AQUIFER RESPONSE TO RECHARGE AND PUMPING

SAN BERNARDINO GROUND-WATER BASIN, CALIFORNIA

By William F. Hardt and John R. Freckleton

U.S. GEOLOGICAL SURVEY

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CONVERSION FACTORS

For readers who prefer to use metric units rather than inch-pound units, the conversion factors for the terms used in this report are listed below.

Multiply	By	To obtain
acres	4,047	square meters
acre-feet (acre-ft)	0.001233	cubic hectometers
acre-feet per year (acre-feet/yr)	0.001233	cubic hectometers per year
feet	0.3048	meters
feet per day (ft/d)	0.3048	meters per day
feet per mile (ft/mi)	0.1894	meters per kilometer
feet per year (ft/yr)	0.3048	meters per year
feet squared per day (ft^2/d)	0.09290	meters squared per day
cubic feet per second (ft^3/s)	0.02832	cubic meters per second
gallons per day per foot [(gal/d)/ft]	0.01242	meters squared per day
inches	25.40	millimeters
inches per year (in/yr)	25.40	millimeters per year
miles	1.609	kilometers
square miles (mi^2)	2.590	square kilometers

DEFINITION OF TERMS

Water year: The water year starts October 1 and ends September 30; it is designated by the calendar year in which it ends.

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 nets of both the United States and Canada, formerly called "Mean Sea Level of 1929."

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ABSTRACT

The effects of recharge and pumping on ground-water levels in the San Bernardino ground-water basin were simuulated by a two-layer Galerkin finite-element digital model. According to model simulations, pumping in the confined area near Warm Creek and the Santa Ana River lowers water levels in both the confined area and the north-central part of the basin. Conversely, recharge in the north-central part of the basin raises water levels in the confined area. The Santa Ana River and Lytle Creek contribute the most recharge to the basin; however, recharge in Waterman Canyon-East Twin Creek raises water levels in the confined area more per unit volume of recharge.

Increased pumping from the confined area was simulated separately from other pumping and recharge conditions in the basin to determine the separate effects of that pumping on basin water levels. For a projected pumping rate of 5,000 acre-feet per year for 3 years, the model simulation indicates a water-level decline of 7 to 15 feet in the confined area. For 25,000 acre-feet per year for 3 years, indicated declines are 40 to 80 feet in the confined area, 10 feet in the upper parts of the Lytle Creek and Santa Ana River areas, and 20 to 30 feet in the Waterman Canyon-East Twin Creek and City Creek areas.

Artificial recharge in each major stream in the basin was modeled to determine the separate effects of each stream system on water levels in the confined area. The quantity of recharge, in acre-feet per year, required to produce a 1-foot rise in water level after 10 years near the center of the confined area at a model node on Warm Creek is 3,400 for Waterman Canyon-East Twin Creek; 7,500 for Lytle Creek; 7,700 for the Santa Ana River; and 11,600 for Devil Canyon Creek. Artificial recharge simulated at Mill Creek did not have an effect on calculated water levels in the confined area during the 10-year period.

Model simulations of historical extremes (1945-74) in recharge and pumping rates were superimposed on the January 1982 water levels. The simulation with lowest recharge and highest pumping rate yielded water-level declines of more than 80 feet in the lower Warm Creek-Santa Ana River part of the confined area.

INTRODUCTION

Background

In the early 1900's, ground-water levels in shallow aquifers in the San Bernardino ground-water basin (fig. 1) were near or above the land surface in the vicinity of Warm Creek and the Santa Ana River adjacent to the San Jacinto fault. Marshlands, springs, and flowing streams were found in these areas. From the early 1940's to the late 1960's, water levels declined more than 100 feet because of ground-water pumping for agriculture and below normal precipitation. As a result, the marshlands dried up and the land was subsequently used for commercial and industrial development.

Since the late 1960's, the ground-water basin has received greater than average quantities of recharge from natural streamflow. Imported water from the California Aqueduct also increased the supply of water to the basin. These increases in recharge caused water levels to rise substantially. Water levels rose further as a result of greater than average precipitation in 1978 and 1980 and increased diversions of natural streamflow to the basins. Since about 1980, water levels in the southern part of the basin have been near or above land surface, and in 1984 the rising water saturated the soils and caused damage to buildings, roads, and public utilities in low-lying areas. These incidents of damage have heightened public concern about the rise of ground-water levels in the basin and have drawn attention to the need for a management plan to protect urban areas in the basin. Such a plan would require that the effects of ground-water recharge and pumping rates on water-level fluctuation in the basin be determined.

Purpose and Scope

This report, prepared in cooperation with the San Bernardino Valley Municipal Water District, describes the results of a study to determine and evaluate the effects of recharge and pumping on ground-water levels in the San Bernardino ground-water basin. A two-layer Galerkin finite-element model that was calibrated in a previous study of the area (Hardt and Hutchinson, 1980) was updated and used to simulate water levels in the basin.

The objective of this study was to evaluate specific water-level changes in response to observed and projected recharge and pumping. This objective was accomplished by (1) compiling and updating geohydrologic data such as ground-water levels; artificial recharge of natural and imported water; and pumping, well-construction, streamflow, and precipitation records; and (2) using a calibrated ground-water flow model constructed for the basin as part of a previous study (Hardt and Hutchinson, 1980) to simulate the effects of recharge and pumping on water levels, particularly in the area of confined ground water near Warm Creek and the Santa Ana River. Streamflow in the major stream channels was simulated separately to determine which streams had the greatest effect on water levels in the area of confined ground water.

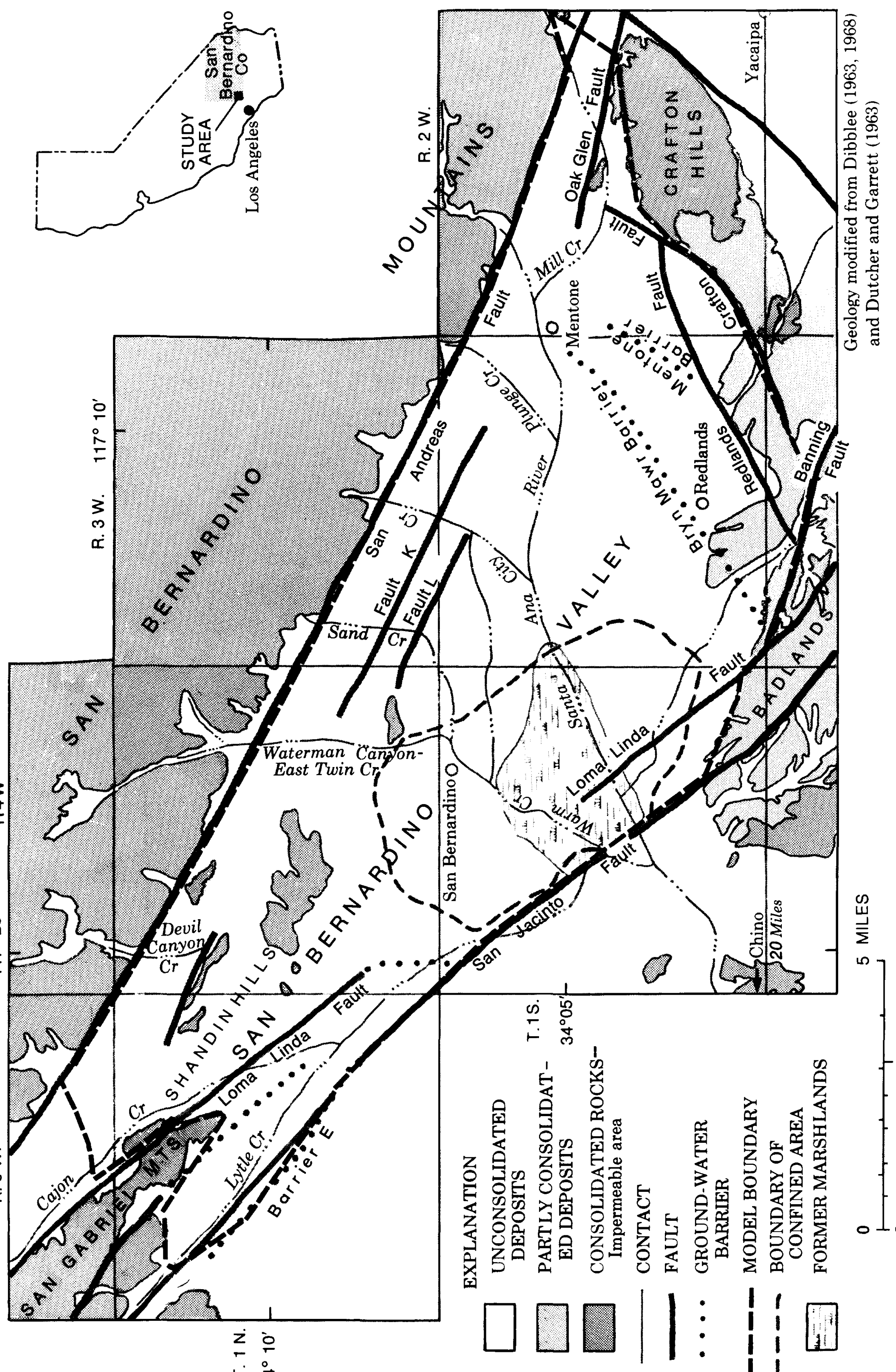


FIGURE 1. – Location, geographic setting, and generalized geology of study area.

Additional data collected for this study consisted of (1) measured surface-water inflow to and outflow from the valley at U.S. Geological Survey gaging stations; (2) measured ground-water levels, obtained twice a year, in several hundred wells throughout the valley and adjacent areas; and (3) tabulated yearly water extractions, consisting of surface-water diversions and ground-water pumping, from the valley and adjacent areas (Webb, 1973a, 1973b; Hanson and Harriger, 1976a, 1976b, 1981a, 1981b; and Western Municipal Water District of Riverside County, 1981, 1982).

Location and General Features

San Bernardino Valley is a semiarid inland valley in southwestern San Bernardino County, about 60 miles east of Los Angeles (fig. 1). The term "San Bernardino Valley" was first used by Mendenhall (1905, p. 9) for an area of indefinite limits beyond the San Bernardino area. Eckis (1934, p. 153) applied the term to that part of the upper Santa Ana Valley east of the San Jacinto fault. Dutcher and Garrett (1963, p. 17) further restricted the term to the area used in this study. The area included in the model is about 120 mi^2 and lies in a northwest-pointing wedge between the San Andreas and San Jacinto faults (fig. 1). The San Bernardino Valley is bordered on the northwest by the San Gabriel Mountains, on the northeast by the San Bernardino Mountains, on the south by the Badlands and Crafton Hills, and on the southwest by a low east-facing escarpment of the San Jacinto fault. Broad alluvial fans, which extend from the base of the mountains and hills that surround the valley, coalesce to form a broad, sloping alluvial plain in the central part of the valley. The land surface slopes generally to the southwest; gradients range from 75 to 150 ft/mi near the edges of the basin and from 30 to 50 ft/mi in the central part near the San Jacinto fault.

The ground-water reservoir in the valley consists of alluvial deposits of sand, gravel, and boulders interspersed with lenticular deposits of silt and clay. In the southwestern part of the valley, adjacent to the San Jacinto fault, the unconsolidated deposits contain numerous clay layers that act as leaky confining beds. Dutcher and Garrett (1963) acknowledged that separate sand and clay units could be correlated for only short distances, but did recognize three aquifers, each separated by 50 to 300 feet of clay and silt. A clay layer upgradient of the San Jacinto fault confines the aquifer system to about 25 mi^2 of the central part of the valley. The position of the demarcation line between the confined and unconfined parts of the aquifer changes constantly because of the varying recharge-discharge relation in the ground-water basin. The confined area near Warm Creek and the Santa Ana River includes about 10 mi^2 of former marshlands (Hardt and Hutchinson, 1980).

Infiltration from streams, irrigation-return flow, ground-water inflow, and precipitation on the valley floor recharge the ground-water basin. Three main streams contribute more than 60 percent of the recharge to the ground-water system; they are the Santa Ana River, Mill Creek, and Lytle Creek. Lesser contributors include Cajon, Devil Canyon, Waterman Canyon-East Twin, City, Plunge, and San Timoteo Creeks. Recharge from irrigation-return flow has decreased due to urbanization of agricultural acreage. Ground-water inflow, estimated to be less than 10 percent of the total recharge, occurs only from the Badlands in the southern part of the study area. Precipitation on the valley floor is of even less importance to basin recharge.

Several faults and other barriers in the study area restrict ground-water movement. Faults are inferred from topographic and water-level data; other barriers are inferred from water-level differences in wells. Water-level differences across these faults and barriers are 50 feet or more. Some faults are only partial barriers to ground-water movement; examples are (some sections of) the Loma Linda fault in the southern part of the basin and fault K in the northern part (fig. 1).

Previous Investigations

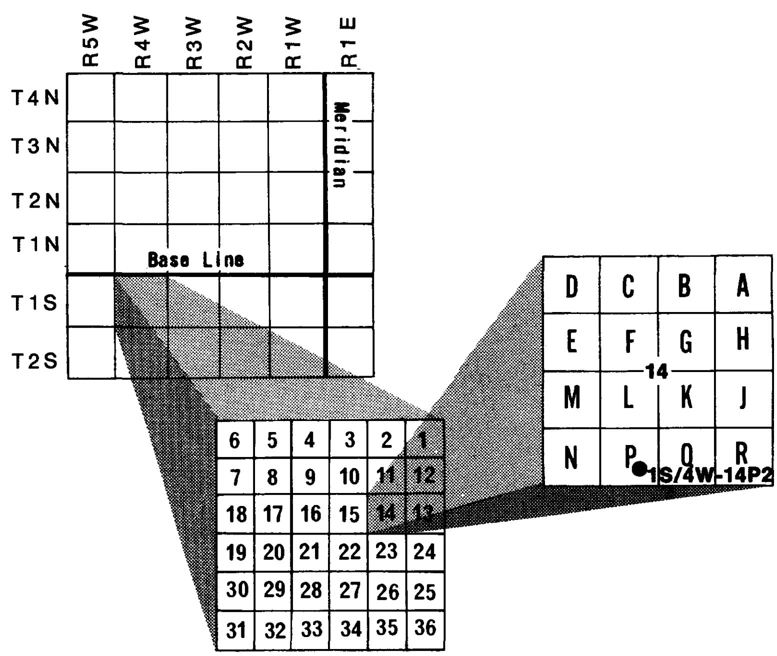
The earliest study of the geohydrology of the San Bernardino Valley produced maps showing surface-water courses, swamps, and irrigated lands (Hall, 1888). Lippincott (1902a, 1902b) and Mendenhall (1905, 1908) made significant geohydrologic analyses of the valley and region. Eckis (1934) summarized the geohydrology and basin storage of California's south coastal basins, including San Bernardino Valley.

Other detailed studies of the geohydrology of the San Bernardino Valley include those by California Department of Water Resources (1957, 1971, 1978, and 1979), Dutcher (1956), Dutcher and Burnham (1960), Burnham and Dutcher (1960), Dutcher and Garrett (1963), and Dutcher and Fenzel (1972).

Artificial recharge to the valley aquifers has been studied by Moreland (1972), Warner and Moreland (1972), and Schaefer and Warner (1975). Studies of ground-water-quality data, particularly relating to nitrate problems include Eccles and Bradford (1977), Eccles and Klein (1978), Klein and Bradford (1979), and Eccles (1979). Studies of specific phases of the hydrologic system include land subsidence (Miller and Singer, 1971), geologic hazards (Fife and others, 1976), geothermal resources (Young and others, 1981), generalized streamflow relations (Busby and Hirashima, 1972), and rising ground water (San Bernardino Municipal Water Department, 1981). Several geohydrologic studies use mathematical modeling to simulate effects of urbanization on runoff (Durbin, 1974) and to project future ground-water-level trends based on different cause-and-effect relations of recharge and discharge (Durbin and Morgan, 1978; and Hardt and Hutchinson, 1980).

Well-Numbering System

Wells are numbered according to their location in the rectangular system for subdivision of public land. For example, in the well number 1S/4W-14P2, the part of the number preceding the slash indicates the township (T. 1 S.); the number and letter following the slash indicate the range (R. 4 W.); the number following the hyphen indicates the section (sec. 14); the letter following the section number indicates the 40-acre subdivision of the section according to the lettered diagram below. The final digit is a serial number for wells in each 40-acre subdivision. The study area lies in the northwest and southwest quadrants of the San Bernardino base line and meridian.



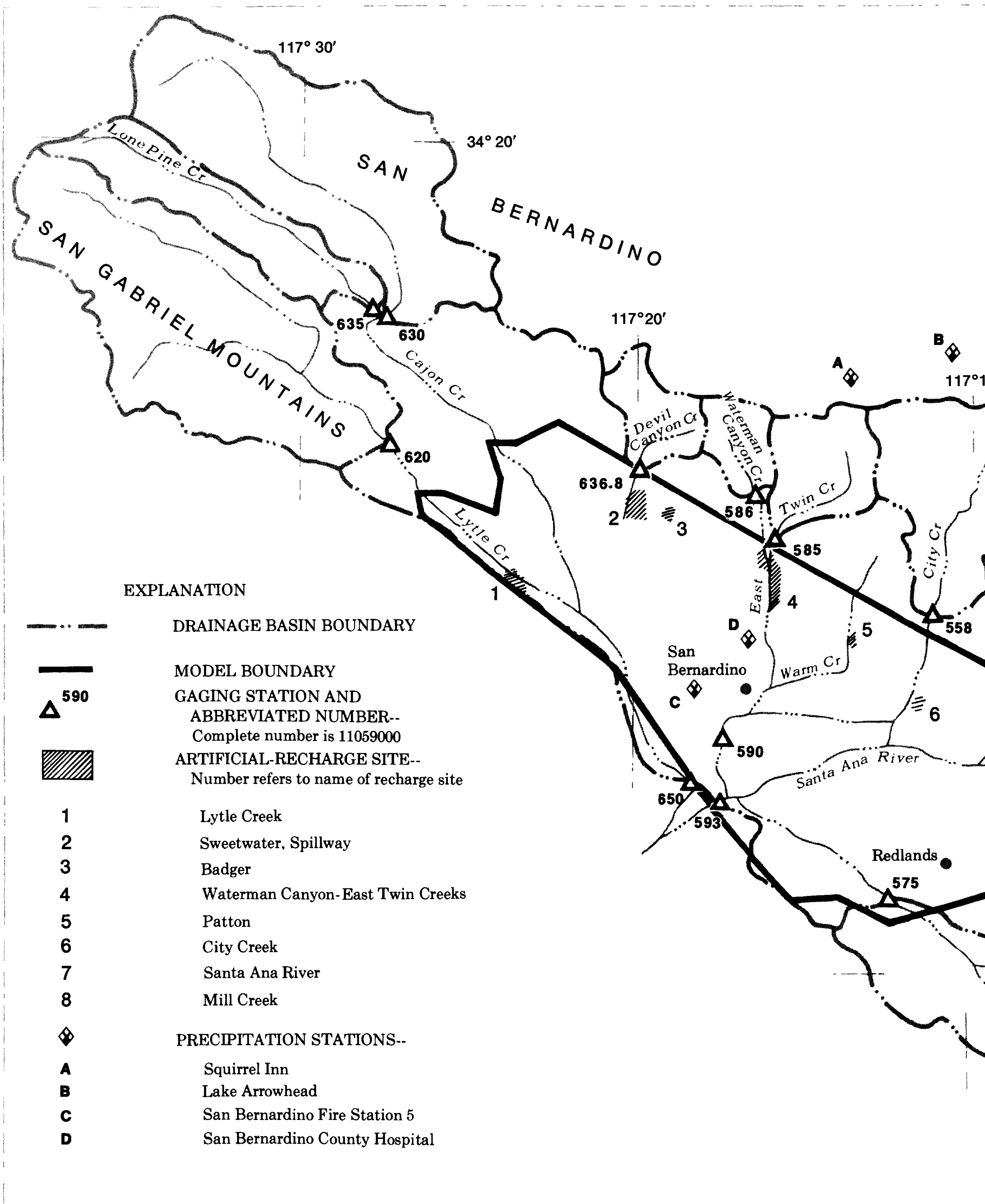
GEOHYDROLOGY

Hydrologically, San Bernardino Valley is a part of the Santa Ana River basin. Surface-water inflow to the valley along the San Gabriel and San Bernardino Mountain fronts and the outflow of Warm Creek, Lytle Creek, and the Santa Ana River are measured at selected gaging stations (fig. 2). Data indicate that inflows are much larger than outflows except during periods of infrequent flooding such as occurred in 1938, 1952, 1969, 1978, and 1980. During the rest of the time outflow is minimal, although wastewater discharge to the Santa Ana River is increasing each year as a result of increased urban and industrial growth in the valley. Except for a small quantity of water lost by evaporation and transpiration, the surface-water flow that enters the valley recharges the ground-water basin.

The distribution of streamflow as recharge to the ground-water basin is not limited to the porous stream channels. Canals and pipelines divert surface-water flow for agricultural use from the San Bernardino Mountains to other parts of the valley at lower altitudes. Flow from the Santa Ana River is diverted to Redlands and to farmlands between the river and the San Bernardino Mountains. Flow from the smaller streams, such as Devil Canyon, Waterman Canyon-East Twin, City, Plunge, and San Timoteo Creeks, generally is recharged locally into the aquifer within a few miles of the mountain front with little or no surface-flow loss out of the valley.

The larger streams, such as the Santa Ana River, Mill Creek, and Lytle Creek, discharge large quantities of water in a short period of time during floods. Some of the water flows out of the valley and is available for use downstream. Although the aquifer above the San Jacinto fault cannot absorb all the available water in this short time period, artificial-recharge facilities adjacent to the river slow the movement and enhance percolation to the aquifer.

The valley overlies a ground-water reservoir of unconsolidated sediments with a thickness of at least 1,200 feet in the area south of San Bernardino adjacent to the San Jacinto fault. Aquifer transmissivity ranges from 670 ft^2/d (5,000 [gal/d]/ft) along the San Bernardino Mountain front to 66,800 ft^2/d (500,000 [gal/d]/ft) in the confined area in the center of the basin. Aquifer storage coefficients range from 0.15 in the unconfined part of the valley to 0.0001 in the confined part. From the basin boundaries toward the center of the confined area south of San Bernardino, the storage coefficients are progressively smaller (Hardt and Hutchinson, 1980, p. 17).



Base from U.S. Geological Survey 1:250,000 quadrangles

FIGURE 2. – Drainage areas and location of precipitation stations, gaging stations, and artificial-recharge sites.

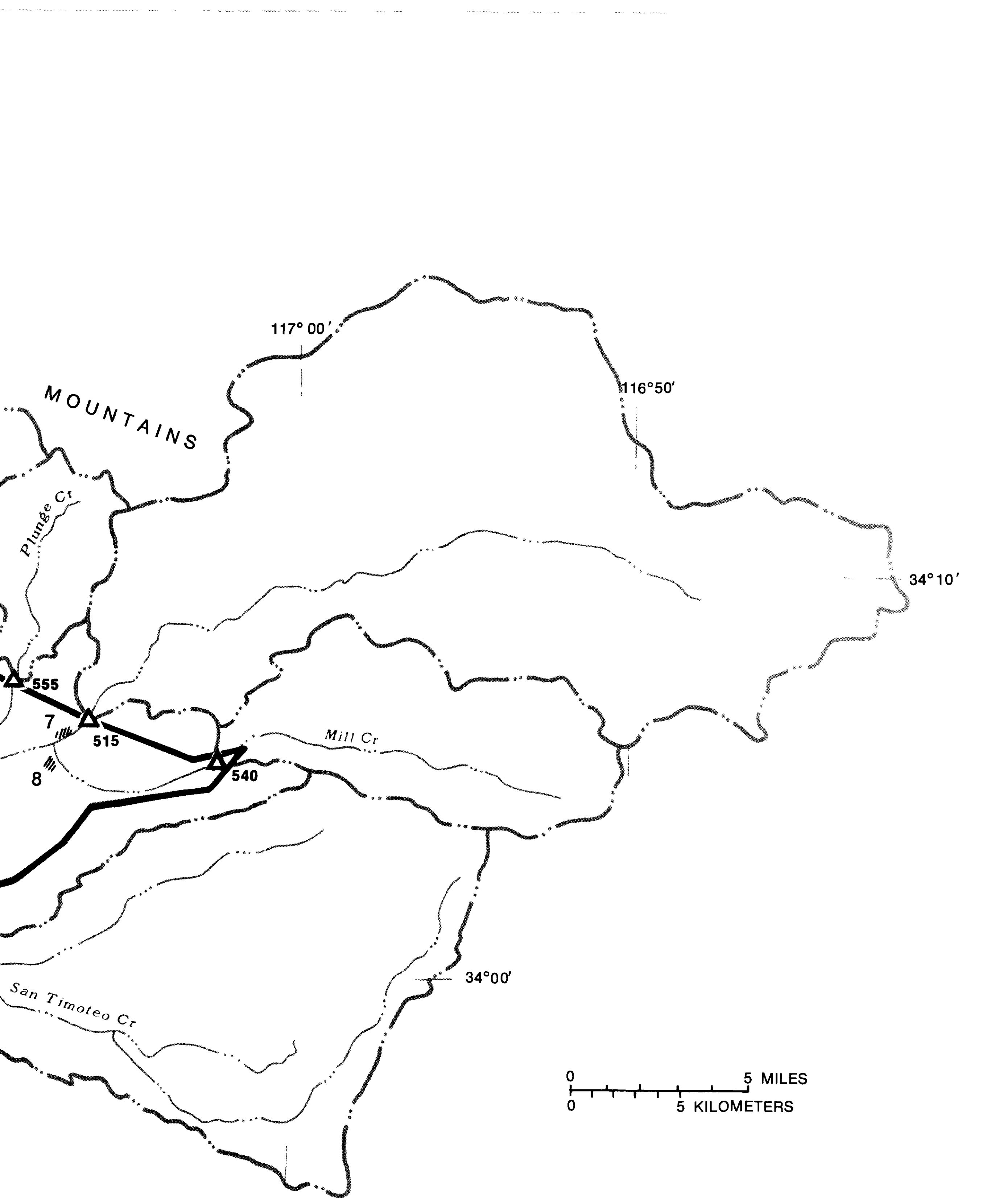


FIGURE 2. – Continued.

Ground-water movement in San Bernardino Valley generally follows the surface-drainage pattern. Surface water enters the aquifer through permeable deposits near the mountain fronts and along stream channels. Ground water moves generally southwestward, except in the Lytle and Cajon Creek areas where it moves southeastward, and converges toward a common line of discharge at the San Jacinto fault beneath the Santa Ana River--at the lowest land-surface altitude in the modeled part of the valley. Because the San Jacinto fault restricts ground-water outflow, ground water is forced upward through and around the various clay beds in the lower altitudes into the overlying strata and onto the land surface. This area constitutes the part of the valley under confined conditions. The size of the confined area fluctuates between 15 and 30 mi^2 depending on the quantity of ground water recharged to the aquifer upgradient and outside of the confined area. Figure 3 shows the boundaries of the confined area for different years of varied climatic conditions.

Historical well data show that deep wells in the confined area had higher hydraulic heads than shallow wells. The confining clay layer abutting the San Jacinto fault is the primary cause of the artesian head in former marshlands between Warm Creek and the Santa Ana River.

The height of the potentiometric surface in the confined area was reported by Lippincott for 1892 when shut-in pressures were measured on 55 artesian wells (Lippincott, 1902a, p. 84). That study indicated that most of the wells had hydraulic heads 10 to 40 feet above land surface. Four wells southeast of the Santa Ana River and adjacent to San Timoteo Creek had hydraulic heads 50 to 75 feet above land surface.

Artesian aquifers act as hydraulic systems, and rising water levels in the city of San Bernardino are a result of a rapid buildup of water pressure in the south end of the confined system that occurs soon after the water enters the unconfined aquifer upgradient. This is contrasted with ground-water movement in a water-table system, in which the water moves physically downgradient at a rate many times slower.

Ground-water levels have been measured in selected wells since about 1905. Historically, the highest water levels were recorded between 1915 and 1920 as a result of greater than normal precipitation during 1904-22 and the floods of 1914 and 1916. The hydraulic head in the upper and lower aquifers declined from 1920 until about 1935; the decline resulted from less than normal precipitation and runoff. During 1935-45, water levels rose throughout the valley, establishing a new equilibrium in 1945. Although water levels in the valley were high, they were lower than in 1915-20.

During 1945-69, water levels declined more than 100 feet, primarily because of increased ground-water pumping that was needed to supply the water demands of a rapidly expanding urban and agricultural economy. Water levels continued to decline until 1969 when heavy floods in January and February reversed the trend. Water levels continued to rise in the confined area through the 1970's into the early 1980's as a result of importation of water from the California Aqueduct starting in 1972, the shifting of ground-water pumping from lower altitudes of the valley to higher altitudes, and the recharge of large quantities of natural streamflow into the aquifers from the floods of 1978 and 1980.

Ground-water pumpage in the valley was generally less than 100,000 acre-ft/yr in the 1930's. After World War II, pumpage ranged from 135,500 acre-ft in 1946 to 213,500 acre-ft in 1961. During 1965-83, ground-water pumpage ranged from 144,900 acre-ft in 1969 to 178,600 acre-ft in 1971. During 1973-83, pumpage varied less than 10 percent from the 11-year average of 153,000 acre-ft/yr.

Changes in annual ground-water storage in the valley are related directly to variations in streamflow and ground-water recharge and, to a lesser degree, to changes in ground-water pumpage. The San Bernardino Valley Municipal Water District calculated the cumulative annual change in ground-water storage in San Bernardino Valley during 1935-82 (fig. 4). The Water District established 1935 as a zero-base period and calculated all changes in ground-water storage from this base. The year 1935 was the end of an 8-year dry period (1928-35) in the valley, even though greater than average precipitation fell in the nearby mountains.

During the early 1940's, cumulative ground-water storage in the valley increased to nearly 600,000 acre-ft more than storage in the zero-base period (fig. 4). After 1945, ground-water storage decreased as pumpage exceeded basin recharge. During 1964-66, storage was about 750,000 acre-ft less than in 1935, resulting in historical low water levels. Beginning in 1978, ground-water storage again exceeded the zero-base period, and from 1978 to 1982 nearly 900,000 acre-ft of additional water was stored in the valley.

The San Bernardino Valley ground-water basin consists of a single reservoir responsive to the interactions of recharge and discharge. Any imbalance between the two, up to a limit, can be compensated for by a change in the quantity of water stored in the alluvial aquifer of the valley. Because of the unique geohydrologic characteristic caused by the restriction of ground-water discharge by the San Jacinto fault, the factor that limits ground-water storage in the valley is the level of the ground-water surface in the lower altitudes, even though storage is available elsewhere.

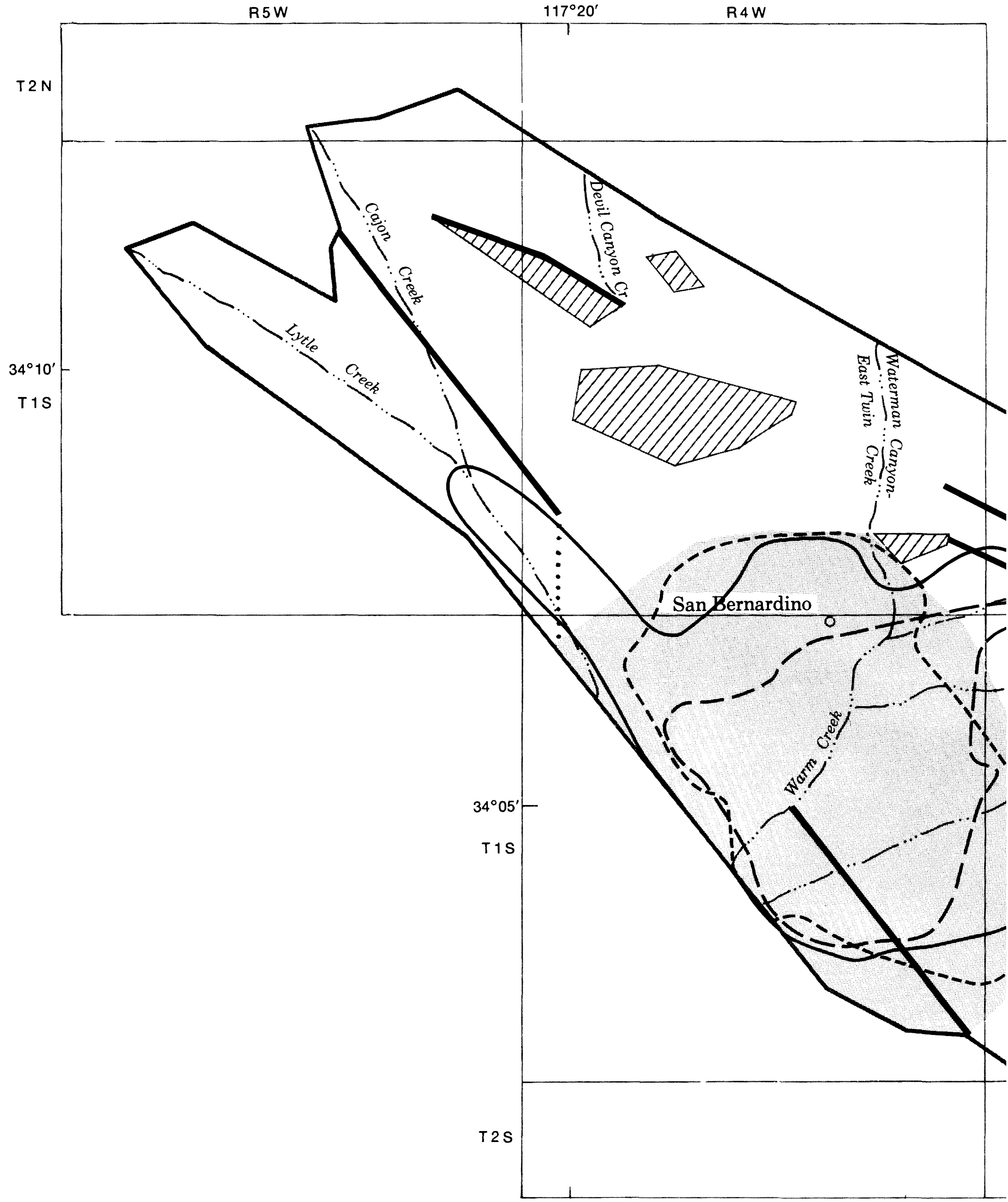


FIGURE 3. – Boundaries of confined area for different periods, 1897-1982.

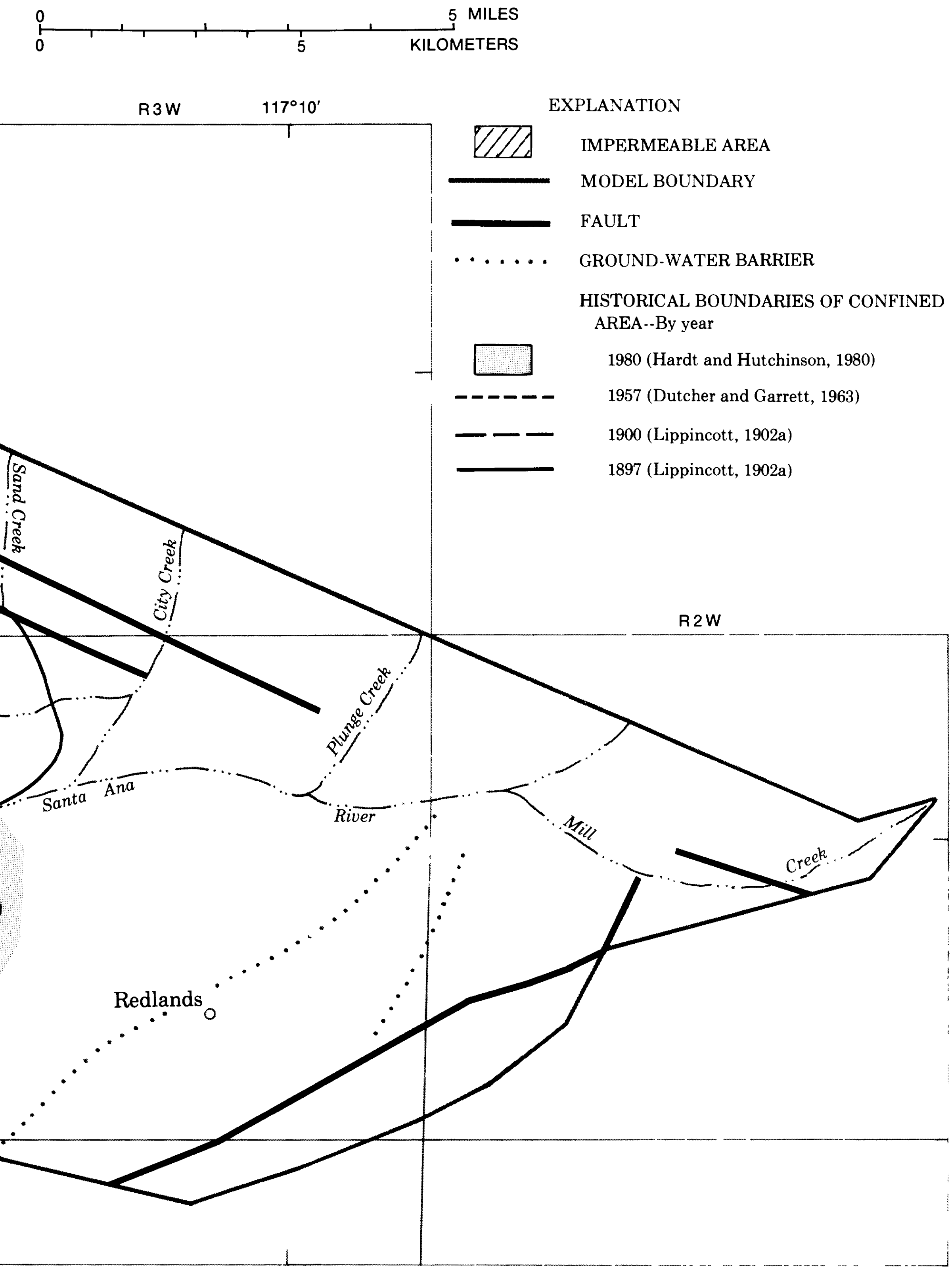


FIGURE 3. – Continued.

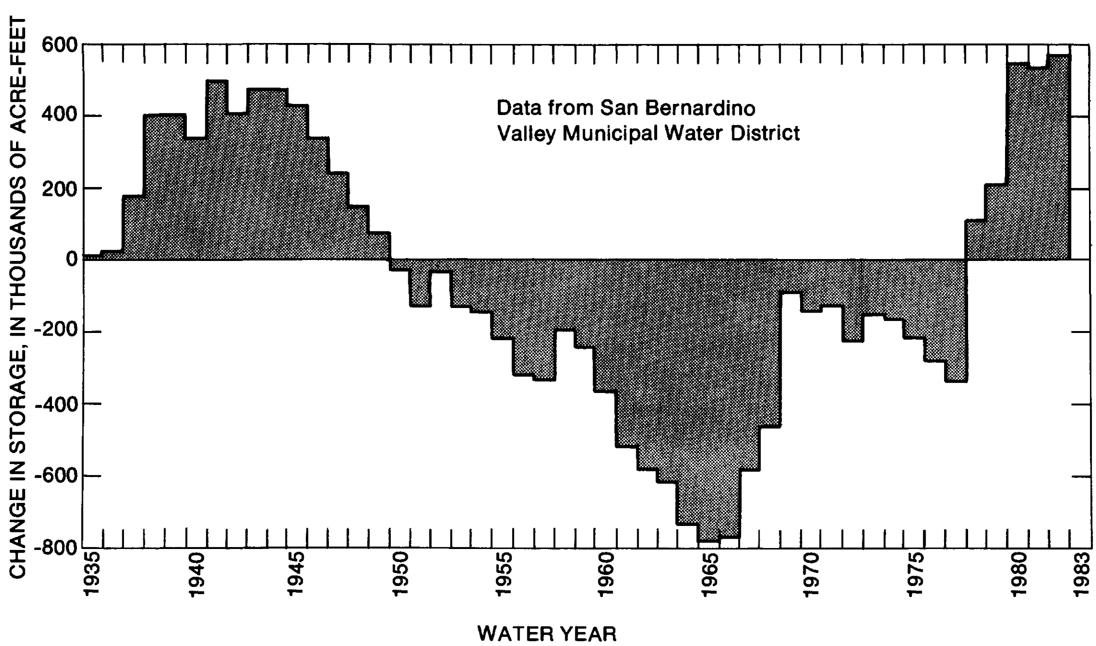


FIGURE 4. – Cumulative annual change in ground-water storage, water years 1935-82.

UPDATE OF HYDROLOGIC DATA

Hardt and Hutchinson (1980) developed a mathematical model for the study area that used hydrologic data collected during 1945-74. From this data base, projections by the model for several different recharge and discharge schemes were made for 1975-2000. In order to appraise the ground-water conditions of the early 1980's, the mathematical model was updated with hydrologic data collected during 1975-82.

Precipitation is the predominant source of water to the valley; smaller quantities of water are imported. To determine the relation between precipitation and the problems of rising water levels, long-term precipitation records for the valley and the adjacent San Bernardino Mountains were studied. The location of precipitation stations is shown in figure 2. Precipitation data for the mountains are particularly useful, because most of the recharge to the valley ground-water system is from mountain streamflow.

Distribution of annual precipitation for water years 1894-1981 for two precipitation stations in the San Bernardino Mountains is shown in figure 5. The records show that water year 1978 had the highest precipitation for a single year, followed by 1969; 1980 had the sixth highest. These wet years have contributed to rising water levels in the valley, and even though 1981 had the sixth-lowest precipitation, water levels remained high. The average annual precipitation for 1894-1981 was 40.3 inches. The highest precipitation was 91.34 inches in water year 1978 and the lowest was 16.39 inches in water year 1928.

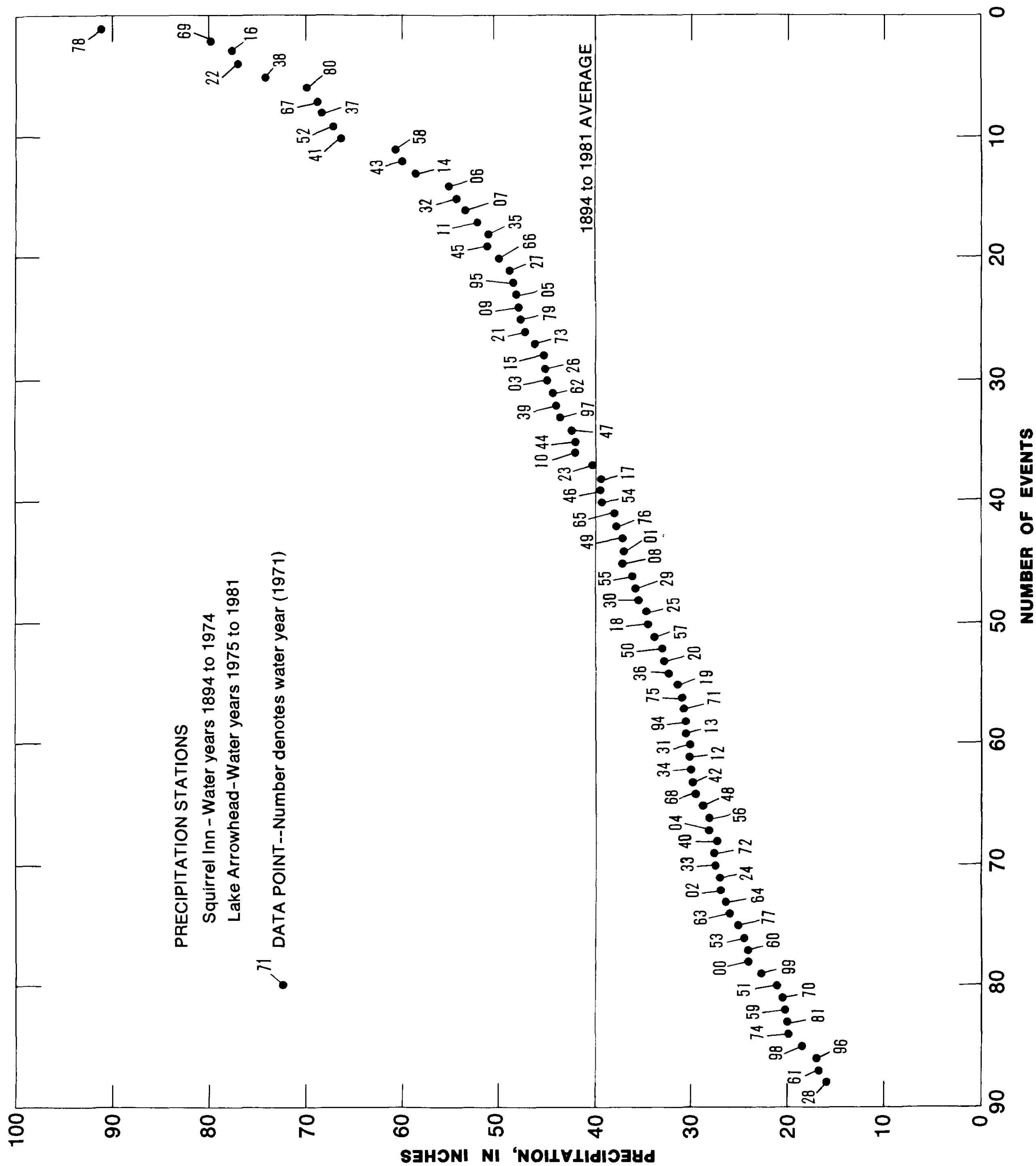


FIGURE 5. – Ranked yearly precipitation distribution, water years 1894-1981.

Figure 6 shows the cumulative departure from average annual precipitation from 1871 to 1982 for the San Bernardino area. For the San Bernardino Mountains, precipitation data were recorded at Squirrel Inn (water years 1894-1974) and Lake Arrowhead (water years 1975-82). For the valley floor, precipitation data were recorded at the city of San Bernardino (1871-1930), San Bernardino Fire Station 5 (1931-52), and San Bernardino County Hospital (1953-82). The wet period from 1978 to 1980 was much shorter than several other wet periods, in particular 1935-46, yet it contributed large quantities of water to the valley. Since 1946, the valley has experienced four dry periods, ranging from 4 to 10 years, and four wet periods, ranging from 1 to 3 years duration.

The wet period starting in 1978 resulted in increased streamflow from floods entering the valley as potential recharge. The quantities of surface inflow to the valley measured at 11 gaging stations and outflow measured at 3 stations during 1975-82 are shown in table 1. The difference between inflow and outflow totals reflects the quantity of water left in the basin from local sources. In addition, water imported from the California Aqueduct since November 1972 increased the quantity of water available to the valley (table 1). Not all of the water left in the basin is considered recharge, because evapotranspiration losses occur and some water is totally consumed.

During 1975-82, total recharge (inflow minus outflow, plus imported water) to the valley aquifers was about 1 million acre-ft (table 1). During 1975-77, total recharge ranged from about 60,000 to 70,000 acre-ft/yr. In 1978, total recharge increased to about 290,000 acre-ft. During 1979-80, total recharge was about 180,000 to 200,000 acre-ft/yr, or about three times the 1975-77 quantity. In 1981, with less surface-water inflow, total recharge decreased to about 70,000 acre-ft. In 1982, total recharge was about 90,000 acre-ft.

Figure 7 is a double-mass curve of cumulative surface-water inflow versus outflow plotted for 1967-82. During 1967-79, about 64 percent of the inflow remained in the basin, but during 1979-82, surface-water outflow increased and only about 32 percent of the inflow remained in the basin. The quantity of surface-water inflow remaining in the basin decreased because the low-altitude areas were saturated and additional storage capacity was minimal.

Gross ground-water pumpage, pumpage for export out of the valley, artificial recharge by water spreading, and quantity of water imported into the valley from the California Aqueduct (by San Bernardino Valley Municipal Water District) for 1975-81 are shown in table 2. These data were helpful in updating the model from the verified 1945-74 transient-state period.

The annual gross ground-water pumpage during 1975-81 varied about 12 percent and ranged from 140,599 acre-ft in 1978 to 160,411 acre-ft in 1977. Ground-water pumpage for export ranged from 54,275 acre-ft in 1978 to 67,658 acre-ft in 1976. Artificial recharge by water spreading ranged from 10,926 acre-ft in 1977 to 103,099 acre-ft in 1978. Water imported from the California Aqueduct by the San Bernardino Valley Municipal Water District ranged from 117 acre-ft in 1980 to 24,563 acre-ft in 1977.

Ground water that is pumped from the basin and exported across the San Jacinto fault to the Riverside area is from the confined area between Warm Creek and the Santa Ana River--the area of highest water levels. During 1975-81, the ratio of annual pumpage exported to gross pumpage ranged from 39 to 43 percent (table 2).

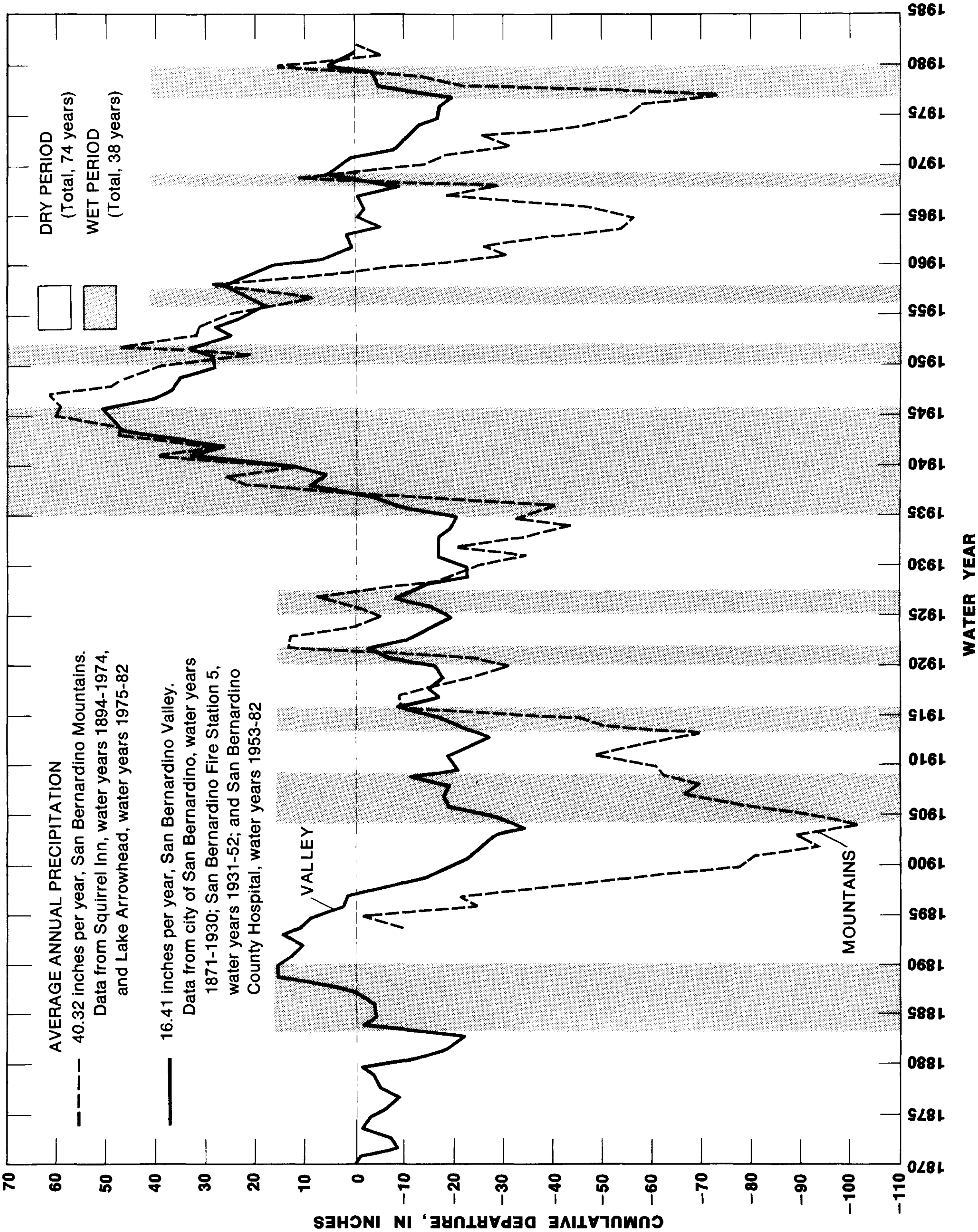


FIGURE 6. — Cumulative departure from average annual precipitation, water years 1871-1982.

TABLE 1.--Surface-water inflow and outflow, 1975-82, San Bernardino Valley

Station No.	Station name	Calendar year							
		1975	1976	1977	1978	1979	1980	1981	1982
		INFLOW (acre-feet)							
11051500	Santa Ana River near Mentone[1]	31,460	30,800	22,940	110,200	102,600	219,600	33,530	61,590
11054000	Mill Creek near Yucaipa[1]	13,930	15,490	13,580	124,900	39,440	87,290	19,750	28,430
11055500	Plunge Creek near East Highlands[1]	2,870	2,860	2,710	20,600	8,560	24,750	2,510	6,920
11055800	City Creek near Highland	2,960	2,600	2,420	28,130	10,190	39,780	3,180	7,500
11057500	San Timoteo Creek near Loma Linda[2]	291	450	425	4,100	4,280	4,140	852	3,227
11058500	East Twin Creek near Arrowhead Springs	1,470	1,300	808	9,430	3,730	15,950	3,430	4,531
11058600	Waterman Canyon Creek near Arrowhead Springs	918	725	511	5,480	2,570	10,240	1,530	2,132
11062000	Lytle Creek near Fontana[1]	15,650	15,640	14,910	129,900	51,700	119,600	17,230	28,740
11063000	Cajon Creek near Keenbrook	3,490	4,890	2,013	64,450	8,590	27,650	4,990	6,114
11063500	Lone Pine Creek near Keenbrook	441	291	237	7,480	2,610	6,220	2,180	1,464
11063680	Devil Canyon Creek near San Bernardino[1]	2,280	1,540	1,690	11,430	3,400	14,126	2,125	3,203
	TOTAL	76,300	76,586	62,244	516,100	237,670	566,900	91,307	153,851
		OUTFLOW (acre-feet)							
11060400	Warm Creek near San Bernardino	1,330	1,760	1,630	51,820	3,100	19,460	7,942	13,920
11059300	Santa Ana River at E Street	19,410	24,000	24,550	153,000	53,630	320,300	27,150	59,140
11065000	Lytle Creek at Colton	130	1,060	635	37,360	2,750	29,990	1,200	3,012
	TOTAL	20,870	26,820	26,815	242,180	61,480	369,750	36,292	76,072
Inflow minus outflow		55,430	49,765	35,429	273,920	176,190	197,150	55,015	77,779
Plus imported water		14,113	12,555	24,563	13,258	4,472	177	15,045	9,233
Total recharge		69,543	62,320	59,992	287,178	180,662	197,267	70,060	87,012

[1] Combined flow, includes diversions.

[2] Formerly 11057000, San Timoteo Creek near Redlands.

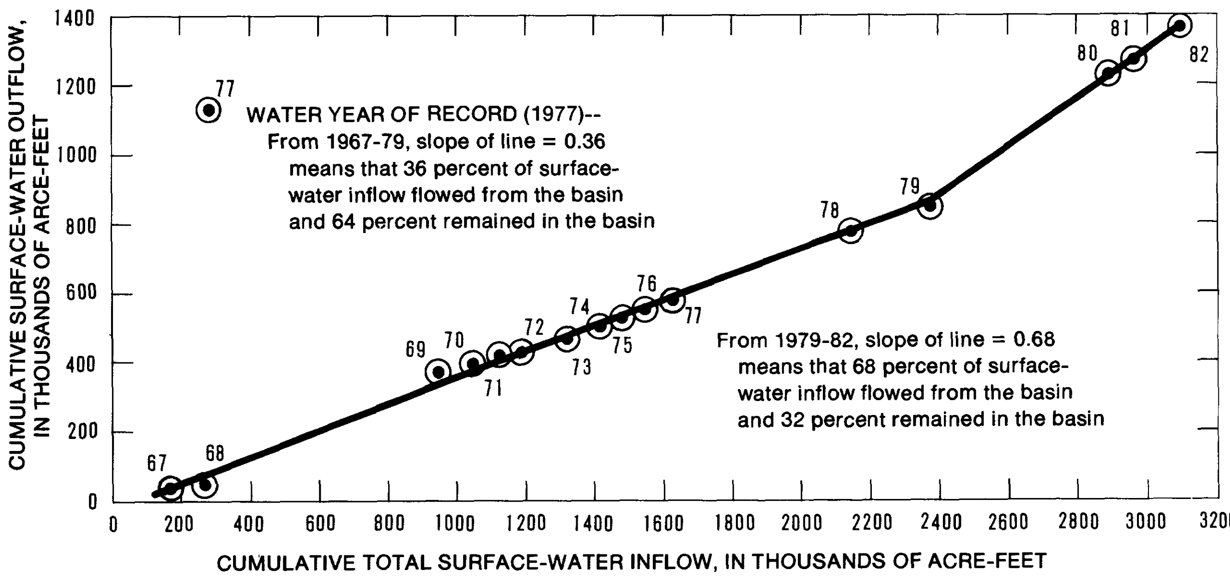


FIGURE 7. – Double-mass curve of surface-water flow for San Bernardino Valley, water years 1967-82.

TABLE 2.--Water distribution, 1975-81

[Data from San Bernardino Valley Municipal Water District and San Bernardino Valley Water District, 1983, and Stetson Engineers, Inc., 1983; e, estimated]

Calendar year	Ground-water pumpage: Gross (acre-ft)	Ground-water pumpage: Exported (acre-ft)	Ground-water pumpage: Annual ratio of exported to gross (percent)	Water imported from California Aqueduct (acre-ft)	Artificial recharge by water spreading (acre-ft)	Streamflow left in storage, inflow minus outflow (acre-ft)	Ratio of artificial recharge by water spreading to streamflow left in storage (percent)
1975	158,928	61,690	39	14,113	19,012	55,430	34
1976	158,685	67,658	43	12,555	17,511	49,765	35
1977	160,411	63,558	40	24,563	10,926	35,429	30
1978	140,599	54,275	39	13,258	103,099	273,920	38
1979	154,929	64,421	42	4,472	74,229	176,190	42
1980	150,668	61,000	40	117	83,605	197,150	42
1981	e150,000	63,500	42	15,045	13,773	55,015	25

The ratio of artificial recharge by water spreading into the valley aquifers to streamflow left in storage from natural streamflow (inflow minus outflow) ranged from 30 to 35 percent during 1975-77. The ratio increased to 38 percent in 1978, and to 42 percent in 1979 and 1980 (table 2). In 1978, artificial recharge by water spreading from natural streamflow increased tenfold from the previous year, which resulted in only a slight increase in the ratio, as the quantity of water left in storage also was large. In 1979 and 1980, the ratio increased to its highest level, as the quantity of artificial recharge by water spreading and streamflow left in storage was high. In 1981, the ratio decreased to only 25 percent. Artificial-recharge practices apparently decreased because of the rising water levels in the low-altitude areas.

Long-term hydrographs of selected wells show the ground-water-level trends in the valley. In the water-spreading area of the upper Santa Ana River, water levels in wells 1S/2W-7K1 and 1S/3W-11H1 rose 175 to 200 feet from early 1978 to 1979. As of 1983, water levels remain about 100 feet higher than in 1977 (fig. 8). The rise in water levels in the upper Santa Ana River-Mill Creek area is attributed to increased precipitation and surface-water runoff, which increased recharge to the aquifer. Water spreading in the upper Santa Ana River area increased more than 525 percent from water years 1978 to 1982 (Stetson Engineers, 1983, p. III-10).

The ground-water-level trend in the confined area during 1945-84 is shown by the hydrograph for well 1S/4W-14P2 (fig. 8). The lowest water level in this well during 1945-84 occurred in 1966, and since then the water level has risen about 120 feet (as of early 1984). The water-level rise was caused primarily by increased recharge resulting from infiltration of high surface-water runoff in 1969 and 1978-82 and, to a lesser degree, by a slight decrease in ground-water pumping.

Two observation wells useful in monitoring water-level response in the confined area are the Meacham well (1N/4W-35L1) and the Williams well (1S/3W-17C3). These wells are near the edge of the confined area: the Meacham well northward near the Waterman Canyon-East Twin Creek drainage, and the Williams well eastward along the Santa Ana River. The annual highest and lowest water levels for these two wells during 1958-83 are shown in figure 8. The long-term water-level trend in the wells is similar--except for 1969-77, during which period the Williams well shows the stabilizing effect of the 1969 flood. Although the Meacham well shows no direct effect of the flood, the water level began to rise in 1970 and continued rising steadily through 1978. In both wells, the water level has risen markedly since 1978.

Water levels in the Meacham and Williams wells in early 1981, when saturation of shallow soils occurred in the confined area, were 40 to 75 feet lower than the water levels measured in the mid-1940's (not shown in fig. 8) when high water levels in the confined area apparently were not a problem. This suggests that the hydrologic characteristics of the basin have been changed, probably by a combination of natural phenomena and human intervention in natural hydrologic processes.

Figure 9 shows water-level contours for January 1982. Outside the confined area, the upper and lower aquifers are considered as one, with a single water-level altitude referenced to sea level. In the confined area, the aquifers have different hydraulic heads because of the confining layers of clay. The upper aquifer is referenced to sea level to conform to those water-level measurements outside the confined area. However, the hydraulic head in the lower aquifer is shown in feet greater than the hydraulic head in

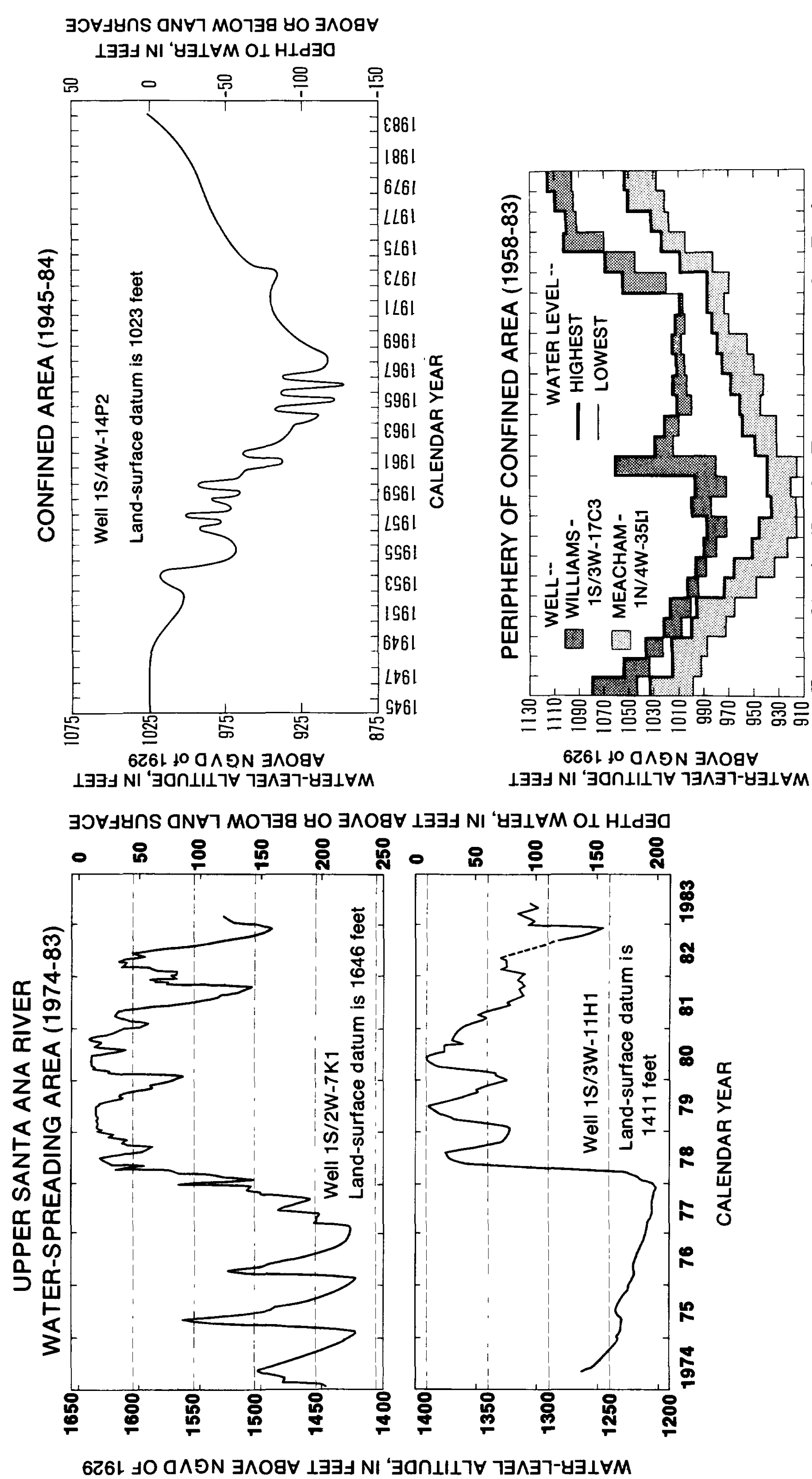


FIGURE 8. – Water-level data for selected observation wells. Well location shown in figure 9.

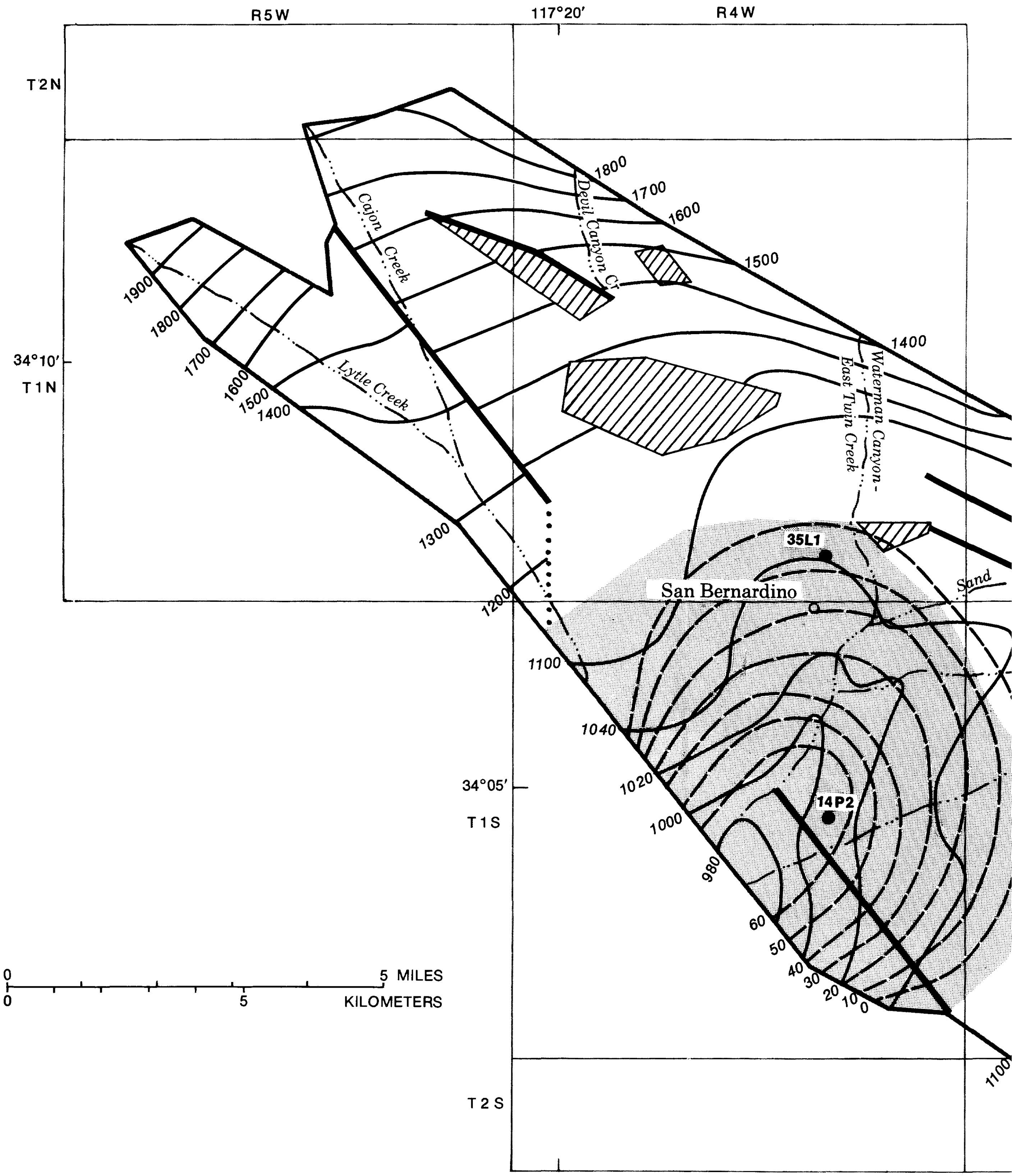


FIGURE 9. – Water-level contours, January 1982.

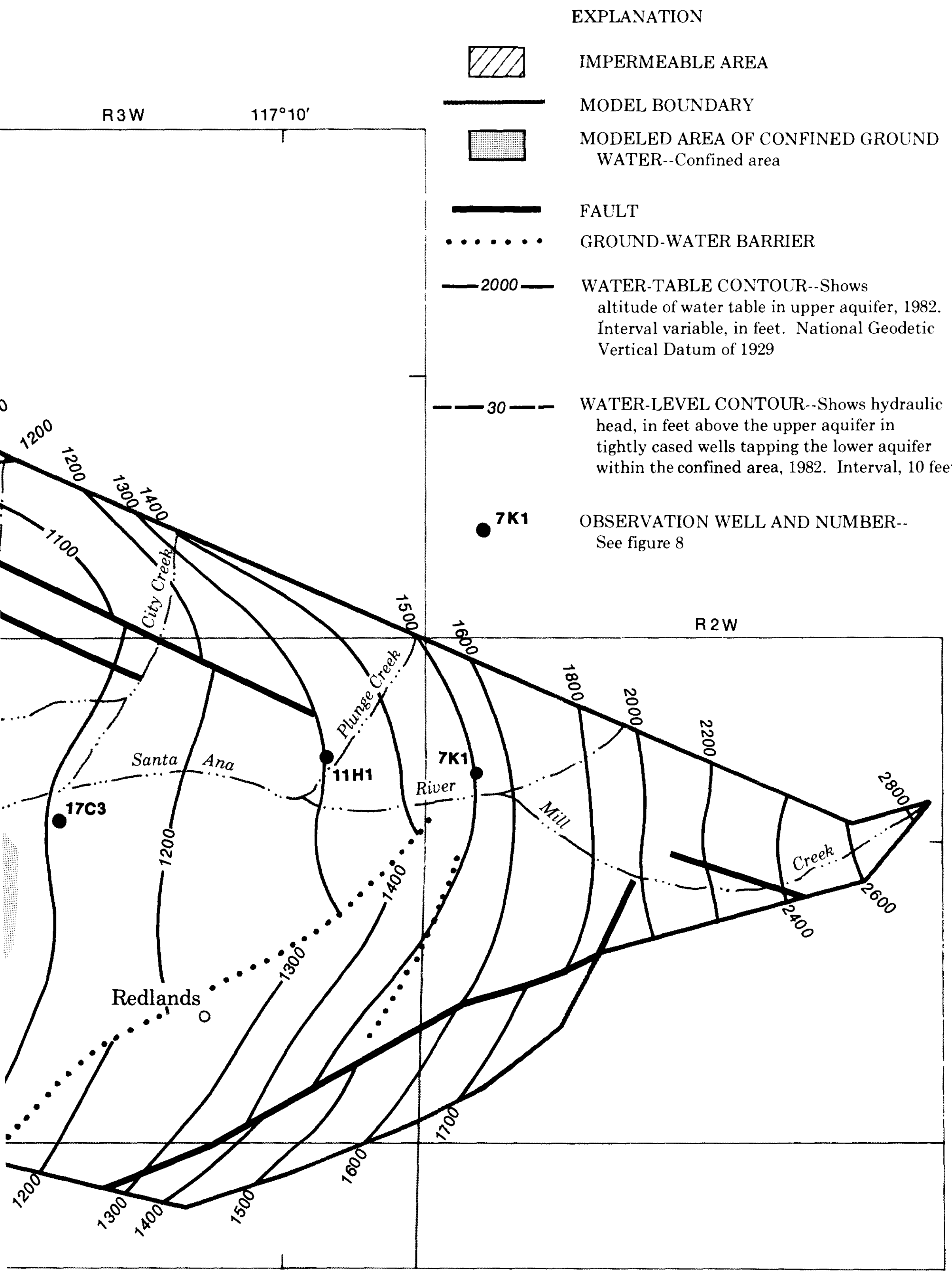


FIGURE 9. – Continued.

the upper aquifer to easily discern the amount of head difference between the two aquifer systems. Data are based on water-level measurements made by several local water agencies and the city of San Bernardino. Data for the lower confined aquifer were sparse because most of the wells measured are perforated throughout the well depth.

In general, the 1982 water-level contours (fig. 9) are similar in configuration to those of 1945 and 1975 (see Hardt and Hutchinson, 1980, figs. 12 and 13, p. 30-33). The area of greatest difference is the central part of the valley, including the confined area. As discussed earlier, the 1982 contours in the confined area are higher than in 1975 and lower than in 1945.

The 1982 water-level contours were used as a base for several of the model simulations that projected specific cause-and-effect relations pertaining to the rising water levels in the low-altitude areas. Other model simulations used a zero water-level base in order to directly measure the effects of a proposed management plan or a particular stream or recharge area upon the confined area.

The input of hydrologic data from 1975 to 1982 into the existing model consisted of pumpage, recharge (natural and artificial), and water levels. The nodal and elemental network for the model and aquifer values of transmissivity and storage remained the same.

MATHEMATICAL-MODEL SIMULATIONS OF AQUIFER RESPONSE TO RECHARGE AND PUMPING

Basis of the Model and Method of Appraisal

The basis of the mathematical model used to simulate aquifer response to recharge and pumping in San Bernardino Valley is described by Hardt and Hutchinson (1980, p. 40-43). For modeling purposes, the valley aquifer geometry is approximated by two layers--each with 296 triangular areas called elements, and 178 nodes (or points) that are the vertices of the elements (fig. 10). Values of the physical properties of the aquifer, such as transmissivity, storage coefficient, and where appropriate, the thickness and vertical permeability (hydraulic conductivity) of the confining clay unit, are assigned to the elements (triangles). Recharge, discharge, and hydraulic head are assigned to the nodes. The model grids represent a two-aquifer system, in which the upper and lower layers have identical patterns, and the elements and nodes are numbered similarly in each layer. Selected model simulations described in this report include an evapotranspiration option used when water levels were less than 10 feet below land surface.

As it is impossible to precisely project recharge and pumping regimens, various conditions of low and high aquifer recharge and pumping were assumed. Supplemental pumping of 5,000 and 25,000 acre-ft/yr has been programmed into the model for the confined area to determine a range of water-level declines in the high-water-level area and to assess the beneficial effects. Each major stream that is a source of recharge to the ground-water system has been modeled separately to isolate the effects of artificial recharge after 1 or 2 years and 10 years on water levels in the confined area.

The upper aquifer of the model represents the ground-water system most affected by rising water levels in the confined area. Therefore, remedial measures to alleviate the problem of rising water levels are focused on the upper aquifer. Water-level changes in the deeper aquifers (lower layer in the model) affect water levels in the upper aquifer, but are of secondary importance. Consequently, this report concentrates on water-level changes in the upper aquifer.

The model was used to verify ground-water conditions for 1945-74 (Hardt and Hutchinson, 1980) using yearly data of recharge (streamflow) and pumpage. Quantities of recharge and pumpage varied as much as several hundred percent from year to year. This same method was used in updating the model for 1975-81. In extending the model verification through 1981, the calibration error was minimal. Consequently, water-level changes were computed using the January 1982 water levels as the initial conditions.

The projections of water-level changes for the upper layer were based on four different simulations: (1) a 3-year simulation from the most recent data (January 1982) which represent the highest water levels since about 1945, (2) a 3-year simulation from a starting base with water levels arbitrarily set to zero, (3) 1- and 10-year simulations of a 10-year pumping program (1972-81) with no recharge, and (4) 1- or 2- and 10-year simulations of a 10-year artificial-recharge program as measured during 1972-81 in the water-spreading areas of the major streams.

Results of Model Simulation

Average Hydrologic Conditions

Long-term hydrologic conditions based on 1945-82 data of average recharge and discharge were simulated using the model and projected to a 3-year period (fig. 11). Initial water levels used in the model reflect field measurements made in January 1982, when the water table was at its highest level in years. Water-level changes shown in figure 11 represent those in the upper aquifer and include an evapotranspiration option in the model. The evapotranspiration option, which essentially constitutes a net pumpage component, is used whenever water levels are less than 10 feet below land surface. Also, on various model simulations, the evapotranspiration option was not used in order to compute the total water-level change that would occur without evapotranspiration. Only one of these simulations is shown in this report, and it is compared to calculated water-level changes with the evapotranspiration simulation (fig. 11). Using the evapotranspiration option in the model better simulates field conditions and yields more realistic results than not using the option.

Although average recharge conditions have not prevailed in the valley since 1978, this model simulation (fig. 11) is considered a baseline to be used in comparing other model simulations under extremes of recharge and discharge. In January 1982, the hydraulic head in the upper aquifer ranged from 25 feet above to 25 feet below land surface in the southwestern part of the confined area. Thus, water levels were already fairly high at the beginning of the 3-year simulation period.

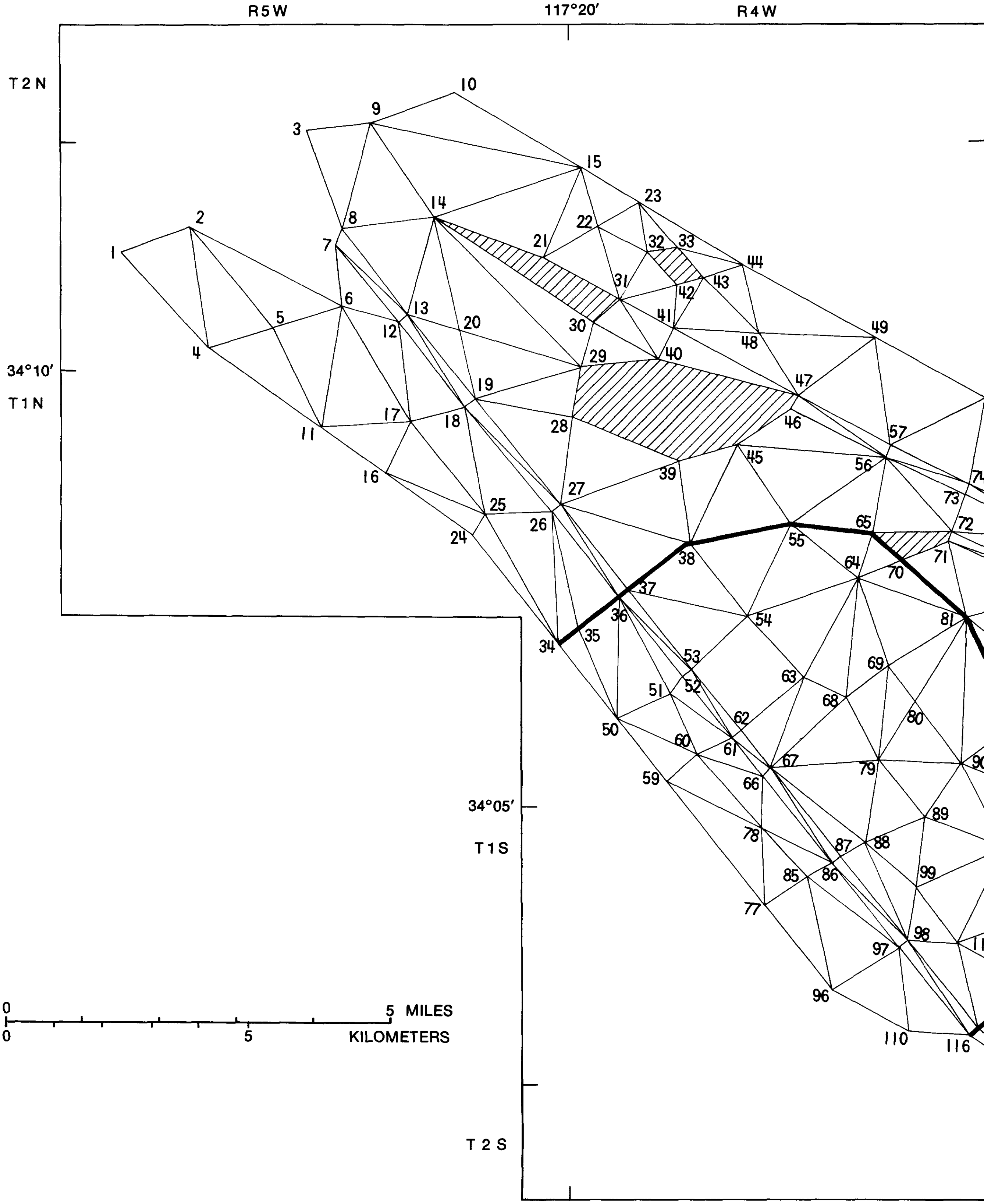


FIGURE 10. – Nodal network for upper and lower layers in finite-element mathematical model.

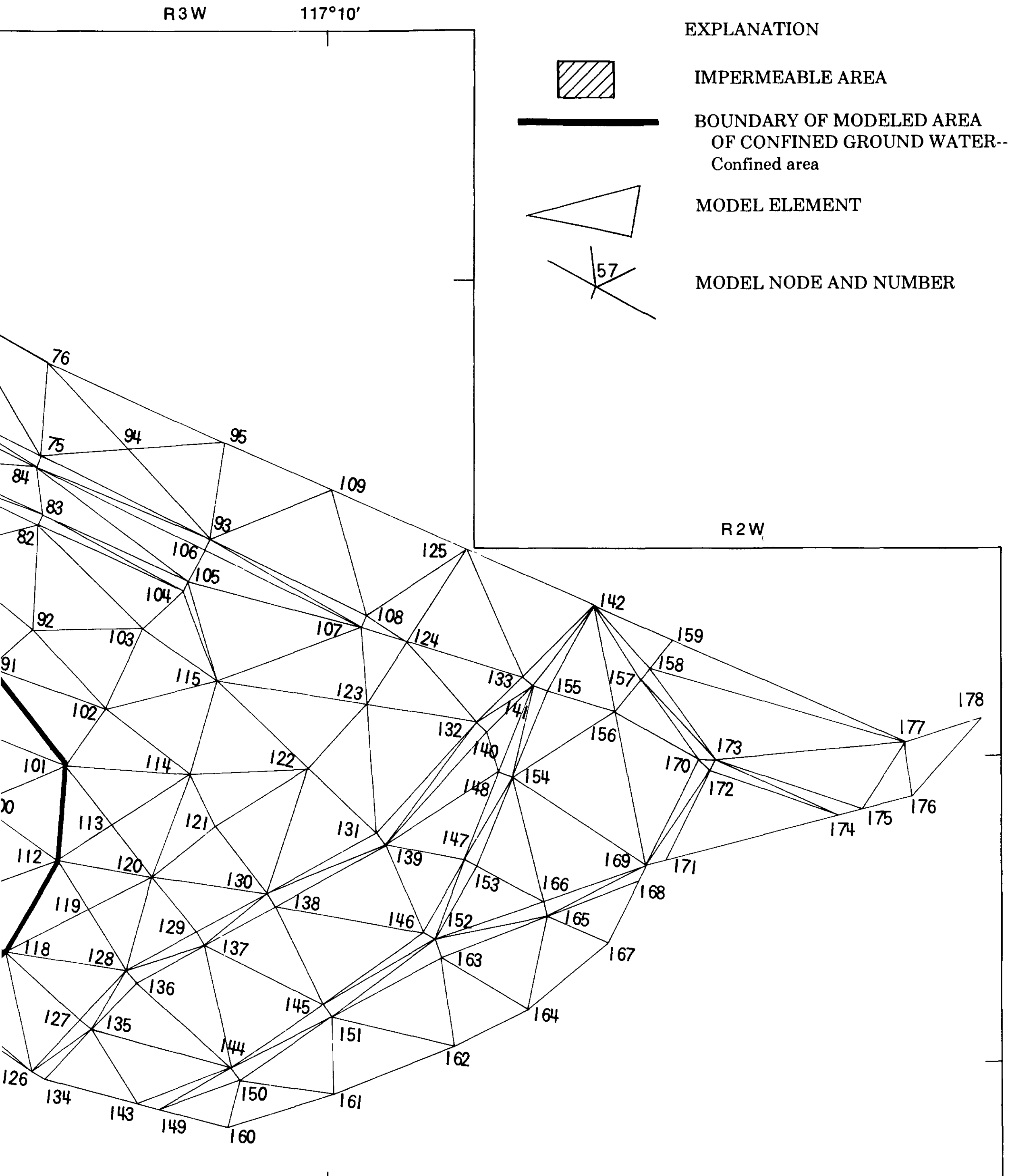


FIGURE 10. – Continued.

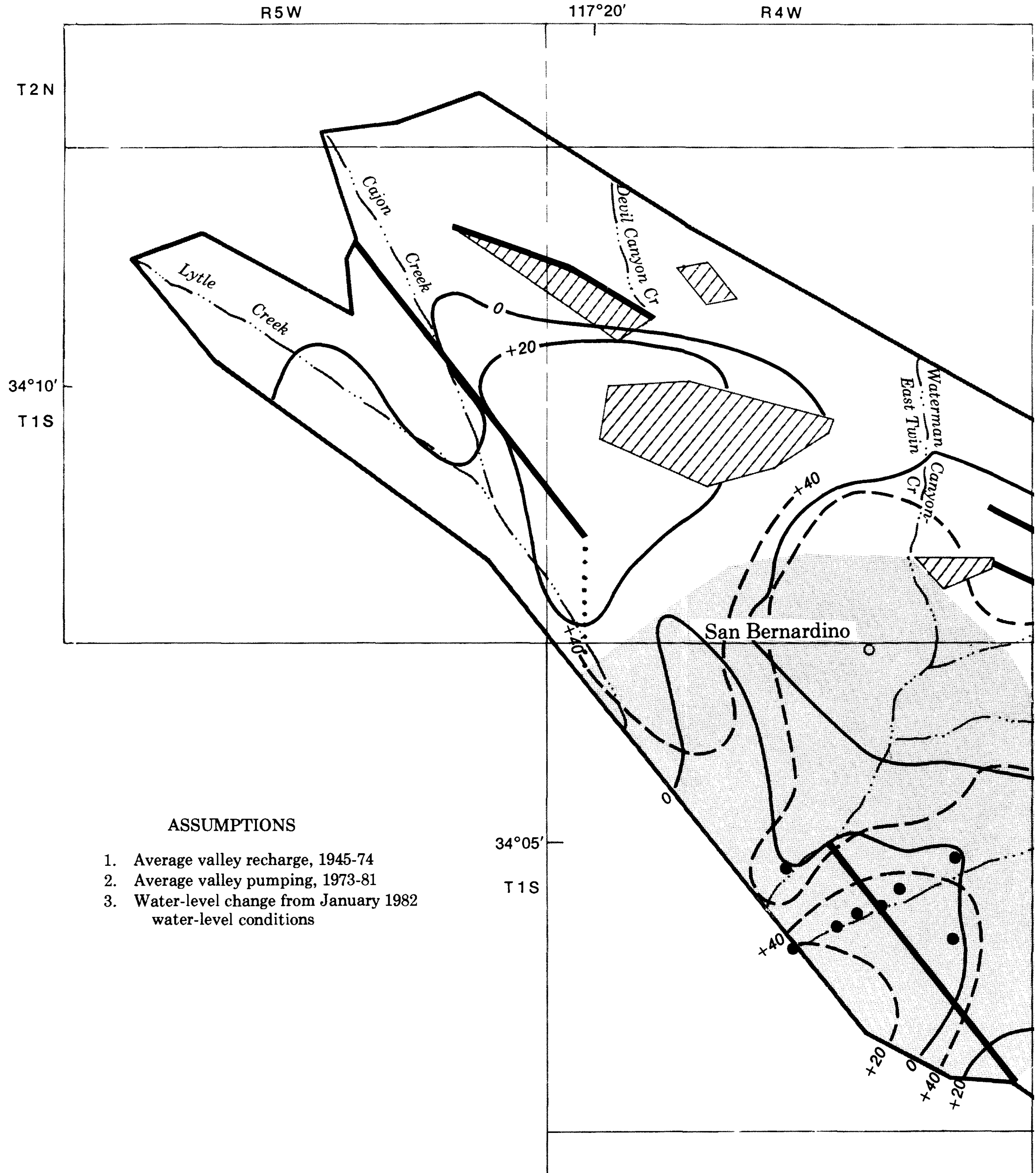


FIGURE 11. – Calculated water-level changes from a high water table (1982) after 3 years of average valley recharge and pumping.

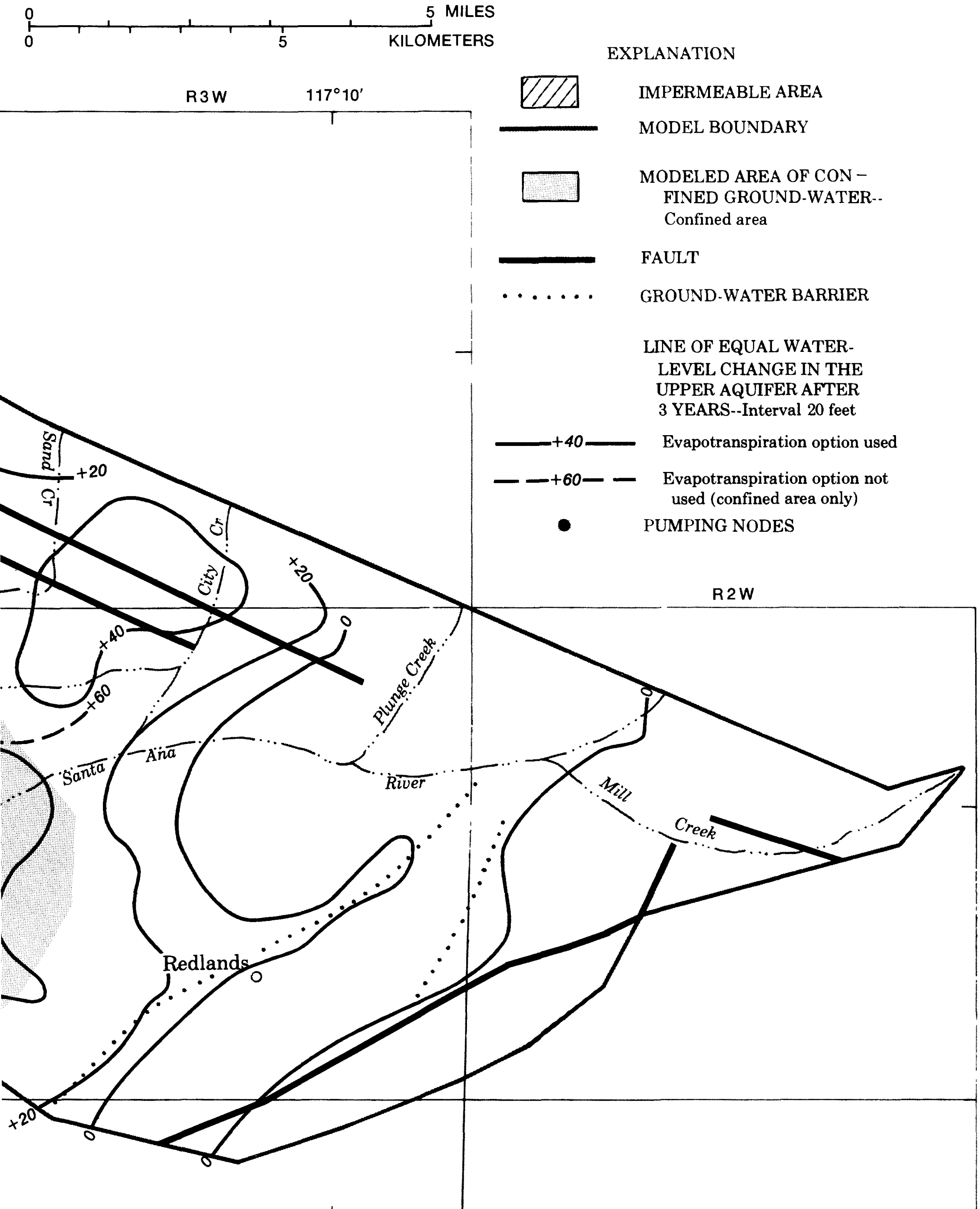


FIGURE 11. – Continued.

For the simulation of 3 years of average hydrologic conditions, recharge was assumed to be equal to the average recharge for the transient-model period (1945-74) (Hardt and Hutchinson, 1980, p. 47). The average recharge was 106,000 acre-ft/yr (exclusive of recharge from pumping return); this is lower than the long-term average because of the extended dry period of 1947-74. Ground-water pumping in the valley during 1973-83 has varied little from the average of about 155,000 acre-ft/yr, and this rate is projected for the foreseeable future. When the evapotranspiration option is used in the model, an additional discharge by evapotranspiration averages about 16,000 acre-ft/yr.

Figure 11 shows calculated water-level changes with and without evapotranspiration simulated. With the evapotranspiration simulated (equivalent to increased pumping induced when water levels are less than 10 feet below land surface), the water levels near the periphery of the confined area were about 20 feet higher after 3 years. In the lower altitudes of the confined area, water levels remained about the same or declined a few feet. Elsewhere in the valley, water levels were stabilized in the upper reaches of the Santa Ana River and Mill Creek, and were about 20 feet higher 6 miles from the mountains in the Lytle Creek area.

With the evapotranspiration not simulated, water levels (shown only for the confined area) rise because evapotranspiration losses are zero. Consequently, in the confined area, computed water levels were 20 to 60 feet higher after 3 years. So, as indicated by this set of model simulations, the evapotranspiration of about 16,000 acre-ft/yr results in water-level declines of about 40 feet in the high-water-level area south of San Bernardino.

In both model simulations, the greatest water-level changes were in the confined area near the San Jacinto fault in the Warm Creek-Santa Ana River area and in the Sand Creek and City Creek area northeast of the confined area. The water-level rises near Sand and City Creeks and elsewhere may be attributed to local natural recharge and irrigation return in excess of local pumpage.

Average Hydrologic Conditions with Additional Pumping from the Confined Area

Two additional model simulations were programmed to determine the effects of additional pumping from the confined area--5,000 acre-ft/yr (fig. 12) and 25,000 acre-ft/yr (fig. 13)--on the average hydrologic condition (fig. 11). Each of these simulations, which used the evapotranspiration option, computed water-level changes from the (base-level) measured 1982 water-level data.

Figure 12 shows the computed water-level changes in the upper aquifer after 3 years, with additional pumping of 5,000 acre-ft/yr in the confined area imposed on the average hydrologic condition (fig. 11). Water levels are projected to decline about 20 feet in a small area adjacent to the San Jacinto fault and to rise 20 to 40 feet in the north-central part of the valley.

To determine the changes in water levels that result from the additional pumping of 5,000 acre-ft/yr from the confined area, a comparison was made between figures 11 and 12. The additional pumping did not significantly lower the water level in the Warm Creek-Santa Ana River area, which is the area of greatest concern because of rising water levels. The positions of the zero water-level-change contours are about the same on the two maps. Slight changes due to the additional pumping were noticed upstream along the Santa Ana River (plus 20-foot contour); on the northwest edge of the confined area (zero-foot contour); and in the central part of the valley, where the area of the plus 20-foot contour decreased. Results of this simulation indicate that additional pumping of more than 5,000 acre-ft/yr would be required to significantly lower water levels in the confined area near the San Jacinto fault.

Figure 13 shows that additional pumping of 25,000 acre-ft/yr for 3 years in the confined area would cause water levels to decline in most of the confined area. Maximum water-level declines of about 60 feet occur in the Warm Creek-Santa Ana River area adjacent to the San Jacinto fault. Water-level changes due only to the additional pumping of 25,000 acre-ft/yr (comparing figs. 11 and 13) are 40 feet adjacent to the San Jacinto fault and 20 feet in much of the area of high water levels.

Additional model simulations were made to determine the isolated effects of pumping 5,000 and 25,000 acre-ft/yr for 3 years from the confined area; that is, the average natural recharge and pumpage and the 1982 water-level base were removed, the initial water levels were set to zero in the model, and no additional pumpage or recharge was programmed.

The greater water-level declines are the result of the higher pumping rate (fig. 14). The area of greatest water-level decline is the pumping center in the Warm Creek-Santa Ana River area near the San Jacinto fault, with lesser declines radiating outward. Computed water-level declines in the confined area after 3 years were about 7 to 15 feet at a pumping rate of 5,000 acre-ft/yr, and 40 to 80 feet at a pumping rate of 25,000 acre-ft/yr. At the higher pumping rate, water-level declines of 10 feet were simulated in the upper reaches of Lytle Creek and the Santa Ana River. In the area of Waterman Canyon-East Twin and City Creeks, the simulated declines were about 20 to 30 feet. Thus, this model simulation (fig. 14) shows that the north-central part of the valley is affected most by pumping in the Warm Creek-Santa Ana River area. Conversely, recharge to the aquifers in the north-central part of the valley can more readily affect water levels in the lower altitudes of the confined area.

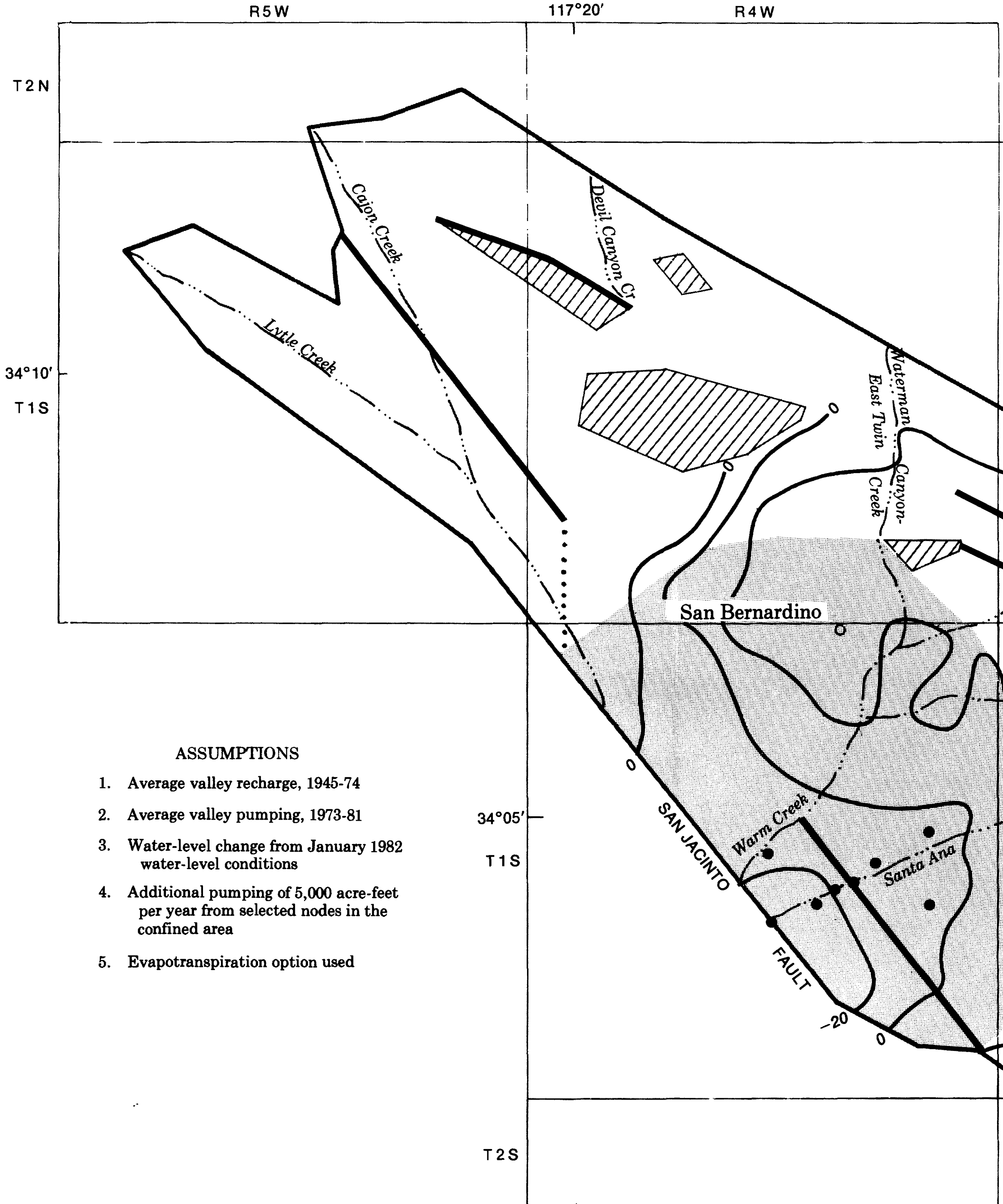


FIGURE 12. – Calculated water-level changes from a high water table (1982) after 3 years of average recharge and pumping with additional pumping of 5,000 acre-feet per year from the confined area.

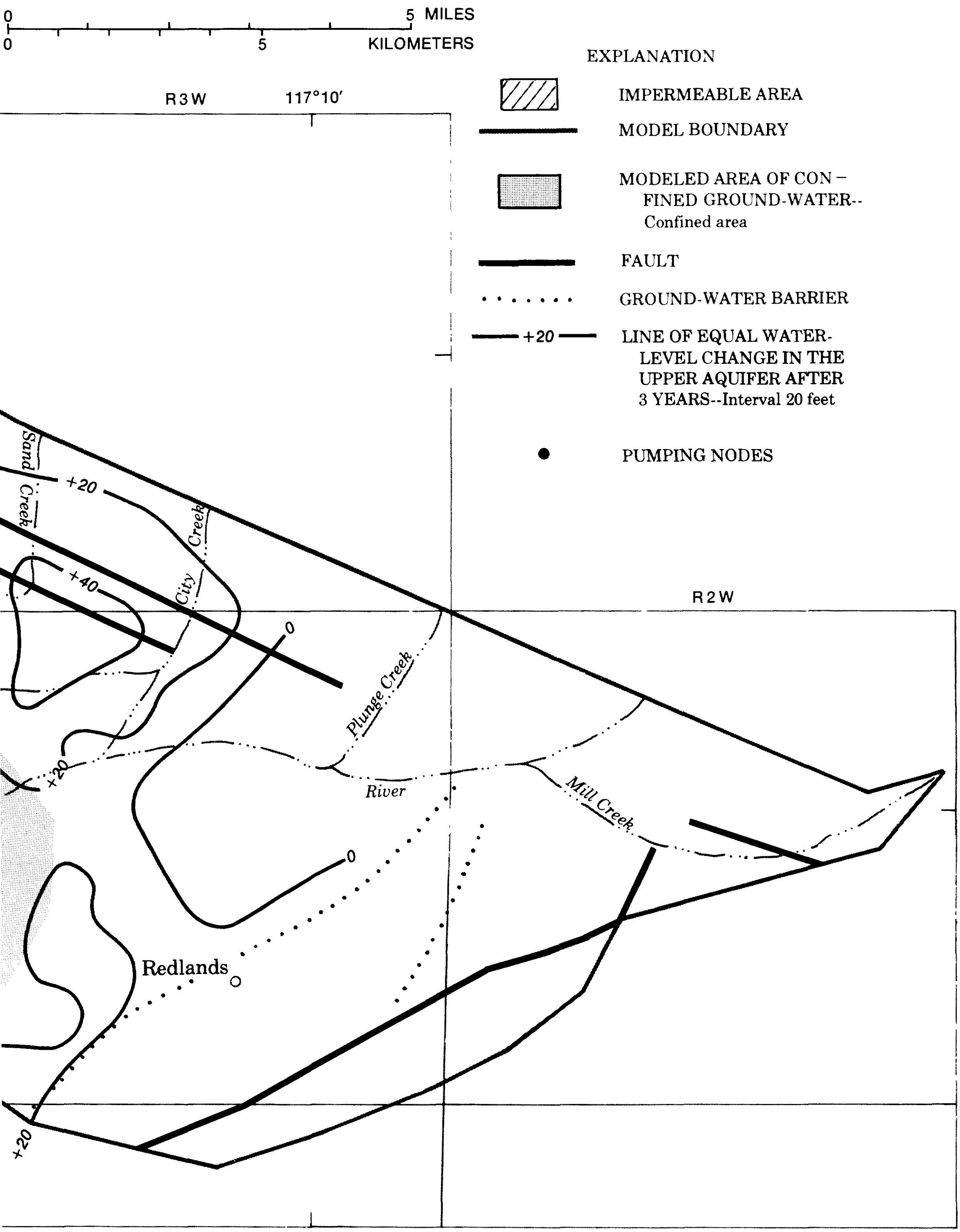


FIGURE 12. – Continued.

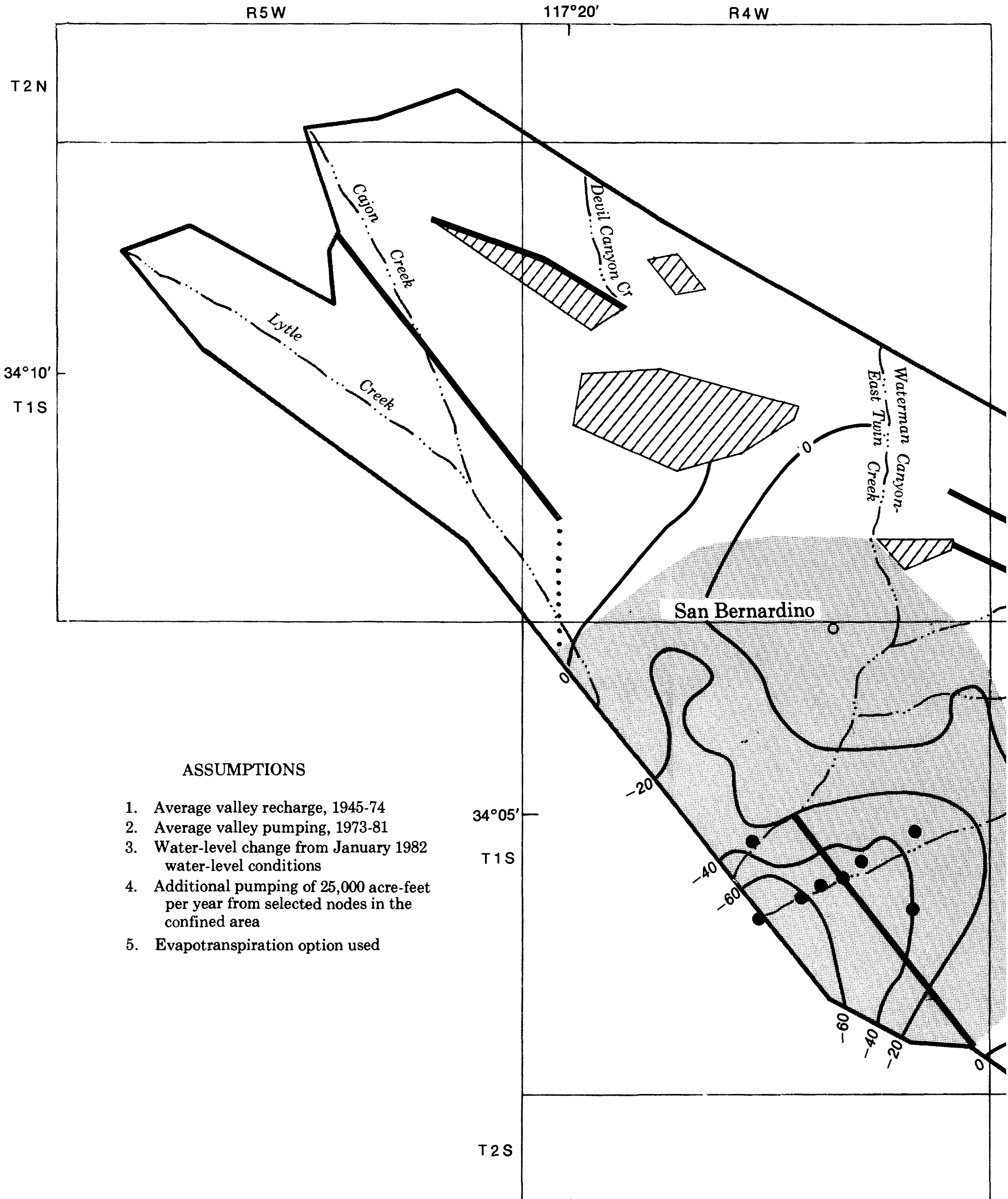


FIGURE 13. – Calculated water-level changes from high water table (1982) after 3 years of average recharge and pumping with additional pumping of 25,000 acre-feet per year from the confined area.

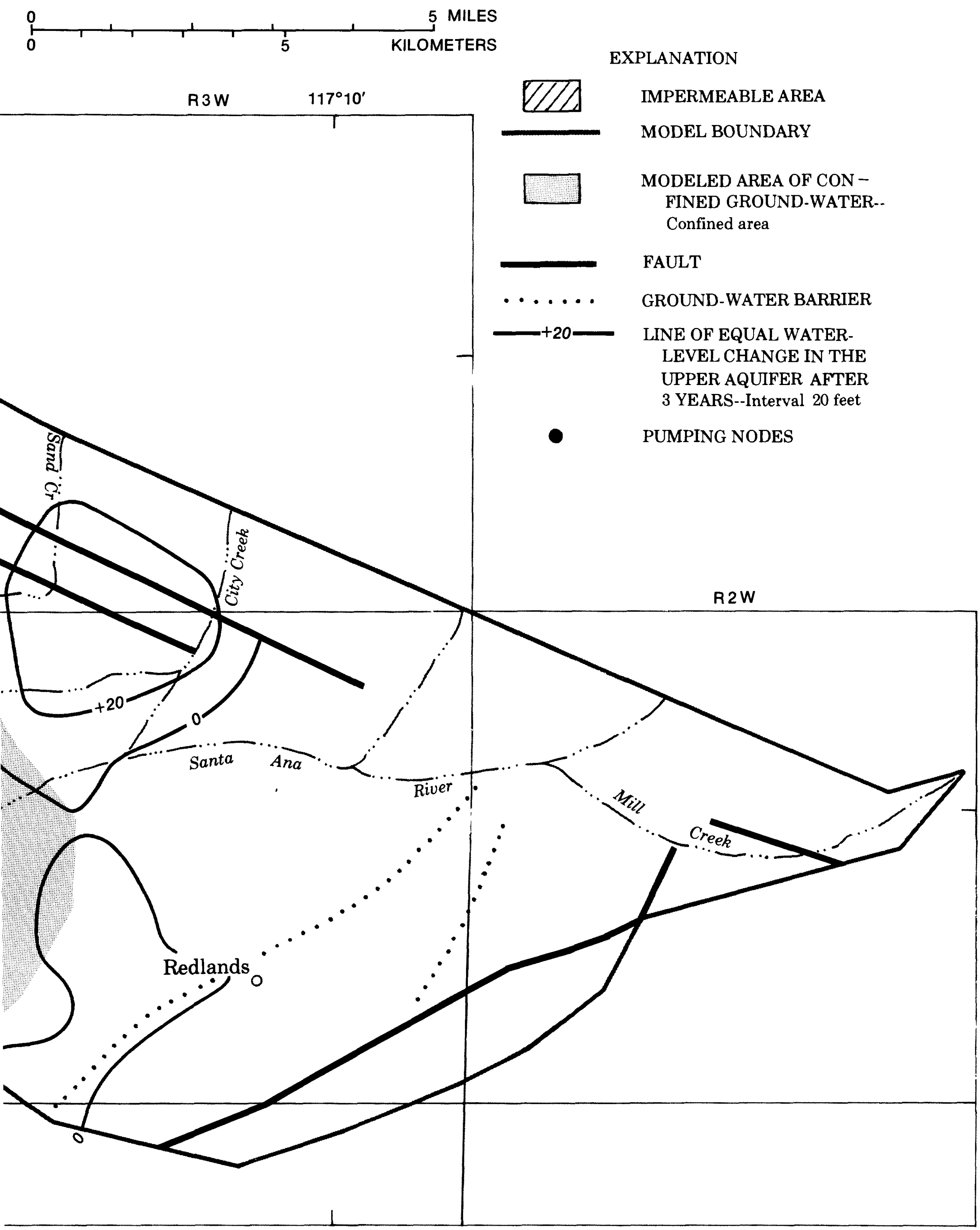


FIGURE 13. – Continued.

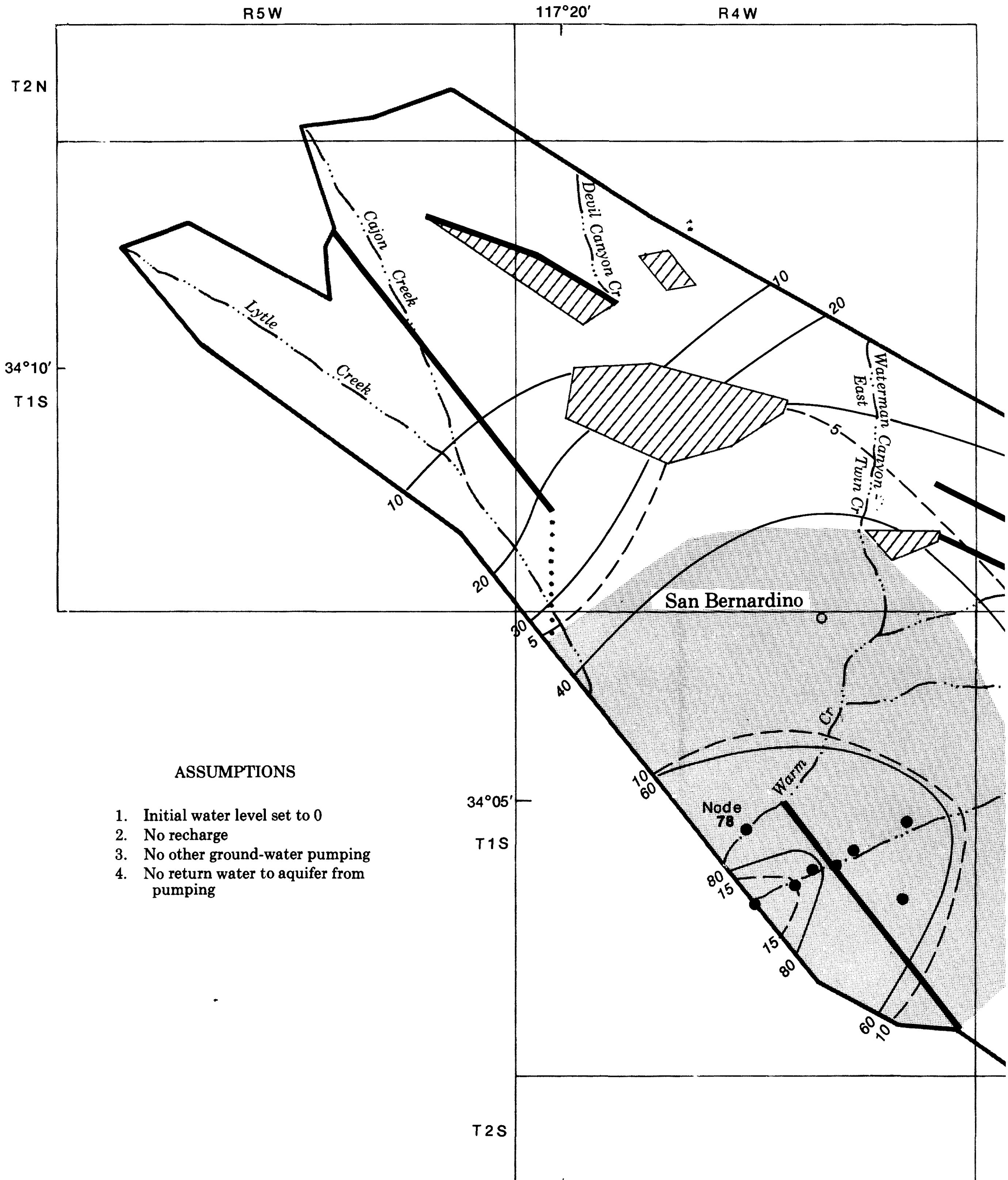


FIGURE 14. – Calculated water-level declines after 3 years, based only on pumping 5,000 and 25,000 acre-feet per year from the confined area.

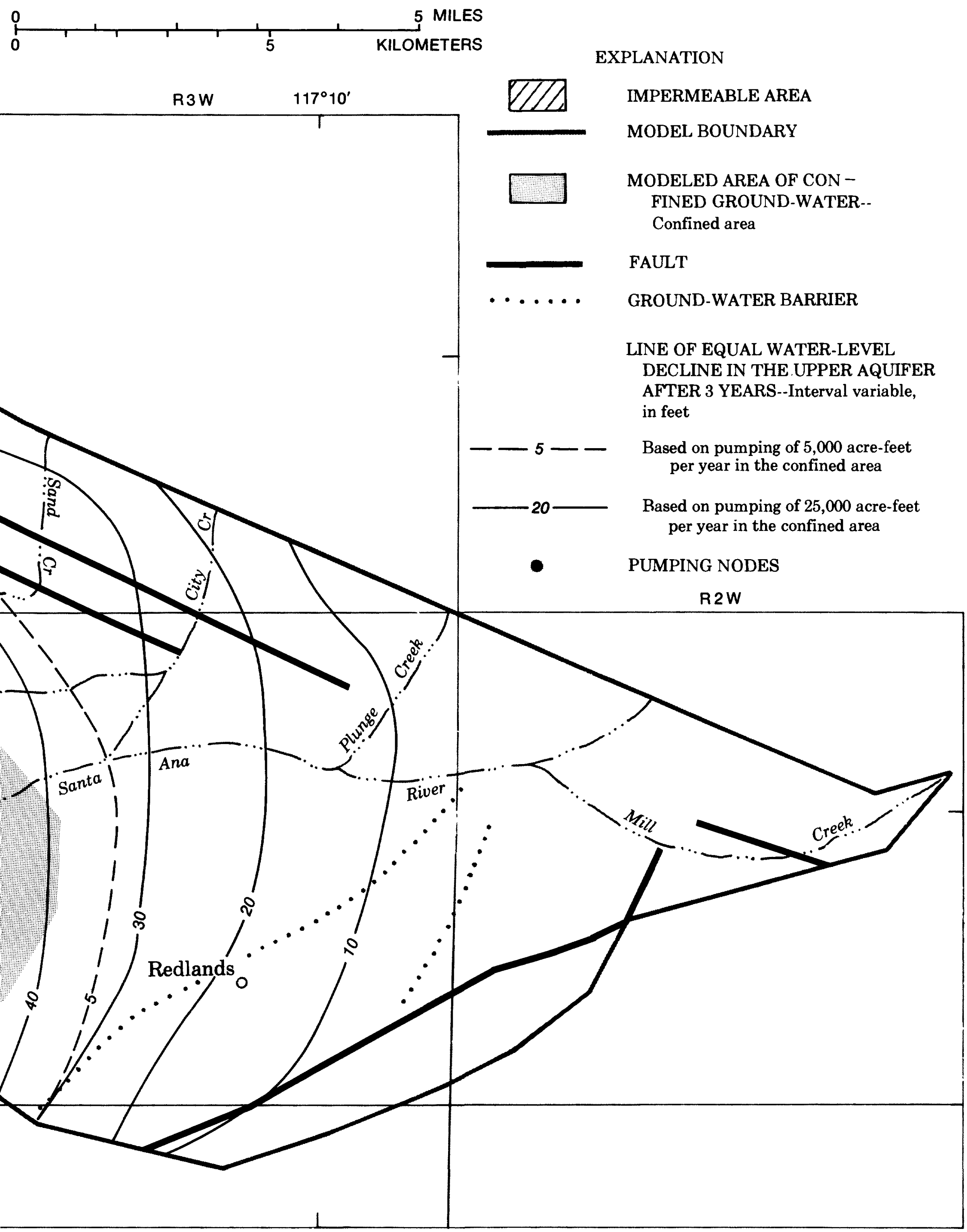


FIGURE 14. – Continued.

Greater than Average Valley Recharge with Average Pumping, and Additional Pumping from the Confined Area

Two model simulations (figs. 15 and 16) are based on (1) the average pumping rate (1973-83) and average recharge (1945-74) in the basin, with additional recharge programmed into the model for the Santa Ana River and Mill, Devil Canyon, and Waterman Canyon-East Twin Creeks, and (2) the conditions described in (1), with additional pumping of 25,000 acre-ft/yr from the confined area. The greater than average valley recharge is based generally on availability of increased streamflow and increased use of water-spreading areas for artificial recharge during the late 1970's. As an approximation, the additional recharge for the major streams was added to the average-hydrologic-conditions simulation. The greater than average valley recharge should not necessarily be considered indicative of actual conditions in the future; the intent is simply to determine how specific quantities of recharge affect water levels in the valley.

The water-level-change map (fig. 11) was compared to a similar map for greater than average recharge and average pumping conditions and compared, also, to a map for greater than average recharge conditions, average pumping, and additional pumping of 25,000 acre-ft/yr from the confined area. All water levels were based on 1982 water levels in the upper aquifer (fig. 9). Superimposing figure 11 with each of the other maps in turn resulted in new maps constructed as the difference in water-level change, in feet, between the two. This readily isolates the effects of additional recharge (fig. 15) and additional pumping from the confined aquifer (fig. 16) as compared to the average hydrologic conditions (fig. 11).

The additional aquifer recharge added to the standard model simulation (fig. 11) included, in acre-feet, about 40,000 for the upper Santa Ana River; 5,000 for Mill Creek; 5,400 for Devil Canyon Creek; and 7,000 for Waterman Canyon-East Twin Creek. As a result of this additional recharge, the confined area showed a water-level rise of about 5 feet after 3 years (fig. 15). The model simulation indicates that water-level rises in the upper Santa Ana River and Mill Creek could be greater than 100 feet. In the Devil Canyon Creek area, the Shandin Hills effectively blocked the recharge water and hindered its movement toward the confined area. Thus, simulated water levels rose 50 feet near the base of the San Bernardino Mountains with additional recharge of only 5,400 acre-ft/yr. Simulated water levels in the Waterman Canyon-East Twin Creek area rose about 30 feet in the 3-year period, and water levels rose 3 to 5 feet in the northern part of the confined area.

Figure 16 represents the same hydrologic stresses in the model as figure 15, except for additional pumping of 25,000 acre-ft/yr from the confined area. In comparison with the water-level changes from average recharge and pumping (fig. 11), figure 16 shows an additional calculated water-level decline of 10 to 35 feet after 3 years in the confined area. In the upper Santa Ana River-Mill Creek recharge areas, calculated water-level rises due to local recharge are similar to those of figure 15, except that the cone of depression from the concentrated pumping in the confined area affects the western edge of the recharge area. The Devil Canyon Creek recharge area is virtually unaffected by increased pumping in the confined area. The Waterman Canyon-East Twin Creek recharge area, which is about 10 feet lower in altitude, is affected by increased pumping in the confined area. Comparison of water-level-change contours in these two illustrations (figs. 15 and 16) shows that increased local ground-water pumping from the confined area would lower water levels and is an effective method of relieving the high hydraulic head in the aquifer.

Historical Yearly Extremes in Valley Recharge and Pumping

The results of four model simulations for conditions of historical annual extremes in recharge and pumping are shown in water-level-change maps in figure 17. Model simulations were made using measured January 1982 water levels as the base and calculating water-level changes at the end of a 3-year period. Four combinations were examined: high recharge, with high and low pumping; and low recharge, with high and low pumping. Historical pumpage ranged from 118,400 acre-ft/yr (1945) to 213,500 acre-ft/yr (1961), and recharge ranged from 30,340 acre-ft/yr (1961) to 244,400 acre-ft/yr (1969). The model evapotranspiration option was used; it simulates water extraction whenever modeled water levels for the upper model layer are within 10 feet of land surface. Use of this option produced third-year evapotranspiration losses that ranged from zero acre-ft/yr for the low recharge-high pumping simulation to 91,440 acre-ft/yr for the high recharge-low pumping simulation. Projected annual evapotranspiration rates for the 3-year period are also shown in figure 17. Of the four simulations, the high recharge-low pumping and the low recharge-high pumping combinations are considered most realistic in terms of probable occurrence. Pumping generally will decrease during periods of high natural recharge and increase during periods of low recharge.

Water-level changes after 3 years of simulation in the confined area from the January 1982 base level showed the following:

Highest recharge-highest pumping.--Simulated water levels were higher in most of the confined area, with maximum rises of 40 to 60 feet along the edges. The zero-change line is elongated along the Santa Ana River, and more than 20 feet of decline occurred in the lower altitudes of the Warm Creek-Santa Ana River area. High pumping rates in the low-altitude area caused water levels to decline even with high recharge rates in the high-altitude areas.

Highest recharge-lowest pumping.--Simulated water levels were as much as 60 feet higher in the confined area. There was zero change in a small part of the lower Warm Creek-Santa Ana River area, and less than 20 feet of decline adjacent to the San Jacinto fault near the confluence of Warm Creek and the Santa Ana River. This model simulation indicates the potential for high water levels in the low-altitude areas during wet years when ground-water pumping is typically less than in dry years.

Lowest recharge-highest pumping.--Simulated water levels declined in the confined area; declines ranged from 20 feet in the northern part to more than 80 feet in the lower Warm Creek-Santa Ana River area. Recharge was too low to overcome the effects of high pumping rates. The greatest water-level declines occurred in the lower Santa Ana River area because of high pumping rates in well fields from which water is exported out of the valley.

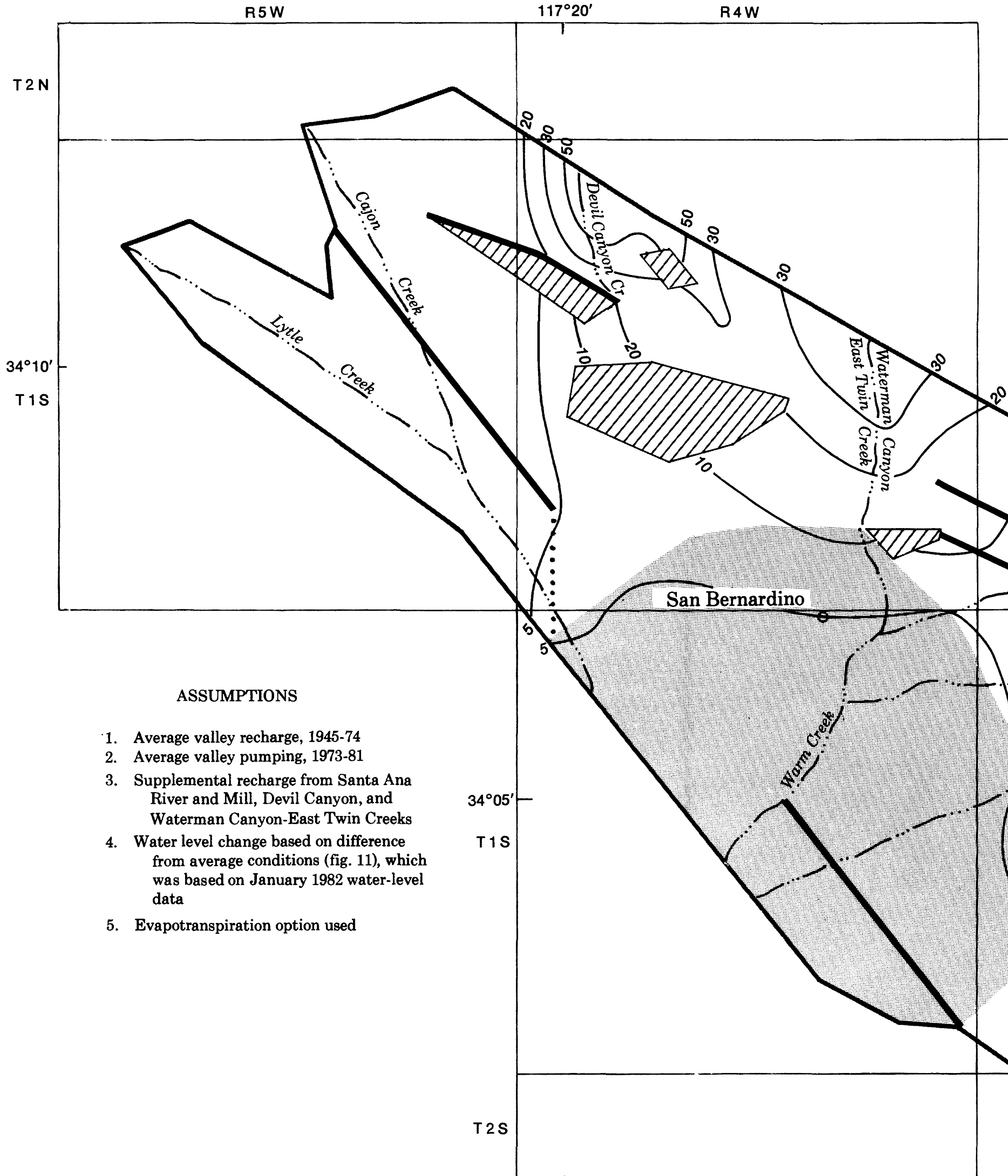


FIGURE 15. – Calculated residual water-level rise from a high water table (1982) after 3 years, caused only by supplemental recharge.

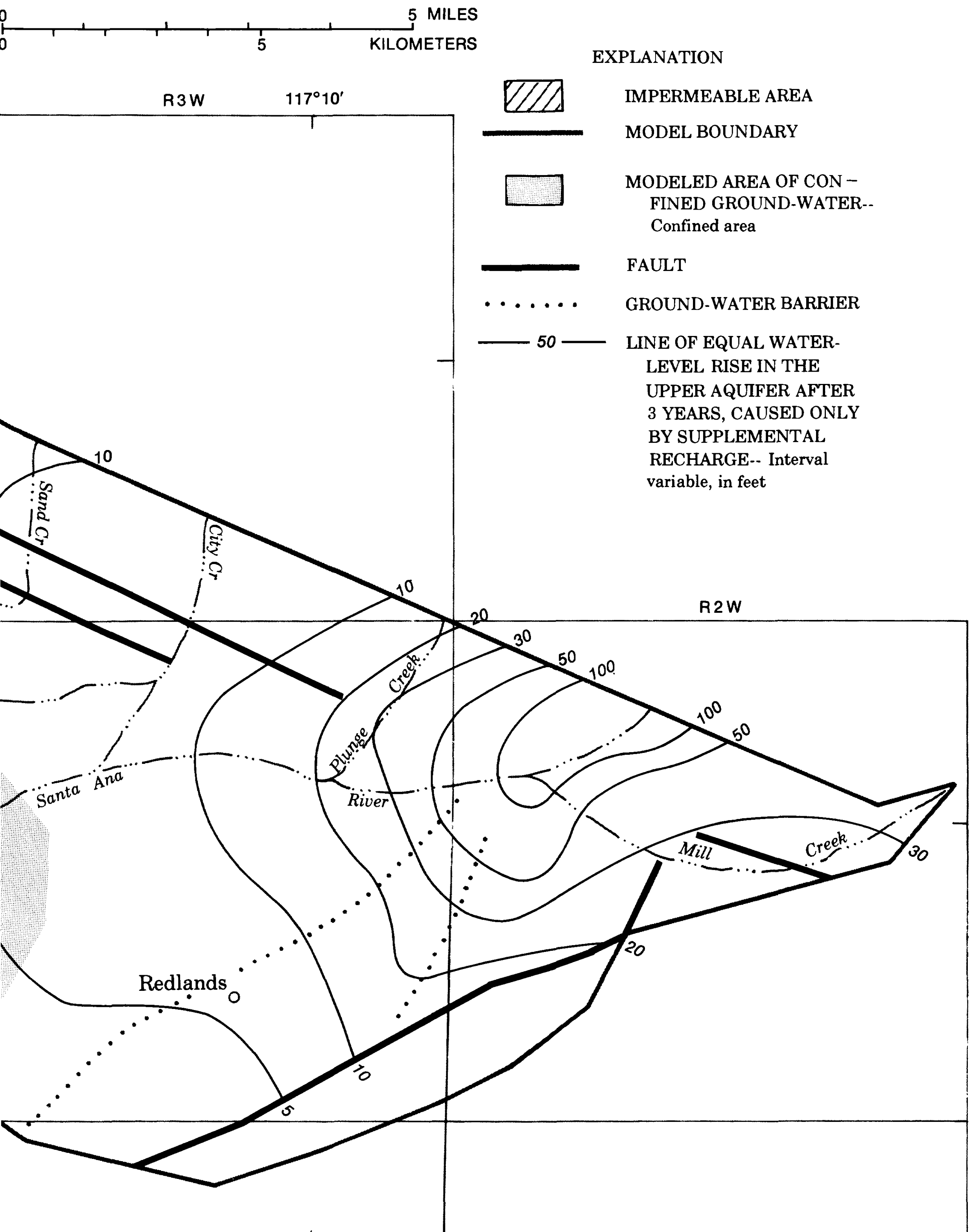


FIGURE 15. – Continued.

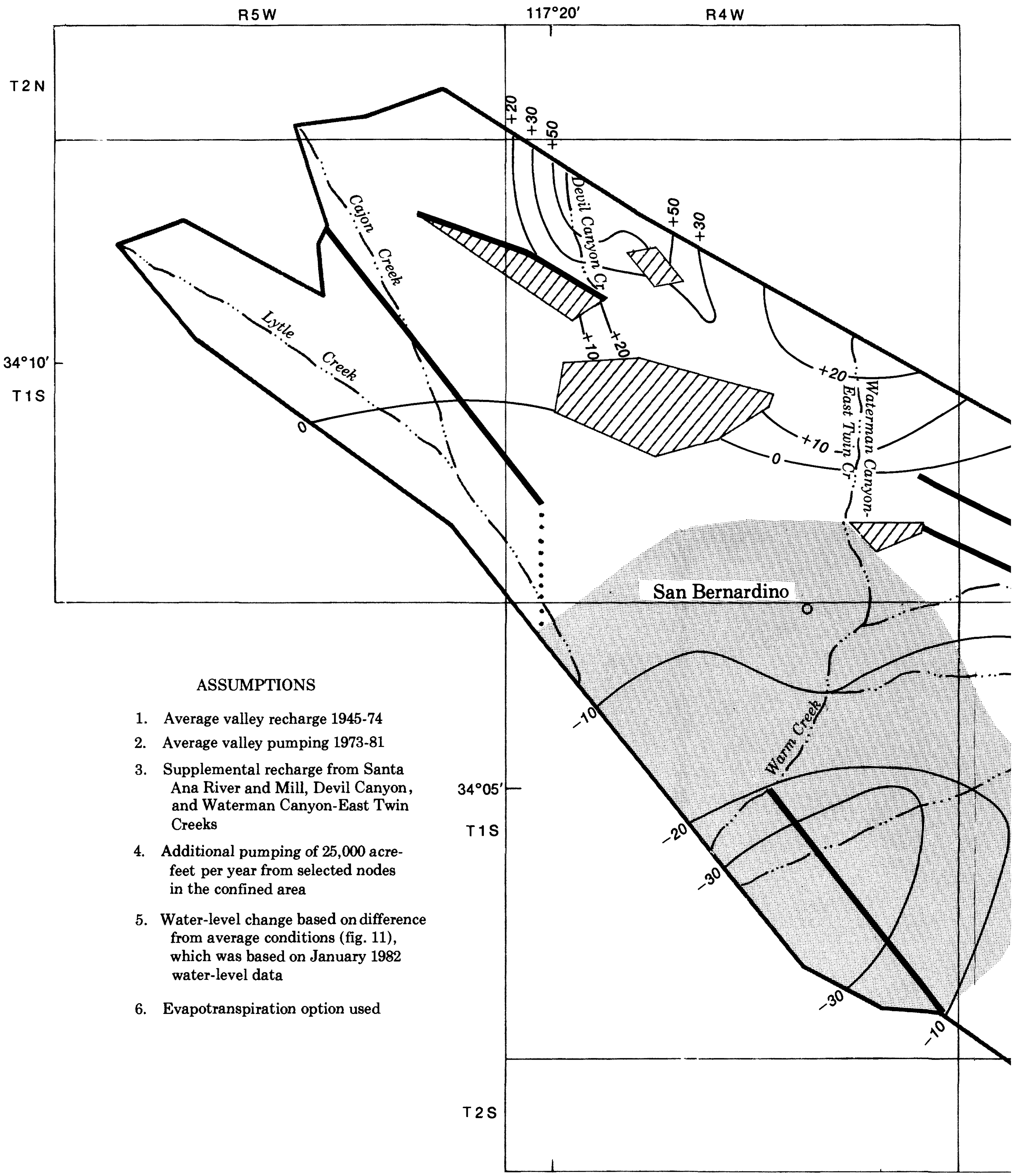


FIGURE 16. – Calculated residual water-level changes from a high water table (1982) after 3 years, caused only by supplemental recharge and additional pumping of 25,000 acre-feet per year from the confined area.

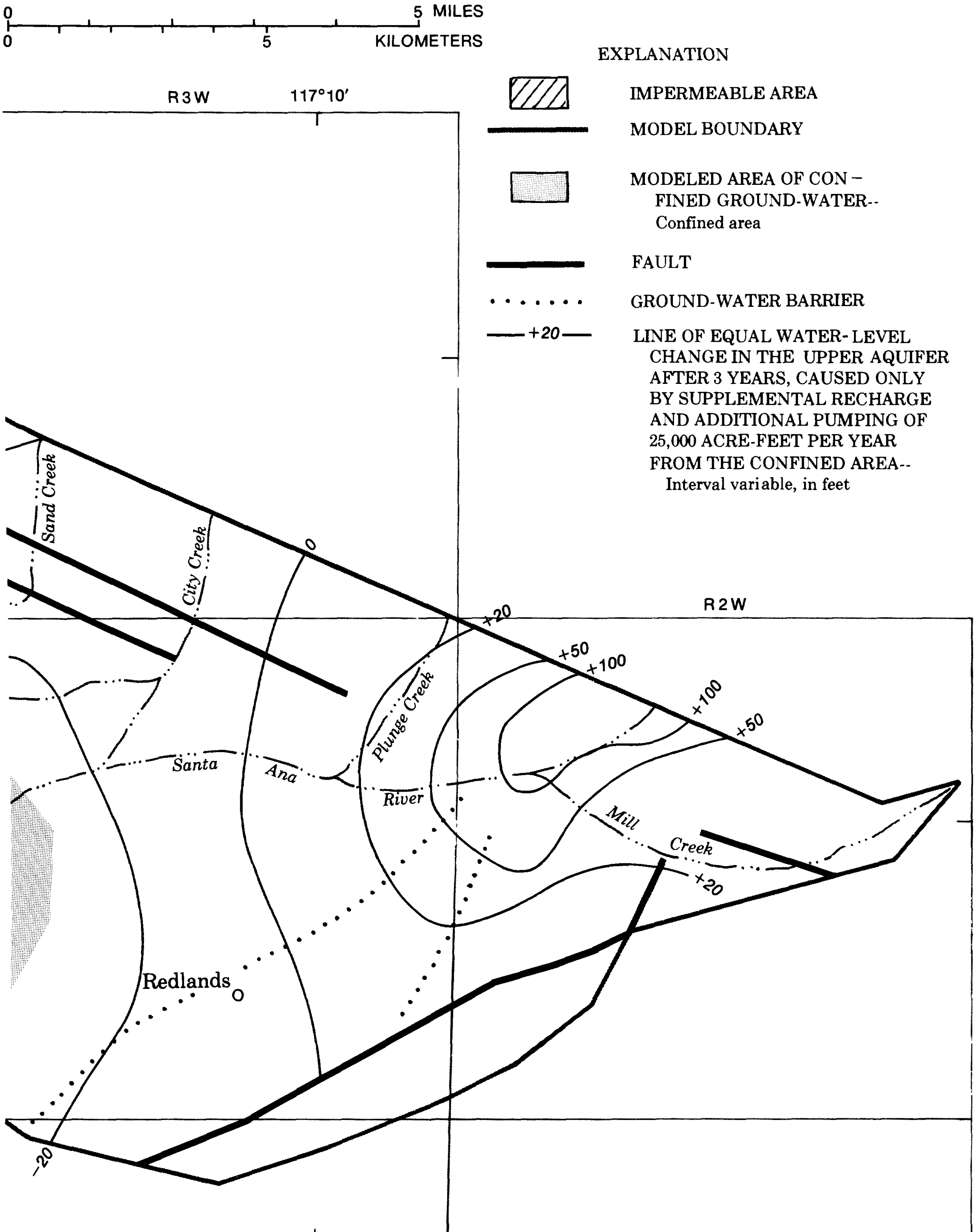


FIGURE 16. —Continued.

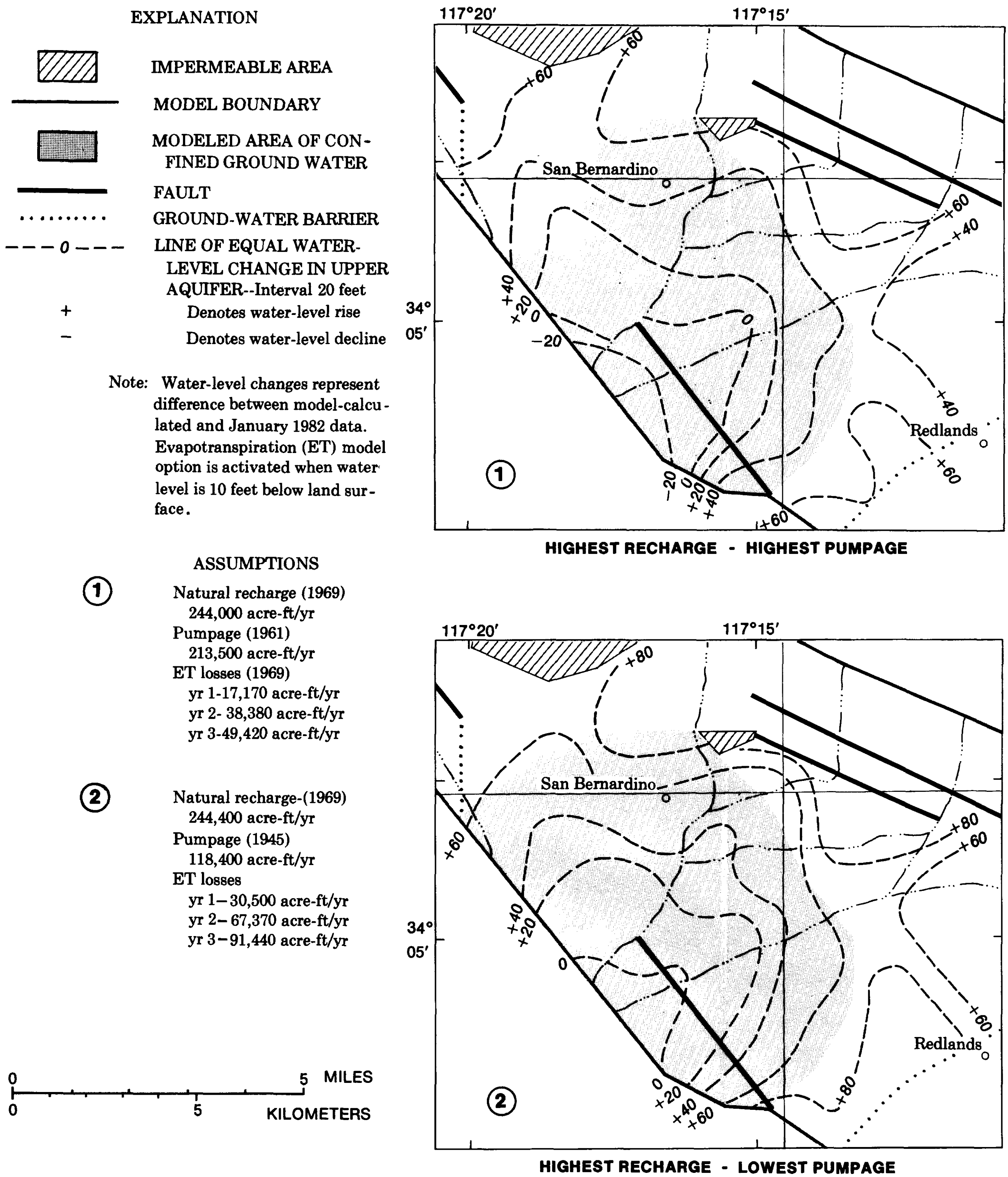
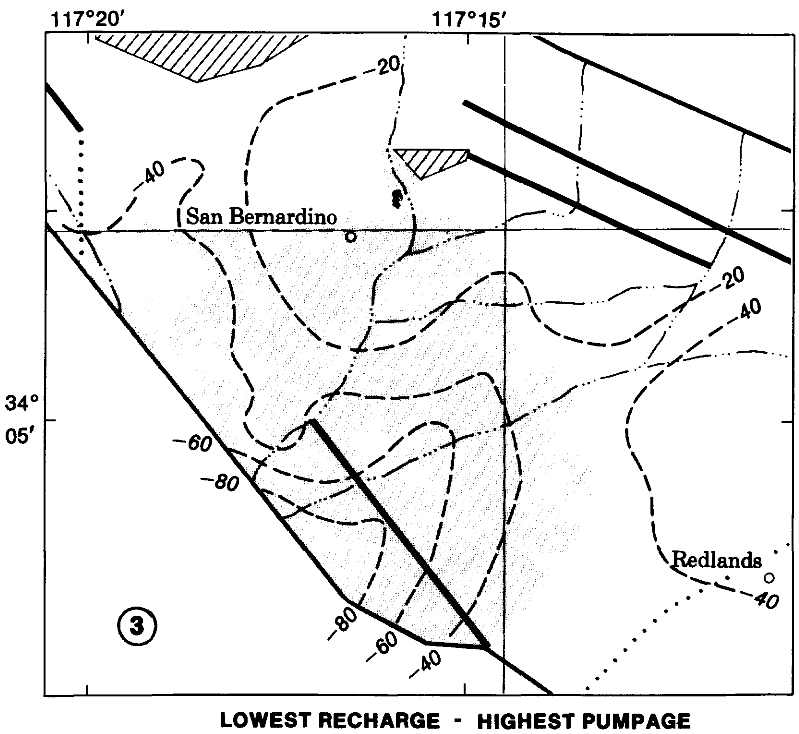
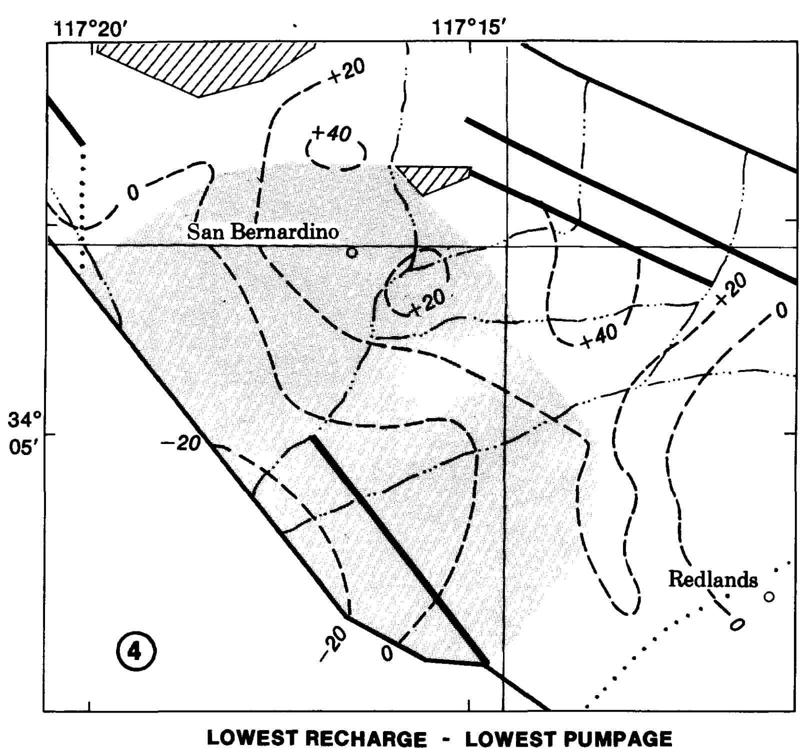


FIGURE 17. — Calculated water-level changes from a high water table (1982) after 3 years of historical extremes (1945-80) of recharge and pumping.



ASSUMPTIONS (continued).

(3) Natural recharge (1961)
30,340 acre-ft/yr
Pumpage (1961)
213,500 acre-ft/yr
ET losses
yr 1 – 2,710 acre-ft/yr
yr 2 – 450 acre-ft/yr
yr 3 – 0 acre-ft/yr



(4) Natural recharge
30,340 acre-ft/yr
Pumpage (1945)
118,400 acre-ft/yr
ET losses
yr 1 – 12,890 acre-ft/yr
yr 2 – 14,820 acre-ft/yr
yr 3 – 14,390 acre-ft/yr

FIGURE 17. – Continued.

Lowest recharge-lowest pumping.--Simulated water levels in the northeastern one-half of the area rose as much as 20 feet, and in the southwestern one-half declined more than 20 feet near the San Jacinto fault. Even though recharge rates were low, recharge from Waterman Canyon-East Twin, Sand, and City Creeks was effective because of the proximity of the streams to the confined area and the low pumping rates.

Valley Ground-Water Pumping, No Recharge

To determine the effects of ground-water pumping on the valley aquifer system, a model simulation was done with pumping only and no recharge to the system. The initial water levels in this model simulation were set to zero, and annual increments of pumpage were then superimposed on the model. Pumpage was based on the 10-year period 1972-81, in which the minimum pumpage was 140,599 acre-ft in 1978, the maximum was 176,700 acre-ft in 1972, and the average was about 156,000 acre-ft/yr. The distribution of the pumping wells, as grouped by model node, is the same as shown by Hardt and Hutchinson (1980, fig. 14, p. 36-37). As the annual pumpage in the valley for the foreseeable future will probably be between these limits, this model simulation can be used as a projection of pumping effects for a 1- to 10-year period.

The calculated maximum water-level declines in the upper aquifer, after 1 year of pumping, were about 75 feet in the Warm Creek-Santa Ana River area adjacent to the San Jacinto fault (fig. 18). Radiating out from this cone of depression, water-level declines were progressively smaller. This pattern of water-level declines indicates that the greatest concentration of pumping is in the confined area. After 10 years of pumping, the pattern of water-level decline was similar to the 1-year decline, only much deeper. Calculated water-level declines were about 350 feet in the Warm Creek-Santa Ana River area and 300 to 325 feet near the periphery of the confined area.

This model simulation shows that without recharge to the aquifers, the south-central part of the valley (the confined area) would have the greatest water-level declines. The cone of depression is the result of concentrated pumping in this area combined with the impermeable-boundary effect owing to the San Jacinto fault. The water-level declines calculated by this model simulation are maximum values. Any aquifer recharge in the valley reduces the water-level declines.

Artificial Recharge in Selected Streams, No Pumping

The artificial-recharge program in the valley is designed to increase the quantity of recharge to aquifers beyond the quantity normally recharged by infiltration of natural streamflow and direct precipitation. Manmade structures restrict or slow down the surface flow in the valley and allow the water to percolate into the ground. The artificial-recharge program consists of water spreading of natural streamflow and imported water from the California Aqueduct. Water imported from northern California became available in November 1972. Because of the greater than average natural streamflow since 1978, the quantity of water imported from the California Aqueduct to the valley was decreased. The exception was 1981 when less natural streamflow was available for recharge and thus additional water was imported. Even then, artificial recharge was the lowest since 1977, reflecting concern for the high water levels in the confined area (table 2).

The main areas of artificial recharge include the Santa Ana River, and Mill, Lytle, Devil Canyon (Sweetwater, Spillway, and Badger sites), and Waterman Canyon-East Twin Creeks (fig. 2). Artificial recharge from natural streamflow and imported water during 1972-81 is shown in table 3. The data are based on records or estimates from Fontana Water Company, San Bernardino Valley Water Conservation District, and San Bernardino Valley Municipal Water District. Uncontrolled water recharged naturally in the stream channels is not included.

Figures 19-23 show calculated water-level rises in response to artificial recharge for 1972-81 (table 3). The model simulations were made separately for the Santa Ana River (fig. 19), Mill Creek (fig. 20), Lytle Creek (fig. 21), Devil Canyon Creek (fig. 22), and Waterman Canyon-East Twin Creek (fig. 23). The methodology consisted of setting the initial water levels in the valley to zero. Ground-water pumping was not simulated in the model. Thus, the effects of artificial recharge at each of the major stream-channel recharge sites were evaluated on the valley aquifers, particularly in the confined area, without the influence of any other hydrologic factors. These model simulations are useful in determining the hydrologic influence of recharge at each stream-channel site. The maps in figures 19-23 show water-level rises after 1 and 10 years. Where the first year had little recharge, the initial water-level-rise contours represent the end of the second year.

TABLE 3.--Artificial-recharge program, 1972-81

[In acre-feet; includes recharge from natural streamflow and imported water]

Year	Santa Ana River	Mill Creek	Lytle Creek	Devil Canyon Creek	Waterman Canyon-East Twin Creek	Total
(1) 1972	3,132	21	966	120	1,156	5,375
(2) 1973	18,227	2,911	8,547	9,309	22,918	61,912
(3) 1974	10,182	1,182	4,490	6,449	9,747	32,050
(4) 1975	8,501	710	620	7,287	6,821	23,939
(5) 1976	6,258	791	1,812	5,243	7,046	21,150
(6) 1977	13,753	314	3,219	10,486	3,637	31,409
(7) 1978	64,874	15,659	51,005	7,867	181	139,586
(8) 1979	45,392	12,363	11,505	4,294	48	73,602
(9) 1980	41,805	14,654	29,299	117	0	85,875
(10) 1981	19,232	3,035	1,175	7,060	34	30,536
TOTAL	231,356	51,640	112,638	58,232	51,588	505,454

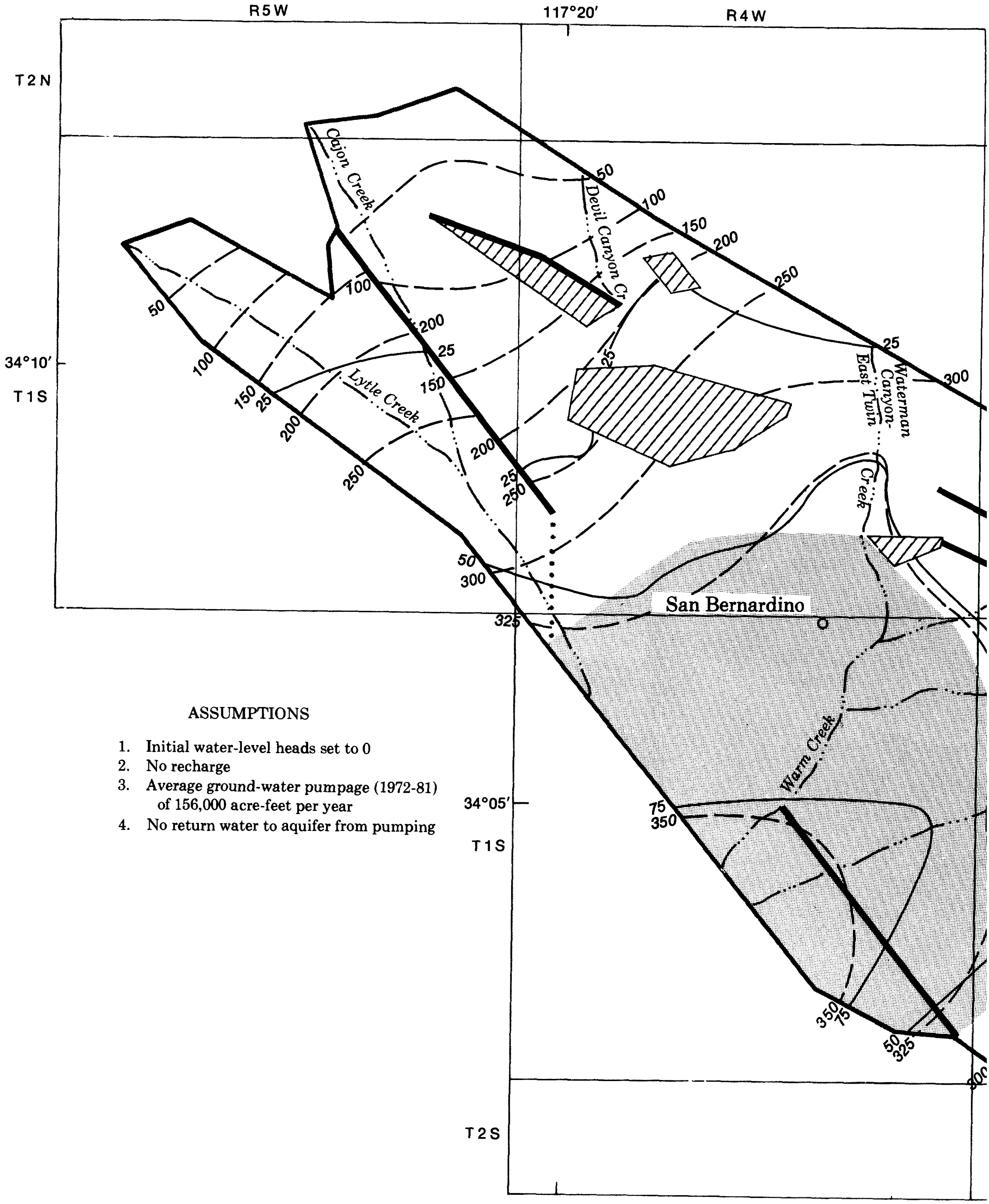


FIGURE 18. – Calculated water-level declines based on average yearly valley pumping and no recharge (after 1 and 10 years).

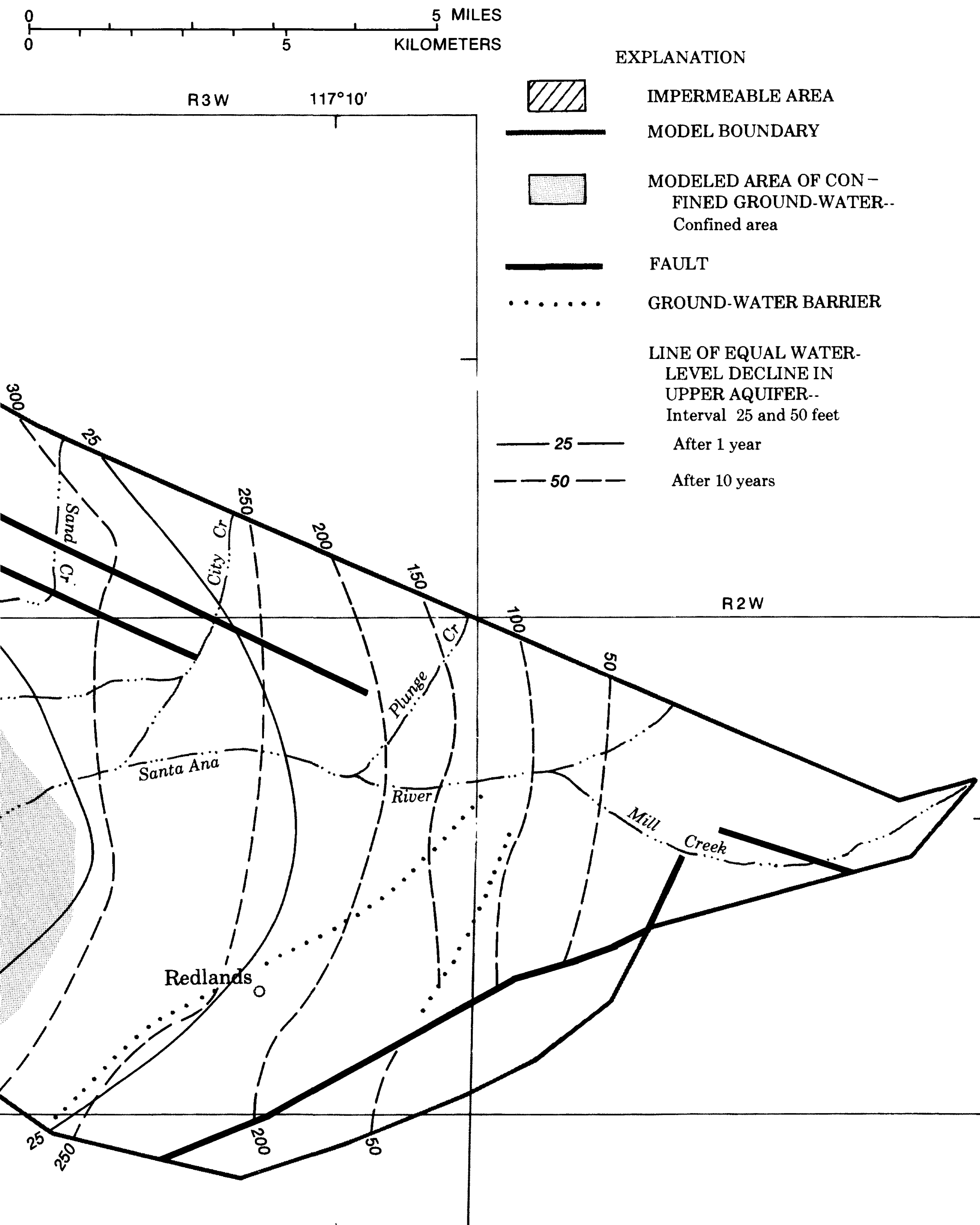


FIGURE 18. – Continued.

Santa Ana River

For 1972-81, 231,356 acre-ft of water was recharged artificially from the Santa Ana River sites near the San Bernardino Mountains. Recharge ranged from 3,132 acre-ft in 1972 to 64,874 acre-ft in 1978. Calculated water-level rises at the recharge sites were a maximum of 4 feet after 1 year, increasing to more than 100 feet after 10 years (fig. 19). After 1 year of minimum recharge, the calculated rise was about 1 foot at the edge of the confined area; after 10 years the calculated rise in the central part of the confined area was about 30 feet. The Redlands fault restricted water-level rises southward to less than 10 feet. Rises in the Lytle Creek and Devil Canyon Creek areas were only a few feet.

Mill Creek

During 1972-81, 51,640 acre-ft of water was recharged artificially from the Mill Creek site upstream from the confluence with the Santa Ana River. Recharge ranged from 21 acre-ft in 1972 to 15,659 acre-ft in 1978. The calculated water-level rise at the recharge site was a maximum of 10 feet after 2 years (based on 2,911 acre-ft of recharge) and increased after 10 years to more than 100 feet (fig. 20). The effects of recharge in Mill Creek are local because of the comparatively low rates of artificial recharge; 5 miles from the recharge site, water levels showed little or no response. Therefore, during 1972-81, the artificial-recharge program for Mill Creek did not have a direct effect on the confined area and the Redlands area.

Lytle Creek

During 1972-81, 112,638 acre-ft of water was recharged artificially from the Lytle Creek site about 5 miles south of the San Gabriel Mountains. Recharge ranged from 620 acre-ft in 1975 to 51,005 acre-ft in 1978. Calculated water-level rises at the recharge site after 1 year were small because of the low initial recharge rate. At the end of 2 years, based on recharge of 8,547 acre-ft, calculated water-level rises were about 40 feet; rises increased to more than 150 feet after 10 years (fig. 21). Calculated water-level rises in the confined area were less than 1 foot after 2 years, increasing to about 10 to 25 feet after 10 years. The major effect of Lytle Creek artificial recharge was along the Lytle Creek drainage basin. Ground-water flow out of the basin was restricted by faults and a barrier. Calculated water-level rises were small at Devil Canyon and were less than 10 feet after 10 years. In the southeastern part of the valley, Lytle Creek had little or no hydrologic effect. The Loma Linda fault near the San Gabriel Mountains was a barrier to ground-water movement northeastward and restricted water-level changes across the fault.

Devil Canyon Creek

During 1972-81, 58,232 acre-ft of water was recharged artificially from the Devil Canyon Creek area. Recharge sites are at Spillway, Sweetwater, and Badger. In addition, the tunnel of the Lucky Project aqueduct transports imported water from the California Aqueduct to the valley from Silverwood Lake on the north side of the San Bernardino Mountains. Recharge ranged from 117 acre-ft in 1980 to 10,486 acre-ft in 1977. Calculated water-level rises in the water-spreading area after 1 year were small because of minimal recharge. Calculated water-level rises at the end of 2 years were a maximum of 50 feet, and increased to more than 100 feet after 10 years (fig. 22). Calculated water-level rises in the confined area were zero feet after 2 years and about 5 feet after 10 years. In general, the Shandin Hills restricted ground-water movement southward, and water-level rises were concentrated in the Devil Canyon area. The rest of the valley was affected very little by the artificial-recharge program because of the particular geohydrologic conditions at Devil Canyon.

Waterman Canyon-East Twin Creek

During 1972-81, 51,588 acre-ft of water was recharged artificially from Waterman Canyon-East Twin Creek. The water-spreading areas consist of an elaborate network of recharge ponds in and adjacent to East Twin Creek at the base of the San Bernardino Mountains. Recharge ranged from less than 200 acre-ft during 1978-81 to 22,918 acre-ft in 1973. Calculated water-level rises after 1 year were small because of the small quantity of recharge. After 2 years, calculated water-level rises at the recharge ponds were a maximum of 100 feet, and decreased to a rise of about 20 feet after 10 years (fig. 23). After the large quantity of recharge in 1973, less water was recharged in the remaining years until 1981. At the end of 1981, calculated water-level rises in the confined area were about 15 feet. Based on equal quantities of recharge, the effect on the water levels in the confined area was more pronounced from recharge at this site than at any of the other sites.

Combined Valley Ground-Water Pumping and Artificial Recharge in Selected Streams

The model was used to calculate water-level changes due to valley pumping (no recharge) and artificial recharge in the Santa Ana River, and Mill, Lytle, Devil Canyon, and Waterman Canyon-East Twin Creeks for 1972-81. The water-level-change map (fig. 24) is, in effect, a composite of figures 18-23. Natural recharge is not included from these streams, nor any recharge from other, smaller streams such as Sand, City, Plunge, San Timoteo, or Cajon Creeks. The purpose of this composite map is to show the effect of the ground-water pumping and the artificial-recharge program on the ground-water system, particularly in the confined area. Initial hydraulic heads in this model simulation were set to zero, and yearly increments of pumpage and artificial recharge were then added to the model.

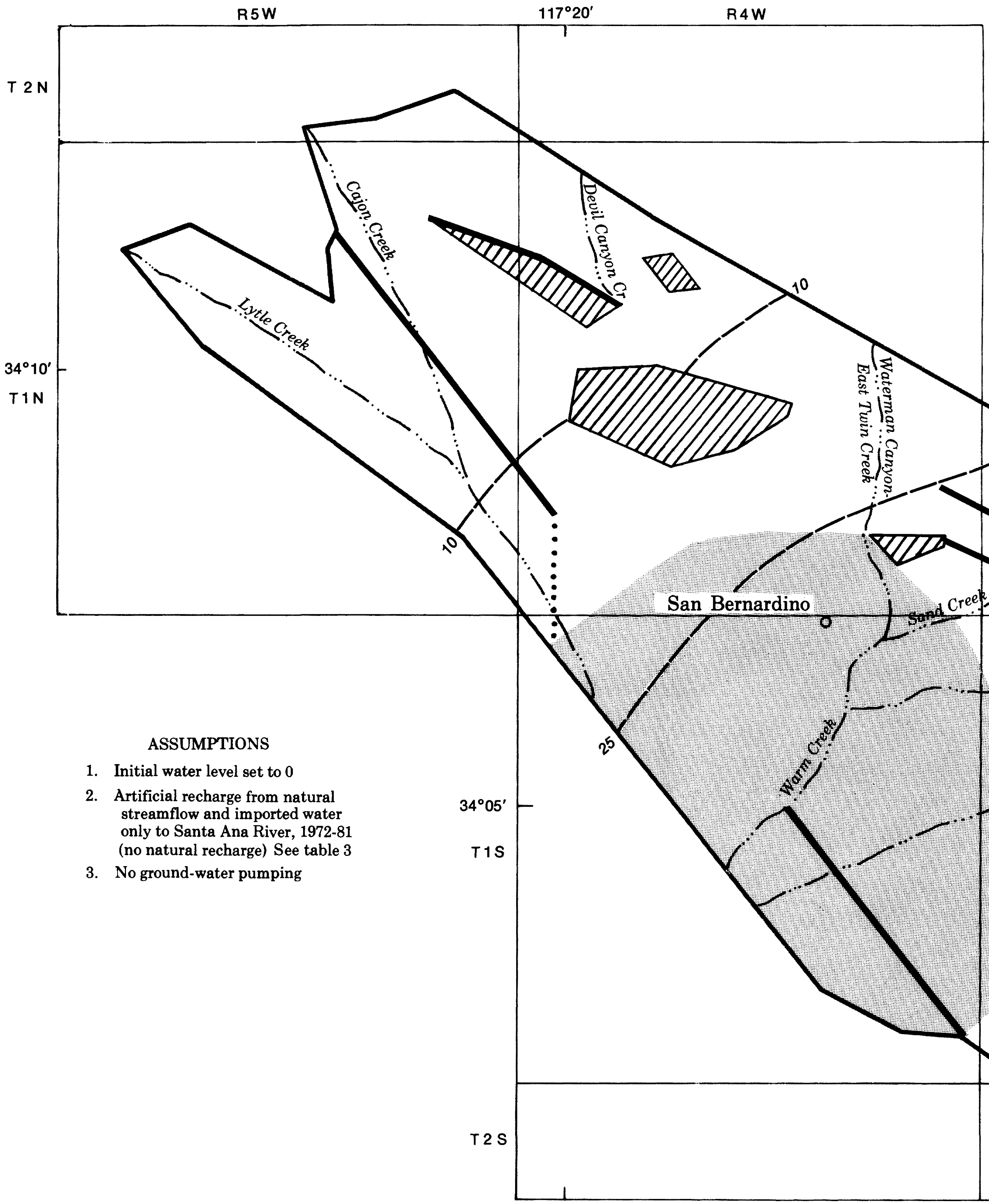


FIGURE 19. – Calculated water-level rises, with no valley pumping, due to artificial recharge in upper Santa Ana River (after 1 and 10 years).

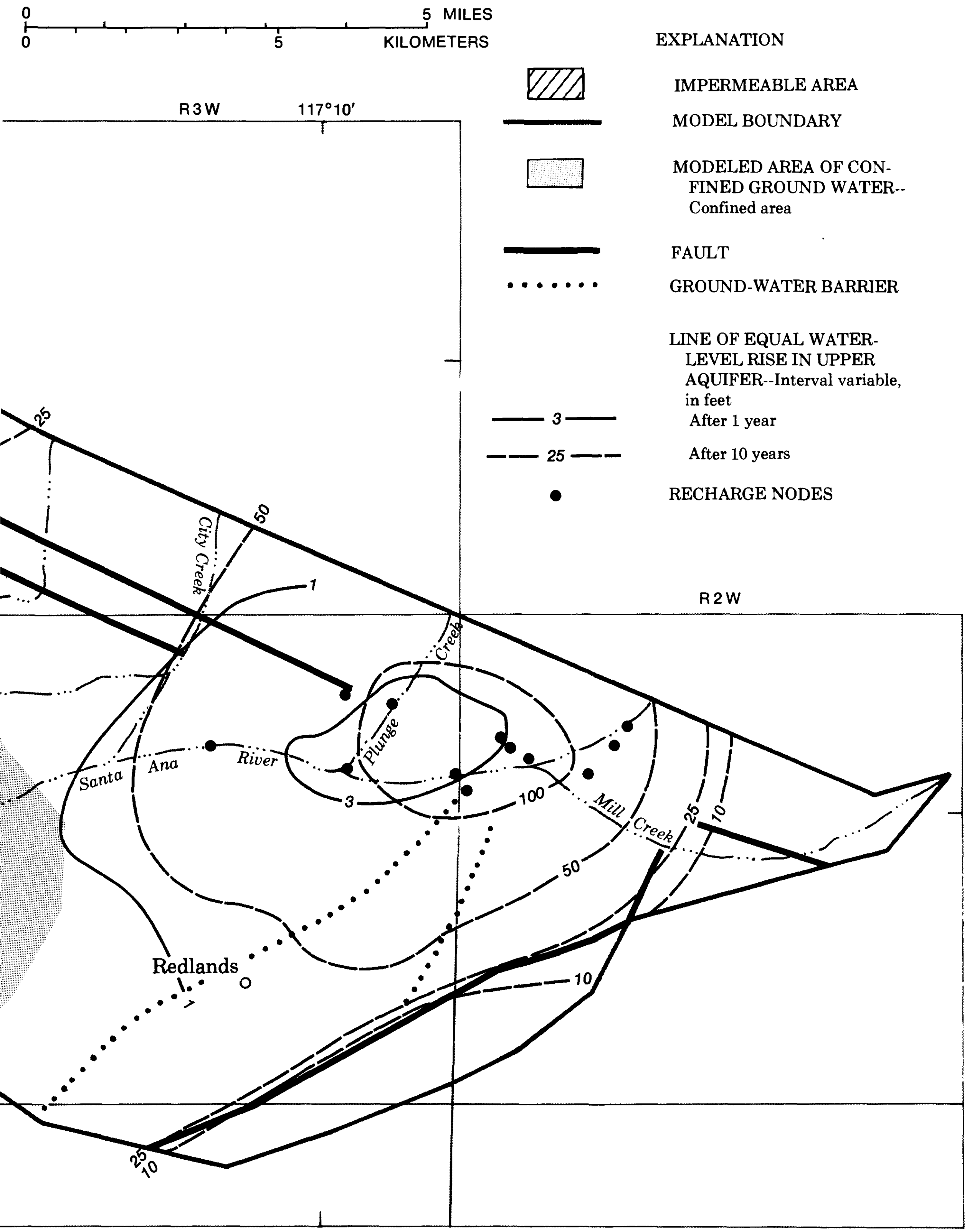


FIGURE 19. – Continued.

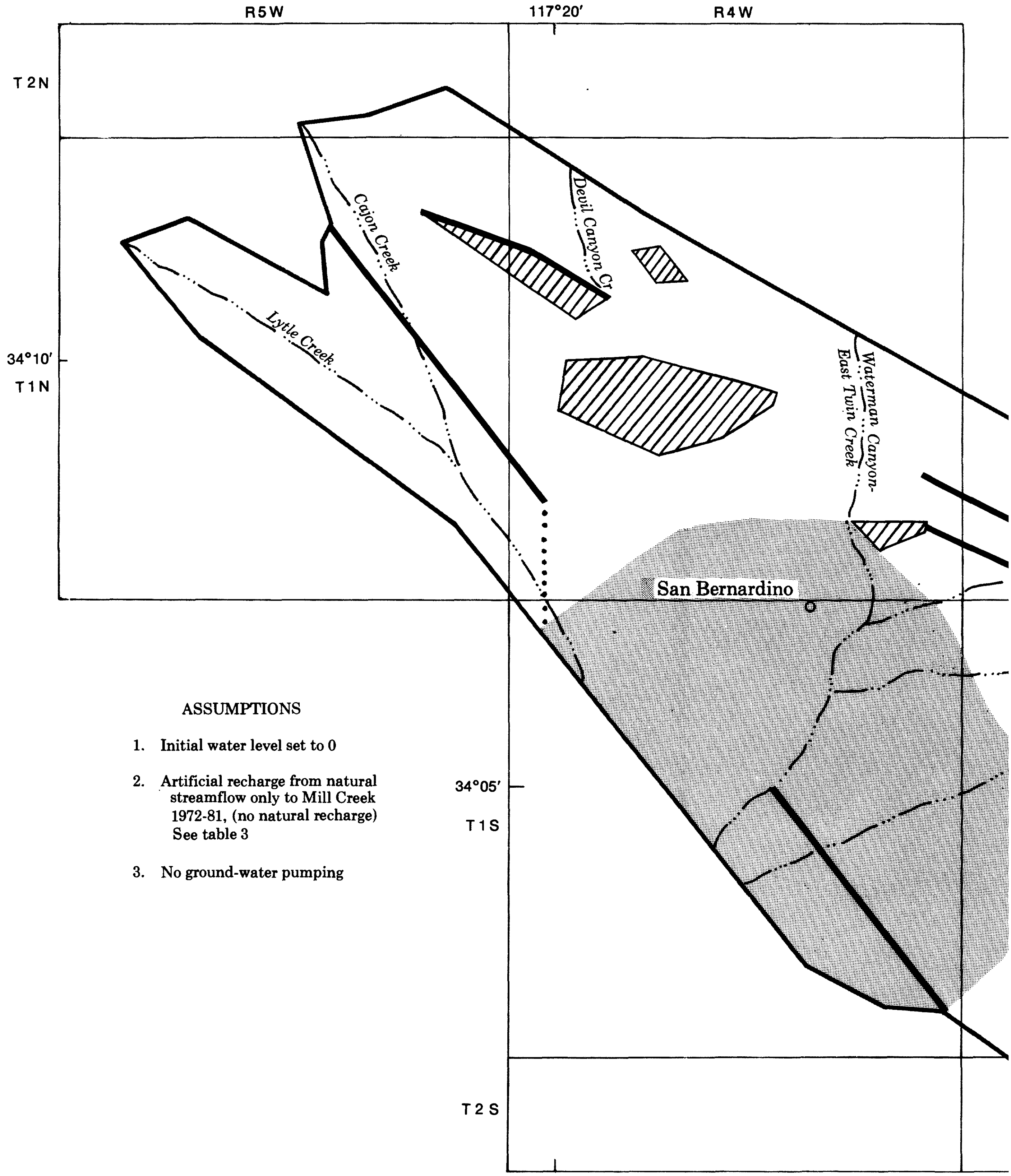


FIGURE 20. – Calculated water level rises, with no valley pumping, due to artificial recharge in Mill Creek (after 2 and 10 years).

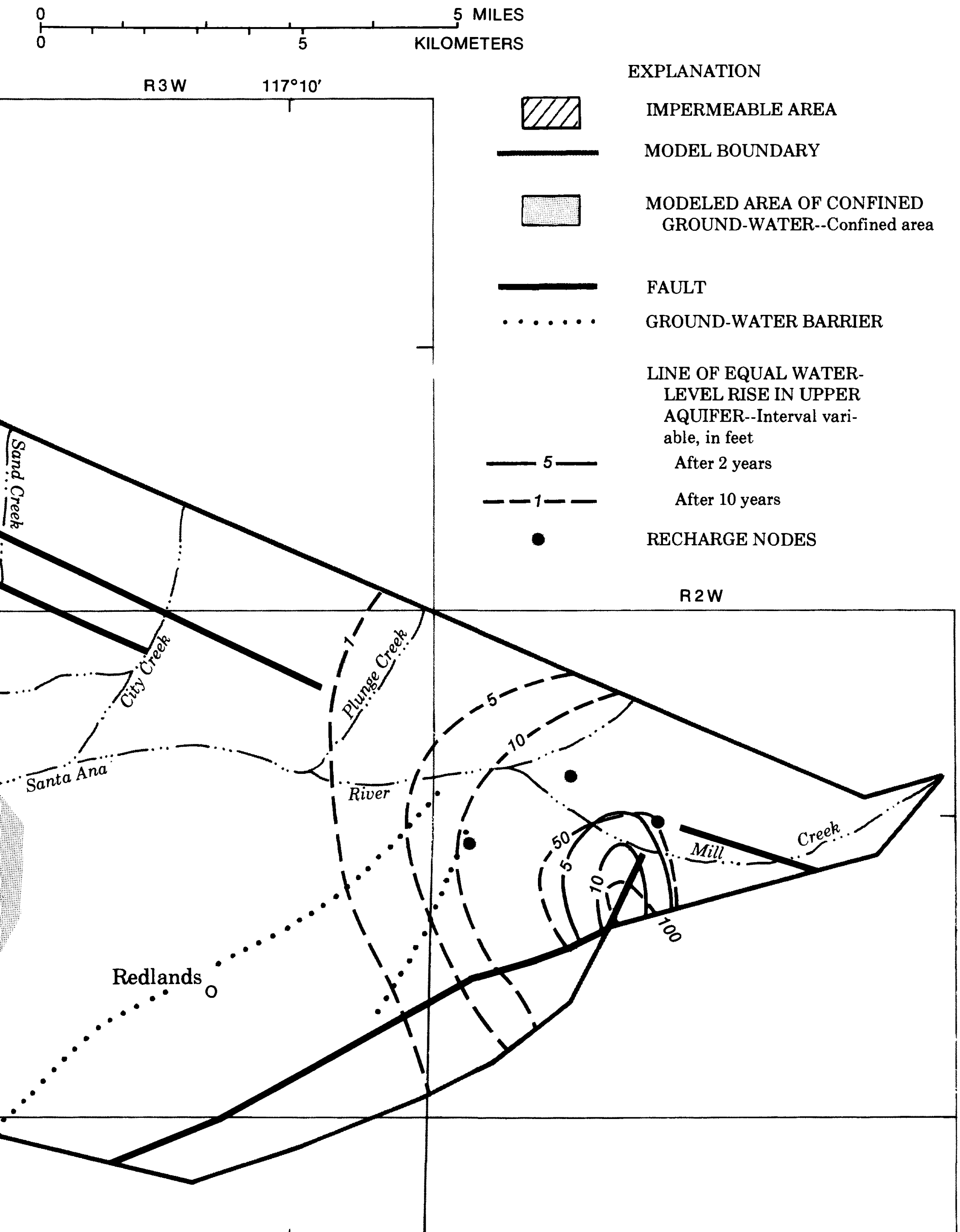


FIGURE 20. – Continued.

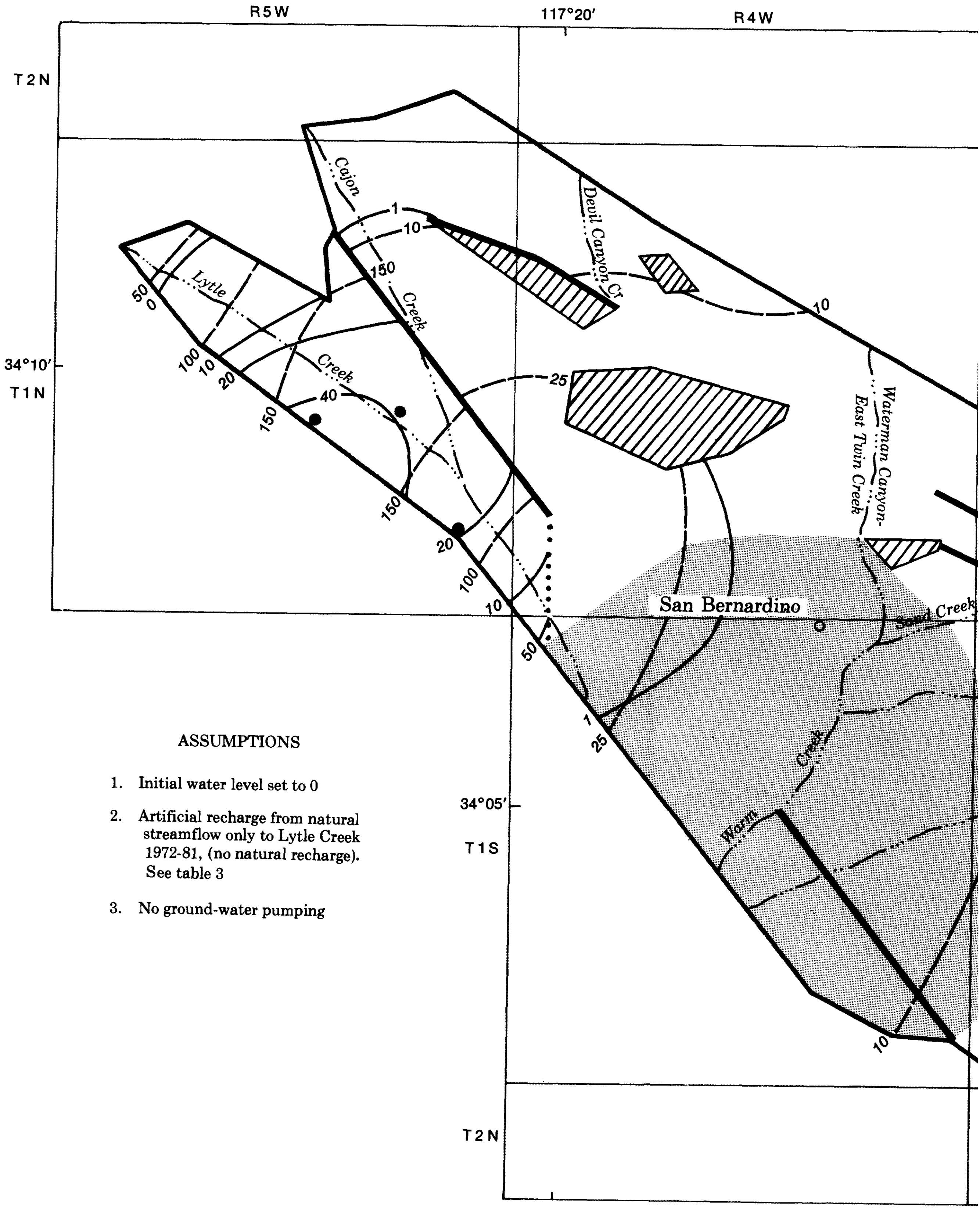


FIGURE 21. – Calculated water-level rises, with no valley pumping, due to artificial recharge in upper Lytle Creek (after 2 and 10 years).

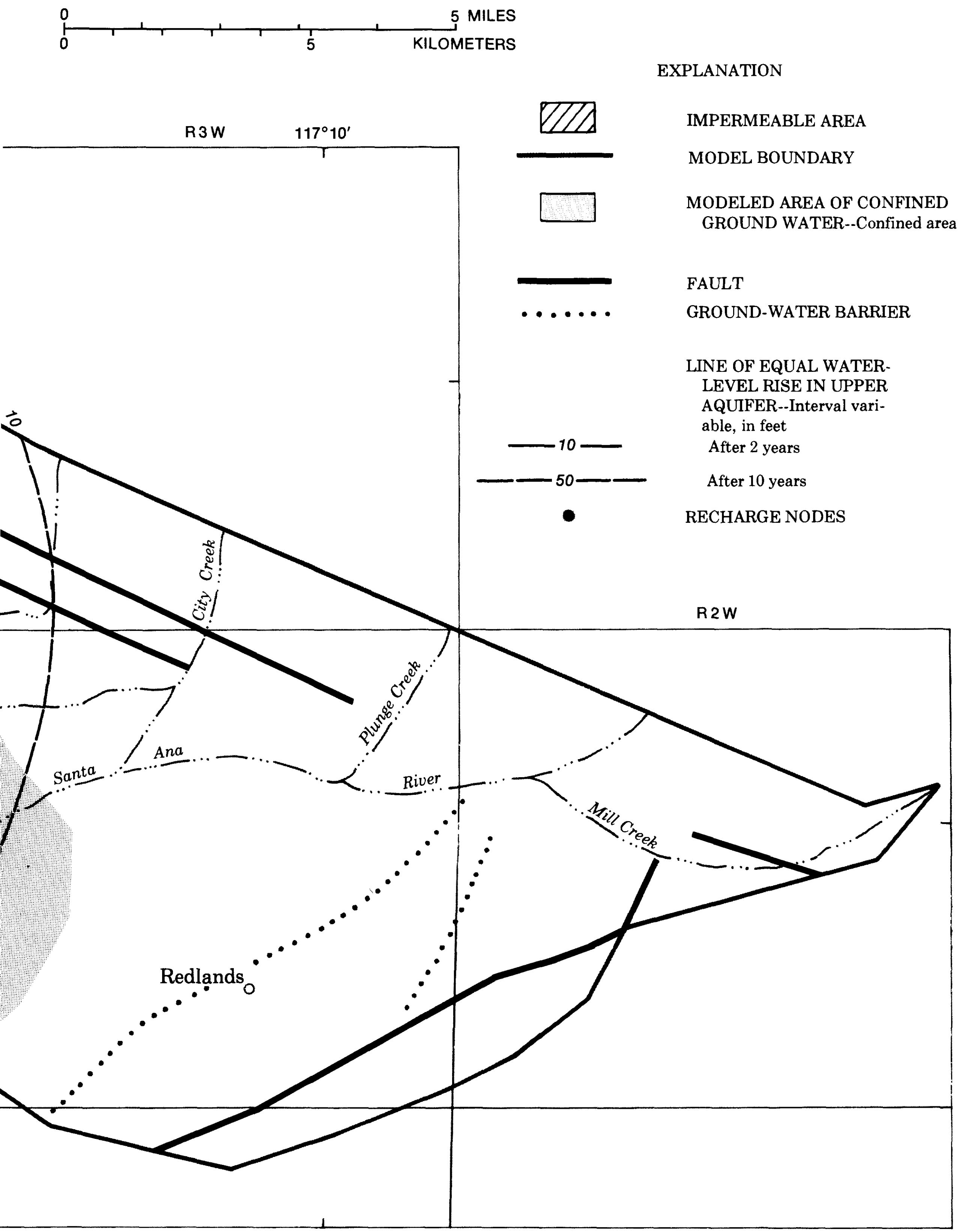


FIGURE 21. – Continued.

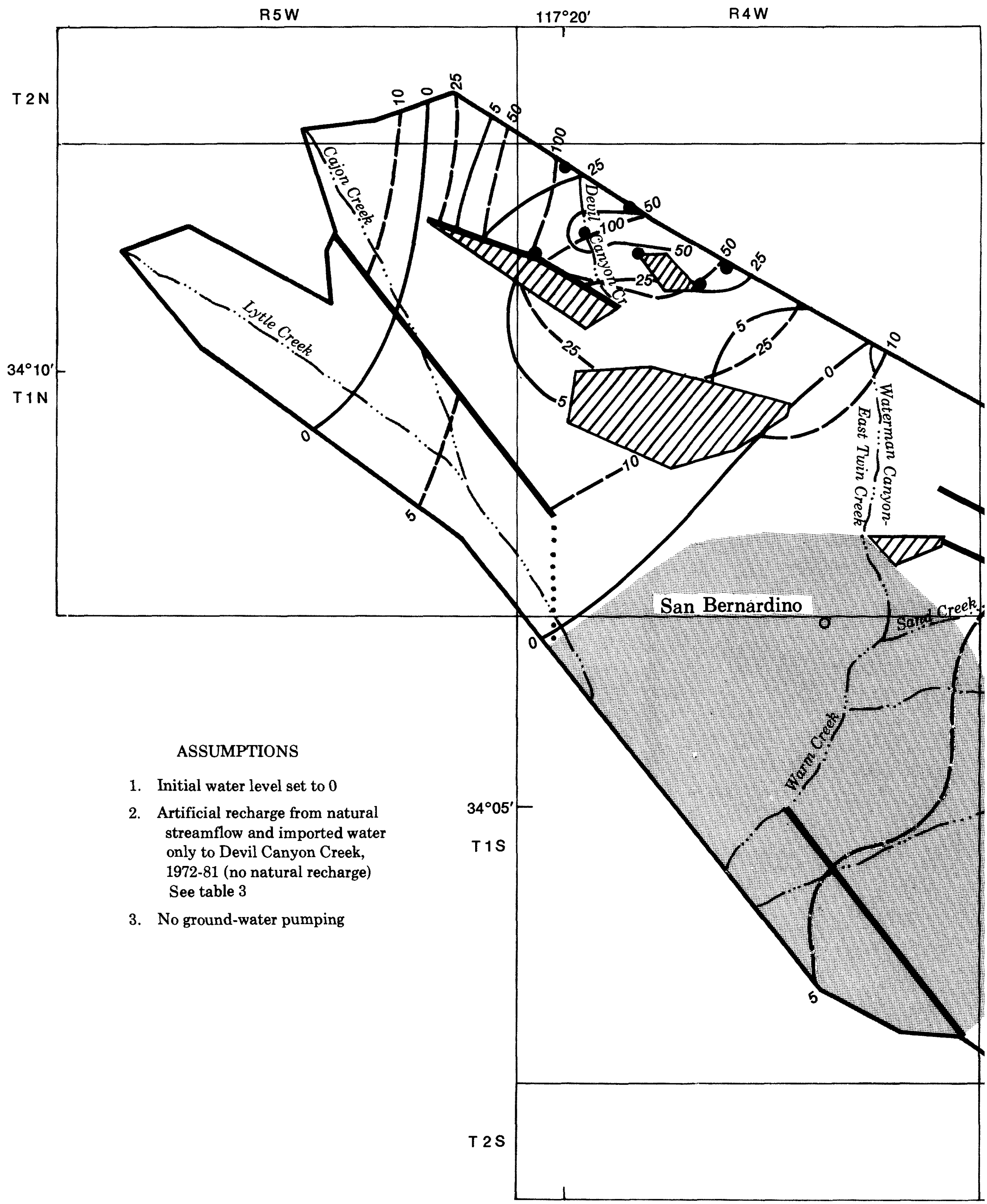


FIGURE 22. – Calculated water-level rises, with no valley pumping, due to artificial recharge in Devil Canyon Creek (after 2 and 10 years).

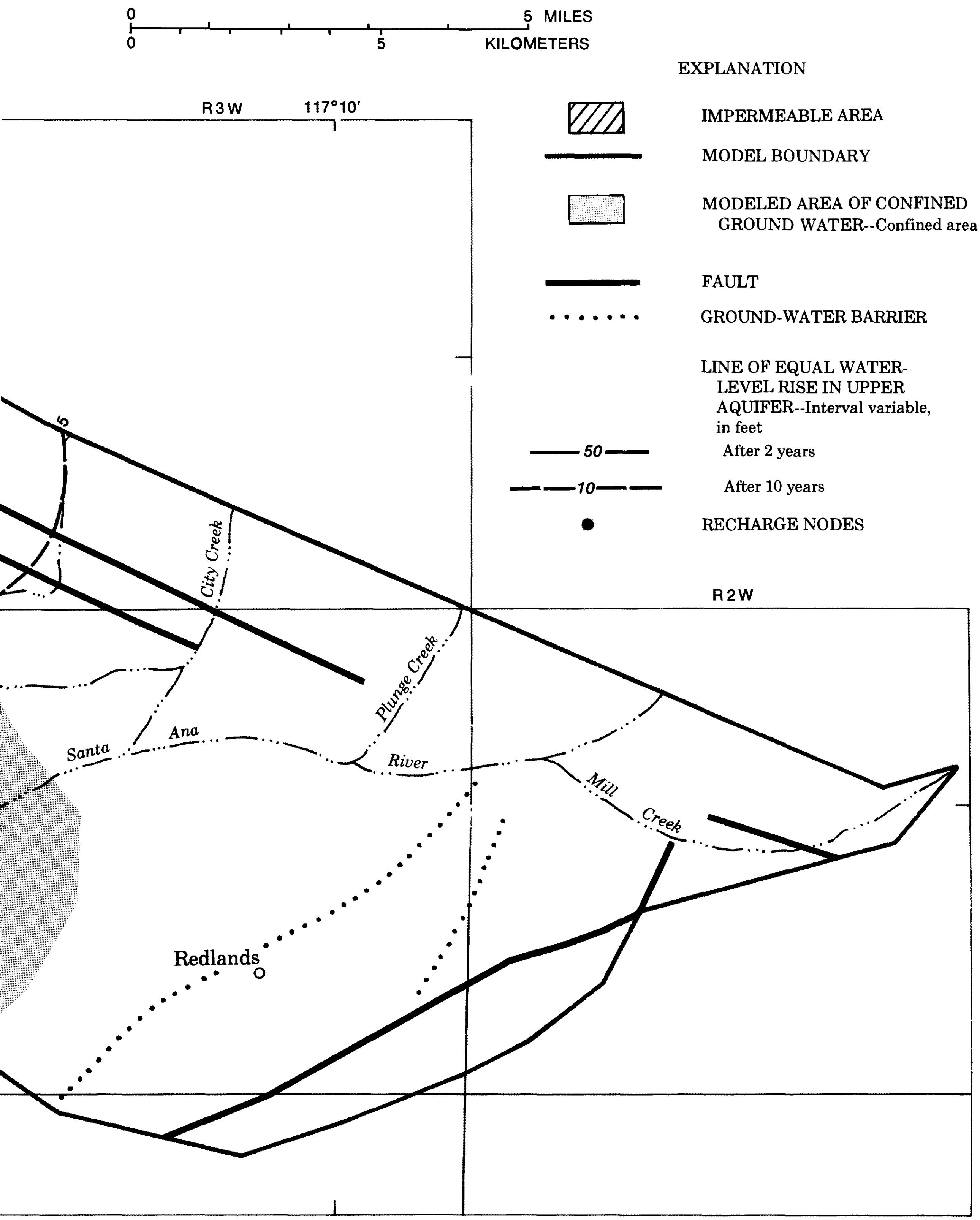


FIGURE 22. – Continued.

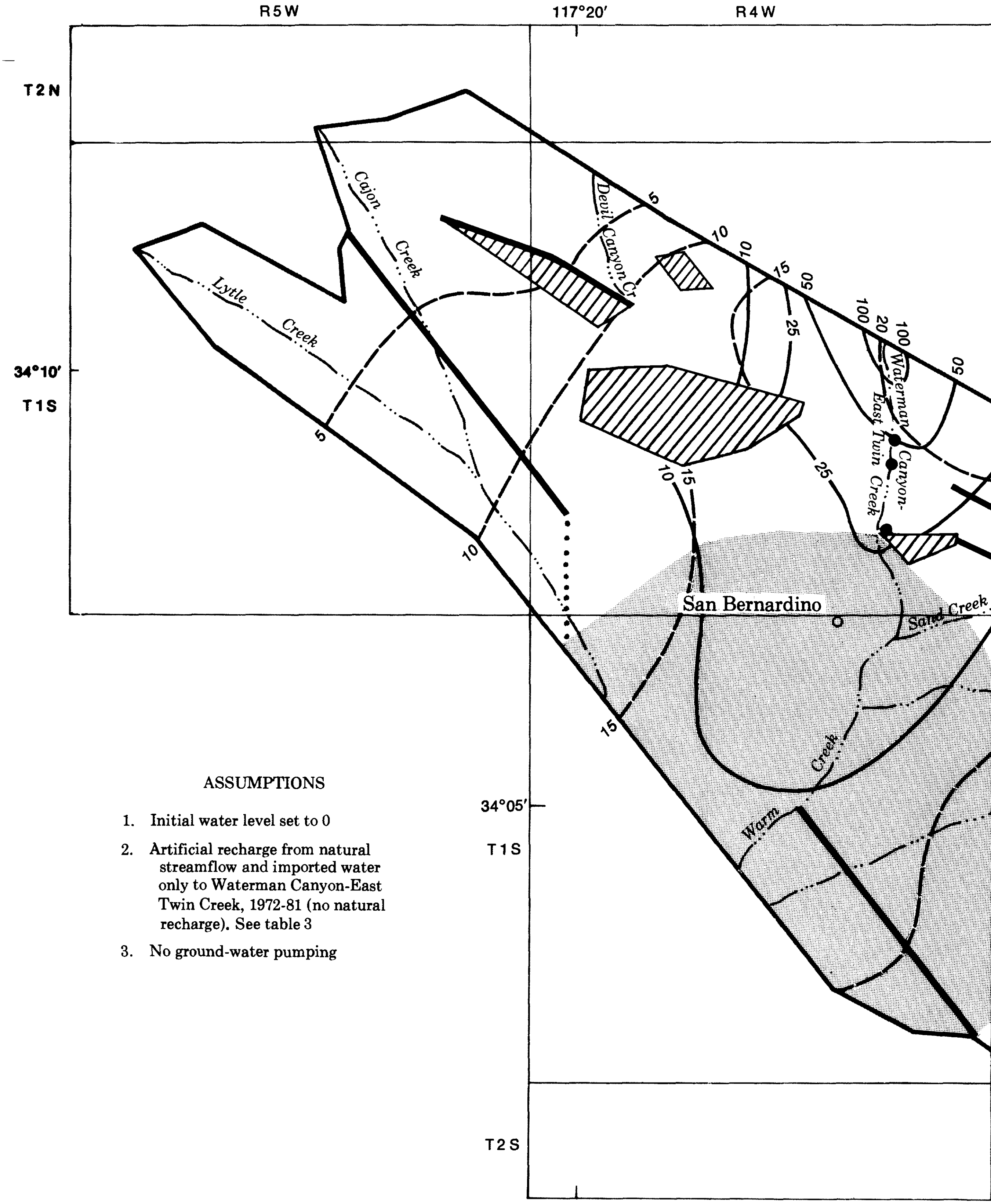


FIGURE 23. – Calculated water-level rises, with no valley pumping, due to artificial recharge in Waterman Canyon-East Twin Creek (after 2 and 10 years).

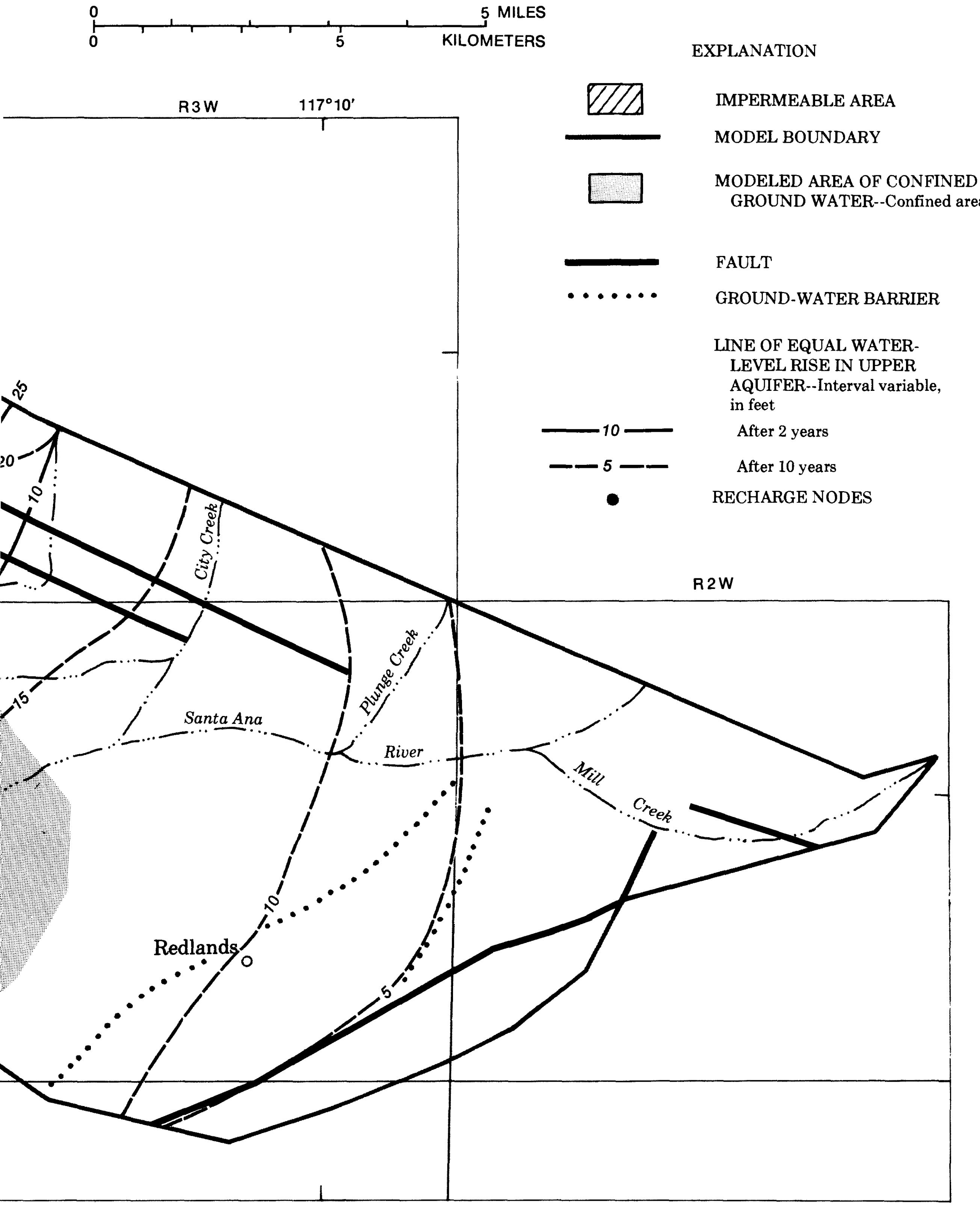
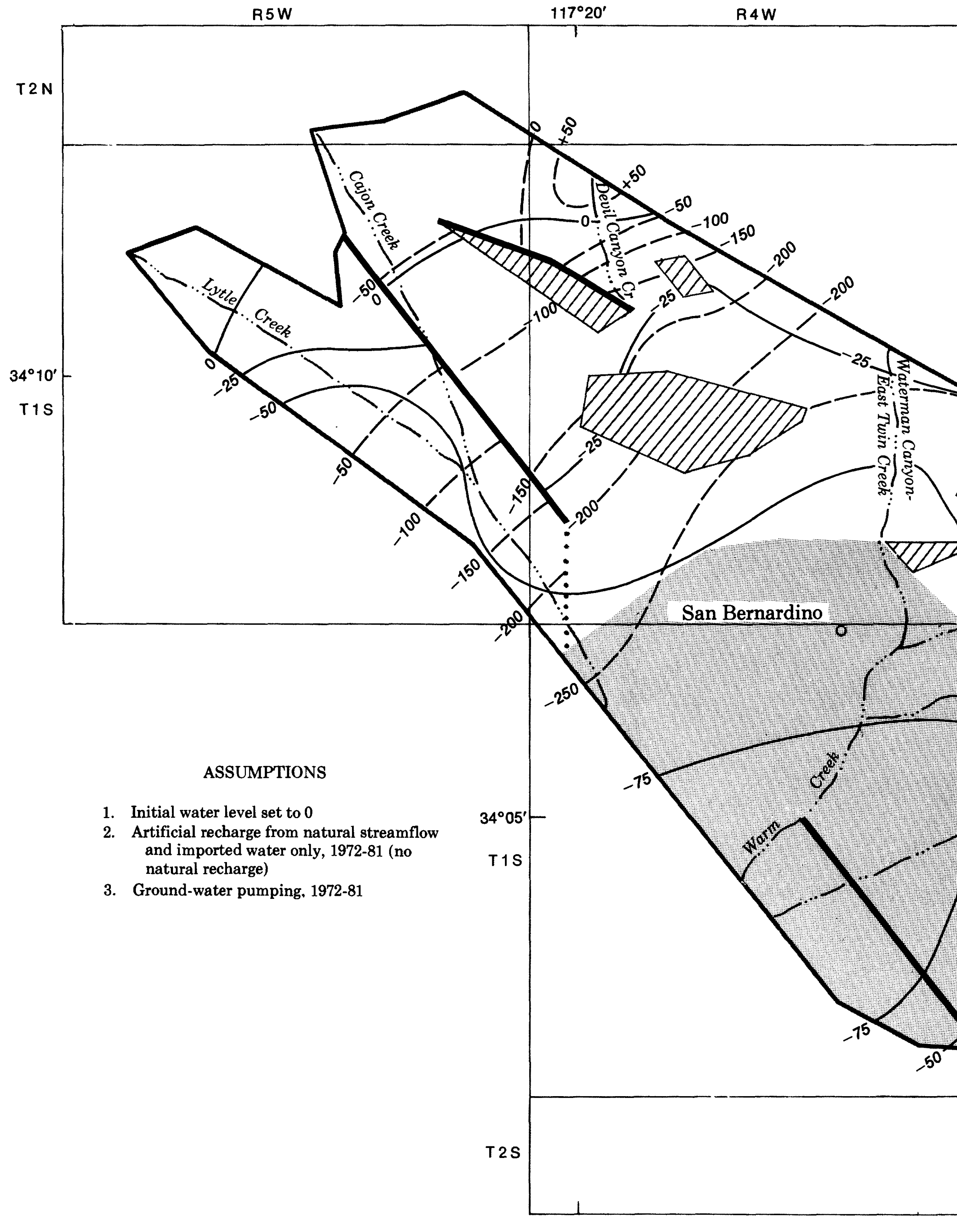


FIGURE 23. – Continued.



ASSUMPTIONS

1. Initial water level set to 0
2. Artificial recharge from natural streamflow and imported water only, 1972-81 (no natural recharge)
3. Ground-water pumping, 1972-81

FIGURE 24. – Calculated water-level changes, with valley pumping, due to artificial recharge in Santa Ana River, and Mill, Lytle, Devil Canyon, and Waterman Canyon-East Twin Creeks (after 1 and 10 years).

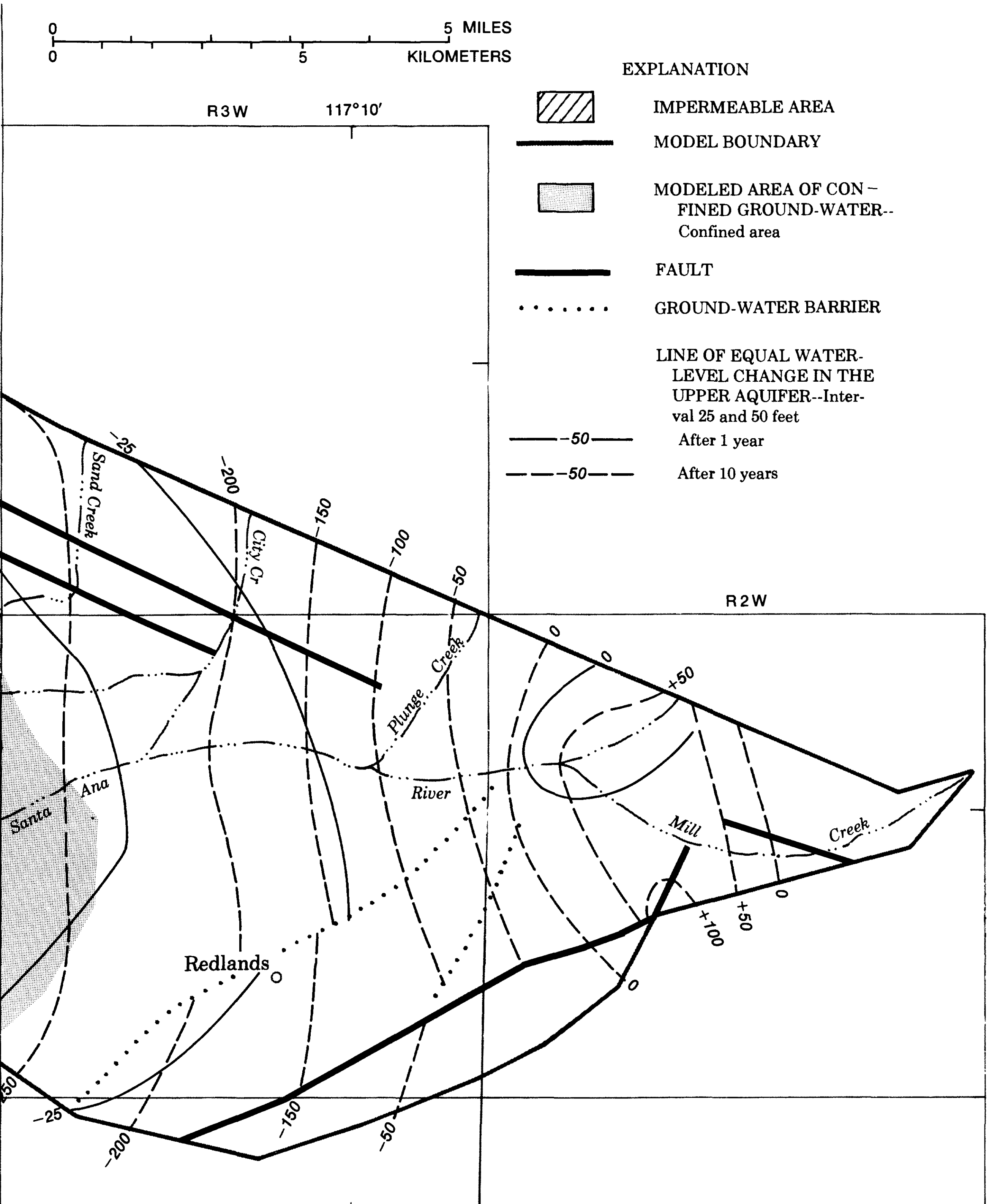


FIGURE 24. – Continued.

Artificial recharge during 1972-81 was about 505,000 acre-ft, or 32 percent of the total pumpage. Consequently, the map showing calculated water-level changes (fig. 24) shows a general net decline except in the water-spreading area of the upper Santa Ana River-Mill Creek and Devil Canyon Creek areas.

At the end of the first year, pumpage exceeded artificial recharge; consequently, calculated water levels declined about 75 feet in the central part of the confined area (fig. 24). Calculated water-level declines progressively decreased away from the confluence of Warm Creek and the Santa Ana River near the San Jacinto fault. The distribution of water-level declines is similar to that of the first-year model simulation of ground-water pumping with no recharge (see fig. 18), as the total artificial-recharge program the first year (1972) was only about 5,400 acre-ft. In the vicinity of the recharge sites at Devil Canyon Creek and the Santa Ana River, water levels did not change.

At the end of 10 years, the calculated water-level-change distribution is similar to that of the first-year simulation. In the central part of the valley from the San Jacinto fault to the Waterman Canyon-East Twin Creek area, the artificial-recharge program was not sufficient to counteract the pumping stresses, and calculated water levels declined about 250 feet (fig. 24); declines progressively decreased toward the sides of the valley. At the recharge ponds of Devil Canyon Creek, Mill Creek, and the Santa Ana River, calculated water levels rose 50 to 100 feet owing to the local artificial-recharge program.

SUMMARY AND CONCLUSIONS

Shallow aquifers in the San Bernardino Valley have experienced an 80-year cycle of declining and rising ground-water levels. Changes in climatic conditions, quantities and location of ground-water pumping, and artificial and natural recharge practices have contributed to these changes. Since 1980, water levels have been at or near land surface in the southern part of the valley adjacent to the San Jacinto fault. These high water levels are of concern to local officials because of potential damage to building foundations and roads.

To evaluate the effects of recharge and pumping on ground-water levels, an existing two-layer Galerkin finite-element digital model was updated and used to simulate water levels in the San Bernardino ground-water basin. According to model simulations, pumping in the confined area lowers water levels in both the confined area and the north-central part of the basin.

Conversely, recharge in the north-central part of the basin raises water levels in the confined area. The Santa Ana River and Lytle Creek contribute the most recharge to the basin; however, recharge in Waterman Canyon-East Twin Creek raises water levels in the confined area more per unit volume of recharge.

Increased pumping from the confined area was simulated separately from other pumping and recharge conditions in the basin to determine the separate effects of that pumping on basin water levels. For a projected pumping rate of 5,000 acre-ft/yr for 3 years, the model simulation indicates a water-level decline of 7 to 15 feet in the confined area. For a projected pumping rate of 25,000 acre-ft/yr for 3 years, the simulation indicates water-level declines of 40 to 80 feet in the confined area, 10 feet in the upper parts of the Lytle Creek and Santa Ana River areas, and 20 to 30 feet in the Waterman Canyon-East Tower and City Creeks areas. Thus, pumping in the confined area affects water levels in both the confined area and the north-central part of the ground-water basin.

Artificial recharge from the major streams in the basin also was simulated separately to determine the separate effects of each stream system on water levels in the confined area. Model simulations indicated that Waterman Canyon-East Twin Creek had the most effect on the confined area, followed in order by Lytle Creek, Santa Ana River, and Devil Canyon Creek. The quantity of recharge from streams needed to produce a 1-foot rise in water levels after 10 years near the center of the confined area at the node on Warm Creek (see fig. 14) was calculated for the various major streams. The quantity of recharge required was 3,400 acre-ft/yr from Waterman Canyon-East Twin Creek; 7,500 acre-ft/yr from Lytle Creek; 7,700 acre-ft/yr from the Santa Ana River; and 11,600 acre-ft/yr from Devil Canyon Creek. Artificial recharge simulated at Mill Creek did not have an effect on calculated water levels in the confined area at the end of the 10-year period. Accordingly, recharge in the north-central part of the ground-water basin has the greatest effect on water levels in the confined area.

Model simulations of historical extremes (1945-74) in recharge and pumping rates were superimposed on the January 1982 water levels (fig. 17). Water-level declines ranged from negligible to more than 80 feet in the lower altitudes of the confined area, depending on the recharge and pumping rates. With the high recharge rate, calculated evapotranspiration losses were high because water levels quickly rose to within 10 feet of the land surface in many parts of the valley. This was particularly true in the water-spreading areas because the 1982 water-level base was already at a high level and, therefore, additional storage was not available. The lowest recharge-highest pumping-rate model simulation yielded the greatest water-level declines, and the highest recharge-lowest pumping-rate model simulation yielded the greatest water-level rises.

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