GEOHYDROLOGY OF THE FOOTHILL GROUND-WATER BASIN NEAR SANTA BARBARA, CALIFORNIA

By John R. Freckleton

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 89-4017

Prepared in cooperation with the CITY OF SANTA BARBARA

Sacramento, California
1989

DEPARTMENT OF THE INTERIOR

MANUEL LUJAN, JR., Secretary

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information
write to:

District Chief
U.S. Geological Survey
Federal Building, Room W-2234
2800 Cottage Way
Sacramento, CA 95825

Copies of this report may be
purchased from:

U.S. Geological Survey
Books and Open-File Reports Section
Box 25425, Building 810
Federal Center
Denver, CO 80225

CONTENTS

	Page
Abstract	1
Introduction	2
Description of area	2
Acknowledgments	2
Well-numbering system	3
Description of the ground-water system	6
Geohydrologic framework	6
Aquifer hydraulic characteristics	7
Recharge and natural discharge	14
Pumpage	17
Ground-water levels and movement	18
Ground-water quality	19
Mathematical model	24
Description of model	25
Assumptions	25
Model boundaries and finite-difference network	25
Model calibration	34
Steady-state-verification calibration	34
Transient-state calibration	37
Sensitivity analysis	38
Limitations of the model	41
Methods to improve model input data	43
Summary and conclusions	44
Selected references	45

ILLUSTRATIONS

	Page
Figure 1. Map showing location and generalized geology of the Foothill and Santa Barbara ground-water basins	4
2. Graph showing annual precipitation at Santa Barbara, 1931-87	6
3. Map showing location of geologic sections	8
4. Geologic sections of the Foothill ground-water basin	10
5. Map showing location of selected wells in the Foothill ground-water basin and vicinity	12
6-7. Graphs showing:	
6. Water-level altitude at well 4N/28W-12H4 and pumpage at well 4N/27W-7D1, January 1985 to May 1986	14
7. Pumpage for the Foothill ground-water basin, 1935-87	17
8. Map showing location of water-level-monitoring-network wells, and composite-water-level contours in December 1985	20
9. Hydrograph showing water-level altitude in well 4N/28W-12B1, 1941-77	24

Page

Figures 10-12. Maps showing:
10. Location of water-quality monitoring wells 26
11. Stiff diagram and dissolved-solids concentration at selected wells 28
12. Foothill basin and Storage Unit I model grids 30
13-18. Diagrams showing:
13. Flux boundaries for model layers 1 and 2 33
14. Location of model stream-recharge blocks, areal-recharge blocks, underflow from the Santa Ynez Mountains, and underflow from area left unmodeled 33
15. Location of drain blocks 34
16. Model pumpage distribution, 1935 34
17. Steady-state-verification distributions of transmissivity for model layers 1 and 2 35
18. Model pumpage distribution, 1935-87 37
19. Hydrographs showing comparison of measured and model-generated water levels at selected wells,1935-87 39
20-21. Diagrams showing:
20. Storage-coefficient distributions for model layers 1 and 2 41
21. Model sensitivity at selected nodes to changes in pumpage, recharge, conductance of outflow drains, transmissivity, storage coefficient, and vertical hydraulic conductivity 42

TABLES

Page

Table 1. Transmissivity estimated from aquifer tests 7
2. Days of flow in Arroyo Burro at gaging station 11119780 15
3. Drainage area, permeable length, and width of streams in Foothill basin 15
4. Water levels in December in monitored wells, 1984-87 19
5. Water quality in monitored wells 22
6. Comparison of estimated and model-calibrated transmissivity values 36
7. Estimated and model-calibrated steady-state-verification water budgets 36
8. Pumpage used in the transient model, Foothill basin, 1935-87 37

CONVERSION FACTORS

The inch-pound system of units is used in this report. For readers who prefer metric (International System) units, the conversion factors for the terms used in this report are listed below:

Multiply	By	To obtain
acres	0.004047	square kilometers
acre-feet (acre-ft)	1,233	cubic meters
acre-feet per acre (acre-ft/acre)	3.047×10^5	cubic meters per square kilometer
acre-feet per year (acre-ft/yr)	1,233	cubic meters per year
cubic feet per second (ft^3/s)	0.02832	cubic meters per second
feet	0.3048	meters
feet per day (ft/d)	0.3048	meters per day
feet per foot (ft/ft)	1	meters per meter
feet per mile (ft/mi)	0.1894	meters per kilometer
feet per second (ft/s)	0.3048	meters per second
feet squared per day (ft^2/d)	0.09290	meters squared per day
gallons per day per square foot [$(gal/d)/ft^2$]	0.04073	cubic meters per day per square meter
inches	25.4	millimeters
inches per year (in/yr)	25.4	millimeters per year
miles	1.609	kilometers
square miles (mi^2)	2.590	square kilometers

Additional abbreviations used:
mg/L milligrams per liter
μg/L micrograms per liter

Specific conductance is given in microsiemens per centimeter (μS/cm) at 25 degrees Celsius. Microsiemens per centimeter is numerically equal to micromhos per centimeter.

DEFINITION OF TERMS

Water year: Except as explicitly modified, "water year" refers to the 12-month period that starts October 1 and ends September 30; it is designated by the calendar year in which it ends and which contains 9 of the 12 months.

Cachuma water year: The Cachuma water year is the 12-month period May 15-May 14.

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 OF THE FOOTHILL GROUND-WATER BASIN NEAR SANTA BARBARA, CALIFORNIA

By John R. Freckleton

ABSTRACT

The 4.5-square-mile Foothill ground-water basin is in southwestern Santa Barbara County, California, northeast of the city of Goleta and northwest of the city of Santa Barbara. In previous reports, the western part of the Foothill basin is referred to as the East subbasin of the Goleta ground-water basin and the eastern part as Storage Unit II of the Santa Barbara ground-water basin. Geohydrologic data presented in this report indicate that the Foothill basin is a separate ground-water basin, which is bordered on the north and northeast by the Santa Ynez Mountains and on three sides by faults that impede ground-water flow. Sedimentary rocks of Tertiary age underlie the ground-water basin and form its lower boundary.

The Santa Barbara Formation, which forms the principal aquifer of the basin, consists primarily of Pleistocene and Pliocene unconsolidated marine sand, silt, and clay, and has a maximum thickness of about 400 feet. The aquifer is confined in places where a zone of low permeability in its upper part separates its major water-bearing zones from overlying Quaternary and Pleistocene alluvium.

Although the Modoc, Mesa, and Mission Ridge faults act as barriers to ground-water movement in the Santa Barbara Formation, application of Darcy's law to discharge areas, as indicated by water-level contours, suggests that ground water can flow over the tops of the faults through the unfaulted younger alluvium in the vicinity of Cieneguitas and Atascadero Creeks and south of the confluence of Arroyo Burro and San Roque Creek.

The main sources of recharge to the Foothill basin are seepage from streams, infiltration of precipitation, and subsurface inflow from consolidated rocks of the Santa Ynez Mountains. Estimates of recharge by streams range from about 160 to 460 acre-feet per year. Precipitation infiltration is estimated to be about 320 acre-feet per year. Subsurface inflow is estimated to range from about 25 to as much as 300 acre-feet per year. During nonpumping conditions, ground-water discharge as underflow and to streams is estimated to range from about 500 to 1,100 acre-feet per year. Ground-water discharge as underflow in 1985 is estimated to be about 280 acre-feet.

Ground-water pumping in the area began in the 1800's. During the period of record, 1935-87, pumpage ranged from 160 to about 2,400 acre-feet per year. Pumpage in 1987 is estimated to be about 1,300 acre-feet.

Ground-water levels declined more than 60 feet during periods of heavy pumping in the early 1950's, but levels generally rose during the mid-1950's to the late 1970's. Measured water levels during 1984-87 indicate a general decline, which may reflect increased pumpage during this period.

Water-quality data indicate markedly different water types, generally with greater concentrations in principal cations and ions and greater dissolved solids, in the Foothill ground-water basin in comparison with nearby basins. Nitrate concentrations in samples from two basin wells exceeded the primary maximum contaminant level (10 milligrams per liter) as established by the U.S. Environmental Protection

Agency. Secondary maximum contaminant levels for dissolved solids, chloride, and sulfate were exceeded in some samples. All sampled ground water would be classified as very hard (greater than 300 milligrams per liter as $CaCO_3$*). Sodium concentrations exceeded 20 milligrams per liter in all water samples and may be a hazard to the health of those who must restrict sodium in their diets. The pH of the sampled water ranged from 7.2 to 8.0.*

A three-dimensional finite-difference model was developed for part of the Foothill basin. The natural system was simulated with two layers in the model. The upper layer represents alluvial aquifers, and the lower layer represents primarily the Santa Barbara Formation. Hydraulic connection between the layers is simulated as a confining zone, which forms the upper part of the Santa Barbara Formation. Steady-state-verification and transient-state model calibrations were used to estimate or confirm estimates of basin recharge and natural discharge. Model-calibrated recharge was calculated to be 905 acre-feet per year. Flow out of the basin was calculated, using the steady-state-verification model, to be 905 acre-feet per year. Model limitations result mainly from imprecise conceptualization of the natural system and from lack of precise input data.

INTRODUCTION

In 1977, the city of Santa Barbara entered into a cooperative agreement with the U.S. Geological Survey to develop and implement a ground-water monitoring program (Hutchinson, 1979) concentrating on Storage Unit I of the Santa Barbara ground-water basin (fig. 1). The study subsequently was extended to an evaluation of the effects of pumping on water levels and water quality (Martin, 1984) and the development of a mathematical ground-water flow model (Martin and Berenbrock, 1986). During the study, the city of Santa Barbara began to increase pumping in the adjacent Storage Unit II (of the Santa Barbara ground-water basin) and in the East subbasin of the Goleta ground-water basin, hereafter referred to (together) as the Foothill basin.

To better understand the hydrology of the Foothill basin, the city of Santa Barbara requested that the U.S. Geological Survey complete a study of the basin similar to a study completed for the coastal Santa Barbara basin (Hutchinson, 1979; Martin, 1984; Martin and Berenbrock, 1986). The purpose of the present study was to define the geohydrology of the Foothill basin, with emphasis on the effects of pumping on the ground-water flow system. As part of the study, a ground-water flow model was developed for the Foothill basin in order to evaluate water-level response to ground-water pumpage. This report describes the results of the geohydrologic study and the model developed for the Foothill basin. Data collected from water-quality and water-level observation wells are included and evaluated in this report, along with estimates of historical pumpage and estimates of transmissivity and storage coefficient.

Description of Area

Located in southwestern Santa Barbara County, northeast of Goleta and northwest of Santa Barbara, the 4.5-square-mile Foothill basin includes the areas formerly called the East subbasin of the Goleta ground-water basin and Storage Unit II of the Santa Barbara ground-water basin (fig. 1).

Developed areas within the basin are primarily residential with limited commercial and industrial activities. Historically, cattle grazing and then agriculture were the main land uses. Cattle grazing virtually ended with the catastrophic drought of 1862-64; at the end of this period, 5,000 head of cattle was listed on county assessment rolls--down from 200,000 a year earlier (Santa Barbara Soil Conservation District, 1968, p. 4). Agriculture remained a dominant land use, steadily increasing through the early 1950's. The completion of the Cachuma Water Project during this period (meant, in part, to insure an adequate and dependable supply of water for agricultural uses) fostered rapid residential growth, followed by commercial and industrial expansion (Santa Barbara Soil Conservation District, 1968, p. 4).

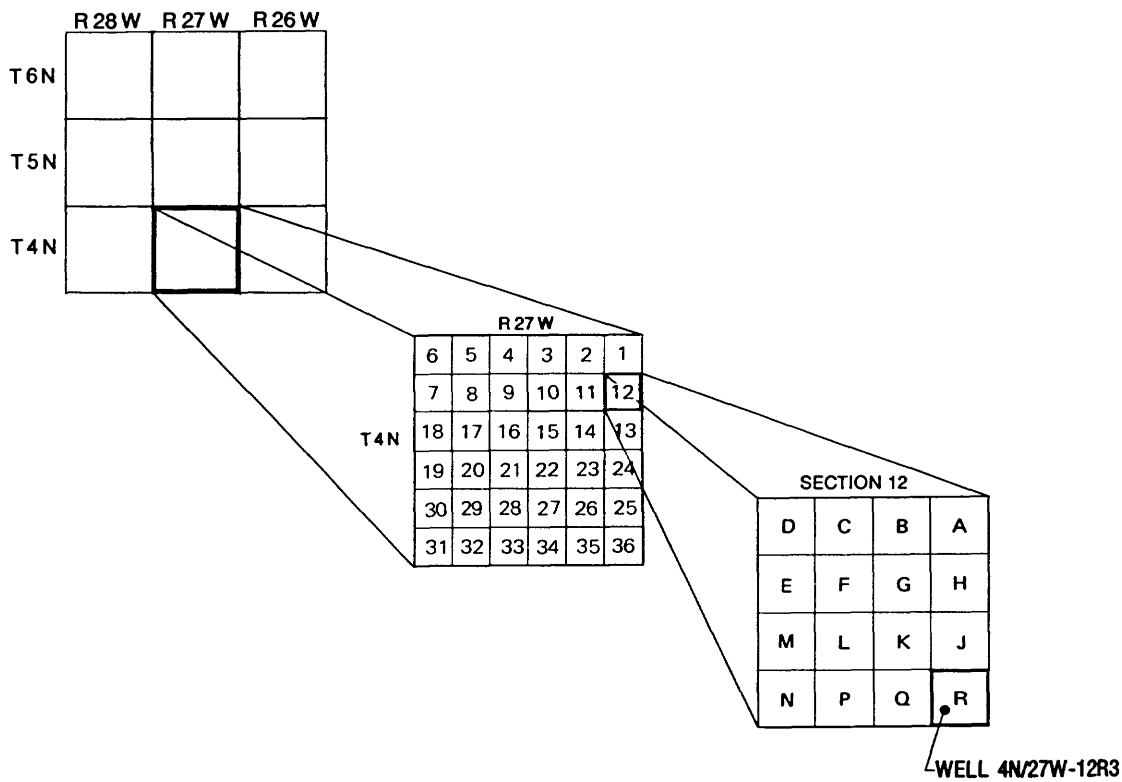
The Goleta-Santa Barbara area is characterized by a Mediterranean-like climate of warm summers and mild winters with little frost hazard. Rainfall occurs principally from November through March; in summer, occasional thundershowers occur in the adjacent mountains. Mean annual precipitation at Santa Barbara for 1931-87 was 17.91 in/yr (fig. 2). Extremes in precipitation include 3.99 inches in 1947 (National Oceanic and Atmospheric Administration) and 50 inches in 1861 (Santa Barbara Soil Conservation District, 1968, p. 4).

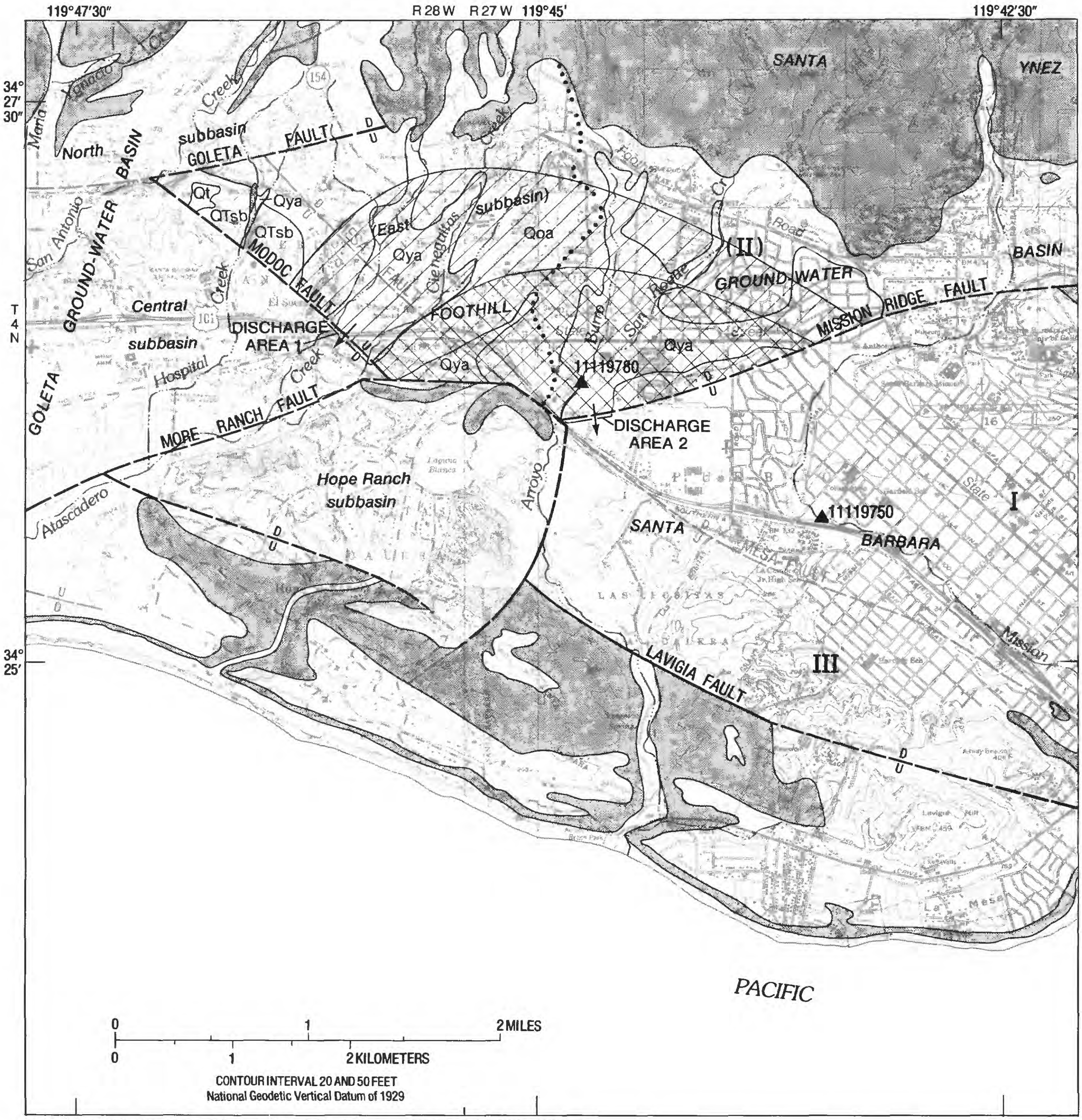
Acknowledgments

Gratefully acknowledged are the cooperative assistance of the city of Santa Barbara's Public Works Department, Division of Water Resources, and that of Michael F. Hoover, consulting geologist, who supplied published and unpublished data on water levels, basin pumpage, water quality, and aquifer-test results. The information provided by local water companies and well owners is likewise acknowledged.

Well-Numbering System

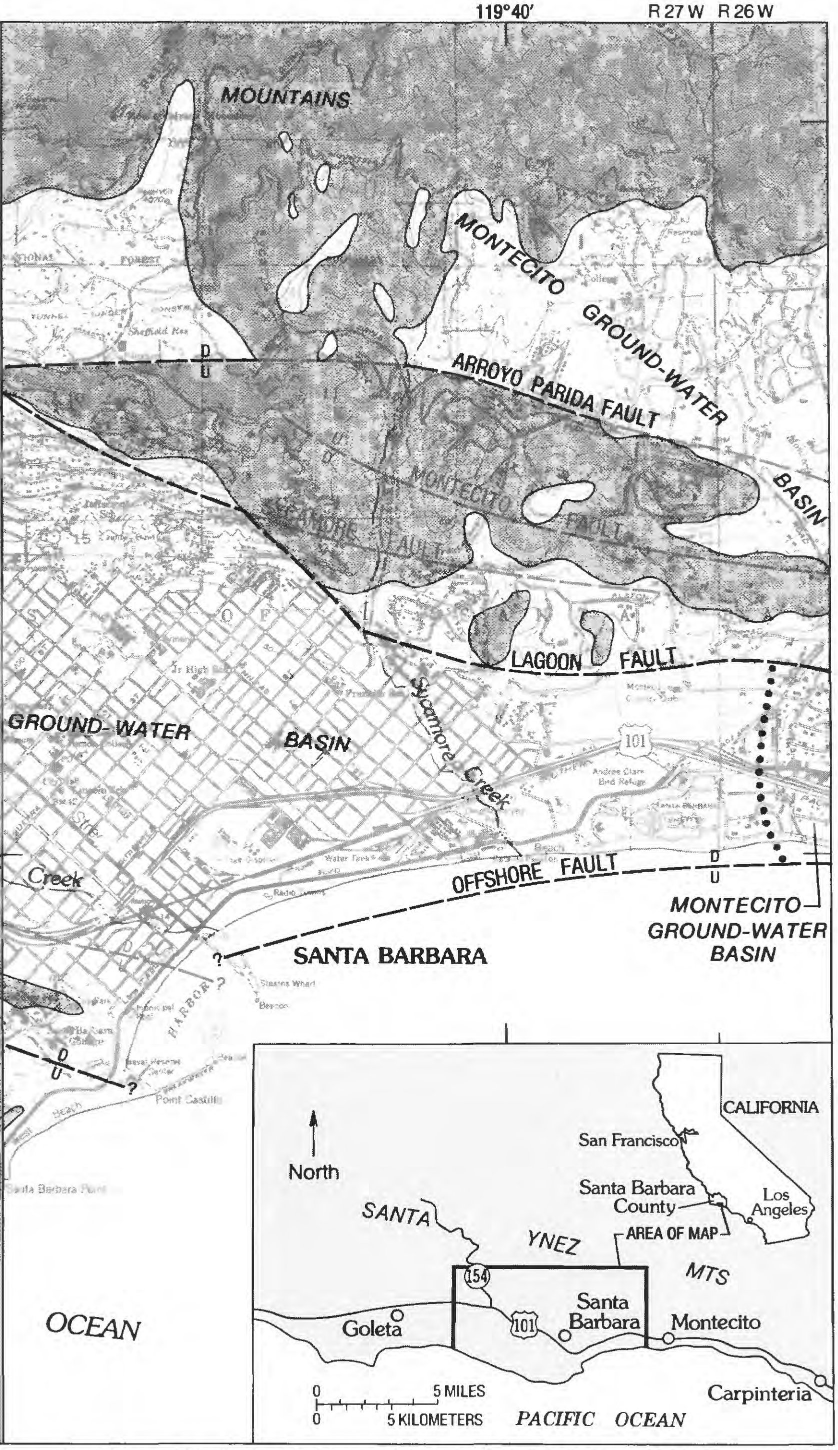
Wells are numbered according to their location in the rectangular system for subdivision of public land. For example, in well number 4N/27W-12R3, the number and letter preceding the slash indicate the township (T. 4 N.); the number and letter following the slash indicate the range (R. 27 W.); the number following the hyphen indicates the section (sec. 12); and the letter following the section number indicates the 40-acre subdivision according to the lettered diagram below. The final digit is a serial number for wells in each 40-acre subdivision.





Base from U.S. Geological Survey, Santa Barbara and Goleta 1:24,000, 1967

FIGURE 1.—Location and generalized geology of the Foothill and Santa Barbara ground-water basins.



EXPLANATION

UNCONSOLIDATED DEPOSITS

Selected unconsolidated deposits in the Foothill ground-water basin (QUATERNARY)

- Qya — Younger alluvium (Holocene)
- Qt — Terrace deposits (Pleistocene)
- Qoa — Older alluvium (Pleistocene)

Marine deposits (QUATERNARY AND TERTIARY)

- QTsb — Santa Barbara Formation (Pleistocene and Pliocene)

All other unconsolidated deposits (QUATERNARY AND TERTIARY)

- Undifferentiated (Holocene to Pliocene)

CONSOLIDATED ROCKS (TERTIARY)

- Shale, sandstone, and conglomerate (Pliocene to Eocene)

D/U ? FAULT—Dashed where approximately located; queried where doubtful. U, upthrown side; D, downthrown side. Black indicates boundary of ground-water basin

GEOLOGIC CONTACT

APPROXIMATE AREA OF GROUND-WATER CONFINEMENT—Foothill ground-water basin

- In alluvium
- In the Santa Barbara Formation

GROUND-WATER STORAGE UNIT—Former designation of storage unit and subbasin name in parentheses (III)

DIRECTION OF GROUND-WATER DISCHARGE

GROUND-WATER DIVIDE

FORMER GROUND-WATER DIVIDE

11119750 STREAM-GAGING STATION AND NUMBER

Geology modified from J.E. Upson (1951), K.S. Muir (1968), and M.F. Hoover (1978)

FIGURE 1.—Continued

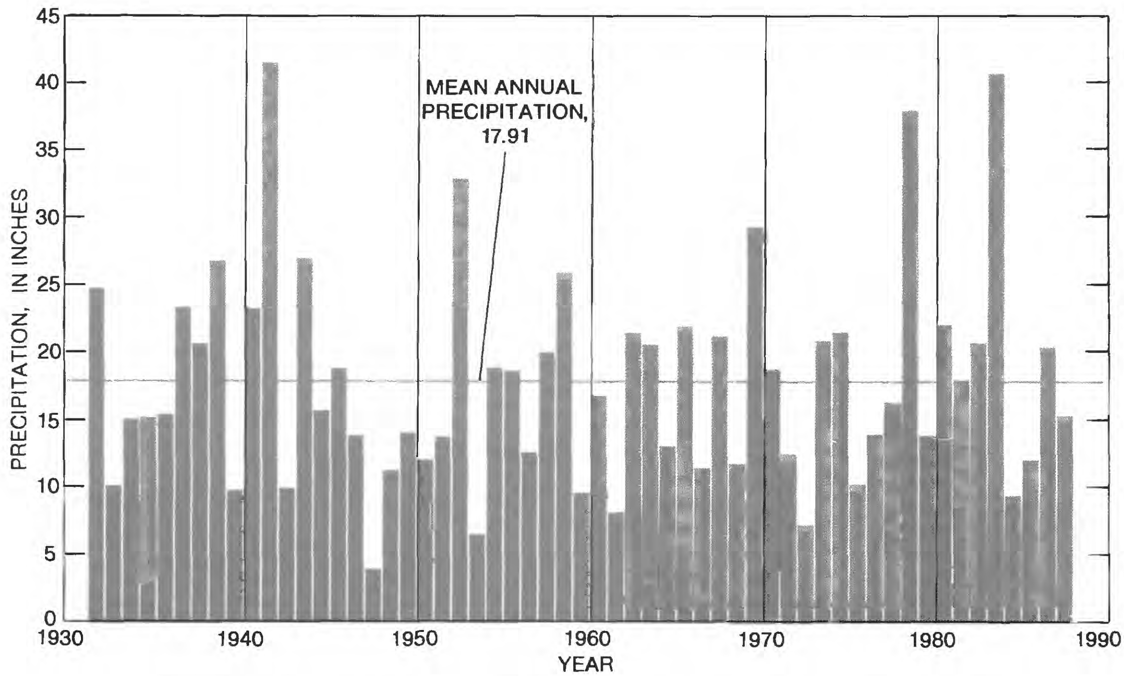


FIGURE 2.—Annual precipitation at Santa Barbara, 1931-87. (Data for 1981-85 from Santa Barbara Airport.)

DESCRIPTION OF THE GROUND-WATER SYSTEM

Geohydrologic Framework

The area referred to as the Foothill basin in this report includes the East subbasin of the Goleta ground-water basin and Storage Unit II of the Santa Barbara ground-water basin (fig. 1). Prior to this study, those units were thought to be separated by a ground-water divide (Evenson and others, 1962, p. 72).

The Foothill basin is bounded by Tertiary sedimentary rocks of the Santa Ynez Mountains on the north and northeast; by the Goleta fault on the northwest; by the Modoc, More Ranch, and Mesa faults on the southwest; and by the Mission Ridge fault on the southeast (fig. 1). The fault boundaries are inferred from water-level differences in wells, and from interpretation of geologic sections derived from drillers' and electric logs (figs. 3 and 4). The faults, for the most part, act as ground-water barriers that impede ground-water flow into and out of the area. Sedimentary rocks of Tertiary age underlie the ground-water basin and form its lower boundary. Also, small outcrops of Tertiary sedimentary rocks occur in the western part of the basin along Hospital Creek and in the eastern part of the basin north of Foothill Road (fig. 1).

The unconsolidated water-bearing deposits that make up the ground-water system include the Santa Barbara Formation of Late Pliocene to Early Pleistocene age, older alluvium and terrace deposits of Pleistocene age, and younger alluvium of Holocene age.

The principal aquifer of the Foothill basin is the Santa Barbara Formation, which consists mainly of marine sand, silt, and clay and has a maximum thickness of about 400 feet (fig. 4). The Santa Barbara Formation is overlain by alluvium everywhere in Foothill basin except where it crops out south of the Goleta fault (fig. 1). The outcrop extends about 1 mile along the Modoc fault and reaches a maximum width of about 0.3 mile. Older alluvium occurs as extensive deposits of gravel, sand, silt, and clay as much as 400 feet in thickness in the eastern part of the basin (fig. 4). The alluvium occupies a large part of the recharge area and allows infiltration of precipitation and intermittent streamflow to the underlying Santa Barbara Formation. The younger alluvium consists of gravel, sand, silt, and clay extending along the major streams and as fingers into the adjoining mountain canyons. Ground water in the Santa Barbara Formation is confined by a zone of low permeability in its upper part. This confining zone ranges in thickness from a few feet to more than 100 feet (fig. 4) and separates major water-producing zones in the Santa Barbara Formation from the water-bearing units in the alluvium. Water in the Santa Barbara Formation is unconfined where the zone of low permeability is missing. Ground water generally is unconfined in the younger and older alluvium; however, there are areas of local confinement.

Aquifer Hydraulic Characteristics

Knowledge of the transmissivity and storage coefficient of water-bearing materials is required to analyze the effects of ground-water pumping. Transmissivity and storage coefficient usually are determined using data from aquifer tests or are estimated from drillers' logs.

Transmissivity is the rate at which water of a prevailing kinematic viscosity is transmitted through a unit width of aquifer under a unit hydraulic gradient. The units of transmissivity may be expressed in many different forms (Lohman, 1972, p. 6); the units used in this report are feet squared per day (ft^2/d).

Transmissivity of the unconsolidated deposits, as estimated from aquifer tests (table 1), ranges from 265 ft^2/d at well 4N/28W-12L6, which is perforated entirely in the Santa Barbara Formation, to 1,217 ft^2/d at well 4N/27W-8L2, which is perforated in both the alluvium and the Santa Barbara Formation. Wells referred to in table 1 are shown in figure 5. In general, transmissivities increase from the north and west toward the south and southeast parts of the basin. Although no aquifer-test data are available along the foothills of the Santa Ynez Mountains, transmissivity of the unconsolidated deposits probably is low because of the thinness of the aquifer material. Rightward kicks in electric logs are indicative of greater relative hydraulic conductivity of aquifer materials. Presence of rightward kicks near the bottom of the alluvium in electric logs at wells 4N/28W-1R2, 4N/27W-6Q12, and 4N/27W-8E1 (fig. 4) indicate that these zones are more transmissive, in general, than the overlying material.

Storage coefficient is the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in hydraulic head (Lohman, 1972, p. 8). Storage coefficient is a dimensionless quantity.

Table 1.--Transmissivity estimated from aquifer tests

[Formation in which well is perforated: A, Alluvium; SB, Santa Barbara Formation. Location of wells is shown in figure 5. ft^2/d, feet squared per day]

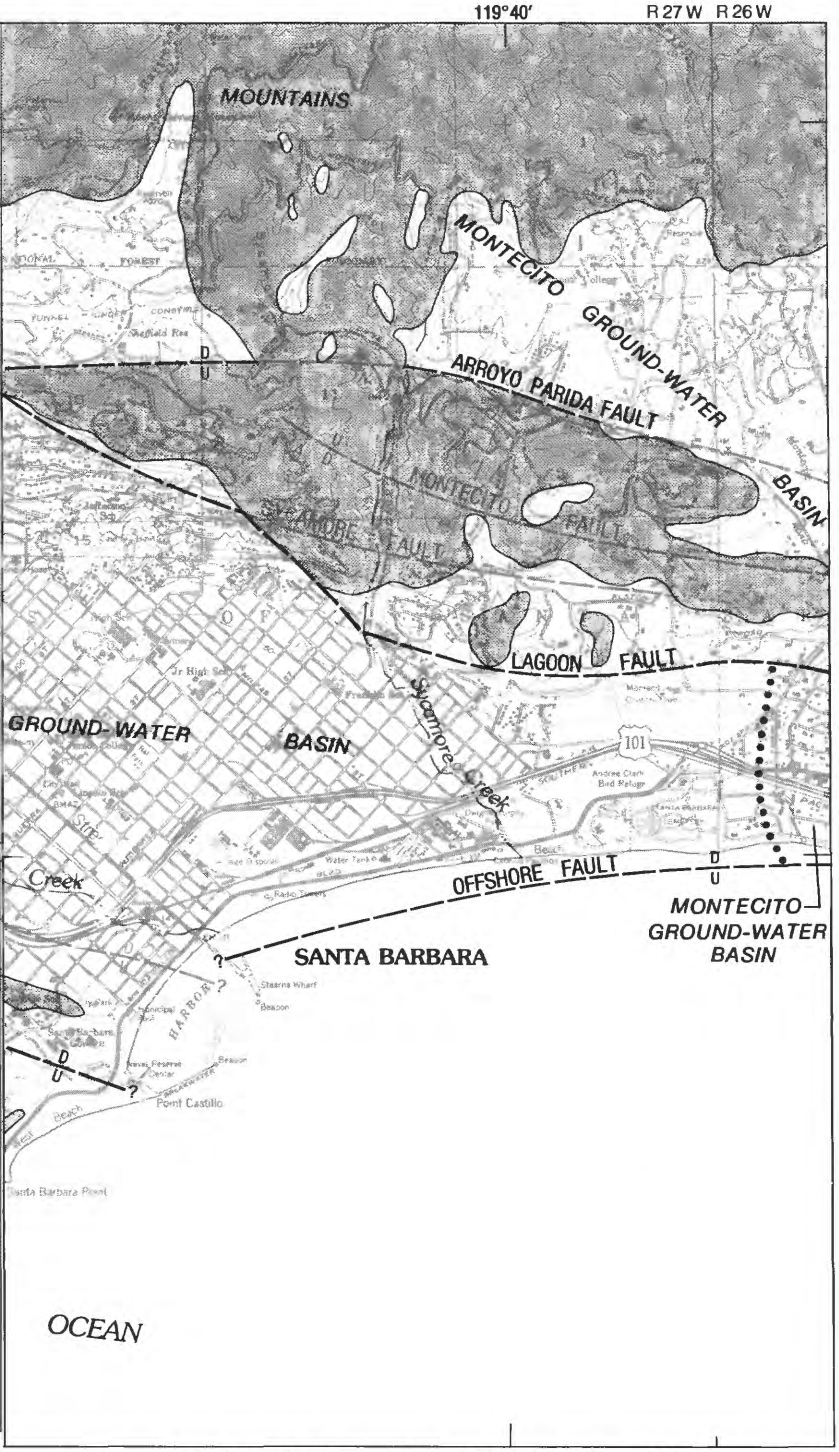
Well No.	Formation in which well is perforated	Trans-missivity (ft^2/d)
4N/27W-6Q12	SB	471
4N/27W-7H5	SB	882
4N/27W-7Q5	SB	856
4N/27W-7R3	SB	950
4N/27W-8L2	A, SB	1,217
4N/28W1R2	SB	294
4N/28W-12H4	SB	882
4N/28W-12K4	A, SB	373
4N/28W-12L6	SB	265
4N/28W-12R3	SB	882

Few data are available to estimate the storage coefficient of unconsolidated deposits in the basin. A value of 0.0022 was calculated by Michael F. Hoover, consulting geologist, from data obtained during an aquifer test at well 4N/28W-12R2 (Hoover, 1978). This value is indicative of confined conditions that occur in the south and southeast parts of the basin. Further evidence of the confined nature of the aquifer in these parts of the basin is the rapid water-level response of well 4N/28W-12H4 to pumpage at well 4N/27W-7D1 (fig. 6); these wells are about 1,300 feet apart and both are perforated in the Santa Barbara Formation. For unconfined conditions, such as occur in the north, northwest, and northeast parts of the basin, the storage coefficient is virtually equal to the specific yield. Specific yield of saturated materials in the +100 to -200 feet depth zone (feet above and below sea level) ranges from 7.5 to 17.5 percent in the Santa Barbara area (Muir, 1968, p. A13) and probably has a similar range in the Foothill basin.

The confining zone that separates the alluvium and the major water-producing zones of the Santa Barbara Formation is a zone of low permeability through which ground-water leakage occurs when there is a difference in hydraulic head between the layers. This zone of low permeability correlates stratigraphically with the "middle

Base from U.S. Geological Survey, Santa Barbara and Goleta 1:24,000, 1967

FIGURE 3.—Location of geologic sections.



Geology modified from J.E. Upson (1951), K.S. Muir (1968), and M.F. Hoover (1978)

EXPLANATION

UNCONSOLIDATED DEPOSITS (QUATERNARY AND TERTIARY)

CONSOLIDATED ROCKS (TERTIARY)

D/U ? FAULT—Dashed where approximately located; queried where doubtful. U, upthrown side; D, downthrown side. Black indicates boundary of ground-water basin

GEOLOGIC CONTACT

E——E′ LINE OF GEOLOGIC SECTION—Sections shown in figure 4

III GROUND-WATER STORAGE UNIT—Former designation of storage unit and subbasin name in parentheses

•••••••• GROUND-WATER DIVIDE

•••• •••• FORMER GROUND-WATER DIVIDE

•7Q5 WELL AND NUMBER

FIGURE 3.—Continued.

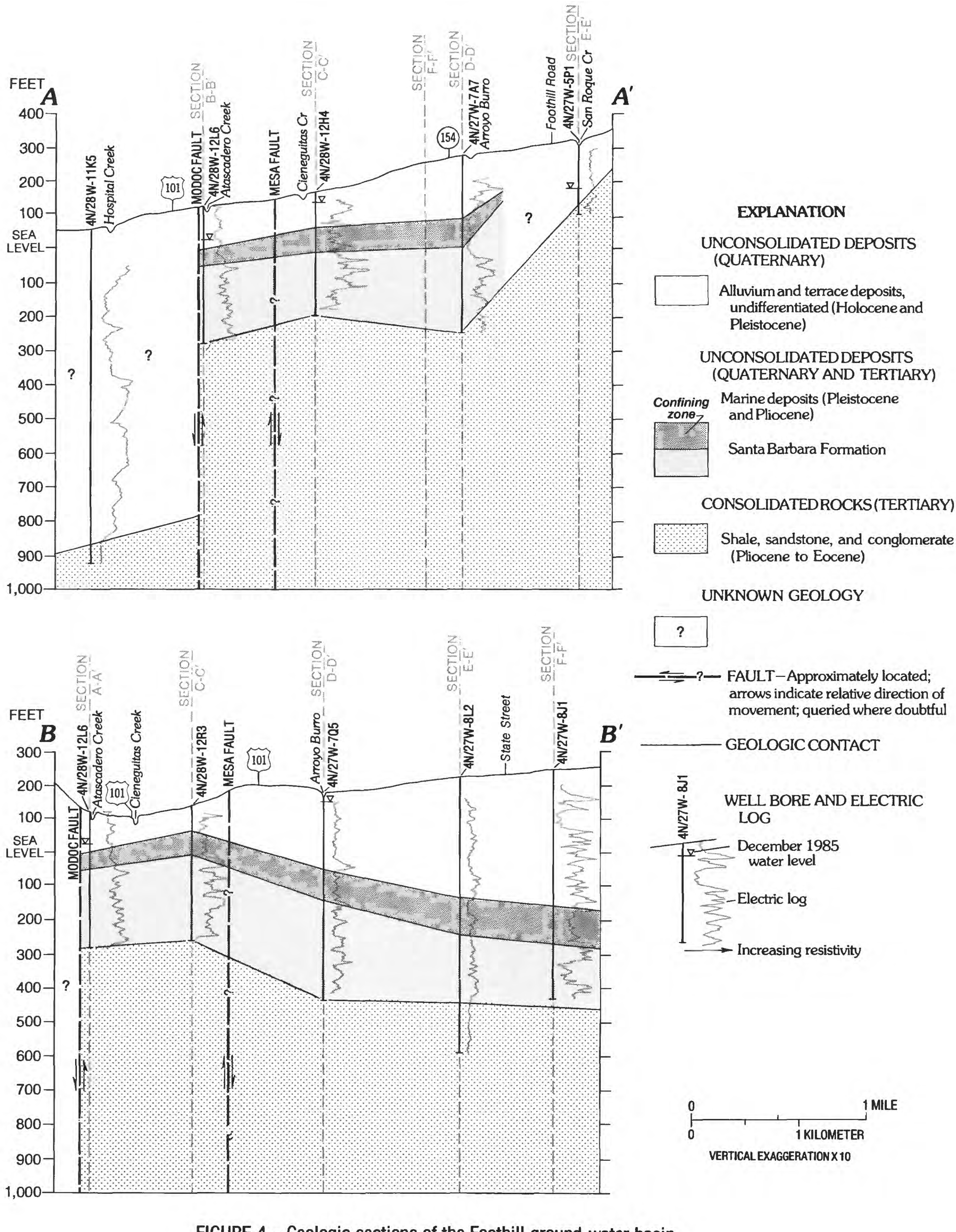


FIGURE 4.—Geologic sections of the Foothill ground-water basin.

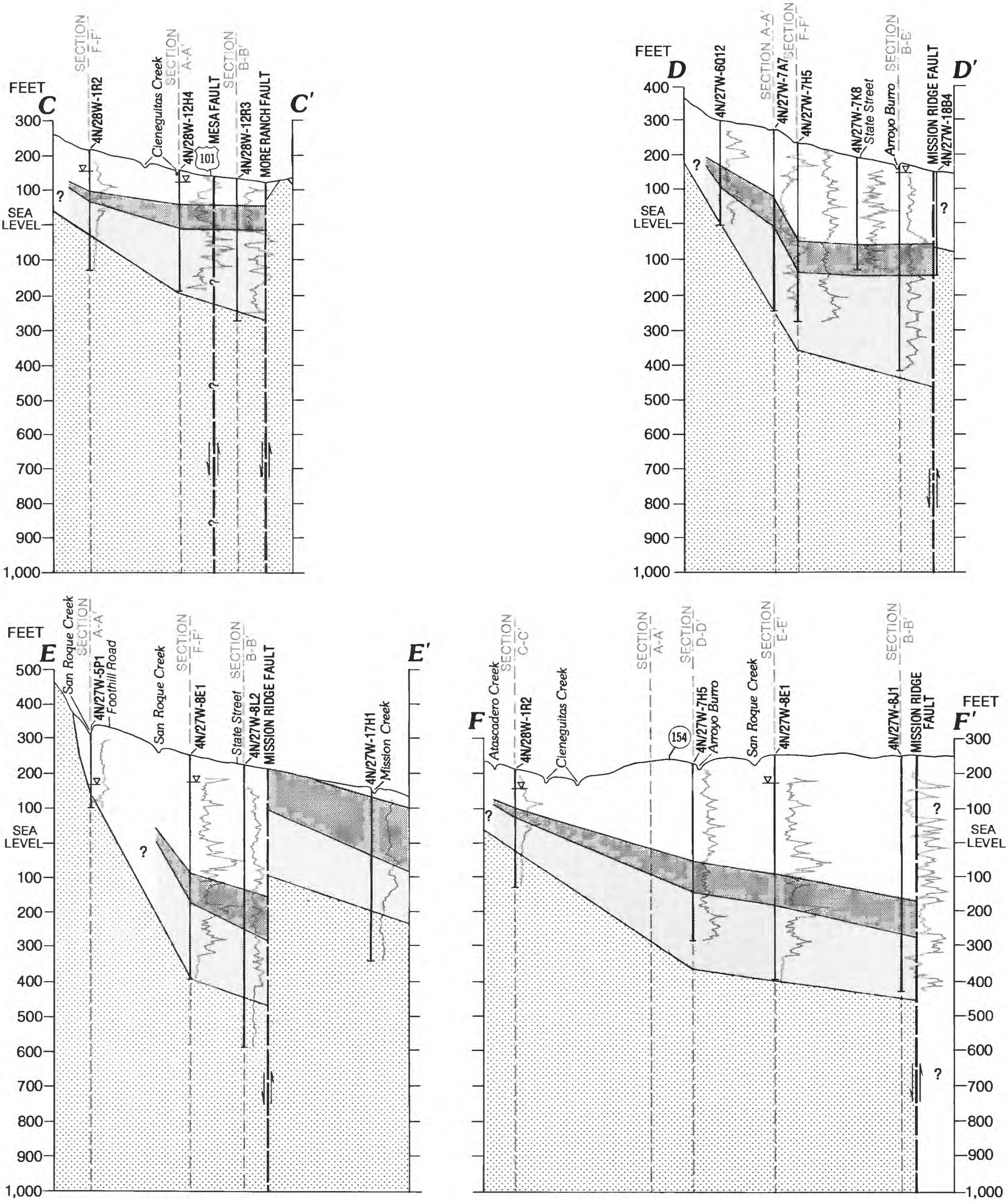
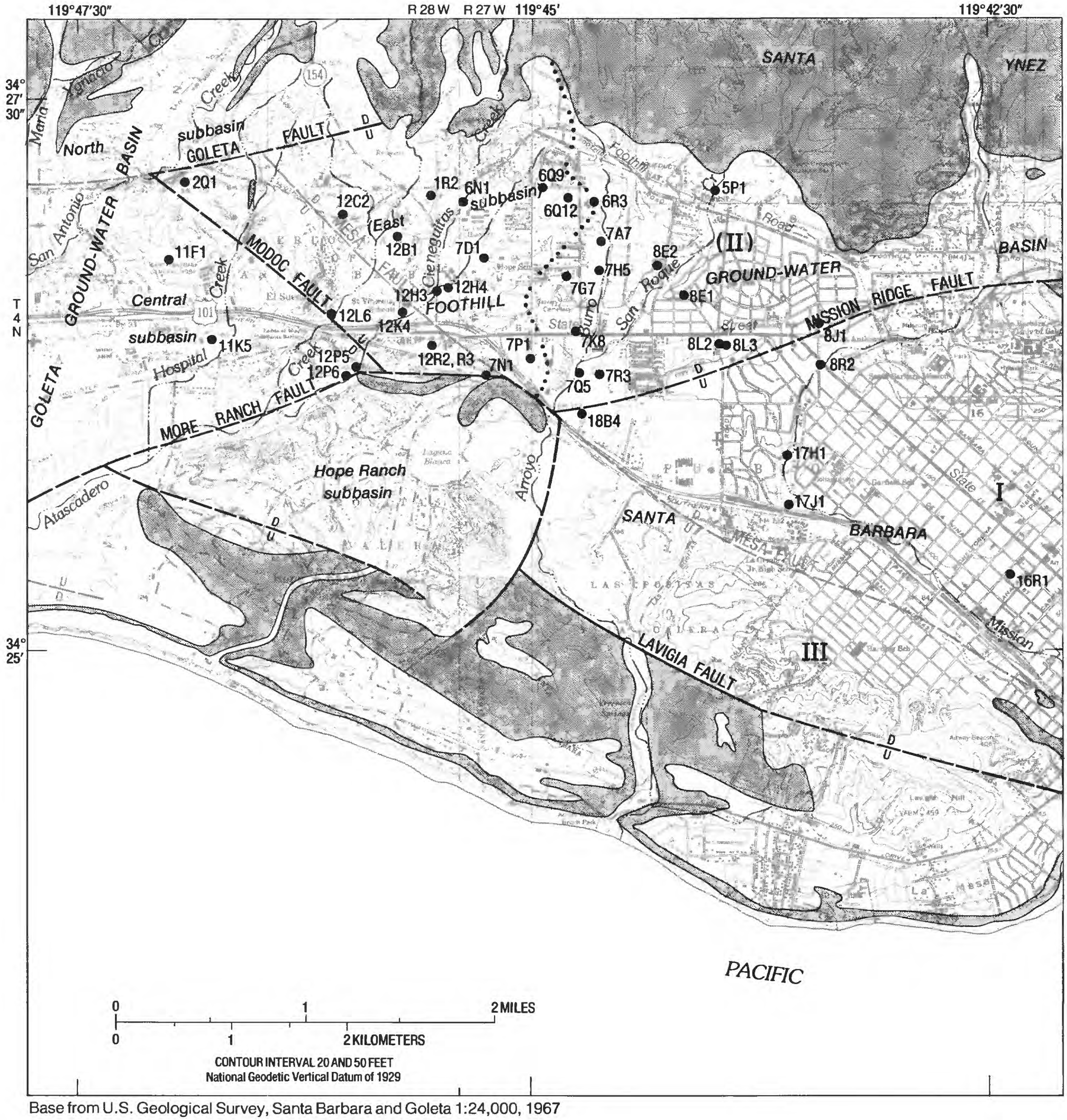
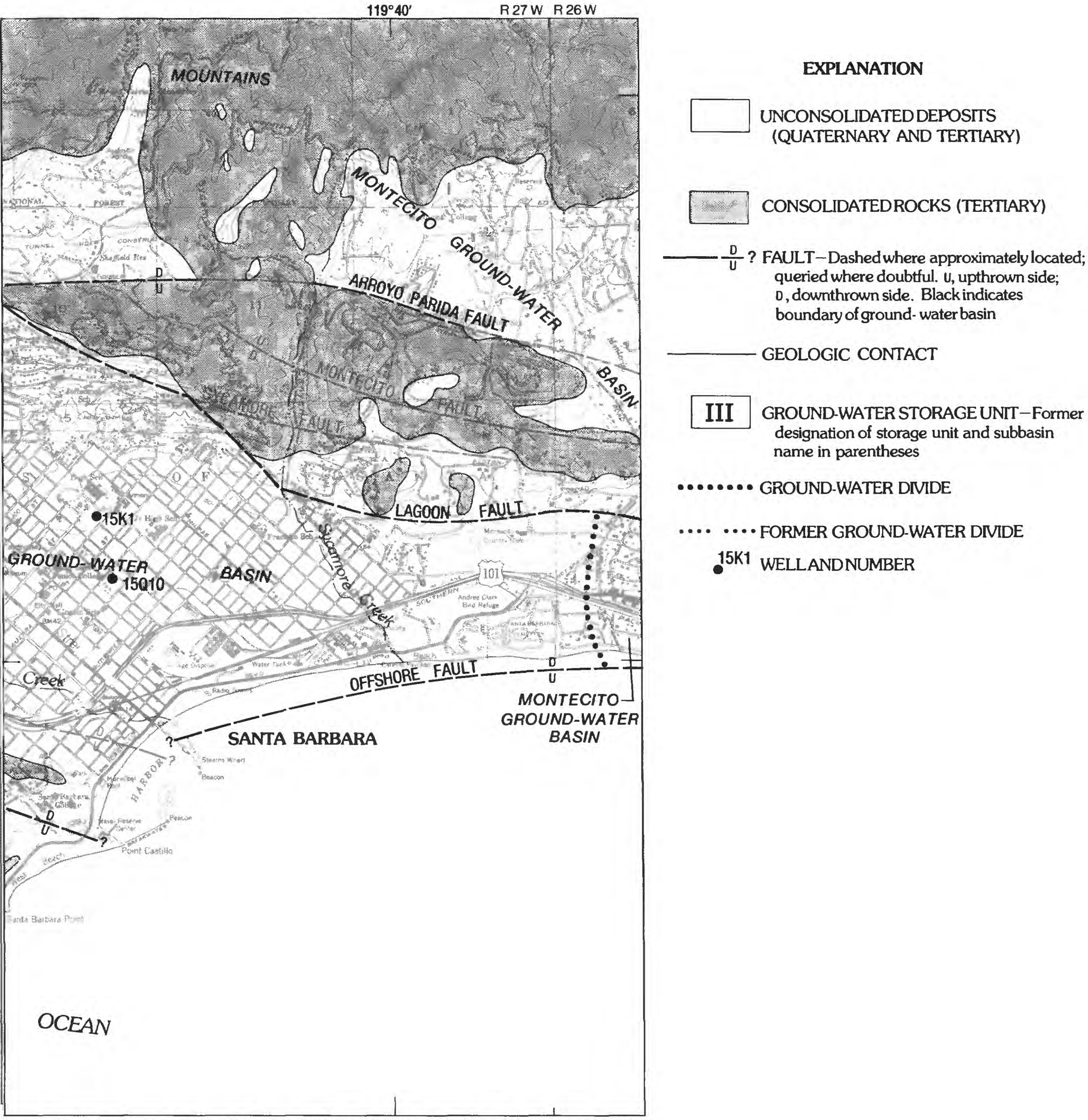


FIGURE 4.—Continued.



Base from U.S. Geological Survey, Santa Barbara and Goleta 1:24,000, 1967

FIGURE 5.—Location of selected wells in the Foothill ground-water basin and vicinity.



Geology modified from J.E. Upson (1951), K.S. Muir (1968), and M.F. Hoover (1978)

FIGURE 5.—Continued.

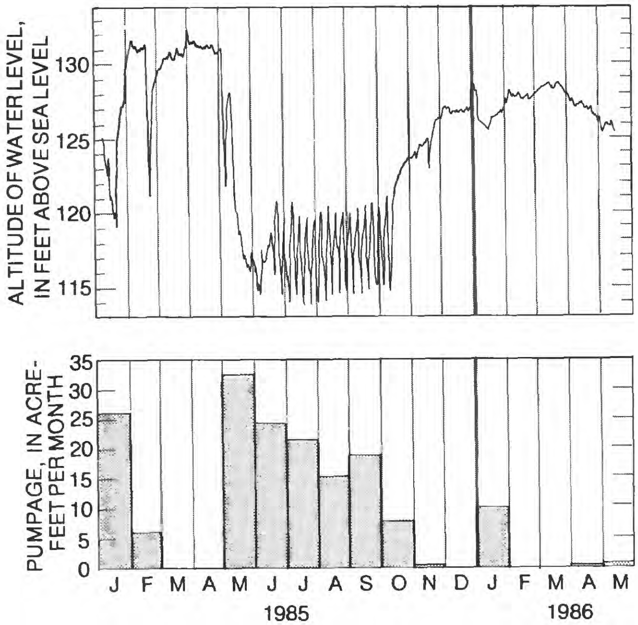


FIGURE 6.—Water-level altitude in well 4N/28W-12H4 and pumpage at well 4N/27W-7D1, January 1985 to May 1986.

zone" of Storage Unit I of the Santa Barbara ground-water basin which Martin and Berenbrock (1986, p. 7) define as the upper part of the Santa Barbara Formation and which consists mainly of fine-grained deposits interspersed with occasional coarse-grained water-bearing deposits. The rate at which leakage occurs is controlled by the thickness and vertical hydraulic conductivity of the confining zone and by the hydraulic-head difference across this zone. A medium has a hydraulic conductivity of unit length per unit time if it will transmit in unit time a unit volume of ground water at the prevailing viscosity through a cross section of unit area, measured at right angles to the direction of flow, under a hydraulic gradient of unit change in head through unit length of flow (Lohman, 1972, p. 6). Martin and Berenbrock (1986, p. 47) estimated a vertical hydraulic conductivity of 3.8×10^{-7} ft/s in the "middle zone," and this value probably can be extrapolated to the confining zone in the Foothill basin because of the stratigraphic correlation.

Recharge and Natural Discharge

The main sources of recharge to the Foothill basin are seepage from streams, infiltration of precipitation, and subsurface inflow from fractured and weathered zones in the consolidated rocks of the Santa Ynez Mountains. Infiltration from irrigation water imported from surface reservoirs is a minor source of recharge. Ground water is discharged naturally from the Foothill basin by subsurface outflow, springs, and evapotranspiration.

The major streams in the area are Arroyo Burro and its tributary, San Roque Creek, which drain southward from the Santa Ynez Mountains. San Roque Creek is perennial in its upper canyon; however, it becomes intermittent in its lower alluvial channel, which lies outside the basin. San Roque Creek has the flattest gradient of the local streams--about 270 ft/mi for the stretch between the altitudes of 1,000 and 250 feet above sea level. The average number of days per year of measurable flow in Arroyo Burro was 267 at gaging station 11119780 (Arroyo Burro Creek at Santa Barbara; fig. 1) for the period of record, calendar years 1971-88. However, a large shopping center built prior to 1971 upstream from the gage discharges air-conditioner-effluent water into the channel; therefore, the number of days of flow recorded there may not be reflective of natural conditions. Mission Creek at gaging station 11119750 (Mission Creek near Mission Street) (fig. 1) had an average of 90 days of flow per year for calendar years 1971-88, and this figure may be more representative of the days of flow in the major streams in the Foothill basin. Table 2 shows the number of days of flow and the yearly total flow, in acre-feet, for gaging station 11119780, downstream from the confluence of Arroyo Burro and San Roque Creek (fig. 1).

Comparison of the days of flow for Arroyo Burro and Mission Creek indicates that air-conditioner-effluent discharge (and possible urban runoff) probably ranges from 0.01 ft^3/s, or less, to 0.05 ft^3/s. On the basis of an average of 267 days of flow, this amounts to less than 27 acre-ft/yr (or about 3.5 percent of the median annual flow for the period of record). Therefore, air-conditioner-effluent discharge will be ignored in subsequent calculations. Also, the yearly average number of days of natural flow in Arroyo Burro at gaging station 11119780 will be assumed to be 90.

Other streams in the basin that provide lesser amounts of recharge are Cieneguitas, Atascadero, and Hospital Creeks, which drain southwestward through the study area into the Goleta Valley (not shown in figures) and then to the ocean via the Goleta Slough. Mission

Table 2.--Days of flow in Arroyo Burro at gaging station 11119780

Calendar year	Days of flow	Streamflow, in acre-feet
1971	161	486
1972	173	601
1973	193	3,150
1974	219	1,660
1975	242	1,720
1976	308	468
1977	179	606
1978	239	6,960
1979	258	923
1980	242	2,890
1981	257	729
1982	364	810
1983	365	6,220
1984	364	289
1985	344	230
1986	365	1,100
1987	329	289
1988	208	328
Average	267	1,637
Median	250	770

Creek upstream from the Mission Ridge fault does not recharge the ground-water basin (Martin, 1984, p. 7).

Recharge due to infiltration of streamflow was estimated by Muir to be 14 percent of runoff in the Santa Barbara area (Muir, 1968, p. A20). Todd (1978, p. 37) cited an infiltration rate of 4.8 $(gal/d)/ft^2$ for Mission Creek downstream from the Mission Ridge fault. Martin (1984, p. 6-7) made seepage-loss measurements of controlled releases to Mission Creek, and calculated an estimated annual recharge rate for water years 1971-78. Martin's estimate of 376 acre-ft/yr amounts to about 39 percent of the median annual discharge (968 acre-ft/yr) for that period, and about 40 percent of the median annual discharge for calendar years 1971-88.

The median annual streamflow at gaging station 11119780 (table 2) was used to estimate streamflow at ungaged streams in the Foothill basin. Median annual streamflow in ungaged streams was calculated by multiplying the ratio of a stream's drainage area (table 3) to the drainage area upstream from the gage at station 11119780 (the sum of San Roque and Arroyo Burro drainage areas) times the median annual gaged streamflow at station 11119780. Estimates of streamflow

Table 3.--Drainage area, permeable length, and width of streams in Foothill basin

Stream	Drainage area (mi^2)	Length (feet)	Width (feet)
San Roque	4.7	3,500	10
Arroyo Burro	2.0	4,200	8
Cieneguitas	1.7	12,500	8
Atascadero	1.1	12,000	8
Hospital	.5	3,800	8
Total	10.0	36,000	--

recharge to the Foothill basin, using the 14-percent figure estimated by Muir and the 40-percent figure derived from Martin's data and the above procedure, are 160 and 460 acre-ft/yr, respectively. Estimates of the percent contribution of each stream to basin recharge are: San Roque Creek and Arroyo Burro above the stream gage at station 11119780, 47 and 20 percent respectively; Cieneguitas, Atascadero, and Hospital Creeks, 17, 11, and 5 percent, respectively. Muir's estimate of recharge from runoff is based on Upson's data for low-flow measurements and an average number of days of flow per year of 80 for the five principal stream channels in the Carpenteria ground-water basin, about 15 miles to the east-southeast, for water years 1941-45 (Upson, 1951, p. 44-45).

Streamflow-recharge estimates using Todd's cited infiltration rate also were calculated. A recharge rate of 390 acre-ft/yr, assuming 90 days of flow, was derived using Todd's rate along with estimates of stream width and permeable length (table 3) in the Foothill basin.

Thus, estimates of streamflow recharge are 390 acre-ft/yr using Todd's cited infiltration rate, 160 acre-ft/yr using Muir's estimate of 14 percent of runoff, and 460 acre-ft/yr using 40 percent of median annual discharge.

In the Santa Barbara area, Muir (1968, p. A18) estimated long-term average annual recharge due to infiltration of rain as 0.138 acre-ft/acre for land covered by grass and weeds. By applying this figure to the Foothill basin recharge area, a value of about 320 acre-ft/yr was derived for recharge due to infiltration of rain.

Recharge of subsurface inflow from consolidated rocks of the Santa Ynez Mountains originates as precipitation on the mountain flanks. Annual precipitation in the southern Santa Ynez Mountains ranges from about 22 inches in the foothills to more than 30 inches at the crest. Much of this precipitation runs off as surface flow, is consumed by plants, or is lost by evaporation; however, some infiltrates into the highly fractured consolidated rocks that crop out on the mountain slopes. This water percolates downward through subsurface formations and flows toward the lowlands. Some of the water emerges as springs or as seepage along stream channels; the remainder enters the ground-water basin as subsurface inflow. The various pathways, rates of flow, and outflow points for this subsurface flow are not known. However, the subsurface flow seems to be relatively direct and rapid, as evidenced by the flow regime of local springs (Todd, 1978, p. 40).

The quantity of subsurface flow that enters the Foothill basin is unknown; however, Muir (1968, p. A18) estimated that about 300 acre-ft/yr enters the Santa Barbara area, which includes the area formerly known as Storage Unit II of the Santa Barbara ground-water basin (now included in the Foothill ground-water basin). Muir's estimate probably can be applied to the Foothill basin as an upper limit for subsurface inflow. The Santa Barbara County Water Agency (1977, p. V9-V10) stated that as much as 5 to 10 percent of total recharge to the adjacent Goleta ground-water basin may be from subsurface inflow. By applying this value to the Foothill basin, along with estimates of 320 acre-ft/yr for rain infiltration and 160 acre-ft/yr for stream infiltration, one obtains an estimate of 25 to 50 acre-ft/yr of subsurface inflow. By using 320 and 460 acre-ft/yr for rain infiltration and stream seepage, respectively, one obtains an estimate of 40 to 80 acre-ft/yr of subsurface inflow.

Another source of recharge is water imported into the basin from the Santa Ynez River. Although most of the imported water is a piped supply that, after losses, is discharged out of the basin as sewage, a few acre-feet per year may recharge the ground-water system through landscape irrigation.

Before ground-water pumping in the area began in the late 1800's (Muir, 1968, p. A21; Upson, 1951, p. 101), discharge from natural outflow balanced the inflow to the basin, maintaining hydrologic equilibrium over the long term. Natural discharge, which occurred before pumping started in the Foothill basin, is estimated (using estimates of recharge) to have ranged from about 500 to 1,100 acre-ft/yr. With the advent of pumping, water levels declined from natural levels, and, as a result, streamflow, evapotranspiration, spring discharge, and subsurface outflow diminished. Subsurface outflow, which is thought to occur through younger alluvium across the Modoc fault in the vicinity of Atascadero and Cieneguitas Creeks (discharge area 1), and through younger alluvium in the Mission Ridge-Mesa fault area south of the confluence of Arroyo Burro and San Roque Creek (discharge area 2), is the major component of natural discharge both historically and in 1985. An estimate of subsurface outflow can be made on the basis of December 1985 conditions by using the following form of Darcy's equation:

$$Q = K\,b\,d\,dh/dl \times 0.0084, \tag{1}$$

where

Q	is subsurface outflow, in acre-feet per year,
K	is hydraulic conductivity for both discharge areas, equal to 3.88 ft/d on the basis of a sand-aquifer-model analysis of sediments in the Santa Barbara area (Williams, 1981, p. 11),
b	is the estimated average saturated thickness of alluvium, equal to 40 feet for discharge area 1 and 200 feet for discharge area 2,
d	is the lineal distance along a selected contour, 2,400 feet along the 25-foot water-level contour for discharge area 1 and 3,700 feet along the 150-foot water-level contour for discharge area 2 (fig. 8),
dh/dl	is the water-level gradient, 0.05 ft/ft for discharge area 1 and 0.005 ft/ft for discharge area 2 (fig. 8), and
0.0084	is the conversion factor for cubic feet per day to acre-feet per year.

By using the above equation, one obtains an estimate for underflow of 156 acre-ft/yr at discharge area 1 and 121 acre-ft/yr at discharge area 2.

Prior to significant pumping in the Foothill basin, the water table intersected stream channels over relatively long reaches. Because ground water discharged to the streams, the streams probably contained more water for longer periods of time and probably were more important as routes of ground-water outflow. At present, the water table is below the altitude of the streambeds and no ground water discharges as streamflow.

Evapotranspiration occurs whenever the water table approaches the land surface or whenever the water table can be tapped by plants. During periods when there are high water levels in the southern end of the basin, native vegetation along stream channels discharges water by transpiration. Evapotranspiration is not a significant source of discharge in the adjacent Goleta ground-water basin (Evenson and others, 1962, p. 99), and, similarly, evapotranspiration is considered to be insignificant, in comparison with other sources of discharge, in the Foothill ground-water basin.

Pumpage

Data on ground-water pumpage for the basin are available for 1935-87 (fig. 7). Pumpage data for 1976-87 have been tabulated for most of the large pumpers, but pumpage data for some private wells are not available. Prior to 1975, estimates of pumpage were derived by the U.S. Geological Survey from records of electrical-power consumption of well pumps (Evenson and others, 1962, p. 97). Mann (1976, table 1) used U.S. Geological Survey data to estimate pumpage for the Goleta-East subbasin for Cachuma water years 1935-36 to 1973-74. Pumpage for parts of the Foothill basin that are not included in the above studies has been included in this report. Included are data from Owen (1976, p. 3.9) and from individual wells.

Pumpage in the Foothill basin increased from about 570 acre-ft in 1935 to about 2,400 acre-ft in 1950 when it reached its peak. Pumpage decreased from 1950 to its historical low of about 160 acre-ft in 1961 as a result, in part, of completion of the Cachuma Project (a water-storage and distribution project) in the early 1950's and of a decrease in agricultural water usage. Pumpage from 1961 to 1973 increased, partly in response to water extraction by the city of Santa Barbara. Since 1978, when pumpage was at its lowest point (about 260 acre-ft) in 17 years, pumpage has been increasing and is estimated to be about 1,300 acre-ft in 1987.

The largest pumpers of water in the basin during 1987 were the city of Santa Barbara and the La Cumbre Mutual Water Company, which together accounted for about 90 percent of the pumpage. Numerous small domestic wells once existed in the area but were abandoned when connection to public-water supplies became an option for water users. Domestic pumpage

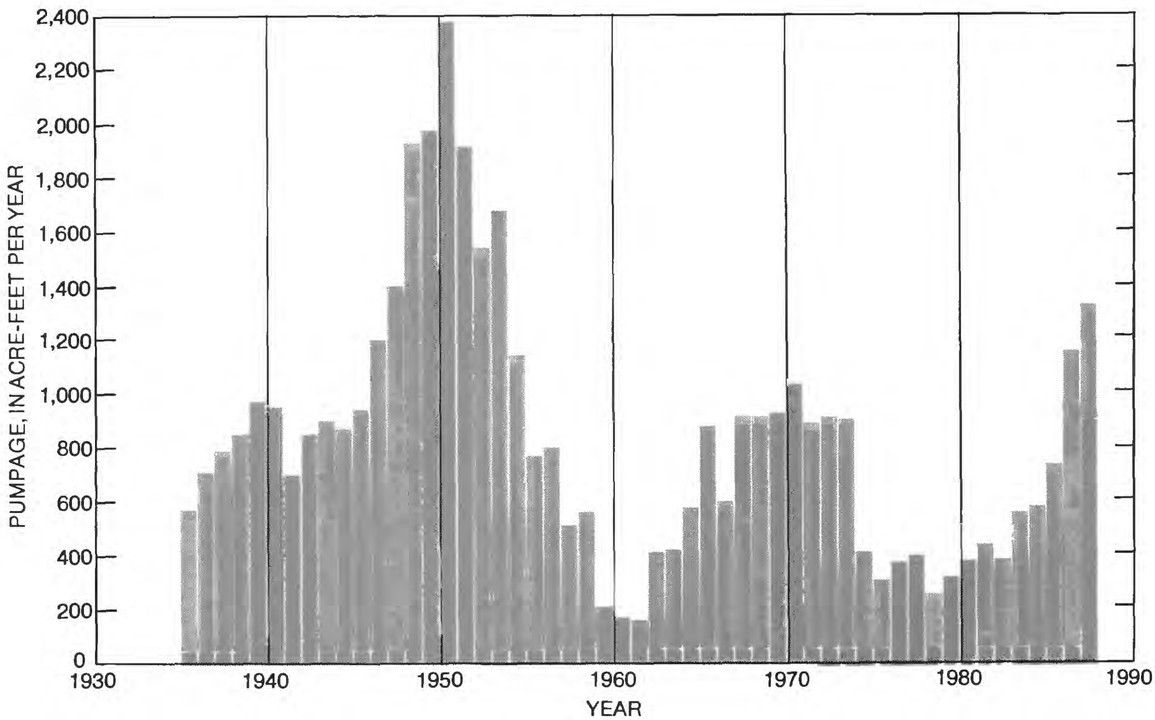


FIGURE 7.—Pumpage for the Foothill ground-water basin, 1935-87

in the basin was significant in the 1950's, when it accounted for about one-half of the total known pumpage in the basin, but it has decreased since then and is presently estimated to be only a few acre-feet per year.

In addition, there are a number of small private water companies and pumpers--including Sunset Mutual Water Company, San Vincenti mobile home park, Calvary Cemetery, and Lincolnwood development. Private pumpage in the basin has been about 150 acre-ft/yr since the mid-1960's.

Ground-Water Levels and Movement

A water-level monitoring network consisting of 14 wells was designed and implemented for this study. The purpose of the monitoring network was to determine the direction of ground-water flow and the effect of pumping on water levels in the basin. Twelve wells in the basin were measured on a monthly basis. One other well, 4N/28W-12P5, which is just outside the basin and south of the Modoc fault, also was measured on a monthly basis. One well in the basin, 4N/28W-12H4, was equipped with a continuous water-level recorder. Figure 8 shows the location of the monitoring wells and composite-water-level contours in the Foothill basin for December 1985.

In this study, the water levels in wells are composite water levels. Wells in the monitoring network have perforated intervals that range in length from 80 feet in well 4N/28W-12H4 to 528 feet in well 4N/27W-8E1 (table 4); thus, the perforated intervals may extend through aquifer materials that possess diverse hydraulic characteristics. Because of this, if hydraulic head were measured by using piezometers placed near a well at various depths within the well's perforated interval, the piezometers generally would not register the same water level as in the well. Therefore, the contours shown in figure 8 are generalized in that they more properly reflect approximate water levels that would be found in wells penetrating tens to hundreds of feet of aquifer material at a particular location.

The Modoc fault, identified by Upson (1951, p. 27-28), trends northwestward and marks part of the southwestern boundary of the Foothill basin (fig. 8). The extent of the Modoc fault was defined by Upson on the basis of large water-level differences (as much as 100 feet) in wells on opposite sides of the fault and the lack of transmission of pumping effects across the fault (Upson, 1951, p. 28, 94). Data collected by Evenson and others (1962, p. 74) further substantiate the existence and location of the fault. The effectiveness of the Modoc fault as a ground-water barrier may be indicated by a water-level difference of about 65 feet (in December 1985) between water levels in well 4N/28W-12L6 north of the fault and well 4N/28W-12P5 south of the fault (table 4).

The More Ranch fault (fig. 8) also forms part of the southwestern boundary of the Foothill basin. Because of impermeable consolidated rocks south of the fault, it acts as a barrier to ground-water flow.

The Mesa fault (fig. 8) trends northwestward through the Santa Barbara area forming a small part of the southwestern boundary of the Foothill basin, and it is believed that this fault continues northwestward through the Foothill basin, paralleling the Modoc fault with a separation of about 3,000 feet. The effect that the Mesa fault may have on the flow of ground water within the Foothill basin is unknown.

The Mission Ridge fault (fig. 8) trends northeastward and forms the southeastern boundary of the basin. This boundary supersedes the ground-water-divide boundary of Evenson and others (1962, p. 72) that is located farther to the west in the area between Atascadero and San Roque Creeks, and the aquifer system is now considered to be continuous in that area. The barrier effect of the Mission Ridge fault is shown by a difference of about 90 feet between the water level in well 4N/27W-8R2 south of the fault and the contoured hydraulic-head altitude on the north side of the fault (Martin and Berenbrock, 1986, p. 14).

The Goleta fault (fig. 8) forms the northwest boundary of the basin and, like the Modoc fault, has been inferred from large differences in water levels in wells on opposite sides of the fault and lack of transmission of pumping effects (Upson, 1951, p. 27).

Although the Modoc, Mesa, and Mission Ridge faults act as barriers to ground-water movement in the Santa Barbara Formation, application of Darcy's law to discharge areas, as indicated by water-level contours (fig. 8), suggests that ground water can flow over the tops of the faults through the unfaulted younger alluvium in the vicinity of Cieneguitas and Atascadero Creeks and south of the confluence of Arroyo Burro and San Roque Creek.

During nonpumping years, ground-water movement in the unconsolidated deposits is from the north, northeast, and northwest parts of the Foothill basin

Table 4.--Water levels in December in monitored wells, 1984-87

[Altitudes are given in feet above or below (-) sea level; depth and perforated interval are given in feet below land surface. Perforated interval: depth of first and last perforation; may not be perforated throughout entire interval. --, no data]

Well No.	Altitude of land surface	Depth of well	Perforated interval	Altitude of water level in December			
				1984	1985	1986	1987
4N/27W-5P1	306	160	60-160	172.33	168.07	DRY	--
4N/27W-6Q12	290	300	190-290	166.00	--	--	--
4N/27W-7D1	180	500	215-480	--	126.61	115.18	102.90
4N/27W-7Q5	175	585	200-580	--	150.00	131.90	--
4N/27W-7R3	175	510	165-500	136.75	132.00	116.50	110.43
4N/27W-8E1	251	641	52-580	172.81	169.55	156.00	146.72
4N/27W-8L3	230	610	260-600	--	--	--	--
4N/28W-1R2	215	200	100-200	158.25	156.64	155.30	150.90
4N/28W-2Q1	360	420	255-410	--	171.06	171.82	--
4N/28W-12C2	215	--	--	--	126.50	123.90	119.33
4N/28W-12H3	150	250	150-240	--	--	--	--
4N/28W-12H4[1]	172	290	200-280	--	126.78	114.94	102.68
4N/28W-12L6	120	325	150-325	--	22.00	17.60	--
4N/28W-12P5	105	--	--	--	-43.08	-41.16	--

[1]Continuous recorder installed in well.

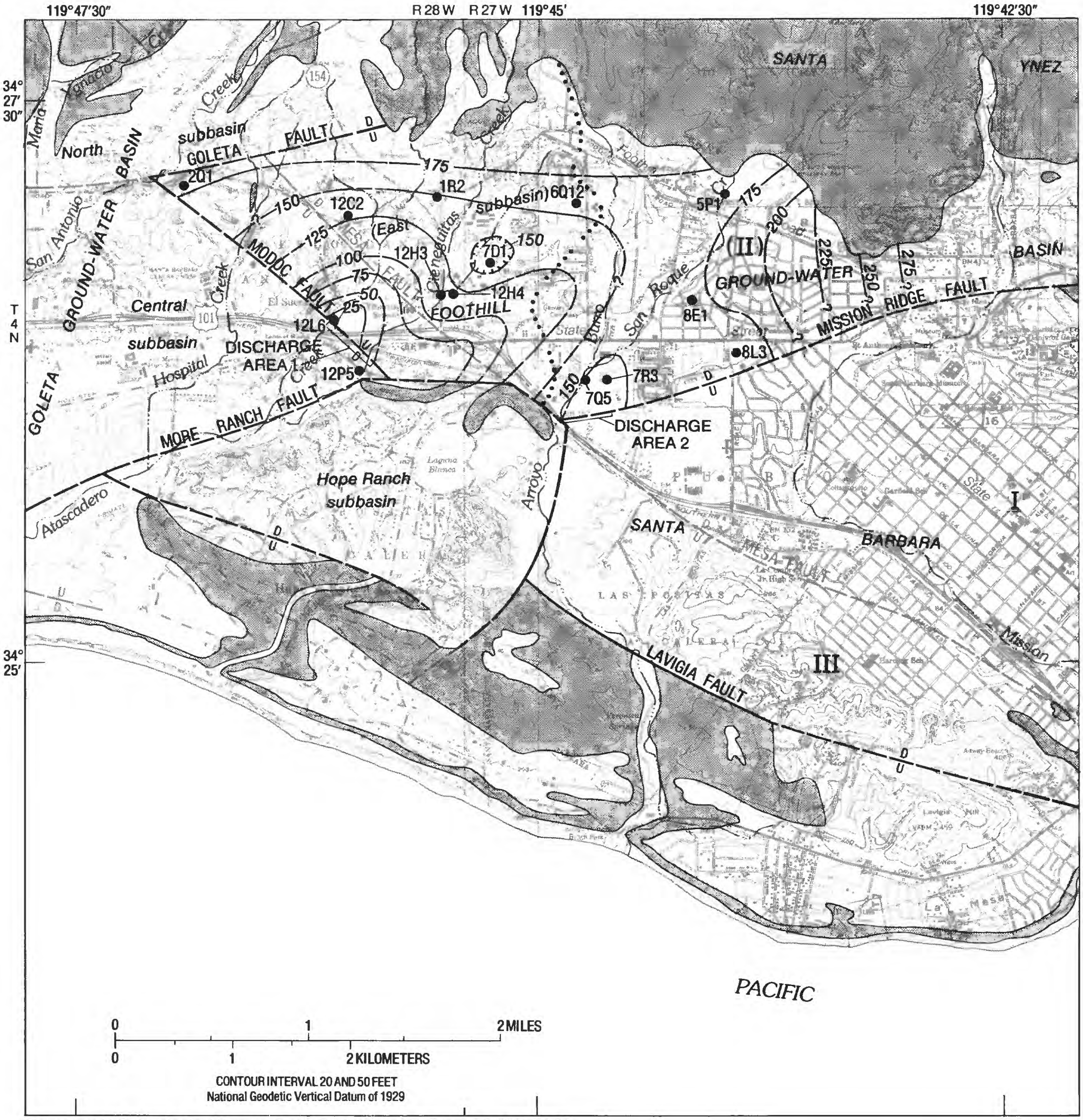
toward the Modoc fault and toward the area where the Mission Ridge and Mesa faults intersect. Ground water crossing the Modoc fault at discharge area 1 enters the Central subbasin of the Goleta ground-water basin. Ground water exiting the Foothill basin near the intersection of the Mission Ridge and Mesa faults (discharge area 2) enters the Hope Ranch subbasin and Storage Units I and III of the Santa Barbara ground-water basin. During pumping years, regional ground-water flow patterns are similar to those during nonpumping years except that flow locally is directed toward wells that extract large quantities of water.

Ground-water levels in many wells declined more than 60 feet during periods of heavy pumping in the early 1950's; a representative hydrograph for well 4N/28W-12B1 is shown in figure 9. Water levels generally rose during the period from the mid-1950's to the late 1970's as a result of decreased pumpage. Water levels generally declined in monitored wells during 1984-87 (table 4) possibly due to increased pumpage during this period (fig. 7).

Ground-Water Quality

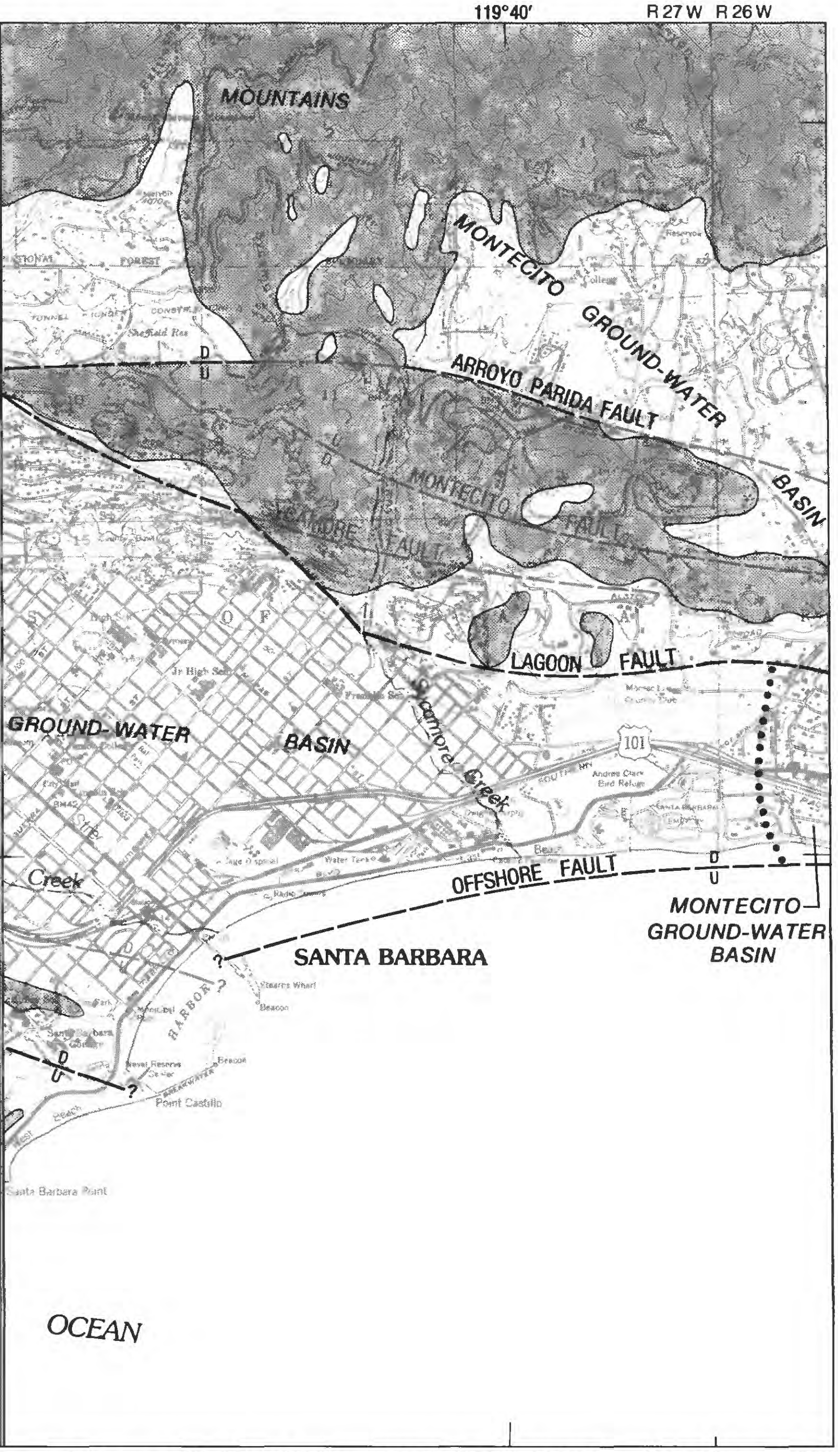
To determine the quality of ground water in the Foothill basin, eight wells were sampled on an annual basis for pH, specific conductance, and major anion and cation constituents. Figure 10 shows the location of the monitored wells, and table 5 gives recent (1977-86) water-quality data.

The areal distribution of dissolved solids and water type is shown in figure 11--which includes Stiff diagrams for the eight basin network wells, along with several diagrams for additional wells in the vicinity. Stiff diagrams visually depict differences in water types (Hem, 1985, p. 175). On the diagrams, cations are plotted to the left of zero and anions are plotted to the right of zero, and the width of the pattern is an approximate indication of total ionic content. Note that the four wells in Storage Unit I of the Santa Barbara ground-water basin have lower values for dissolved solids in comparison with the wells in the Foothill basin. Note also the differences in shape of the Stiff diagrams for wells in the two units. These differences seem to indicate a strong hydraulic separation of the Foothill basin from Storage Unit I.



Base from U.S. Geological Survey, Santa Barbara and Goleta 1:24,000, 1967

FIGURE 8.—Location of water-level-monitoring-network wells, and composite-water-level contours in December 1985.



Geology modified from J.E. Upson (1951), K.S. Muir (1968), and M.F. Hoover (1978)

EXPLANATION

UNCONSOLIDATED DEPOSITS (QUATERNARY AND TERTIARY)

CONSOLIDATED ROCKS (TERTIARY)

D/U ? FAULT—Dashed where approximately located; queried where doubtful. U, upthrown side; D, downthrown side. Black indicates boundary of ground-water basin

GEOLOGIC CONTACT

III GROUND-WATER STORAGE UNIT—Former designation of storage unit and subbasin name in parentheses

GROUND-WATER DIVIDE

FORMER GROUND-WATER DIVIDE

—100——? COMPOSITE-WATER-LEVEL CONTOUR—Shows altitude of water level in wells perforated in various depth zones. Dashed where approximate, queried where doubtful. Contour interval 25 feet. Datum is sea level. (See table 3 for water-level measurements)

●8L3 WELL AND NUMBER

FIGURE 8.—Continued.

Table 5.--Water quality

[Constituents and hardness are in milligrams per liter except where noted. Constituents are perforated throughout the interval. µS/cm at 25 °C, microsiemens per centimeter,

Well No.	Date of sample	Well depth (feet)	Perforated interval (feet)	Specific conductance (µS/cm	pH (standard units) at 25 °C)	Hardness as $CaCO_3$	Calcium	Magnesium	Sodium
4N/27W-5P1	05-09-84	160	60-160	1,280	7.4	540	140	46	83
	08-01-85			1,560	7.4	680	180	55	88
4N/27W-7D1	07-08-85	500	215-480	1,520	7.4	620	150	59	100
	08-12-86			1,490	7.6	560	140	52	91
4N/27W-7G7	11-07-77	450	45.5-450	--	--	480	120	44	77
	05-16-84			1,300	7.5	550	140	49	78
	08-12-86			1,390	8.0	550	140	49	74
4N/27W-7H5	05-08-84	500	200-500	1,180	7.5	500	140	37	62
	07-10-85			1,160	7.4	500	140	36	59
	08-13-86			1,030	8.0	460	130	32	50
4N/27W-8L3	04-07-83	610	260-600	979	7.3	370	97	32	67
	05-07-84			944	7.3	370	94	32	62
	07-08-85			942	7.3	380	98	32	61
4N/28W-1R2	05-08-84	200	100-200	2,830	7.2	880	220	81	300
	07-30-85			2,580	7.5	550	140	48	210
4N/28W-12H3	05-08-84	250	150-240	1,520	7.4	610	150	57	110
	07-10-85			1,450	7.5	610	150	58	97
	08-12-86			1,520	7.9	600	150	55	100
4N/28W-12R3	05-08-84	380	142-370	1,010	7.4	410	110	32	67
	07-09-85			1,030	7.4	440	120	33	69
	08-12-86			998	7.5	410	110	32	65
U.S. Environmental Protection Agency (1976 and 1979) primary (P) or secondary (S) limit for selected constituents					(S) [1]6.5-8.5				

[1]The secondary maximum contaminant level for pH is expressed as the range between the lower and
[2]The recommended maximum concentration for fluoride is adjusted according to the average maximum

in monitored wells

dissolved. <, less than, -- no data. Perforated interval: depth of first and last perforation; may not be at 25 degrees Celsius; μg/L micrograms per liter. Location of wells is shown in figure 10]

Alkalinity as $CaCO_3$	Sulfate	Chloride	Fluoride	Silica	Dissolved solids, calculated sum of constituents	Nitrite plus nitrate as N	Barium (μg/L)	Boron (μg/L)
248	410	58	0.5	20	1,000	0.30	--	180
270	460	69	.4	21	1,000	.44	--	90
297	360	130	.6	30	1,000	1.70	39	180
308	350	120	.6	27	1,000	1.90	--	190
--	250	74	--	--	--	--	--	100
265	310	82	.4	28	870	2.00	--	110
255	340	94	.5	26	880	12.00	--	130
265	270	58	.4	29	760	2.30	--	80
259	250	51	.3	30	740	10.00	36	70
254	260	46	.4	25	700	4.20	--	80
264	180	57	.3	37	630	2.60	53	100
234	190	49	.4	38	610	1.90	--	80
224	200	44	.3	39	630	1.40	48	90
398	680	340	.7	23	1,900	<.10	--	620
346	510	360	.6	22	1,500	1.50	--	260
313	420	83	.6	30	1,100	1.10	--	200
294	410	70	.6	31	1,000	1.30	32	190
289	430	87	.5	29	1,000	1.20	--	210
270	220	45	.4	34	750	.63	--	90
243	220	45	.3	35	700	.62	57	100
262	220	48	.4	33	670	.71	--	100
	(S) 250	(S) 250	(P) [2]1.4-2.4		(S) 500	(P) 10	(P) 1,000	(S) 750

upper limits.
daily air temperature.

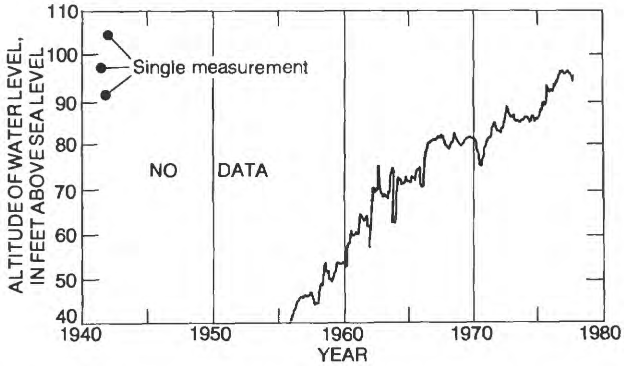


FIGURE 9.—Water-level altitude in well 4N/28W-12B1, 1941-77.

Certain chemical constituents, when present at varying concentrations in drinking water, can produce adverse effects in humans; therefore, the U.S. Environmental Protection Agency (1977 and 1979) established primary and secondary standards for drinking water. Primary standards pertain to constituents that may present a health hazard; whereas, secondary standards pertain to constituents that may be detrimental to aesthetic quality but do not present a health hazard. Standards for constituents analyzed for in this study are shown in table 5. As shown in the table, all wells sampled yielded water in which the pH, dissolved solids, or concentration of one or more constituents exceeded primary or secondary standards for maximum contaminant levels.

Nitrate is the only constituent that exceeded primary maximum contaminant levels. In table 5, nitrate is reported as nitrite plus nitrate as N (nitrate-nitrogen). Serious, and occasionally fatal, poisoning of infants has occurred following ingestion of water with a nitrate-nitrogen concentration greater than 10 mg/L (U.S. Environmental Protection Agency, 1986, p. 228-229). Of the network wells, 4N/27W-7G7 and 4N/27W-7H5 yielded water with a nitrate-nitrogen level at or above the primary maximum contaminant level of 10 mg/L. Nitrate-nitrogen concentration ranged from less than 0.1 to 12 mg/L in samples from network wells.

Dissolved-solids concentrations exceeded the secondary maximum contaminant level in samples from all monitor wells. Concentrations in samples from four wells were equal to or greater than 1,000 mg/L. High dissolved-solids concentrations in water may be objectionable to users because of taste and staining.

Chloride concentration exceeded the secondary maximum contaminant level of 250 mg/L in water from only one well, 4N/28W-1R2; concentrations were 340 and 360 mg/L in 1984 and 1985, respectively. The recommended limit is based mainly on the esthetics of taste. Chloride ions frequently have been cited as having a low taste threshold in water. Chloride concentration in water from network wells ranged from 44 to 360 mg/L (table 5).

Sulfate equaled or exceeded the secondary maximum contaminant level of 250 mg/L in samples from six of the eight network wells (table 5). The presence of sulfate in water has been shown to have a cathartic effect; however, this generally results from consumption of water in which sulfate concentration exceeds 750 mg/L. The sulfate concentration in samples from the network wells ranged from 180 to 680 mg/L.

All the sampled ground water would be classified as very hard (greater than 300 mg/L as $CaCO_3$). The lowest value was 370 mg/L in well 4N/27W-8L3; the highest value was 880 mg/L in well 4N/28W-1R2. Water is classified from soft to very hard on the basis of soap requirements for adequate lather formation and on the rate of scale formation in water heaters and low-pressure boilers (U.S. Environmental Protection Agency, 1976, p. 75).

Sodium concentration exceeded 20 mg/L in all samples and may be a hazard to the health of those who must restrict sodium in their diets (U.S. Environmental Protection Agency, 1977, p. 121). Sodium concentration ranged from 50 mg/L at well 4N/27W-7H5 to 300 mg/L at well 4N/28W-1R2.

Water having a pH close to neutral (7.0) is desirable to avoid corrosion of metal. Water having a pH at the extremes and out of the acceptable range (6.5-8.5) of the U.S. Environmental Protection Agency's secondary standard may be slightly corrosive to some metals. The pH of the sampled water ranged from 7.2 to 8.0 (table 5).

MATHEMATICAL MODEL

To simulate ground-water flow in the Foothill basin and therefore attain a better understanding of the geohydrologic system, a two-layer three-dimensional block-centered finite-difference mathematical model was developed. A mathematical model incorporates estimates of the physical and hydrologic characteristics of a ground-water system into a procedure that approximates the solution to a partial differential equation that describes the flow and time-varying hydraulic-head distribution in the system. The physical characteristics are the boundaries of the basin, the initial hydraulic-head configuration (for the transient model), and the type, location, and quantities of recharge and discharge. Hydrologic characteristics reflect the ability of the system to transmit water (transmissivity), to store and release water (storage coefficient), to conduct water (drain conductance) in a series of drains simulating head-dependent boundaries, and to allow for the vertical passage of water through the confining zone (vertical hydraulic conductivity).

Description of Model

The Fortran-based modular computer code used for this study was developed by McDonald and Harbaugh (1984). In this code, the partial differential equation that describes ground-water flow is approximated by difference equations that are solved over a network composed of rectangular blocks representing the area being modeled. Solutions to the differential equation or the difference equations are hydraulic heads in the various model blocks at specific times. A detailed explanation of the physical and mathematical concepts on which this model is based and an explanation of how those concepts were incorporated in the modular structure of the computer code, are included in McDonald and Harbaugh (1984).

The translation of the physical and hydrologic characteristics of the ground-water system into a form that can be approximated by a mathematical model necessarily involves simplifications and assumptions about the geohydrologic framework. The results produced by a model will reflect the interpretation and degree of uncertainty that went into its design as well as any deficiencies in data used in its development.

Assumptions

A mathematical model is an approximation of the real aquifer system because not all the characteristics of the actual system can be included. Simplifying assumptions are required to make the problem manageable. Some of the more important simplifying assumptions that relate directly to the mathematical model are:

1. The aquifer system is represented as two layers. The water-bearing units in the Foothill basin can be grouped into an upper layer (layer 1) of younger and older alluvium and a lower layer (layer 2) mainly representing the Santa Barbara Formation. Although there are multiple water-bearing zones within these units, the presence of the confining zone at the upper part of the Santa Barbara Formation presents a natural dividing zone for conceptual separation of the aquifer system. Examination of drillers' and electric logs suggests that it is reasonable to model the system as two layers. One aspect of model representation of the basin involves matching the sophistication being built into the mathematical model to the quantities of data available for the physical system. In particular, additional model layers may be added to the mathematical model in the hope of improving simulation; however, the correspondence of the additional layers to physical reality may not be supported by the available data. In this study the mathematical model was kept simple, reflecting available data, but it can be refined to incorporate changes that may be suggested by additional data.

2. Ground-water movement in both water-bearing layers is horizontal.

3. The water-bearing layers are isotropic.

4. Ground-water movement within the confining zone is vertical.

5. Changes in hydraulic head within the confining zone do not cause corresponding changes in the volume of water that is stored in this zone.

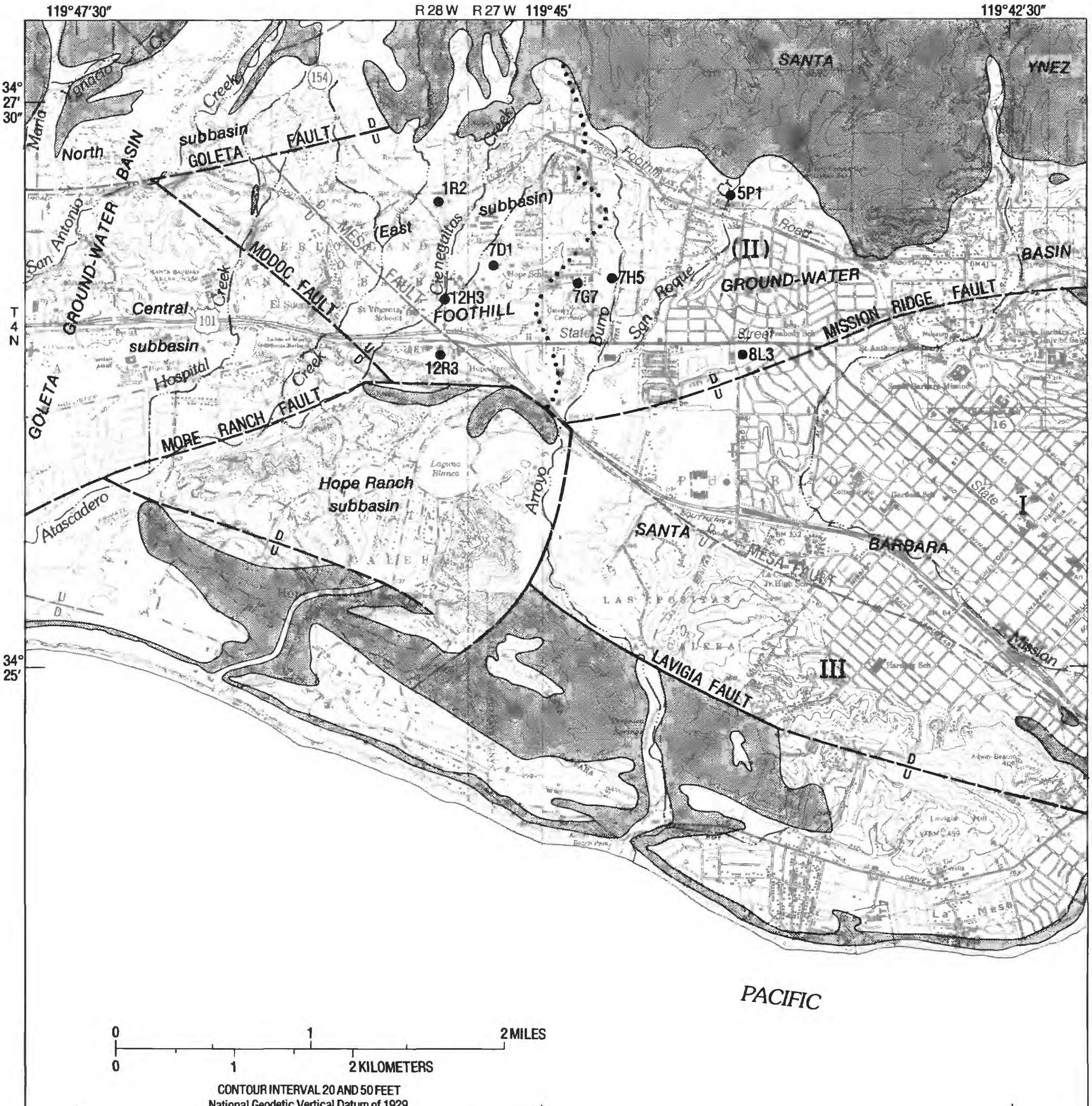
6. Changes in ground-water storage in the layers occur instantaneously with changes in hydraulic head.

7. The transmissivity and storage coefficient of the aquifer system do not change with water-level changes.

8. Recharge occurs instantaneously.

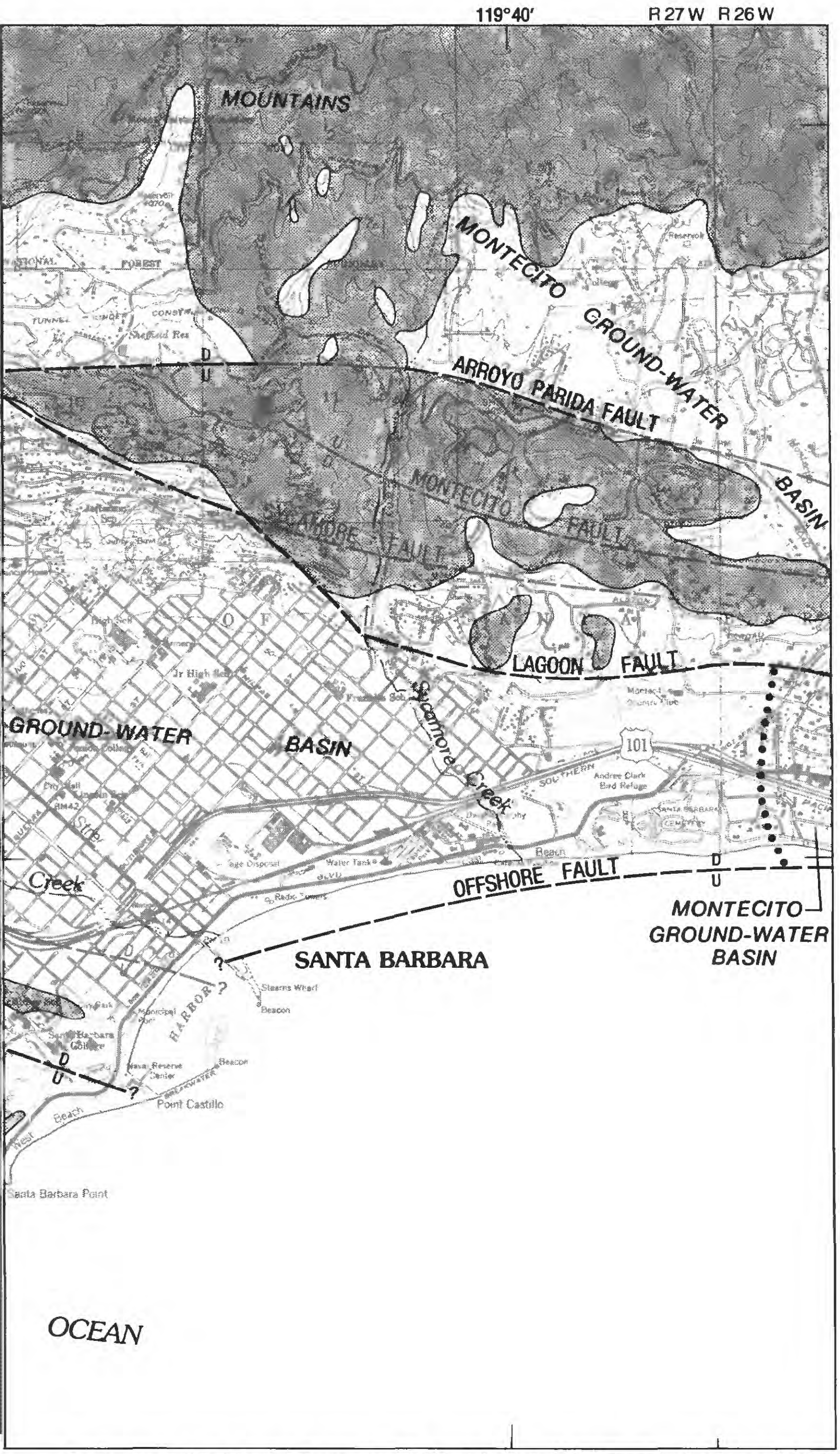
Model Boundaries and Finite-Difference Network

The physical extent of the Foothill basin was determined through analysis and interpretation of geologic and hydrologic data. For the model, the boundaries are the foothills of the Santa Ynez Mountains on the north and northeast; the Goleta fault on the northwest; the Modoc, More Ranch, and Mesa faults on the southwest; and the Mission Ridge fault on the southeast. The model does not cover the full extent of the Foothill basin (fig. 12). The unmodeled area in the eastern part of the basin is one of low permeability for which there are few available hydrologic data. Underflow that originates as areal recharge and underflow to the unmodeled area is simulated as



Base from U.S. Geological Survey, Santa Barbara and Goleta 1:24,000, 1967

FIGURE 10.—Location of water-quality monitoring wells.



EXPLANATION

UNCONSOLIDATED DEPOSITS (QUATERNARY AND TERTIARY)

CONSOLIDATED ROCKS (TERTIARY)

D/U ? FAULT—Dashed where approximately located; queried where doubtful. U, upthrown side; D, downthrown side. Black indicates boundary of ground-water basin

GEOLOGIC CONTACT

III GROUND-WATER STORAGE UNIT—Former designation of storage unit and subbasin name in parentheses

GROUND-WATER DIVIDE

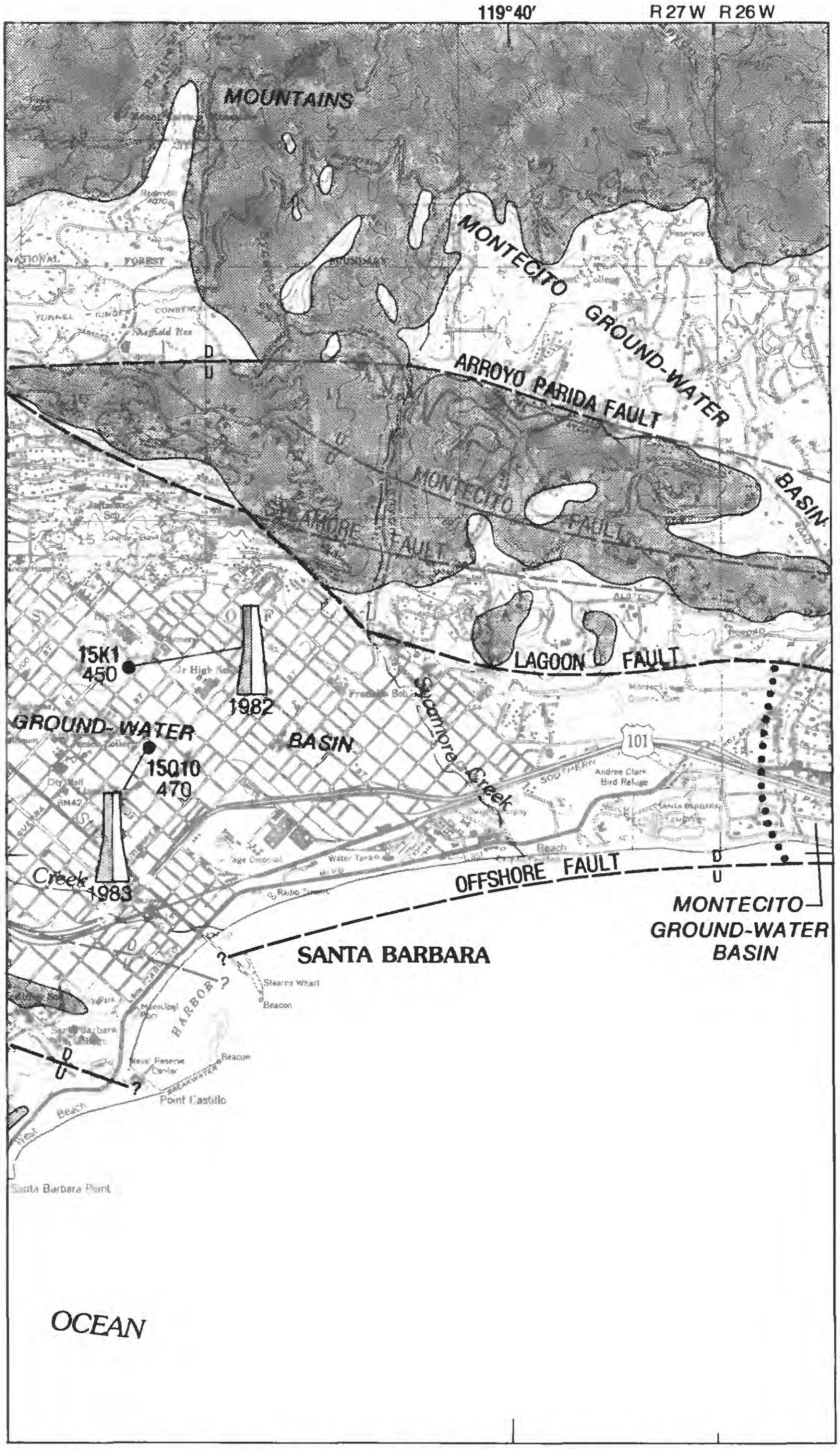
FORMER GROUND-WATER DIVIDE

5P1 WELL AND NUMBER

Geology modified from J.E. Upson (1951), K.S. Muir (1968), and M.F. Hoover (1978)

FIGURE 10.—Continued.

FIGURE 11.—Stiff diagram and dissolved-solids concentration at selected wells.



Geology modified from J.E. Upson (1951), K.S. Muir (1968), and M.F. Hoover (1978)

EXPLANATION

UNCONSOLIDATED DEPOSITS (QUATERNARY AND TERTIARY)

CONSOLIDATED ROCKS (TERTIARY)

D/U ? FAULT—Dashed where approximately located; queried where doubtful. U, upthrown side; D, downthrown side. Black indicates boundary of ground- water basin

GEOLOGIC CONTACT

III GROUND-WATER STORAGE UNIT—Former designation of storage unit and subbasin name in parentheses

GROUND-WATER DIVIDE

FORMER GROUND-WATER DIVIDE

16R1—WELL AND NUMBER

580—DISSOLVED-SOLIDS CONCENTRATION—In milligrams per liter

WATER-QUALITY DIAGRAM (From Stiff, 1951)

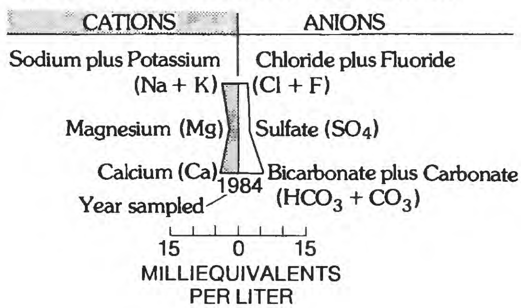
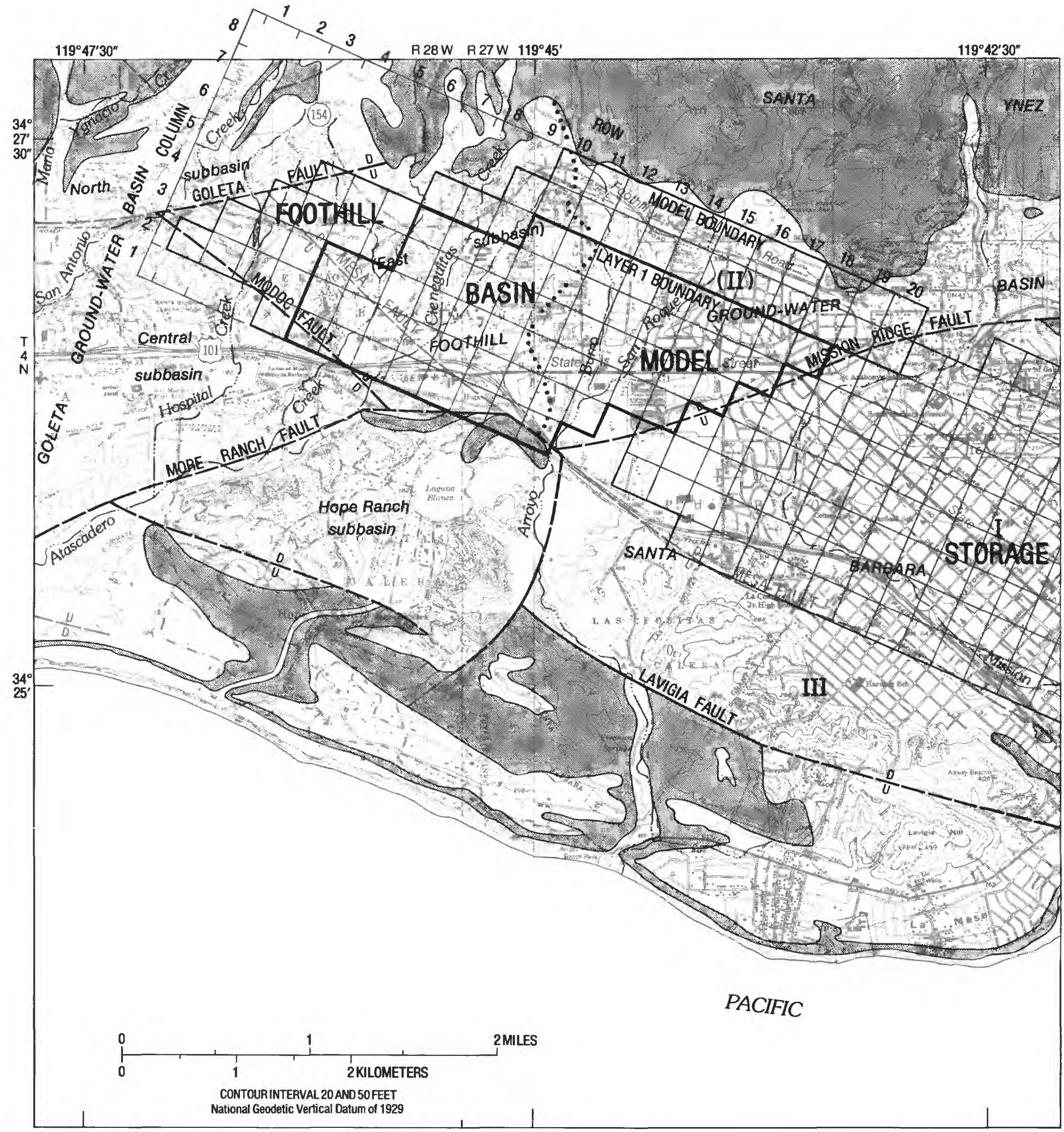
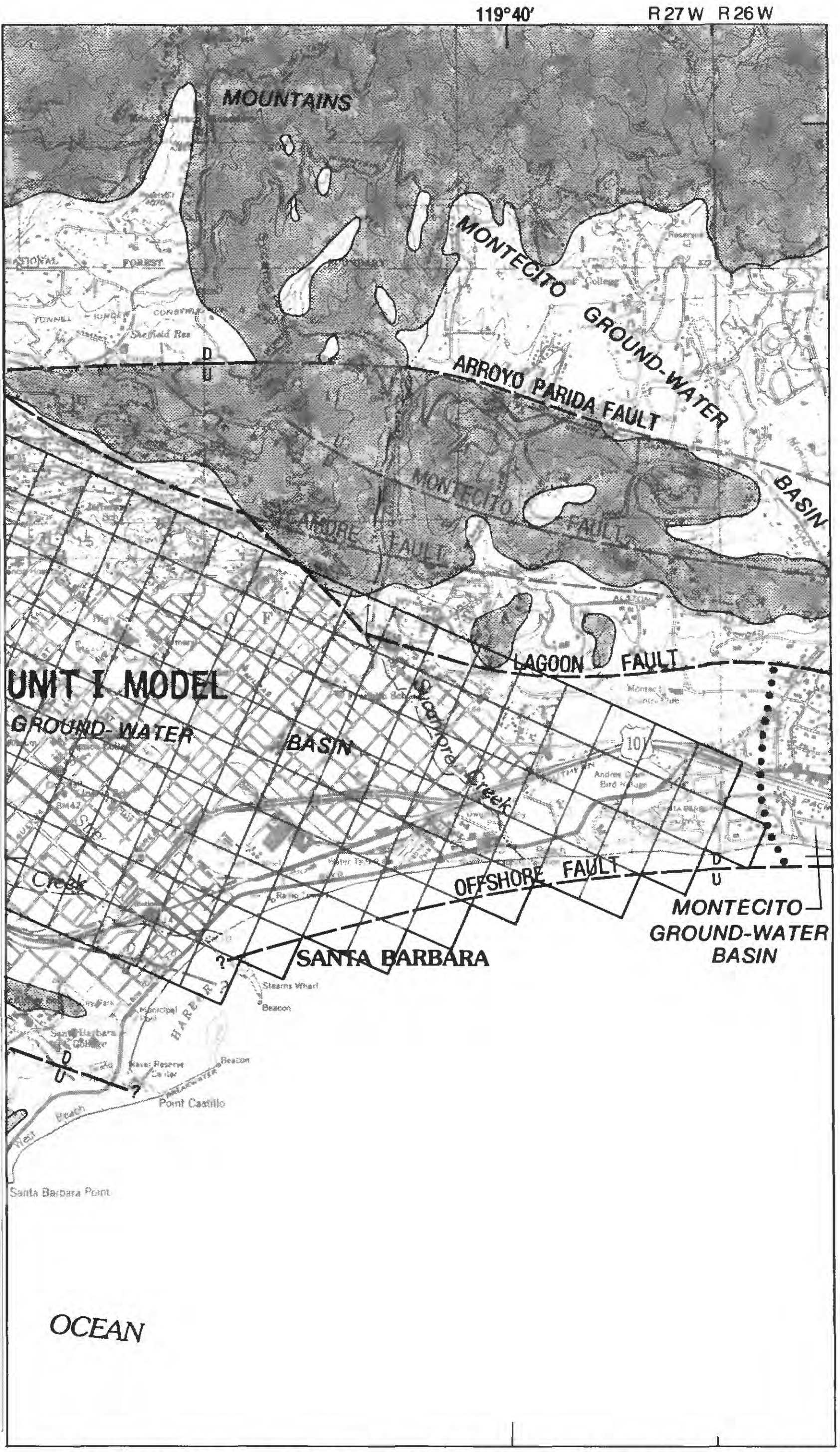


FIGURE 11.—Continued.



Base from U.S. Geological Survey, Santa Barbara and Goleta 1:24,000, 1967

FIGURE 12.—Foothill basin and Storage Unit I model grids.



Geology modified from J.E. Upson (1951), K.S. Muir (1968), and M.F. Hoover (1978)

EXPLANATION

UNCONSOLIDATED DEPOSITS (QUATERNARY AND TERTIARY)

CONSOLIDATED ROCKS (TERTIARY)

D/U ? FAULT—Dashed where approximately located; queried where doubtful. U, upthrown side; D, downthrown side. Black indicates boundary of ground-water basin

GEOLOGIC CONTACT

III GROUND-WATER STORAGE UNIT—Former designation of storage unit and subbasin name in parentheses

GROUND-WATER DIVIDE

FORMER GROUND-WATER DIVIDE

FIGURE 12.—Continued.

constant flux at a point on the southeastern model boundary. For modeling purposes, the Goleta and More Ranch faults are considered to be no-flow boundaries--that is, in the model no water is allowed to enter or leave the aquifer system along these boundaries. Although there is undoubtedly some flow across the Goleta and More Ranch faults, it probably is slight. Part of the north-northeastern boundary was modeled as a constant-flux boundary. Tertiary sedimentary rocks at the base of layer 2 were modeled as a no-flow boundary.

The Modoc, Mission Ridge, and Mesa faults are simulated, for the most part, as no-flow boundaries. However, underflow out of the basin is thought to occur across the Modoc fault through unfaulted younger alluvium along Cieneguitas and Atascadero Creeks (discharge area 1). Similarly, underflow across the Mission Ridge-Mesa fault area through unfaulted younger alluvium is thought to occur just south of the confluence of Arroyo Burro and San Roque Creek (discharge area 2). Parts of these fault boundaries are simulated in the model as a series of drains, which allow ground water to flow out of the model area when computed hydraulic heads exceed the specified altitudes of the drains. Drains also were simulated along the major creeks to model ground water lost from the aquifer to the streambeds when water levels in the aquifer exceeded the altitude of the bottom of the streambed. The rate at which water enters a drain is approximated in the model using the equation (McDonald and Harbaugh, 1984, p. 288):

$$Q_D = C_D(H_a - H_D), \tag{2}$$

where

Q_D is the rate water flows into the drain $[L^3T^{-1}]$,
C_D is the conductance of the interface between the aquifer and the drain $[L^2T^{-1}]$,
H_a is the head in the aquifer near the drain [L], and
H_D is the altitude of the drain [L].
(L and T are units of length and time, respectively.)

Altitudes of the underflow drains (H_D), which were determined from analysis of drillers' and electric logs and by model calibration, represent the altitude of the contact between the faulted older alluvium and the unfaulted younger alluvium. Altitudes of stream drains (also H_D) were obtained from topographic maps. When the head in the aquifer (H_a) is less than the altitude of a drain, there is no flow into the drain. The conductance of the drain (C_D) was adjusted during steady-state-verification and transient-state model calibration.

The model network consists of a rectangular grid system of 158 blocks, with 59 blocks representing layer 1 (the upper layer) and 99 blocks representing layer 2 (the lower layer) (fig. 12). Each side of a block represents a distance of 1,000 feet. The grid spacing and orientation were chosen to coincide with those picked by Martin and Berenbrock (1986, p. 18) for a model of Storage Unit I of the Santa Barbara ground-water basin, the basin adjacent to and southeast of the Foothill basin. The present model and that of Martin and Berenbrock share the common Mission Ridge fault boundary and, because of the similar grid spacing and orientation, the two models can be incorporated easily into a combined flow model. Both model networks are shown in figure 12.

The point at the geometric center of a block is referred to as a node. Nodes are the locations where the model calculates hydraulic heads. Blocks and their associated nodes are referenced to a row-and-column structure in which a row number and column number separated by a comma designate a particular block or node in the model; for example, the set 9,1 indicates the block or node located in the 9th row, 1st column (fig. 12). An additional number, either 1 or 2, added to the node number, as in 9,1,1 indicates the layer in which the node is located. Each block in the model network is assigned values of transmissivity, storage coefficient (for the transient simulation) and, where appropriate, drain conductance and vertical hydraulic conductivity. Model flux boundaries of constant-flux recharge and head-dependent discharge are shown on the finite-difference network in figure 13. Constant flux in the model corresponds to components of stream recharge to layers 1 and 2, areal recharge (representing recharge of precipitation) to layers 1 and 2, underflow from the Santa Ynez Mountains to layer 2, and underflow from the area of the basin not modeled to layer 2 (fig. 14). Head-dependent discharge corresponds to stream drain blocks in layers 1 and 2, and outflow corresponds to underflow drain blocks in layer 1 (fig. 15). The flow between model layers through the confining zone also is head dependent.

EXPLANATION FOR FIGURE 13

CONSTANT FLUX

HEAD DEPENDENT

NO FLOW

LAYER 1 PERIMETER

LAYER 2 PERIMETER

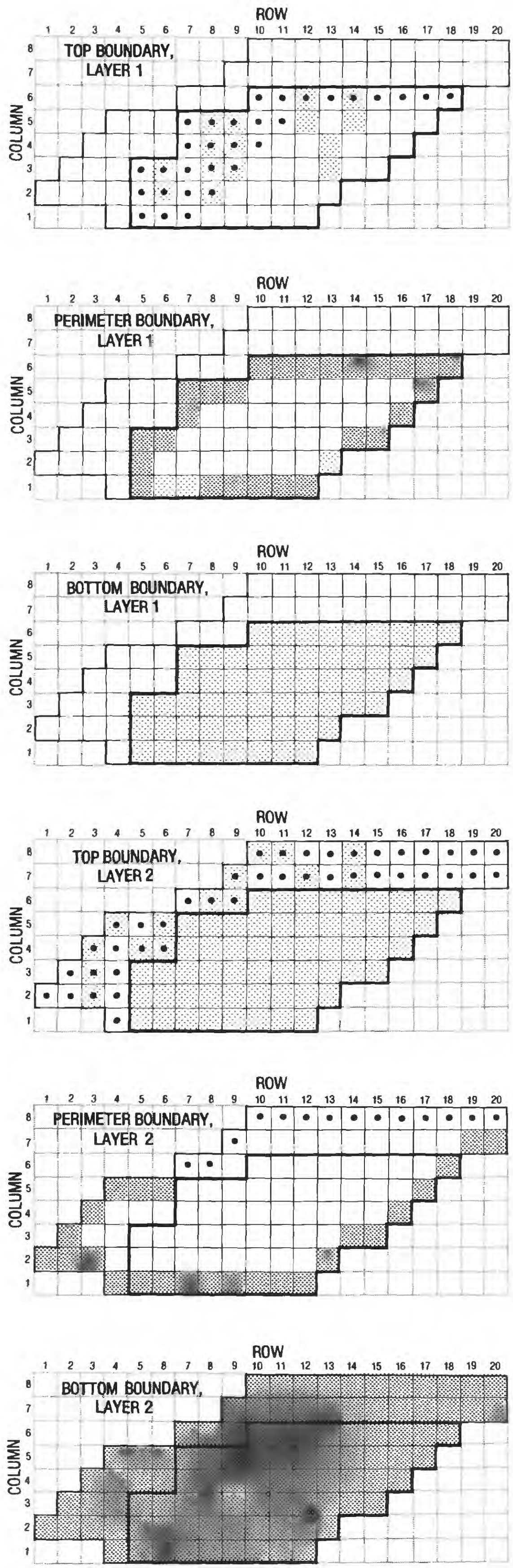


FIGURE 13.—Flux boundaries for model layers 1 and 2.

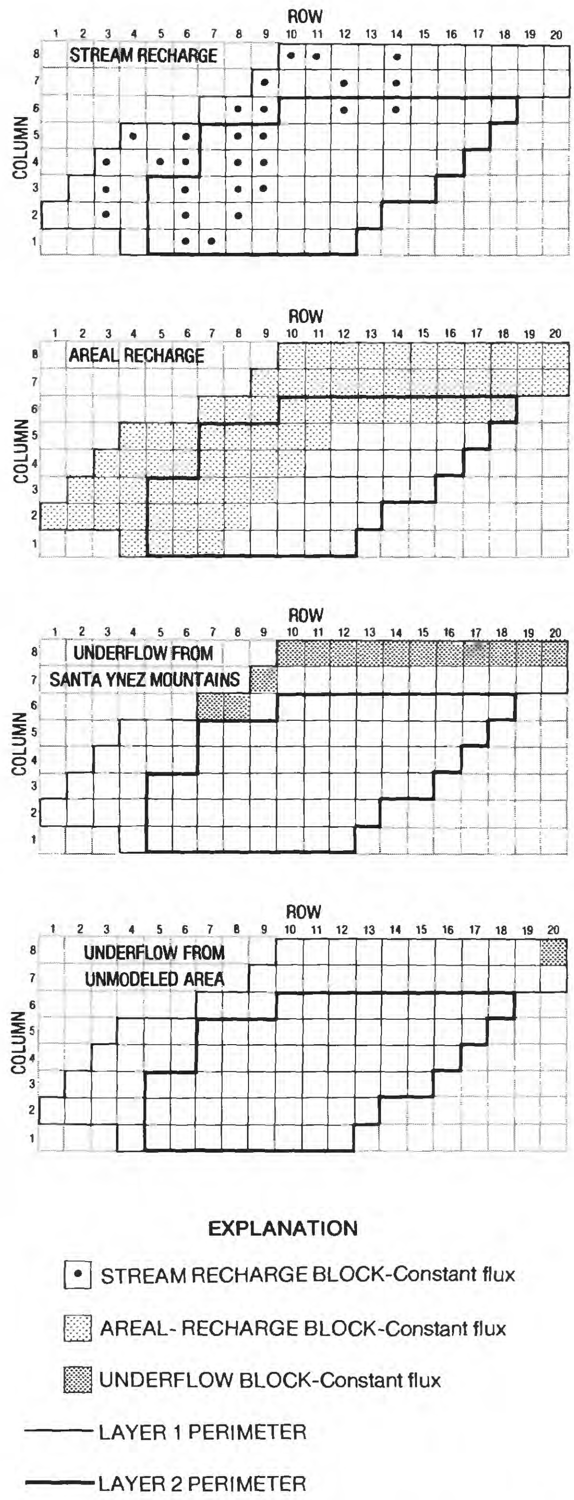
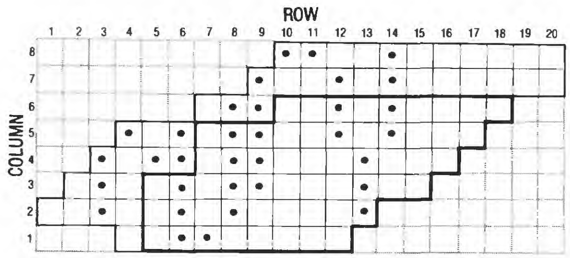


FIGURE 14.—Location of model stream-recharge blocks, areal-recharge blocks, underflow from the Santa Ynez Mountains, and underflow from area left unmodeled.



EXPLANATION

DRAIN BLOCK-Stream or outflow drain

LAYER 1 PERIMETER

LAYER 2 PERIMETER

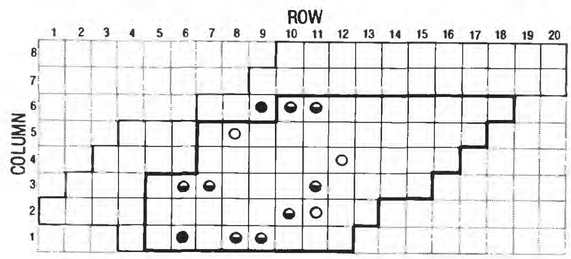
FIGURE 15.–Drain blocks.

Model Calibration

The model was calibrated to simulate two different conditions: first, a steady-state condition, and then a transient-state condition. A steady-state condition exists when recharge equals discharge, and hydraulic heads in the basin (considering periods of several years) do not change with time. Under natural conditions, in which there are no human-induced extractions or additions of water to the system, and when recharge is uniform through time, the basin is in an equilibrium or steady-state condition. For purposes of this report, the model was made to simulate an artificial steady state in order to check the reasonableness of the system response. This was done because of a lack of data that could be used to define natural steady-state conditions. The resulting model simulation is referred to as the steady-state verification. Interruption of the balance between recharge and discharge (by pumping, for example) causes fluctuating ground-water levels in the basin, and the system is said to be in a transient-state condition. The calibration involves duplicating historical water-level measurements for the basin through adjustment of the model. These calibrations are subjective, and they are based, to a large extent, on trial and error.

Steady-State-Verification Calibration

Ideally, steady-state calibration involves adjusting model parameters until model-generated hydraulic heads approximate known basin water levels for a period considered to be steady state. Water-level data are not available for Foothill basin to define natural steady-state conditions; however, it is important to investigate the model's response to such conditions. In particular, even if there is no known period of natural steady-state conditions, it is important to ensure that if basin pumping is stopped, the basin model (operated without pumpage) does not generate hydraulic heads that violate the physical principles under which the basin operates. For example, the basin model operated without pumpage must not generate hydraulic heads, in the unconfined areas, that are greater than land surface. Steady-state simulations may include pumpage (but, as noted earlier, should be investigated without pumpage) if the water levels are not changing during the period selected for simulation. The first year for which basin-wide pumpage data are available is 1935 (figure 16 shows the known pumpage locations); however, the basin was not in steady state at that time. For purposes of this report, steady-state-verification calibration of the model involved adjusting (in conjunction with the transient model) transmissivity, drain conductance, vertical hydraulic conductivity, and the distribution and quantities of recharge to the basin until the model satisfied two conditions: that it was physically reasonable and that model-calibrated parameters transferred to the transient model allowed the transient model to approximate water levels for 1935-87. The distribution and quantities of natural discharge were controlled by adjusting drain conductances at the basin boundaries and stream drains; these adjustments also were made with the aim of satisfying the above two conditions.



EXPLANATION

PUMPAGE FROM LAYER 1

PUMPAGE FROM LAYER 2

PUMPAGE FROM LAYERS 1 AND 2

LAYER 1 PERIMETER

LAYER 2 PERIMETER

FIGURE 16.–Model pumpage distribution, 1935.

Transmissivity, recharge, drain conductance, and vertical hydraulic conductivity were adjusted in order to find an acceptable (meets the conditions stated previously) steady-state-verification hydraulic-head configuration. This was an iterative process in which adjustments were made to both the steady-state-verification and transient-state models. For this study, the steady-state-verification model has no associated steady-state time period. An initial transmissivity distribution was constructed from values of transmissivity estimated from aquifer tests and by extrapolation of data, on the basis of geologic concepts, to areas lacking tests. Transmissivity used in the model is intended to represent areal and depthwise averages of the true system, even though large variations in transmissivity caused by changes in lithology are possible in distances that are small in comparison with model-block size. Transmissivities estimated from aquifer tests may be influenced by well-design factors, such as the effects of perforating the test well through multiple water-bearing zones. A comparison of estimated and model-calibrated transmissivities is given in table 6. Figure 17 shows the calibrated steady-state-verification distribution of transmissivity for the entire model.

Four components of recharge were simulated in the model: recharge from stream seepage; areal recharge, which represents direct infiltration of precipitation; underflow from the foothills of the Santa Ynez Mountains; and underflow from the unmodeled part of the basin. Recharge from stream seepage was simulated by constant-flux blocks in the model that represent the major creeks that traverse the basin (fig. 14). A total of 438 acre-ft/yr was used for stream recharge in the model. Minor adjustments were made to the original stream-recharge distribution during calibration. Average annual areal recharge in the modeled area (fig. 14) was estimated, by using the calibration procedure, to be 319 acre-ft/yr. Underflow from the foothills of the Santa Ynez Mountains (fig. 14) directly into the modeled area was estimated, using the calibration procedure, to be 58 acre-ft/yr. To account for water originating as underflow and rainfall infiltration entering from the unmodeled part of the basin, underflow, in the amount of 90 acre-ft/yr, was introduced as constant flux into block 20,8,2 (fig. 14). For steady-state verification, total calibrated recharge was 905 acre-ft/yr.

Drains were used to simulate subsurface outflow through unfaulted younger alluvium across the Modoc and Mission Ridge-Mesa faults area (discharge areas 1 and 2, respectively) and in streams (fig. 15). Drain conductance and altitude of outflow drains were adjusted during calibration to control the amount of outflow, which in turn affects basinwide water levels. Calibrated drain conductance is 5.0×10^{-3} ft/s for outflow drains and 0.1 ft/s for stream drains. Flow into the drains (out of the basin) was calculated for steady- state verification to be 905 acre-ft/yr--of which, 484 acre-ft/yr was flow to the outflow drains and 421 acre-ft/yr was flow to stream drains.

The thickness of the confining zone was estimated, by using electric and geologic logs and geologic sections (fig. 4), to range from a few feet to about 100 feet. The vertical hydraulic conductivity of the confining zone was assumed to be uniform throughout and was calculated during steady-state-verification and transient-state model simulations to be 3.8×10^{-7} ft/s, which is reasonable for the fine-grained sand, silt, and clay that compose the confining zone.

Table 7 shows the estimated water budget for natural steady-state conditions and the water budget calculated by calibration of the steady-state-verification model.

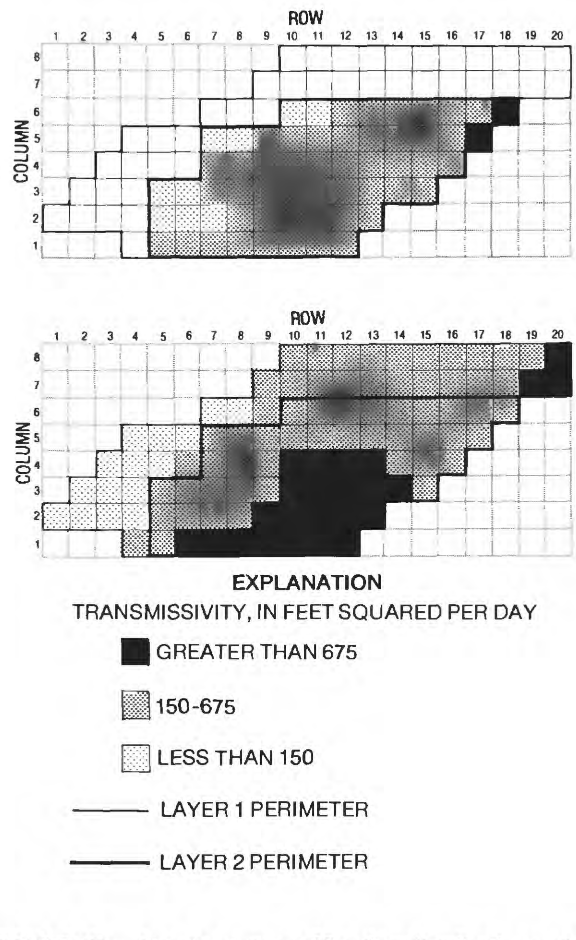


FIGURE 17.—Steady-state-verification distributions of transmissivity for model layers 1 and 2.

Table 6.--Comparison of estimated and model-calibrated transmissivity values

[ft^2/d, feet squared per day]

Model block (row, column)	Well No.	Layer in which well is perforated	Transmissivity (ft^2/d)	
			Estimated	Model calibrated
6,1	4N/28W-12L6	2	265	681
7,5	4N/28W-1R2	2	294	168
8,2	4N/28W-12K4	1, 2	373	674
9,1	4N/28W-12R3	2	882	733
9,3	4N/28W-12H4	2	882	662
11,6	4N/27W-6Q12	2	471	390
12,5	4N/27W-7H5	2	882	588
13,2	4N/27W-7Q5	2	856	793
13,2	4N/27W-7R3	2	950	793
16,4	4N/27W-8L2	1, 2	1,217	1,283

Table 7.--Estimated and model-calibrated steady-state-verification water budgets

[Values given in acre-feet per year]

Water-budget component	Estimated	Model calibrated
Recharge:		
Stream	160-460	438
Areal	320	[1]319
Underflow from the Santa Ynez mountains	25-300	[1]58
Underflow from the area left unmodeled	--	[2]90
Total	[3]500-1,100	905
Discharge:		
As underflow and to streams	[3]500-1,100	[4]905

[1]Does not include recharge from the area left unmodeled.

[2]Includes about 48 acre-ft/yr areal recharge and about 42 acre-ft/yr underflow from the Santa Ynez Mountains.

[3]Upper and lower limits are rounded to the nearest 100 acre-ft/yr.

[4]Includes about 484 acre-ft/yr to outflow drains and 421 acre-ft/yr to stream drains.

Transient-State Calibration

Transient state refers to the condition in which storage in the aquifer is changing in response to an imbalance between recharge and discharge in the ground-water system. The hydraulic-head configuration changes with time as water is received into or taken out of storage. With the advent of pumping in the late 1800's, (Muir, 1968, p. A21; Upson, 1951, p. 101), the Foothill basin entered a human-induced transient state.

A calibrated transient-state model must approximate historical time-varying hydraulic-head configurations. Few data were available for transient-state calibration, and in order to proceed with the calibration, a series of necessary assumptions had to be made.

The period picked for the transient simulation was 1935-87. Pumpage data (table 8) are available for this period; however, exact quantities and distribution of pumpage are not known precisely and may vary significantly from these data. According to available pumpage records, 65 wells were active at various times during 1935-87. The pumpage for each well was assigned to one (closest to the well) of 32 areal node locations (fig. 18) representing 58 nodes in the model. If a well was perforated in both model layers, the pumpage was distributed to the layers in proportion to the transmissivity of the layers at the well node. Reported pumpages, when available, were entered for individual wells; otherwise, pumpage was distributed to a well, as a fraction of the reported basinwide pumpage, on the basis of the well's electrical usage. Basinwide pumpage values for 1935-75, shown in table 8, were adapted from Mann (1976) and reflect adjustments due to the redefinition of the areal extent of the ground-water basin. Pumpage values for 1976-87 are from individual well records. Pumpage data from Mann (1976) are referenced to the Cachuma water year; however, for this report, pumpage is assumed to have occurred in the calendar year in which a particular Cachuma water year ended.

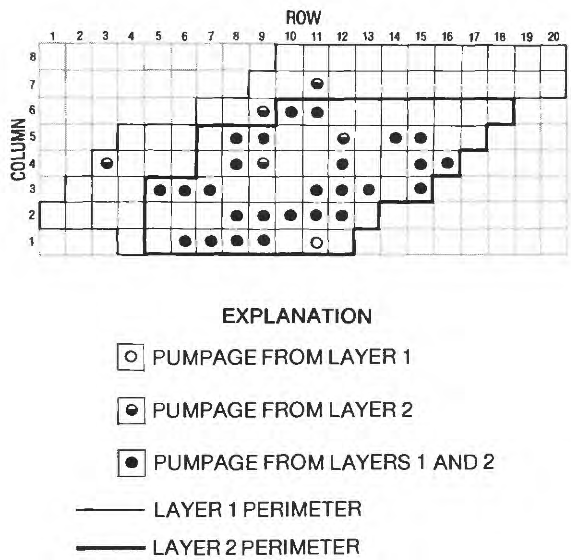


FIGURE 18.– Model pumpage distribution, 1935-87.

Table 8.--Pumpage used in the transient model, Foothill ground-water basin, 1935-87

[Pumpage, in acre-feet]

Calendar year	Pumpage	Calendar year	Pumpage
1935	570	1961	160
36	710	62	410
37	790	63	420
38	850	64	577
39	970	65	878
40	950	66	600
41	700	67	914
42	850	68	913
43	900	69	926
44	870	70	1,032
45	940	71	890
46	1,200	72	912
47	1,400	73	903
48	1,929	74	411
49	1,975	75	307
50	2,377	76	373
51	1,915	77	398
52	1,541	78	256
53	1,681	79	317
54	1,141	80	377
55	770	81	439
56	800	82	382
57	510	83	557
58	560	84	581
59	210	85	737
60	170	86	1,155
		87	1,328

Hydraulic heads from the steady-state-verification model (including pumpage from 1935) were assumed as initial basin heads for the transient simulation. Recharge adjustments were made during the transient calibration in conjunction with the steady-state-verification calibration. The calibrated recharge rate was 905 acre-ft/yr. Figure 14 shows the locations of model recharge.

Return flow from pumped ground water that is used for crop or landscape irrigation and recharge from water-main or sewer leakage were not modeled explicitly. These recharge components are small, and their omission probably does not introduce significant error.

The transmissivity distribution for the calibrated transient model is the same as the distribution for the steady-state-verification model (fig. 17). Minor adjustments to drain conductances and altitudes of the outflow drains, as well as to underflow fluxes, were made during calibration.

Ideally, transient-state calibration involves matching, as closely as possible, model-generated hydraulic heads to measured water levels in the basin. The matching may consist of duplicating water-level contour maps or hydrographs at selected wells. The calibration method used for this report is the matching of hydrographs at selected wells.

Adjustments that were confined to the transient-state calibration procedure consisted of varying the values of storage coefficient, which was the least-well-known parameter, and their distribution in the model until a suitable match (errors affecting the match are discussed in the "Limitations of the Model" section) was obtained between the model-generated hydrographs and the corresponding measured hydrographs at wells (fig. 19). Because of limited data, the estimates of storage coefficient were derived mainly by geohydrologic interpretation and examination of the values and distribution of transmissivities used in the model. Figure 20 shows the calibrated storage-coefficient distribution for the model.

Sensitivity Analysis

Sensitivity of the transient model was determined for changes in pumpage, recharge, conductance of the outflow drains, transmissivity, storage coefficient, and vertical hydraulic conductivity. Results of the sensitivity analysis are presented in a series of diagrams that show model response at selected nodes to changes in the sensitivity parameters (fig. 21*A*-*F*). The sensitivity analysis involved holding all input parameters constant except the one being studied, and then varying that parameter from 0.5 to 2.0 times the calibrated value of the parameter. Model response in terms of calculated hydraulic head was then noted for selected years including the start of the transient simulation (1935), the year of greatest pumpage of record (1950), 1960, 1975, and the end of the simulation (1987).

At all sensitivity nodes, hydraulic heads greater than calibrated values were generated by doubling recharge or storage coefficient or by halving pumpage or drain conductance. In addition, at node 7,3,1 higher hydraulic heads were produced by halving the vertical hydraulic conductivity. Hydraulic heads less than calibrated values were generated at all sensitivity nodes by doubling pumpage or drain conductance or by halving recharge or storage coefficient. Halving the transmissivity at node 7,3,1 or doubling the vertical hydraulic conductivity at nodes 7,3,1 and 10,6,1 also produced hydraulic heads less than the calibrated values. Doubling the transmissivity produced hydraulic heads at the sensitivity nodes that were sometimes greater and sometimes less than the calibrated values, as did halving the transmissivity or vertical hydraulic conductivity at nodes 8,5,1 and 10,6,1 or doubling the vertical hydraulic conductivity at node 8,5,1.

The model was most sensitive to changes in pumpage, recharge, and storage coefficient and least sensitive to changes in vertical hydraulic conductivity, drain conductance, and transmissivity. Of the most sensitive parameters, the least well known was storage coefficient. It can be seen from figure 21*B*,*D*, and *F* that uncertainty in storage-coefficient values can produce significant deviation in hydraulic-head values, especially during periods of heavy pumping. Of the three least sensitive parameters, the most sensitive was transmissivity; however, the least well known of these parameters were drain conductance and vertical hydraulic conductivity.

Calibrated values of the sensitivity parameters fall within, or are close to, the range of estimated values given in previous sections of this report; however, the accuracy of some of these values may be affected by areal and vertical distribution, which are not as well known. For example, the areal component of recharge was applied to the model at a uniform rate over the recharge area, but it undoubtedly is nonuniform in actuality. Likewise, pumpage data suffer in accuracy because of imprecise knowledge of the areal and vertical distribution of the data.

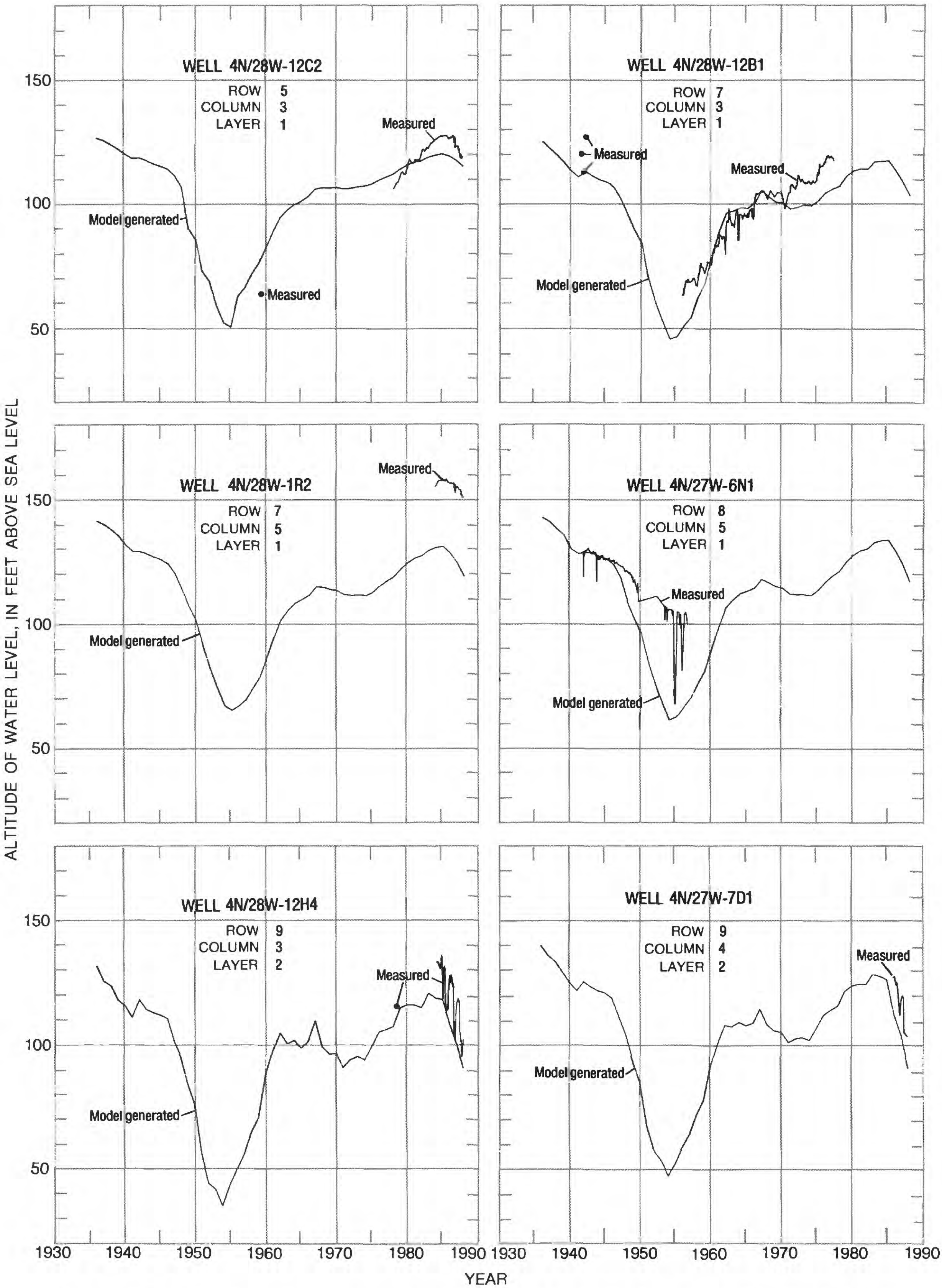


FIGURE 19.—Comparison of measured and model-generated water levels at selected wells, 1935-87.

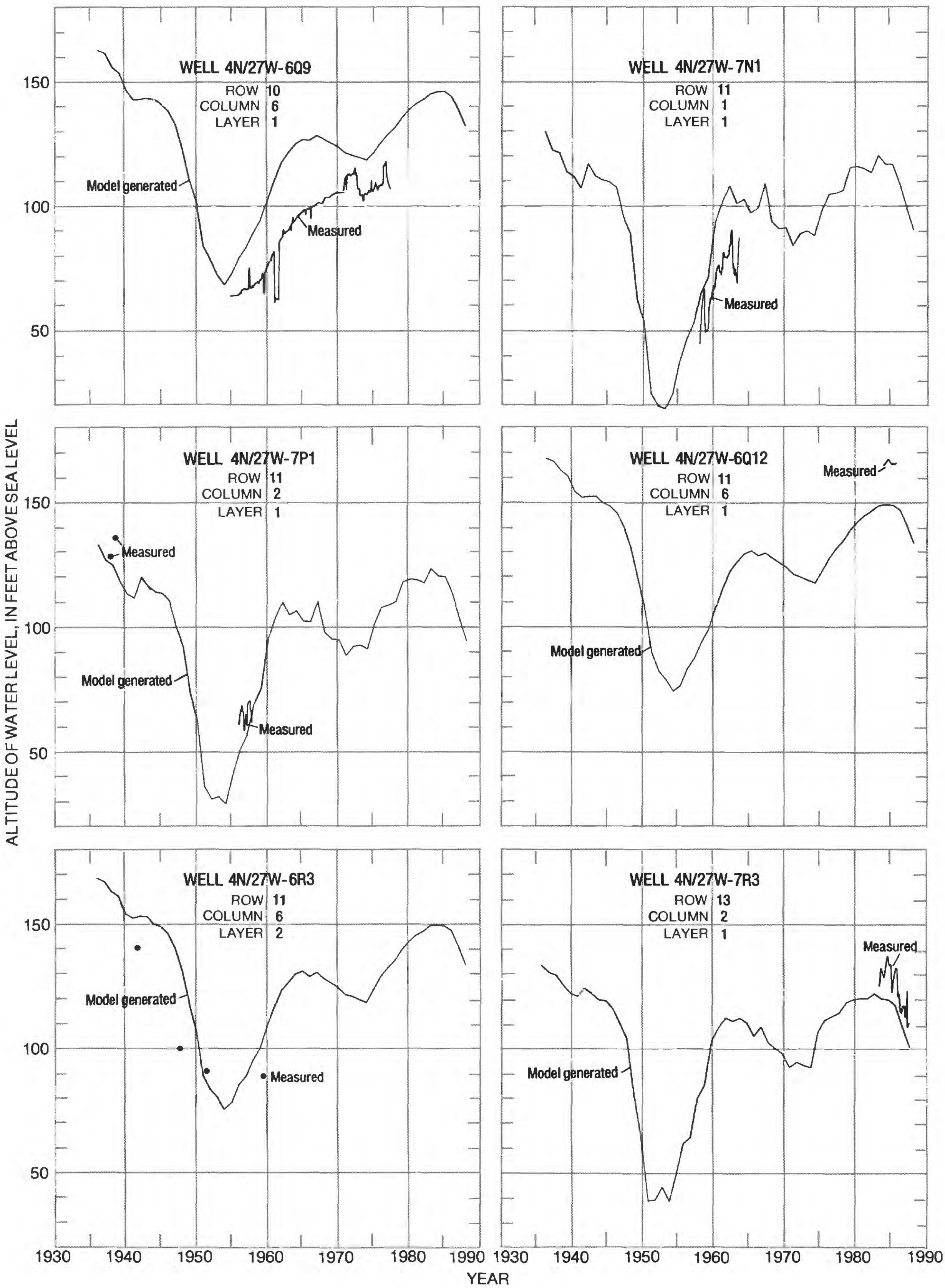


FIGURE 19.—Continued.

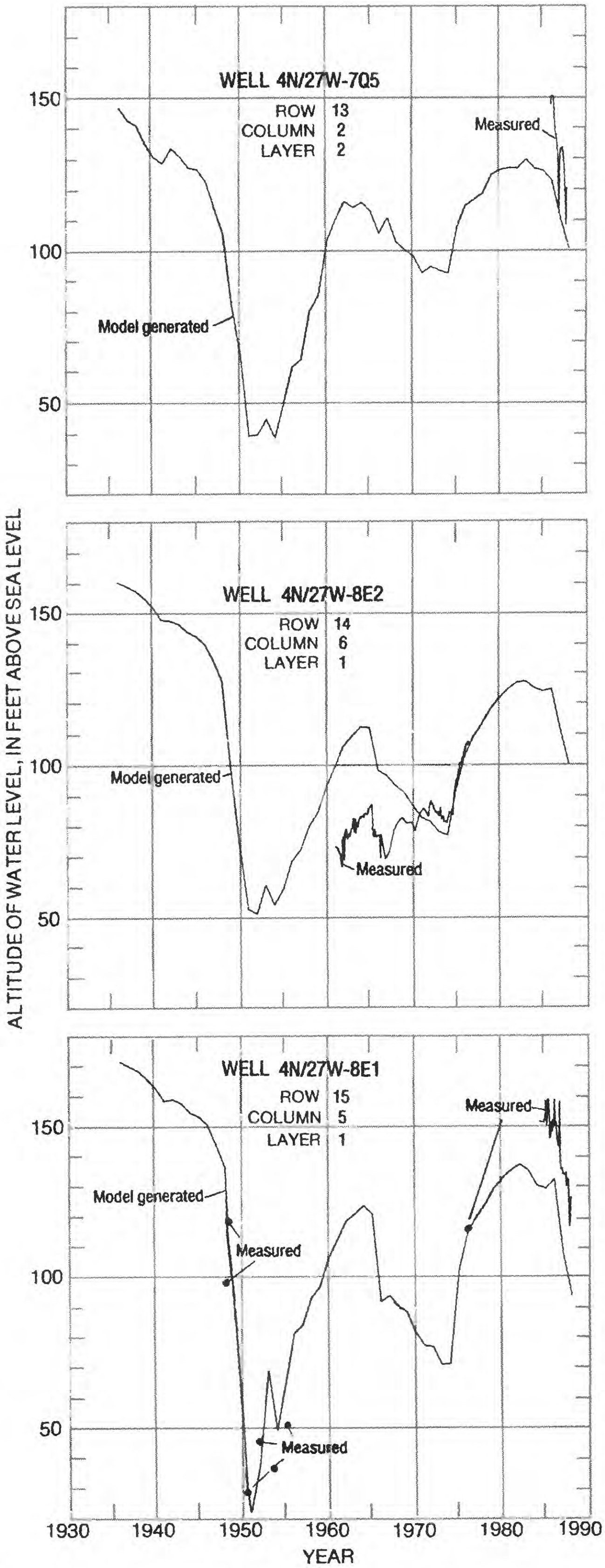


FIGURE 19.—Continued.

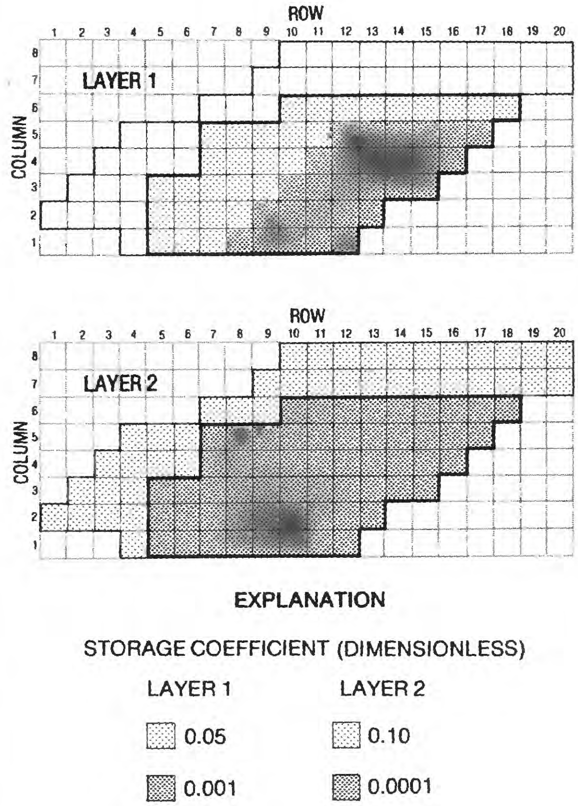
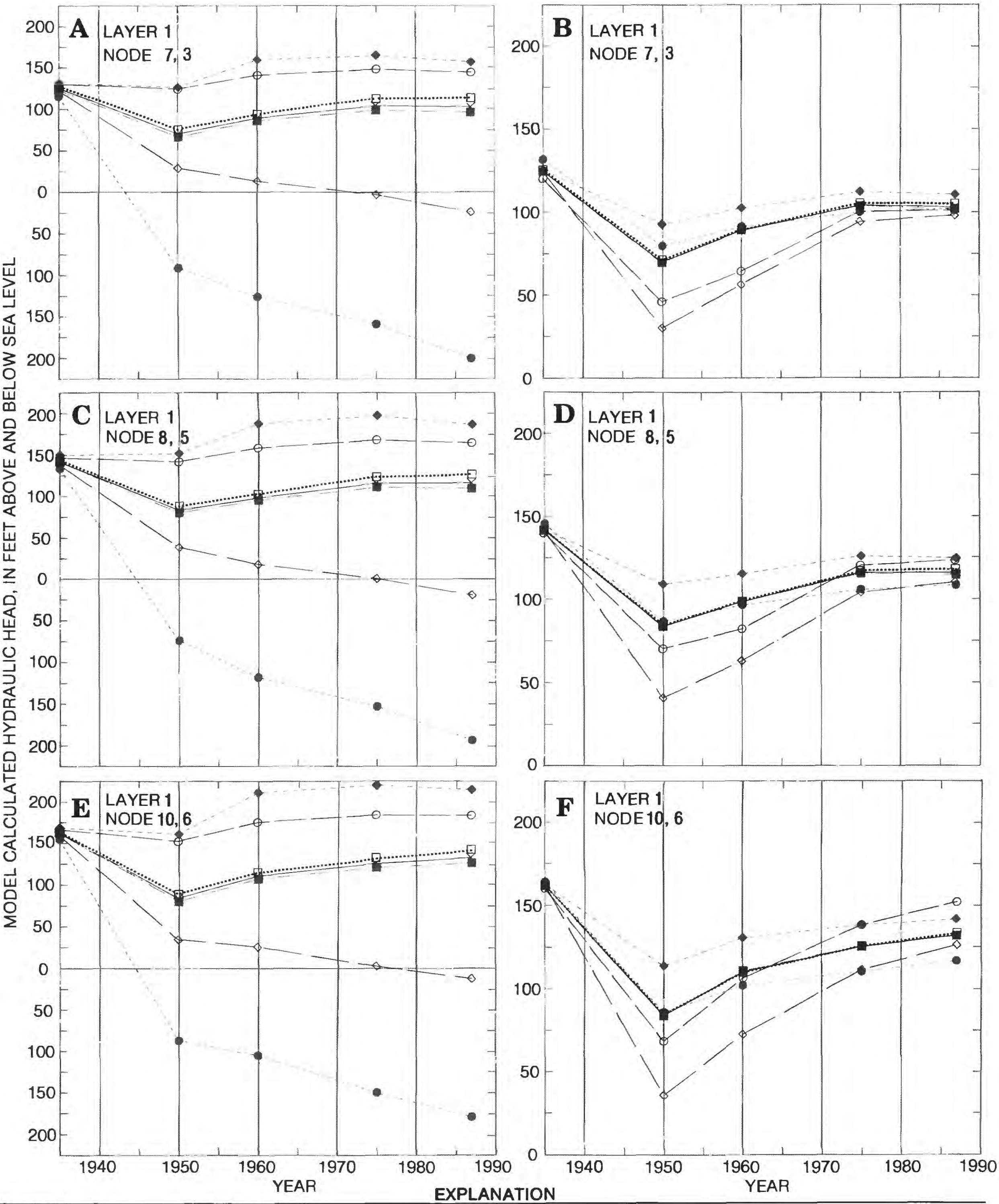


FIGURE 20.—Storage-coefficient distributions for model layers 1 and 2.

Limitations of the Model

The deviation of computed hydraulic heads from measured water levels results from simplifications associated with the conceptual model; from errors in estimated aquifer characteristics, estimated recharge and discharge, and historical water-level data; and from errors of prediction.

Two important simplifications of the conceptual model involve the assumptions that transmissivity and storage coefficient do not change with changes in water level. As noted in the "Assumptions" section, the water-bearing units were grouped into an upper and a lower layer. Because each layer was represented as a single layer in the model, changes in storage coefficient with changes in water level were not simulated within each layer. In the actual basin, storage coefficients can var considerably with time and depth, largely because o



EXPLANATION

GRAPHS:	A, C, E		GRAPHS:	B, D, F	
Amount of change	ONE-HALF	DOUBLE	Amount of change	ONE-HALF	DOUBLE
PUMPAGE	—○—	--●--	TRANSMISSIVITY	—○—	--●--
RECHARGE	-◇—	-◆-	STORAGE COEFFICIENT	—◇—	-◆-
DRAIN CONDUCTANCE	···⊡···	■—	VERTICAL HYDRAULIC CONDUCTIVITY	···⊡···	·■—

GRAPHS A-F: ——×—— CALIBRATED VALUE

FIGURE 21.—Model sensitivity at selected nodes to changes in pumpage, recharge, conductance of outflow drains, transmissivity, storage coefficient, and vertical hydraulic conductivity.

dewatering of nonhomogeneous material in the aquifers and aquifer compaction. The model makes no provision for vertical changes in the storage properties of the aquifer material; however, areal differences in storage coefficients are accomplished in the model by assigning appropriate values to the individual blocks. The model is rather limited in its ability to accommodate the various changes in storage coefficient that actually occur. Transmissivity in the unconfined areas of the basin can be modeled to change with changes in water level in a single layer. However, in the Foothill basin, the major water-bearing zones and the most transmissive aquifer materials occur near the bottom of a model layer. For example, large rightward kicks can be seen near the bottom of layer 1 in the electric logs at wells 4N/28W-1R2, 4N/27W-6Q12, and 4N/27W-8E1, and a large kick can be seen in the electric log at well 4N/27W-5P1 near the bottom of layer 2 (fig. 4), indicating a greater transmissivity at these depths. Thus, for the Foothill basin, the use of single layers with changing transmissivity does not accurately reflect the changes in transmissivity of a layer. Therefore, transmissivity was held constant in the model in order to more accurately represent the system as conceptualized.

Estimates of the aquifer characteristics--transmissivity, storage coefficient, vertical hydraulic conductivity, and drain conductance--were refined during model calibration with the aim of minimizing the deviation of computed hydraulic heads from measured values while keeping the parameter values within physically reasonable limits. Errors introduced into the model as a result of the deviation of model parameters from the actual values probably are small, especially in those areas where these parameters were based on measured field data.

Errors associated with the input data include those that result from the estimation or measurement of natural recharge, natural discharge, pumpage, and initial hydraulic heads. Techniques used to obtain estimates of recharge, discharge, and pumpage tend to bias the estimates, and this bias subsequently is transferred to the model parameters during the calibration process. Incorrectly estimating the altitude of land surface at wells from topographic maps introduces error into hydrographs used in the calibration process. Also, measurements of water levels in hydrograph wells that are being affected by nearby pumping will not be representative of conditions on the larger scale that the model simulates. Additionally, interpretation errors arise where field-data measurements are extrapolated to areas without any data. Input data errors may be rather large and are a serious concern.

The predictive accuracy of the model is a reflection of all the previously discussed sources of error and the degree to which future basin operation differs from those conditions used in calibrating the model. For example, it would be inappropriate to simulate major pumping stresses in the northeast, north, and northwest parts of the basin where no major pumping stresses were simulated in the calibrated model. Also, uncertainty in the mathematical representation of boundary conditions requires that care be taken when interpreting model results near the boundaries. Because storage-coefficient values are not well known, results of long-term transient simulations may differ significantly from actual conditions. Because of the model's ability to match absolute changes in water level (fig. 19), its best application lies in predicting what the differences in water levels will be among various recharge and discharge management scenarios.

Methods to Improve Model Input Data

Model input data can be improved as follows:

1. Pumpage--Install meters on extraction wells in the basin.

2. Recharge--Measure streamflow-infiltration rates on major streams in the area.

3. Water-level measurements--Make monthly water-level measurements at selected basin wells, and drill new wells in order to determine water-level differences in the confined and unconfined zones.

4. Aquifer hydraulic characteristics--Do a basinwide test in which all major wells are shut down for a period of time. Measure water levels at these wells and other observation wells during this period. At the end of the period, resume pumping, and continue measurements at observation wells. Aquifer tests at individual wells also can be done. Results of these tests can be used to estimate aquifer transmissivity and storage coefficient and to observe the basin's response to pumping.

5. Geohydrologic framework--Refine through test drilling and geophysical investigations.

6. Conceptualization--Use data obtained from implementation of items 1-5 to interpret the operation of the natural system and refine the mathematical model.

SUMMARY AND CONCLUSIONS

The Foothill ground-water basin consists of the areas referred to in previous reports as the East subbasin of the Goleta ground-water basin (the western part of the Foothill basin) and Storage Unit II of the Santa Barbara ground-water basin (the eastern part of the Foothill basin). The 4.5-square-mile Foothill basin is bordered by the Santa Ynez Mountains on the north and northeast; the Goleta fault on the northwest; the Modoc, More Ranch, and Mesa faults on the southwest; and the Mission Ridge fault on the southeast. The faults, for the most part, act as ground-water barriers that impede ground-water flow into and out of the area. Sedimentary rocks of Tertiary age underlie the ground-water basin and form its lower boundary.

The aquifer system is composed of alluvium, terrace deposits, and the Santa Barbara Formation. The principal aquifer of the basin is the Santa Barbara Formation, which consists primarily of unconsolidated marine sand, silt, and clay and has a maximum thickness of about 400 feet. The aquifer is confined in places where a zone of low permeability in its upper part separates its major water-bearing zones from the alluvium. Alluvium occurs as extensive deposits of gravel, sand, silt, and clay as much as 400 feet in thickness. Unfaulted younger alluvium may allow ground water to flow out of the basin in the vicinity of Cieneguitas and Atascadero Creeks and south of the confluence of Arroyo Burro and San Roque Creek.

Transmissivity of the unconsolidated deposits, as estimated from aquifer tests, ranges from about 300 to 1,200 ft^2/d. In general, transmissivities increase from the north and west toward the south and southeast. A storage coefficient of 0.0022, indicative of confined conditions, was calculated by Michael F. Hoover, consulting geologist, from data obtained during an aquifer test at well 4N/28W-12R2. Specific yield of saturated material ranges from 7.5 to 17.5 percent in the Santa Barbara ground-water basin area and probably has a similar range in saturated material in the Foothill ground-water basin. Vertical hydraulic conductivity of the confining zone separating the principal water-bearing zones of the Santa Barbara Formation and the alluvium is computed to be 3.8×10^{-7} ft/s.

The main sources of recharge to the Foothill basin are seepage from streams, infiltration of precipitation, and subsurface inflow from consolidated rocks of the Santa Ynez Mountains. Estimates of stream recharge range from about 160 to 460 acre-ft/yr. Precipitation infiltration is estimated to be about 320 acre-ft/yr. Subsurface inflow is estimated to range from about 25 to as much as 300 acre-ft/yr. During natural steady-state conditions, ground-water discharge as underflow and to streams is estimated to range from about 500 to 1,100 acre-ft/yr. Ground-water discharge as underflow in 1985 is estimated to be about 280 acre-ft.

Ground-water pumping in the area began in the late 1800's. During the period of record, 1935-87, ground-water pumpage ranged from 160 to about 2,400 acre-ft/yr. Pumpage in 1987 is estimated to be about 1,300 acre-ft. Two major water extractors in the basin are the city of Santa Barbara and La Cumbre Mutual Water Company; together they accounted for about 90 percent of the 1987 basin pumpage.

During nonpumping periods, ground water moves from the north, northeast, and northwest toward the Modoc, Mesa, and Mission Ridge faults where it exits the basin as underflow. During pumping periods, ground-water flow patterns are similar except that flow locally is directed toward wells, and the quantity of subsurface outflow is diminished. Ground-water levels declined more than 60 feet during periods of heavy pumping in the early 1950's, but levels generally rose from the mid-1950's to the late 1970's. Measured water levels during 1984-87 indicate a general decline, probably reflecting increased pumping during this period.

Water-quality data indicate markedly different water types in the Foothill ground-water basin in comparison with nearby basins. Nitrate concentrations in water samples from two wells exceeded the primary maximum contaminant level (10 mg/L) established by the U.S. Environmental Protection Agency. Secondary maximum contaminant levels for dissolved solids were exceeded in all sampled basin wells, and levels for chloride and sulfate were exceeded in samples from some wells. All sampled ground water would be classified as very hard (greater than 300 mg/L as $CaCO_3$). Sodium concentrations exceeded 20 mg/L in all water samples and may be a hazard to the health of those who must restrict sodium in their diets. The pH of the sampled water ranged from 7.2 to 8.0.

A three-dimensional finite-difference model was developed for part of the Foothill basin. The natural system was simulated with two layers in the model. The upper layer represents alluvial aquifers and the lower layer represents primarily the Santa Barbara Formation. Hydraulic connection between the layers is simulated as a leaky confining zone, which forms the upper part of the Santa Barbara Formation. Steady-state-verification and transient-state model calibrations were used to estimate or confirm estimates of basin recharge and natural discharge. Model-calibrated recharge was estimated to be 905 acre-ft/yr. Stream recharge used in the model was 438 acre-ft/yr, and areal recharge was 367 acre-ft/yr (includes areal recharge from the unmodeled area). Underflow from the Santa Ynez Mountains into the basin was simulated at 100 acre-ft/yr (includes underflow into the unmodeled area). The model is most sensitive to changes in recharge and pumpage. Model limitations result mainly from imprecise conceptualization of the natural system and from lack of precise data on pumpage, recharge, water levels, and aquifer hydraulic characteristics. The most accurate predictions that can be made with the model are those predictive simulations that compare the differences of computed hydraulic heads for a range of discharge and recharge scenarios.

SELECTED REFERENCES

Bowers, J.C., Butcher, M.T., Lamb, C.E., Polinoski, K.G., and Smith, G.B., 1986, Water resources data for California, water year 1984. Volume 1: Southern Great Basin from Mexican border to Mono Lake basin, and Pacific slope basins from Tijuana River to Santa Maria River: U.S. Geological Survey Water-Data Report CA-84-1, 375 p.

Bowers, J.C., Butcher, M.T., Lamb, C.E., Singer, J.A., and Smith, G.B., 1984, Water resources data for California, water year 1982. Volume 1: Southern Great Basin from Mexican border to Mono Lake basin, and Pacific slope basins from Tijuana River to Santa Maria River: U.S. Geological Survey Water-Data Report CA-82-1, 363 p.

-----1985, Water resources data for California, water year 1983. Volume 1: Southern Great Basin from Mexican border to Mono Lake basin, and Pacific slope basins from Tijuana River to Santa Maria River: U.S. Geological Survey Water-Data Report CA-83-1, 367 p.

Evenson, R.W., Wilson, H.D., Jr., and Muir, K.S., 1962, Yield of the Carpinteria and Goleta ground-water basins, Santa Barbara County, California, 1941-58: U.S. Geological Survey Open-File Report, 112 p.

Hem, J.D., 1985, Study and interpretation of the chemical characteristics of natural water [3d ed.]: U.S. Geological Survey Water-Supply Paper 2254, 263 p.

Hoover, M.F., 1978, Geologic hazards evaluation of the city of Santa Barbara, California: [Report prepared by Michael F. Hoover, consulting geologist], 35 p.

Hutchinson, C.B., 1979, Ground-water monitoring at Santa Barbara, California: Phase 1--Coastalmonitor-well installation and initial measurements: U.S. Geological Survey Open-File Report 79-923, 24 p.

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

Mann, J.F., Jr., 1976, Safe yield of the Goleta ground water basin: [Report prepared for Goleta County Water District by John F. Mann, Jr., consulting geologist and hydrologist], 31 p.

Martin, Peter, 1984, Ground-water monitoring at Santa Barbara, California: Phase 2--Effects of pumping on water levels and on water quality in the Santa Barbara ground-water basin: U.S. Geological Survey Water-Supply Paper 2197, 31 p.

Martin, Peter, and Berenbrock, Charles, 1986, Ground-water monitoring at Santa Barbara, California: Phase 3--Development of a three-dimensional digital ground-water flow model for Storage Unit I of the Santa Barbara ground-water basin: U.S. Geological Survey Water-Resources Investigations Report 86-4103, 58 p.

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

Muir, K.S., 1968, Ground-water reconnaissance of the Santa Barbara-Montecito area, Santa Barbara County, California: U.S. Geological Survey Water-Supply Paper 1859-A, 28 p.

National Oceanic and Atmospheric Administration, published monthly and annually (all data prior to 1940 by U.S. Weather Bureau), Climatological data: National Oceanic and Atmospheric Administration, Climatological data, monthly publications and annual summaries, various pagination.

Owen, L.W., 1976, City of Santa Barbara optimum water use study: Irvine, California, Don Owen and Associates, 221 p.

Santa Barbara County Water Agency, 1977, Adequacy of the groundwater basins of Santa Barbara County: Santa Barbara County Water Agency, Chapter 5, p. 1-23.

Santa Barbara Soil Conservation District, 1968, Goleta watershed report, 62 p.

Stiff, H.A., Jr., 1951, The interpretation of chemical water analysis by means of patterns: Journal of Petroleum Technology, v. 3, no. 10, p. 15-17.

Todd, D.K., 1978, Ground-water basin data: Status and needs, a report to the city of Santa Barbara, California: Berkeley, California, David Keith Todd Consulting Engineers, Inc., 94 p.

Upson, J.E., 1951, Geology and ground-water resources of the south-coast basins of Santa Barbara County, California, *with a section on* Surface-water resources, by H.G. Thomasson, Jr: U.S. Geological Survey Water-Supply Paper 1108, 144 p.

U.S. Environmental Protection Agency, 1977, National interim primary drinking water regulations: Office of Water Supply, Report EPA-570/9-76-003, 159 p.

-----1979, National secondary drinking water regulations: Federal Register, v. 44, no. 140, July 19, 1979, p. 42195-42202.

-----1986, Quality criteria for water, 1986: U.S. Environmental Protection Agency, EPA-440/5-86-001, various pagination.

U.S. Geological Survey, 1973-75, Water resources data for California, water years 1972-74; Part 1, surface water records, volume 1: Colorado River basin, southern Great Basin, and Pacific slope basins excluding Central Valley: U.S. Geological Survey Water-Data Reports CA-72-1 to CA-74-1, published annually.

-----1976-82, Water resources data for California, water years 1975-81; volume 1: Colorado River basin, southern Great Basin from Mexican border to Mono Lake basin, and Pacific slope basins from Tijuana River to Santa Maria River: U.S. Geological Survey Water-Data Reports CA-75-1 to CA-81-1, published annually.

Williams, D.E., 1981, The well/aquifer model--initial test results: Los Angeles, California, Roscoe Moss Company, 60 p.