GEOHYDROLOGY AND GROUND-WATER-FLOW SIMULATION OF THE SURPRISE SPRING BASIN AQUIFER SYSTEM, SAN BERNARDINO COUNTY, CALIFORNIA

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 89-4099

Prepared in cooperation with the
U.S. MARINE CORPS, DEPARTMENT OF THE NAVY

GEOHYDROLOGY AND GROUND-WATER-FLOW SIMULATION OF THE SURPRISE SPRING BASIN AQUIFER SYSTEM, SAN BERNARDINO COUNTY, CALIFORNIA

By Clark J. Londquist *and* Peter Martin

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 89-4099

Prepared in cooperation with the

U.S. MARINE CORPS, DEPARTMENT OF THE NAVY

Sacramento, California
1991

U.S. DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, JR., *Secretary*

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, *Director*

For sale by the Books and
Open-File Reports Section,
U.S. Geological Survey
Federal Center, Box 25425
Denver, CO 80225

For additional information write to:
District Chief
U.S. Geological Survey
Federal Building, Room W-2234
2800 Cottage Way
Sacramento, CA 95825

CONTENTS

FIGURES

TABLES

Conversion Factors

For readers who prefer to use the International System of Units (SI) rather than inch-pound units, the conversion factors for terms used in this report are listed below.

Multiply	By	To obtain
acre	0.004047	square kilometer
acre-foot (acre-ft)	0.001233	cubic hectometer
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per year
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot per day per foot [(ft/d)/ft]	1.0000	meter per day per meter
foot per second (ft/s)	0.3048	meter per second
foot per year (ft/yr)	0.3048	meter per year
foot squared per day (ft^2/d)	0.0929	meter squared per day
gallon per minute per foot [(gal/min)/ft]	0.06308	meter squared per minute
gallon per day (gal/d)	0.003785	cubic meter per day
inch (in.)	25.4	millimeter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer

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

$$°F = 1.8(°C)+32.$$

Abbreviations:

mg/L   milligram per liter

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 Sea Level Datum of 1929.

GEOHYDROLOGY AND GROUND-WATER-FLOW SIMULATION OF THE SURPRISE SPRING BASIN AQUIFER SYSTEM, SAN BERNARDINO COUNTY, CALIFORNIA

By Clark J. Londquist *and* Peter Martin

Abstract

The Surprise Spring ground-water basin is presently (1989) the main source of potable water used by the U.S. Marine Corps Air Ground Combat Center at Twentynine Palms, California. The basin encompasses about 80 square miles in the southeastern part of the Mojave Desert in southern California. Continental deposits of Quaternary and Tertiary age fill the basin to a maximum depth of 2,000 feet. The ground-water system in the basin consists of two interconnected aquifers: the upper and lower units of the continental deposits of late Tertiary age. The upper unit consists predominantly of unconsolidated sand of moderately high permeability. The lower unit consists of consolidated to partly consolidated poorly sorted sand, silt, and clay of low permeability. The area has extensive faults. Many of these faults act as partial barriers to ground-water movement. Faults form most boundaries of the basin and divide the basin into three main zones.

Recharge to the basin occurs solely as ground-water inflow across the western boundary of the basin. From the western boundary, ground water moves east and southeastward toward Surprise Spring in the southeastern part of the basin. Before ground-water development, ground water was discharged from the basin as transpiration by mesquite trees near Surprise Spring, as spring discharge, and as ground-water outflow across Surprise Spring fault near Surprise Spring. Soon after pumping began in 1953, the spring stopped flowing; by 1985, almost all the mesquite trees had died.

From 1953 through 1985, the military pumped from as many as eight supply wells in the basin. During this period, approximately 66,500 acre-feet of ground water was pumped out of the basin. All pumpage was from the upper unit of the continental deposits of late Tertiary age. Ground-water pumping has caused ground-water levels to decline by as much as 100 feet near Surprise Spring where most pumpage occurred. In areas far removed from the supply wells, water-level declines have been minimal.

A three-dimensional finite-difference model was developed and calibrated to simulate steady-state and transient-state ground-water conditions in the Surprise Spring ground-water basin. The model was used as a tool to develop a better understanding of the aquifer system and to determine the long-term availability of ground water by evaluating and projecting ground-water conditions resulting from historic and proposed pumping in the basin. The model satisfactorily reproduced the observed ground-water conditions in the basin from 1953 through 1985. Model results indicate that by 1985 about 97 percent of the water pumped from the basin was withdrawn from storage and the remainder was from natural discharge.

Two simulations of future hydraulic-head declines resulting from a projected total ground-water pumpage of about 257,500 acre-feet from 1985 through the year 2035 were made using the model. If all the projected pumpage is from the six supply wells operating in 1985, the maximum simulated hydraulic-head decline from 1985 to 2035 would be 154 feet near Surprise Spring. If, however, the projected increase in pumpage is from three proposed wells, located north and west of the present well field, the maximum simulated hydraulic-head decline during the same 50-year period would be about 80 feet near the new wells and only 55 feet in the area of Surprise Spring. These projected declines are in addition to the measured water-level declines that already had occurred in the basin from predevelopment conditions through 1985.

INTRODUCTION

This study is one of a series by the U.S. Geological Survey in cooperation with the U.S. Marine Corps to evaluate the geohydrologic conditions at the Twentynine Palms Marine Corps Base. The Marine Corps Base presently (1989) obtains all its potable water supply from wells in the Surprise Spring ground-water basin. Between 1953 and 1986, ground-water pumpage from the basin for use at the base caused ground-water levels to decline by as much as 100 feet near Surprise Spring where most pumping occurred. Future water demands associated with planned expansion of the Marine Corps Base will probably cause a further decline of water levels. To plan for the anticipated expansion of the base, there is a need to develop methods to evaluate and project ground-water conditions resulting from present and planned pumping in the Surprise Spring ground-water basin.

PURPOSE AND SCOPE

In 1982, the U.S. Marine Corps requested the U.S. Geological Survey to determine the long-term availability of ground water at the Marine Corps Base with special emphasis on the Surprise Spring ground-water basin as part of a two-phase study. The first phase, completed in 1985, involved completing a detailed gravity survey to estimate the thickness of the sedimentary deposits in the Surprise Spring, Deadman, and Mesquite basins (Moyle, 1984). In addition, ground-water levels were measured, and ground-water quality data were collected in the Surprise Spring and Deadman basins (Akers, 1986). Previous estimates were refined for available ground water in storage in the Surprise Spring and Deadman basins (Akers, 1986), and a preliminary assessment of the feasibility of artificially recharging the Surprise Spring ground-water basin (Akers, 1986) was made.

The second phase of the study, described in this report, used the geohydrologic information collected during phase 1 of the study to develop and calibrate a digital ground-water-flow model of the Surprise Spring ground-water basin. The model will help refine the understanding of the geohydrology of the basin and can be used to help determine the long-term availability of ground water in the basins by evaluating the changing ground-water conditions resulting from historic and proposed pumping in the basin.

During the initial development of the digital model, it became apparent that additional geohydrologic data were needed to describe the Surprise Spring ground-water basin. Additional geohydrologic information collected during this phase of the study included (1) defining sources of recharge and discharge, rates and direction of ground-water flow, and variations of aquifer properties and hydraulic head[1] using data collected from new monitoring wells; (2) determining sources of recharge and direction of ground-water movement within and between basins by collecting and analyzing ground-water-quality data; and (3) delineating geologic barriers that might influence the occurrence, source, or adequacy of the ground-water supply from a geophysical survey. The results of this additional data collection are summarized briefly in this report.

LOCATION AND DESCRIPTION OF STUDY AREA

The Twentynine Palms basin, in the southeastern part of the Mojave Desert about 130 miles east of Los Angeles (fig. 1), is a broad, eastward-sloping alluvial plain completely surrounded by mountains or upland areas. The basin, which includes Surprise Spring ground-water basin, ranges in altitude from about 3,600 feet above sea level at the base of the San Bernardino Mountains on the west to about 1,800 feet above sea level at Deadman Lake on the east. This area was named the Twentynine Palms basin by previous investigators.

The Twentynine Palms basin is divided into at least six identifiable ground-water basins by several northwest-trending faults and an anticlinal structure known as the transverse arch which are partial barriers to ground-water flow (fig. 1). These basins are referred to in this report, from west to east, as the Pipes, Reche, Giant Rock, Surprise Spring, Deadman, and Mesquite basins. The principal area of concern for this study is the Surprise Spring ground-water basin which encompasses about 80 mi^2.

[1]Hydraulic head is the height above a standard datum of the surface of a column of water that can be supported by the static pressure at a given point. Hydraulic head is the sum of the elevation head and the pressure head.

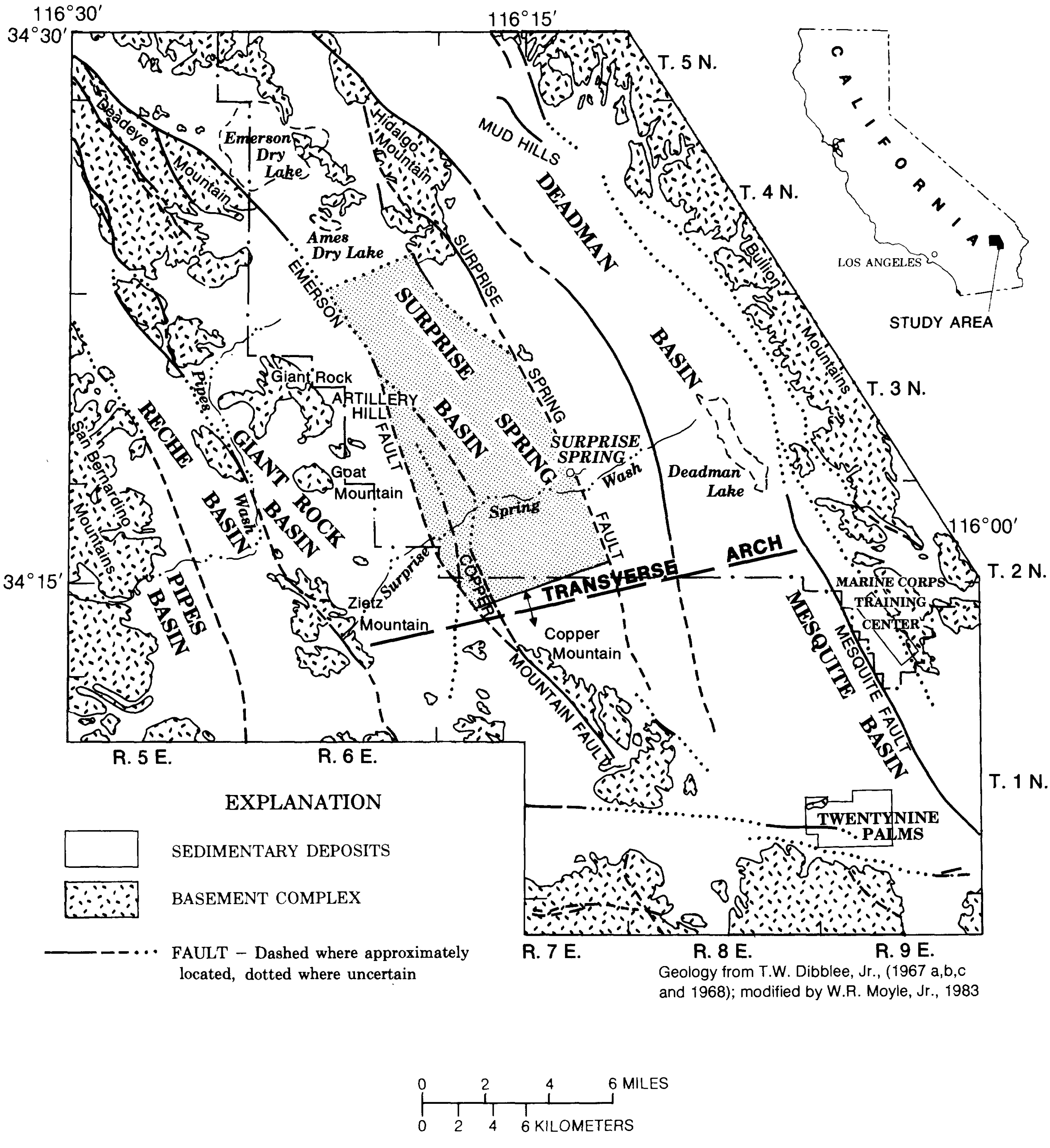


Figure 1. Location of study area and ground-water basins.

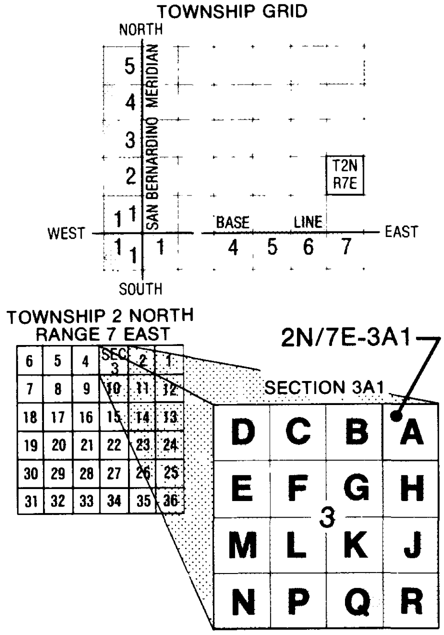
The Surprise Spring ground-water basin is bordered on the west by the Emerson fault and on the east by the Surprise Spring fault. The northern and southern boundaries are not as well defined; however, the northern extent of the basin is probably an unnamed fault south of Ames Dry Lake, and the southern boundary lies north of the transverse arch (fig. 2).

The climate in the study area is characterized by hot arid summers and cool winters. Average annual precipitation ranges from 4 to 6 inches (F.S. Riley and G.F. Worts, Jr., U.S. Geological Survey, written commun., 1953), with most falling during the winter months.

Most of the Surprise Spring ground-water basin lies within the Marine Corps Base. This area is rural and virtually undeveloped and is used principally for military training.

WELL-NUMBERING SYSTEM

Wells are numbered by the State of California according to their location in the township and range system for subdivision of public land. As an example, the well number 2N/7E-3A1 indicates that the well is located in township (T. 2 N.) and range (R. 7 E.). The number that follows the hyphen indicates the section (sec. 3), and the letter indicates the 40-acre subdivision of the section within which the well falls. The final digit is a sequence number for wells contained in the 40-acre subdivision. A graphic representation of the well-numbering system follows.



The U.S. Marine Corps has its own system for numbering supply wells and test wells. A cross reference of State and U.S. Marine Corps well numbers is shown in table 1.

Table 1. Cross index of State and U.S. Marine Corps well numbers for the Surprise Spring ground-water basin and vicinity

State well No.	U.S. Marine Corps	State well No.	U.S. Marine Corps	State well No.	U.S. Marine Corps	State well No.	U.S. Marine Corps
2N/6E-11M1	GR 1	2N/7E-26B1	--	3N/7E-18D1	TW-6	3N/7E-34D1	TW 75-1
2N/6E-12H1	WOW14	2N/8E-7K1	LZ SANDHILL	3N/7E-19N1	AH 2	3N/7E-35P2	SW-4A
2N/6E-24C1	--	3N/6E-2J1	EL 2	3N/7E-20C1	TW-75-2	3N/7E-36G1	TW 67-2
2N/7E-2C1	TW-5	3N/6E-3N1	WOW 29	3N/7E-20M1	AH 1	3N/7E-36K1	TW 67-1
2N/7E-2D1	SW-5A	3N/6E-4L1	WOW 8	3N/7E-27H1	HOLE 3	4N/6E-27C2	WOW 4
2N/7E-3A1	SW-3A	3N/6E-4L2	WOW 9	3N/7E-28D1	HOLE 1	4N/6E-27D1	WOW 4A
2N/7E-3B1	SW-2A	3N/6E-4P1	WOW 7	3N/7E-28R1	SW-7A	4N/6E-27F1	WOW 5
2N/7E-3E1	SW-6A	3N/6E-4P2	TW TP-1	3N/7E-29G1	TW-75-3	4N/6E-28M1	WOW 2
2N/7E-4H1	TW-12	3N/6E-16A1	EL-1	3N/7E-29R1	SW-9A	4N/6E-28R1	WOW 3
2N/7E-5B1	VSTOL	3N/6E-27B1	AH 3	3N/7E-31E1	TW 9	4N/6E-32B1	TW TP-2
2N/7E-14K1	TW-11	3N/6E-35N1	WOW 19	3N/7E-32D1	HOLE 2	4N/6E-34E1	WOW 6
2N/7E-19A1	--	3N/6E-13N1	TW-10	3N/7E-32J1	SW-8A		

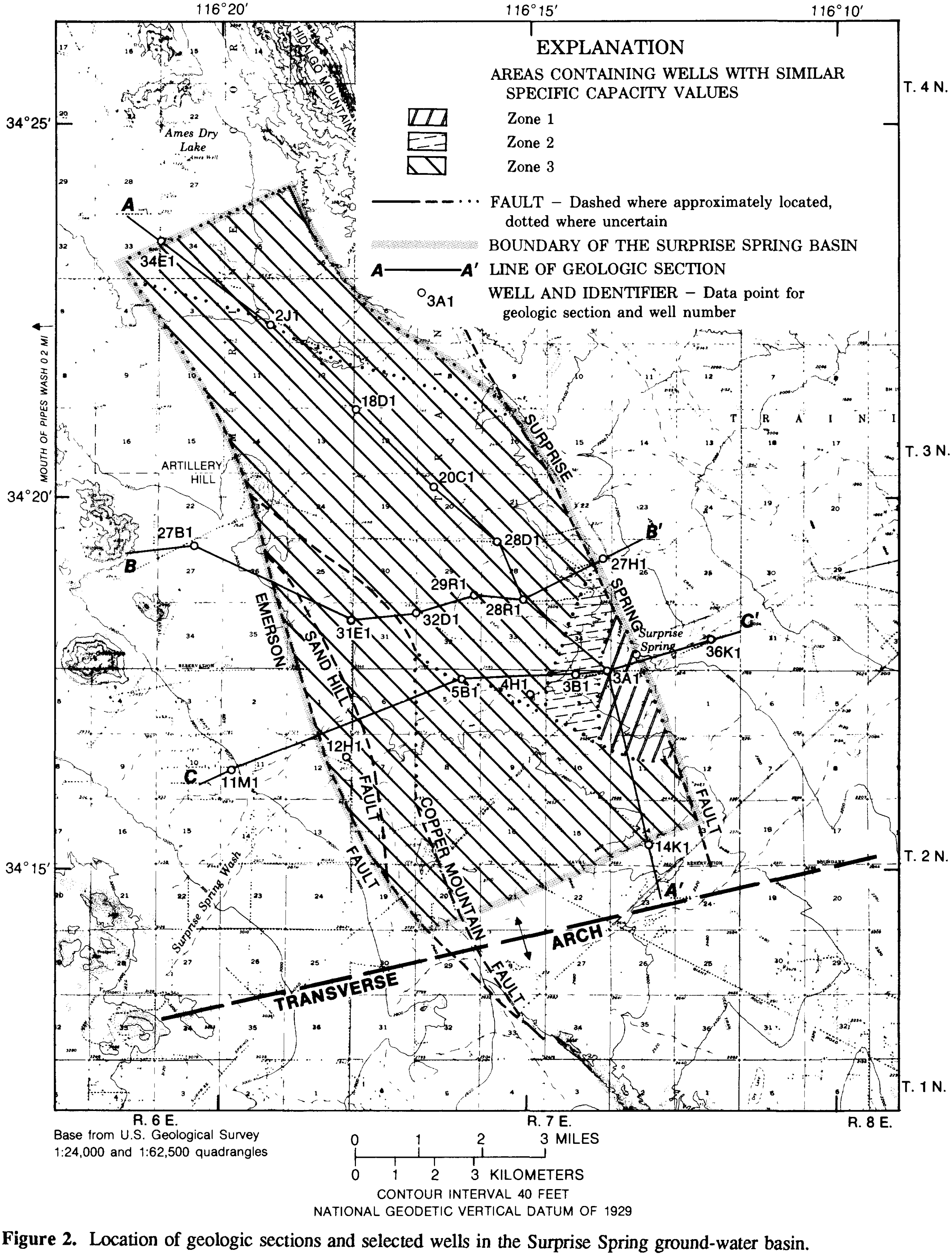


Figure 2. Location of geologic sections and selected wells in the Surprise Spring ground-water basin.

GEOHYDROLOGY

An understanding of the geohydrology of the Surprise Spring ground-water basin was necessary before an accurate digital model of the basin could be developed. This involved describing the geology and boundaries of the aquifer system, defining the aquifer properties, determining the recharge to and from the aquifer system, and the effect of ground-water development on the ground-water system. The geohydrology of the Surprise Spring and surrounding ground-water basins is discussed in reports by Schaefer (1978), Moyle (1984), and Akers (1986). Only a brief summary of the geohydrology of Surprise Spring ground-water basin is included here. A more complete description of the surrounding basins is contained in these earlier reports.

GEOLOGIC DESCRIPTION OF AQUIFER SYSTEM

Continental deposits of Quaternary and Tertiary age fill the Surprise Spring ground-water basin to a maximum depth of 2,000 feet in the western part of the basin (Moyle, 1984). The deposits are unconsolidated at land surface and become more consolidated with depth. The unconsolidated deposits are the only water-bearing material from which appreciable ground water may be obtained. The continental deposits are underlain by a nearly impermeable complex of igneous and metamorphic rocks of pre-Tertiary age that forms the mountains that surround the area. These rocks do not contain water except in areas where they are jointed and fractured.

The Tertiary deposits were divided into an upper and lower unit (F.S. Riley and G.F. Worts, Jr., U.S. Geological Survey, written commun., 1953) from an outcrop in the Mud Hills, north of the Surprise Spring basin (fig. 1). In this exposure, the upper unit is about 1,000 feet thick and is composed of about 60 percent coarse sand that is free of interstitial clay and is probably moderately permeable. The remaining 40 percent of the material is fine grained, varying from very fine silty sand to clay with low permeability. The lower unit of the Tertiary deposits is almost 1,500 feet thick at the Mud Hills outcrop and differs from the upper unit by being poorly sorted, having poorly defined bedding, and containing numerous metamorphic and volcanic fragments and much interstitial clay (F.S. Riley and G. F. Worts, Jr., U.S. Geological Survey, written commun., 1953). The description of the lower unit indicates that its permeability is very low. These lithologic units were recognizable over distances as great as 5 miles in outcrops in the Mud Hills (F.S. Riley and G.F Worts, Jr., U.S. Geological Survey, written commun., 1953). The exposed stratigraphic section in the Mud Hills dips gently to the south; therefore, they postulated that the composition of these units probably persists for some distance beneath the basin floor south of the Mud Hills. For the purposes of this report, the upper and lower units of the Tertiary deposits were considered as two interconnected aquifers.

The Quaternary deposits that overlie the Tertiary deposits are between 50 and 150 feet thick. These deposits were formed primarily by the erosion of the pre-Tertiary igneous and metamorphic rocks but also contain some reworked Tertiary sediments. The Quaternary deposits are generally limited to alluvial fans along mountain fronts, stream-channel deposits in washes, alluvial plains on the basin floor, and playa deposits in the many dry lake beds in the area. These deposits vary from poorly sorted coarse material in the alluvial fans to fine sand, silt, and clay in the playa deposits. In general, the Quaternary deposits are above the water table and are not an important water-bearing unit.

Inspection of the lithologic and electric logs of wells in the Surprise Spring basin suggests that the deposits penetrated by these wells are similar to the upper unit of the Tertiary deposits (F.S. Riley and G.F. Worts, Jr., U.S. Geological Survey, written commun., 1953). Most of these wells are less than 600 feet deep, and they do not penetrate the lower unit of the Tertiary deposits. However, well 3N/6E-2J1 and the pilot holes for wells 2N/7E-3A1, 3N/7E-20C1, 3N/7E-28D1, and 3N/7E-32D1 in the Surprise Spring ground-water basin and wells 3N/7E-27H1 and 3N/7E-36K1 in the Deadman basin appear to have penetrated the lower unit based on the presence of predominantly fine-grained deposits in the lithologic logs and relatively low resistivities on the electric logs (fig. 3). For the saturated unconsolidated deposits in the area, a high resistivity on the electric log indicates coarse-grained water-bearing deposits that yield water freely to wells, whereas a low resistivity indicates either fine-grained deposits that do not yield water freely to wells or ground water of high salinity. Resistivity on the electric log is also high opposite the unsaturated deposits and saturated consolidated deposits in the area.

The lower unit of the Tertiary deposits contains water of higher salinity than the upper unit. During the drilling of well 3N/7E-32D1, the dissolved-solids concentration of the drilling mud increased from 210 mg/L at 500 feet below land surface (approximate contact between the upper and lower units) to 510 mg/L at the completion depth of 820 feet below land surface. Well 3N/6E-2J1, perforated solely in the lower unit of the Surprise Spring ground-water basin, contains ground water with a dissolved-solids concentration of 1,100 mg/L (fig. 4). Wells perforated solely in the upper unit of the basin generally yield water with dissolved-solids concentrations of less than 300 mg/L (fig. 4).

FAULTS AND GROUND-WATER BOUNDARIES

The Surprise Spring ground-water basin is dominated by extensive faulting that has displaced the pre-Tertiary igneous and metamorphic rocks that underlie the basin, the continental deposits of late Tertiary age, and locally the Quaternary alluvium. Many of the faults are partial barriers to ground-water movement. The barrier effect of the faults is believed to be caused primarily by the compaction and extreme deformation of the water-bearing deposits immediately adjacent to the faults (F.S. Riley and G.F. Worts, Jr., U.S. Geological Survey, written commun., 1953). Cementation of the fault zone by the deposition of minerals from ground water also is believed to be an important barrier effect (F.S. Riley and G.F. Worts, Jr., U.S. Geological Survey, written commun., 1953; Schaefer, 1978, p. 5).

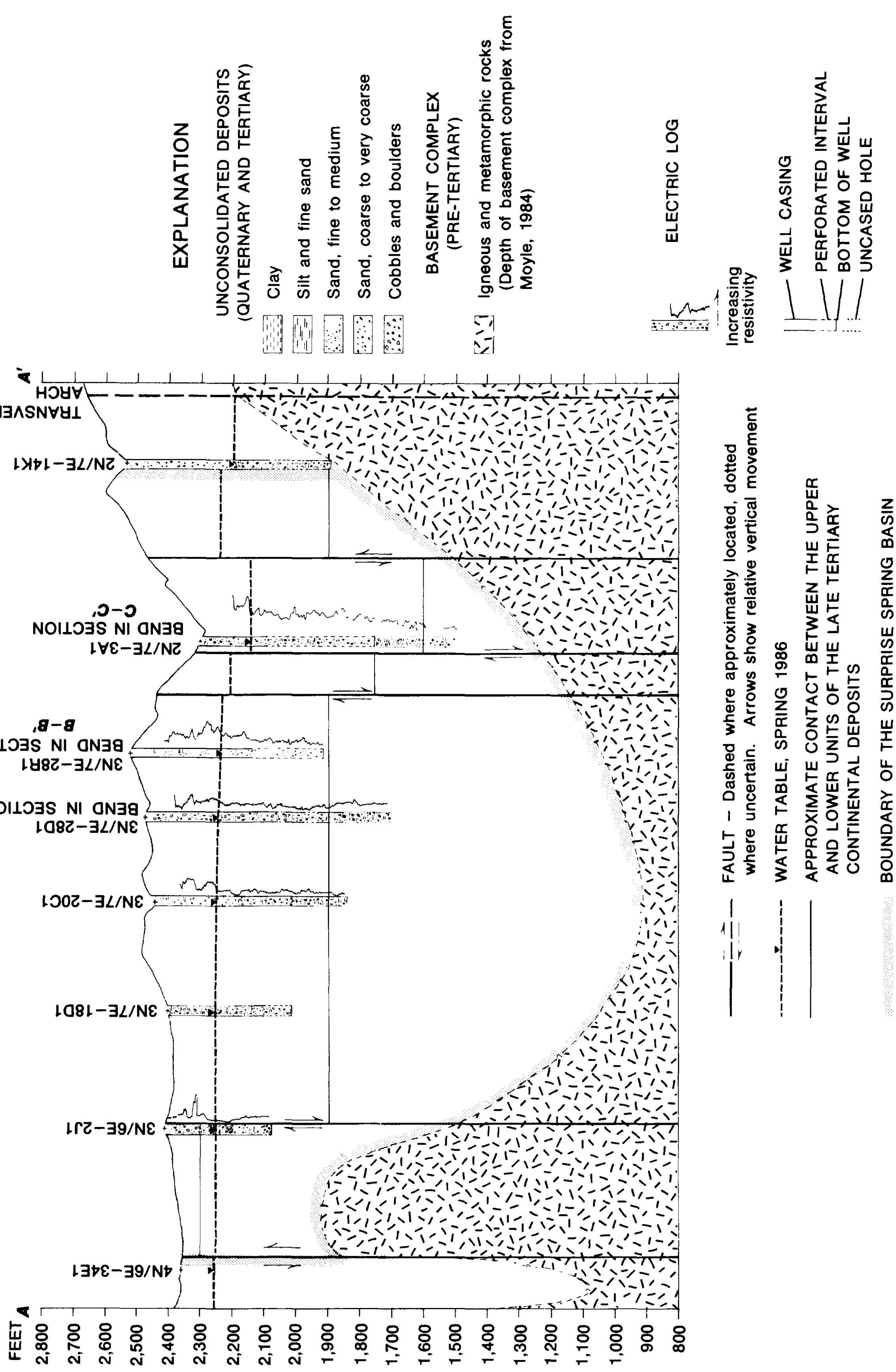
Water-level data from the Surprise Spring ground-water basin and surrounding area prior to ground-water development (fig. 5) indicate that the Emerson fault that forms the western boundary of the Surprise Spring ground-water basin and the Surprise Spring fault that forms the eastern boundary of the basin are partial barriers to ground-water movement. Water levels west of Emerson fault are about 60 feet higher than water levels east of the fault, and water levels east of the Surprise Spring fault are about 400 feet lower than water levels west of the fault in the Surprise Spring ground-water basin (fig. 5).

A northeastward-trending fault south of Ames Dry Lake is believed to be the northern boundary of the Surprise Spring ground-water basin. A gravity survey by Moyle (1984) indicated that the basement complex drops steeply away from land surface on the north side of this fault (fig. 3, sec. *A-A'*). In general, ground-water movement north of the fault is northward toward Emerson Lake, whereas ground-water movement south of the fault is toward the southeast (fig. 5).

The southern boundary of the basin is an indeterminate barrier north of well 2N/7E-14K1 (fig. 5), apparently associated with the transverse arch (F.S. Riley, U.S. Geological Survey, written commun., 1954). The transverse arch is a westward-trending anticline that forms a topographic high south of Surprise Spring ground-water basin (F.S. Riley and G.F. Worts, Jr., U.S. Geological Survey, written commun., 1953). A gravity survey completed by Moyle (1984) indicates that the basement complex is within 500 feet of land surface along the alignment of the arch south of the basin (fig. 3, sec. *A-A'*). The southern boundary of Surprise Spring ground-water basin was placed north of well 2N/7E-14K1 (fig. 5) because the water level in this well in 1953, prior to ground-water development, was almost 50 feet lower than any other water level in the basin. In addition, the water level in this well has shown little or no response to more than 30 years of ground-water development near Surprise Spring, which is less than 3 miles north of the well (figs. 5 and 6).

Within the Surprise Spring ground-water basin, several faults are partial barriers to ground-water movement. Two faults are located just west of Surprise Spring. One fault is between wells 2N/7E-3A1 and 2N/7E-3B1, and the other is between wells 2N/7E-3B1 and 2N/7E-4H1 (fig. 2). The location of these faults was inferred from abrupt water-level changes that developed across the faults as pumpage in the basin increased (F.S. Riley and G.F. Worts, Jr., U.S. Geological Survey, written commun., 1953, and F.S. Riley, U.S. Geological Survey, written commun., 1954). A seismic refraction profile completed for this study indicates that the faults extend at least as far south as Surprise Spring Road (D.H. Wilson, U.S. Geological Survey, written commun., 1986). Comparison of electric logs of wells on different sides of the faults indicates that there is a downward displacement of about 150 feet on the Surprise Spring side of both faults (fig. 3, section *C-C'*).

Another fault that forms a partial barrier to ground-water movement is located in the western part of the basin, between wells 3N/7E-31E1 and 3N/7E-32D1 (fig. 2) (F.S. Riley and G.F. Worts, Jr., U.S. Geological Survey, written commun., 1953). The barrier effect of this fault is shown by the altitude of the water table in well 3N/7E-31E1 just west of the fault,


FEET
2,800
2,700
2,600
2,500
2,400
2,300
2,200
2,100
2,000
1,900
1,800
1,700
1,600
1,500
1,400
1,300
1,200
1,100
1,000
900
800
A
A'
4N/6E-34E1
3N/6E-2J1
3N/7E-18D1
3N/7E-20C1
3N/7E-28D1
BEND IN SECTION
3N/7E-28R1
BEND IN SECTION
B-B'
2N/7E-3A1
BEND IN SECTION
C-C'
2N/7E-14K1
TRANSVERSE
ARCH
EXPLANATION
UNCONSOLIDATED DEPOSITS
(QUATERNARY AND TERTIARY)
Clay
Silt and fine sand
Sand, fine to medium
Sand, coarse to very coarse
Cobbles and boulders
BASEMENT COMPLEX
(PRE-TERTIARY)
Igneous and metamorphic rocks
(Depth of basement complex from
Moyle, 1984)
ELECTRIC LOG
Increasing
resistivity
WELL CASING
PERFORATED INTERVAL
BOTTOM OF WELL
UNCASED HOLE
FAULT -- Dashed where approximately located, dotted
where uncertain. Arrows show relative vertical movement
WATER TABLE, SPRING 1986
APPROXIMATE CONTACT BETWEEN THE UPPER
AND LOWER UNITS OF THE LATE TERTIARY
CONTINENTAL DEPOSITS
BOUNDARY OF THE SURPRISE SPRING BASIN

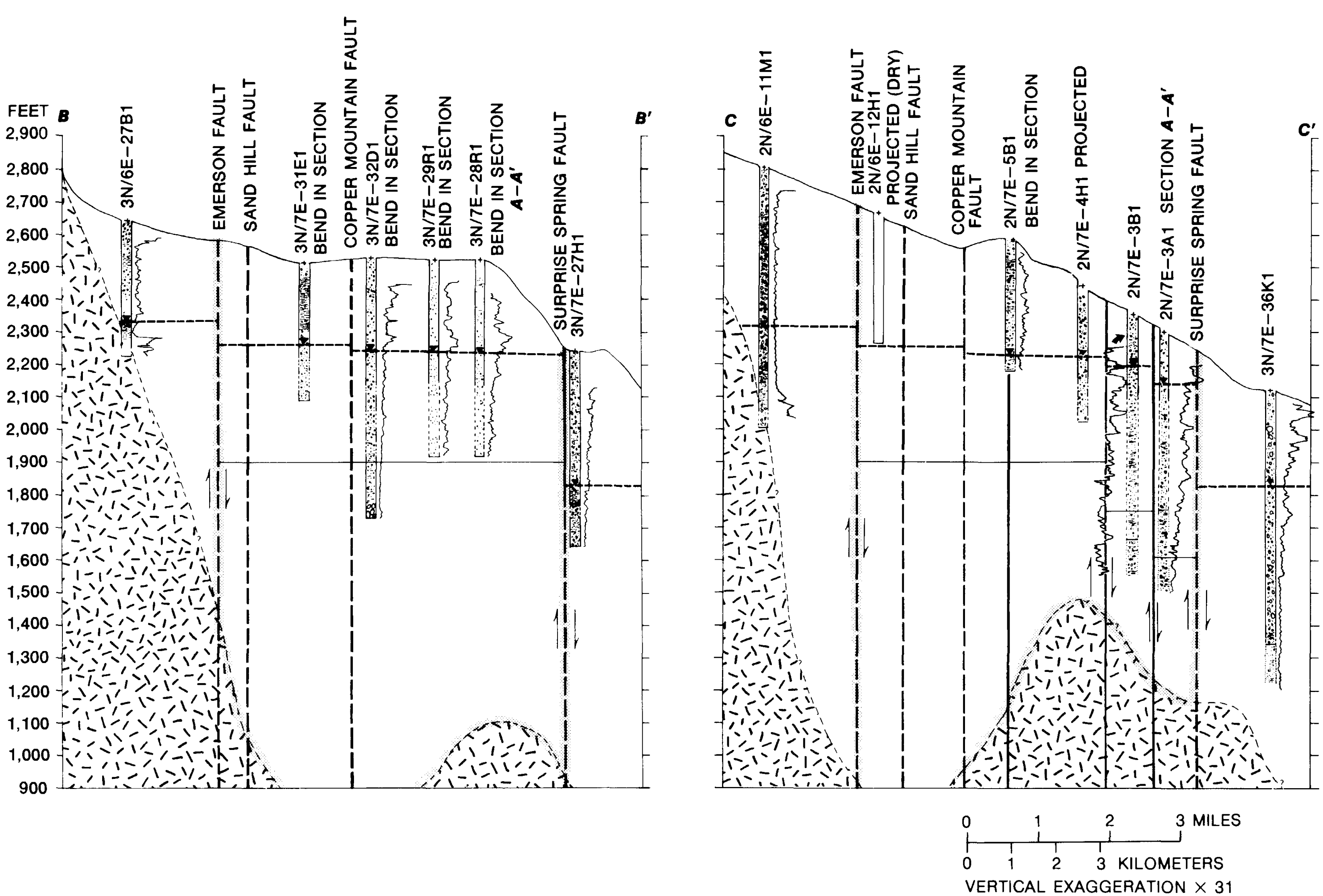


Figure 3. Geologic sections and electric well logs in the Surprise Spring ground-water basin.

which is about 20 feet higher than the altitude of the water table in well 3N/7E-32D1 just east of the fault in 1987 (fig. 6). Topographic features indicate that this fault extends from Artillery Hill southeastward to Surprise Spring fault.

The Sand Hill and Copper Mountain faults extend into the southwestern corner of the basin (fig. 2); however, no data are available to determine if these faults are barriers to ground-water movement. In the northern part of the basin, a fault is believed to extend from about 3 miles north of Artillery Hill southeastward to the Surprise Spring fault (fig. 2). There is no significant change in altitude of the water table across this fault (figs. 5 and 6); however, the ground-water quality is significantly different (fig. 4). The dissolved-solids concentration of water sampled from wells north of the fault is more than 500 mg/L higher than that sampled from wells south of the fault. The high dissolved-solids concentrations are believed to be indicative of ground water in the lower unit of the continental deposits of late Tertiary age. Lithologic and electric logs (fig. 3, sec. *A-A'*) indicate that the north side of the fault has been displaced upward relative to the south side and that the upper unit of the continental deposits of late Tertiary age is unsaturated.

Topographic evidence indicates that there may be several other faults within the basin, but to date (1989), there is no other evidence to confirm their presence.

AQUIFER PROPERTIES

Aquifer properties, including transmissivity, hydraulic conductivity, and storage coefficient, affect the rate at which water moves through the aquifer, the amount of water in storage, and the rate and areal extent of water-level declines caused by ground-water development. The values of the aquifer properties in the Surprise Spring ground-water basin vary considerably because of the heterogeneity of the material in the aquifer. The aquifer properties were estimated from well logs, specific capacity tests, and from data in previous reports.

TRANSMISSIVITY AND HYDRAULIC CONDUCTIVITY

Transmissivity is a measure of the ability of an aquifer to transmit water, and hydraulic conductivity is the capacity of a rock or unconsolidated material to transmit water. The transmissivity of an aquifer is equal to the hydraulic conductivity multiplied by the aquifer thickness.

For this study, the transmissivity and hydraulic conductivity of the upper unit of the continental deposits of late Tertiary age were estimated from specific capacity data because there were no long-term aquifer test results available. Specific capacity is the yield of a well per unit of drawdown; for example, gallon per minute per foot [(gal/min)/ft] of drawdown. The U.S. Geological Survey and Southern California Edison Co. have made many specific capacity tests on supply wells in the Surprise Spring ground-water basin (table 2). The data indicate a great range in specific capacity values in the basin; however, within a particular area, values are similar. For the purpose of this study, the basin was divided into three zones, each containing wells

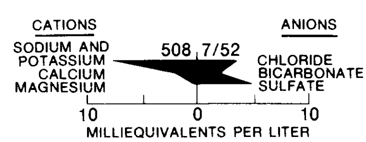
EXPLANATION FOR FIGURE 4

– – – · · FAULT – Dashed where approximately located, dotted where uncertain

BOUNDARY OF THE SURPRISE SPRING BASIN

o13N1 WELL NUMBER AND LOCATION

● 3A1 SUPPLY WELL NUMBER AND LOCATION



WATER-QUALITY DIAGRAM
Difference in configuration reflects differences in chemical character. The area of the diagram is an indication of dissolved-solids concentration. Upper left number above diagram is dissolved solids in milligrams per liter; upper right number is month and year of measurement. The larger the area of the diagram, the greater the dissolved-solids concentration

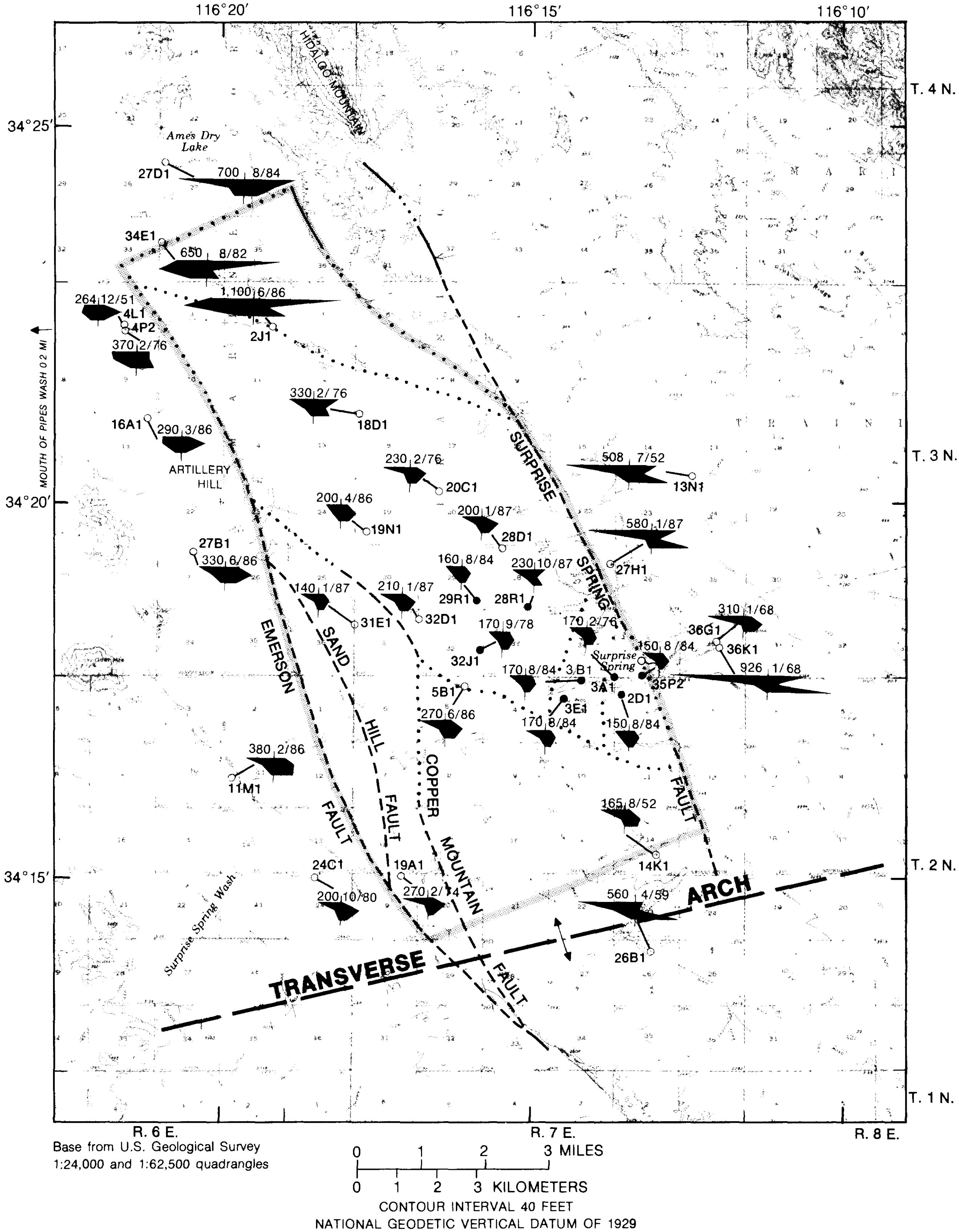


Figure 4. Ground-water quality in the Surprise Spring ground-water basin and surrounding area.

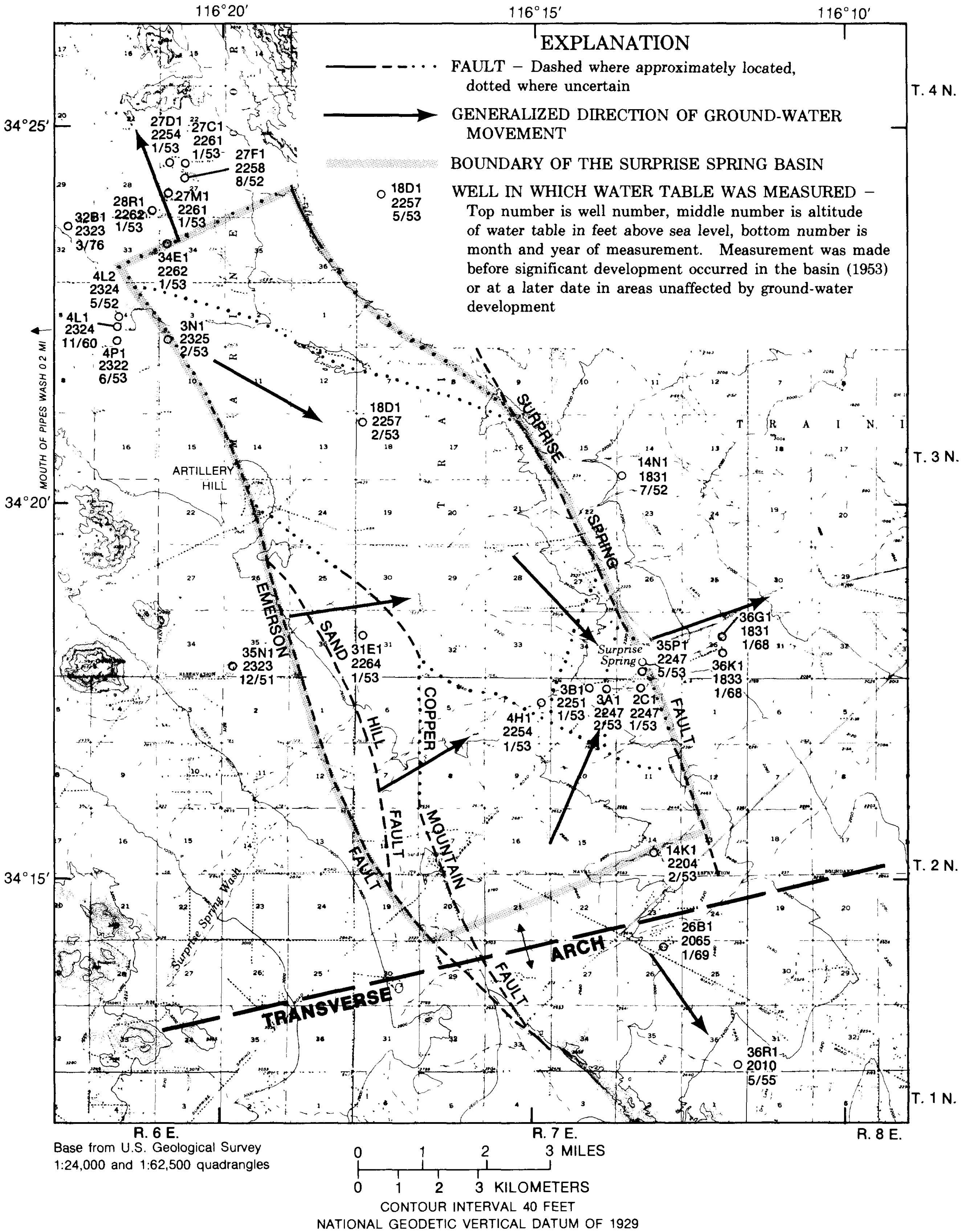


Figure 5. Altitude of the water table and generalized direction of ground-water movement based on water-level measurements prior to ground-water development, 1953.

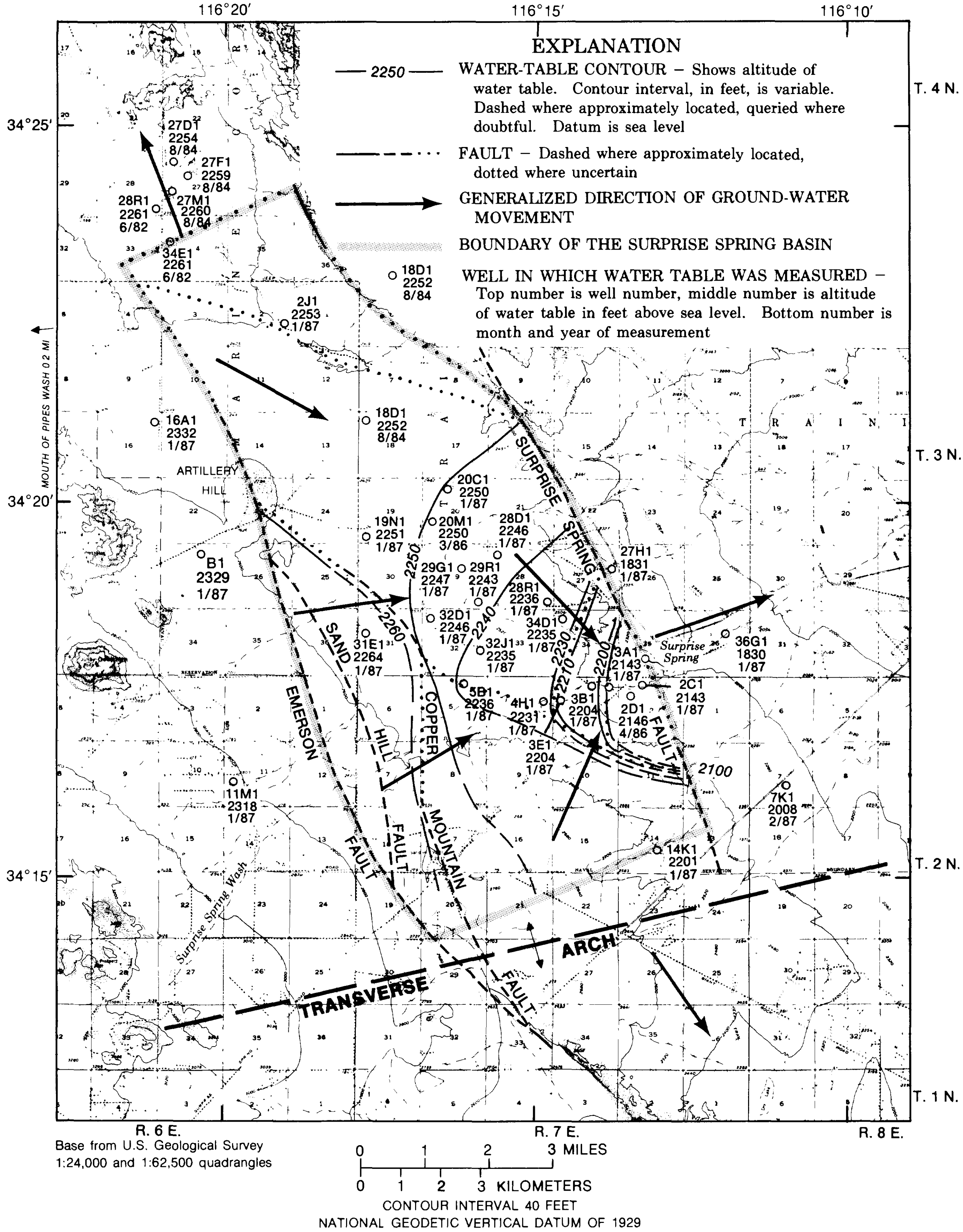


Figure 6. Altitude of the water table and generalized direction of ground-water movement based on water-level measurements, 1986-87.

Table 2. Specific capacity values for supply wells in Surprise Spring ground-water basin

[Source of data: USGS, U.S. Geological Survey; SCE, Southern California Edison Co.; Geological Survey data from Giessner and Robson (1966), Giessner (1965), and U.S. Geological Survey data files, San Diego, California; (gal/min)/ft, gallon per minute per foot]

State well No.	Date month/year	Specific capacity [(gal/min)/ft]	Source of data
Zone 1			
2N/7E-2D1	12/69	64.6	SCE
	5/72	81.4	SCE
	10/73	80.0	SCE
	8/74	72.7	SCE
	7/75	73.0	SCE
Average		74.3	
2N/7E-3A1	5/54	65.8	USGS
	2/57	94.8	USGS
	5/61	67.7	USGS
	4/62	60.3	USGS
	5/63	73.3	USGS
	5/64	74.1	USGS
	12/65	72.0	USGS
	5/68	110.2	SCE
	5/72	108.3	SCE
	10/72	110.7	SCE
	8/74	115.1	SCE
	7/75	94.6	SCE
Average		87.2	
3N/7E-35P2	5/61	82.9	USGS
	6/62	84.0	USGS
	4/63	89.2	USGS
	5/64	89.7	USGS
	3/66	86.7	USGS
	5/68	132.8	SCE
	8/74	132.8	SCE
	7/75	103.2	SCE
Average		100.2	
Zone 2			
2N/7E-3B1	1/53	20.3	USGS
	5/54	24.6	USGS
	12/54	24.9	USGS
	2/57	30.0	USGS
	5/61	24.7	USGS
	4/62	24.0	USGS
	5/63	24.6	USGS
	5/64	26.6	USGS
	5/68	32.4	USGS
	5/72	37.1	SCE
	10/72	35.8	SCE
	8/74	37.4	SCE
	7/75	35.6	SCE
Average		29.1	
2N/7E-3E1	12/68	22.5	USGS
	12/69	25.2	SCE
	5/72	35.9	SCE
	10/72	36.0	SCE
	5/73	38.6	SCE
	8/74	42.2	SCE
	7/75	35.5	SCE
Average		33.7	
Zone 3			
3N/7E-28R1	8/78	17.1	USGS
3N/7E-29R1	8/78	18.4	USGS
3N/7E-32J1	9/78	25.3	USGS

with similar specific capacity values. Zone 1 includes the area east of the fault just west of Surprise Spring, zone 2 includes the area northwest of zone 1 and southeast of the second unnamed fault that also is northwest of Surprise Spring, and zone 3 includes the remainder of the saturated upper unit of the continental deposits of late Tertiary age in the basin (fig. 2). Wells in zone 1 have the highest average specific capacity values ranging from 74 to 100 (gal/min)/ft, wells in zone 2 have the next highest values ranging from 29 to 34 (gal/min)/ft, and wells in zone 3 have the lowest values ranging from 17 to 25 (gal/min)/ft.

Thomasson and others (1960, p. 222) reported that for valley-fill deposits in the Sacramento Valley of California, the specific capacity in units of gallon per minute per foot multiplied by 230 approximates the transmissivity in units of squared feet per day. This relation between specific capacity and transmissivity was assumed to be representative of the upper unit of the Tertiary deposits in the Surprise Spring basin. Available transmissivity data (unpublished) tend to support this assumption. The hydraulic conductivity of the deposits was estimated by dividing the transmissivity calculated by specific capacity data by the saturated thickness of the aquifer (table 3). The estimated transmissivity and hydraulic conductivity values determined by this method range from 3,930 ft^2/d and 11.2 feet per day (ft/d) in zone 3 to 23,050 ft^2/d and 38.4 ft/d in zone 1. These values are too low if the entire aquifer is not supplying water to the well. To correct for this, a common practice is to assume that the values of transmissivity calculated from specific capacity tests apply only to the perforated interval of the well (Heath, 1983, p. 61). To apply this value to the entire aquifer thickness, the calculated transmissivity is divided by the length of the perforated interval to determine the hydraulic conductivity. This value is then multiplied by the entire saturated thickness of the aquifer (table 3). The transmissivity and hydraulic conductivity values determined by this method range from 7,240 ft^2/d and 20.7 ft/d in zone 3 to 36,360 ft^2/d and 60.6 ft/d in zone 1. These values are too large if the zone supplying water to the well is thicker than the screen length. The values determined by these methods in table 3 probably represent the low and high range of the actual transmissivity and hydraulic conductivity of the upper unit of the continental deposits of late Tertiary age.

Aquifer test or pump test data are not available for the lower unit of the continental deposits of late Tertiary age. These deposits appear to be similar, however, to the older continental deposits in the Borrego Valley. Moyle (1982) assigned a hydraulic conductivity value of 1 ft/d for the older continental deposits in the Borrego Valley; this value is assumed to be valid for the lower unit of the continental deposits of late Tertiary age.

Table 3. Estimated transmissivity and hydraulic conductivity values for the Surprise Spring ground-water basin

[(gal/min)/ft, gallon per minute per foot; ft^2/d, foot squared per day; ft/d, foot per day; ft, foot]

State well No.	Average capacity (gal/min)/ft (A)	Transmissivity (ft^2/d) (B=A×230)	Saturated thickness of aquifer (1985) (ft) (C)	Hydraulic conductivity based on total saturated thickness (ft/d) (D=B÷C)	Length of perforated interval (ft) (E)	Hydraulic conductivity based on length of perforated interval (ft/d) (F=B÷E)	Transmissivity (ft^2/d) (G=C×F)
Zone 1							
2N/7E-2D1	74.3	17,090	600	28.5	282	60.6	36,360
2N/7E-3A1	87.2	20,060	600	33.4	340	59.0	35,400
3N/7E-35P2	100.2	23,050	600	38.4	400	57.6	34,560
Zone 2							
2N/7E-3B1	29.1	6,690	475	14.1	430	15.6	7,410
2N/7E-3E1	33.7	7,750	475	16.3	260	29.8	14,160
Zone 3							
3N/7E-28R1	17.1	3,930	350	11.2	190	20.7	7,240
3N/7E-29R1	18.4	4,230	350	12.1	190	22.3	7,800
3N/7E-32J1	25.3	5,820	350	16.6	190	30.6	10,710

STORAGE COEFFICIENT

The storage coefficient of an aquifer is the volume of water released from or taken into storage per unit of surface area per unit change in head (Lohman, 1972). For confined aquifers, the water released from storage when the hydraulic head declines comes from expansion of water and from compaction of the aquifer (Heath, 1983, p. 28). Most of the lower unit of the continental deposits of late Tertiary age is considered to be a confined aquifer because it is overlain by the upper unit and is not being dewatered. No aquifer tests are available to determine the storage coefficient; however, the storage coefficient of a confined aquifer can be estimated by multiplying the aquifer thickness by a specific storage coefficient of 1×10^{-6} ft^{-1} (Lohman, 1972, p. 53). Most of the lower unit ranges from 500 to 1,000 feet in thickness; therefore, the storage coefficient is estimated to range from 0.0005 to 0.001.

For unconfined aquifers, the storage coefficient is virtually equal to the specific yield. Specific yield of an aquifer is the ratio of the water which will drain freely from the material to the total volume of the formation and will always be less than the porosity. On the basis of lithologic logs, specific yield of the upper unit of the continental deposits of late Tertiary age was estimated to be 0.13 (F.S. Riley and G.F. Worts, Jr., U.S. Geological Survey, written commun., 1953). More recently, W.R. Moyle, Jr. (U.S. Geological Survey, written commun., 1983) estimated that the specific yield of the upper unit was about 0.14. No previous estimates are available for the specific yield of the unconfined parts of the lower unit of the continental deposits of late Tertiary age. However, as previously stated, these deposits are assumed to be similar to the older continental deposits in the Borrego Valley. Moyle (1982) estimated that the specific yield of the older continental deposits in the Borrego Valley was about 0.05. This value is probably valid for the specific yield of the lower unit of the continental deposits of late Tertiary age in Surprise Spring ground-water basin.

NATURAL RECHARGE AND DISCHARGE

The principal source of recharge to Surprise Spring ground-water basin is derived from runoff in the San Bernardino Mountains (F.S. Riley and G.F. Worts, Jr., U.S. Geological Survey, written commun., 1953). Recharge from direct precipitation over the basin and from surface-water inflow is insignificant. The average annual precipitation for the area is about 4 to 6 inches and is generally not large enough to meet evapotranspiration and soil-moisture requirements. Surface-water inflow to the area is infrequent and sporadic, generally occurring only for short durations after intense storms in the surrounding mountains.

Most runoff from the San Bernardino Mountains infiltrates the permeable deposits along Pipes Wash and its tributaries and then recharges Surprise Spring ground-water basin as ground-water inflow across the Emerson fault that forms the western boundary of the basin. Lewis (1972, p. 19) estimated that about 500 acre-feet of runoff through Pipes wash recharges Pipes basin (fig. 1) annually. From Pipes basin, some ground water probably moves eastward through the alluvial deposits between Giant Rock and the Zietz Mountains and recharges the Surprise Spring ground-water basin along Emerson fault (Schaefer, 1978, p. 7). Floodflows in Pipes Wash occasionally reach as far downstream as Emerson Dry Lake suggesting that at least some recharge to Surprise Spring ground-water basin occurs north of Artillery Hill as ground-water inflow across Emerson fault beneath the mouth of Pipes Wash. W.R. Moyle, Jr. estimated that the maximum ground-water inflow into Surprise Spring ground-water basin is 500 acre-ft/yr (Akers, 1986, p. 14). Available hydrologic data are not sufficient to determine which direction most ground-water inflow follows, but in any case the ground-water inflow recharges the western part of the basin. After entering the basin, the ground water flows to the east and southeast towards Surprise Spring (figs. 5 and 6).

Before pumping began in the basin, all ground-water discharge from the basin occurred as (1) transpiration by mesquite trees which were predominate in the immediate vicinity of Surprise Spring, (2) discharge of Surprise Spring, or (3) ground-water outflow across Surprise Spring fault near Surprise Spring. Before ground-water pumpage began in the basin, an estimated 75 acre-ft/yr was being lost to transpiration, and about 15 acre-ft/yr was being discharged from Surprise Spring (F.S. Riley and G.F. Worts, Jr., U.S. Geological Survey, written commun., 1953). By July 1955, the spring had stopped flowing, and by 1985 almost all the mesquite had died. There may have been some ground-water outflow across the transverse arch, but the quantity is considered to have been insignificant.

GROUND-WATER DEVELOPMENT

Prior to the 1950's, only a small amount of pumpage occurred within the Surprise Spring ground-water basin. The first significant pumpage in the area began in 1950-51, when four high-capacity irrigation wells were drilled just north of the northern boundary of the basin in the Ames Dry Lake area. These wells pumped about 3,000 acre-feet of ground water from 1950 through 1952 (F.S. Riley and G.F. Worts, Jr., U.S. Geological Survey, written commun., 1953). In 1952, the land was acquired by the Federal Government and irrigation was discontinued.

Pumpage from within the basin began in 1953 when the Marine Corps Base drilled two supply wells near Surprise Spring (2N/7E-3A1 and 3B1) to provide water for the base (fig. 4). In 1962, another well (3N/7E-35P2) was added to the system and in 1970 two more wells (2N/7E-2D1 and 3E1) were put into operation (fig. 4). All these wells are within 2 miles of Surprise Spring. In 1978, three wells (3N/7E-28R1, 29R1, and 32J1) were constructed and tested northwest of the original well field (fig. 4); these wells were not put into production until 1980. All pumpage from these wells has been metered. Figure 7 shows the reported annual pumpage from each supply well from 1953 through 1985. The total quantity of ground water pumped from these wells during this period was about 66,500 acre-feet; all this water was piped out of the basin.

Water levels in the basin began to decline almost immediately after the supply wells began pumping. Comparison of predevelopment water levels (fig. 5) and water levels measured in 1986-87 (fig. 6)

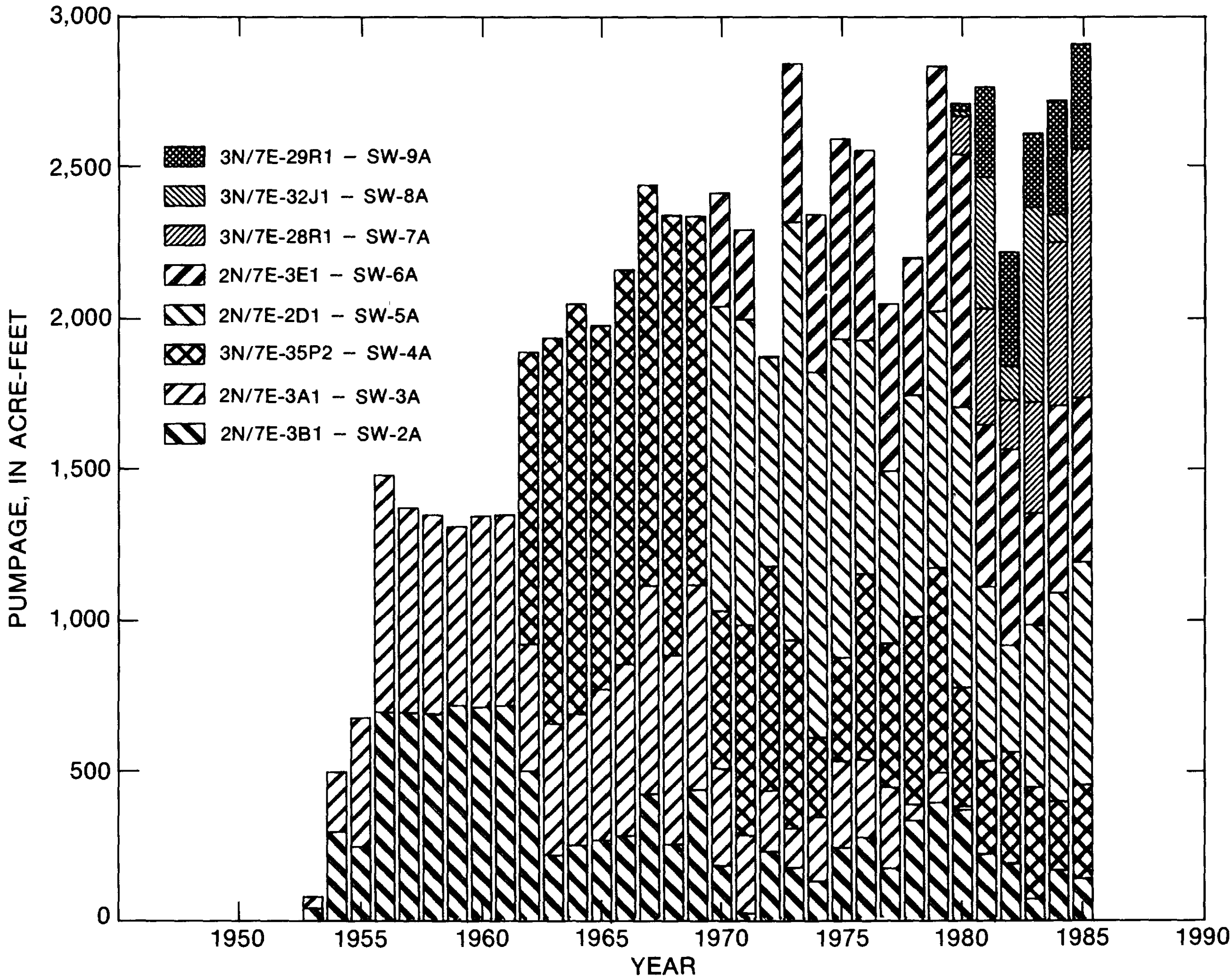


Figure 7. Annual pumpage from supply wells in the Surprise Spring basin, 1953-85.

indicates that most of the water-level decline has occurred in the area of Surprise Spring. Long-term hydrographs of three wells in the vicinity of the spring (2N/7E-2C1, 3B1, and 4H1) are shown in figure 8. Two unnamed faults lie between these wells (fig. 2). As shown in the hydrographs, the water-level altitude and the rates of water-level decline are different on either side of the faults. The water-level decline from 1953 through 1985 was more than 100 feet in well 2N/7E-2C1, approximately 50 feet in well 2N/7E-3B1, and approximately 25 feet in well 2N/7E-4H1. However, as shown in figures 5 and 6, water levels in wells on the same side of the faults are almost identical. The large water-level change across the faults indicates that those faults are partial barriers to ground-water flow.

GROUND-WATER-FLOW MODEL

The objective in developing a ground-water-flow model for the Surprise Spring ground-water basin was to better understand the aquifer system in the study area and to determine the long-term availability of ground water in the basin by evaluating and projecting ground-water conditions resulting from historic and proposed pumpage in the basin. A numerical ground-water-flow model uses a set of equations that numerically describe an aquifer system. A numerical model, however, cannot exactly duplicate the actual system because of the complex geohydrologic relations in the aquifer system. Model development requires the use of assumptions and approximations that simplify the actual system. It cannot be overemphasized that the model is only as accurate as the assumptions and data used in its development.

To define this aquifer system numerically, it was necessary to divide the aquifer system into a grid, determine the boundary conditions for the aquifer, develop an initial hydraulic head distribution, and identify the aquifer properties within the model area. These data made it possible to estimate the rates and

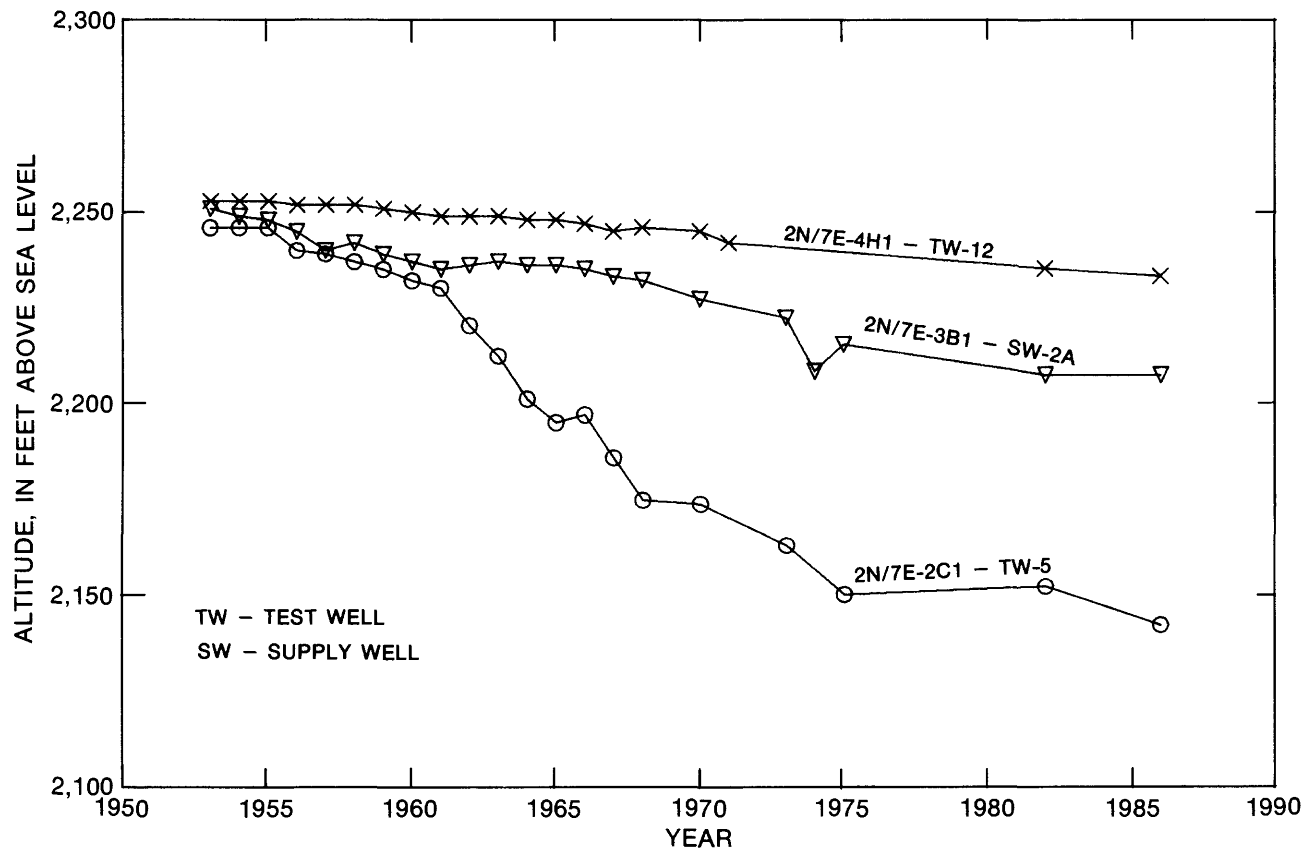


Figure 8. Water-level altitudes of selected wells in the Surprise Spring ground-water basin.

distribution of recharge and discharge in the aquifer system. The accuracy of the model is directly related to the accuracy of these input data.

The numerical model chosen for this study was developed by McDonald and Harbaugh (1984) and uses the finite-difference numerical method of solution. A full explanation of the theoretical development, the solution used, and the mathematical treatment of each simulated condition is discussed by McDonald and Harbaugh (1984).

MODEL GRID

In the finite-difference modeling method, a rectangular grid is used to divide the study area into rows and columns. Each rectangle is called a model block, and the center point of each block is called a node. The model grid is overlayed on maps that show the areal distribution of the various model input parameters. The average value of a given parameter within a block is determined from a map and entered into the model as the value of that parameter for the entire block. This process is repeated until a value for the specific parameter has been assigned to every block in the model area.

The finite-difference grid designed for this model was oriented parallel to the Surprise Spring fault (fig. 9) and used an identical grid for each horizontal layer of the model. The aquifer system in the Surprise Spring ground-water basin was simulated as two horizontal layers of the continental deposits of late Tertiary age. Layer 1, the upper layer, represents the upper unit, and layer 2, the lower layer, represents the lower unit. Depending on their location, the size of the blocks ranges from 0.01 to 0.12 mi^2. The smaller blocks allow for a more detailed approximation of the flow system where the density of data is high or where large variations in aquifer properties or stress occur. The use of larger blocks provides a more general approximation of the flow system, but allows the model area to be covered with fewer blocks. Using fewer blocks helps to reduce computer storage and execution time.

MODEL BOUNDARIES

All model boundaries (fig. 9) coincide with the aquifer limits determined by geohydrologic interpretations. The top boundary of the model is the water table, which is simulated as a free-surface boundary allowed to move vertically in response to imbalances between inflow and outflow. Layer 1 of the model is bounded on the west by the Emerson fault, on the south by the northern limits of the transverse arch, on the east by Surprise Spring fault, and on the north by a northwestward-trending fault that extends from the Surprise Spring fault on the east to the Emerson fault on the west. Layer 2 of the model has the same lateral boundaries as layer 1, except that the northern boundary for layer 2 includes Hidalgo Mountain on the northeast and a northeast-trending fault south of Ames Dry Lake. On the north, the bottom boundary of the model is the contact between the bottom of the continental deposits and the crystalline bedrock. Model boundaries were simulated as either general head, constant-flux, or no-flow boundaries.

The Surprise Spring fault in the area of Surprise Spring was simulated as a general-head boundary in layer 1 (fig. 9). A general-head boundary simulates a source of water outside the model area which either supplies water to or receives water from the adjacent model blocks at a rate proportional to the hydraulic-head differences between the source and model block (McDonald and Harbaugh, 1984, p. 343). The rate at which water is exchanged between the model block and the outside source is given by the expression:

$$Q = C(HB-h), \qquad (1)$$

where

Q is the rate at which water is supplied to the model block from the boundary [L^3t^{-1}],
C is the constant of proportionality for the boundary [L^3t^{-1}],
HB is the hydraulic head outside the model boundary [L], and
h is the hydraulic head in the model block [L], [L] is unit of length, [t] is unit of time.

In this model, hydraulic head (HB) on the east side of the Surprise Spring fault ranged in altitude from 1,853 feet above sea level on the north to 1,843 feet above sea level on the south. The HB values at individual model blocks were held constant for the entire simulation period. This is probably valid because measured water levels on the Deadman basin side of the fault have not changed during the period of record, 1953-87 (figs. 5 and 6). Simulated hydraulic heads in the model blocks adjacent to Surprise Spring declined from about 2,250 to 2,140 feet above sea level during this same period. Ground water moves from the model area across Surprise Spring fault to the Deadman basin during the entire simulation period. The value of *C* was determined during the steady-state calibration of the model.

A constant-flux boundary was used to simulate inflow to the model area at selected blocks along the western boundary of layer 1 (fig. 9). At a constant-flux boundary, water flows into or out of the model at a specified rate that remains constant for the entire stress period. The inflow is simulated by placing recharge wells at the boundary blocks. The rate of inflow at these blocks was determined during the steady-state calibration of the model and was assumed to remain constant during the transient-state calibration.

No-flow boundaries were used to simulate the lateral model boundaries around the remainder of layer 1, the lateral model boundaries around all of layer 2, and the bottom surface of the model. A no-flow boundary indicates that there is no exchange of water between the model block and the area outside the model.

MODEL CALIBRATION

The calibration of a ground-water-flow model requires the trial-and-error process of adjusting initial estimates of aquifer properties and recharge and discharge to obtain the best match between model simulated hydraulic heads and measured water levels and selected water budget items. The initial estimates are adjusted within limits that are based on the geologic and hydrologic properties of the basin and the degree of confidence placed on the original data estimates. The closeness of the final match is controlled by the complexity of the real system as well as the time constraints on the study.

The model was calibrated to simulate the steady-state conditions that were present within the basin prior to 1953 and to transient conditions during the 33-year period from 1953 through 1985. A steady-state condition occurs when the inflows and outflows of an aquifer system are equal, and the volume of water stored within the system is not changing. Transient conditions occur in an aquifer system when inflows do not equal outflows, and hydraulic heads and volumes of water in storage are changing.

STEADY-STATE MODEL

Steady-state hydraulic heads are dependent on the quantities of recharge to and discharge from the ground-water system, the transmissivity of the aquifer system, and the leakance between layers. The calibration procedure for steady-state conditions consisted of modifying prior estimates of these parameters. Because hydraulic heads are constant under steady-state conditions, the storage component of the system can be ignored during the steady-state calibration process.

The model was calibrated to approximate steady-state water-level measurements from seven wells in the basin (fig. 10) These measurements are assumed to be representative of the hydraulic heads in the area prior to ground-water development. No water-level measurements are available for layer 2; therefore, layer 2 was assumed to have the same initial hydraulic-head distribution as layer 1.

Simulation of natural recharge and discharge.--All recharge to the model area is assumed to occur as ground-water inflow to layer 1 across the western model boundary. This inflow was simulated using a constant-flux boundary. During the calibration process, the boundary inflow was varied with the original estimates considered to be the minimum and maximum allowable values (table 4). Inflow was simulated along Emerson fault at the mouth of Pipes

EXPLANATION FOR FIGURE 9

———	NO-FLOW BOUNDARY, LAYER 1
— — —	GENERAL HEAD BOUNDARY, LAYER 1
- - - - -	CONSTANT-FLUX BOUNDARY, LAYER 1
———	NO-FLOW BOUNDARY, LAYER 2 – Shown only in areas where layer 2 boundary does not coincide with layer 1 boundary
D —— ***D'***	LINE OF SECTION – Section ***D–D'*** shown in figure 20
— — — · · ·	FAULT – Dashed where approximately located, dotted where uncertain
●32J1	SUPPLY WELL AND IDENTIFIER
○	PROPOSED PRODUCTION WELL
⊡	LOCATION OF SURPRISE SPRING AND AREA OF EVAPOTRANSPIRATION

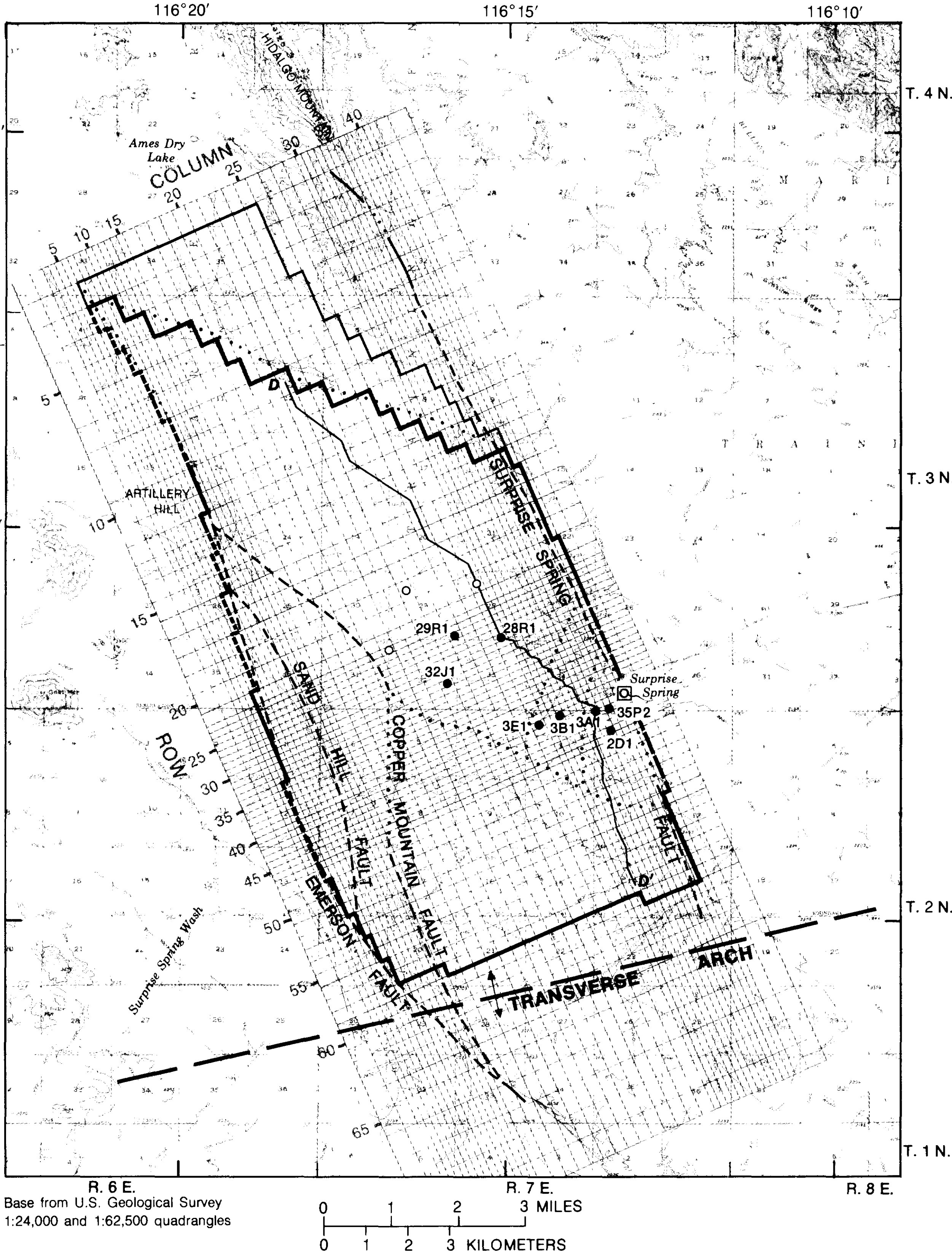


Figure 9. Model grid and boundary locations.

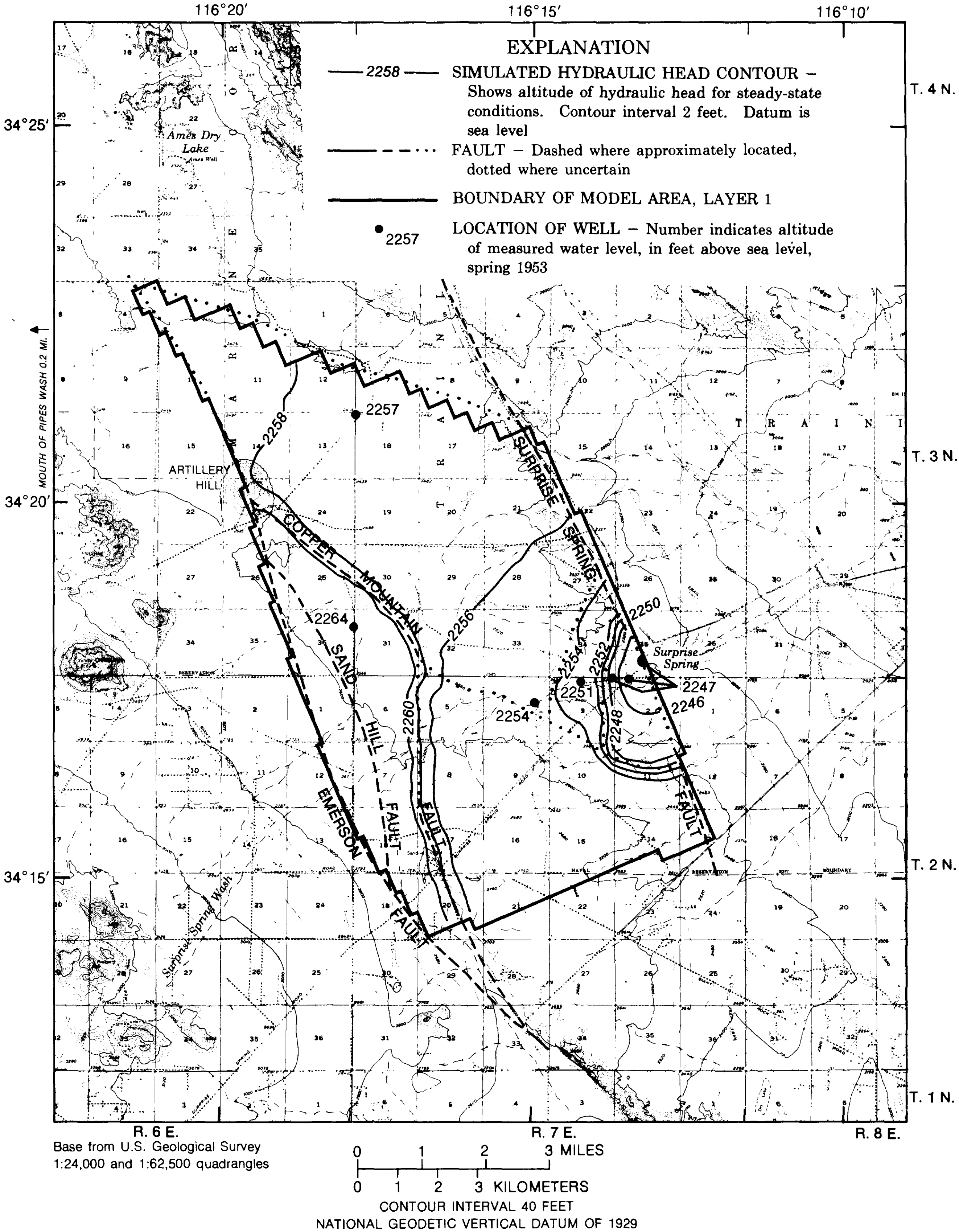


Figure 10. Altitudes of measured water levels, spring 1953, and simulated hydraulic heads for steady-state conditions.

Table 4. Estimated ranges of rates of inflows and outflows to Surprise Spring ground-water basin under steady-state conditions

[Negative sign indicates outflow from the aquifer system]

Inflow and outflow	Acre-foot per year	
	Maximum	Minimum
Inflow across Emerson fault	500	90
Discharge of Surprise Spring	-15	-15
Evapotranspiration	-75	-75
Outflow across Surprise Spring fault	-410	0

Wash, in the area just south of Artillery Hill, and in the area where Surprise Spring Wash enters the model area (fig. 9). The distribution and quantity of inflow were modified during the steady-state calibration of the model by varying the location of the constant-flux nodes and the constant-flux rates along the western boundary (fig. 9). Final calibrated inflow across the western boundary was about 128 acre-ft/yr; with about 64 acre-ft/yr coming from the mouth of Pipes Wash, about 53 acre-ft/yr coming from just south of Artillery Hill, and about 11 acre-ft/yr coming from Surprise Spring Wash.

Discharge from the model area consisted of the flow from Surprise Spring, transpiration by predominately mesquite trees in the immediate vicinity of the spring, and ground-water outflow across Surprise Spring fault into Deadman basin. Spring discharge of 15 acre-ft/yr was simulated in the model during the steady-state calibration as pumpage from a well in layer 1 at the location of the spring (fig. 9).

Transpiration by the mesquite at Surprise Spring is simulated at three model blocks near the spring (fig. 9). Prior to ground-water development, ground-water loss to transpiration was about 75 acre-ft/yr (F.S. Riley and G.F. Worts, Jr., U.S. Geological Survey, written commun., 1953). For modeling purposes, this volumetric rate was assumed to be the maximum transpiration rate because water levels were at or near land surface. The transpiration rate was assumed to decrease linearly from 4 ft/yr when the water level is at land surface to zero when the depth to water became equal to or greater than 50 feet. The estimates of the discharge rate at Surprise Spring and the maximum transpiration rate of the mesquite near the spring (table 4) were considered to be reasonably accurate; therefore, these values were not varied during the calibration process.

The ground-water outflow across Surprise Spring fault was simulated by a general-head boundary along the fault (fig. 9) and is described in the section on boundary conditions. All outflow was assumed to be from layer 1 of the model. Ground-water outflow was varied by adjusting the conductance of the general-head boundary. The final calibrated conductance value was 0.43 ft/d (5.0×10^{-6} ft/s), which resulted in a simulated outflow across Surprise Spring fault of about 40 acre-ft/yr for steady-state conditions.

Transmissivity and hydraulic conductivity.--Transmissivity is simulated in the model as the product of the saturated thickness of a particular model block and the hydraulic conductivity assigned to that block. The saturated thickness of layer 1 is simulated in the model by subtracting the altitude of the bottom of layer 1 from the water-table altitude. The altitude of the bottom of layer 1 for the aquifer and fault zones is shown in figure 11 and was estimated from geologic sections constructed for this study (fig. 3). The saturated thickness of layer 2 (fig. 12) is determined in the model by subtracting the altitude of the bottom of layer 2 from the altitude of the bottom of layer 1. The altitude of the bottom of layer 2 was estimated from a gravity survey of the area (Moyle, 1984). Where layer 1 is unsaturated or where layer 2 is not overlain by layer 1, the saturated thickness of layer 2 is determined in the model by subtracting the bottom altitude of layer 2 from the water-table altitude. The altitude of the water table fluctuates in response to changes of inflow and outflow; therefore, the saturated thickness also will change with time.

The initial hydraulic conductivity distribution for layer 1 was derived from various well logs, specific capacity tests, and reports from previous investigators. On the basis of this information, layer 1 of the model was divided areally into three large zones within each of which hydraulic conductivity was assumed to be uniform and into six narrow zones representing the various faults within the area (fig. 11). Initial estimates of hydraulic conductivity for layer 1, calculated on the basis of the total saturated thickness of the layer, range from a high of 38.4 ft/d in zone 1 to a low of about 11.2 ft/d in zone 3 (table 3). Hydraulic conductivity values estimated on the basis of length of the perforated interval in the wells, range from 60.6 ft/d in zone 1 to 15.6 ft/d in zone 2 (table 3). Initially the fault zones were assumed to have the same hydraulic conductivity as the surrounding material. Layer 2 was modeled as one large zone, with a uniform hydraulic conductivity of 1 ft/d, containing five narrow zones of lower hydraulic conductivity corresponding to the faults in layer 1 (fig. 13).

The original estimates of hydraulic conductivity were adjusted during the steady-state calibration process. The hydraulic conductivity was changed uniformly within the zones. The hydraulic conductivities of the fault zones were originally set equal to the hydraulic conductivity of the adjacent aquifer material and then decreased until the model simulated hydraulic-head gradients across the faults matched the measured water-level gradients across the faults. Adjusting hydraulic conductivity uniformly within the zones is justified because, as shown in table 3, specific capacity values and calculated transmissivity and hydraulic conductivity values are similar within zones.

Calibrated hydraulic conductivity values for the three large zones in layer 1 were 35 ft/d in zone 1, 25 ft/d in zone 2, and 22 ft/d in zone 3 (fig. 11). In general, the calibrated values were greater than the hydraulic conductivity values estimated from specific capacity data calculated from the total aquifer saturated thickness and less than the hydraulic conductivity values calculated from the well perforated intervals (table 3). The hydraulic conductivity of the fault zones had to be decreased 1 to 2 orders of magnitude from the initial estimate in order to better approximate the measured water-level differences across the faults (fig. 11).

The hydraulic conductivity for the southwest part of layer 1 (fig. 11) and for layer 2 (fig. 13) could not be directly calibrated because of the absence of water-level information for these areas. Although some wells in the model area penetrated the top of layer 2, all are screened in the upper layer. Therefore, the hydraulic conductivity of layer 1 in the southwest part of the study area and layer 2 throughout the model area could be calibrated only by adjusting the hydraulic conductivity within one of these areas and then observing the effects of the adjustment in areas of layer 1 where water-level information was available. During this calibration process, it became apparent that simulated hydraulic heads in layer 1 were not greatly affected by changes to the hydraulic conductivity in the southwest part of layer 1 or in layer 2. Therefore, the aquifer properties in the southwest part of layer 1 were assumed to be similar to those in the remainder of zone 3 of layer 1, and the original estimates for hydraulic conductivity for layer 2 were assumed to be reasonable and could be used without modification in the model. The hydraulic conductivity of the fault zones in layer 2 were adjusted so that the hydraulic conductivities of the fault zones maintained the same relation to the hydraulic conductivity of the adjacent aquifer material as the corresponding fault zones for layer 1 (fig. 13).

Leakage between layers.--Vertical leakage of water between layers 1 and 2 occurs whenever there is a hydraulic head difference between those layers. The rate at which this leakage occurs is described by the equation:

$$Q = KV/B\ (H2-H1), \qquad (2)$$

where

Q is the vertical leakage, volume flux per unit area [Lt^{-1}],
KV is the effective value of vertical hydraulic conductivity between layers [Lt^{-1}],
B is the length of the vertical flow path [L],
$H1$ is the hydraulic head in layer 1 [L], and
$H2$ is the hydraulic head in layer 2 [L],
[L] is unit of length, [t] is unit of time.

EXPLANATION FOR FIGURE 11

AQUIFER PROPERTIES -

		Hydraulic conductivity in feet per day — Calibrated	Altitude of bottom of layer 1, in feet above sea level	Specific yield percent — Calibrated
		General aquifer zone		
	Zone 1	35	1,600	0.25
	Zone 2	25	1,750	.16
	Zone 3	22	1,900	.16
		Fault zone		
		0.43	1,900	0.16
		.05	1,900	.16
		.09	1,900	.16
		.50	1,900	.16
		.11	1,750	.16

- - · · FAULT - Dashed where approximately located, dotted where uncertain

—— BOUNDARY OF MODEL AREA, LAYER 1

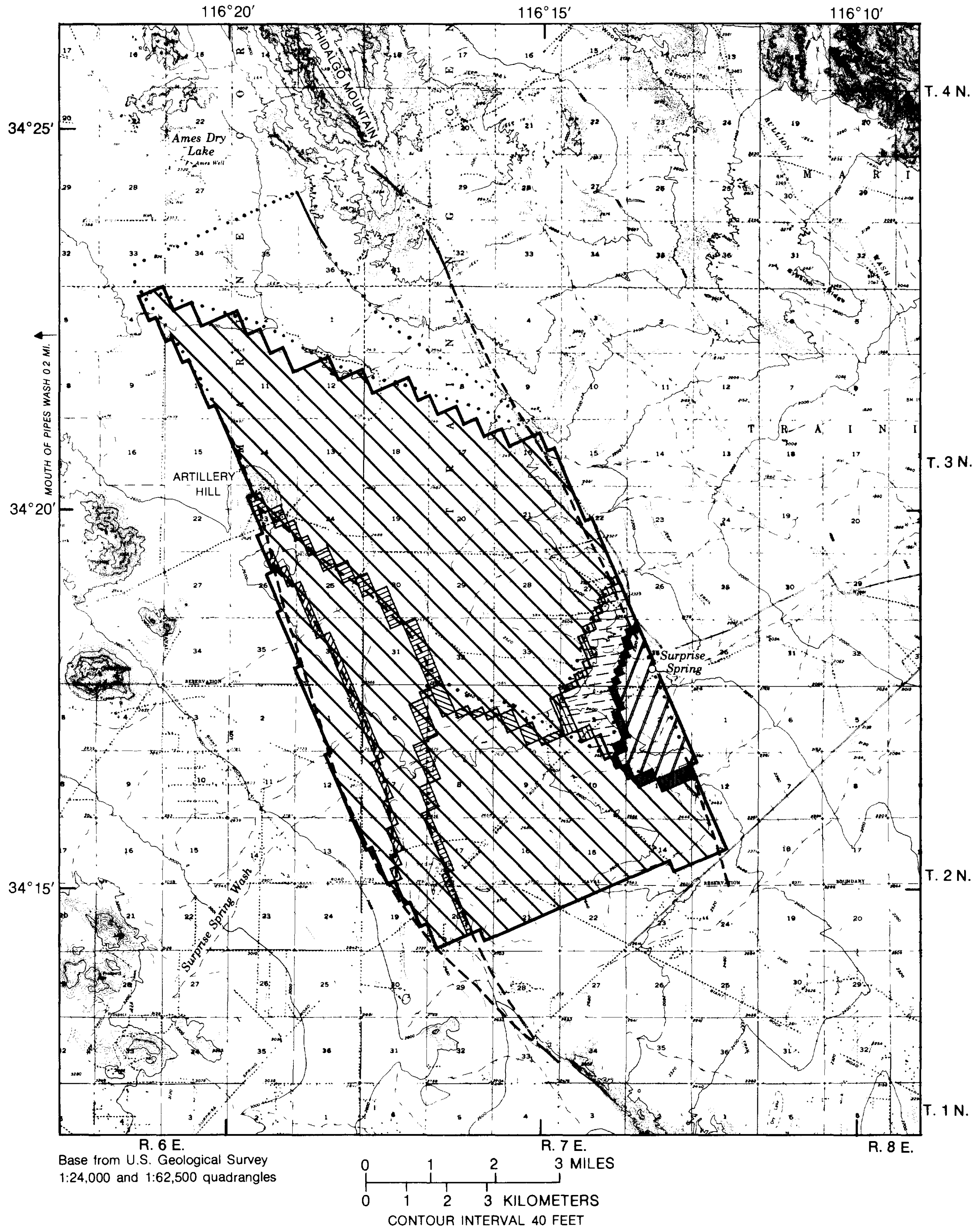


Figure 11. Distribution of simulated aquifer properties within model layer 1.

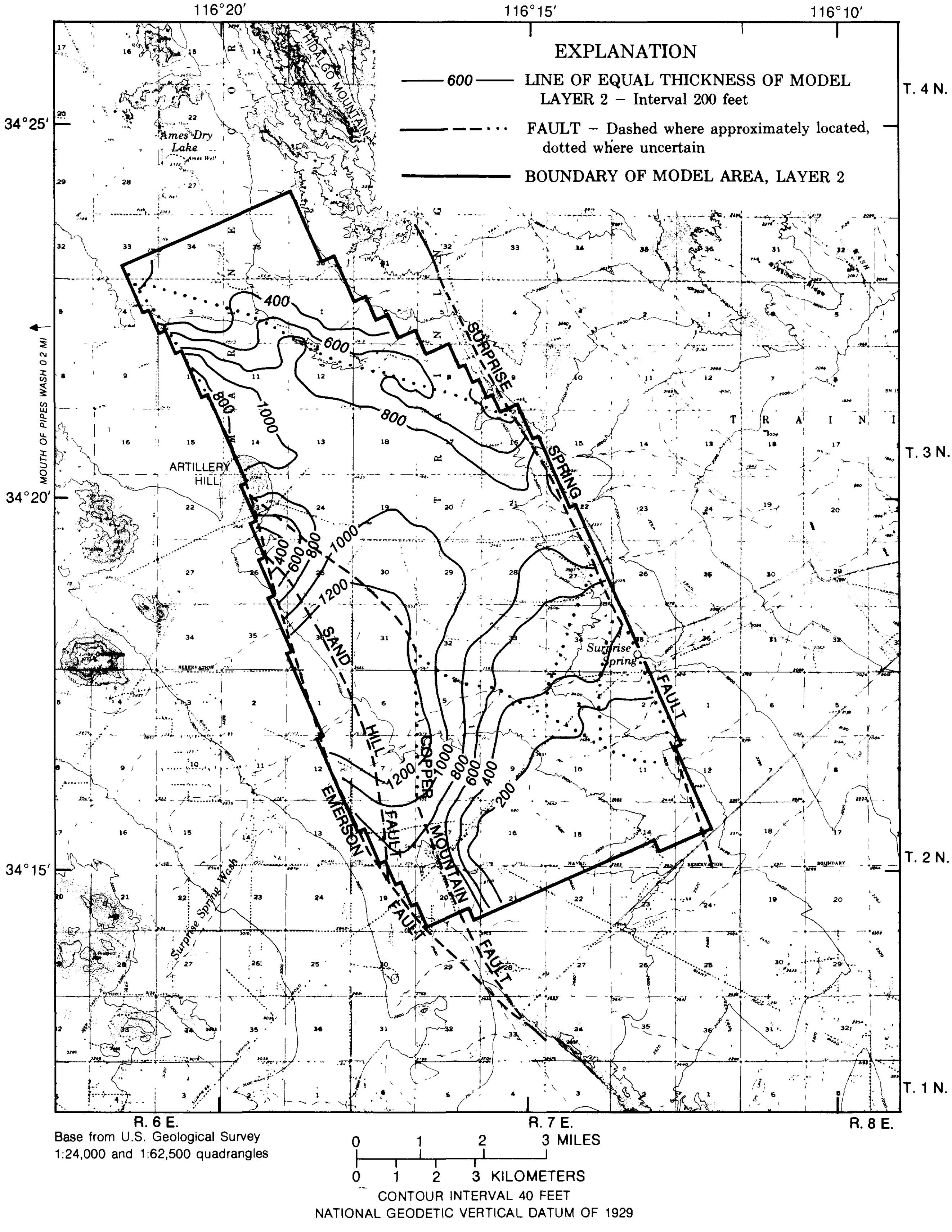


Figure 12. Areal distribution of thickness of model layer 2.

KV/B in the above equation is referred to as the leakance term in this report.

The model (McDonald and Harbaugh, 1984) used for this study requires that the leakance term be entered as input data. Therefore, the leakance term is calculated outside the model using the following equation:

$$KV/B = \frac{2}{\frac{B1}{KV1} + \frac{B2}{KV2}}, \qquad (3)$$

where

KV/B is the leakance between layers [t^{-1}],
$KV1$ is the vertical hydraulic conductivity of material in layer 1 [Lt^{-1}],
$KV2$ is the vertical hydraulic conductivity of material in layer 2 [Lt^{-1}],
$B1$ is the saturated thickness of layer 1 [L], and
$B2$ is the saturated thickness of layer 2 [L].

The vertical hydraulic conductivities of layers 1 and 2 were assumed to be equal to one-tenth of the horizontal hydraulic conductivity of the layers. The values of saturated thickness used in equation 3 were those that occurred prior to ground-water development in the area. The relation between vertical and horizontal hydraulic conductivity was not adjusted during model calibration. The original estimates of saturated thickness also were not adjusted during the calibration process. Consequently, leakance values were varied only to reflect calibrated changes in the horizontal hydraulic conductivity of layer 1. The calibrated values of leakance ranged from about 0.001 to about 0.09 (ft/d)/ft over most of the area. Within the fault zones, leakance values ranged from about 0.000006 to about 0.0003 (ft/d)/ft.

TRANSIENT-STATE MODEL

After a satisfactory steady-state calibration was achieved, ground-water conditions during 1953-85 were used to calibrate the model to transient-state conditions. Transient-state conditions in Surprise Spring ground-water basin are the result of stress on the system imposed by pumping from wells used for supplying water to the Marine Corps Base. The pumpage has resulted in ground-water levels declining by as much as 100 feet near Surprise Spring between 1953 and 1985.

The magnitude of water-level declines is dependent on natural recharge and discharge, ground-water pumpage, the storage coefficient of both layers, hydraulic conductivity of both layers, and the leakance between the layers. For the transient calibration, the natural recharge, conductance of the Surprise Spring fault, hydraulic conductivity values, maximum transpiration rate, and leakance between layers were presumed to be the same as those used in the steady-state calibration and were not adjusted. Discharge from Surprise Spring was not simulated because flow at the spring stopped soon after pumping began. Ground-water pumpage has been metered since pumpage began in the basin, and the metered values were used in the model without modification (fig. 7). Therefore, the calibration procedure for transient conditions consisted of modifying estimates of storage coefficient for both layers until simulated declines in hydraulic head approximated measured declines in water levels.

Simulated steady-state hydraulic heads were used as initial conditions for the transient-state calibration. The transient period, 1953-85, was divided into 33 yearly stress periods. Simulated hydraulic heads were compared to long-term hydrographs from four wells (fig. 14) and to spring 1986 and 1987 water-level measurements in 19 wells within the basin (fig. 15).

The storage coefficients used for layer 1 were initially assumed to be equal to the specific yield of the aquifer material. Estimates of specific yield in the Surprise Spring ground-water basin range from 13 (F.S. Riley and G.F. Worts, Jr., U.S. Geological Survey, written commun., 1953) to 14 percent (Akers, 1986). On the basis of these estimates, a storage coefficient of 0.14 was assumed representative of layer 1. This value was modified during the transient-state calibration of the model (fig. 11). Calibrated specific yield values for layer 1 were all higher than the original estimates. In zone 1 near Surprise Spring, specific yield was increased from the initial estimate of 14 to 25 percent, and in zones 2 and 3, specific yield was increased from 14 to 16 percent (fig. 11). Although these values are higher than had been estimated by previous investigators, they are still within acceptable limits for unconsolidated alluvial material (Lohman, 1972, p. 8). Inspection of geologic logs of wells in layer 1 indicates that zone 1 consists of a higher percentage of gravel and coarse sand than zones 2 and 3, which explains the higher specific yield in zone 1.

Initial transient simulations indicated that the simulated hydraulic heads in layer 1 were not highly sensitive to changes in storage coefficient values in layer 2. Consequently, the original estimates of layer 2 storage coefficients were assumed to be reasonable and were not modified during the remainder of the transient calibration.

Table 5. Model-simulated water budgets

[Negative sign indicates water removed from aquifer system; acre-ft/yr, acre-foot per year]

	Rates at end of steady-state simulation		Rates at end of 1953 through 1985 simulation	
	Acre-ft/yr	Percent	Acre-ft/yr	Percent
Inflow across Emerson fault	127.5	100	127.5	100
Total inflow	127.5		127.5	
Pumpage	0	0	2,904	99
Discharge of Surprise Spring	15	12	0	0
Evapotranspiration	75	59	0	0
Outflow across Surprise Spring fault	37.5	29	30	1
Total outflow	127.5		2,934	
Change in storage	0.0		-2,806.5	

Where layer 2 is overlain by layer 1, the storage coefficient for layer 2 was estimated by multiplying the thickness of the layer (fig. 12) by a specific storage value of 0.000001 per foot (Lohman, 1972, p. 53). Where layer 2 is not overlain by layer 1 the storage coefficient was assumed to be equal to the specific yield of 5 percent estimated for the older continental deposits in Borrego Valley (Moyle, 1982). When the hydraulic head in layer 2 declines below the bottom of layer 1, the storage coefficient used in the model converts to the specific yield value of 5 percent.

If a satisfactory match between simulated hydraulic heads and measured water levels could not be obtained by adjusting the specific yield of layer 1, the calibration process was started over. In the subsequent steady-state calibration, the hydraulic conductivity was adjusted only in areas where the simulated hydraulic heads from the previous transient-state simulation did not match measured water levels. In addition, the distribution and quantity of recharge was either increased or decreased depending on whether the previous transient simulation indicated that the model needed more or less water to simulate the responses of the aquifer system. After the steady-state model was recalibrated, another attempt was made at simulating transient conditions. This process was repeated numerous times until a satisfactory match between simulated hydraulic heads and measured water levels was obtained; further calibration of the aquifer properties and recharge conditions did not significantly improve the match.

MODEL RESULTS

At the end of the calibration process, the simulated hydraulic heads for the steady-state conditions were generally within 4 feet of the measured water levels (fig. 10). The simulated hydraulic heads at the end of the transient calibration process were generally within 5.5 feet of the measured water levels (fig. 15). Hydrographs showing measured water levels and simulated hydraulic heads at four wells in the model area (fig. 14) indicate that the model is able to duplicate both the annual hydraulic-head fluctuations and long-term trends, at least in the areas of these wells.

The water budgets generated by the model at the end of the steady-state and transient-state simulations are included in table 5. The calibrated steady-state inflows are about 128 acre-ft, which were balanced by

EXPLANATION FOR FIGURE 13

AQUIFER PROPERTIES -

	Hydraulic conductivity in feet per day
	Calibrated
	General aquifer zone
(blank)	1
	Fault zone
	0.20
	.002
	.004
	.023
	.004

- - · · FAULT - Dashed where approximately located, dotted where uncertain

—— BOUNDARY OF MODEL AREA, LAYER 2

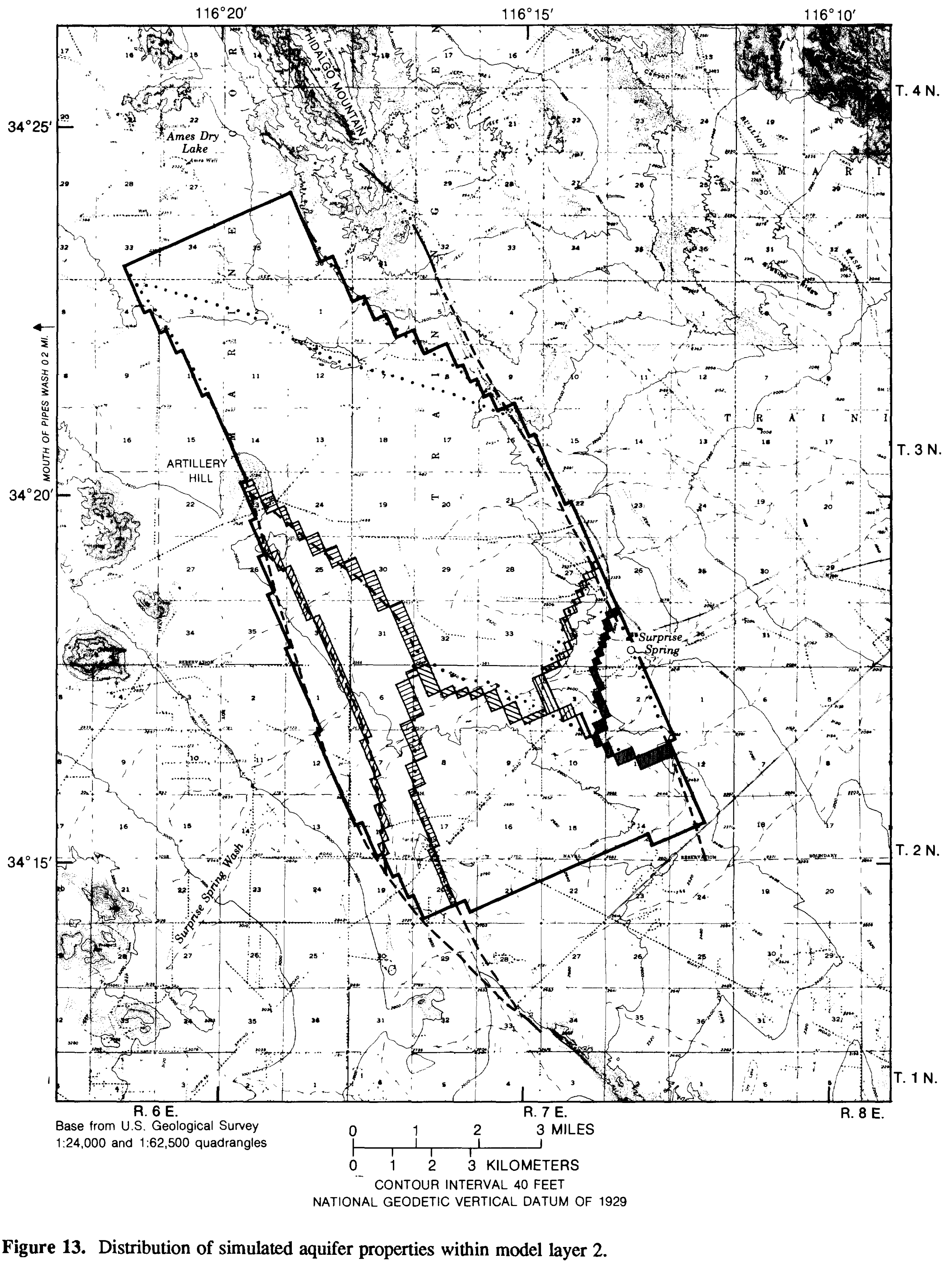


Figure 13. Distribution of simulated aquifer properties within model layer 2.

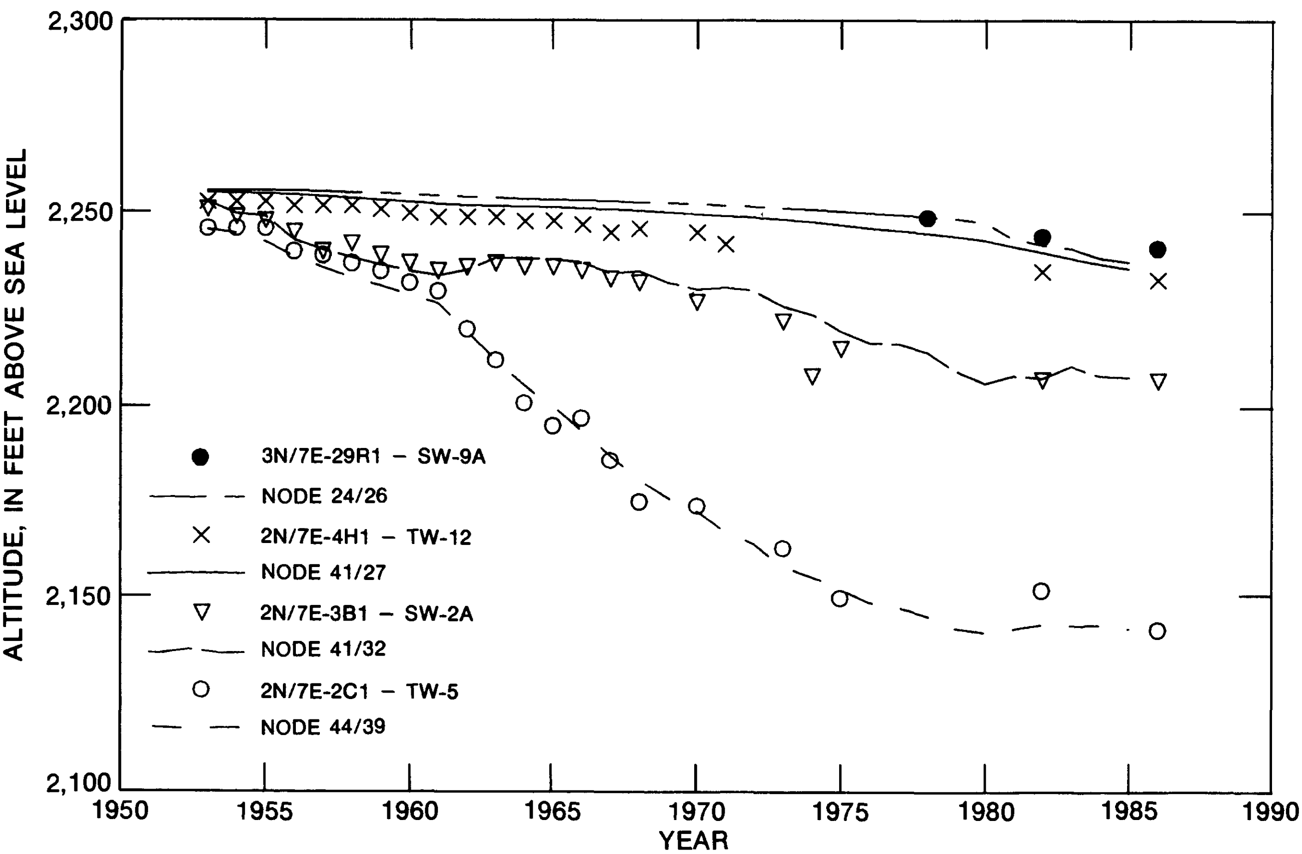


Figure 14. Altitudes of measured water levels and simulated hydraulic heads in selected wells, 1953-86.

outflows. Both the inflows and outflows were within the range of the original estimates of these values (table 4). The simulated water budget for the end of the transient calibration process shows that about 97 percent of the water being pumped from the area is derived from storage within the basin and that the remainder is derived from the capture of natural discharge. The water budget for the transient simulation also indicates that transpiration had ceased by the end of 1985. This is supported by the fact that by 1985 almost all the mesquite that had been growing in the area of Surprise Spring had died.

MODEL SENSITIVITY

Sensitivity analysis is a modeling procedure that evaluates the model sensitivity to variations in the input parameters. The procedure involves keeping all input parameters constant except for the one being analyzed and to vary that parameter through a range that included the uncertainties in the parameter. Simulated hydraulic head changes were used to analyze model sensitivity. Exact values of head change from sensitivity analyses should be viewed critically, but relative changes can provide insight to the manner in which the parameter may affect the results of a model simulation.

To determine the effect of changing the various input parameters on the simulated hydraulic heads, several model simulations of 5 years' duration were made. The simulated heads from the end of the transient calibration process were used for starting heads, and the 1985 pumpage rates were used as stresses on the system for each simulation. For the first simulation, the data from the end of the calibration process were used, and for each subsequent simulation, one input parameter (such as hydraulic conductivity) was varied. The simulated hydraulic heads for layer 1 at the end of each subsequent simulation were compared to those at the end of the first simulation along section *D-D'* (fig. 9). The model sensitivity was tested by varying the hydraulic conductivity for layer 1 by 0.5 to 2.0 times the calibrated values. The hydraulic conductivity of the fault zones was varied separately from that of the aquifer zones. The specific yield of layer 1 was varied from 0.1 to 0.3, which is the measured range of specific yield for most unconfined aquifers (Lohman, 1972, p. 8). The inflow

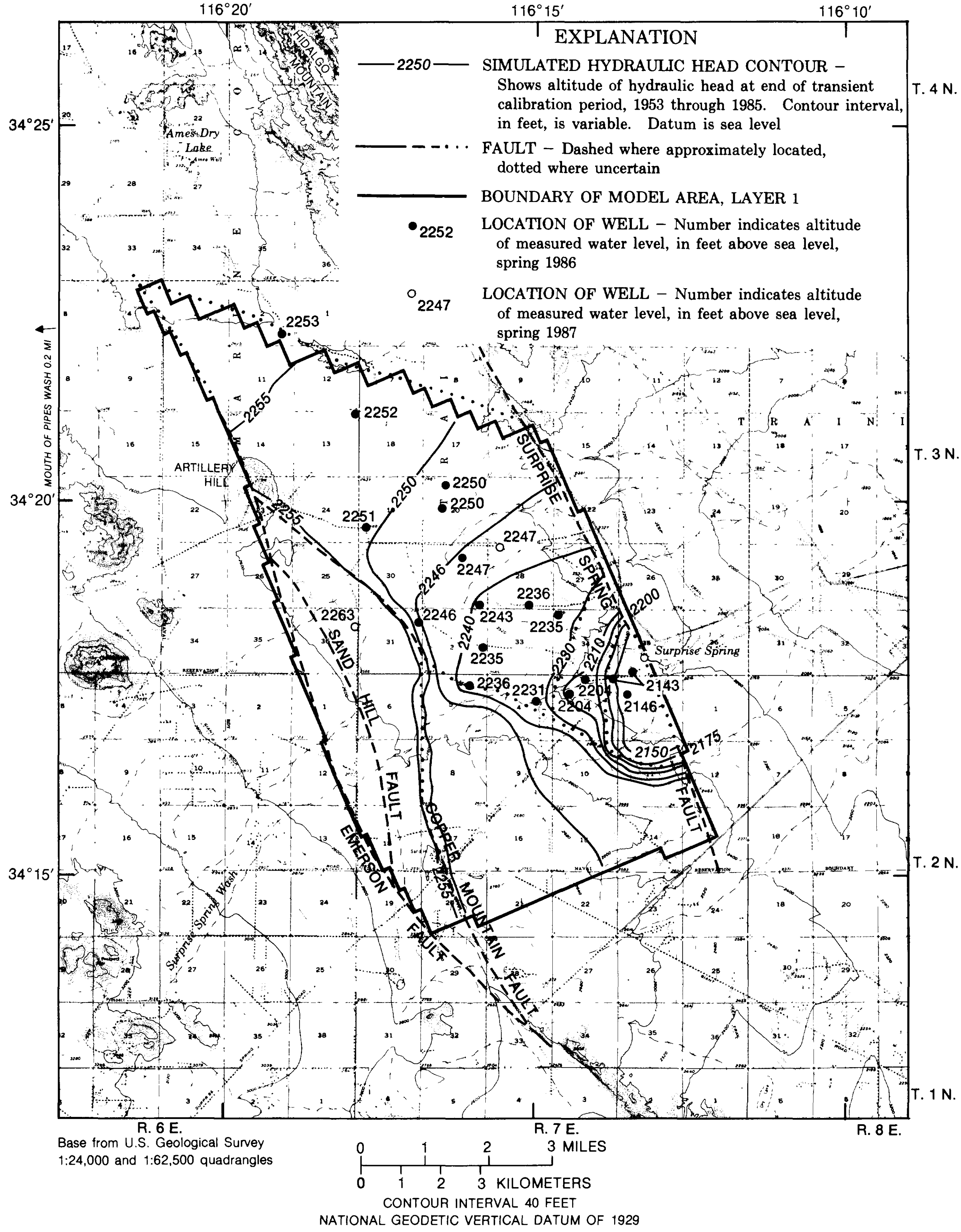


Figure 15. Altitudes of measured water levels, spring 1986 and spring 1987, and simulated hydraulic heads at the end of the transient calibration period, 1953 through 1985.

across the model boundaries was varied from 90 to 500 acre-ft/yr, the estimated minimum and maximum rates of inflow. The constant of proportionality across the general head boundary used to simulate Surprise Spring fault leakance between layers, and all parameters for layer 2 were varied plus or minus one order of magnitude.

Cross sections of the simulated hydraulic head changes (fig. 16) indicate that the model is most sensitive to the hydraulic conductivity across the fault zones in layer 1. Increasing these values by a factor of 2 caused simulated head changes in layer 1 as great as 15 feet along the cross section between rows 41 and 52, which is in the area of Surprise Spring (fig. 9). Decreasing the hydraulic conductivity across the fault zones of layer 1 by a factor of 0.5 resulted in simulated head changes in layer 1 in this same area of about 10 feet. Increasing or decreasing the hydraulic conductivity of the other aquifer zones by these same factors caused simulated head changes of about 9 feet. Varying the other input parameters to their maximum or minimum acceptable values or by a factor of plus or minus one order of magnitude resulted in simulated head changes of less than 5 feet.

SIMULATED EFFECTS OF FUTURE PUMPAGE

Because the calibrated model reasonably simulated ground-water conditions in the Surprise Spring ground-water basin from 1953 through 1985, the model was used to simulate the effects of future pumping in the basin. For this study, three model simulations were made to determine the aquifer response to different pumpage patterns in the basin from 1986 through 2035. The first simulation was used to determine the aquifer response if base pumpage remained constant at the 1985 level. Simulations 2 and 3 were made to determine the aquifer response if pumpage in the basin was increased to supply the projected population growth at the base between 1985 and 2035.

The population has been projected to increase from about 10,400 in 1985 to 15,000 by 1991, after which the population should remain fairly stable until 2035 (Neste and others, 1986). Water use at the base is estimated to be about 250 gal/d per person (Neste and others, 1986). For modeling purposes the base population, and therefore the base water use, was assumed to increase uniformly each year from 1986 through 1991 and then to remain constant thereafter. Also, the estimated daily per capita water use was increased by 25 percent to about 313 gal/d per person to allow for greater than anticipated water use on the base. Under these assumptions, the water use on the base would increase from about 2,900 acre-ft/yr in 1985 to about 5,300 acre-ft/yr in 1991 and remain stable until 2035.

Each test simulation was run using the simulated hydraulic heads from the end of the transient calibration process as initial conditions and was run for fifty 1-year stress periods, representing the time period from 1986 through 2035. For simulation 1, the pumpage from the six existing supply wells was held constant at their 1985 rates for the entire simulation (table 6) (fig. 17). The total projected quantity of ground-water pumpage from 1986 through 2035 was about 145,200 acre-ft. For simulation 2, the projected pumpage increase for each year from 1986 through 1991 was distributed equally among the six supply wells that were pumped during 1985 (fig. 18). This additional pumpage was added to the 1985 pumpage for each well (fig. 7). For the stress periods from 1992 through 2035, the pumpage was held constant at the 1991 rate (table 6). For simulation 3, the projected increase in pumpage was distributed equally among three supply wells proposed to be constructed by the U.S. Marine Corps north and west of the existing wells (fig. 19). The pumpage from each of these wells was increased equally each year from 1986 through 1991 and then held constant at the 1991 rate from 1992 through 2035. The pumpage from the six supply wells was held constant at the 1985 rates for the entire simulation (table 6). The total quantity of ground-water pumpage from 1986 through 2035 for simulations 2 and 3 was about 257,500 acre-ft.

Under conditions proposed for the first simulation, hydraulic heads are projected to decline by about 40 feet between 1985 and 2035 in the area of Surprise Spring and from about 20 to 40 feet over most of the remainder of the area (fig. 17). For simulation 2, hydraulic heads are projected to decline between 1985 and 2035 as much as 154 feet in the area of Surprise Spring and from about 40 to 80 feet over most of the remainder of the area (fig. 18). For simulation 3, the largest declines between 1985 and 2035 would be about 80 feet in the vicinity of the proposed wells; the decline in the area of Surprise Spring would be only about 55 feet (fig. 19). These projected declines are in addition to the measured water-level declines

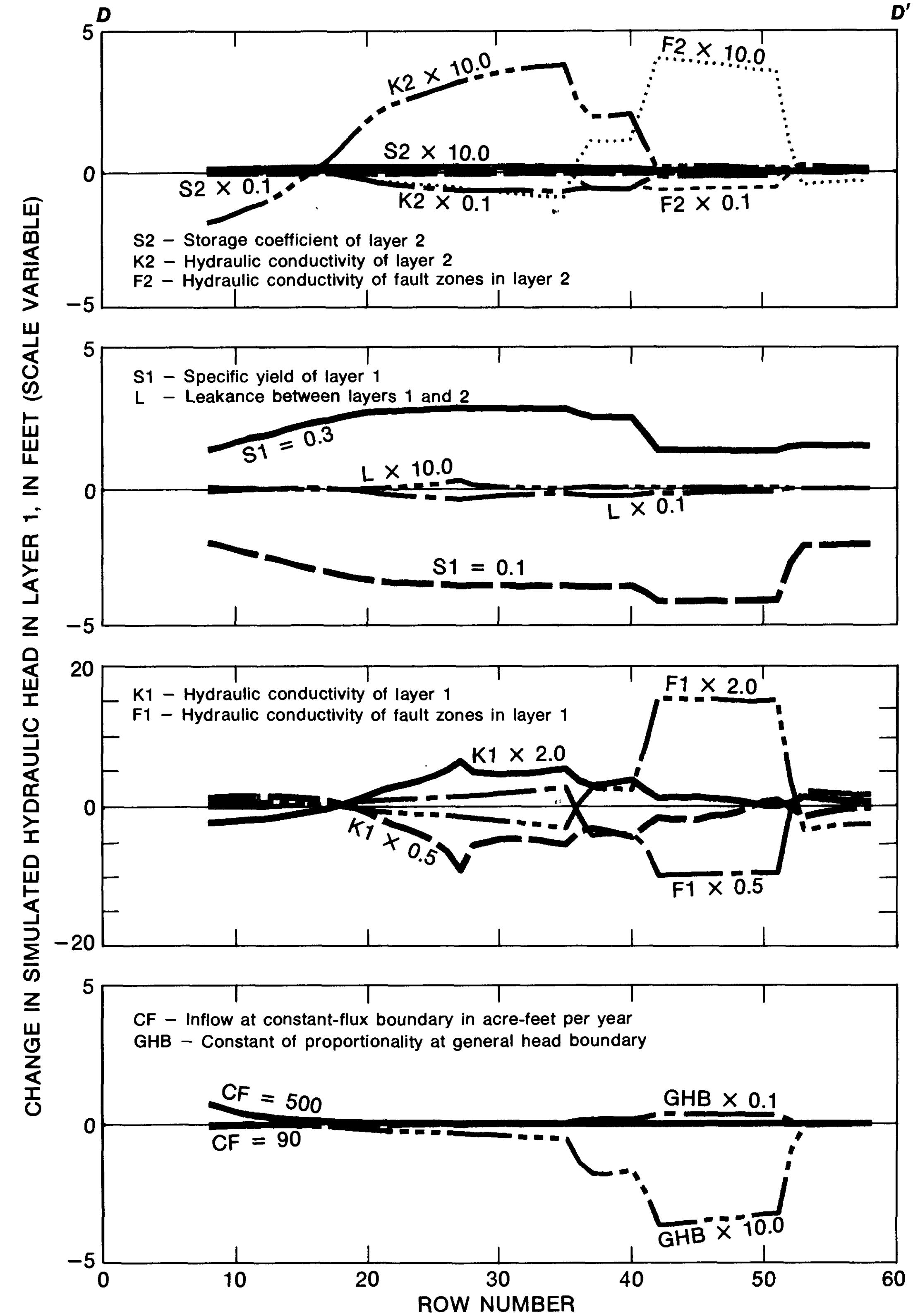


Figure 16. Results of sensitivity analysis on simulated hydraulic heads in layer 1 along cross section *D-D'*.

Table 6. Estimated pumping rates for simulations 1, 2, and 3

[Pumping rates in acre-foot per year]

Stress period	Supply wells						New supply wells			Totals
	SW-2A	SW-4A	SW-5A	SW-6A	SW-7A	SW-9A	NW-1	NW-2	NW-3	
Simulation 1										
1985	133.4	312.0	735.9	549.2	826.1	347.2	--	--	--	2,903.6
1986-2035	133.4	312.0	735.9	549.2	826.1	347.2	--	--	--	145,190.0
Simulation 2										
1986	191.8	377.6	801.5	614.8	891.8	412.8	--	--	--	3,290.3
1987	279.2	443.3	867.2	680.5	957.4	478.5	--	--	--	3,706.1
1988	330.4	509.0	932.9	746.2	1,023.1	544.2	--	--	--	4,085.8
1989	396.1	574.6	998.5	811.8	1,088.8	609.8	--	--	--	4,479.6
1990	461.7	640.3	1,064.2	877.5	1,154.4	675.5	--	--	--	4,873.6
1991	527.4	706.0	1,129.9	943.2	1,220.1	741.2	--	--	--	5,267.8
1992-2035	527.4	706.0	1,129.9	943.2	1,220.1	741.2	--	--	--	231,783.2
Total										257,466.4
Simulation 3										
1986	133.4	312.0	735.9	549.2	826.1	347.2	131.3	131.3	131.3	3,297.7
1987	133.4	312.0	735.9	549.2	826.1	347.2	262.7	262.7	262.7	3,691.9
1988	133.4	312.0	735.9	549.2	826.1	347.2	394.1	394.1	394.1	4,086.1
1989	133.4	312.0	735.9	549.2	826.1	347.2	525.4	525.4	525.4	4,480.0
1990	133.4	312.0	735.9	549.2	826.1	347.2	656.8	656.8	656.8	4,874.2
1991	133.4	312.0	735.9	549.2	826.1	347.2	788.2	788.2	788.2	5,268.4
1992-2035	133.4	312.0	735.9	549.2	826.1	347.2	788.2	788.2	788.2	231,809.6
Total										257,507.9

that have already occurred in the basin. In the vicinity of Surprise Spring where measured water-level declines from 1953 through 1985 are about 100 feet, the total decline from 1953 through 2035 is projected to be about 140 feet for simulation 1, about 254 feet for simulation 2, and about 155 feet for simulation 3. Figure 20 shows the effects of the various proposed pumping simulations on hydraulic heads along section *D-D'* (fig. 9).

LIMITATION OF THE MODEL

Within specified limits, a digital model is useful for projecting aquifer responses to various changes in aquifer stresses. However, a model is only an approximation of the actual system based on average and estimated conditions. The accuracy with which a model can project aquifer responses is directly related to the accuracy of the input data used in the model calibration and is inversely related to the magnitude of the proposed changes in the stresses being applied to the model and to the length of the simulation period.

The model has been calibrated to simulate long-term trends in heads within specific areas of layer 1. As shown in figures 14 and 15, the model is able to duplicate hydraulic heads fairly accurately over long periods of time in the area of the present production wells. In areas of the basin where there are sparse or no geohydrologic data, however, the accuracy of the model is uncertain. Data are particularly sparse in the southwestern part of the basin. Observation wells in this area would help to determine if the input values used in the model are satisfactory.

Faults can have a significant effect on the flow of ground water through an area. Therefore, in order to accurately model this flow, the location and hydrologic properties of the faults must be precisely known. Because of the limited data available over most of the area, the location and geometry of the

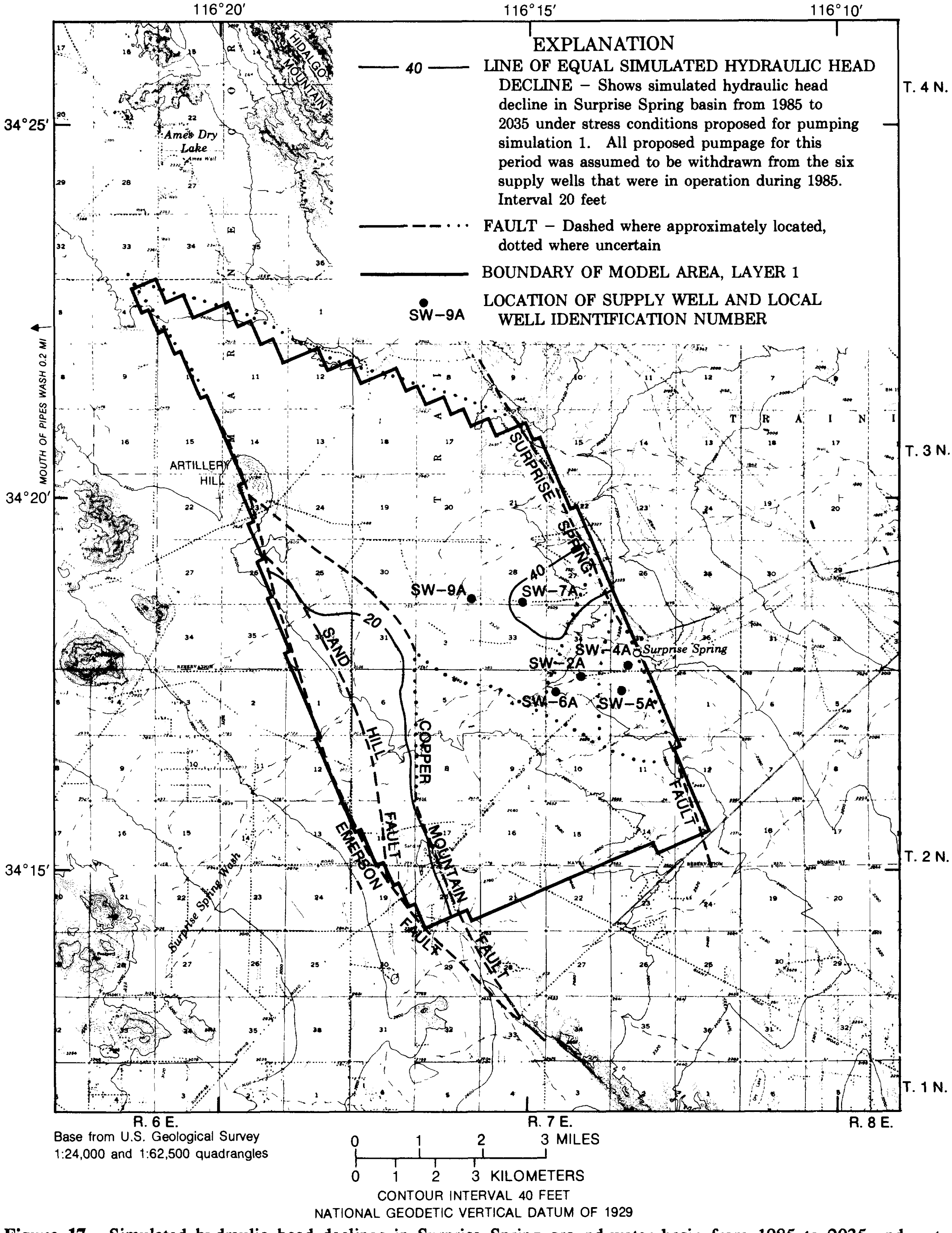


Figure 17. Simulated hydraulic head declines in Surprise Spring ground-water basin from 1985 to 2035 under stress conditions proposed for pumping simulation 1.

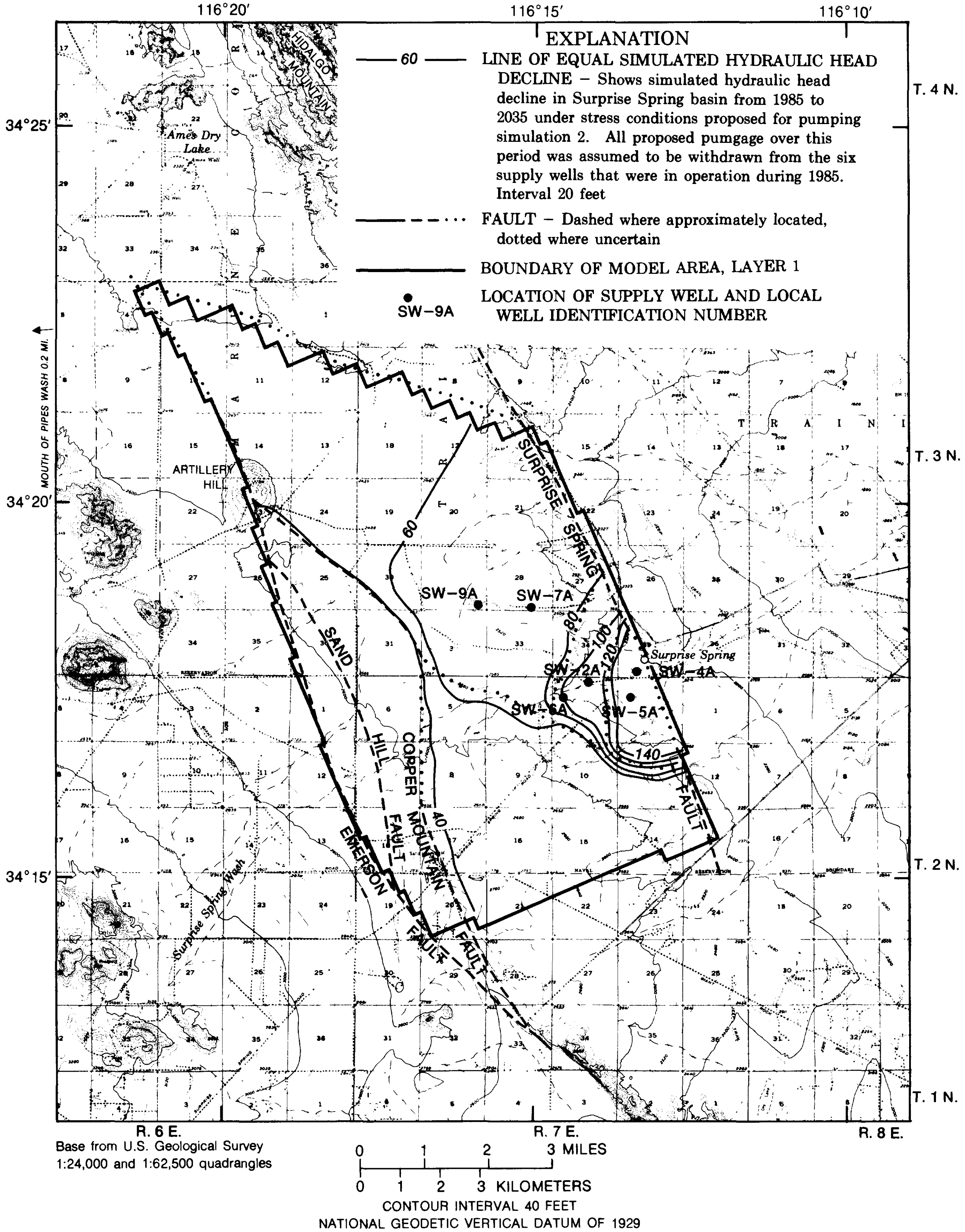


Figure 18. Simulated hydraulic head declines in Surprise Spring ground-water basin from 1985 to 2035 under stress conditions proposed for pumping simulation 2.

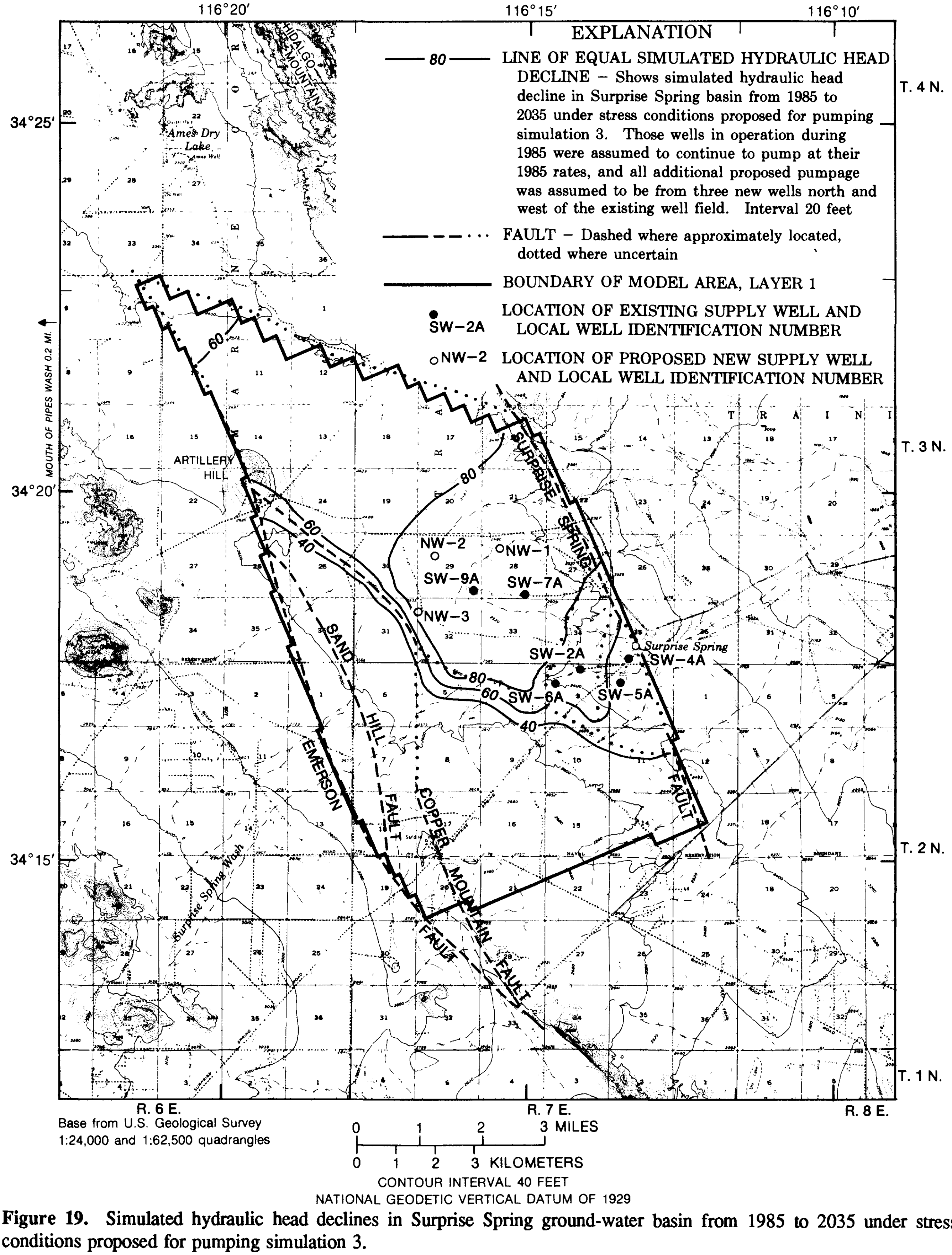


Figure 19. Simulated hydraulic head declines in Surprise Spring ground-water basin from 1985 to 2035 under stress conditions proposed for pumping simulation 3.

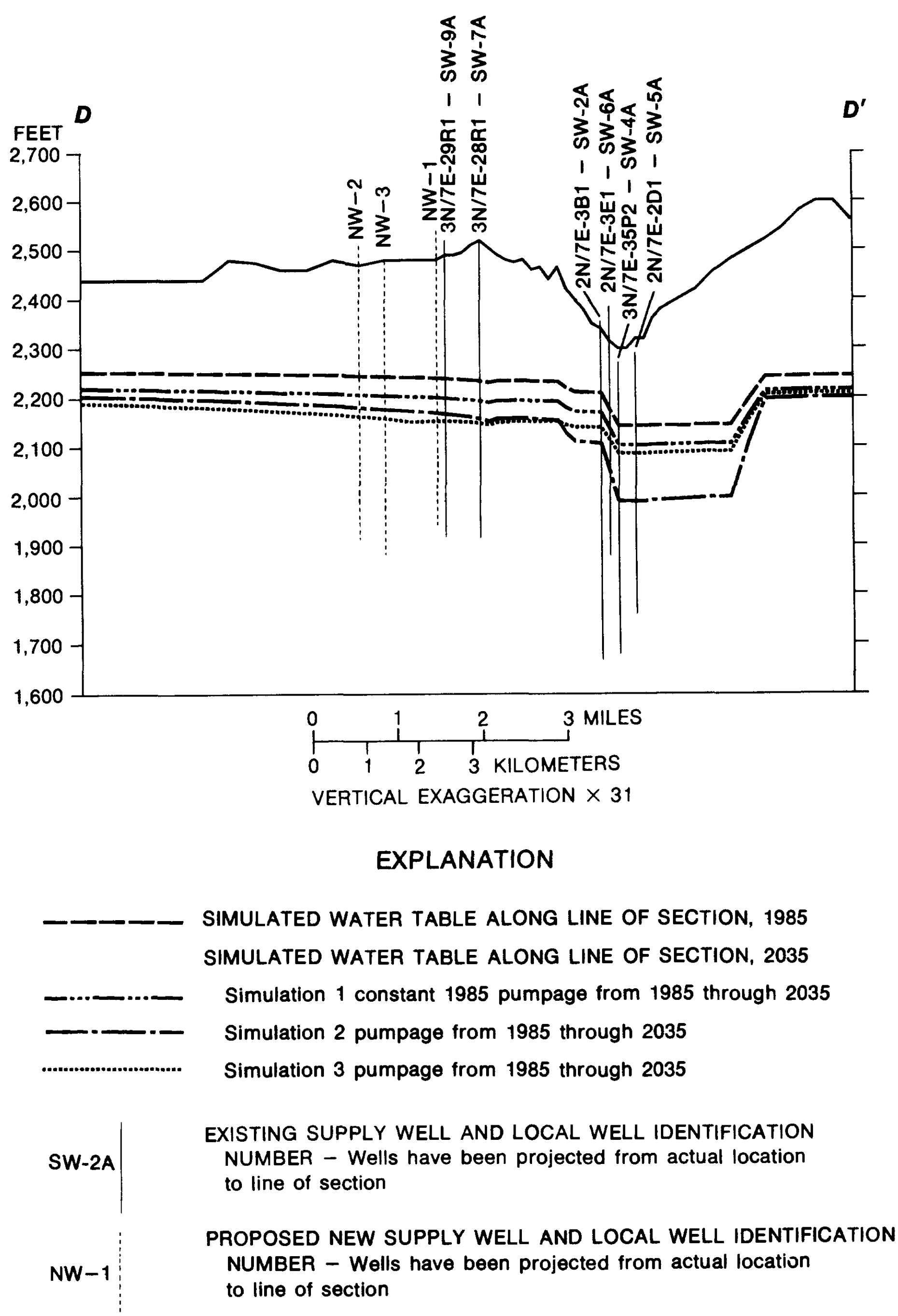


Figure 20. Effects of pumping simulations 1, 2, and 3 on simulated hydraulic heads along section *D-D'*.

faults simulated within the model is uncertain. Topographic features indicate that there may be other faults in the area which were not included in the model. As more information becomes available, the simulated location of faults may need to be changed, and new faults may need to be added. Because the model is sensitive to these faults (fig. 16), any changes in the location or hydraulic characteristics of the faults could greatly affect the simulated hydraulic heads.

Another limitation of the model is that within a model layer the vertical hydraulic conductivity is constant. However, the aquifer material probably changes at depth, becoming finer grained and more cemented. Therefore, as the layer is dewatered, the hydraulic conductivity may decrease, causing the actual transmissivity to be lower than that simulated by the model based solely on decreasing saturated thickness and constant hydraulic conductivity. If the aquifer has a transmissivity less than the simulated transmissivity, then the simulated hydraulic-head declines in high stress areas would be less than the measured water-level declines.

SUMMARY AND CONCLUSIONS

The principal conclusions regarding the ground-water resources of the Surprise Spring ground-water basin are:

- Continental deposits of Quaternary and Tertiary age fill the basin to a maximum depth of 2,000 feet. The deposits are unconsolidated at land surface and become more consolidated with depth. These deposits are underlain by a nearly impermeable complex of igneous and metamorphic rocks of pre-Tertiary age that forms the mountains that surround the area.
- The ground-water system consists of two inter-connected aquifers: The upper and lower units of continental deposits of late Tertiary age. In the model analysis made during this study, each aquifer was simulated as an individual horizontal layer. Layer 1, the upper layer, represents the upper unit of the continental deposits of late Tertiary age; layer 2, the lower layer, represents the lower unit.
- The upper unit of continental deposits of late Tertiary age consists predominantly of unconsolidated sand of moderately high permeability. The lower unit of continental deposits of late Tertiary age consists of consolidated to partly consolidated poorly sorted sand, silt, and clay of low permeability. Available data indicate that at least locally the lower unit contains ground water of poor quality.
- The Surprise Spring ground-water basin is bounded on the west by the Emerson fault and on the east by the Surprise Spring fault. The northern and southern boundaries are not as well defined; however, the northern extent of the basin is probably an unnamed fault south of Ames Dry Lake, and the southern boundary is a barrier north of, and associated with, the transverse arch.
- Faults within the basin have divided the basin into three main zones. Zone 1 includes the area east of the unnamed fault near Surprise Spring, zone 2 includes the area north and west of zone 1 and south and east of the second unnamed fault that surrounds Surprise Spring, and zone 3 includes the remainder of the basin. Available data indicate that aquifer properties are similar within each zone. For the model analysis, hydraulic conductivity and storage coefficient values were assumed to be uniform within each zone.
- The faults that bound the basin and many of the faults within the basin are partial barriers to ground-water movement. The barrier effect of the faults is believed to be caused primarily by compaction and extreme deformation of the water-bearing deposits immediately adjacent to the faults. The net effect is that the fault zones are less permeable than the surrounding deposits. The model analysis made during this study indicates that the hydraulic conductivity of the fault zones is one to two orders of magnitude lower than the hydraulic conductivity of the surrounding deposits.
- Wells in zone 1 of layer 1 have the highest measured specific capacity values ranging from 74 to 100 (gal/min)/ft, wells in zone 2 have the next highest values ranging from 29 to 34 (gal/min)/ft, and wells in zone 3 have the lowest values ranging from 17 to 25 (gal/min)/ft. Specific capacity values are not available for layer 2.
- The model analysis indicates that the hydraulic conductivity of layer 1 is 35 ft/d in zone 1, 25 ft/d in zone 2, and 22 ft/d in zone 3. Model calibrated specific yield values for layer 1 range from 25 percent in zone 1 to 16 percent in zones 2 and 3.
- Layer 2 was simulated in the model analysis as one large zone with a uniform hydraulic conductivity of 1 ft/d, except for zones of low hydraulic conductivity corresponding to the faults. Where layer 2 is not overlain by layer 1, the storage coefficient was assumed to be equal to 0.05. Where layer 2 is overlain by layer 1, the storage coefficient was determined in the model analysis by multiplying the thickness of layer 2 by the specific storage value of 1×10^{-6}.
- Recharge to the basin occurs as ground-water inflow across the Emerson fault that forms the western boundary of the basin. Recharge from direct precipitation over the area and from surface-water

inflow is considered to be insignificant. Model analysis indicates that natural recharge and predevelopment discharge equaled 130 acre-ft/yr; of this quantity, about 15 acre-ft/yr left the basin as discharge at Surprise Spring, about 75 acre-ft/yr left the basin as transpiration primarily by mesquite trees in the vicinity of the spring, and the remainder left the basin as outflow across Surprise Spring fault. Prior to development of the ground-water basin, there may have been some ground-water outflow across the transverse arch, but the quantity is considered to have been insignificant.

- The Marine Corps Base has been the sole user of ground water in the basin. From 1953 through 1985 the base pumped from as many as eight supply wells; about 66,500 acre-ft of ground water was pumped and transported out of the basin. All pumpage was from layer 1. Soon after ground-water development began, Surprise Spring stopped flowing, and by 1985 almost all the mesquite trees had died. Model analysis indicates that by the end of the simulation period (1985), 97 percent of pumpage was derived from storage within the basin, and the remainder was derived from the capture of natural discharge.

- Water levels in the basin began to decline almost immediately after the supply wells began to pump. From 1953 to 1987, measured water levels declined by more than 100 feet near Surprise Spring in zone 1. Water-level declines were about 50 feet in zone 2 and about 25 feet in the part of zone 3 closest to Surprise Spring. In areas of zone 3 far from the supply wells, water-level declines were minimal.

- The model developed for this study is most sensitive to changes in the hydraulic conductivity of layer 1, particularly the fault zones, and is relatively insensitive to other model parameters.

- Projected increases in water use by the Marine Corps Base will cause significant declines of water levels in the basin. The model was used to estimate the water-level declines that could result from increased pumpage in the basin based on projected increase in personnel at the Marine Corps Base between 1985 and 2035. The base population has been projected to increase from 10,400 to 15,000 from 1985 through 1991 and then remain stable until the year 2035. Water use during this period is projected to increase from about 2,900 to 5,300 acre-ft/yr from 1985 through 1991 and then remain stable until 2035. The total quantity of ground-water pumpage during this period is projected to be about 257,500 acre-ft. If the projected pumpage comes entirely from the six production wells that were in operation during 1985, simulated hydraulic-head decline would be as much as 154 feet in the area of Surprise Spring and from 40 to 80 feet over most of the remainder of the area from 1985 to 2035. If, however, the projected increase in pumpage comes from three proposed wells located north and west of the present well field, the simulated hydraulic-head decline during this same 50-year period would be about 80 feet in the vicinity of the new wells and only 55 feet in the area of Surprise Spring. These projected declines are in addition to measured water-level declines that occurred in the basin from predevelopment conditions through 1985.

- The model developed for this study has been calibrated to simulate hydraulic heads fairly accurately over long periods in the area of the supply wells. However, in areas of the basin where there are sparse or no geohydrologic data, the accuracy of the model is uncertain. Data are particularly sparse in the southwestern part of the basin. Observation wells are needed in this area to help determine if the data values used in the model are reasonable. Possible sites for the observation wells are in T.2 N., R.7 E., sec. 9 along Surprise Spring Road and in T.2 N., R.7 E., in the southern part of sec. 11. The pilot holes for the observation wells would need to be at least 800 feet deep.

SELECTED REFERENCES

Akers, J.P., 1986, Geohydrology and potential for artificial recharge in the western part of the U.S. Marine Corps Base, Twentynine Palms, California, 1982-83: U.S. Geological Survey Water-Resources Investigations Report 84-4119, 18 p.

Dibblee, T.W., Jr., 1967a, Geologic map of the Deadman Lake quadrangle, San Bernardino County, California: U.S. Geological Survey Miscellaneous Geological Investigations Map I-488, scale 1:62,500.

-----1967b, Geologic map of the Emerson Lake quadrangle, San Bernardino County, California: U.S. Geological Survey Miscellaneous Geological Investigations Map I-490, scale 1:62,500.

-----1967c, Geologic map of the Joshua Tree quadrangle, San Bernardino and Riverside Counties, California: U.S. Geological Survey Miscellaneous Geological Investigations Map I-516, scale 1:62,500.

-----1968, Geologic map of the Twentynine Palms quadrangle, San Bernardino and Riverside Counties, California: U.S. Geological Survey Miscellaneous Geological Investigations Map I-561, scale 1:62,500.

Giessner, F.W., 1965, Ground-water conditions during 1964 at the Marine Corps Base, Twentynine Palms, California: U.S. Geological Survey Open-File Report, 30 p.

Giessner, F.W., and Robson, S.G., 1966, Ground-water conditions during 1965 at the Marine Corps Base, Twentynine Palms, California: U.S. Geological Survey Open-File Report, 27 p.

Heath, R.C., 1983, Basic ground-water hydrology: U.S. Geological Survey Water-Supply Paper 2220, 84 p.

Lewis, R.E., 1972, Ground-water resources of the Yucca Valley-Joshua Tree area, San Bernardino County, California: U.S. Geological Survey Open-File Report, 51 p.

Lohman, S.W., 1972, Ground-water hydraulics: U.S. Geological Survey Professional Paper 708, 70 p.

McDonald, M.G., and Harbaugh, A.W., 1984, A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 83-875, 528 p.

Moyle, W.R., Jr., 1982, Water resources of Borrego Valley and vicinity, California, phase 1--definition of geologic and hydrologic characteristics of basin: U.S. Geological Survey Open-File Report 82-855, 39 p.

-----1984, Bouguer gravity anomaly map of the Twentynine Palms Marine Corps Base and vicinity, California: U.S. Geological Survey Water-Resources Investigations Report 84-4005, scale 1:62,500.

Neste, Brudin, and Stone, 1986, Water supply and wastewater treatment study for Marine Corps Air Ground Combat Center, Twentynine Palms, California: San Diego, California, Neste, Brudin, and Stone, Inc., Engineers--Planners, 110 p. plus appendix.

Schaefer, D.H., 1978, Ground-water resources of the Marine Corps Base, Twentynine Palms, San Bernardino County, California: U.S. Geological Survey Water-Resources Investigations Report 77-37, 29 p.

Thomasson, H.G., Jr., Olmsted, F.H., and LeRoux, E.F., 1960, Geology, water resources, and usable groundwater storage capacity of part of Solano County, California: U.S. Geological Survey Water-Supply Paper 1464, 693 p.

☆U S GOVERNMENT PRINTING OFFICE: 1991-586-561/59119

POSTAGE AND FEES PAID
U.S. DEPARTMENT OF THE INTERIOR
INT 413

U.S. DEPARTMENT OF THE INTERIOR
Geological Survey, Room W-2234
2800 Cottage Way, Federal Building
Sacramento, CA 95825

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE $300
SPECIAL 4TH CLASS BOOK RATE

Londquist and Martin--GEOHYDROLOGY AND GROUND-WATER FLOW SIMULATION, SURPRISE SPRING BASIN, SAN BERNARDINO COUNTY, CA--WRIR 89-4099