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THE EFFECTS OF GROUND-WATER DEVELOPMENT ON THE WATER SUPPLY IN THE POST HEADQUARTERS AREA, WHITE SANDS MISSILE RANGE, NEW MEXICO

By

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ABSTRACT

Water-level declines in the Post Headquarters area, White Sands Missile Range, N. Mex., have been accompanied by slight but progressive increases in the concentration of dissolved solids in water withdrawn from the aquifer. Projected water-level declines through 1996 are estimated from a digital simulation model to not exceed 200 feet (61 metres). A conceptual model of water quality provides three potential sources for water that is relatively high in dissolved solids: brine from the Tularosa Basin to the east, slightly saline water beneath the subjacent aquatard, and very slightly saline water from the less permeable units within the aquifer itself. Management of the well field to minimize drawdown and spread the cone of depression would minimize the rate of water-quality deterioration. A well designed monitoring network may provide advance warning of severe or rapid water-quality deterioration..

The Soledad Canyon area 10 miles (16.1 kilometres) south of the Post Headquarters offers the greatest potential for development of additional water supplies.

INTRODUCTION

The Post Headquarters of White Sands Missile Range is located about 20 mi (30 km) east of Las Cruces, N. Mex. and 40 mi (60 km) north of El Paso, Tex. (fig. 1). The population of the headquarters was 4,167 persons in 1970. This is approximately five percent fewer persons than were stationed at the missile-testing facility in 1960.

The Post Headquarters is located in an arcuate reentrant formed by the junction of the San Andres, San Augustin, and Organ Mountains. These mountains form part of the western boundary of the Tularosa Basin, an elongated desert valley which slopes gently southward and contains many playas that have no drainage outlets. Barren alkali flats and sparse vegetation characterize the basin floor.

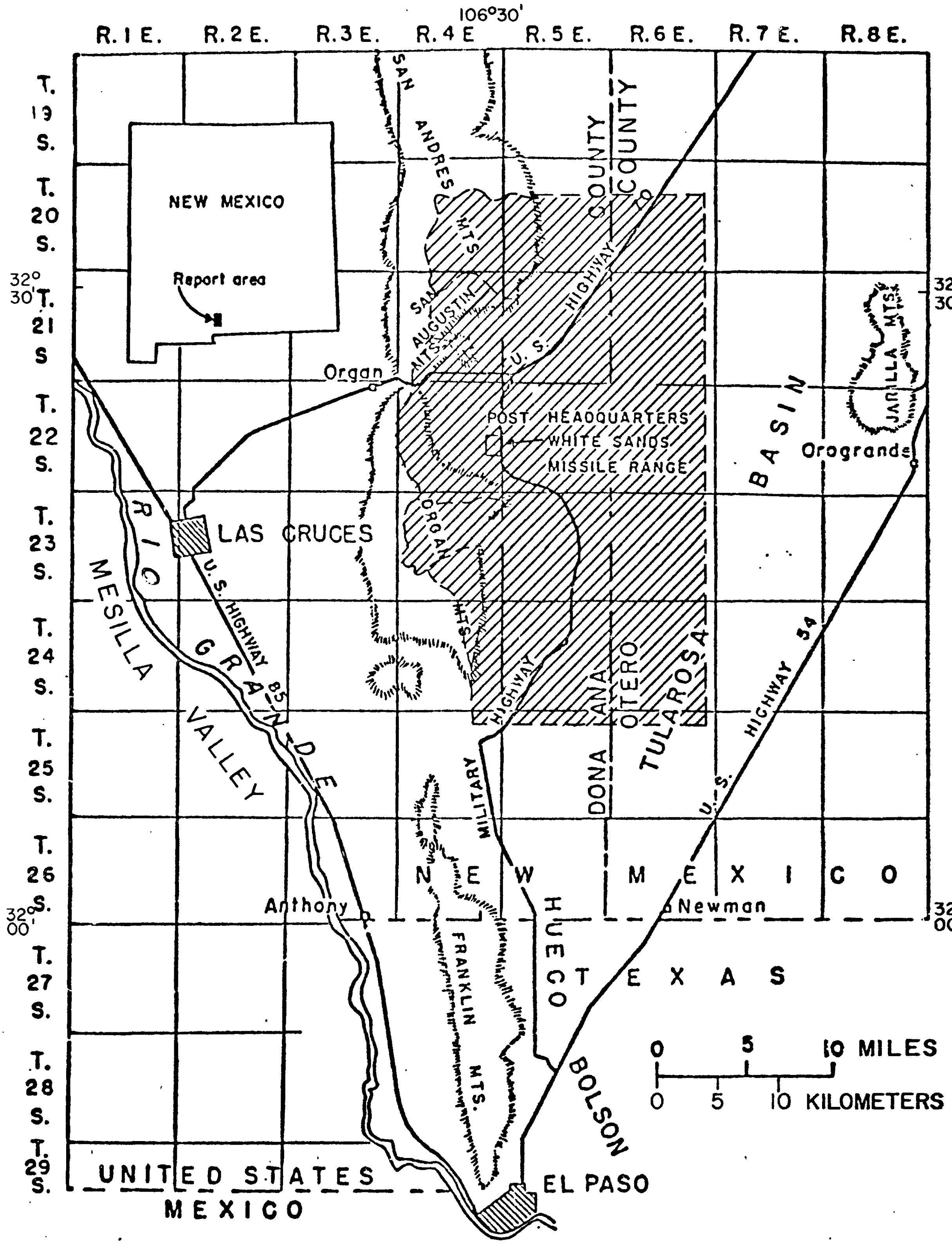


Figure 1.--Index map.

The area included in this study encompasses approximately 400 mi^2 (1,000 km^2) surrounding the Post Headquarters. The western boundary of the study area is formed by the drainage divide along the axis of the three mountain ranges which partially encircle the headquarters. The headwaters of three drainage areas are included in the study: SMR (Small Missile Range) drainage on the north, the Post Headquarters drainage, and the Soledad Canyon area on the south. The Soledad Canyon area does not include Soledad Canyon drainage but is known to the military as the Soledad Canyon area because of the access to this area by way of Soledad Canyon from the west. Actually the area includes the drainage of several Canyons among which are Johnson Canyon, Glendale Canyon, Rucker Canyon, and South Canyon. In this report this area is referred to as the Soledad Canyon Area.

When streams from these areas reach the basin floor, the channels become braided and lose their identity. Therefore, the eastern limit of the study area was arbitrarily set at approximately 15 mi (24 km) east of the mountain axis. Where data were available, the area of investigation was extended to make optimum use of the data.

The central part of the Tularosa Basin east of the Post Headquarters contains saline water. Freshwater is present locally in the basin adjacent to the mountain front, and a particularly large quantity of freshwater is located in the reentrant at the Post Headquarters where most water development has taken place.

The possibility of saline-water encroachment from the central part of the Tularosa Basin into the Post Headquarters well field has long been recognized as a major threat to the water supply. To date, only small changes have been noted in the chemical quality of water collected from several observation wells. A small but recognizable increase in dissolved-solids concentration has been noted in water collected from most of the production wells. Continued withdrawals may result in additional deterioration of water quality. Therefore the Facilities Engineering Directorate, White Sands Missile Range, requested the U.S. Geological Survey to analyze the available data in order to determine if these data were adequate to predict future effects of pumping on ground-water levels, the most favorable locations and spacing of wells for future development, and the amount of potable ground water available to wells in the Post Headquarters and adjoining areas.

In 1953-55 an investigation of the water resources of the headquarters area was made by the U.S. Geological Survey (Herrick, 1960). This report described the geology and ground-water resources in an area of about 2,000 mi^2 (5,000 km^2).

Hydrologic investigations by the U.S. Geological Survey in the Post Headquarters well-field area since 1955 include seasonal measurements of water levels, periodic chemical analysis of water from production wells and observation wells, interpretation of changes in the level of ground water, the observation of well drilling, and the rehabilitation of production and observation wells. Nearly all of these data are summarized in a report by Kelly (1973).

This report is the result of the cooperative efforts between the U.S. Geological Survey and the Facilities Engineering Directorate, White Sands Missile Range. The authors gratefully acknowledge the help received from various staff members and employees of White Sands Missile Range, and especially that of J. F. Landis, Chief of the Utilities Division, Facilities Engineering Directorate.

In this report figures for measurements are given both in English units and in metric units (with the exception of tables, which contain English units only). The following table contains conversion factors of the dual system of metric "The International System of Units (SI)" and English units:

English		Multiplied by	Metric	
Unit	Abbreviation		Unit	Abbreviation
inch	in	25.4	millimetre	mm
foot	ft	.3048	metre	m
foot-squared per day	ft^2/d	.0929	metre squared per day	m^2/d
mile	mi	1.609	kilometre	km
square mile	mi^2	2.590	square kilometre	km^2
cubic foot per second	ft^3/s	28.32	cubic decimetre per second	dm^3/s
		.02832	cubic metre per second	m^3/s
acre-foot	acre-ft	1233.	cubic metre	m^3
		1.233×10^{-3}	cubic hectometre	hm^3
gallon	gal	3.785×10^{-3}	cubic metre	m^3
		3.785×10^{-9}	cubic hectometre	hm^3
gallon per minute	gal/min	6.309×10^{-2}	litre per second	(l/s)
gallon per day per foot	(gal/d)/ft	.0124	metre squared per day	m^2/d
gallon per minute per foot	(gal/min)/ft	0.207	litre per second per metre	(l/s)/m

GEOLOGIC FRAMEWORK

In general, most of the consolidated rocks have little significant effect on the hydrology of the Post Headquarters area. These units have little permeability which could be utilized for the production of ground water. Although a few stock wells have been developed in these rocks, well yields are very low. Consequently the igneous and lithified sedimentary rocks in the area function only as a lower limit of the aquifer and as a gathering basin for precipitation which falls in the mountainous area surrounding the reentrant. Ultimately some of the precipitation enters the alluvial aquifer, from which it can be pumped.

Herrick (1960, p. 30) recognized that there was a wide range in the age of alluvial sediments which accumulated in the Post Headquarters area and adjacent Tularosa Basin; however he considered them all as one geologic unit. Subsequently, Hood (1968, p. 84-85) distinguished three different units of bolson deposits in the Small Missile Range: an upper unit of gravel and coarse-grained, angular to sub-angular sand with very little interbedded silt and clay; a middle unit characterized by fine-grained sand and interbedded clay; and a lower unit described as "a tightly cemented conglomerate," which was identified as "bedrock" by the driller. The sample log by Hood (1968, p. 98) identifies this conglomerate as well-cemented arkosic sandstone.

The reentrant in which the Post Headquarters is located is divided roughly in half by U.S. Highway 70. Most of the area of the reentrant north of this highway and a small part of the reentrant south of the highway is underlain by a pediment surface eroded on granitic rocks. This surface is blanketed by a thin veneer of unconsolidated sediments; only Mineral and Antelope Hills protrude above this eroded surface. The Hazardous Test Area and part of the Small Missile Range are located on this pediment.

Throughout much of Tertiary and Quaternary time faulting occurred along the western edge of the Tularosa Basin, causing the basin to lower with respect to the bounding San Andres and Organ Mountains. Faulting also traversed the Headquarters reentrant, and most of the area south of U.S. Highway 70 was downthrown a minimum of 2,500 ft (760 m) below the pediment. Many of the fault scarps are evident in the unconsolidated surface material, thus indicating very recent movement. Ruhe (1967, p. 21) suggested that some of this structural movement may have occurred as recently as 1,100 years ago.

A number of test wells have been drilled into the sediments that accumulated in the reentrant. Samples and logs from these wells indicate that sediments which accumulated near fault scarps are more gravelly and more poorly sorted than those near the center of the reentrant. Further to the east the sediments are generally well sorted and more fine grained. Consequently, the highest permeabilities are present near the center of the reentrant where the deposits are rather coarse grained and better sorted. The Post Headquarters well field has been developed in this area.

The sand percentage for the depth interval 500 to 1,000 ft (150 to 300 m) was calculated for wells in the Post Headquarters area (fig. 2). This interval was selected because most of it is below the water table and above a widespread clay unit. Although several exceptions were found, the sand percentage generally decreases basinward. The percentage is as low as 20 percent in the eastern part of the project area, but more than 80 percent in test well T-9.

Although these deposits have a number of similarities to those described by Knowles and Kennedy (1958) in the Hueco bolson and by Leggat and others (1963) in the Mesilla Valley, the data are insufficient for correlation of the sediments on the Missile Range with those in adjacent areas.

One of the most characteristic units of the Post Headquarters well field is a widespread and persistent clay unit (fig. 3). This deposit has been identified in the Gregg well, more than 10 mi (16.1 km) east of the well field, and as far south as test well T-16 on Fort Bliss Military Reservation. In test well T-12 the clay is approximately 100 ft (30 m) thick and is separated from the underlying conglomerate by a sequence of interbedded sand and clay.

(page 19 follows)

These data indicate that the conglomerate was deposited and partially lithified after the Tertiary intrusive rocks had been emplaced. Subsequent faulting offset the conglomerate as much as 2,500 ft (760 m) in the reentrant. A thin sequence of alternating layers of sand and clay was deposited before a widespread clay unit was laid down in the Tularosa Basin. This clay unit probably represents a playa lake deposit similar to those which are now common in the Tularosa Basin and in much of southern New Mexico (Hawley and Kottlowski, 1969, p. 100). The clay unit was then buried by a thick sequence of interbedded sand and clay that is extremely variable in lithology and areal extent. These deposits are composed of typical bolson-fill sediments.

The ground water in these bolson deposits of the faulted reentrant has been utilized for the municipal supply for the Post Headquarters. The water-bearing deposits in this reentrant are called the White Sands aquifer in this report.

WATER RESOURCES

Springs located along the flanks of the Organ and San Andres Mountains were used by Indians. Later these same springs were the sole source of water for the miners who flocked to the region after the Civil War. Best known were the San Augustin Springs that discharged from the fan deposits at the mouth of Rock Springs Canyon southwest of the Post Headquarters where Cox Ranch headquarters now is located. There has been little flow from these springs since about 1950.

Prior to establishment of the Missile Range in the mid-1940's, only a few domestic and stock wells were constructed in the region by homesteaders and ranchers. Most of these wells were less than 100 ft (30.5 m) deep and tapped perched water zones in the mountain canyons and along the mountain front. Locally, windmills were installed on abandoned mine shafts and used to pump water for livestock. Most of the old wells were measured by early workers at White Sands Missile Range, but subsequently have fallen into disrepair or have been destroyed. A summary of these data were tabulated by Davis and Busch (1968, table 3).

When White Sands Proving Grounds (later named Missile Range) was opened in 1946, a municipal well field was established in secs. 31 and 32, T.22 S., R.5 E., approximately 2 mi (3 km) southeast of the Post Headquarters. Nearly all these wells were less than 400 ft (120 m) deep, and torch-cut slots were ineffective in screening out the very fine sand which was the principal water-bearing unit. Also, these wells were grouped in a tight cluster which probably resulted in significant well interference. Consequently, this original well field proved unsatisfactory and all wells were abandoned by 1953.

Pumpage records from the original well field are incomplete prior to 1948; however, pumpage for that year was 82.3 million gallons (312,000 m^3) produced from 9 wells (fig. 4).

The first supply well (SW-10) was constructed in the Post Headquarters area in August 1948. Additional wells were added to the field to meet the water demands; in 1972 the total production for the Post Headquarters area was withdrawn from nine wells. Plans have been made to add two additional wells to the field in 1976. The largest annual total production prior to 1973 was 939.0 million gallons (3.55 million m^3) in 1971 (fig. 4). The decline in water level recorded in Main Gate well (fig. 4) reflects the downward trend of the water table which has been caused by this withdrawal.

Twenty-five observation wells have been completed in the study area to monitor water-level changes and water quality. Eighteen of these wells are located in the Post Headquarters area and two are located in the Hazardous Test Area. In addition, five exploratory holes were drilled in the Small Missile Range north of the Post Headquarters. One of these test wells (SMR-1) was completed as a supply well; three are used as observation wells; and one failed to penetrate potable water and was destroyed.

(page 25 follows)

In 1971 a total of 57 boreholes were drilled and logged in the study area to furnish additional control for mapping the water table and for data on water quality. Twenty of these boreholes are being monitored to supplement the existing observation-well network.

Data for more than 100 wells and boreholes located in the project area have been tabulated by Kelly (1973, table 1).

The water consumption in the Post Headquarters area is about three times greater during the summer than during the winter. Water consumption for industrial purposes does not vary appreciably during the year and major changes in population at the Post are not reflected in the overall water consumption. Therefore it is estimated that as much as one-third of all water pumped in the Post Headquarters area is used for irrigation of grass and shrubbery.

Consolidated rocks

Consolidated rocks are not important aquifers in the study area; however, they do yield small quantities of water to wells. Also numerous springs originate in these rocks. Only one production well has been constructed and tested in the consolidated rocks.

Test well HTA-1 was drilled on the pediment north of U.S. Highway 70. This well entered Precambrian granite at a depth of 82 ft (25 m) and was drilled to 250 ft (76 m). The driller noted that drilling became increasingly difficult with depth (Doty, 1968a, p. 27). Presumably a weathered zone was present at the upper surface of the granite and fractures became less numerous with depth. The completed well was pumped for 8 hours at a rate of 25 gal/min (1.6 l/s) with a drawdown of 18 ft (5.5 m). On the basis of this test a transmissivity of 228 ft^2/day (21 m^2/day) and a specific capacity of 1.4 (gal/min)/ft (0.29 (l/s)/m) of drawdown were computed. The well was equipped with a submersible pump in 1969 and has been used as a supply well for installations at the Hazardous Test Area since that time.

Test well HTA-2 also was drilled in this area; however, a bailer test conducted during the drilling indicated that the well had an extremely low yield, and consequently it was plugged and abandoned. In several places, windmills have been installed over abandoned mine shafts that were sunk in the igneous rocks. Numerous intermittent springs flow from the igneous rocks at the higher elevations of the nearby mountains. However none of these are considered to be important sources of water for the Post Headquarters.

Chemical analysis of water from well HTA-1 indicates that the water is potable; however it contains a somewhat high concentration of fluoride.

Two wells have been drilled at Organ, N. Mex. for municipal supply. These wells are believed to have penetrated the Magdalena Limestone which crops out north of the Post Headquarters. Both are rather low-yielding wells, and the water contains approximately 1,500 mg/l (milligrams per litre) dissolved solids. Calcium and sulfate are the principal ions.

Bolson deposits

More than 40 mi^2 (100 km^2) of the drainage area of the reentrant is higher than the 4,200-ft (1,280-m) land-surface contour line. This contour was selected as an arbitrary eastern boundary because it commonly marks the foot of the mountain front along the San Andres-Organ Mountain complex. In the Post Headquarters area, this contour is located approximately half a mile east of Headquarters Avenue which it parallels.

Most of the area north of U.S. Highway 70 consists of an eroded surface of igneous rocks that is blanketed by a veneer of bolson deposits. This is important to the aquifer only as a recharge area.

South of these igneous rocks the Post Headquarters is located near the center of a 14 mi^2 (36 km^2) area that is underlain by a thick sequence of bolson deposits containing the White Sands aquifer that has been developed for municipal supply (fig. 3). In general, this aquifer is bounded on three sides by faulted igneous rocks and on the east by an interface between saline water and freshwater. Extensive geophysical exploration by Herrick (1960, p. 40) and Zohdy and others (1969), as well as numerous test wells, show that these deposits are more than 2,000 ft (610 m) thick beneath the headquarters area. Farther east, at test well T-14, sediments are more than 6,000 feet (1,830 m) thick.

These aquifer deposits are quite variable in lithologic characteristics. Most of the sand and gravel strata contain some clay; well-defined sands generally are quite thin. The deposits commonly are poorly sorted and probably are relatively impermeable; in general the more coarse-grained deposits are found near the fault zones. Throughout much of the central part of the reentrant, the deposits are moderately well-sorted and relatively coarse-grained. Fine-grained sediments predominate east of the Post Headquarters area. Therefore it seems likely that the most permeable material is located in the central part of the reentrant, whereas areas of lower permeability are present along the mountain front and in the main part of the Tularosa Basin.

At a depth of approximately 1,000 ft (300 m), a well-defined clay unit was penetrated by a number of test wells (fig. 3). Locally this unit also contains minor quantities of silt and fine sand. An underlying conglomeratic deposit was penetrated by several holes drilled along the fault zones. This deposit is rather well lithified in some areas, whereas in other locations it is difficult to distinguish from the overlying bolson deposits. Consequently, it seems likely that the conglomerate was not identified in all the wells in which it was penetrated. The conglomerate probably would yield water to properly constructed wells; however, there are no data on the hydrologic characteristics of this unit nor the chemical quality of the water.

The heterogeneity of the bolson deposits, both vertically and laterally, has resulted in a wide range in values for the different hydrologic parameters. These are given in tables 1 and 2. It should be noted that although this is considered to be a water-table aquifer, a number of test wells have encountered artesian conditions. During short periods of pumping, on which many of the hydrologic parameters are based, the observed effects on a well may reflect these artesian conditions. However, during long periods of pumping the artesian effects probably would become less apparent and eventually the response to pumping would be that typical of a water-table aquifer. Consequently, the use of hydrologic data from specific wells may be grossly misleading when applied to the regional hydrologic environment and to the long-term development of the aquifer.

The calculated transmissivity of an aquifer, designated by "T" throughout this report, is a measure of the ease with which an aquifer transmits water. It is expressed in feet-squared per day.

Table 1.--Hydrologic characteristics of the aquifer in the vicinity of supply and test wells

Location	Well no.	Completion depth (feet)	Saturated thickness penetrated (feet)	Calculated transmissivity [(gal/d)/ft]	(ft2/day)	Specific capacity [(gal/min)/ft]	[(l/s)/m]	Sand fraction 500-1,000 feet or total depth (percent)
T.20 S., R.5 E.								
SW¼SW¼NW¼ sec. 34	SMR-3	1,000	703	350,000	46,900	96	19.3	52
T.21 S., R.4 E.								
NW¼NW¼SE¼ sec. 23	HTA-1	-	-	1,700	228	1.4	.3	-
T.21 S., R.5 E.								
SE¼SW¼SE¼ sec. 14	SMR-5	Plugged	666	no test	-	-	-	70
NW¼SW¼NE¼ sec. 16	SMR-1	473	192	7,900	1,158	5.9	1.2	-
SE¼NE¼SE¼ sec. 17	SMR-2	765	460	20,000	2,680	12.3	2.5	-
SE¼SW¼SW¼ sec. 20	SMR-4	580	306	100,000	13,400	29	6.0	32
NE¼NE¼NE¼ sec. 32	T-13	710	501	6,000	804	3.1	.6	38
T.22 S., R.4 E.								
NW¼SW¼SE¼ sec. 1	T-9	598	208	-	-	.1	.02	80
SE¼SE¼SE¼ sec. 1	T-1	450	50	no test	-	-	-	56
SE¼SE¼NE¼ sec. 11	T-8	895	342	1,200	160	2.0	.4	52
SE¼NW¼NE¼ sec. 12	SW-20	842	380	590,000	79,000	132	27.3	61
SE¼NW¼SE¼ sec. 12	SW-19	800	391	79,600	10,700	44	9.1	45

Table 1.--Hydrologic characteristics of the aquifer in the vicinity of supply and test wells - Continued

Location	Well no.	Completion depth (feet)	Saturated thickness penetrated (feet)	Calculated transmissivity [(gal/d)/ft]	(ft²/day)	Specific capacity [(gal/min)/ft]	[(l/s)/m]	Sand fraction 500-1,000 feet or total depth (percent)
T.22 S., R.4 E. - Continued								
SE¼SW¼SE¼ sec. 12	SW-18	800	405	4,780	632	18.1	3.7	44
			385	5,440	743	21.2	4.4	
NW¼SW¼NE¼ sec. 13	SW-17	800	504	30,000	4,020	26.1	5.4	44
NW¼NW¼SW¼ sec. 13	SW-13	534	234	5,000	670	3.5	.7	64
SW¼NE¼NE¼ sec. 13	T-2	400	62	no test	-	-	-	35
NW¼NW¼SE¼ sec. 13	SW-14	810	453	8,000	1,070	7.8	1.6	40
SE¼NE¼SE¼ sec. 13	SW-15	820	482	28,300	3,790	18.6	3.9	42
NE¼SW¼SE¼ sec. 13	SW-16	890	540	33,000	4,420	45.0	9.3	40
SW¼SW¼NW¼ sec. 14	T-6	515	311	no test	-	2.7	.6	-
NW¼NW¼NE¼ sec. 14	T-3	450	69	no test	-	-	-	32*
SE¼NW¼NE¼ sec. 23	SW-12	570	285	5,000	670	3.2	.7	59
SE¼SE¼SE¼ sec. 23	T-12	1,820	1,589	1,360	182	1.5	.3	49
NE¼NW¼NW¼ sec. 24	SW-11	500	195	2,500	335	12.0	2.5	-
NE¼NW¼NE¼ sec. 24	SW-10	505	139	61,600	8,170	23.6	4.9	-

Table 1.--Hydrologic characteristics of the aquifer in the vicinity of supply and test wells - Concluded

Location	Well no.	Completion depth (feet)	Saturated thickness penetrated (feet)	Calculated transmissivity [(gal/d)/ft]	Calculated transmissivity (ft^2/day)	Specific capacity [(gal/min)/ft]	Specific capacity [(l/s)/m]	Sand fraction 500-1,000 feet or total depth (percent)
T.22 S., R.4 E. - Concluded								
NE¼NW¼NE¼ sec. 24	SW-10A	805	404	114,000	15,300	37.5	7.8	48
NE¼NE¼NE¼ sec. 24	Main Gate	430	73	17,600	2,360	11.5	2.4	-
T.22 S., R.5 E.								
SW¼NW¼SW¼ sec. 5	T-10	555	305	13,900	1,862	7	1.5	14
NE¼SE¼SW¼ sec. 7	T-7	1,000	660	12,000	1,620	12	2.5	22
NW¼NE¼NE¼ sec. 15	T-14	370	239	no test	-	-	-	45
NW¼NW¼NW¼ sec. 16	T-4	400	177	no test	-	-	-	39
NW¼NW¼NW¼ sec. 20	T-5	400	130	no test	-	-	-	40
NE¼SW¼NE¼ sec. 29	T-11	800	521	12,750	1,698	6	1.2	35
SE¼SE¼NE¼ sec. 33	T-15	670	483	no test	-	-	-	40
T.22 S., R.6 E.								
SE¼NW¼SE¼ sec. 8	Gregg	500	270	19,600	2,626	12.4	2.6	54
T.23 S., R.5 E.								
NW¼NE¼SW¼ sec. 5	T-18	704	447	1,150	254	1.0	.2	32*
SW¼NW¼SE¼ sec. 10	T-16	710	523	37,600	5,040	10.8	2.2	61
NE¼SE¼NW¼ sec. 27	T-17	564	322	16,400	2,197	5.7	1.2	54

*Lower portion of hole in bedrock.

Table 2.--Specific capacity of supply wells*

Well number	Year																					
	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972
10	-	-	-	-	17.7	18.7	10.1	9.6	10.9	13.1	11.9	11.7	12.8	-	-	-	-	-	-	-	-	-
10A	-	-	-	-	-	-	-	-	-	-	-	-	-	39.6	44.4	57.5	90.0	53.3	51.6	45.8	47.9	46.8
11	-	-	-	-	-	16.6	20.7	23.5	23.4	23.3	24.8	24.2	47.3	-	31.0	25.0	29.8	32.6	16.3	25.3	26.4	-
12	-	-	9.7	12.3	4.8	8.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
13	13.9	-	-	-	16.5	30.9	8.3	10.4	16.8	6.9	8.9	12.9	9.0	8.5	8.0	9.2	-	14.4	6.6	9.1	15.8	9.5
14	-	-	-	-	13.5	15.9	13.6	9.6	31.2	11.7	11.0	6.6	7.5	5.9	-	-	-	-	-	-	-	-
15	-	-	-	-	32.0	26.9	29.0	25.0	22.6	23.0	22.1	29.0	20.0	14.6	21.5	15.6	16.5	16.6	15.2	15.4	12.5	15.0
16	-	-	-	-	25.7	30.6	40.8	43.1	31.0	26.4	28.4	35.9	55.5	41.0	41.6	46.8	44.0	46.6	36.8	38.2	38.5	47.0
17	-	-	-	-	-	-	-	-	-	-	-	35.0	33.1	31.1	26.0	37.4	-	40.4	30.8	30.2	39.8	29.3
18	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11.8	9.2	14.0	11.1	8.4	8.9	-	7.6
19	-	-	-	-		-	-	-	-	-	-	-	-	-	62.0	60.6	51.3	66.7	50.2	53.3	62.8	55.3
20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	156.4	117.3	-	156.4	111.2	194.4	125.0	117.1
SMR-1	-	-	-	-	-	-	-	-	-	-	-	7.7	7.7	6.3	6.3	-	-	-	-	-	-	-

*Specific capacity values are given in gallons per minute per foot of drawdown.

A total of 29 aquifer tests have been conducted on wells in the study area; these tests are the major source of hydrologic data available for the White Sands aquifer. The calculated transmissivities obtained during these tests range from a maximum of about 79,000 ft^2/d (7,300 m^2/d) to a minimum of 160 ft^2/d (15 m^2/d) (table 1). However, 27 tests provided transmissivities of 15,000 ft^2/d (1,400 m^2/d) or less; the average of these 27 transmissivities was about 3,000 ft^2/d (280 m^2/d) and the median was about 2,000 ft^2/d (190 m^2/d).

Supply well 20, which has an aquifer transmissivity of 79,000 ft^2/d (7,300 m^2/d), was drilled about equidistant from the fault zone and from supply well 19 which has a value of 10,700 ft^2/d (990 m^2/d). The unusually high transmissivity of the aquifer at supply well 20 probably is due to its proximity to the fault zones that commonly are areas of high permeability; although not indicated by the sample log, the deposits penetrated by supply well 20 probably are much better sorted, and therefore more permeable than elsewhere in the aquifer. The aquifer at test well SMR-3 has a transmissivity of 46,900 ft^2/d (4,360 m^2/d). This well was constructed on an alluvial fan at the mouth of Bear Canyon, at the extreme north end of the study area. As no other wells have been tested in this area, it is assumed that these alluvial deposits are highly permeable, but are not characteristic of the aquifer in general.

No data are available for determining the transmissivities of the clay unit and the conglomerate that underlie the aquifer. Although the clay probably represents the base of the aquifer, the more silty facies of this unit would yield water if the head of water in the overlying aquifer is lower than the head of water in the silty facies. Similarly, the conglomerate probably would yield water to the overlying formations, as well as to properly constructed wells. The transmissivity of the conglomerate would be a function of the degree of lithification which is quite variable; no tests have been made to determine the yield of wells completed in this unit.

Doty (1968b, p. 21) conducted an aquifer test on test well T-12 to determine the hydrologic characteristics of the lower portion of the aquifer, which he considered to be consolidated bolson fill. A transmissivity of 182 ft^2/d (17 m^2d) was obtained during the test. Later evaluation of the geophysical logs revealed that the test well had penetrated Precambrian rocks at a depth of 1,370 ft (418 m); all of the perforations were below 1,430 ft (436 m). Consequently, the transmissivity value obtained represents that of fractured igneous rocks rather than of consolidated bolson fill as originally suspected.

The coefficient of storage of a water-table aquifer is essentially the average specific yield of the material composing the aquifer. Specific yield is defined as the ratio of the volume of water that a rock unit will yield by gravity to its own volume. This value can be estimated by dividing the quantity of water pumped from the aquifer during a known period of time by the volume of the aquifer that was dewatered. Calculations made by Herrick (1960, p. 57) for that part of the aquifer near the Main Gate well indicated that the specific yield of the bolson deposits is approximately 15 percent. A similar value was calculated by Ballance and Longwill (written commun., 1968) for that part of the aquifer that was dewatered between 1949 and 1964. During the current investigation, the specific yield was calculated to be about 15 percent for the period 1948 through 1972.

Climatological data have been collected at the Post Headquarters area since 1949. Analysis of the precipitation data by Scott (1970, p. 10) indicated that the mean-annual rainfall for the 20-year period of October 1949 to September 1969 was 10.32 in (262.1 mm). The altitude of this station is about 4,250 ft (1,300 m). The average annual precipitation at the Cox Ranch was approximately 13 in (330 mm) between 1923 and 1952. Altitude of the ranch is about 4,525 ft (1,379 m). The Organ Peak station, which was operated between May 1968 and May 1973 at an altitude of 8,400 ft (2,560 m) recorded an average annual precipitation of 19.45 in (494.0 mm). A considerable amount of variation was indicated by the record at Organ Peak; the 1970 total was 14.88 in (378.0 mm) of precipitation, whereas in 1972 the total was 28.84 in (732.5 mm). On the basis of these data, the overall average precipitation for the reentrant is assumed to be approximately 16 in (410 mm) per year. This quantity of precipitation falling on the reentrant would total about 44,400 acre-ft (54.8×10^6 m^3) of precipitation for the 52 mi^2 (135 km^2) drainage area of the Post Headquarters.

Ballance and Basler (1966, p. 11) determined that only 3 percent of the precipitation on the bolson deposits entered stream channels or arroyos and acted as runoff. Scott (1970, p. 10) determined that the average annual runoff from the Post Headquarters area was only 0.016 inch (0.41 mm), about 0.1 percent of the rainfall. This high absorption rate of the unconsolidated material was recognized by W. R. Bauersfeld and T. E. Kelly on December 12, 1971. During the course of an aquifer test on supply well 18, 608 gal/min (38 l/s) were pumped into an arroyo. Measurements of the flow of water in the arroyo 1,500 ft (457 m) below the point of discharge indicated that the alluvium is capable of absorbing approximately 0.20 gal/min per linear foot (0.041 l/s per linear metre) along the bed of the arroyo. During this test the weather was not conducive to a high rate of evaporation.

These data indicate that most of the precipitation on the bolson deposits is absorbed and is probably held in the upper few feet of soil. This moisture is then consumed by evapotranspiration. The small fraction of precipitation which is concentrated into stream channels or arroyos also infiltrates the unconsolidated material. However, the moisture-holding capacity of the upper few feet is likely to be exceeded allowing the water to percolate downward rather than be consumed by evapotranspiration. On the basis of these findings it is estimated that about 3 percent of the precipitation on the bolson deposits reaches the aquifer as recharge.

Similarly, most of the precipitation on the granitic mountains is consumed by evapotranspiration. Fractures and soil cover hold some of the precipitation and return it to the atmosphere via evapotranspiration. Excess water finds its way into the stream channels or arroyos in the bolson material and infiltrates this unconsolidated material. In the absence of data, it is estimated that about 3 percent of the precipitation on the mountains may recharge the aquifer. Total annual recharge for the reentrant is therefore estimated to be about 1,300 acre-ft (1.6×10^6 m^3).

WATER QUALITY

The U.S. Geological Survey has defined saline water as water that contains more than 1,000 mg/l of dissolved solids (Krieger and others, 1957, p. 4). For convenience, waters discussed in this report are classified as "slightly saline," "moderately saline," "very saline," or "brine," according to the water-quality ranges suggested by Winslow and Kister (1956):

Description	Dissolved solids, milligrams per liter
Slightly saline	1,000 to 3,000
Moderately saline	3,000 to 10,000
Very saline	10,000 to 35,000
Brine	More than 35,000

McLean (1970) has shown that most of the Tularosa Basin is underlain by brine that locally exceeds a concentration of 200,000 mg/l dissolved solids. However, in a few isolated areas along the flanks of the basin there has been enough precipitation and runoff to maintain freshwater zones capable of supporting development. The Post Headquarters is located in one of these freshwater areas. However, the proximity of the brine has long been a critical factor in the development and use of the water resources at the Post Headquarters area of White Sands Missile Range.

East of the interface between the brine and the freshwater (fig. 5), brine is characteristic of the Tularosa Basin. However, test wells T-4, T-11, and T-13 all contain brine in the lower portion of the hole whereas the samples from shallower levels in the holes were potable. Consequently, Davis and Busch (1968, fig. 14) proposed that the brine extended beneath the Post Headquarters area and the well field. Zohdy and others (1969, fig. 12) based a similar conclusion upon geophysical methods.

Two water samples have been collected from the deposits which underlie the aquifer in the Post Headquarters area. A sample collected from the clay unit between 908 and 1,000 ft (277 and 305 m) below the surface in test well T-5 had a specific conductance of 672 micromhos (Herrick, 1960, p. 208) which is approximately equivalent to 440 mg/l dissolved solids (using the general conversion factor of 0.65). This sample was collected by a drill-stem test and some contamination by drilling fluid was reported. During the aquifer test conducted on the igneous rocks penetrated by test well T-12, a sample was collected which contained 272 mg/l dissolved solids. These samples, and the lack of brine in other deep test wells indicate that the brine does not underlie the Post Headquarters or the well field at depths shallower than 2,000 ft (610 m) below land surface. Furthermore, the current evidence indicates that the western edge of the interface between the brine and freshwater may be as much as 2 mi (3.2 km) east of the nearest production wells (fig. 5).

In general, the White Sands aquifer contains water having less than 600 mg/l dissolved solids (table 3). Most of the water samples collected from wells south of U.S. Highway 70, including those in the Post Headquarters well field, have dissolved solids concentrations generally less than 400 mg/l and as low as 200 mg/l. This is primarily a calcium bicarbonate type water.

Table 3.--Chemical quality of water for selected samples from wells and test wells in the project area

Location	White Sands Missile Range well identification	Depth of sample	Date of collection	Temperature (°C)	Milligrams per liter															Specific conductance (micromhos at 25°C)	pH
																		Hardness as $CaCO_3$			
					Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids	Calcium magnesium	Noncarbonate		
T.20 S., R. 5 E. SW¼SW¼NW¼ sec. 34	SMR-3	1,000	1-14-67	26	24	0.00	86	47	38		262	0	200	41	0.5	7.2	573	406	192	396	7.5
T.21 S., R. 4 E. SW¼SW¼SW¼ sec. 11	HTA-windmill	189	11-16-66	-	24	.02	82	13	60		238	0	115	34	4.0	22	471	260	65	746	7.7
NW¼NW¼SE¼ sec. 23	HTA-1	250	10- 5-66	22	34	.00	82	-	53		221	0	116	28	4.0	29	468	260	79	711	7.5
T.21 S., R. 5 E SE¼SW¼SE¼ sec. 14	SMR-5	666	12-18-67	22	15	.02	575	685	2,500		278	0	6,450	1,930	3.3	.4	12,300	4,250	4,020	13,900	7.5
NW¼SW¼NE¼ sec. 16	SMR-1	473	6-25-60	27	-	-	74	51	-		292	0	142	24	1.0	4.6	484	396	156	785	7.8
SE¼NE¼SE¼ sec. 17	SMR-2	747	9-29-60	29	30	.31	75	40	39	2.2	275	0	162	29	1.5	4.3	531	352	126	781	7.7
SE¼SW¼SW¼ sec. 20	SMR-4	1,016	11-20-67	29	36	.01	64	9.8	126		222	0	173	70	1.3	12	601	200	18	920	7.7
NE¼NE¼NE¼ sec. 32	T-13	501	12-12-72	24.5	38	.09	51	12	36	3.3	150	0	80	28	.9	2	332	180	54	512	7.7
T.22 S., R. 4 E NW¼SW¼SE¼ sec. 1	T-9	904	8- 9-72	25.5	23	.02	100	23	51	3.7	208	0	66	30	.5	7.7	389	240	68	606	7.3
SE¼SE¼SE¼ sec. 1	T-1	450	7-14-53	-	24	.03	44	9.5	32		188	0	41	14	.4	.5	257	149	0	409	7.4
SE¼SE¼NE¼ sec. 11	T-8	623	8- 9-72	24.5	25	.03	53	20	45	3.0	122	0	150	37	.7	.5	396	210	110	632	8.1
SE¼NW¼NE¼ sec. 12	SW-20	838	8-20-71	-	45	.01	52	11	29	2.0	166	0	86	19	.1	1.9	334	180	39	478	7.7
SE¼NW¼SE¼ sec. 12	SW-19	800	6-16-71	-	42	.01	39	7.9	26	1.9	161	0	49	11	.1	1.2	262	130	0	213	7.5
SE¼SW¼SE¼ sec. 12	SW-18	800	3-31-64	-	24	.09	15	1.5	79		112	0	56	16	.02	3.5	-	44	0	382	7.4
NW¼SW¼NE¼ sec. 13	SW-17	900	6-16-71	-	33	.01	33	.5	41	1.8	133	0	64	18	.06	1.9	270	100	0	378	7.9
NW¼NW¼SW¼ sec. 13	SW-13	534	6-16-71	-	43	.01	63	15	27	2.6	148	0	100	19	.06	12	396	220	96	540	7.7
SW¼NE¼NE¼ sec. 13	T-2	400	6-18-53	-	36	-	60	8.4	39		138	31	64	26	.50	.1	333	184	18	505	8.7
NW¼NW¼SE¼ sec. 13	SW-14	810	6-18-64	24	41	.14	36	7.5	25		139	0	43	9.5	.4	3.1	234	121	7	341	7.3
SE¼NE¼SE¼ sec. 13	SW-15	820	6-16-71	-	43	.02	40	7.7	26	2.0	141	0	46	9.9	.5	1.5	251	130	16	334	7.8
NE¼SW¼SE¼ sec. 13	SW-16	890	6-16-71	-	44	.01	35	7.7	24	1.8	137	0	44	9.2	.5	1.4	240	120	7	329	7.8
SW¼SW¼NW¼ sec. 14	T-6	480	12-12-72	22	33	.06	49	11	30	1.9	195	0	52	16	.8	.04	290	170	8	421	7.3
NW¼NW¼NE¼ sec. 14	T-3	450	6- 1-53	-	33	-	60	12	56		300	0	50	15	.5	.1	375	199	0	610	7.6
SE¼SE¼SE¼ sec. 23	T-12	1,820	3-30-67	24	35	.25	34	6.3	39		126	0	73	10	.5	.3	272	111	8	410	7.4
NE¼NW¼NW¼ sec. 24	SW-11	500	6-17-71	-	50	.01	40	10	23	2.2	125	0	61	14	.5	4.7	283	140	39	373	7.7
NE¼NW¼NE¼ sec. 24	SW-10A	805	6-17-71	-	45	.01	32	6.9	24	1.7	133	0	48	8	.5	1.1	236	110	0	317	7.8
T.22 S., R. 5 E SW¼NW¼SW¼ sec. 5	T-10	523	12-12-72	24	35	.05	32	7.3	28	2.0	127	0	46	16	.3	.98	234	110	6	336	8.1
NE¼SE¼SW¼ sec. 7	T-7	947	12-12-72	23	30	.04	29	3.8	47	2.2	116	0	56	22	.5	1.6	255	88	53	384	7.9
SE¼SW¼SW¼ sec. 8	B-47	325	6- 7-72	-	36	.01	39	6.8	26	2.6	144	0	55	10	.5	1.3	253	130	7	379	7.3
NW¼NE¼NE¼ sec. 15	T-14	218	12-12-72	22.5	52	.09	41	5.2	45	4.4	137	0	79	23	.4	1.1	322	120	11	463	7.7
NW¼NW¼NW¼ sec. 16	T-4	313	12-12-72	22.0	24	.04	25	4.3	30	2.4	87	0	43	21	.4	1.1	198	80	9	303	8.0
NW¼NW¼NW¼ sec. 20	T-5	331	12-12-72	23.0	35	.02	37	7.1	40	2.2	111	0	54	35	.4	2.7	277	120	31	432	7.9
NE¼SW¼NE¼ sec. 29	T-11	555	12-12-72	23.5	32	.03	31	6.1	38	2.3	115	0	46	33	.4	.87	249	100	8	386	7.9
SE¼SE¼NE¼ sec. 33	T-15	424	12-12-72	22.0	2.3	.09	44	1.0	140	5.2	0	19	130	210	.7	.05	556	110	82	1,040	8.8
T.22 S., R. 6 E SE¼NW¼SE¼ sec. 8	Gregg	500	9- 7-61	-	40	-	455	478	3,340		317	0	8,730	708	6.4	.3	13,900	3,100	2,840	14,900	7.4
T.23 S., R. 5 E NW¼NE¼SW¼ sec. 5	T-18	506	5-29-69	32	32	.09	38	1.9	98		153	0	119	42	3.1	.2	409	103	0	541	7.4
SW¼NW¼SE¼ sec. 10	T-16	310	3-28-69	25	38	.56	34	5.6	33		127	0	48	16	.6	3.2	240	108	4	355	8.1
NE¼SE¼NW¼ sec. 27	T-17	440	5-10-69	27	28	.05	30	1.7	34		113	0	42	11	.6	4	207	32	0	301	7.8
SW¼SW¼SW¼ sec. 35	F-1	1,012	5- 3-53	-	34	0	42	3.8	44	.4	94	0	59	54	.5	4	299	120	0	471	7.4

Samples collected from the Small Missile Range wells are slightly more mineralized than those from the Post Headquarters well field. Sulfate is the primary anion and the water has greater hardness than the wells in the Post Headquarters area. Locally, chloride is present in significant quantities.

A plot of the principal anions and cations in samples from these two areas show that the two waters are quite distinct even though the total concentration of ions is similar (fig. 6). Two samples from wells in the Hazardous Test Area plot midway between the samples from the other two areas in this figure.

Water samples have been collected and analyzed intermittently from 14 of the supply wells and test wells. In 10 of these wells (SW-11, SW-12, SW-13, SW-15, SW-16, SW-17, T-4, T-5, T-11, T-13) the concentration of dissolved solids in the water has progressively increased since the first samples were collected. The water quality in the remaining 4 wells (SW-10, SW-14, T-7, T-10) has remained unchanged. The average rate of increase of dissolved-solids concentration is shown in figure 5. The progressive change in water quality is best illustrated by analyses of samples collected from supply well 13. In May 1956, water from this well contained 208 mg/l dissolved solids; calcium and bicarbonate were the principal ions. Dissolved solids increased progressively through June 1971, when a concentration of 396 mg/l was determined by chemical analysis. Calcium was the principal cation in this sample, but there were nearly equal proportions of sulfate and bicarbonate. The increase in dissolved solids was due primarily to the increasing amounts of sulfate and calcium.

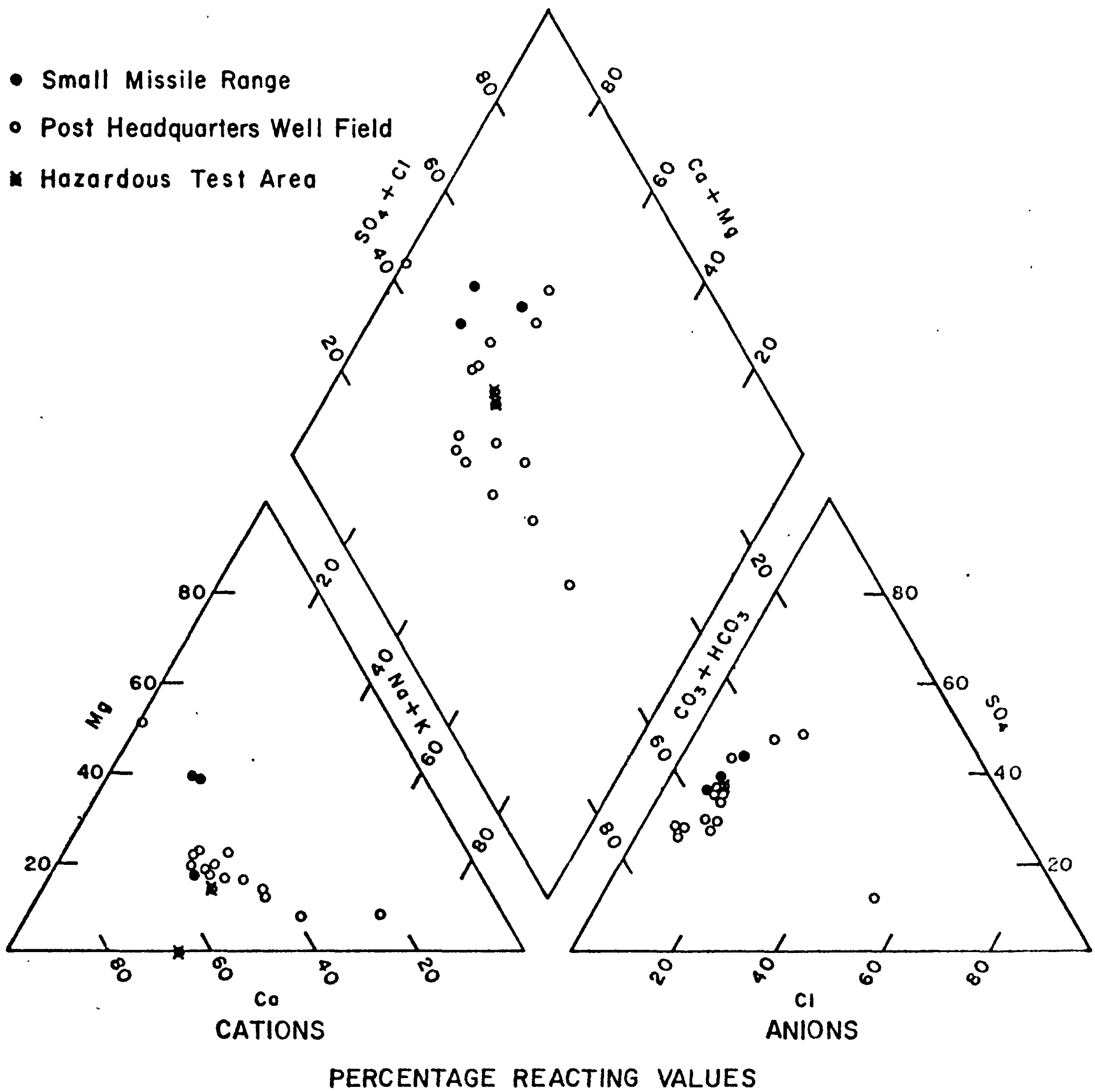


Figure 6.--Piper diagram showing distribution of principal chemical constituents in selected water samples.

With the exception of T-13, water from the test wells located east of the well field has shown the greatest increases in dissolved solids.

Water from test well T-4 has increased an average of 16.8 mg/l dissolved solids per year between 1967 and 1973 (fig. 7). Water from supply well 13 has shown an increase of 7.0 mg/l dissolved solids per year prior to 1965 and 20 mg/l since then (fig. 8). Water from supply well 16, which is still in use (1973) has increased only 0.8 mg/l dissolved solids per year (fig. 9).

It should be noted that none of the wells were consistently sampled from the same depth, and this may be partially responsible for some change in quality. Nevertheless, the quality changes illustrated in figures 7, 8, and 9, as well as in other wells, are too consistent to be attributed entirely to variations in sample depths.

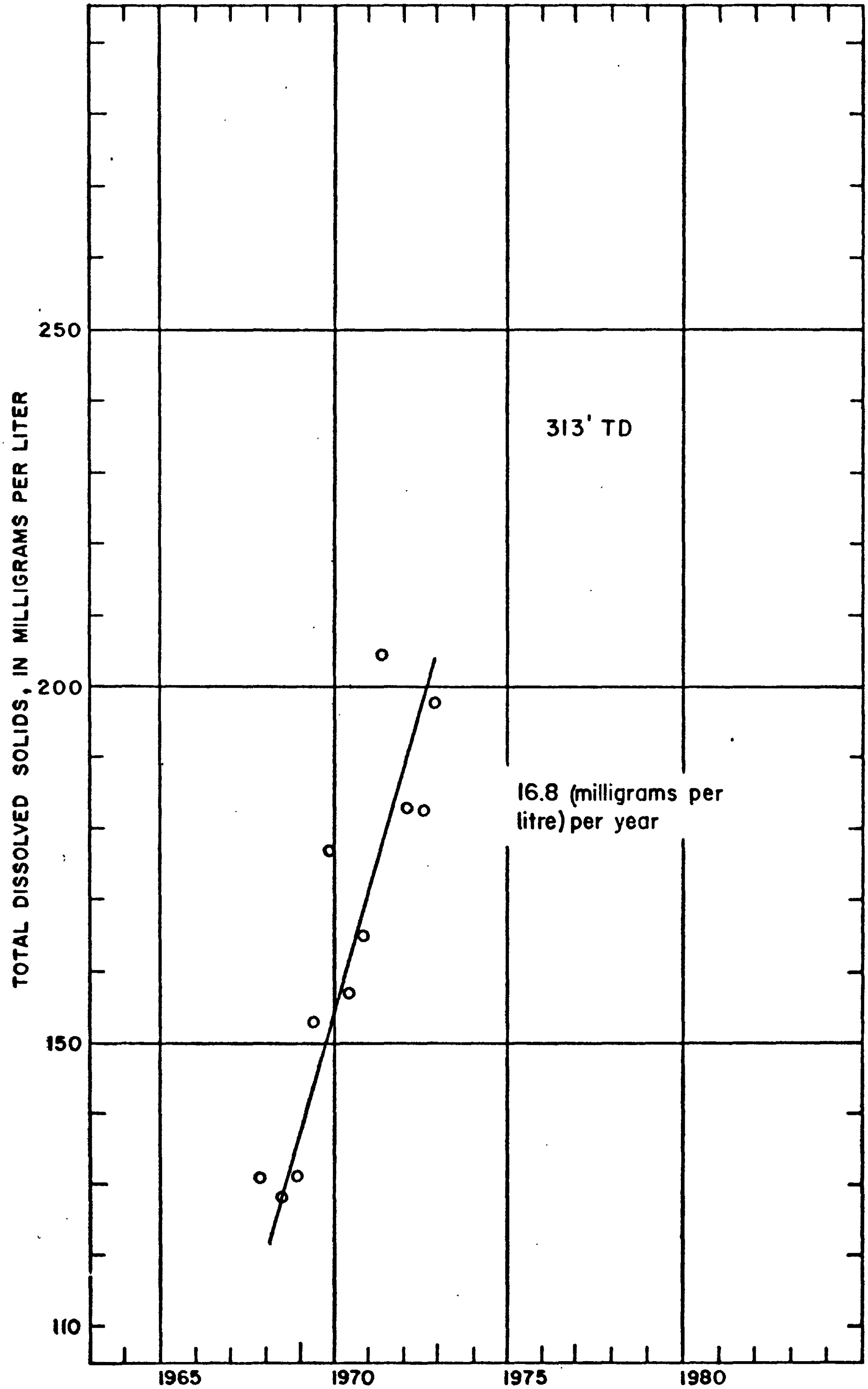


Figure 7.--Diagram showing changes in dissolved solids in samples from well T-4.

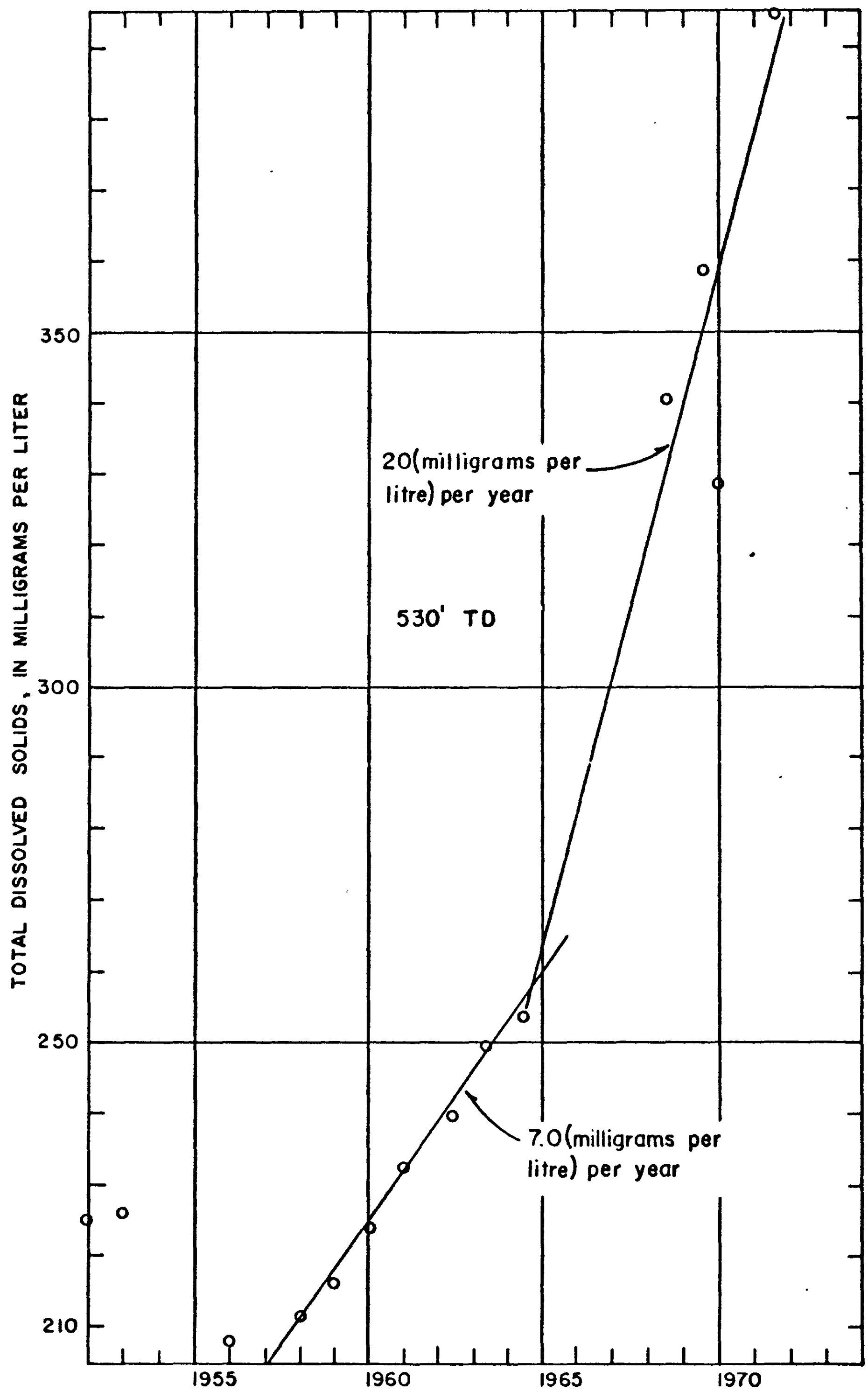


Figure 8 --Diagram showing changes in dissolved solids in samples from supply well-13

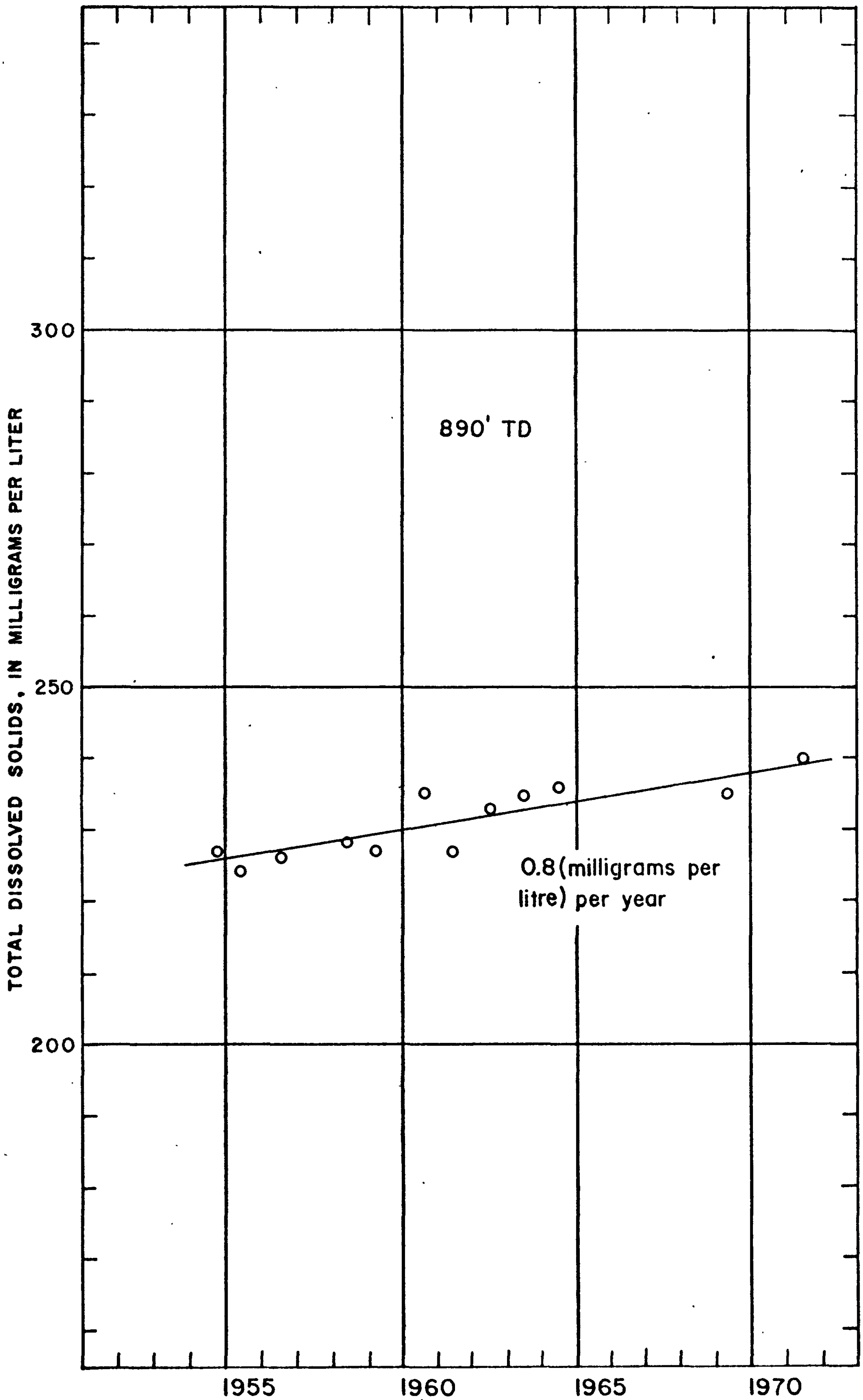


Figure 9 --Diagram showing changes in dissolved solids in samples from supply well 16.

Although all the water samples collected are of excellent chemical quality and meet the recommended standards set by the U.S. Public Health Service (1962) for drinking water, the small but progressive increase in dissolved-solids concentrations indicates that more-saline water is now entering the Post Headquarters area. Water from the heavily pumped supply wells has shown only slight-to-moderate increases in dissolved solids. In 1973, none of the water exceeded 400 mg/l dissolved solids. If the well field were underlain by brine that characterizes the Tularosa Basin, as suggested by earlier workers, the increase in dissolved solids probably would have been much more significant. Upward leakage from a source containing slightly saline water could account for these moderate increases. A sample from below 908 ft (277 m) in test well T-5 indicates that the clay unit of the underlying deposits is a possible source of this saline water.

The most significant changes in dissolved-solids concentrations were observed from water samples collected from three test wells (T-4, T-5, and T-11) that are located in close proximity to the brine fresh-water interface (fig. 5). Chemical analyses of water samples from test wells T-7 and T-10 indicate little or no recognizable increase in dissolved-solids concentrations. These data indicate that the interface between brine and freshwater probably is moving progressively toward the well field and that the greatest amount of movement has occurred in the vicinity of test wells T-4 and T-11.

EVALUATION OF THE AQUIFER

The White Sands aquifer has been the main source of water for the White Sands Missile Range since 1948. The withdrawal of ground water from the White Sands aquifer has resulted in lower water levels and small but progressive increases in dissolved solids. The continuation of these trends will eventually limit the ability of the aquifer to supply adequate quantities of water of suitable quality. The purpose of this evaluation is to estimate the probable effects of continued ground-water withdrawal on both water levels and water quality.

Projected water-level declines are obtained from a digital simulation model of the White Sands aquifer. An attempt to accomplish this with an analog model proved unsuccessful (W. C. Ballance and S. M. Longwill, written commun. 1968). This was attributed to the lack of accurate knowledge of the geologic and hydrologic conditions. Subsequently, additional data have been collected and the state of the art of digital modeling has been advanced. With the improvements in both data and method of analysis, a digital model of ground-water flow is now possible.

Projected changes in water quality are not quantified. A digital model of the transport of dissolved solids would be possible if the appropriate parameters could be determined. For the White Sands aquifer, the limited knowledge of both the predevelopment water-quality distribution and the subsequent changes make the determination of these parameters impossible. Dissolved-solids concentration in water produced from the White Sands aquifer is discussed only qualitatively. Due to this limitation of the evaluation, a data-collection network to provide advance warning of quality deterioration is suggested.

Digital simulation model of ground-water flow

A digital model is a mathematical description of a physical and hydrologic system. Such a model is only as accurate as the values used to describe the hydrogeologic variables. The ideal model should have accurate quantitative values that describe aquifer storage, transmissivity, boundaries, and hydraulic stresses in time and space. Since these parameters are only poorly defined in many model studies, it is necessary to calibrate the model.

Flow equations

The movement of ground water is three dimensional. That is, flow vectors can be resolved into three components: two horizontal components and a vertical component. Vertical flow components will be modified most in the vicinity of pumping wells. Here, the primary effect of restricted vertical flow on the aquifer's response to ground-water withdrawal is to delay the release of water from storage. For the long-term analysis attempted here, this effect should be negligible. A two-dimensional model therefore is considered a reasonable approximation of the aquifer under a long-term stress.

The equation used in this model was:

$$\frac{\partial}{\partial x} bK(x,y)\frac{\partial h}{\partial x} + \frac{\partial}{\partial y} bK(x,y)\frac{\partial h}{\partial y} = S_y(x,y)\frac{\partial h}{\partial t} + Q(x,y),$$

where

b is the saturated thickness (L);

h is the hydraulic head (L);

$K(x,y)$ is the hydraulic conductivity (LT^{-1});

$S_y(x,y)$ is the specific yield (dimensionless);

t is time (T);

$Q(x,y)$ is pumpage per unit area (LT^{-1})

The equation is approximated with a finite-difference equation by applying Taylor's theorem (Pinder and Bredehoeft, 1968).

A finite-difference rectangular grid is superimposed on a map, subdividing the area modeled into a large number of nodes (fig. 10). At each node the saturated thickness of the aquifer, the hydraulic conductivity, and the storage coefficient are entered into the program. Boundary conditions and pumpage are also entered at the appropriate nodes. The finite-difference equation is solved at each node using the iterative alternating direction implicit (IADI) technique. For this study, these difference equations were solved on a CDC6600 computer using a program developed by Pinder (1970b) and modified by Trescott (1973).

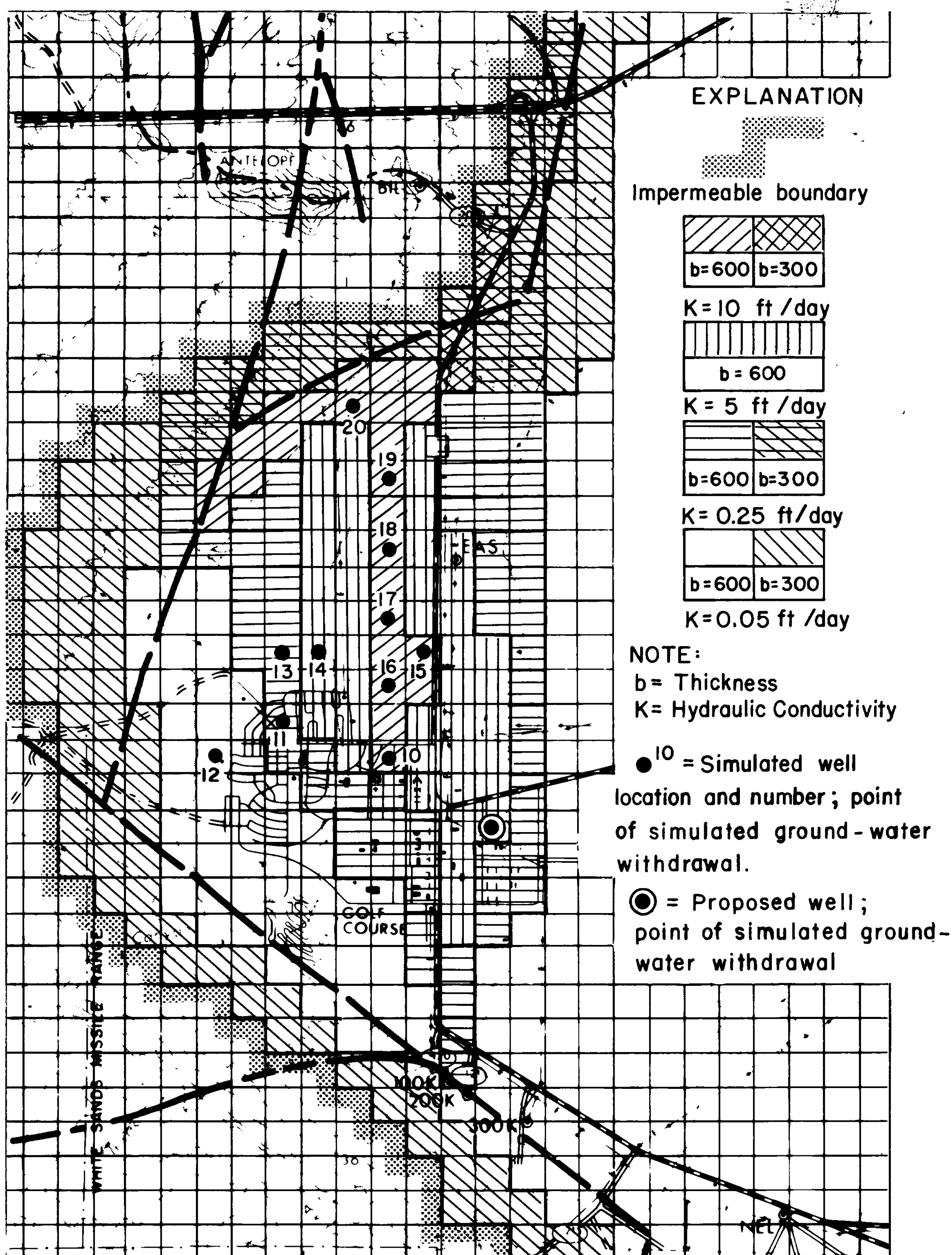


Figure 10.-- Finite-difference grid, aquifer parameters, and boundaries of the modeled Post Headquarters area.

Physical system assumed for the model

To define the physical system assumed for the model it is necessary to specify the physical boundaries of the model. Within these boundaries, three physical parameters need to be specified at each node: saturated thickness, hydraulic conductivity, and specific yield.

The areal extent of the model is shown on figure 10. The impermeable boundary to the west simulates the crystalline rock underlying the mountains which form the reentrant. The impermeable boundaries to the north, east, and south were arbitrarily located at a considerable distance from the pumping wells. Although the actual boundaries are even more distant, the assumed boundaries are sufficiently distant from the pumping wells to produce negligible error.

Transmissivity is a measure of the ability of an aquifer to transmit water under a hydraulic gradient and is the product of hydraulic conductivity and saturated thickness. The withdrawal of ground water decreases the saturated thickness and hence the transmissivity. To simulate this effect in the model, both saturated thickness and hydraulic conductivity were estimated at each node.

The saturated thickness of the aquifer was estimated to be 600 ft (183 m) except for the western margin where it thins to 300 ft (91 m) before terminating along the mountains forming the reentrant (fig. 10). This aquifer thickness was selected because the extensive clay layer was assumed to be an effective barrier to ground-water flow.

Initial estimates of hydraulic conductivity were based on several aquifer tests which have been conducted on the White Sands aquifer (table 1). These estimates were modified during the calibration procedure to the values shown in figure 10.

The specific yield was estimated to be 0.15 from the ratio of total ground-water withdrawals to volume of dewatered sediments.

Hydrologic system assumed for the model

Prior to 1948, the White Sands aquifer was in a steady-state condition; that is, there had been no major ground-water withdrawals and no major changes in water levels, recharge, or discharge. The withdrawal of water since 1948 has produced changes in water levels, but not in recharge or discharge.

Brine flows through the modeled area from north to south in the central part of the Tularosa basin. Locating the arbitrary boundaries far to the north, east, and south makes it reasonable to assume that these flow rates remain unchanged.

Freshwater recharges the aquifer by infiltration from arroyos discharging from the mountains. The rate of infiltration depends only on the permeability of the channel material and the availability of flow. Being independent of the head in the aquifer, the rate of recharge should be unaffected by ground-water withdrawal.

The freshwater moves easterly through the reentrant with most of the flow concentrated in the more permeable material above the extensive clay layer. Although some leakage through the clay layer does occur, the model of ground-water flow assumes this quantity to be negligible.

The flow of freshwater through the reentrant may be augmented by a wedge of freshwater flowing southerly along the mountain front. Part of the freshwater flows easterly, mixing with or overriding the brine. The remainder flows south along the mountain front. Again, the distance to the north, east, and south boundaries is such that these flow rates remain unchanged.

The only change in the hydrologic system is the withdrawal of ground water to meet the demands of the White Sands Missile Range Post Headquarters. Locations of supply wells are indicated in figure 10. Pumpage of the supply wells for 1948 through 1971 was simulated to calibrate the model. Two possible distributions of ground-water withdrawal were simulated for 1972 through 1995. For both, actual 1972 and 1973 pumpages were used. For one, the pumpage distribution of 1973 was assumed to continue unchanged. For the other, a new well was assumed to begin operation in 1976.

Calibration criteria and results

As the measured aquifer parameters (saturated thickness, hydraulic conductivity, and specific yield), hydrologic stress (pumpage), and system response (change in water levels) are subject to error, a calibration procedure was used to improve estimates of parameter values and provide a subjective basis for judging the validity of projected water-level declines. The data required to calibrate a model are the response (change in water levels) to a known hydrologic stress (pumpage). Aquifer parameters are then adjusted so that the response simulated by the model approximates the observed response.

For the White Sands aquifer, the period from 1948 to 1972 was selected as a calibration period. Ground-water withdrawals from 1948 through 1971 are shown in table 4. The change in water level due to these withdrawals was estimated by subtracting the 1972 water levels (fig. 11) from the 1949 predevelopment water levels (fig. 12). The resulting contour configuration is shown in figure 13. The pre-development water levels were estimated from very meager data. As such, the error may be fairly large. Thus, simulation of exact contours would be extremely fortuitous. Simulated changes in water levels were expected to approximate the general shape of the contours in figure 13. Also, disagreements were expected to be smaller to the east of the highway where the predevelopment water surface flattens. Saturated thickness of the aquifer, hydraulic conductivity, and specific yield were estimated for each node of the rectangular grid. Of these, hydraulic conductivity is the least accurately defined and the most variable over the modeled area. Because of this, the model was calibrated by modifying the areal distribution of hydraulic conductivity. The water-level-change contours of figure 14 were simulated using the hydraulic-conductivity values shown in figure 10. Disagreement between the contours of figure 14 and figure 13 could be due to errors in the estimated water levels in 1949 (fig. 12).

Table 4.--Ground-water withdrawal for 1948 through 1971

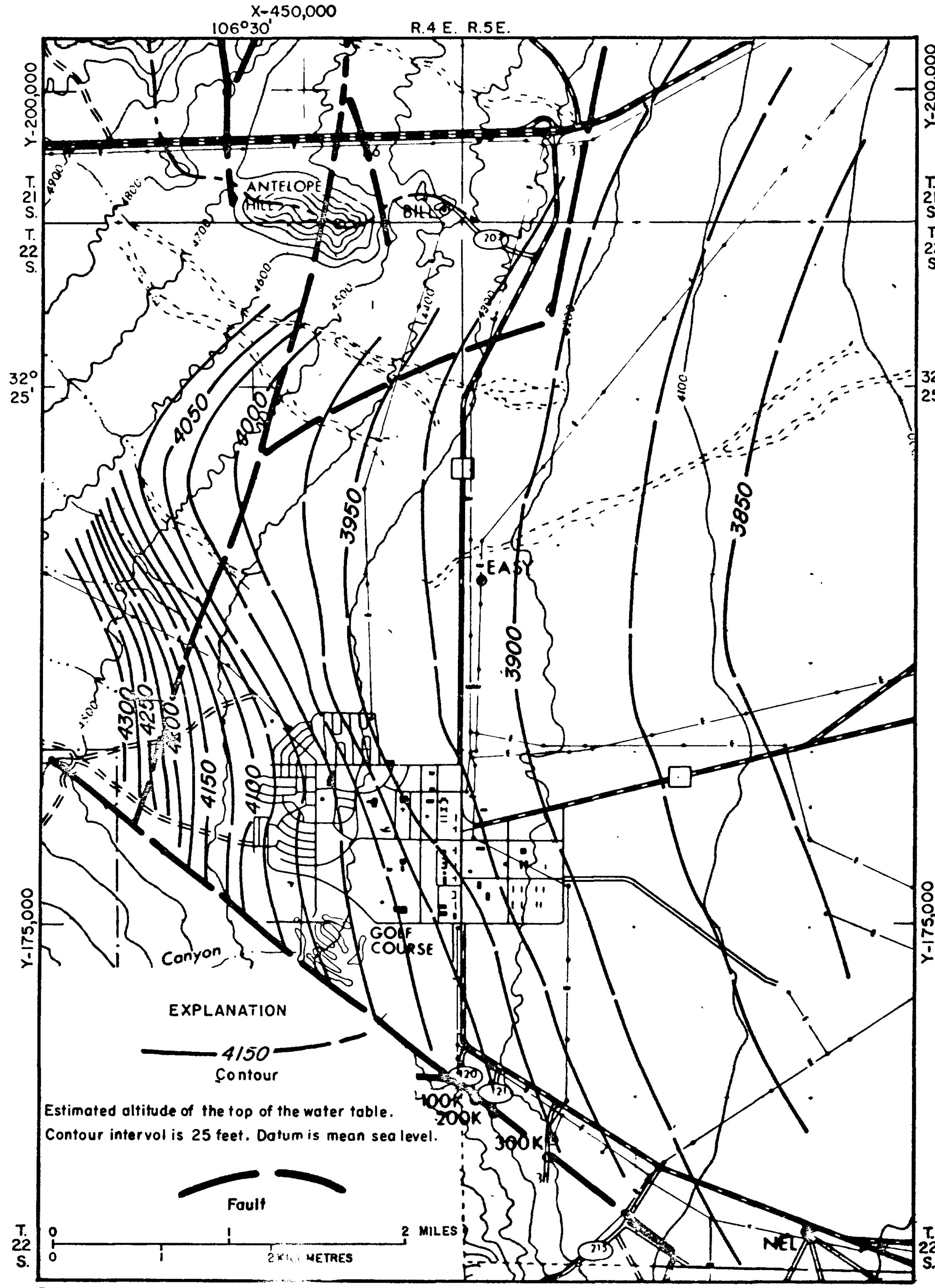
(Well locations shown on figure 10. Average annual withdrawal rate[1/])

Year	Supply well											Total
	10,10A	11	12	13	14	15	16	17	18	19	20	
1948	0.0017	-	-	-	-	-	-	-	-	-	-	0.00
1949	.0054	-	-	-	-	-	-	-	-	-	-	.01
1950	.0614	-	-	-	-	-	-	-	-	-	-	.06
1951	.1175	0.1794	-	-	-	-	-	-	-	-	-	.30
1952	.2758	.2953	0.1179	0.1267	-	-	-	-	-	-	-	.82
1953	.3306	.3262	.1853	.1609	-	-	-	-	-	-	-	1.00
1954	.3006	.2133	.2221	.1774	0.2720	0.0897	-	-	-	-	-	1.28
1955	.1132	.0001	.0211	.0793	.5399	.4411	0.2116	-	-	--	-	1.41
1956	.2524	.1324	.0145	.2292	.3275	.3440	.2611	--	-	-	-	1.56
1957	.2655	.2026	-	.1669	.3678	.3747	.2959	-	-	-	-	1.67
1958	.2541	.2335	-	.2634	.0922	.5284	.4164	-	-	-	-	1.79
1959	.3191	.1838	-	.2834	.5360	.5430	.5120	-	-	-	-	2.38
1960	.3147	.3198	-	.2669	.5081	.6379	.5566	-	-	-	-	2.60
1961	.1556	.3033	-	.1822	.4561	.6093	.5701	0.4857	-	-	-	2.76
1962	.0693	.2407	-	.1717	.2335	.5079	.8536	.7179	-	-	-	2.79
1963	.1754	.2789	-	.2182	.3077	.4541	.8185	.6996	-	-	-	2.95

Table 4.--Ground-water withdrawal for 1948 through 1971 - Concluded

Year	Supply well											Total
	10,10A	11	12	13	14	15	16	17	18	19	20	
1964	0.8174	0.2401	-	0.1203	0.2018	0.6032	0.7898	0.6344	0.0476			3.45
1965	.4862	.1412	-	.0852	-	.1202	.1843	.1552	.1910	0.4969	0.6895	2.55
1966	.4365	.1505	-	.1078	-	.1879	.2427	.2458	.3708	.5484	.8037	3.09
1967	.4956	.2517	-	.1078	-	.3862	.4082	.3486	.4373	.6007	.7091	3.75
1968	.3619	.2565	-	.1170	-	.3302	.4065	.4056	.4110	.4951	.5756	3.36
1969	.3584	.3588	-	.1778	-	.3414	.4891	.5149	.5089	.2986	.6104	3.66
1970	.6147	.2671	-	.0731	-	.1274	.4705	.5444	.4000	.7996	.5175	3.81
1971	.6943	.2856	-	.1838	-	.0337	.5797	.6387	.4112	.7995	.7648	4.39

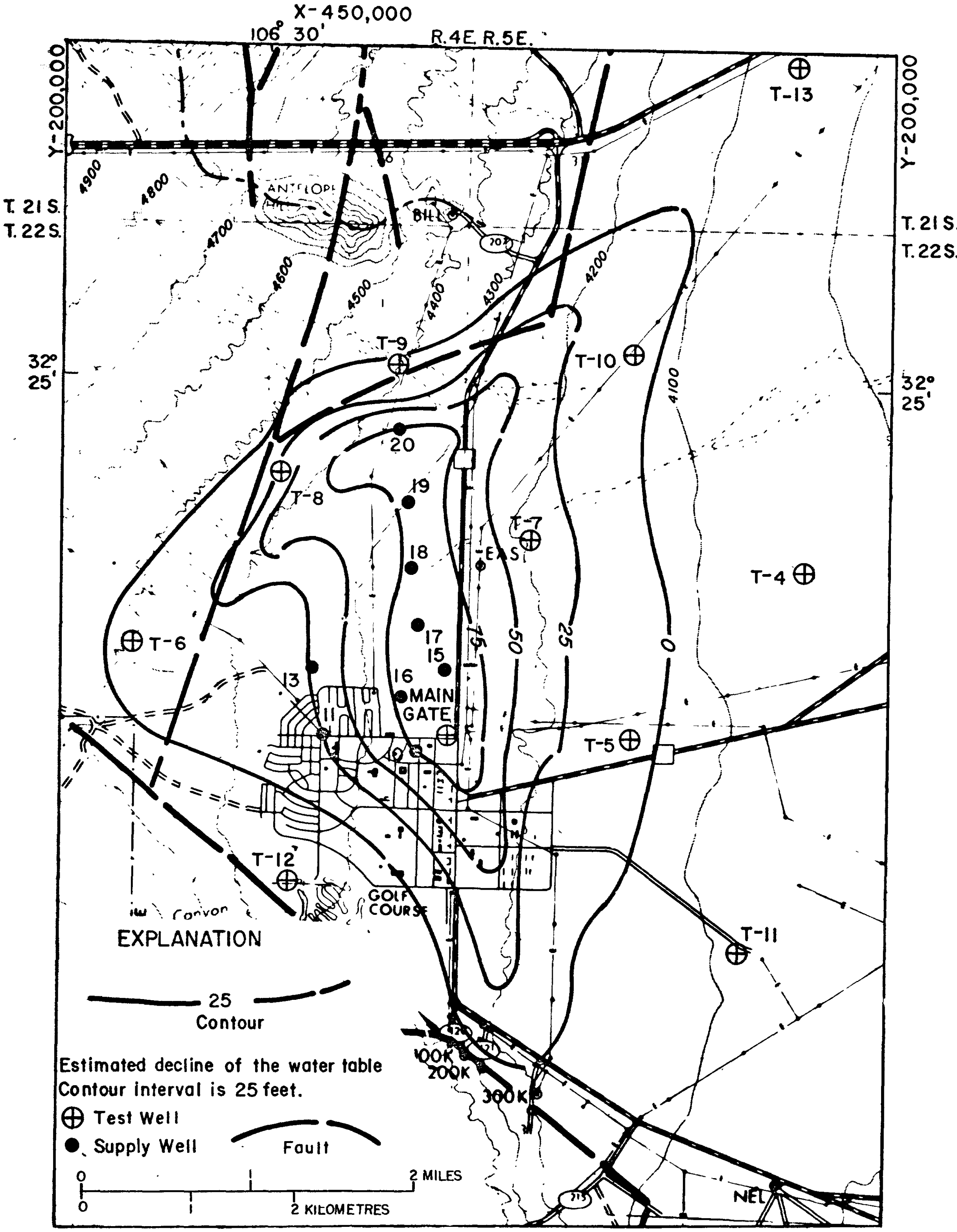
1/ Ground-water withdrawal rates in cubic feet per second for the 1948 to 1972 calibration period.



Base from White Sands Missile Range Master Plan Basic Information Maps, 1972

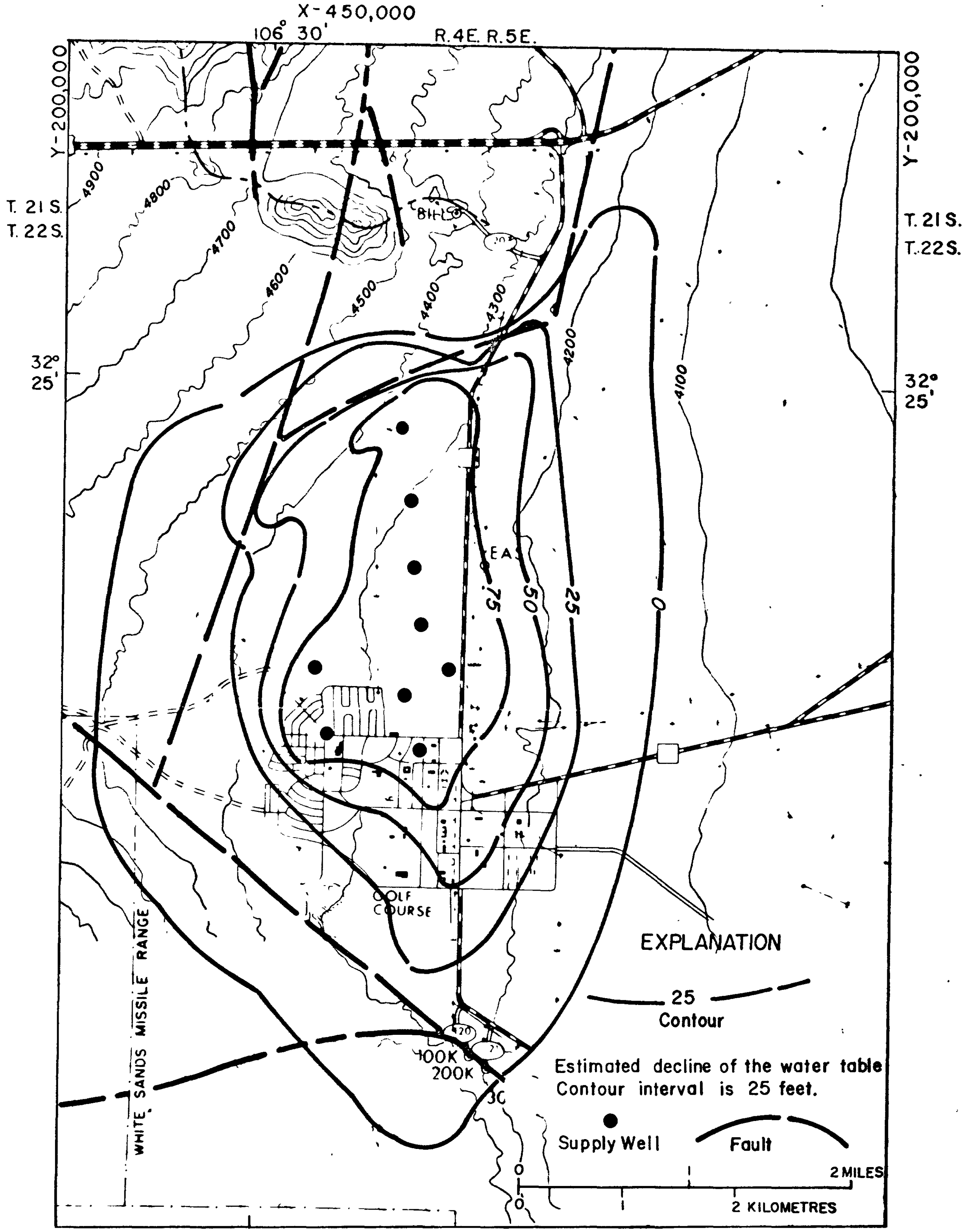
Compiled by T.E. Kelly, 1972. Adapted from W.C. Ballance and S.M. Longwill (written commun. 1966)

Figure 12.-- Contour map of water table, 1949 (estimated).



Base from White Sands Missile Range
Master Plan Basic Information Maps, 1972

Figure 13.-- Measured water-level change for the period 1949 through 1972.



Base from White Sands Missile Range
Master Plan Basic Information Maps, 1972

Figure 14.-- Simulated water-level declines for the period 1949 through 1972. (Measured contours are shown in figure 13.)

Projected water-level declines

The systems response to the continued withdrawal of ground water was simulated on the digital model. Two distributions of withdrawal stress were used. In each, the measured withdrawal for 1972 and 1973 was used. The total annual withdrawal rate for 1974 through 1995 was assumed to equal the 1973 withdrawal. The aquifer parameters used are shown in figure 10.

The first stress simulated by the model assumed that the 1973 withdrawal rates were continued (table 5). The 1986 and 1996 water-level declines calculated by the digital model are shown in figures 15 and 16 respectively. The decline in water level since 1948 in the vicinity of the Main Gate well is calculated to increase from the 1972 level of about 80 ft (24 m) to about 125 ft (38 m) in 1986 and about 160 ft (49 m) in 1996. The simulated decline through 1996 does not exceed 200 ft (61 m) anywhere in the modeled area.

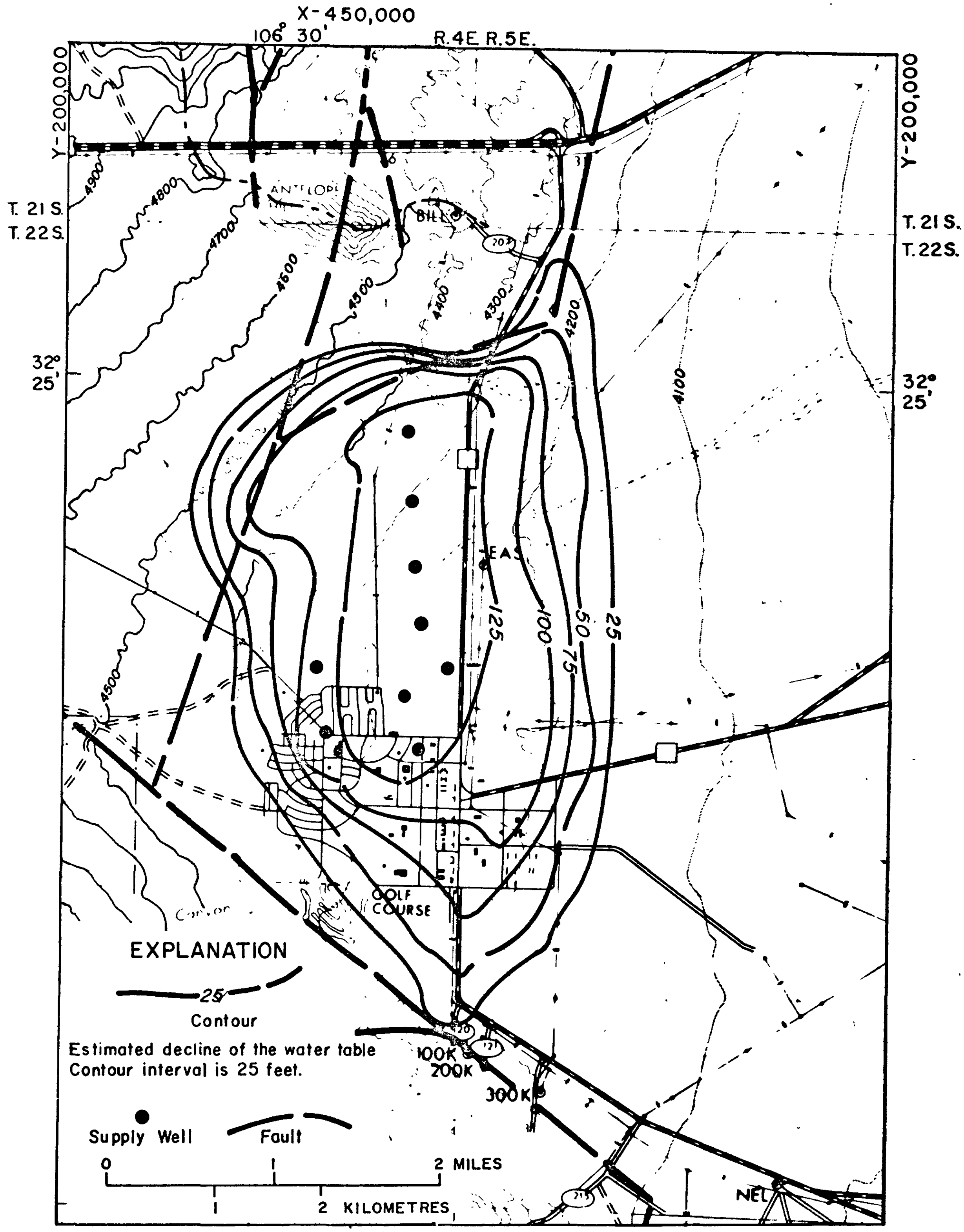
An alternative being considered by the Post Headquarters is to install an additional one or two wells to the southeast of the Headquarters area. The response to this modified stress was also simulated. It was assumed that one new well is put into operation in 1976. It was further assumed that the new well withdraws ground water at ten percent of the total 1973 rate for the existing well field. The withdrawal rate for existing wells were assumed to decrease so that the total annual withdrawal rate was maintained at the 1973 level. Withdrawal rates for each well are shown in table 6. The location assumed for the new well is indicated on figures 17 and 18. The 1986 and 1996 water-level declines calculated by the digital model are shown in figures 17 and 18 respectively. The decline in water levels since 1948 in the vicinity of the Main Gate well is calculated to increase from the 1972 level of about 80 ft (24 m) to about 135 ft (41 m) in 1986 and about 175 ft (53 m) in 1996. The simulated decline through 1996 does not exceed 200 ft (61 m) anywhere in the modeled area.

Table 5.--Ground-water withdrawal for 1972-73 and projected withdrawals through 1996, assuming no new wells are added to the field.

Well locations shown on figures 10, 15 and 16. Average annual withdrawal in cubic feet per second

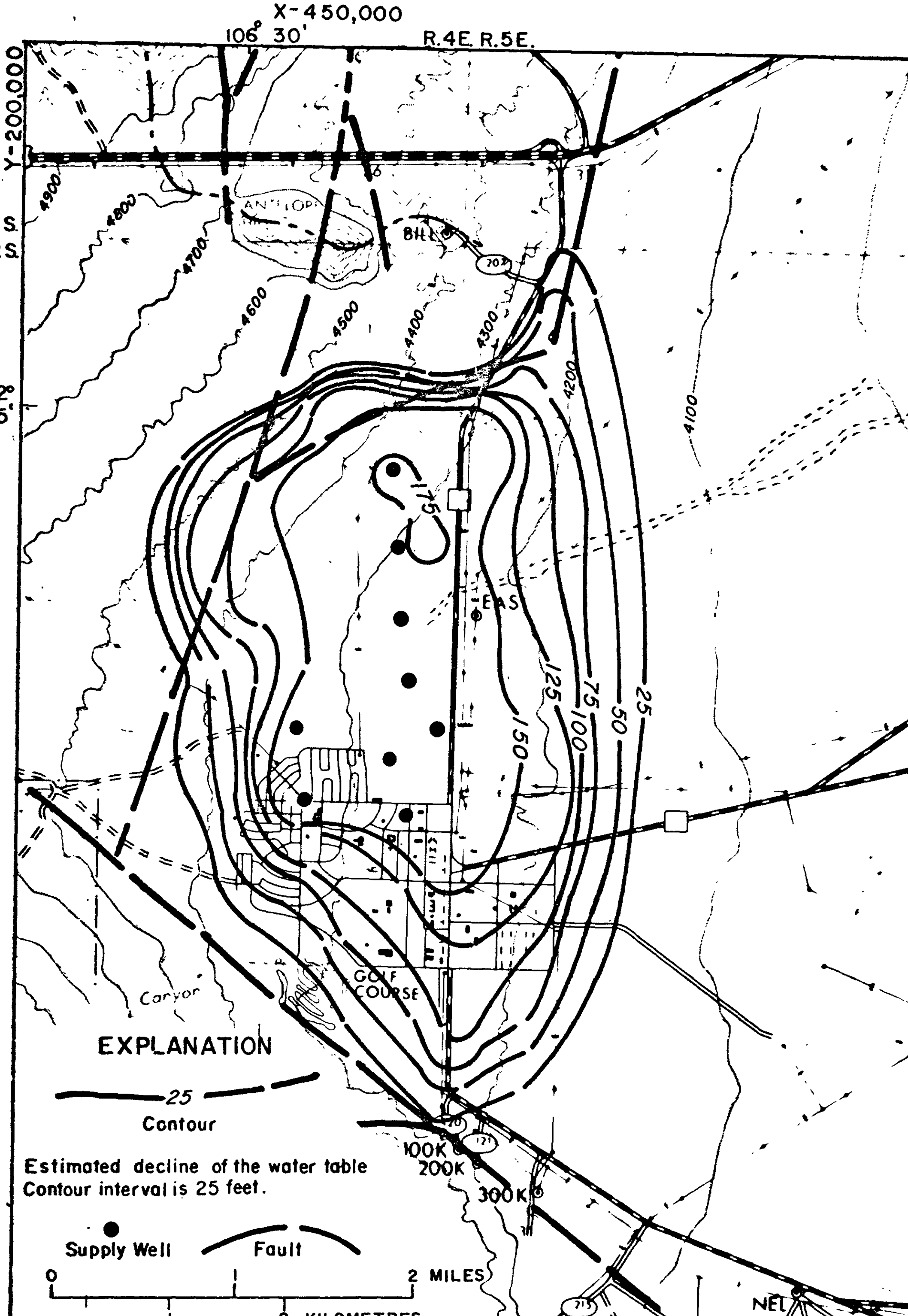
Period		Supply well									
From	To	10A	11	13	15	16	17	18	19	20	Total
1972		0.5971	0.2520	0.0479	0.0190	0.4951	0.5376	0.1216	0.8214	0.8139	3.71
1973		.6020	.3469	.0519	.0134	.4040	.4866	.3423	.7724	.6720	3.69
*1974	1995	.6020	.3469	.0519	.0134	.4040	.4866	.3423	.7724	.6720	3.69

* estimated



Base from White Sands Missile Range
Master Plan Basic Information Maps, 1972

Figure 15.--Simulated water-level declines for the period 1949 through 1986, assuming no new wells are added to the field.



Base from White Sands Missile Range Master Plan Basic Information Maps, 1972

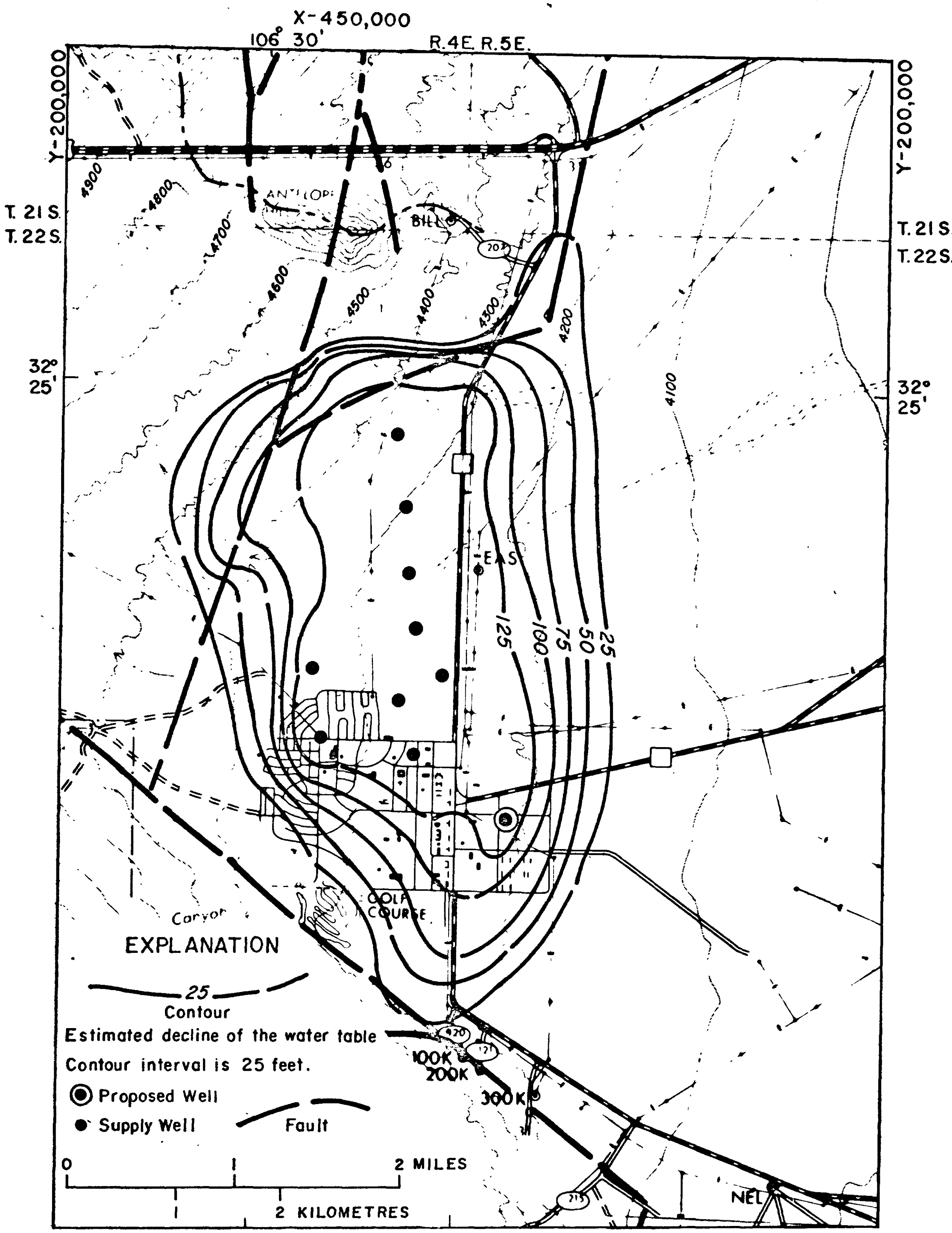
Figure 16.-- Simulated water-level declines for the period 1949 through 1996, assuming no new wells are added to the field.

Table 6.--Ground water withdrawal for 1972-73 and projected withdrawals through 1996, assuming one new well is added to the field in 1976.

Well locations shown on figures 10, 17, and 18. Average annual withdrawal in cubic feet per second

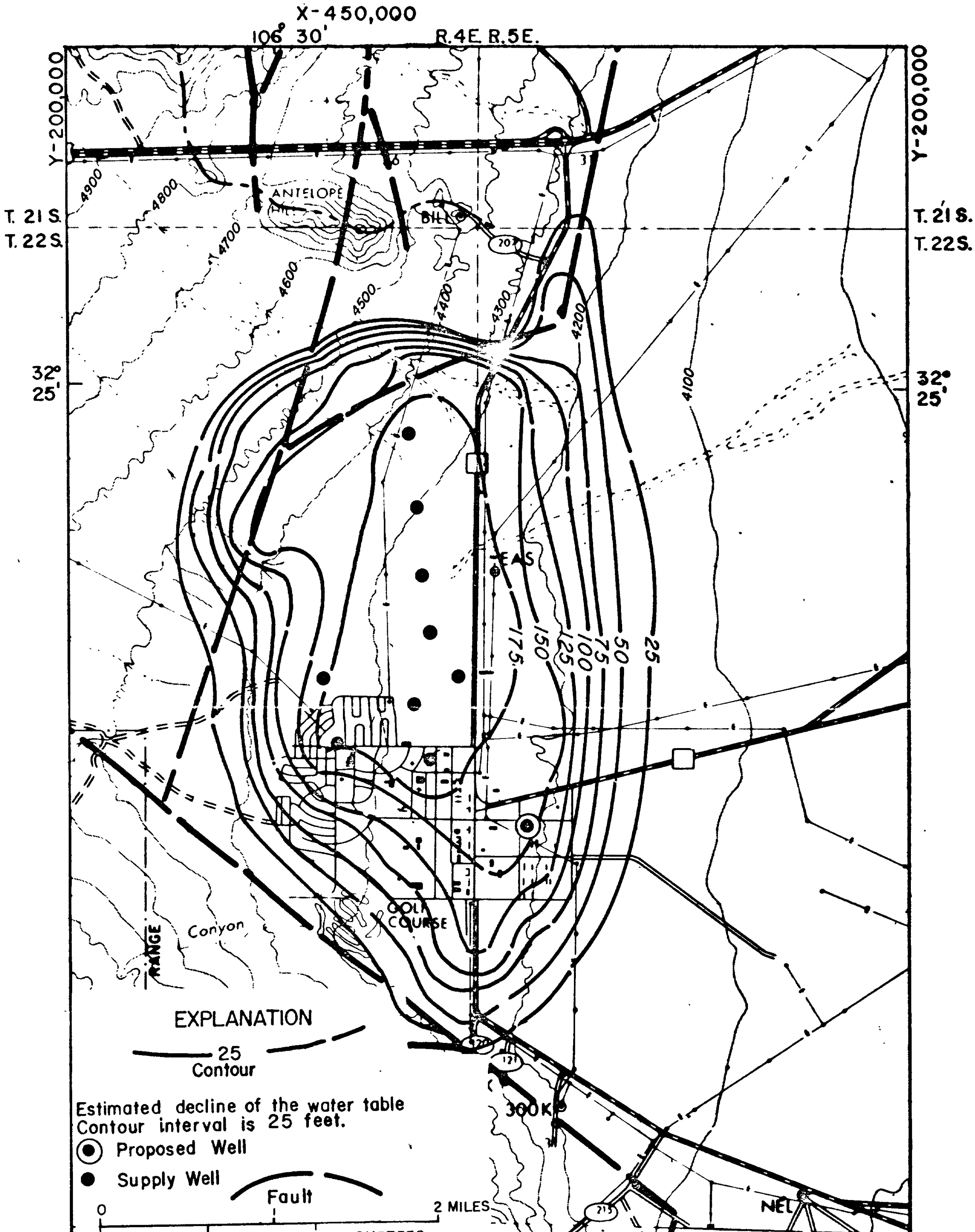
Period From	Period To	Supply well 10A	11	13	15	16	17	18	19	20	New	Total
1972		0.5971	0.2520	0.0479	0.0190	0.4951	0.5376	0.1216	0.82.4	0.8139		3.71
1973		.6020	.3469	.0519	.0135	.4040	.4866	.3423	.7724	.6720		3.69
*1974	1975	.6020	.3469	.0519	.0135	.4040	.4866	.3423	.7724	.6720		3.69
*1776	1995	.5418	.3122	.0467	.0121	.3636	.4379	.3081	.6952	.6048	0.3691	3.69

* estimated



Base from White Sands Missile Range Master Plan Basic Information Maps, 1972

Figure 17.-- Simulated water-level declines for the period 1949 through 1986, assuming one new well is added to the field in 1976.



Base from White Sands Missile Range
Master Plan Basic Information Maps, 1972

Figure 18.-- Simulated water-level declines for the period 1949 through 1996, assuming one new well is added to the field in 1976.

Conceptual model of water quality

The limited data on water quality are insufficient to support a quantitative model. However, a small but progressive increase in dissolved solids has been noted in several wells. Continuation of this trend will eventually limit the usefulness of the water supply. Accordingly, a conceptual model of the transport of dissolved solids is presented to indicate the possible causes of these increases in dissolved solids. This conceptual model may be useful in the development of a data-collection network to monitor changes in water quality.

Factors affecting water quality

Two basic mechanisms are available to transport substances dissolved in ground water: convection and dispersion. Convection refers to the transport of a solute by the flowing solution. The rate of transport by convection is therefore directly proportional to the hydraulic conductivity and the hydraulic gradient and inversely proportional to the effective porosity. Dispersion acts to transport a solute by the mixing of two fluids due to molecular diffusion and the nature of flow in a porous medium. Transport by dispersion is a function of the concentration gradients, and the type of material through which the water is flowing.

Gravity segregation has also influenced the water-quality distribution. Gravity segregation refers to the differential effects of gravity on two fluids of different densities. The effects of gravity segregation on a flow system in steady state is approximated by the Ghyben-Herzberg relationship (Walton, 1970, p. 195). The Ghyben-Herzberg relationship states that in steady state the slope of the interface between two miscible fluids of different densities will be inversely proportional to the density difference, directly proportional to the hydraulic gradient, and in the opposite direction from the hydraulic gradient.

Finally, as ground water comes into contact with the minerals composing the porous media, the concentrations of those minerals in the solute tends to approach an equilibrium. For freshwater in which the concentration is normally low, the effect is to increase the concentration of the minerals in the solute.

Water-quality subdivisions

Prior to 1948, the aquifer is assumed to have been in a steady-state condition relative to water quality as well as to water flow. That is, the areal distribution of solute concentrations was not changing.

Solute concentrations were distributed in such a manner that the mechanisms described above merely served to counterbalance each other. Our limited knowledge of the geohydrology of the White Sands aquifer suggests four water-quality subdivisions. Within each subdivision, the concentration of dissolved solids is believed to be fairly uniform. This section will describe the areal distribution of and estimate the range of dissolved-solids concentrations within each group.

The most widely distributed and most saline unit is the brine which lies to the east of the Post Headquarters area in the central part of the Tularosa Basin. Dissolved solids concentration here may exceed that of seawater (about 35,000 mg/l). Due to gravity segregation, this unit wedges beneath the less saline, and therefore less dense, units to the west. The diffuse interface is maintained by the balance of convection and dispersion.

In the vicinity of the Post Headquarters well field the water in and beneath the extensive clay layer is believed to be less saline than the brine. Concentrations here may range between 1,000 and 3,000 mg/l. The source for this water is the freshwater recharge along the mountain front. However, due to the low permeability of the clay and the underlying conglomerate, this water moves more slowly, has been in contact with the formation longer, and hence is slightly more saline than the freshwater overlying the clay layer.

The clays and sands of the freshwater aquifer constitute the remaining two groups. Because of their lower permeability, the water contained in the clays may be slightly more saline than that in adjacent sands. Its proximity to the sands may, however, make it slightly less saline than the water beneath the extensive clay layer. Water in the clays may have a dissolved-solids concentration of 500 to 1,000 mg/l while that in the sands is below 500 mg/l.

Effects of ground-water withdrawal

Ground-water withdrawal in the Post Headquarters area has had the effect of lowering water levels in the area and increasing the dissolved-solids concentrations in the water withdrawn. According to the conceptual model described above, there are three potential causes for the increase in dissolved-solids concentrations: encroachment of brine from the east, leakage of slightly saline water through the subjacent confining bed, and slow drainage of very slightly saline water from the less permeable units within the aquifer itself.

Since the model is not quantitative, it provides no estimate of which source or combination of sources is responsible for the observed increase in dissolved-solids concentrations. It also provides no estimate of the probable nature of future increases. However, if the increases are due in part to encroachment from the east or leakage from below, a properly designed monitoring network may provide advance warning of severe or rapid water-quality deterioration. Water-quality changes both to the east and beneath the production zone should be monitored. If the increase is due to delayed drainage from clays within the aquifer, a carefully collected water sample from the clay zones may provide an estimate of how high the concentrations may become. Regardless of the source, management of the well field to minimize drawdown and spread the cone of depression would minimize the rate of water-quality deterioration.

AREAS OF POTENTIAL DEVELOPMENT

The selection of future production-well sites involves not only locating the most productive areas with respect to quantity but also locating the areas where pumping of potable water will cause the least movement of saline water toward the area of the wells. Quality of the water in the aquifer may also be a factor.

There are three locales within the study area which should be considered for potential development of water supplies in addition to further development of the Post Headquarters area: the Soledad Canyon area, the Bear Canyon area, and the Small Missile Range (fig. 11).

Increasing salinity seems to be the immediate threat to the Post Headquarters well field. However, it is possible that construction of several additional production wells in the Headquarters area would benefit optimum development of the ground-water resources. By spreading out the effects of pumping, and simultaneously equalizing the amount of production from each well, the rate of increase in salinity would be minimized, thus allowing for maximum utilization of the freshwater in the Post Headquarters area.

Two wells had been proposed previously for construction in sec. 19, T.22 S., R.5 E. in the southeastern part of the Post Headquarters area during fiscal year 1974. They are now tentatively scheduled for construction in fiscal year 1976. These wells will create additional spreading of the cone of depression and cause a more uniform drawdown of the water table (figs. 17 and 18). The construction of these two wells would be the most effective remedial action available to reduce the current trend toward increasing salinity in the well field.

At least three other wells probably could be installed in the Headquarters area. Supply well 12, which was abandoned in 1955, could be replaced. A new well at this site, and one located in the center of sec. 24, T.22 S., R.4 E., would utilize water at the southern end of the aquifer. Although this area was heavily pumped during the early stages of development, the water levels have subsequently recovered. Another well could be constructed in the northwest quarter of sec. 13, T.22 S., R.4 E., approximately half a mile west of supply well 18. This well would spread the cone of depression toward the west. All of these wells should be constructed for the purpose of spreading the cone of depression and not to increase the total production of water from the well field. An increase in withdrawal would only accelerate the rate of water-quality deterioration.

The Soledad Canyon area is located south of the Post Headquarters (fig. 11). It is bounded on the north and west by the axis of the Organ Mountains and on the southwest by Rattlesnake Ridge. [The Soledad Canyon development area has a total areal extent of approximately 38 mi^2 (98 km^2).] Data from several test wells drilled in the area indicate that the freshwater lense locally is greater than 1,000 ft (300 m) thick and more than 38 mi^2 (98 km^2) in areal extent (fig. 5). Inasmuch as this area of interest is entirely within the boundaries of Fort Bliss Military Reservation, much of which is artillery range, little hydrologic data are available for the area.

Geologically the Soledad Canyon area is quite similar to the Post Headquarters area; therefore, it may be assumed that the hydrologic conditions may also be similar. Test wells T-16, T-17, T-18, F-1, and F-3 have all penetrated relatively thick sequences of unconsolidated bolson fill containing freshwater (fig 5). The distribution of these test wells shows that freshwater is more widely distributed in this area than it is in the Headquarters area. No test wells have been drilled near the mountain front where the aquifer probably would be the most productive.

Considering the size of the Soledad Canyon area, it offers the greatest potential for development. A well field similar to that in the Post Headquarters area could probably be developed there without serious danger of encroachment of the interface between the saline water and freshwater within the foreseeable future. The water quality probably would be similar to that now in use in the Post Headquarters area.

The major disadvantage to the development of this area is its distance from the Post Headquarters; approximately 10 mi (16 km) of pipeline would be required to bring this water to the Post Headquarters. It should also be noted that the lack of data for much of the Soledad Canyon area leaves uncertain the values of many of the hydrologic parameters. Also, it may be assumed that with development, the concentration of dissolved solids in the water would increase. However, the rate of increase may differ from that in the Post Headquarters area.

A test-drilling program should be undertaken in order to more accurately define the limits of the freshwater in the Soledad Canyon area. The areal distribution of the clay layer and the occurrence of saline water should be determined. The area of particular interest should be secs. 18, 19, 29, 30, 31, and 32, T.23 S., R.5 E., and secs. 5, 6, 7, 8, .24 S., R.5 E. In the course of the test drilling several observation wells should be installed in the area to monitor water-level fluctuations and water-quality changes prior to utilization of ground water in the area. This would greatly benefit future planning.

Water in a large alluvial fan formed at the mouth of Bear Canyon probably could be developed for an additional supply of freshwater. This alluvial deposit is located principally in sec. 33, T.20 S., R.5 E., and in sec. 4, T.21 S., R.5 E. The area is hydrologically unique because a relatively large drainage basin empties into the fan deposits through a narrow canyon. Thus large quantities of ground water probably flow through the alluvial material and into the Tularosa Basin.

Test well SMR-3 was drilled on the southeast flank of this fan. The sediments encountered were principally sand, gravel, and some clay; near-surface deposits were well-cemented with calcium carbonate (Doty, 1968a, p. 13). Freshwater was collected from a maximum depth of 1,010 ft (308 m). An aquifer test on this well shows that the deposits have a transmissivity of 46,000 ft^2/d (4,360 m^2/d) (table 1). Depth-to-water measurements in this well indicated that there has been little change in the water level since the well was constructed in 1967 (Kelly, 1973, fig. 10).

Two of the disadvantages of utilizing water from the fan at Bear Canyon are the limited extent of the fan and its distance from the Post Headquarters. Three wells would probably be the maximum number that should be installed on the fan. Approximately 10 mi (16 km) of pipeline would be necessary to transport this water to the Post Headquarters. The water from test well SMR-3 is somewhat harder and more highly mineralized than water now in use at the Post Headquarters (table 3).

Owing to the relatively limited areal extent of the fan deposits at the mouth of Bear Canyon, it would be advisable to drill a test well approximately half a mile west of the mouth of the canyon. This test would determine the thickness of alluvium in the canyon itself and provide additional information on the amount of water in storage which could be utilized by wells.

The Small Missile Range area extends from the Bear Canyon drainage divide southward across T.21 S., R.5 E. to the Post Headquarters area, and has a total drainage area of about 22 mi^2 (57 km^2).

Aquifer tests that have been conducted on wells in the Small Missile Range area indicate that, in general, the yields of wells in this area are somewhat less than those in the Post Headquarters well field (table 1). Thickness of the aquifer is unknown. None of the test wells that have been drilled in this area have reached consolidated rocks; however, a water sample from a depth of 1,016 ft (309.7 m) contained freshwater. The depth to saline water, if present, is unknown. Therefore it may be assumed that the aquifer has a maximum thickness of more than 1,000 ft (304 m).

A number of observation wells have been installed in the Small Missile Range area. During the 12-year record on test well SMR-2, the water level has declined about 8 ft (2.4 m); slight declines have been noted in other observation wells (Kelly, 1973, fig. 10). These changes in water level cannot be attributed to pumpage in the Post Headquarters well field because the water level in test well T-13, which is located midway between the well field and the Small Missile Range, has remained relatively static. Measurements should be continued on these wells in order to determine the cause for this gradually declining head. The data would also provide background information in the event of future development in the Small Missile Range.

The area suitable for development in the Small Missile Range is confined to a rather narrow belt between the mountain front on the west and the interface between the saline and freshwater on the east. Consequently the amount of water in storage may be somewhat limited and extensive development of this area may produce more rapid encroachment and upconing of saline water than has occurred in the Post Headquarters area. The water quality in the Small Missile Range is similar to that in the Bear Canyon area; both the hardness and the dissolved solids are slightly higher than those in water produced from the Post Headquarters well field.

SUMMARY

The production wells at the Post Headquarters well field at White Sands Missile Range, New Mexico, obtain water from unconsolidated Tertiary clastics that are typical bolson and playa deposits. A widespread clay unit which directly underlies the aquifer, and a more deeply buried conglomerate, probably contain slightly saline water; there is no evidence to indicate that the aquifer is underlain by brine.

Withdrawal of ground water from the aquifer since 1948 has produced a steady decline of the water table. The decline in the vicinity of the Main Gate well was about 80 ft (24 m) in 1972. Calculations from a digital simulation model indicate that this decline would increase to about 125 ft (38 m) by 1986 and about 160 ft (45 m) by 1996.

Water samples have been collected and analyzed intermittently from 14 supply and test wells. In 10 of these wells the dissolved-solids concentration of the water has progressively increased since the first samples were collected. A conceptual model of water quality indicates that this trend will probably continue. Advance warning of severe or rapid water-quality deterioration could be obtained by monitoring the quality of water, both to the east of and beneath the production zone. Managment of future development to minimize drawdown and spread the cone of depression would minimize the rate of water-quality deterioration.

Three locales within the study area could be developed for additional water supplies: Soledad Canyon area, Small Missile Range, and Bear Canyon. Of these, the Soledad Canyon area south of the Post Headquarters offers the greatest potential. Although additional exploration in the area is needed, the geologic conditions and areal extent indicate that the aquifer at the Soledad Canyon area could possibly support a well field similar to that now in use at the Post Headquarters. Both the Small Missile Range and Bear Canyon areas are capable of additional development although they are considerably smaller in areal extent than the Soledad Canyon area.

REFERENCES

Ballance, W. C., and Basler, J. A., 1966, Runoff from a paved small watershed at White Sands Missile Range, New Mexico: U.S. Geol. Survey open-file report, 21 p., 3 figs.

Darton, N. H., 1928, Geologic map of New Mexico: U.S. Geol Survey, scale 1:500,000.

Davis, L. V., and Busch, F. E., 1968, Summary of hydrologic investigations by the U.S. Geological Survey at White Sands Missile Range, New Mexico: U.S. Geol. Survey open-file report, 146 p., 27 figs.

Doty, G. C., 1968a, Phase I test wells, White Sands Missile Range, Dona Ana County, New Mexico: U.S. Geol. Survey open-file report, 39 p., 12 figs.

————1968b, Test wells in the Post area, White Sands Missile Range, Doña County, New Mexico: U.S. Geol. Survey open-file report, 29 p., 16 figs.

Dunham, K. C., 1935, The geology of the Organ Mountains, with an account of the geology and mineral resources of Dona Ana County, New Mexico: State Bur. Mines and Mineral Resources Bull. 11, 272 p., 35 figs.

Hawley, J. W., Kottlowski, F. E., Strain, W. S., Seager, W. R., King, W. E., and LeMone, D. V., 1969, The Santa Fe Group in the south-central New Mexico border region, in Kottlowski, F. E., and LeMone, D. V., eds., symposium: State Bur. Mines and Mineral Resources Circ. 104, p. 52-76.

Hawley, J. W., and Kottlowski, F. E., 1969, Quarternary geology of the south-central New Mexico border region, in Kottlowski, F. E., and LeMone, D. V., eds., symposium: State Bur. Mines and Mineral Resources Circ. 104, p. 89-104.

Herrick, E. H., 1960, Ground-water resources of the Headquarters (Cantonment) area, White Sands Proving Ground, Doña Ana County, New Mexico: U.S. Geol. Survey open-file report, 203 p., 33 figs.

Hood, J. W., 1968, Ground-water investigations at White Sands Missile Range, New Mexico, July 1960-June 1962: U.S. Geol. Survey open-file report, 153 p., 28 figs.

Kelly, T. E., 1973, Summary of ground-water data, Post Headquarters and adjacent areas, White Sands Missile Range: U.S. Geol. Survey open-file report 72-308, 66 p., 33 figs.

King, W. E., Hawley, J. W., Taylor, A. M., and Wilson, R. P., 1969, Hydrogeology of the Rio Grande Valley and adjacent intermontane areas of southern New Mexico: Water Resources Research Inst. rept. no. 6, 141 p., 7 figs.

Knowles, D. B., and Kennedy, R. A., 1958, Ground-water resources of the Hueco Bolson northeast of El Paso, Texas: U.S. Geol. Survey Water-Supply Paper 1426, 183 p., 14 figs.

Kottlowski, F. E., 1960, Reconnaissance geologic map of Las Cruces 30-minute quadrangle: State Bur. Mines and Mineral Resources Geol. Map 14.

Kottlowski, F. E., Flower, R. H., Thompson, M. L., and Foster, R. W., 1956, Stratigraphic studies of the San Andres Mountains, New Mexico: State Bur. Mines and Mineral Resources Mem 1, 132 p.

Kottlowski, F. E., and LeMone, D. V., 1969, Border Stratigraphy symposium: State Bur. Mines and Mineral Resources Circ. 104, 123 p.

Krieger, R. A., Hatchett, J. L., and Poole, J. L., 1957, Preliminary survey of the saline-water resources of the United States: U.S. Geol. Survey Water-Supply Paper 1374, 172 p.

Leggat, E. R., Lowry, M. E., and Hood, J. W., 1963, Ground-water resources of the lower Mesilla Valley, Texas and New Mexico: U.S. Geol. Survey Water-Supply Paper 1669-AA, 49 p., 23 figs.

Lohman, S. W., 1972, Ground-Water Hydraulics: U.S. Survey Prof. Paper 708, 70 p.

McLean, J. S., 1970, Saline ground-water resources of the Tularosa Basin, New Mexico: [Dept. of Interior] U.S. Office of Saline Water Research and Devel. Prog. Rept. 561, 128 p.

Pinder, G. F., 1970a, A digital model for aquifer evaluations: U.S. Geol. Survey Techniques Water-Resources Inv., book 7, chap. C1, 18 p.

———1970b, An iterative digital model for aquifer evaluation: U.S. Geological Survey open-file report, 44 p.

Pinder, G. F., and Bredehoeft, J. D., 1968, Application of a digital computer for aquifer evaluation: Water Resources Research 4(5), p. 1069-1093.

Ruhe, R. V., 1967, Geomorphic surfaces and surficial deposits in southern New Mexico: New Mexico Bur. Mines and Mineral Resources Mem. 18, 66 p., 33 figs.

Scott, A. G., 1970, Estimated mean-annual runoff at Post Headquarters area, White Sands Missile Range, New Mexico: U.S. Geol. Survey open-file report, 13 p., 3 figs.

Seager, W. R., Hawley, J. W., Clemons, R. E., 1971, Geology of San Diego Mountain area, Dona Ana County, New Mexico: New Mexico Bur. Mines and Mineral Resources Bull. 97, 38 p., 5 figs.

Strain, W. S., 1966, Blancan mammalian fauna and Pleistocene formations, Hudspeth County, Texas: Texas Memorial Museum [Austin] Bull. 10.

———1969, Late Cenozoic strata of the El Paso area, in Kottlowski, F. E., and LeMone, D. V., eds., Border stratigraphy symposium: New Mexico Bur. Mines and Mineral Resources Circ. 104, p. 122-123.

Trescott, P. C., 1973, Iterative digital model for aquifer evaluation: U.S. Geol. Survey open-file report, 63 p.

U.S. Public Health Service, 1962, Drinking water standards, 1962: Public Health Service Pub. 956, 61 p.

Walton, W. C., 1970, Groundwater resources evaluation: New York, McGraw-Hill Book Co., 664 p.

Winslow, A. G., and Kister, L. R., 1956, Saline water resources of Texas: U.S. Geol. Survey Water-Supply Paper 1365, 105 p.

Zohdy, A. A. R., Jackson, D. B., Mattick, R. E., and Peterson, D. L., 1969, Geophysical survey for ground water at White Sands Missile Range, New Mexico: U.S. Geol. Survey open-file report, 144 p., 17 figs.

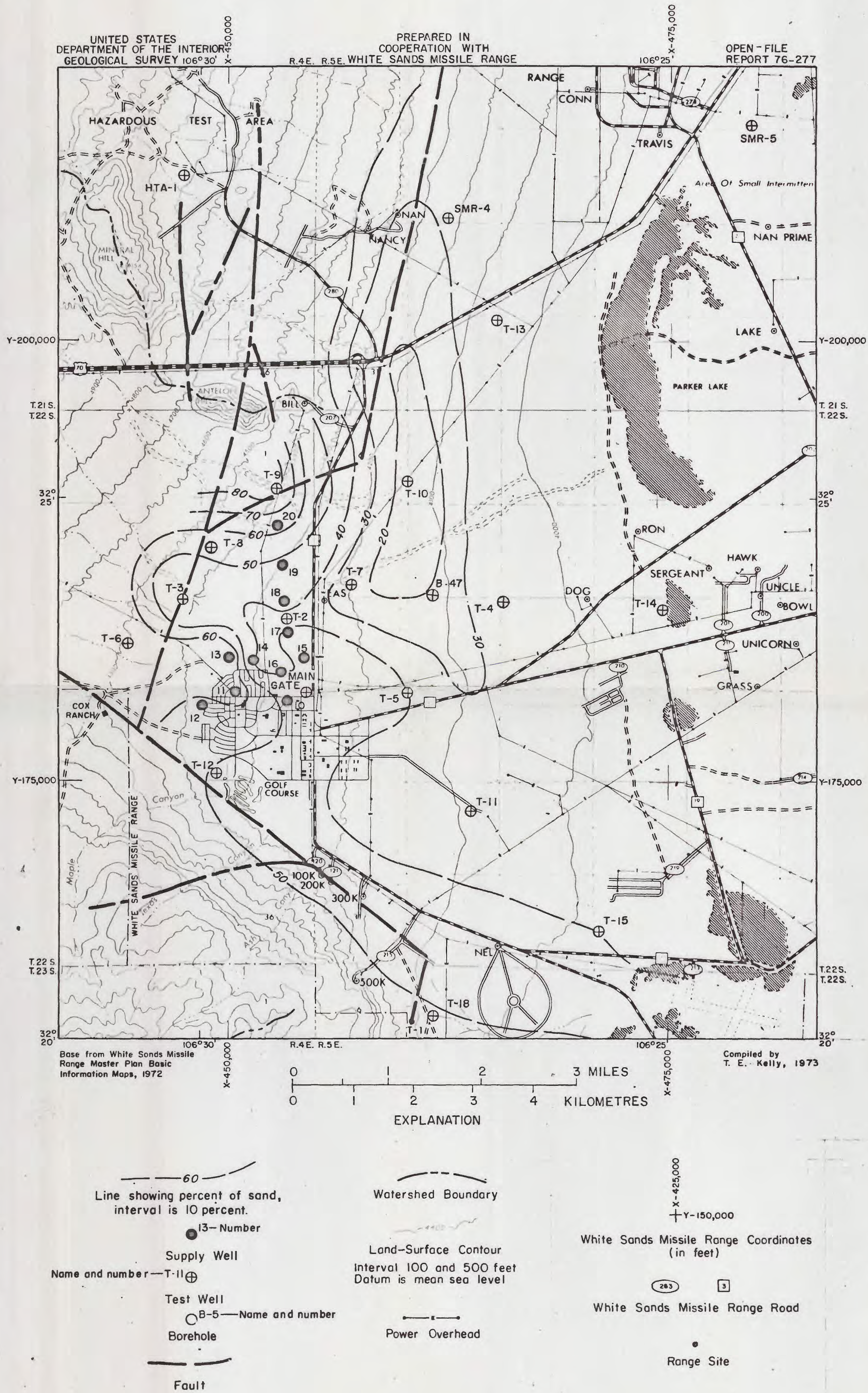


Figure 2-- Map showing percentage of sand between 500 and 1,000 feet (150 to 300 metres).

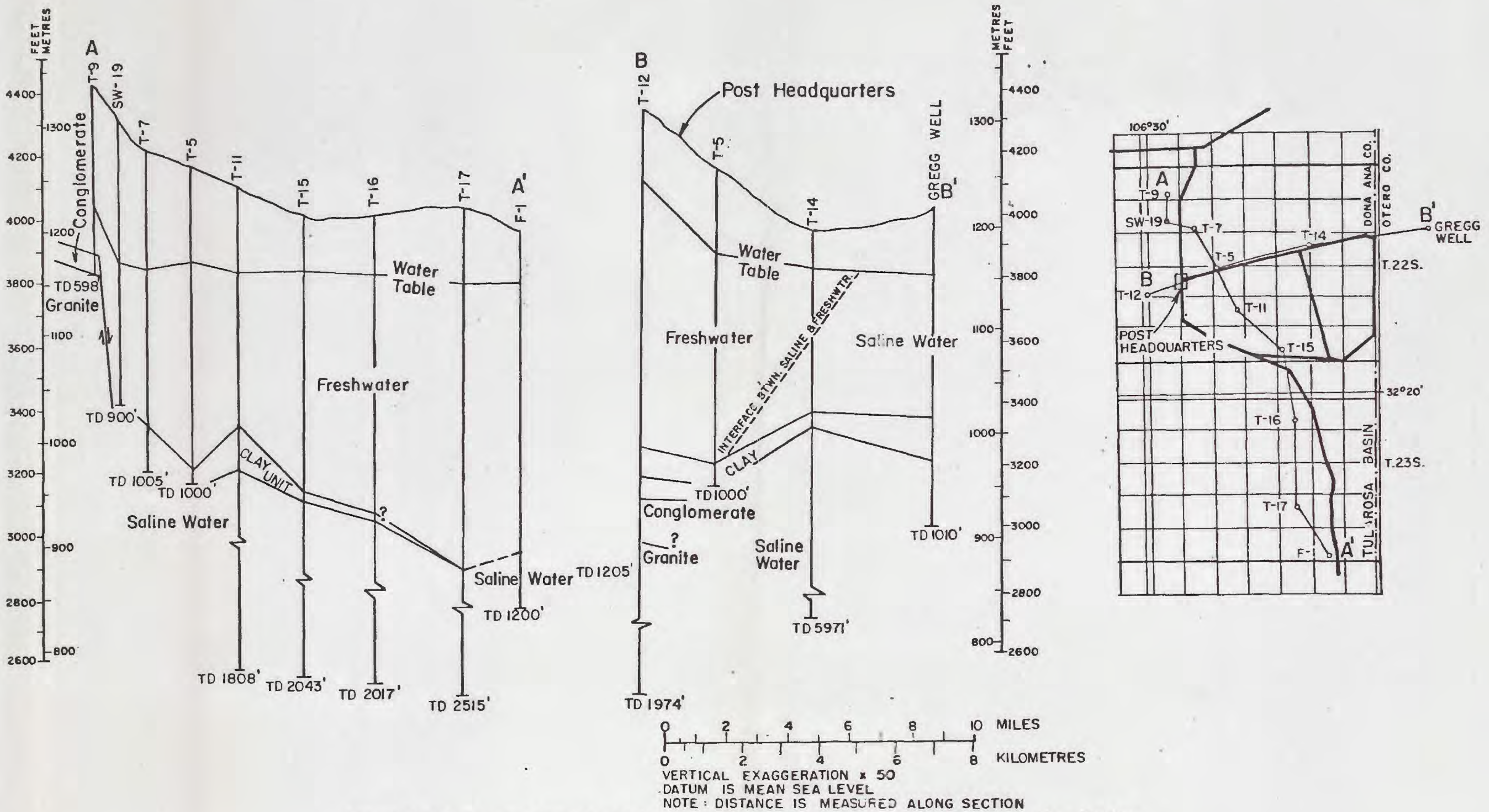


Figure 3.--Sections showing geologic and hydrologic units in south-central New Mexico.

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Figure 4.--Hydrograph of Main Gate well and monthly pumpage figures for well field.