SIMULATED WATER-LEVEL DECLINES CAUSED BY GROUND-WATER WITHDRAWALS NEAR HOLLOMAN AIR FORCE BASE, OTERO COUNTY, NEW MEXICO

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CONVERSION FACTORS

For readers who prefer to use metric (International System) units, conversion factors for units used in this report are listed below.

Multiply inch-pound unit	By	To obtain metric unit
inch	25.40	millimeter
foot	0.3048	meter
mile	1.609	kilometer
square mile	2.590	square kilometer
cubic foot per second	0.02832	cubic meter per second
foot squared per day	0.09290	meter squared per day

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

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ABSTRACT

The U.S. Geological Survey, in cooperation with the U.S. Air Force, Holloman Air Force Base, studied the potential change in water levels that could occur as a result of increased ground-water withdrawals from the middle Tertiary to Holocene basin-fill and alluvial deposits in the vicinity of the Air Force base. Ground water supplies most of the water used in the area. The 400-square-mile area of unconsolidated material is relatively flat except for alluvial fans adjacent to the Sacramento Mountains miles east of the base. Perennial streams are not present in the study area. The aquifer has a saturated thickness that ranges from 0 to 3,000 feet.

Intermittent streamflow from the nearby mountains infiltrates the alluvial fans and recharges the aquifer system. Ground water is discharged from the area by underflow, evapotranspiration, and withdrawals from wells.

Values of transmissivity that range from 500 to 6,000 feet squared per day and a specific yield of 0.09 were used in a two-dimensional finite-difference model to evaluate the effects of proposed future ground-water withdrawals. Based on a 10-percent increase in withdrawals at the Holloman well fields, four alternatives of how Hollomon Air Force Base might distribute that pumpage were simulated: (1) 20 percent of the withdrawals would be taken from the Boles well field and the other 80 percent from the Douglas and San Andres well fields; (2) 60 percent of the withdrawals would be taken from the new Dog Canyon wells and the other 40 percent from the proposed Escondido Canyon wells; (3) 10 percent of the withdrawals would be taken from the Boles well field, 30 percent from the Douglas and San Andres well fields, 30 percent from the Dog Canyon wells, and 30 percent from the Escondido Canyon wells; and (4) alternatives 1 and 2 would be alternated from year to year. The model results indicated that by 2001, alternative 2 resulted in the greatest water-level decline in the well-field areas, as much as 60 feet, and that alternative 1 resulted in the least water-level decline in the well-field areas, about 26 feet.

INTRODUCTION

This report describes the results of a study to estimate the possible effects of ground-water withdrawals on the water table in the vicinity of Holloman Air Force Base in Otero County, New Mexico. Ground water near Holloman Air Force Base is withdrawn for public, irrigation, industrial, and domestic supplies. The availability of fresh, potable ground water has been of great concern to water users in this area since development began in the early 1900's. The quality of ground water deteriorates as it moves from east to west, away from the Sacramento Mountain front; thus, major developments of water supplies have been limited to an area about 6 to 10 miles wide that is adjacent to and parallels the mountain front. In order to determine the possible effects on the ground-water system if the present distribution of stresses is altered, a digital model was constructed to represent the aquifer system. This study was conducted by the U.S. Geological Survey in cooperation with Holloman Air Force Base to support the ongoing planning of ground-water-resources development by the Air Force base.

Data used in this study were derived from published reports, from files at Holloman Air Force Base, and from the City of Alamogordo. These data were interpreted to make estimates of hydrologic properties of the aquifer and to estimate the effects of future stress on the aquifer.

Location and Extent of the Area

The study area is an approximately rectangular area that encompasses about 400 square miles of the southeastern part of the Tularosa basin (fig. 1). Holloman Air Force Base is near the area's center. The study area is bounded on the east by the Sacramento Mountains. The northern, southern, and western boundaries were selected on the basis of modeling and hydrologic considerations.

Land-surface altitudes in and near the study area range from about 8,000 feet above sea level in the Sacramento Mountains to about 4,000 feet along the western boundary. The most prominent features are the west-facing escarpment of the Sacramento Mountains on the eastern side of the area and the white gypsiferous sands of White Sands National Monument along part of the western side of the area.

The communities located within the study area are Alamogordo, La Luz, and Valmont. Holloman Air Force Base serves as the primary economic base for the area, along with ranching, agriculture, and tourism.

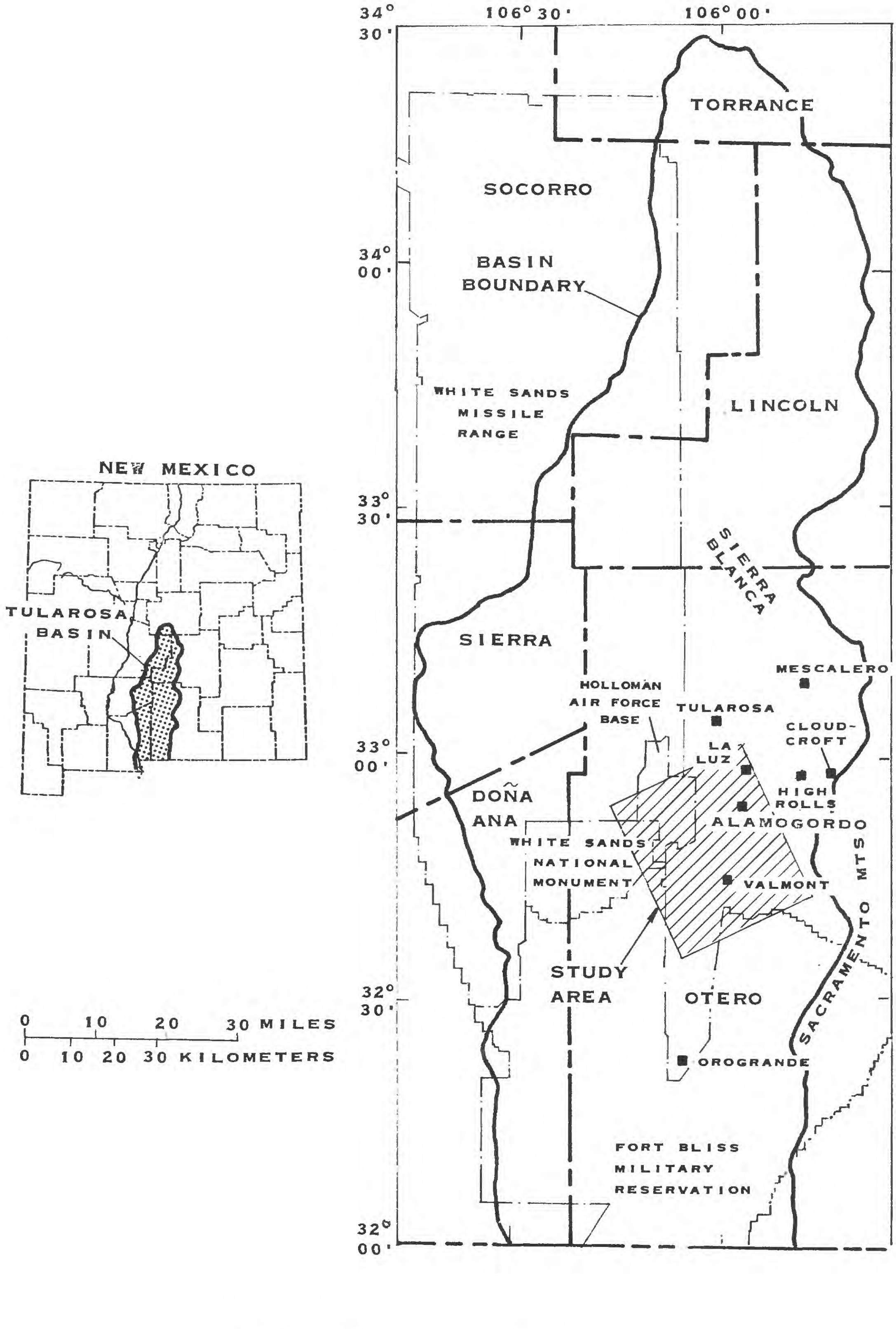


Figure 1.--Location of the study area.

Previous Investigations

The water resources of the Tularosa basin originally were described by Meinzer and Hare (1915). Meeks (1950) discussed ground water in the Alamogordo area, and Hood (1958) described the ground-water resources of the Boles well field, 8 miles south of Alamogordo. Herrick and others (1960) discussed the water resources of the Tularosa basin and adjoining areas. The distribution of water quality in this area was reported by Herrick and Davis (1965). A water and sewer report for the City of Alamogordo was prepared by McMorries and others (1967). The extent and thickness of the saline-water zones in the area were delineated by McLean (1970). Gordon Herkenhoff and Associates (1975) prepared a Water Master Plan for the City of Alamogordo. Ballance (1976) investigated the ground-water resources of the Holloman Air Force Base well-field area. The freshwater resources in the southeastern part of the Tularosa basin were discussed by Garza and McLean (1977).

GEOHYDROLOGY OF THE STUDY AREA

The study area lies within the central part of the Tularosa basin, a broad, north-south-trending intermontane basin that covers an area of 6,540 square miles in New Mexico. The study area includes the steep west-facing escarpment and drainage area of the Sacramento Mountains from T. 15 S. to T. 19 S. and extends westward into R. 7 E. and R. 8 E. (fig. 2). Drainage from the mountains has created alluvial fans that slope westward from the mountain front to the relatively flat basin floor.

Rocks exposed in the Sacramento Mountain escarpment range in age from Precambrian to Permian. The Precambrian rocks include slightly metamorphosed sandstone, siltstone, shale, and some diabase sills. The Paleozoic rocks are mainly limestone, dolomite, shale, and sandstone; small amounts of gypsum, chert, and conglomerate are also present (Hood, 1958, p. 17). A detailed description of the geology of the escarpment can be found in Otte (1959) and Pray (1961).

Unconsolidated rocks of middle Tertiary to Holocene age form the alluvial-fan and basin-fill deposits that are present west of the escarpment and that comprise the primary source of ground water. These deposits are referred to as the bolson aquifer in this report. The particle sizes range from boulders high on the alluvial fans to very fine sand and clay at the western margin of the study area. Although data about the deep unconsolidated deposits are sparse, it is assumed that their depositional pattern is similar to that of the near-surface deposits because all the material was derived from weathering of the same source rocks. The thickness of the unconsolidated deposits is estimated to range from 0 to slightly more than 3,000 feet.

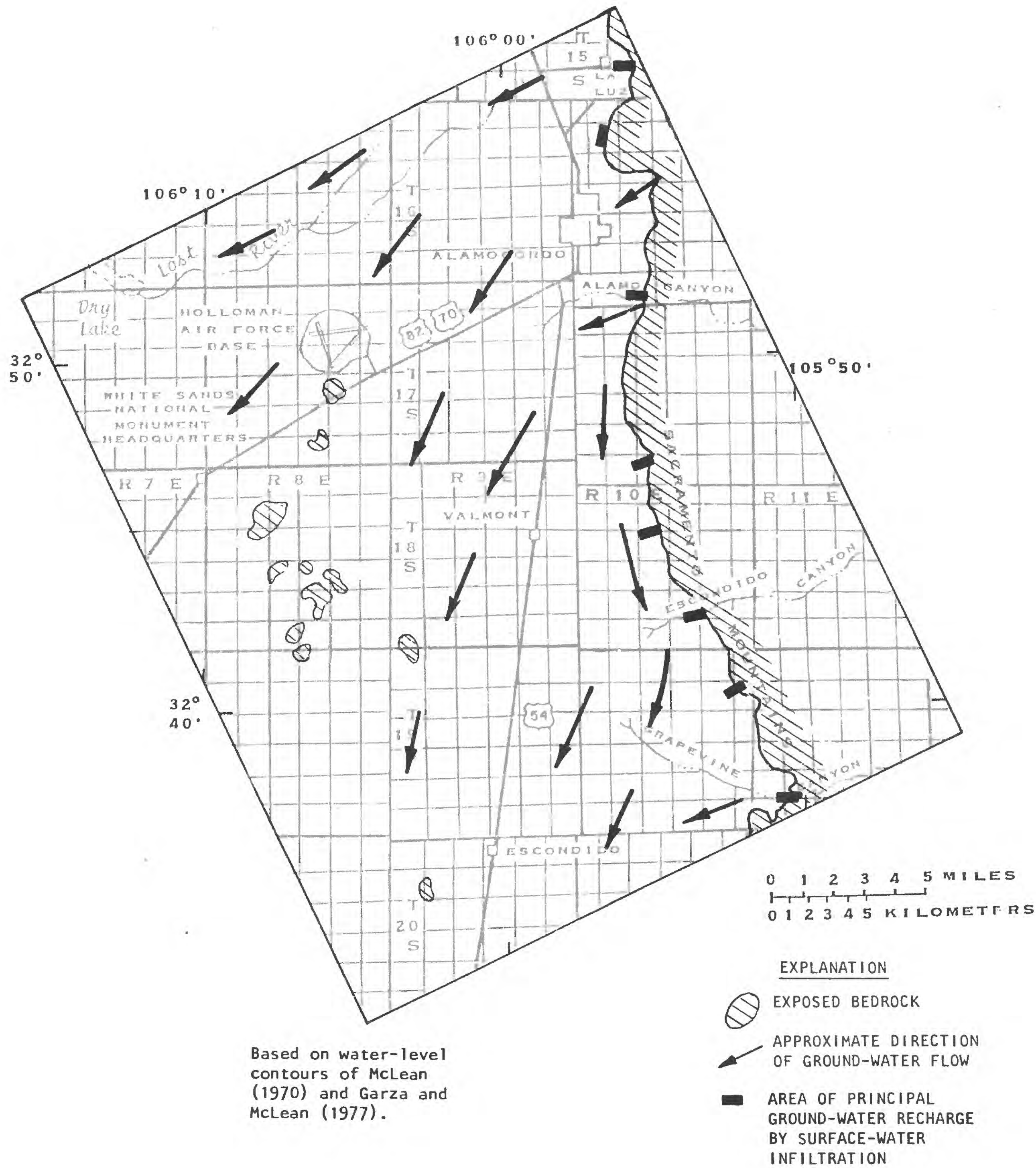


Figure 2.--General direction of ground-water flow in the area of Holloman Air Force Base.

The basic ground-water flow system of the bolson aquifer is described in detail in reports by Hood (1958), McLean (1970), and Garza and McLean (1977). The saturated thickness of this aquifer ranges from 0 to about 3,000 feet. Aquifer-test results published in these reports indicate that the transmissivity of the aquifer ranges from 200 to 20,000 feet squared per day and averages about 1,340 feet squared per day. Storage coefficients range from 0.00043 to 0.085. The specific yield was estimated to be about 0.08 by Garza and McLean (1977, p. 37) and about 0.09 by Hood (1958, p. 72) and Ballance (1976, p. 15).

Annual precipitation near Holloman Air Force Base generally ranges from 8 to 10 inches; high altitudes in the Sacramento Mountains receive about 25 inches per year. Recharge to the bolson fill takes place primarily along the mountain base as infiltration from runoff. Most streams that flow from the Sacramento Mountains are intermittent and have significant discharge only after rainfall or snowmelt in the mountain areas. It was estimated by Garza and McLean (1977, p. 20) that long-term recharge to the bolson fill is approximately 20 percent of the surface-water runoff.

The regional direction of ground-water movement is shown in figure 2. The ground water flows in a south or southwest direction throughout most of the area, but near some recharge areas adjacent to the mountain front, flow is to the west.

Natural discharge takes place by ground-water flow to the south and west and by evapotranspiration where the water table is near land surface. In addition to natural discharge, some ground water is withdrawn for domestic, public, industrial, and irrigation uses.

The Boles, Douglas, and San Andres well fields supply ground water to Holloman Air Force Base. Annual well-discharge data for Holloman Air Force Base (1947-69) and the city of Alamogordo (1959-69) were obtained from a report by Garza and McLean (1977). The data for Holloman Air Force Base were updated using well records provided by the base. Data for the city of Alamogordo (1970-81) were not available; however, well discharge was estimated on the basis of per-capita-use and historical-use data (table 1).

Ground-water withdrawals for irrigation were estimated from irrigated-acreage maps for 1969 prepared by Garza and McLean (1977) and from unpublished maps for 1978 prepared by the New Mexico State Engineer Office. Withdrawals for 1969 were extrapolated back to 1947 when withdrawals were assumed to be negligible. The withdrawals for 1970-77 were interpolated from the 1969 and 1978 data. The withdrawals from 1978 to 1981 were assumed to remain constant (table 2).

Table 1. Estimated municipal ground-water withdrawals (cubic feet per second) for Holloman Air Force Base and Alamogordo

Year	Well field (node)			
	Boles (13-14,17)	Douglas (13,14)	San Andres (14,14)	Alamogordo (23,25)
1947	0.08	-	-	-
1948	.37	-	-	-
1949	.24	-	-	-
1950	.11	-	-	-
1951	.40	-	-	-
1952	.57	-	-	-
1953	.85	-	-	-
1954	.59	-	-	-
1955	1.04	-	-	-
1956	1.35	-	-	-
1957	.56	-	-	-
1958	.04	-	-	-
1959	.01	-	-	0.81
1960	.29	-	-	.88
1961	1.53	0.13	-	.69
1962	.84	.16	-	.32
1963	.87	.31	0.19	.48
1964	1.12	1.49	.52	1.14
1965	.50	1.27	.52	1.04
1966	.42	.88	.27	1.05
1967	1.03	1.12	.80	1.09
1968	.66	.67	.76	1.14
1969	.73	1.14	1.48	1.18
1970	.43	.45	2.23	1.22
1971	.63	.56	2.80	1.26
1972	.57	.51	2.56	1.30
1973	.49	.48	2.38	1.35
1974	.32	.50	2.85	1.40
1975	.33	.41	2.57	1.44
1976	.84	.26	2.42	1.48
1977	.46	.33	2.32	1.52
1978	.57	.15	1.39	1.56
1979	.67	.40	2.20	1.60
1980	.81	.09	2.24	1.64
1981	1.13	.01	2.14	1.68

Table 2. Estimated irrigation withdrawals (cubic feet per second), by node, in the vicinity of Holloman Air Force Base

Year	Node 17,27	17,24	16,24	19,24	15,23	16,23	15,22	14,22	17,20	12,18	13,18	11,17	10,14	10,13	11,12	Total
1947	0.01	0.02	0.02	-	0.01	0.02	0.03	0.01	0.01	-	-	-	0.01	-	-	0.14
1948	.03	.03	.03	-	.02	.03	.06	.02	.02	-	-	-	.02	-	-	.26
1949	.04	.05	.05	-	.04	.05	.09	.04	.03	-	-	-	.03	-	-	.43
1950	.06	.06	.06	-	.05	.07	.12	.05	.04	-	-	-	.04	-	-	.55
1951	.07	.08	.08	-	.06	.08	.15	.06	.05	-	-	-	.05	-	-	.68
1952	.09	.09	.09	-	.07	.10	.18	.07	.05	-	-	-	.05	-	-	.79
1953	.10	.11	.11	-	.09	.12	.21	.09	.06	-	-	-	.06	-	-	.95
1954	.12	.13	.12	-	.10	.14	.24	.10	.07	-	-	-	.07	-	-	1.09
1955	.13	.14	.14	-	.11	.15	.27	.11	.08	-	-	-	.08	-	-	1.21
1956	.15	.16	.15	-	.12	.17	.30	.12	.09	-	-	-	.09	-	-	1.35
1957	.16	.17	.17	-	.13	.19	.33	.13	.10	-	-	-	.10	-	-	1.48
1958	.18	.19	.18	-	.15	.20	.36	.15	.11	-	-	-	.11	-	-	1.63
1959	.19	.20	.20	-	.16	.22	.39	.16	.12	-	-	-	.12	-	-	1.76
1960	.21	.22	.21	-	.17	.24	.42	.17	.13	-	-	-	.13	-	-	1.90
1961	.22	.23	.23	-	.18	.25	.45	.18	.14	-	-	-	.14	-	-	2.02
1962	.24	.25	.24	-	.19	.27	.48	.19	.15	-	-	-	.15	-	-	2.16
1963	.25	.26	.26	-	.21	.29	.51	.21	.16	-	-	-	.16	-	-	2.31
1964	.27	.28	.27	-	.22	.31	.54	.22	.16	-	-	-	.16	-	-	2.43
1965	.28	.29	.29	-	.23	.32	.57	.23	.17	-	-	-	.17	-	-	2.55
1966	.30	.31	.30	-	.24	.34	.60	.24	.18	-	-	-	.18	-	-	2.69
1967	.31	.33	.32	-	.26	.36	.63	.26	.19	-	-	-	.19	-	-	2.85
1968	.33	.34	.33	-	.27	.37	.66	.27	.20	-	-	-	.20	-	-	2.97
1969	.34	.36	.35	-	.28	.39	.69	.28	.21	-	-	-	.21	-	-	3.11

Table 2. Estimated irrigation withdrawals (cubic feet per second), by node, in the vicinity of Holloman Air Force Base - Concluded

Year	Node 17,27	17,24	16,24	19,24	15,23	16,23	15,22	14,22	17,20	12,18	13,18	11,17	10,14	10,13	11,12	Total
1970	0.33	0.36	0.31	0.01	–	–	0.65	0.25	0.19	0.03	0.03	0.01	–	0.03	0.02	3.10
1971	.33	.36	.27	.03	–	–	.60	.22	.17	.06	.06	.03	–	.06	.06	3.13
1972	.32	.36	.23	.04	–	–	.56	.19	.14	.10	.10	.04	–	.10	.08	3.14
1973	.31	.36	.20	.06	–	–	.51	.16	.12	.13	.13	.05	–	.13	.10	3.14
1974	.30	.36	.16	.08	–	–	.47	.13	.10	.16	.16	.06	–	.16	.12	3.14
1975	.30	.36	.12	.09	–	–	.42	.10	.07	.19	.19	.08	–	.19	.16	3.15
1976	.29	.36	.08	.11	–	–	.38	.06	.05	.22	.22	.09	–	.22	.18	3.14
1977	.29	.36	.04	.13	–	–	.33	.03	.03	.25	.25	.10	–	.25	.20	3.14
1978	.28	.36	0	.14	0.28	0.39	.28	0	0	.28	.28	.11	0.21	.28	.22	3.11
1979	.28	.36	0	.14	.28	.39	.28	0	0	.28	.28	.11	.21	.28	.22	3.11
1980	.28	.36	0	.14	.28	.39	.28	0	0	.28	.28	.11	.21	.28	.22	3.11
1981	.28	.36	0	.14	.28	.39	.28	0	0	.28	.28	.11	.21	.28	.22	3.11

GROUND-WATER MODEL

Conceptual Model of the Ground-Water Flow System

The idealized ground-water flow system of the study area is shown in figure 3. The system is bounded to the east and below by bedrock of such small permeability that it is considered to be impermeable for purposes of this analysis. Ground water flows through two porous materials: the older basin fill and the more recent alluvial-fan deposits. The only significant source of recharge is surface water entering these materials along the mountain front from streams in the numerous canyons. As stated previously, the general direction of ground-water flow is downgradient in a south or southwest direction, through and away from the study area. Other discharges of ground water include evapotranspiration where the water table is close enough to land surface for plant roots to reach it and withdrawals from wells. Perennial or seasonal surface-water drainage is not present in the area. It is assumed that prior to withdrawals by wells, the system was in a state of dynamic equilibrium where inflow along the mountains equaled outflow from the study area plus evapotranspiration (steady state).

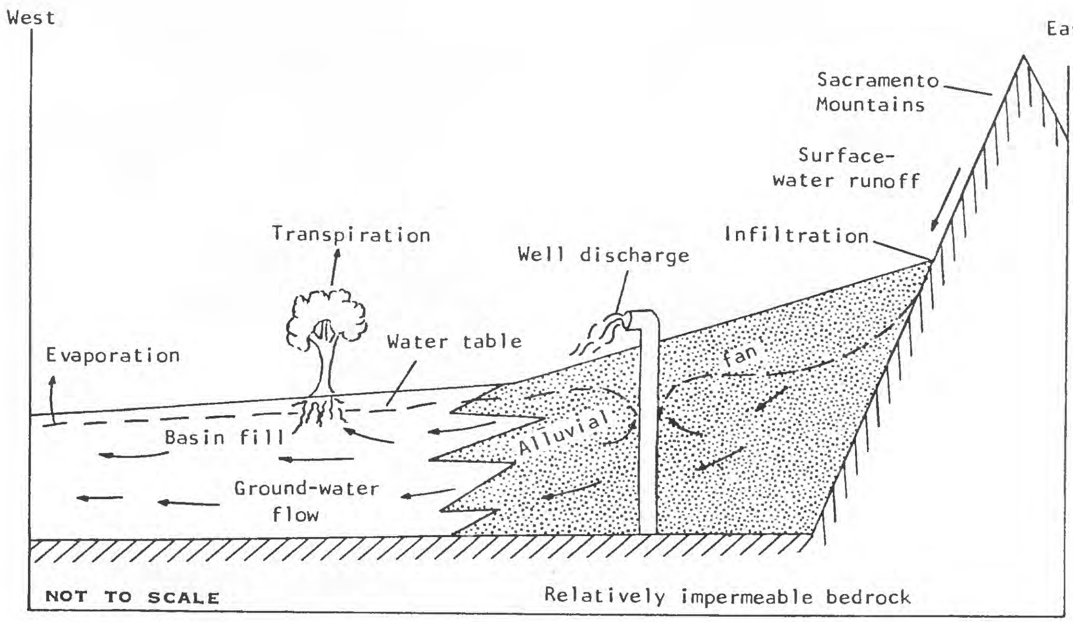


Figure 3.--Idealized hydrologic section of the Tularosa basin ground-water system.

Flow Equation and Model Concept

Digital-computer models that simulate ground-water flow do so by numerically approximating the ground-water flow equation. For an unconfined, nonhomogeneous, isotropic, two-dimensional aquifer system, the flow equation is the partial differential equation:

$$\frac{\partial}{\partial x}\left(Txx \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(Tyy \frac{\partial h}{\partial y}\right) = Sy \frac{\partial h}{\partial t} + W(x,y,t) \quad (1)$$

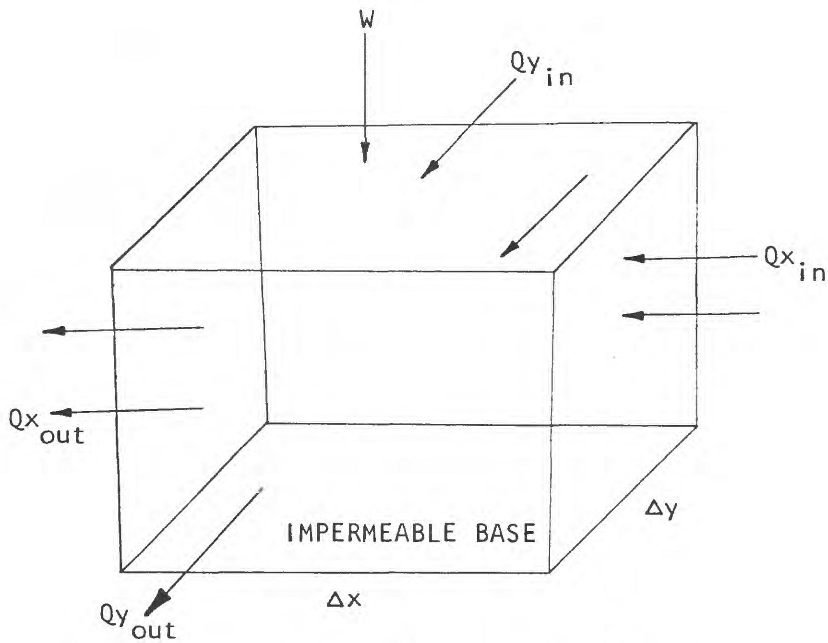
where:

T is the transmissivity, which can be computed as the hydraulic conductivity (K) times the aquifer thickness (b);
h is the hydraulic head;
Sy is the specific yield (dimensionless);
W is the volumetric flux of recharge or withdrawal per unit surface area of the aquifer;
t is time; and
x and y are surface areas aligned at right angles.

Development of numerical-approximating algorithms is based on two concepts. The first concept is the conservation of mass; simply illustrated, it is a mass balance of a segmented block of an aquifer (fig. 4) showing the quantity of water going in and going out and the change in storage. The second concept is the conservation of momentum, using Darcy's law to compute one-dimensional horizontal flow. Darcy's law (Q = K I A) states that discharge (Q) is equal to the hydraulic conductivity (K) times the gradient or slope of the water table (I) times the cross-sectional area (A) of interest. Thus, the inflow and outflow in the mass-balance equation (fig. 4) are computed using Darcy's law.

Initial Large-Grid Model

The computer program used to simulate the ground-water flow system is a finite-difference, iterative, alternating-direction, implicit version modified from Trescott (1973), similar to the model used widely by the U.S. Geological Survey (Trescott and others, 1976). Initially, a finite-difference grid was superimposed on a map, dividing the area into blocks 1 square mile in area corresponding to standard sections. Hydraulic properties or values for transmissivity, specific yield, and volumes of recharge and discharge were assigned to each model block. This initial model was used to gain an understanding of the flow system, its boundaries, and the sensitivity of the model to changes in assigned hydraulic properties. This model was also a test to see whether the two-dimensional flow model could be used to simulate the flow system under predevelopment conditions, which were assumed to have been at steady state.



$$\Delta S = \left[Qx_{in} + Qy_{in}\right] - \left[Qx_{out} + Qy_{out}\right] + W$$

EXPLANATION

W VOLUMETRIC FLUX OF RECHARGE OR WITHDRAWAL PER UNIT SURFACE AREA OF THE AQUIFER

Q QUANTITY OF WATER ENTERING OR EXITING THROUGH THE X OR Y FACE OF THE BLOCK

ΔS CHANGE IN QUANTITY OF WATER STORED IN THE BLOCK

Figure 4.--Flow into and out of a block in the aquifer system.

Initial model simulations used a uniform and constant value of transmissivity. Specific-yield values are not necessary for steady-state simulation. Inflow to the aquifer system from the canyon streams was represented in the model as a constant value of recharge at each block closest to the mouth of a canyon. Recharge from each canyon was based on the drainage area, estimated average precipitation, and a unit recharge value. Areal recharge from precipitation directly on the basin-fill deposits was considered to be negligible.

A major concern was to specify the appropriate boundary conditions. The eastern boundary was considered to be an impermeable no-flow boundary, with the exception of the constant-flux cells that represent recharge from streams. The northern boundary also was simulated as a no-flow boundary. In water-table maps by Meinzer and Hare (1915), Hood (1958), Ballance (1976), and Garza and McLean (1977), water-table contours in this area are shown to be almost due north-south and to indicate westward flow with almost no flow moving across this boundary. There are no natural hydrologic boundaries for the study area to the west or south. Previous studies have indicated that the major discharge is ground-water flow to the southwest. Constant-head values initially were selected along these boundaries on the basis of the cited water-table maps.

Evapotranspiration was computed by the model using a function that allows maximum evapotranspiration to occur when the water table is at land surface and to decrease to zero at some given depth. The maximum evapotranspiration rate was selected to be 4 feet per year, and no evapotranspiration was assumed to occur at depths of 15 feet or greater. Phreatophytes commonly growing along the arroyos and on the alluvial fans are saltcedar, mesquite, and creosote bush.

Gross annual lake evaporation at Alamogordo, as shown by maps prepared by the U.S. Bureau of Reclamation and the State of New Mexico (1976), is 75 inches per year. Only a few small ponds exist in the study area and relatively small areas where water levels are within 15 feet of the land surface.

Initial model simulations showed the simulated water levels to be sensitive to changes in transmissivity. Order-of-magnitude changes in transmissivity from those that created a reasonable water-table configuration caused dramatic changes in the computed water table.

Whereas previous investigators had stated that evapotranspiration does occur, none had considered it to be very significant in the mass balance of the study area. Initial computer simulations indicated that about one-half of the water entering the ground-water system is discharged by evapotranspiration. A sensitivity test that did not include any evapotranspiration resulted in a water-table contour map that was relatively unchanged. However, when comparing the simulated water levels with land-surface altitudes, several areas had water levels above land surface. This indicates that the initial values used for simulating evapotranspiration are reasonable and sufficiently accurate.

To evaluate the accuracy of the constant-head values along the west and south boundaries of the model, a new algorithm was used in the model that would compute the flux needed at each of the boundary blocks to cause the gradient at the block to be the same as the gradient at the adjacent interior block. This algorithm needs to provide the same head configuration as would occur if the aquifer were actually semifinite. Simulation results using this algorithm indicated that the previously selected constant-head values were too small, especially near the southwest corner. However, these simulations also showed that the head configuration near the mountain front and in the eastern quarter of the study area, that is, the area of greatest interest, was relatively insensitive to the western and southern boundary conditions.

To determine a realistic transmissivity throughout the study area, a uniform hydraulic conductivity was assigned, and the bedrock surface as mapped by McLean (1970) was entered into the model. The variable saturated thickness resulting from the irregular bedrock surface and sloping water-table surface generated a nonuniform transmissivity distribution. Many of the drillers' logs and geophysical logs showed that the basin-fill deposits become progressively finer grained toward the center of the basin, and some showed a greater thickness of clay and silt with increased depth. The transmissivity values supplied to the model were modified to account for the two different layers of porous material by calculating the altitude of the interface between the bolson-fill and the alluvial-fan deposits. Transmissivity was then computed by adding the thickness of the bolson fill times its hydraulic conductivity to the saturated thickness of the alluvial fan times its hydraulic conductivity.

Steady-State Calibration

Because the initial large-grid model indicated that the steady-state ground-water system could be adequately simulated with a two-dimensional ground-water flow model, a more detailed grid system was developed. The new grid's "north-south" axis was oriented slightly west of north (fig. 5), so that the northern no-flow boundary was more closely normal to the water-level contours. The block dimension in the generally north-south direction was 5,210 feet; the block dimensions in the generally east-west direction ranged from 7,813 feet in the western part of the area to 2,930 feet in the eastern half. Thus, the blocks in the area of greatest interest were about 0.5 square mile in size.

Recharge to the aquifer from surface-water runoff was computed based on the estimated surface-water flow from each respective basin. Hood (1958) showed that the quantity of precipitation in this area ranges from 8 to 24 inches per year and is greatly influenced by land-surface altitude. By computing the drainage area of each basin and the annual precipitation on the basis of the mean basin altitude, the quantity of precipitation and runoff occurring annually in each basin was estimated. The quantity of runoff that infiltrates to the basin fill was estimated by Garza and McLean (1977) to be about 20 percent. The drainage area, mean basin altitude, and constant-flux value for each canyon used in the model are listed in table 3. The adjusted constant-flux recharge used in the model was about 23 percent of the estimated runoff. The recharge sites are shown in figure 6.

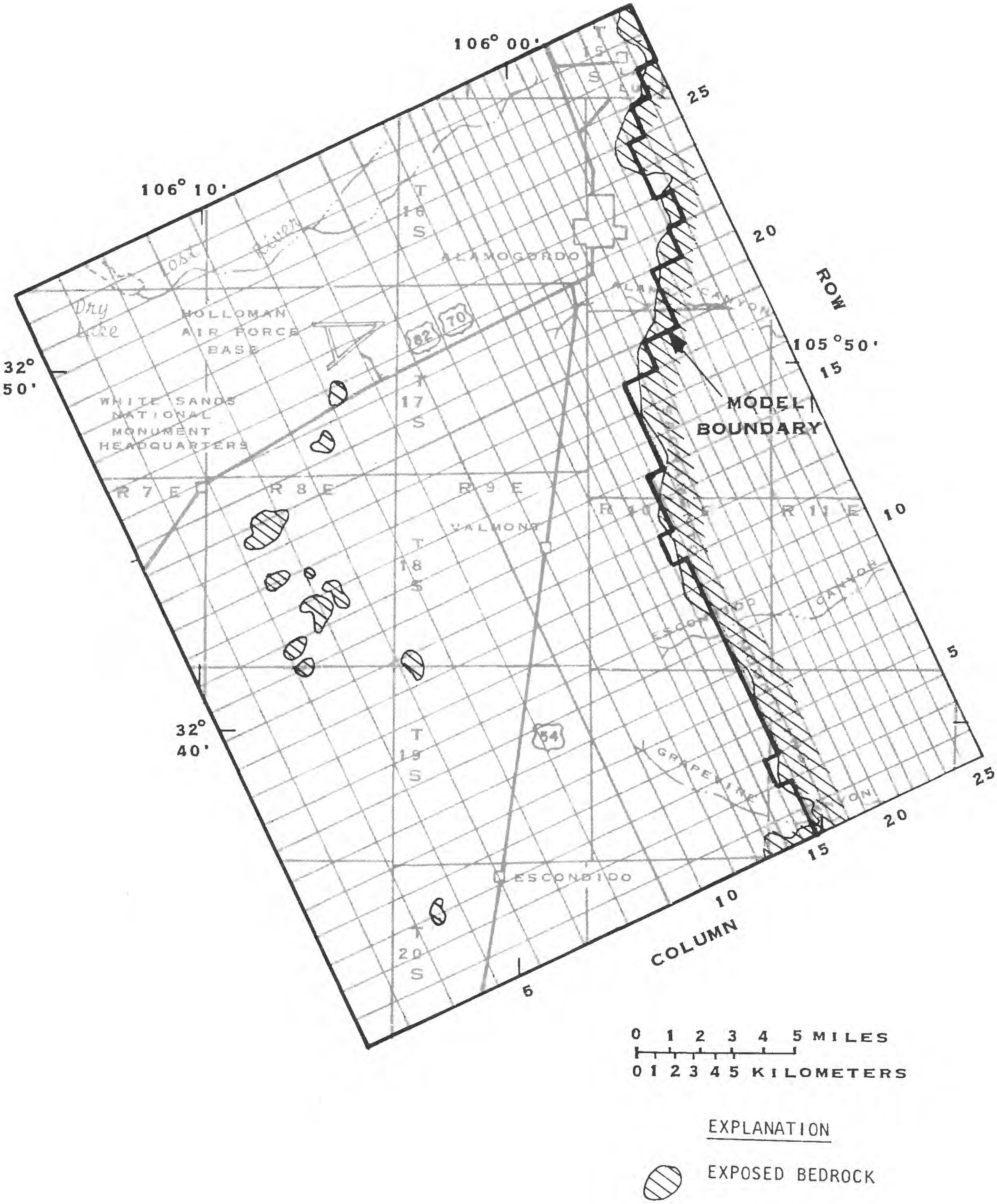
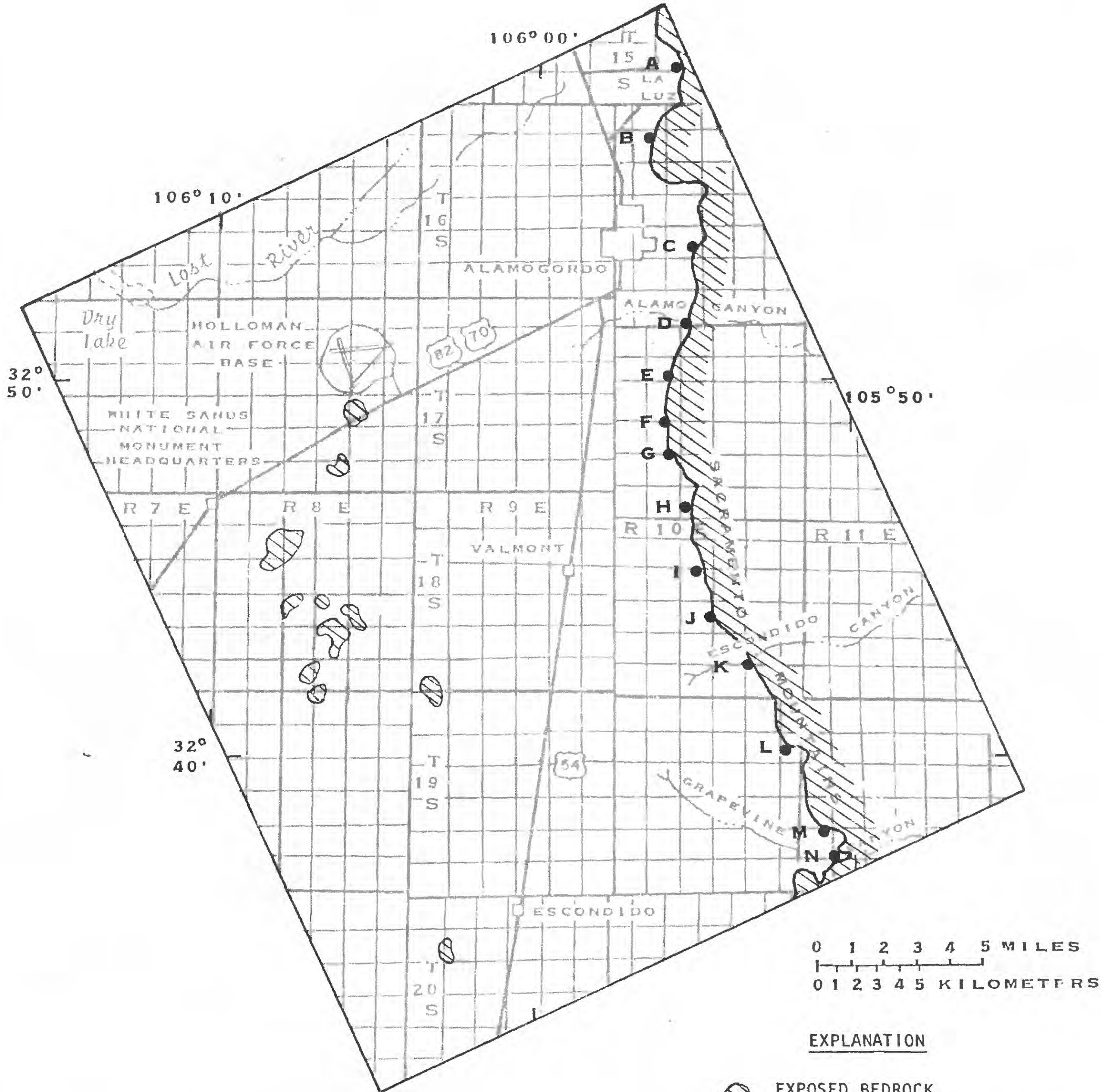


Figure 5.--Model grid used for final simulations.



EXPLANATION

EXPOSED BEDROCK

N ● RECHARGE AREA--Point where surface water from mountain stream flows onto basin-fill material. Letter next to recharge point identifies drainage basin in table 3

Figure 6.--Location of recharge areas.

Table 3. Area of drainage basins and estimated recharge to the ground-water system

Drainage canyon	Location (shown in figure 6)	Approximate drainage area (square miles)	Approximate mean altitude of basin (feet above sea level)	Estimated streamflow (cubic feet per second)	Estimated recharge to ground-water system (cubic feet per second)
La Luz	A	58	7,250	6.29	1.45
Beeman	B	20	6,200	1.86	.43
Marble	C	5		.46	.11
Alamo	D	26.5	6,900	2.73	.63
Mule	E	3.4	6,200	.32	.07
Arrow	F	3.4		.32	.07
Lead	G	3.4		.32	.07
San Andres	H	16.5	7,050	1.74	.40
Dog	I	15.3	7,150	1.64	.38
Deadman	J	1.4	7,000	.15	.03
Escondido	K	12.8		1.35	.31
Ellis Wright	L	10	5,900	1.03	.24
Bug Scuffle	M	2.2	5,700	.22	.05
Grapevine	N	12.8		1.33	.31

Constant-head values were assigned to the western and southern boundaries. These heads were determined using the technique described earlier that computes the heads such that the gradient at the boundary is the same as the gradient one set of nodes to the interior. Thus, for each simulation with changes in hydraulic properties, new constant-head values had to be estimated.

Available water-table contour maps were drawn from sparse data obtained at distances greater than 2 miles from the mountain front. There was much subjective interpretation of the data, and most of the maps were drawn after ground-water withdrawals had begun. Therefore, some areas did not represent predevelopment steady-state water-level conditions. Because of these considerations, model calibration was not based on matching any particular water-level map. Instead, 46 wells, located in areas that were considered to be unaffected by ground-water withdrawals, were selected for calibration, and the measured water level in each well was assigned to the node that represented the appropriate area. Most of these wells are in an area about 10 miles wide that parallels the mountain front. After each model simulation, the mean error and the root mean error of the residuals between the simulated water levels and the measured water levels were computed. The mean error (ME) and root mean error (RME) are defined as:

$$ME = \Sigma (ho - hc) \ / \ n \qquad (2a)$$

$$RME = \sqrt{\Sigma (ho - hc)*(ho - hc) \ / \ n} \qquad (2b)$$

where:

ho is the measured water level assigned to a node;
hc is the simulated water level at a node; and
n is the number of nodes to which water levels have been assigned.

The root mean error is similar to the standard error of estimate computed when using regression analysis.

The model was first calibrated using uniform values of hydraulic conductivity for the bolson fill and for the most recent alluvial fans because there were insufficient data on which to base any distribution of these properties. A hydraulic conductivity of 0.43 foot per day for the basin fill, 1.72 feet per day for the alluvial fans, and 4,200 feet for the altitude separating alluvial-fan material from bolson fill (Hood, 1958) resulted in the smallest mean error and root mean error and the water-table configuration shown in figure 7. The mean error in water level of the 46 nodes with measured data was -0.4 foot, and the root mean error was 32.5 feet. A mass balance on the entire modeled area indicated that 4.2 cubic feet per second of water recharges the aquifer along the mountain front, 1.2 cubic feet per second leaves the western and southern boundaries, and 3.0 cubic feet per second is lost to evapotranspiration under steady-state conditions. The areas where the water table was within 15 feet of land surface (those areas where evapotranspiration was simulated as occurring) are shown in figure 7.

The assumption of uniform distribution of hydrologic properties had several shortcomings. The 4,200-foot altitude separating the bolson fill from the most recent alluvial fans seemed reasonable on the basis of the land-surface contours of the fans. Upon close examination, however, the water level in areas of the Holloman Air Force Base well fields was below 4,200 feet. Thus, the model did not simulate any saturated upper alluvial-fan material in these areas where it has been reported to occur. A related problem was that the maximum transmissivity used in simulation was about 1,500 feet squared per day. Ballance (1976) reported transmissivities as large as 20,000 feet squared per day in the Douglas and San Andres well fields (fig. 8). In addition, the residuals between measured and simulated heads showed some regional bias, indicating a need to increase transmissivity along the mountain front south of Alamogordo and to decrease it north of Alamogordo.

Several changes were made in assigned values of hydraulic properties in an attempt to decrease the root mean error from that of the uniform-hydrologic-property simulation. These changes included: (1) making minor modifications in the bedrock surface, mostly steepening along the mountain front; (2) increasing the average hydraulic conductivity of the basin fill and the alluvial fans about 10 percent to 0.5 foot squared per day; (3) increasing hydraulic conductivity in much of the southeastern part of the study area near the mountains 20 percent; (4) gradually increasing the interface altitude of the contact between the basin fill and alluvial fans from 4,200 feet to 4,250 feet in the La Luz fan area and decreasing the interface altitude to a low of 3,200 feet at the edge of the mountains in the area near the Holloman Air Force Base well fields; and (5) increasing the ratio of the hydraulic conductivity of the alluvial fans to the basin fill from 4:1 to 10:1. Given the paucity of data, the changes were somewhat subjective. The resulting hydraulic properties, however, were within the range of measured values. The distribution of transmissivity for the simulation with the stated changes is shown in figure 8. Values of transmissivity ranged from 500 to 6,000 feet squared per day.

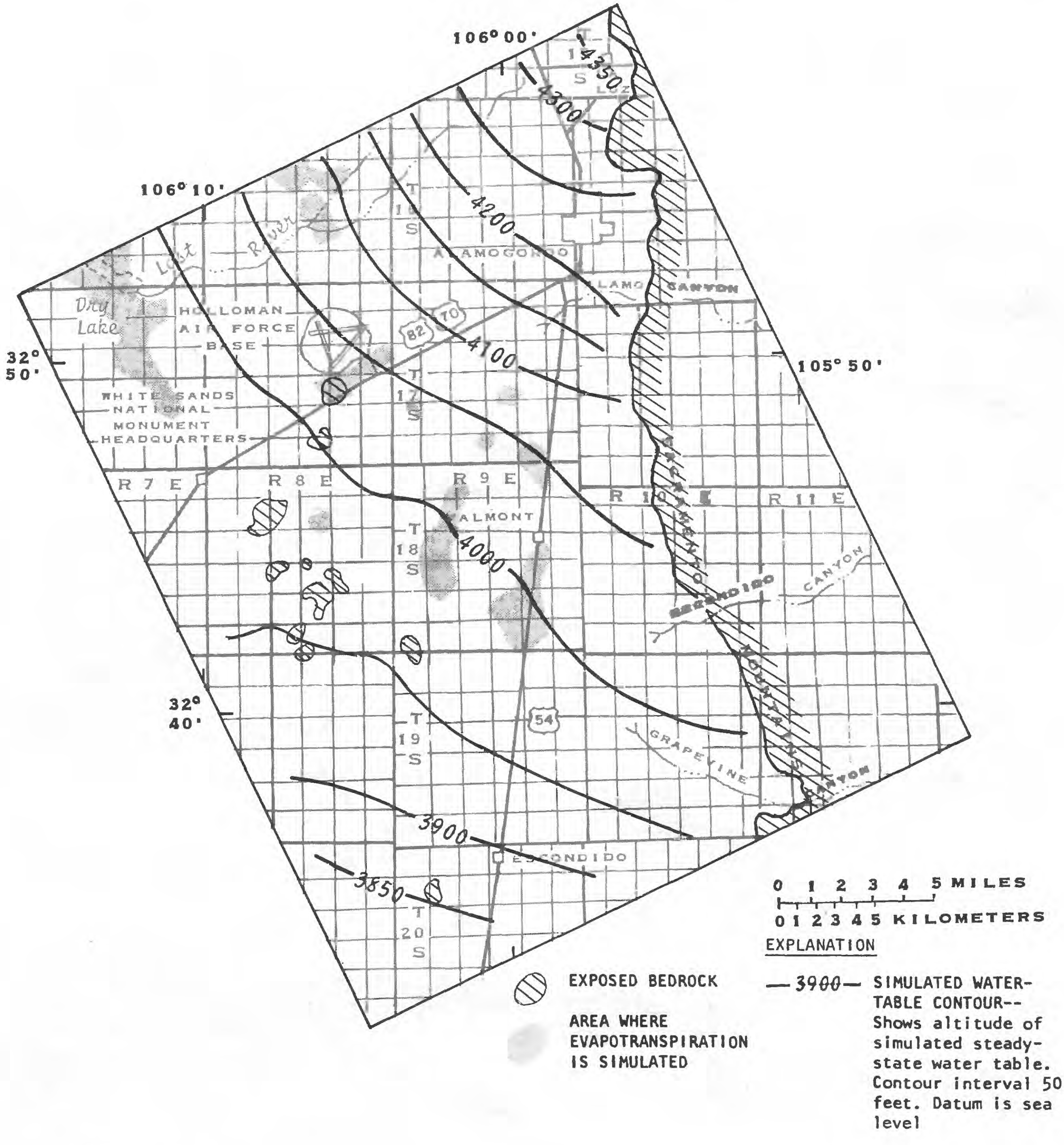


Figure 7.--Simulated steady-state water-table contours and areas where evapotranspiration occurs for uniform distribution of hydrologic properties.

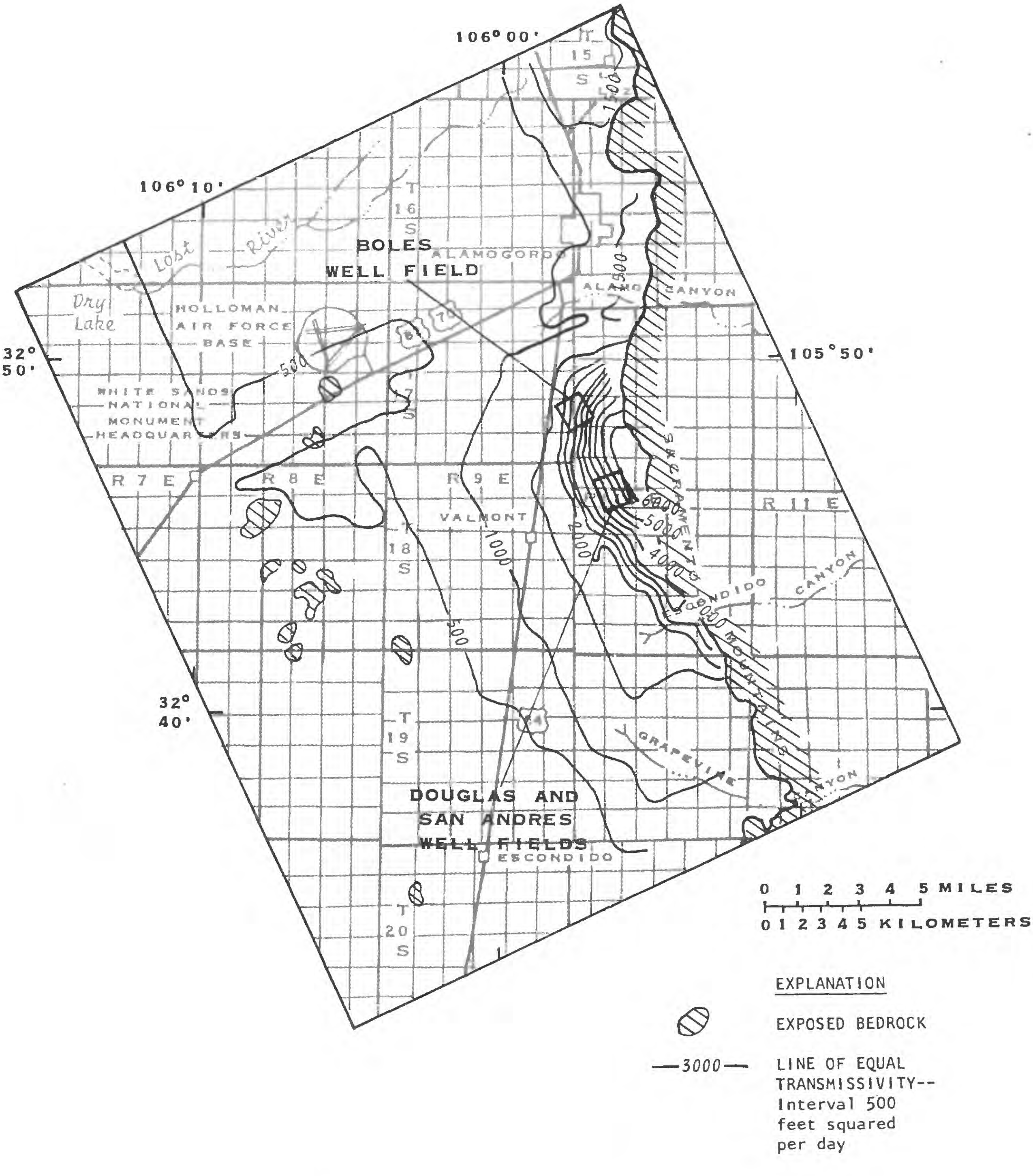


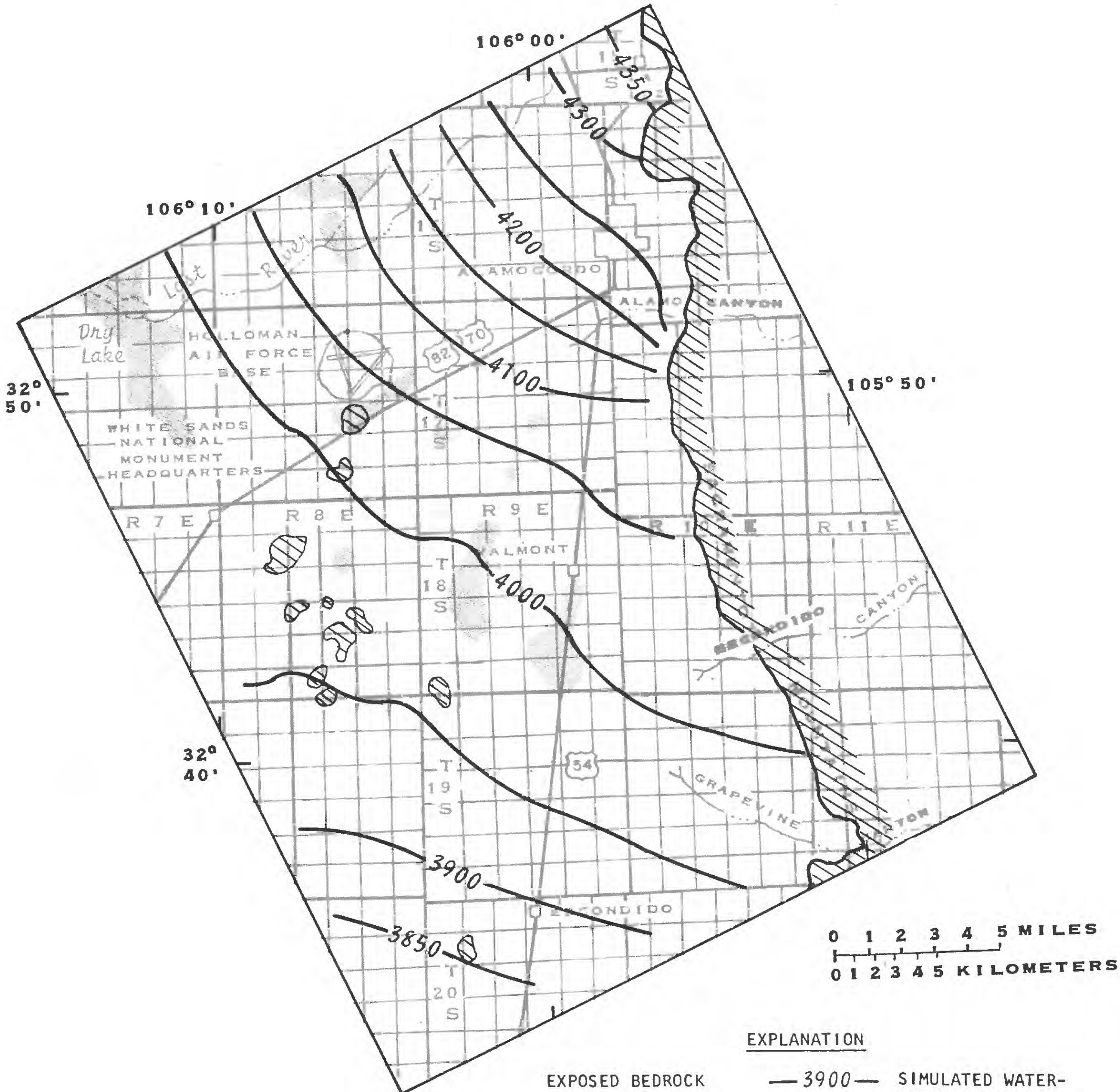
Figure 8.--Transmissivity distribution used in the final steady-state simulation.

Recharge from some of the mountain canyons was also adjusted to reflect geologic and hydrologic factors such as springs and seeps in the area. These small adjustments were made to more closely match simulated water levels to measured water levels. The final calibrated steady-state water-table configuration is shown in figure 9. Whereas the water table did not appear to have changed very much from that of the uniform-hydraulic-property simulation, the new mean error was 0.4 foot, and the root mean error was 22.1 feet. The calibrated recharge was 4.4 cubic feet per second: 1.3 cubic feet per second flowed from the area along the western and southern boundaries, and 3.1 cubic feet per second evapotranspired. The areas of evapotranspiration (fig. 9) remained the same as in the previous simulations.

Transient Calibration

Although ground water has been used in the basin since the early 1900's, significant ground-water withdrawals in the study area did not begin until about 1947 when the Boles well field (fig. 10) began production. These withdrawals have produced water-level declines, which have been measured at several places. To determine the accuracy of the model in simulating transient conditions, estimated historical ground-water withdrawals were applied to the system, and simulated water-level changes were compared to the measured changes.

The first simulation made was based on estimated municipal ground-water withdrawals during 1947-81 (table 1). The stresses were distributed by assigning the withdrawals at the Boles well field to two nodes and the Douglas and San Andres well fields to one node each (fig. 10). The Alamogordo municipal pumpage was also assumed to occur within one node (fig. 10). The first simulation was made disregarding withdrawals for irrigation. A uniform specific yield of 0.09 was used, based on mass-balance computations in the Holloman well fields by Hood (1958) and Ballance (1976).



EXPLANATION

EXPOSED BEDROCK

AREA WHERE EVAPOTRANSPIRATION IS SIMULATED

—*3900*— SIMULATED WATER-TABLE CONTOUR--Shows altitude of simulated steady-state water table. Contour interval 50 feet. Datum is sea level

Figure 9.--Simulated steady-state water-table contours and areas of evapotranspiration for distributed hydraulic properties.

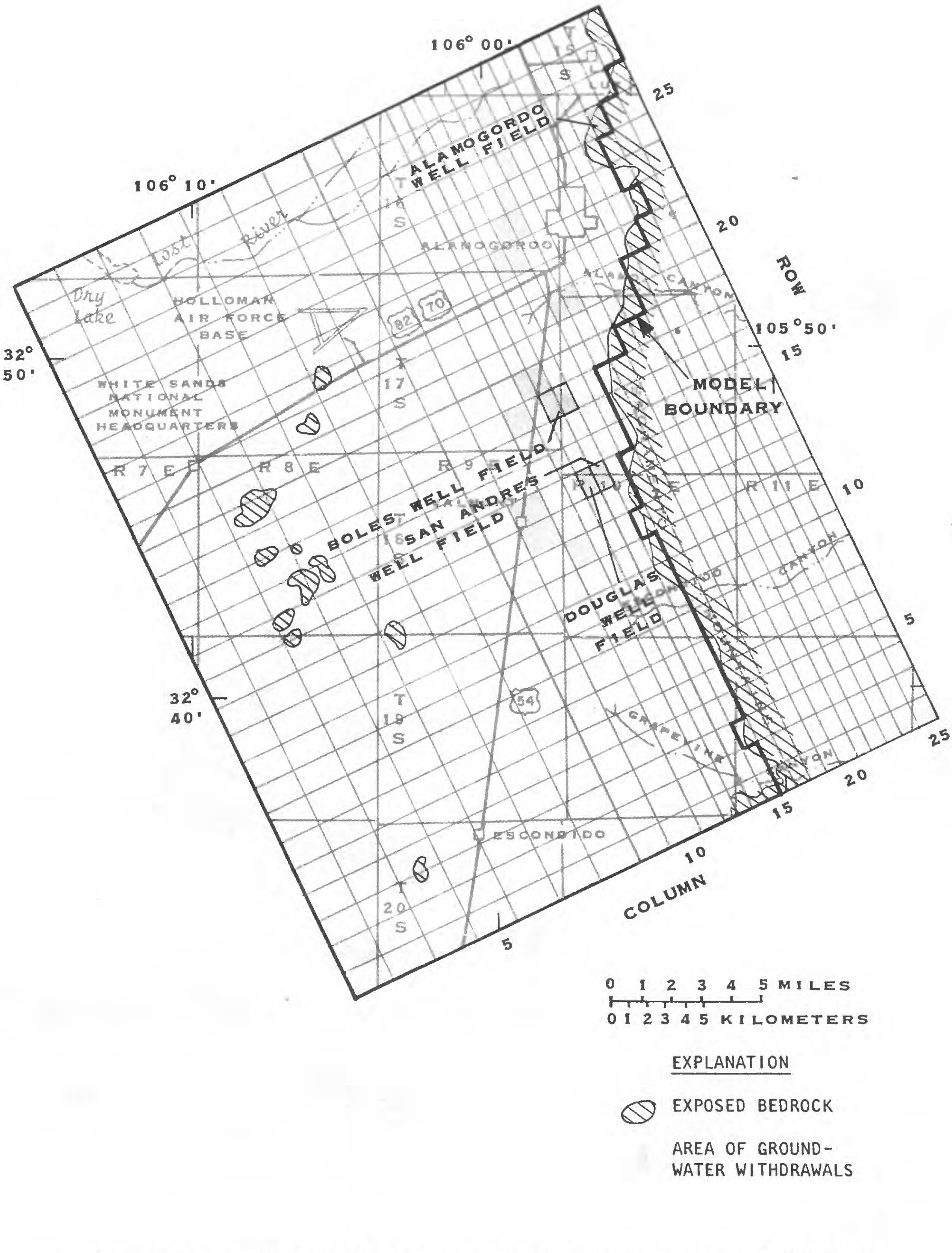


Figure 10.--Model grid and location of ground-water withdrawals.

The simulated water-table configuration after 35 years of variable withdrawals is shown in figure 11. The average withdrawal rate was 2.65 cubic feet per second. The computed mass balance indicated that 89 percent of the water withdrawn was derived from storage and 11 percent resulted from a decrease in evapotranspiration. The areas where evapotranspiration was occurring at the end of the 35 years are shown in figure 11. Water levels declined almost 90 feet north of Alamogordo and as much as 40 feet at the Holloman well fields (fig. 9).

Simulated hydrographs at the four well fields are shown in figure 11. Hood (1958) reported a maximum water-level decline of about 20 feet in the Boles well field during 1947-55. Several other wells had measured water-level declines ranging from 5 to 15 feet. Ballance (1976) presented a water-level-decline map for 1953-55 to 1966 in which the Boles well field was encircled by a 10-foot contour and the decline in the Douglas-San Andres well-field area was about 15 feet. Garza and McLean (1977) indicated water-level declines of about 0.5 foot per year from 1953 to 1970 in the Holloman well-field areas, which is a total decline of 8.5 feet. The simulated hydrographs (fig. 11) match these reported declines reasonably well. Few data are available for the area from Alamogordo north. Garza and McLean (1977) showed water-level-decline contours in the same general area as the simulated declines (fig. 11). Their greatest water-level decline was 2.2 feet per year from 1956 to 1968, for a total decline of about 26 feet. The point where that decline occurred is north of the simulated Alamogordo well field, where a decline of almost 50 feet was simulated for that period (fig. 11). The only well where water levels were measured frequently during 1947-81 is in sec. 13, T. 16 S., R. 9 E. ("observation well" in fig. 11). The simulated water-level decline of less than 10 feet (fig. 11) is considerably less than the measured decline of about 25 feet. This well is in the area where ground water is used for irrigation. Because withdrawals for irrigation were not included in this simulation, the measured and computed water levels do not match.

For the second transient simulation, ground-water withdrawals for irrigation were estimated (table 2). As described previously, the ground-water withdrawals for irrigation were based on irrigated-acreage maps for 1969 and 1978 and on the assumption that ground-water irrigation was insignificant in 1947. Withdrawals for 1947-81 were estimated by determining the irrigated acreage within each modeled node, assigning a uniform consumptive-use rate, and assuming a linear rate of change in withdrawals.

The simulated 1981 water-table configuration after 35 years of variable withdrawals for municipal and irrigation use is shown in figure 12. The average withdrawal rate was 4.8 cubic feet per second. The simulated mass balance indicated that 92 percent of the water withdrawn was derived from storage and 8 percent was from a decrease in evapotranspiration. A comparison of figures 11 and 12 indicates that the effects of withdrawals for irrigation are most prominent in the area west of Alamogordo. Hydrographs and drawdown contours in the Holloman well fields were only slightly affected by the irrigation withdrawals. The simulated drawdown at the Alamogordo well field increased by only a small amount. The most significant improvement gained by including the estimated irrigation withdrawals was the match of the simulated and measured water-level changes at the observation well. Simulated drawdown was just less than 30 feet, close to the 25-foot measured change.

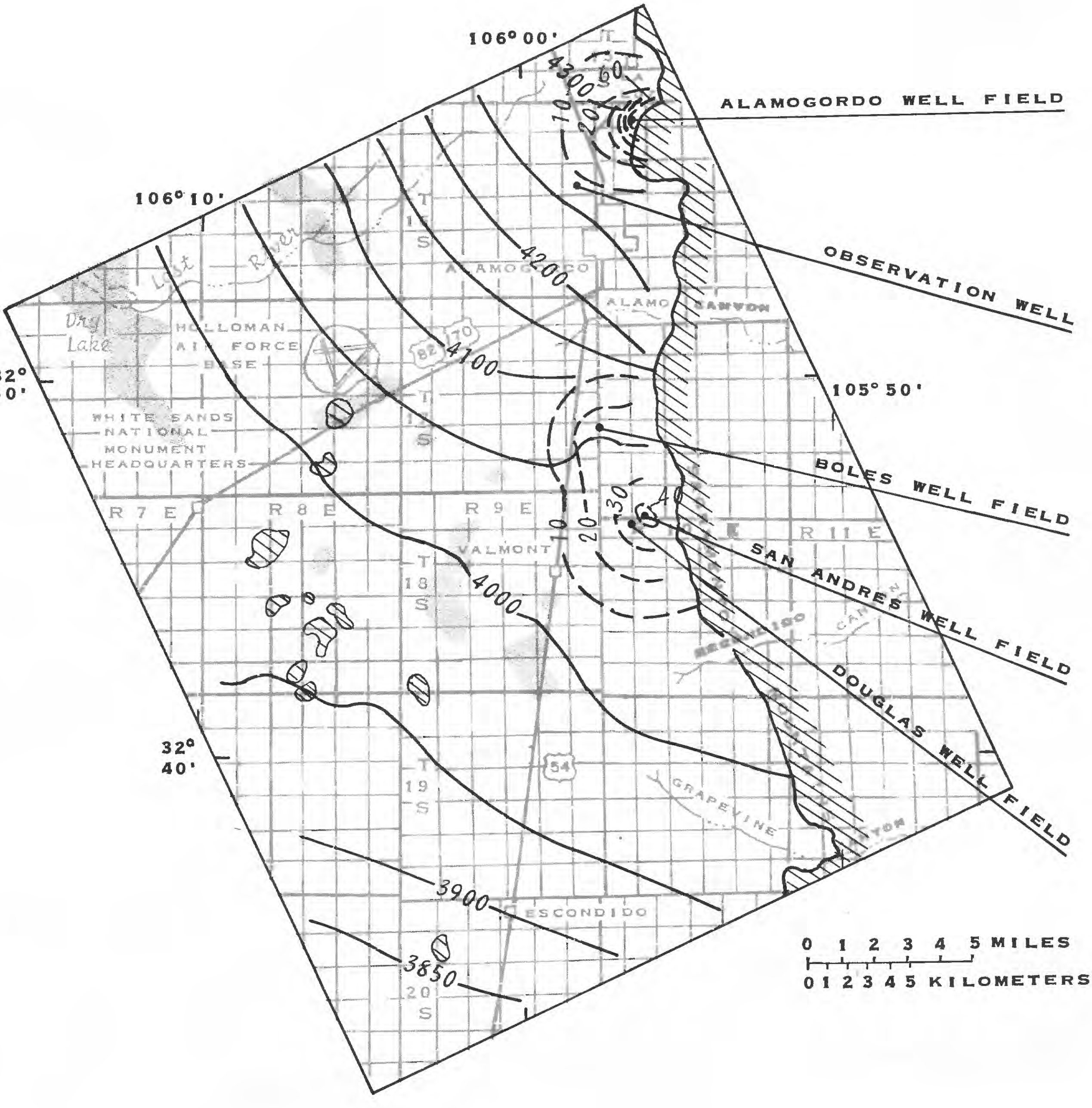
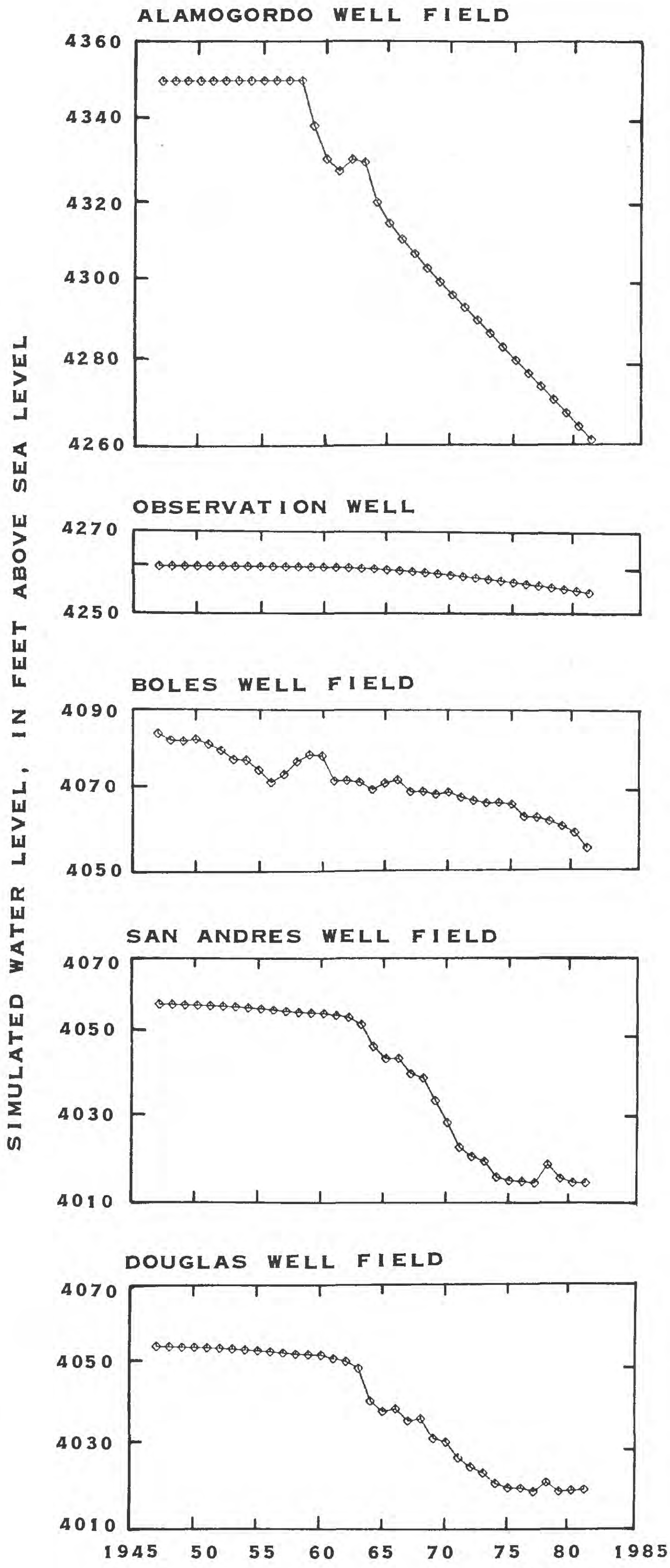


Figure 11.--Simulated 1981 water table, areas of evapotranspiration, water-level decline, and hydrographs for 1947-81 for municipal pumpage.



EXPLANATION

EXPOSED BEDROCK

AREAS WHERE EVAPO-TRANSPIRATION IS SIMULATED

—4000— SIMULATED WATER-TABLE CONTOUR--Shows altitude of simulated 1981 water table. Interval 50 feet. Datum is sea level

--10-- LINE OF EQUAL WATER-LEVEL DECLINE--Interval 10 feet

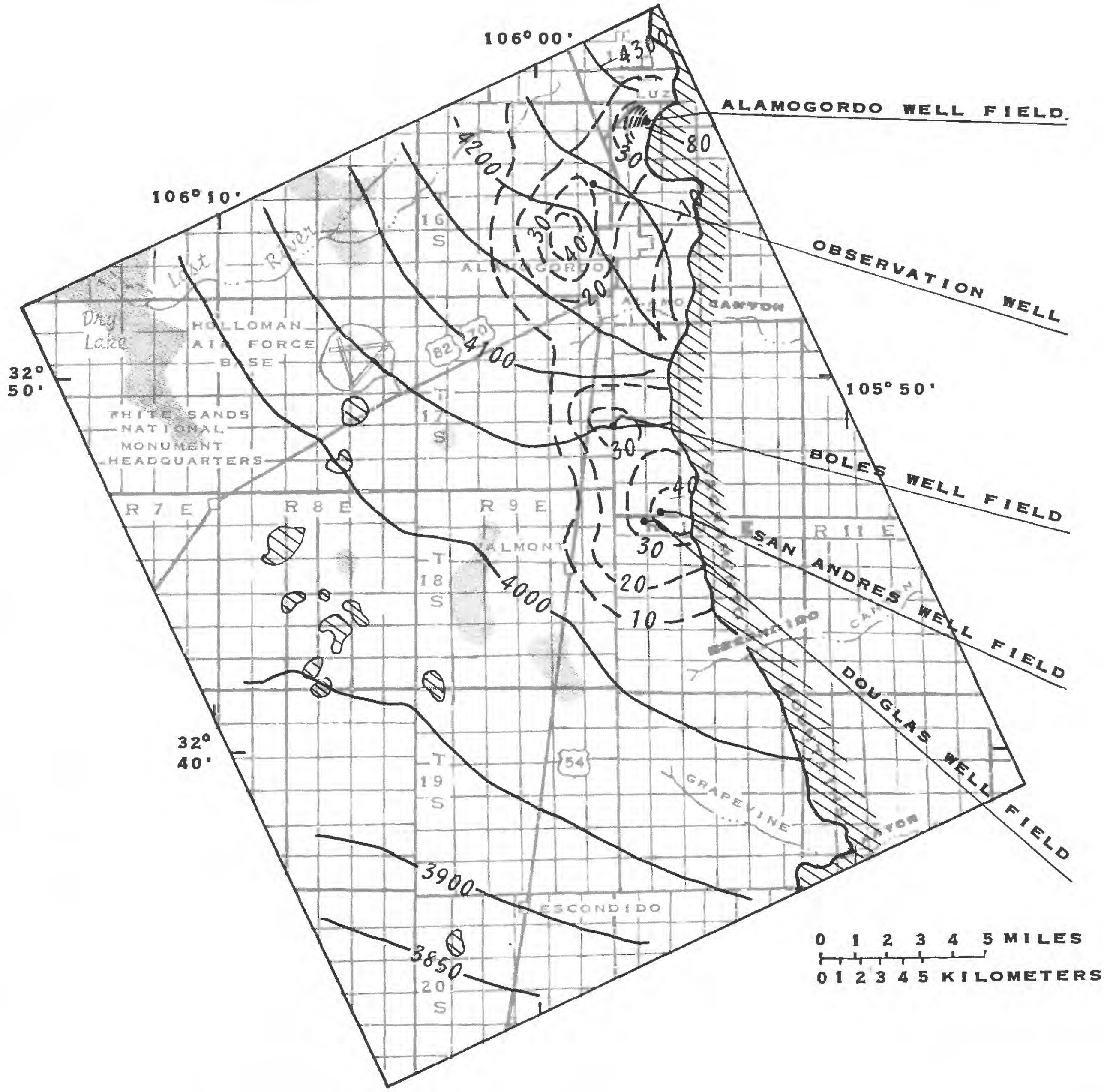
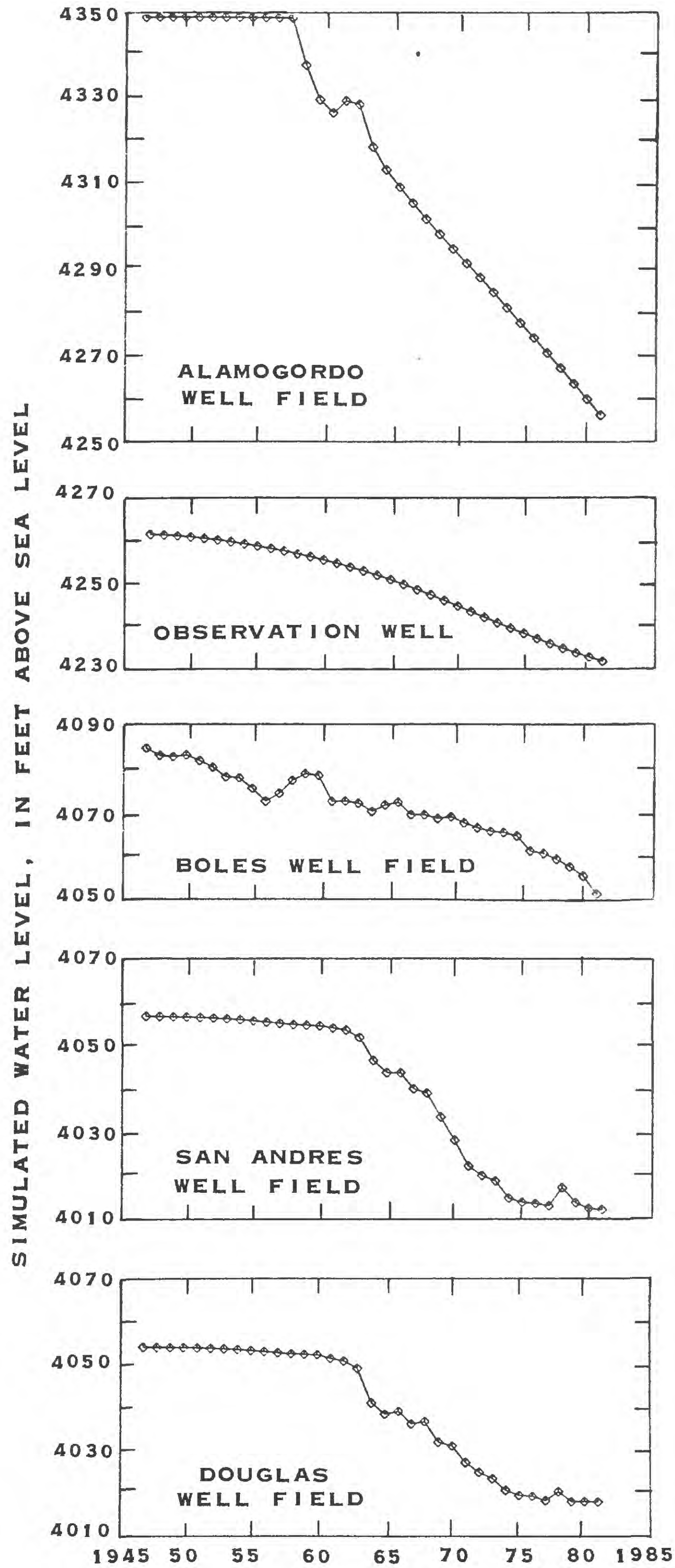


Figure 12.--Simulated 1981 water table, areas of evapotranspiration, water-level decline, and hydrographs for 1947-81 for municipal and irrigation pumpage.



EXPLANATION

EXPOSED BEDROCK

AREAS WHERE EVAPO-TRANSPIRATION IS SIMULATED

4000 — SIMULATED WATER-TABLE CONTOUR--Shows altitude of simulated water table. Interval 50 feet. Datum is sea level

--40 — LINE OF EQUAL WATER-LEVEL DECLINE--Interval 10 feet

SIMULATED FUTURE WATER-LEVEL DECLINES CAUSED BY GROUND-WATER WITHDRAWALS

To evaluate the water-level declines caused by future ground-water withdrawals, several alternative management plans were simulated with the calibrated model. A 20-year period was selected, and various patterns of projected withdrawals that could occur were simulated. The boundary conditions were the same as those for the transient-calibration simulations. The initial conditions for these simulations included the final water levels computed by the model during the transient calibration.

The three major uses of ground water that were modeled were withdrawals for Holloman, Alamogordo, and irrigation. In order to limit the number of simulations presented in this report, withdrawals for Alamogordo and irrigation were kept constant for the 20 years at their 1981 rates. Withdrawals by Holloman were kept constant at a rate 10 percent greater than that of 1981. Four alternatives of how Holloman Air Force Base might distribute that pumpage were simulated: (1) 20 percent of the withdrawals would be taken from the Boles well field and 80 percent from the Douglas and San Andres well fields; (2) 60 percent of the withdrawals would be taken from the new Dog Canyon wells (sec. 16, T. 18 S., R. 10 E.) and the other 40 percent from the proposed Escondido Canyon wells (sec. 27, T. 18 S., R. 10 E.); (3) 10 percent of the withdrawals would be taken from the Boles well field, 30 percent from the Douglas and San Andres well fields, 30 percent from the Dog Canyon wells, and 30 percent from the Escondido Canyon wells; and (4) alternatives 1 and 2 would be alternated from year to year.

Total withdrawals for each of these four pumping patterns were the same, and the simulated results were similar in many aspects. The total withdrawal rate was 8.4 cubic feet per second, with 3.6 cubic feet per second (43 percent) of that being for Holloman. Recharge and flow leaving the modeled area remained constant for all four alternatives. Water withdrawn from storage was the same for each alternative; that is, the volume was the same for all alternatives even though the area affected and amount of the drawdowns were considerably different. Storage provided 84 percent of the water withdrawn; the remaining 16 percent was derived from a decrease in evapotranspiration. The simulated water table after 20 years and the distribution of water-level declines created by each alternative are presented in the following discussion. In addition to the observation well used during the calibration, three other points were selected to illustrate the effects of the various pumping patterns. These points are identified as A, B, and C in the following text and figures. The drawdown distribution north of Alamogordo was little affected by the alternatives simulated.

Alternative 1

For alternative 1, all of Holloman's water would be supplied from the existing well fields. The simulated 2001 water table, the 1982-2001 water-level decline, and 1982-2001 hydrographs for selected locations are shown in figure 13. This alternative resulted in the least drawdown at any one point and the broadest distribution of drawdown throughout the study area. The Boles well field, from which water was withdrawn at the rate of 0.72 cubic foot per second, had a water-level decline of 18 feet at the end of 20 years. The Douglas well field, from which water was withdrawn at the rate of 0.72 cubic foot per second, had a water-level decline of 26 feet at the end of 20 years. The San Andres well field, from which water was withdrawn at the rate of 2.2 cubic feet per second, had a water-level decline of 24 feet at the end of 20 years. There were no withdrawals at the Dog Canyon wells, which had a water-level decline of 17 feet, or at the Escondido Canyon wells, which had a water-level decline of 9 feet. The water-level decline at point A was 17 feet; at point B, 12 feet; and at point C, 6 feet.

Alternative 2

Under this alternative, all of the water for Holloman would be taken from the new and proposed wells at Dog Canyon and Escondido Canyon. The simulated 2001 water table, the 1982-2001 water-level change, and 1982-2001 hydrographs for selected locations are shown in figure 14. This distribution of withdrawals resulted in the greatest point drawdowns and the smallest area affected by drawdown. The areas around the Boles, Douglas, and San Andres well fields were simulated to have water-level increases from the 1981 levels. Water levels at the Boles well field recovered 6 feet; at the Douglas well field, 1 foot; and at the San Andres well field, 8 feet. The water-level decline at the Dog Canyon wells, from which water was withdrawn at the rate of 2.2 cubic feet per second, was 50 feet, and the water-level decline at the Escondido Canyon wells, from which water was withdrawn at the rate of 1.4 cubic feet per second, was 60 feet. The water-level decline at point A was 4 feet; at point B, 24 feet; and at point C, 21 feet.

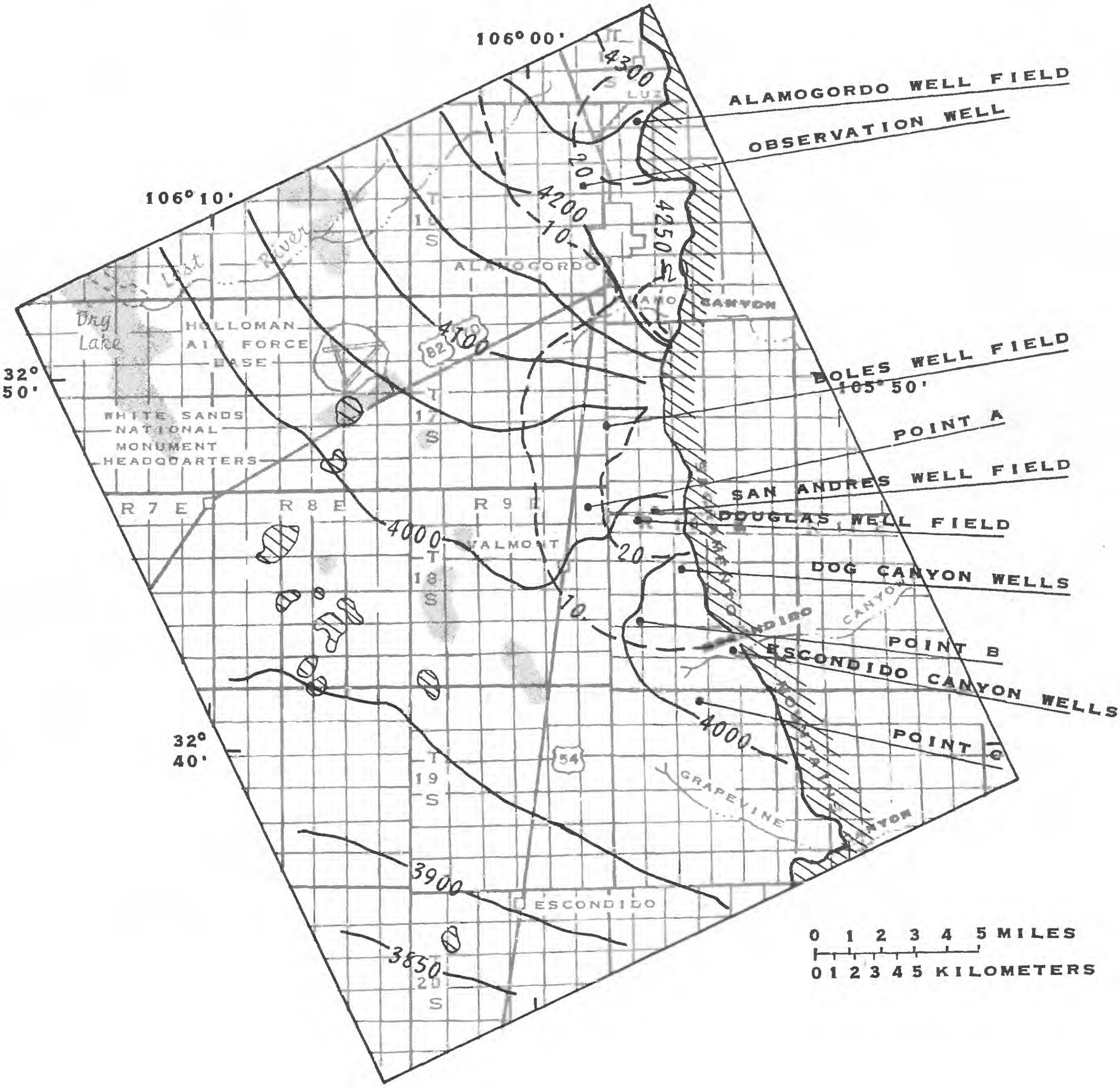
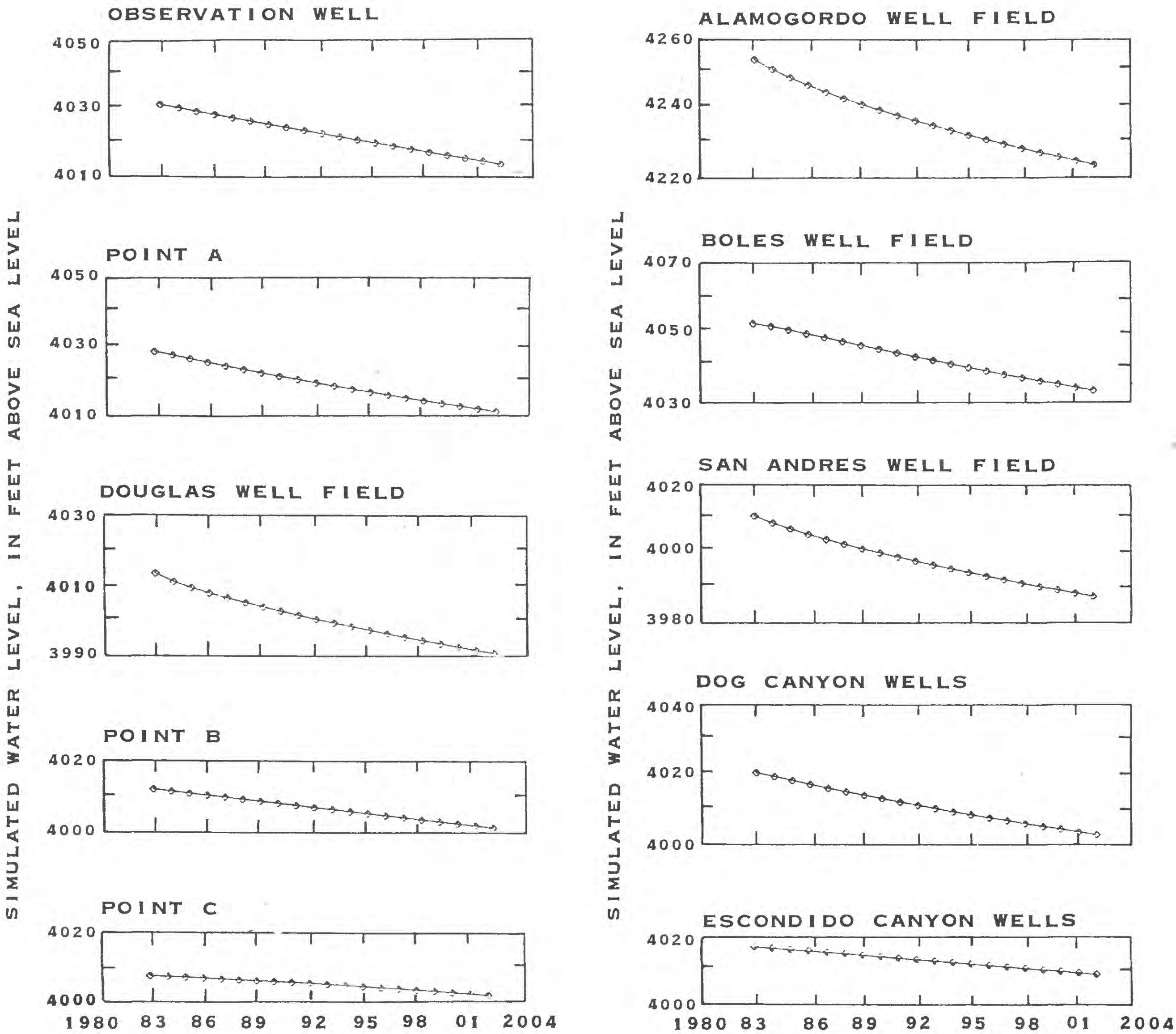


Figure 13.--Simulated 2001 water table, areas of evapotranspiration, water-level decline, and hydrographs for 1982-2001 for alternative 1.



EXPLANATION

EXPOSED BEDROCK

AREAS WHERE EVAPO-TRANSPIRATION IS SIMULATED

—3900— SIMULATED WATER-TABLE CONTOUR--Shows altitude of simulated water table. Interval 50 feet. Datum is sea level

--10-- LINE OF EQUAL WATER-LEVEL DECLINE--Interval 10 feet

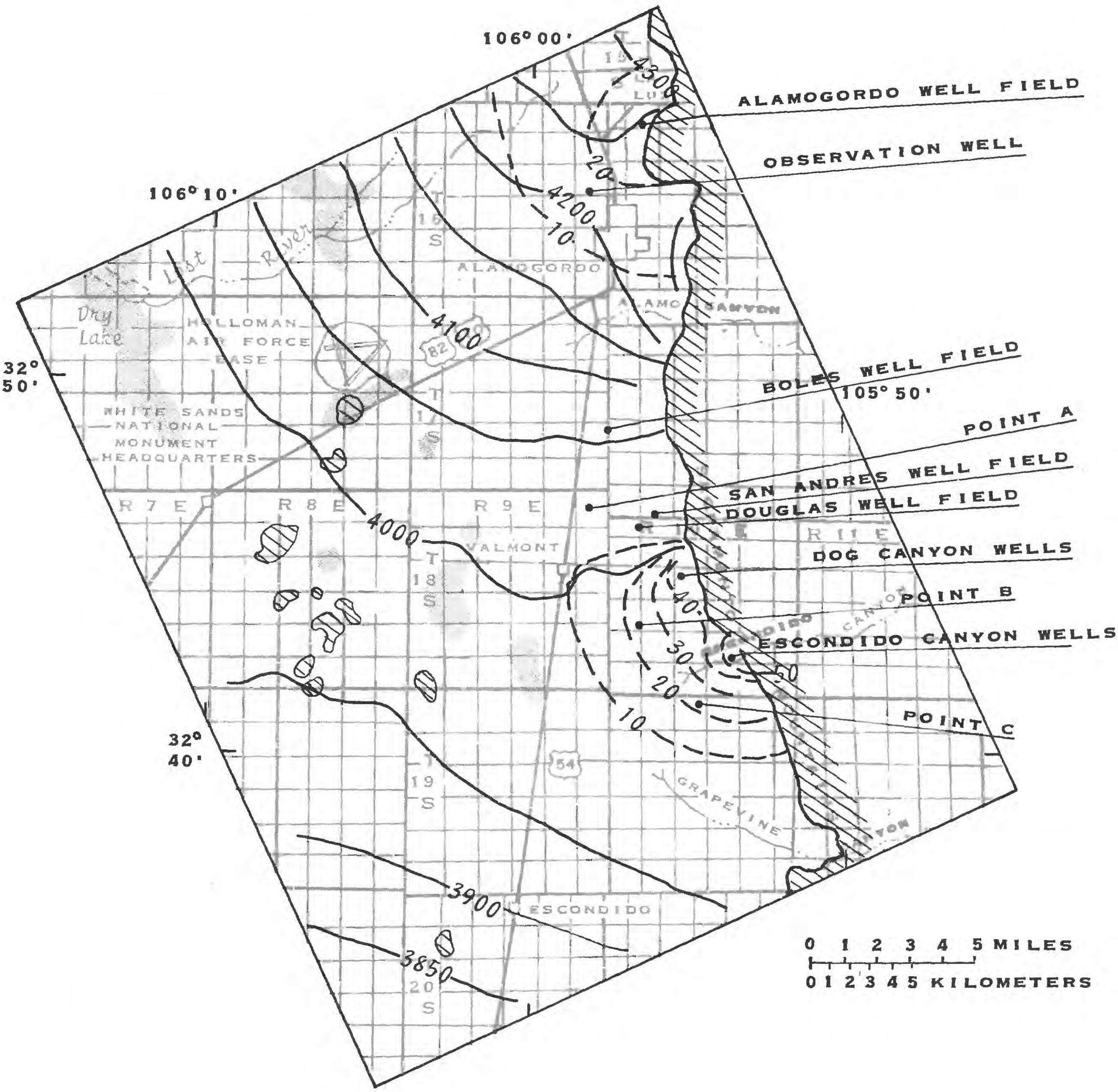
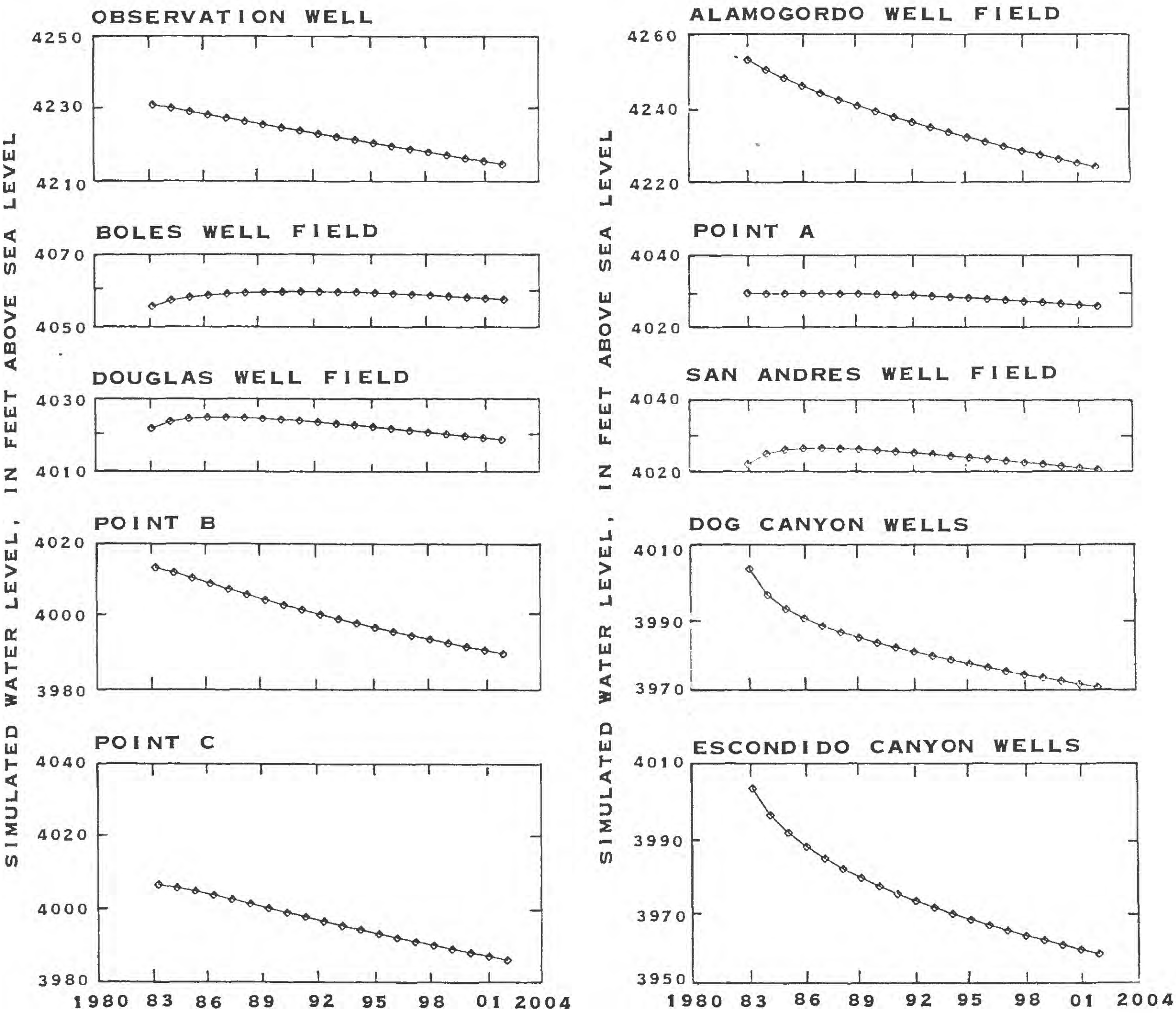


Figure 14.--Simulated 2001 water table, areas of evapotranspiration, water-level decline, and hydrographs for 1982-2001 for alternative 2.



EXPLANATION

EXPOSED BEDROCK

AREAS WHERE EVAPOTRANSPIRATION IS SIMULATED

—3900— SIMULATED WATER-TABLE CONTOUR--Shows altitude of simulated water table. Interval 50 feet. Datum is sea level

--10--- LINE OF EQUAL WATER-LEVEL DECLINE--Interval 10 feet

Alternative 3

Under this alternative, withdrawals would be distributed among the existing and proposed Holloman wells in an attempt to lessen drawdowns. The simulated 2001 water table, the 1982-2001 water-level decline, and 1982-2001 hydrographs for selected locations are shown in figure 15. This distribution of withdrawals reduced the widespread water-level declines resulting from alternative 1 and limited somewhat the extreme water-level declines resulting from alternative 2. During the first part of this simulation, water levels in the vicinity of the existing well fields recovered slightly because simulated withdrawal rates were less than historical rates. At the end of the 20-year simulation, the water-level decline at the Boles well field, from which water was withdrawn at the rate of 0.36 cubic foot per second, was 4 feet. The water-level decline at the Douglas well field, from which water was withdrawn at the rate of 0.27 cubic foot per second, was 8 feet. The water-level decline at the San Andres well field, from which water was withdrawn at the rate of 0.81 cubic foot per second, was 2.5 feet. The withdrawal rate at the Dog Canyon wells was reduced to 1.1 (from 2.2) cubic feet per second in alternative 2, which resulted in a water-level decline of 33 feet. The water-level decline at the Escondido Canyon wells, from which water was withdrawn at the rate of 1.08 cubic feet per second, was 44 feet. The water-level decline at point A was 9 feet; at point B, 19 feet; and at point C, 16 feet.

Alternative 4

Under this alternative, the sites of the withdrawals would be alternated with time in an attempt to lessen drawdowns. The total water supply needed by Holloman Air Force Base was simulated as being withdrawn from the Boles, Douglas, and San Andres well fields at the rates described for alternative 1 for 1 year and then from the proposed Dog Canyon and Escondido Canyon wells at the rates described for alternative 2 for the next year. This distribution of pumpage was alternated each year for the 20-year simulation period. The simulated 2001 water table, the 1982-2001 water-level decline, and 1982-2001 hydrographs for selected locations are shown in figure 16. Final water-level declines for alternatives 3 and 4 were very similar. The water-level decline at Boles well field was 5 feet; at Douglas well field, 10 feet; and at San Andres well field, 3 feet. The water-level decline was 39 feet at the Dog Canyon wells and 38 feet at the Escondido Canyon wells. The annual drawdown-recovery cycles for the pumping wells are shown in the hydrographs in figure 16. The water-level decline at point A was 11 feet; at point B, 18 feet; and at point C, 13 feet.

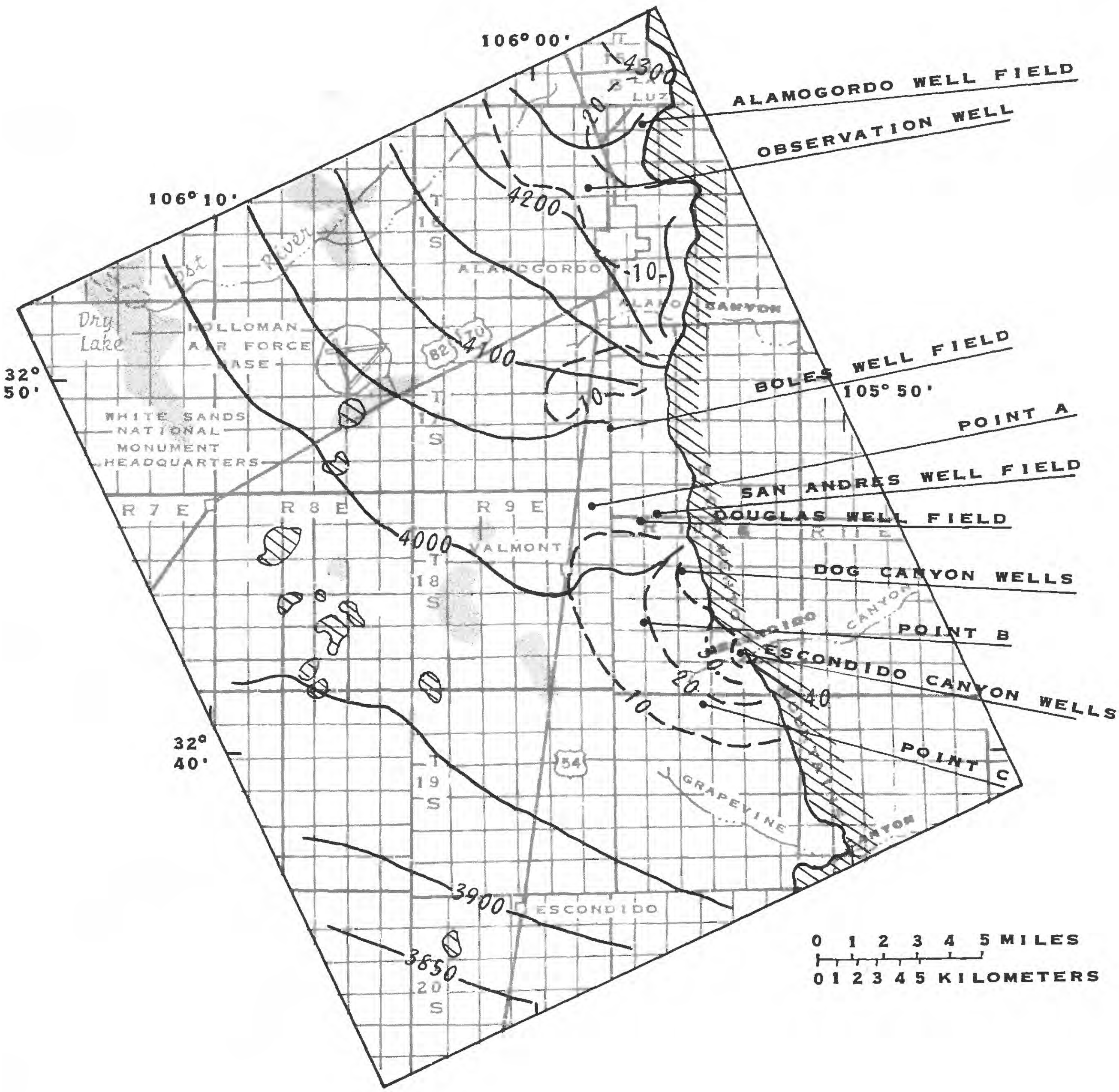
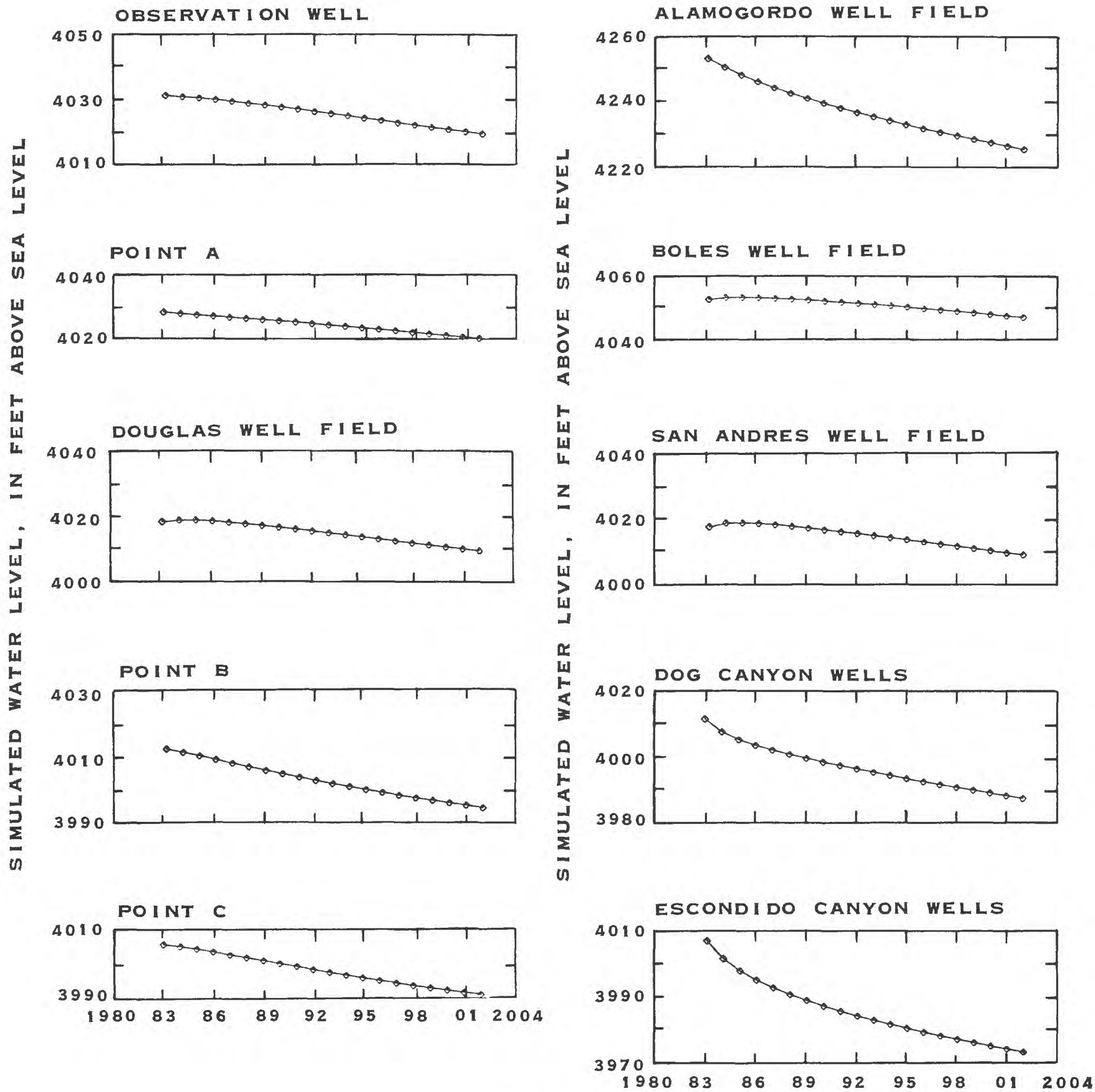


Figure 15.--Simulated 2001 water table, areas of evapotranspiration, water-level decline, and hydrographs for 1982-2001 for alternative 3.



EXPLANATION

EXPOSED BEDROCK

AREAS WHERE EVAPOTRANSPIRATION IS SIMULATED

—3900— SIMULATED WATER-TABLE CONTOUR--Shows altitude of simulated water table. Interval 50 feet. Datum is sea level

--10-- LINE OF EQUAL WATER-LEVEL DECLINE--Interval 10 feet

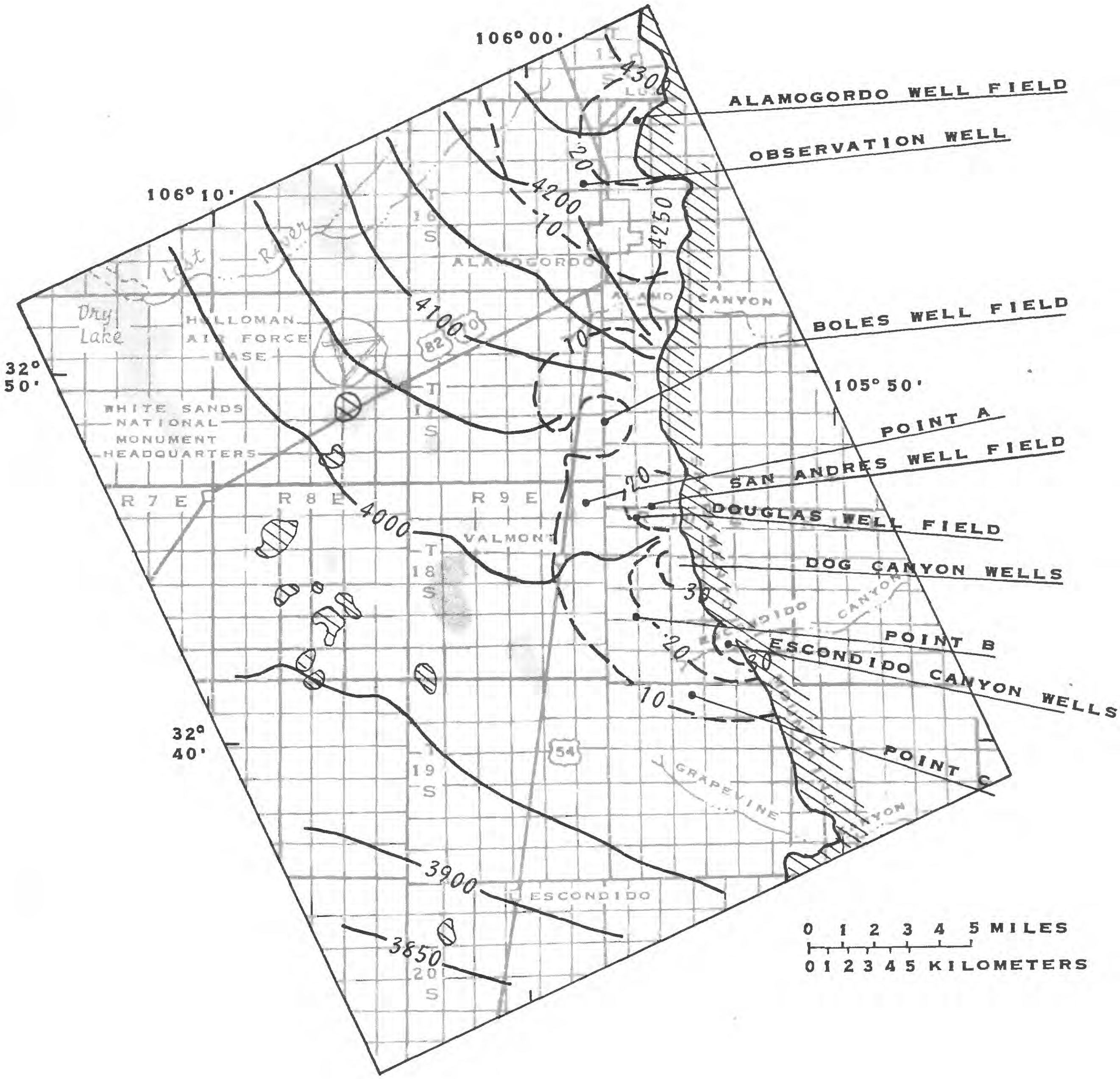
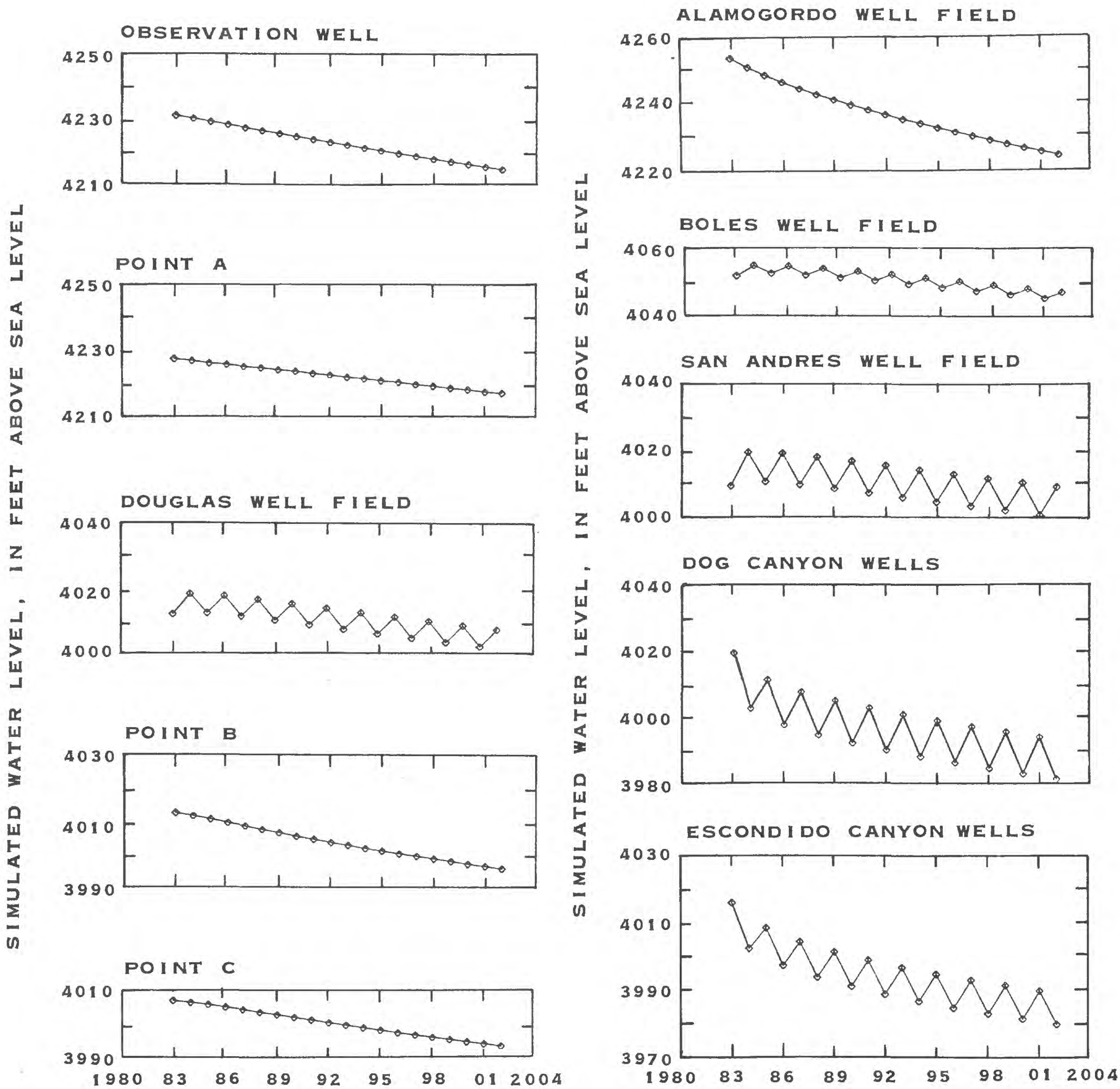


Figure 16.--Simulated 2001 water table, areas of evapotranspiration, water-level decline, and hydrographs for 1982-2001 for alternative 4.



EXPLANATION

EXPOSED BEDROCK

AREAS WHERE EVAPO-TRANSPIRATION IS SIMULATED

—3900— SIMULATED WATER-TABLE CONTOUR--Shows altitude of simulated water table. Interval 50 feet. Datum is sea level

—-10-— LINE OF EQUAL WATER-LEVEL DECLINE--Interval 10 feet

SUMMARY

This study used a two-dimensional finite-difference model to simulate the geohydrology of an area of about 400 square miles in the vicinity of Holloman Air Force Base in Otero County, New Mexico. The aquifer consists of unconsolidated alluvial-fan and basin-fill deposits. Saturated thickness ranges from 0 to 3,000 feet. Recharge to the aquifer primarily takes place along the eastern boundary of the study area where water from intermittent streams infiltrates into the alluvial-fan deposits. Perennial streams are not present in the area. Discharge from the system is by ground-water flow to the south and west, by evapotranspiration in areas where the water table is near the surface, and by ground-water withdrawals for domestic, public, commercial, and irrigation uses.

A model to simulate the aquifer under steady-state and transient conditions was constructed. Steady-state and transient calibrations of the model were made using values of transmissivity ranging from 500 to 6,000 feet squared per day, a specific yield of 0.09, and estimates of annual recharge and discharge. The mean error and root mean error of the residuals between the simulated and measured water levels at 46 nodes were 0.4 foot and 22.1 feet, respectively, for the steady-state calibration representing pre-1947 conditions.

Four alternative plans for future ground-water withdrawals at Holloman Air Force Base were simulated through 2001. The alternatives differed not in the withdrawal rate (10 percent greater than the rate in 1981) but rather in the locations of the withdrawals. Withdrawals for Alamogordo public supply and other uses were kept constant at their 1981 rates. The maximum water-level declines for the four alternatives ranged from 26 to 60 feet.

The model results indicated that by 2001, alternative 2 resulted in the greatest water-level decline. Wells in the Escondido Canyon area showed declines of 60 feet. Alternative 1 resulted in the least water-level decline. Wells in the Douglas well field showed declines of 26 feet. Maximum declines in alternatives 3 and 4 were about midway between the two extremes.

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