranged from a minimum of about 1,000 acre-ft in 1947 to a maximum of about 6,700 acre-ft in 1965. EAFB pumpage in 1990 was about 6,150 acre-ft.

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The data collected for this investigation includes lithologic, borehole geophysical, surface geophysical, ground-water level and quality, land subsidence, and aquifer-system compaction information. The lithologic and borehole geophysical data indicate a multiple-aquifer system south and west of Rogers Lake and a single-aquifer system in the Graham Ranch area.

Values for depth-to-bedrock differ among the three surface geophysical methods used in this study, but the shape and orientation of the basin's structural configuration generally are coincident. Gravity and seismic refraction data define the East Antelope structural basin as a relatively narrow N. 50° - 60° E. trending trough extending to the southwest from beneath the southern part of Rogers Lake. Seismic refraction survey data are concordant with the gravity and surface-resistivity data, and delineate the Graham Ranch area as a partly isolated sediment-filled basin.

Long-term water-level declines of as much as 90 ft have been recorded on EAFB. Ground-water levels, lithologic, and geophysical evidence at the Holly site indicate two separate aquifers, correlative with the principal and deep aquifers of the Lancaster ground-water subbasin. The very slight, nonseasonal, yet steady water-level decline in the shallow zone suggests that the principal aquifer is not hydraulically connected to the deep aquifer, where water levels have fluctuated seasonally as much as 8 to 10 ft.

The quality of ground water near Rogers Lake and in the Graham Ranch areas ranges from soft to moderately hard, and the water commonly has a high dissolved-solids concentration. The concentrations of most constituents are generally less than the U.S. Environmental Protection Agency primary and secondary drinking-water regulations for maximum contaminant levels. The quality of the water from the well at the Buckhorn site is characterized as a very hard and slightly saline type, and exceeds recommended Environmental Protection Agency limits for dissolved solids, chloride, and manganese.

On the basis of comparison differential surveys, more than 1 ft of land subsidence has occurred since 1961 over the southwestern part of EAFB. An extensometer installed at the Holly site, near the South Track well field, showed an average annual rate of compaction of 5.57×10^{-2} ft/yr from May 1990 to November 1991. This current annual rate would account for only 1.67 ft of the total 3.2 ft of subsidence measured from 1961 to 1990, indicating that compaction rates at the Holly site probably were higher in years prior to 1990.

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