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

By Peter Martin and Charles Berenbrock

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UNITED STATES DEPARTMENT OF THE INTERIOR

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CONVERSION FACTORS

The inch-pound system of units is used in this report. For readers who prefer the International System (SI) of 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	1,233	cubic meters
acre-feet per year (acre-ft/yr)	1,233	cubic meters per year
feet	.3048	meters
feet per day (ft/d)	.3048	meters per day
feet per second (ft/s)	.3048	meters per second
feet per year (ft/yr)	.3048	meters per year
feet squared per day (ft^2/d)	.0929	meters squared per day
feet squared per second (ft^2/s)	.0929	meters squared per second
gallons per minute (gal/min)	.00379	cubic meters per minute
inches per year (in/yr)	25.4	millimeters per year
miles	1.609	kilometers
square miles (mi^2)	2.590	square kilometers

Abbreviation used:
mg/L - milligrams per liter

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ABSTRACT

A three-dimensional finite-difference model was developed to simulate the ground-water system in Storage Unit I of the Santa Barbara ground-water basin. The purpose of the study was to evaluate present knowledge and concepts of the ground-water system, and to develop a tool to help manage the ground-water resources.

Water-bearing rocks in the 7 square miles of Storage Unit I consist of unconsolidated deposits that range in thickness from less than 300 feet along the north perimeter of the unit to more than 1,000 feet near the Pacific Ocean. The ground-water system was simulated as two horizontal layers separated by a confining bed. The model boundaries coincide with mapped faults on all sides. The faults were considered no-flow boundaries except for the offshore fault that forms the south boundary. This boundary was simulated as a general-head boundary, which allows water to move into and out of the modeled area.

The model was calibrated by simulating both steady-state conditions (approximated by July 1978 and February 1983 water levels) and transient-state conditions (represented by May 1978 through December 1979 water-level changes). The calibrated model was then used to simulate the period from January 1980 through December 1983 in order to verify the model. Model results generally closely matched measured data throughout Storage Unit I.

During the transient and verification simulations, 9,980 acre-feet of ground water was pumped from Storage Unit I for municipal use. Results of the model indicate that 42 percent (4,190 acre-feet) of the water pumped from the system was withdrawn from storage, 33 percent (3,290 acre-feet) was derived from changes in underflow across the offshore fault, and 25 percent (2,500 acre-feet) was derived from decreased ground-water discharge to drains. The model simulated that municipal pumpage induced about 1,380 acre-feet of water to move across the offshore fault toward Storage Unit I. The inflow of water from the ocean side of the fault is verified by increased chloride concentrations in water samples from coastal monitor wells.

Several model simulations were used to estimate aquifer response to different municipal pumpage patterns that could be used as management alternatives. Results of the simulations indicate that spreading municipal pumpage more evenly throughout Storage Unit I by increasing the number of wells while reducing the pumping rate at the individual wells to maintain the same total pumpage significantly reduces the inflow of ground water across the offshore fault.

INTRODUCTION

Although the city of Santa Barbara obtains most of its water supply from surface-water reservoirs, ground water is used as a supplemental source. City policy adopted in 1976 maximizes use of its ground-water resources (Owen, 1976). Because the city of Santa Barbara is adjacent to the Pacific Ocean, there is a possibility of saltwater intrusion if the ground-water resources are not properly managed. The ground-water flow model developed in this study can be a useful tool in understanding and managing the ground-water resources.

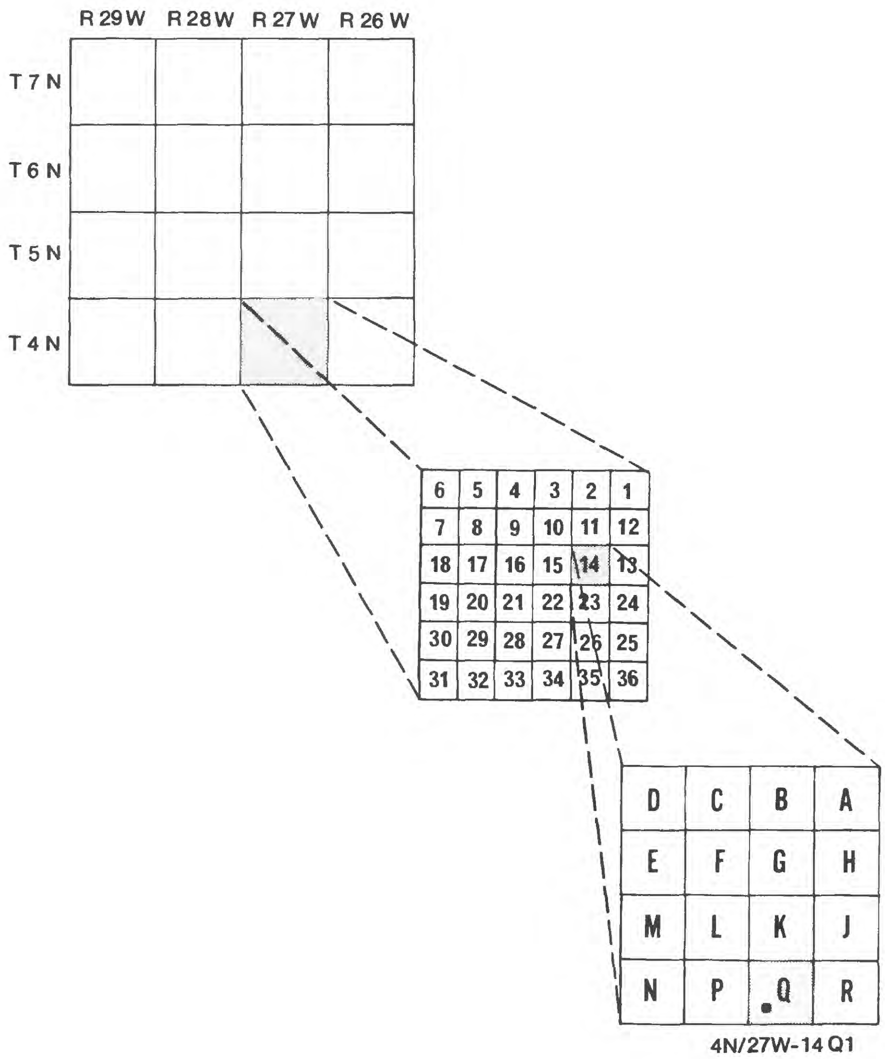
Purpose and Scope

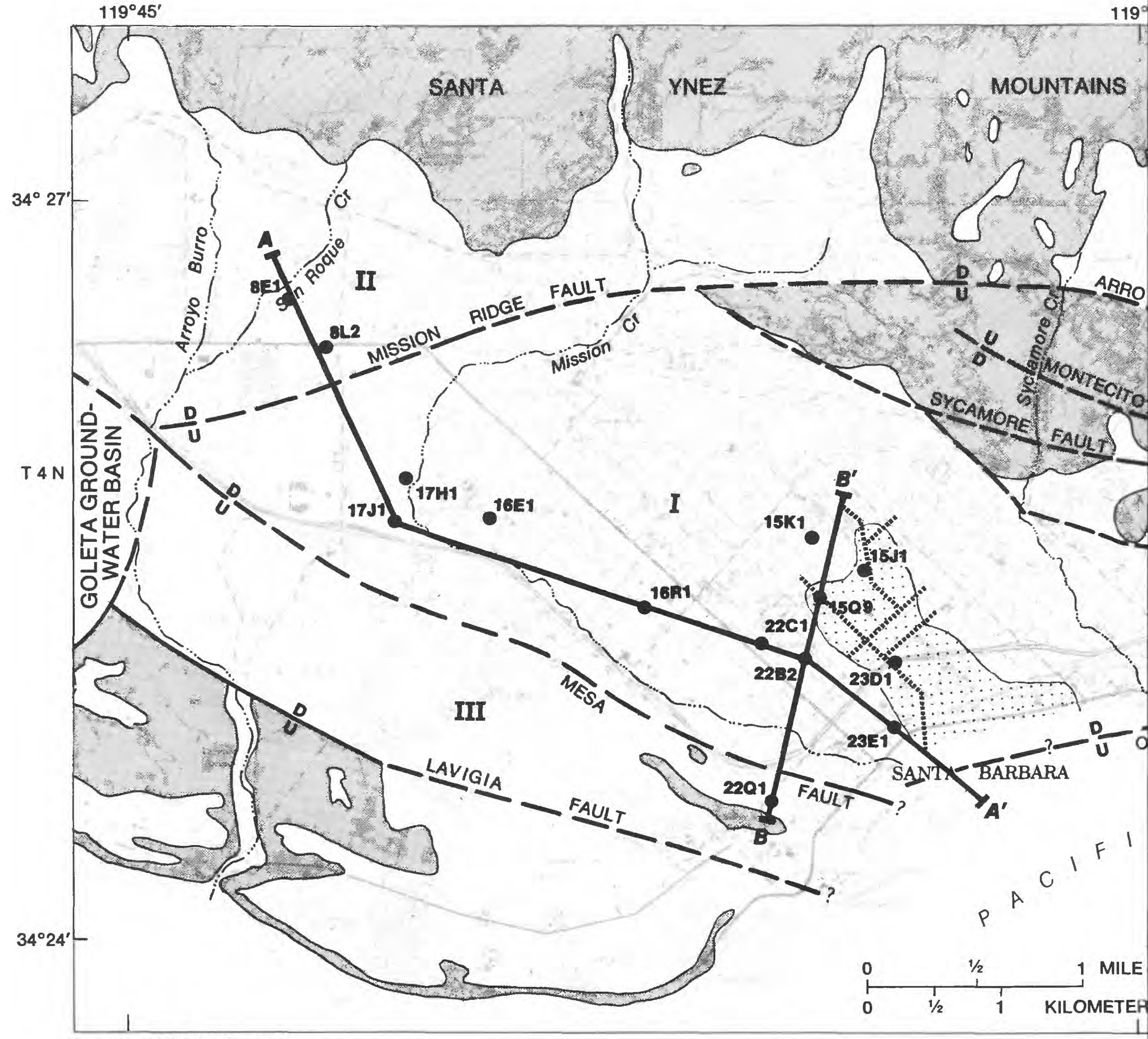
In 1977, the city of Santa Barbara entered into a cooperative study with the U.S. Geological Survey to develop and implement a three-phase ground-water monitoring program in Storage Unit I of the Santa Barbara ground-water basin (fig. 1). The first phase of the program, completed in 1978 (Hutchinson, 1979), resulted in the drilling of eight monitor wells at two sites along the coast to provide an early warning of saltwater intrusion into the freshwater aquifer. The second phase of the program, completed in 1980 (Martin, 1984), analyzed and evaluated the effects of ground-water pumping on water levels and on water quality in the ground-water basin. The purpose of the third phase of the program, described in this report, is to develop a digital flow model for Storage Unit I of the Santa Barbara ground-water basin to help define the hydrogeology and aid in management of the water resources of Storage Unit I.

The third phase of the program included (1) updating, evaluating, tabulating, and filing in computer storage pumping and other hydrologic data compiled in the second phase of the program; (2) developing a digital flow model for Storage Unit I that simulates steady-state and transient-state conditions; (3) verifying the model and the calibrated input values with data collected during the monitoring program; and (4) using the calibrated model to simulate the response of the aquifer to a variety of operational conditions.

Well-Numbering System

Wells are numbered according to their location in the rectangular system for subdivision of public land. For example, in the well number 4N/27W-14Q1, the part of the number preceding the slash indicates the township (T. 4 N.); the number following the slash indicates the range (R. 27 W.); the number following the hyphen indicates the section (sec. 14); 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 general features of the Santa Barbara ground-water basin.

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EXPLANATION

UNCONSOLIDATED DEPOSITS

CONSOLIDATED ROCKS

FAULT – Dashed where approximately located, queried where doubtful. **U**, upthrown side; **D**, downthrown side

GROUND-WATER DIVIDE

I — GROUND-WATER STORAGE UNIT -- Faults control storage-unit boundaries

UNDERGROUND DRAIN

APPROXIMATE AREA OF THE FORMER SANTA BARBARA ESTERO

15J1 — DATA POINT FOR GEOLOGIC SECTION AND WELL NUMBER

A — A′ LINE OF GEOLOGIC SECTION (Shown in fig. 2)

FIGURE 1. – Continued.

DESCRIPTION OF THE STUDY AREA

Location and General Features

The Santa Barbara ground-water basin is on the south coast of Santa Barbara County about 120 miles northwest of Los Angeles (fig. 1). The basin is bounded on the north by foothills of the Santa Ynez Mountains, on the west by the Goleta ground-water basin, on the south by the Pacific Ocean, and on the east by the Montecito ground-water basin. Hydrologically, the Santa Barbara ground-water basin is divided into three storage units by the Mesa and Mission Ridge faults. (See fig. 1.) The principal area of concern for this study is Storage Unit I, which encompasses about 7 mi^2.

The Santa Barbara area has a Mediterranean-type climate of warm, dry summers and mild winters. The area has distinct wet and dry seasons; 95 percent of the precipitation falls between November and March. The mean annual precipitation at the lower altitudes of Santa Barbara is 17.41 inches (National Oceanic and Atmospheric Administration, 1978).

The Santa Barbara ground-water basin is drained by Sycamore, Mission, and San Roque Creeks, and Arroyo Burro. All these streams are intermittent in their lower reaches, where they lose water by seepage as they flow over the unconsolidated deposits of the basin.

Prior to the development of Santa Barbara, a marshy lagoon known as the Santa Barbara Estero existed in the southern part of Storage Unit I between the Santa Barbara High School and the ocean (fig. 1). This area has been filled in, and a network of drains has been installed to dewater the area.

Definition of the Aquifer System

For this study, the lithologic units mapped by Dibblee (1966) and Muir (1968) were generalized in the Santa Barbara area into "consolidated rocks" and "unconsolidated deposits" (fig. 1).

Consolidated sedimentary rocks of Tertiary age underlie the ground-water basin and compose the surrounding hills. These consolidated rocks, predominantly marine in origin, are nearly impermeable except for slightly permeable sandstones and where fractured. The consolidated rocks form the lower boundary of the ground-water basin and also form much of the perimeter boundary of the basin. (See fig. 1.)

The unconsolidated deposits in Storage Unit I consist of the Santa Barbara Formation of late Pliocene and early Pleistocene age and alluvium of Holocene age. These deposits range in thickness from less than 300 feet just south of the Mission Ridge fault to more than 1,000 feet adjacent to the north side of the Mesa fault near the Pacific Ocean (fig. 2). The Santa Barbara Formation lies unconformably on the consolidated rocks and, in most of Storage Unit I, underlies the alluvium. This formation is of marine origin and consists of fine to coarse sand, silt, clay, and occasional gravel layers. The alluvium, as described in this report, includes terrace deposits, older alluvium, and younger alluvium and consists of poorly sorted sand, gravel, silt, clay, and widely scattered cobbles and boulders.

On the basis of data from electric and geologic logs of selected wells, Martin (1984, p. 5) subdivided the unconsolidated deposits into five main zones (fig. 2): (1) the shallow zone, (2) the upper producing zone, (3) the middle zone, (4) the lower producing zone, and (5) the deep zone.

The shallow zone includes the alluvium from the land surface to the top of the upper producing zone. Water-bearing deposits are present in the shallow zone; however, this zone consists primarily of fine-grained deposits of low permeability. The fine-grained deposits of the shallow zone confine or partly confine the underlying upper producing zone in the southern part of Storage Unit I near the Pacific Ocean. The shallow zone ranges in thickness from less than 100 feet south of Mission Ridge fault to about 300 feet near the Pacific Ocean. The water-bearing deposits of the shallow zone were not considered an important part of the aquifer system and were not simulated in the mathematical model.

The upper producing zone near the base of the alluvium consists of medium to coarse sand with some fine gravel (Martin, 1984, p. 5). This zone is distinct and continuous throughout most of Storage Unit I and ranges in thickness from less than 10 feet south of Mission Ridge fault to about 50 feet beneath the city of Santa Barbara. The upper and lower producing zones are the two main water-bearing zones tapped by wells in the Santa Barbara area.

The middle zone underlies the upper producing zone and overlies the lower producing zone. This middle zone consists of the upper part of the Santa Barbara Formation and is mainly fine-grained deposits interspersed with occasional coarse-grained water-bearing deposits. The fine-grained deposits yield virtually no water to wells, but the interbedded coarse-grained deposits supply some water to wells. The fine-grained deposits of the middle zone confine or partly confine the underlying lower producing zone throughout most of Storage Unit I. The middle zone ranges in thickness from less than 50 feet south of Mission Ridge fault to about 350 feet near the Pacific Ocean.

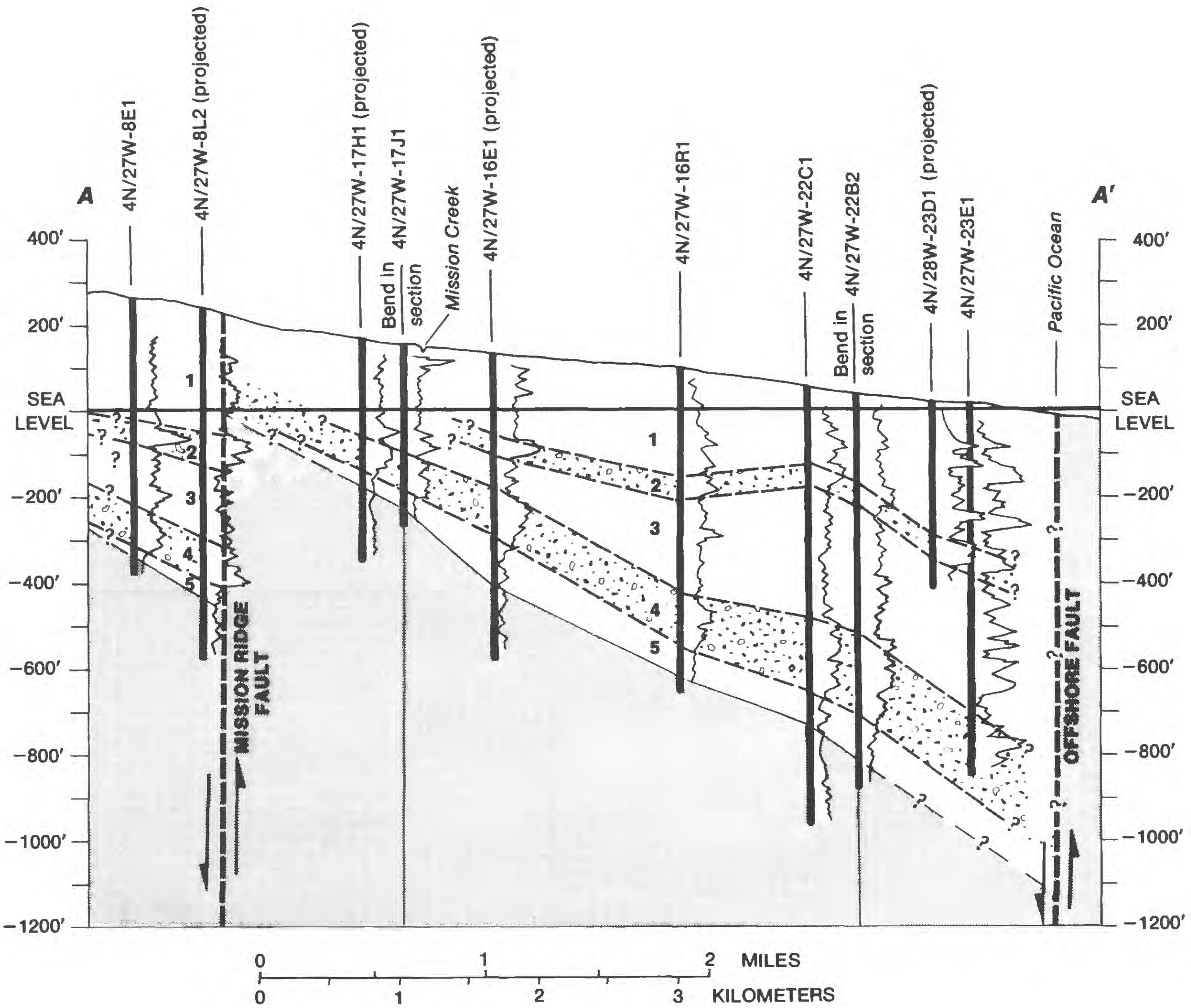


FIGURE 2. – Geologic sections of the Santa Barbara ground-water basin.

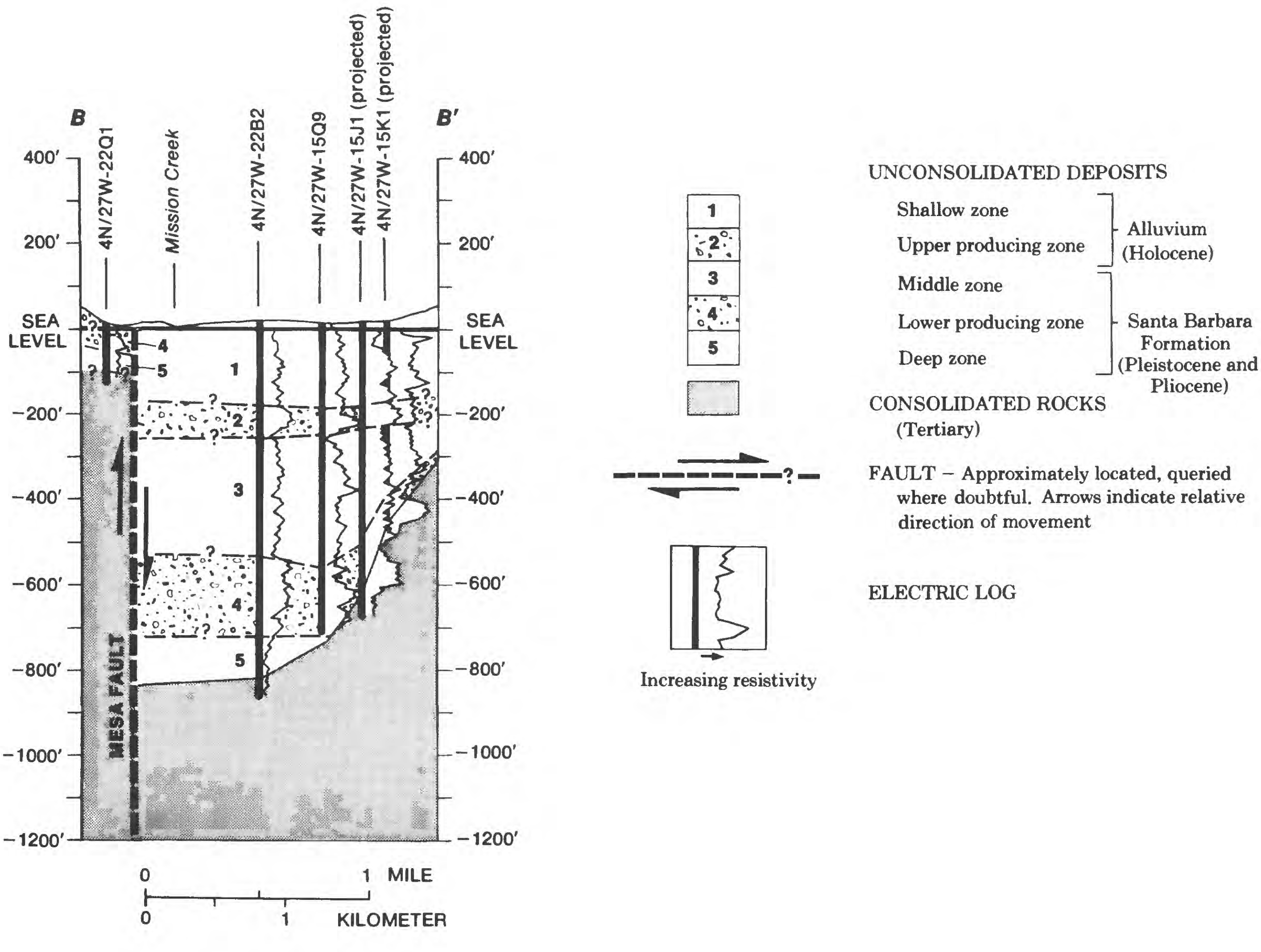


FIGURE 2. – Continued.

The lower producing zone, near the base of the Santa Barbara Formation, consists of medium to coarse sand with fine gravel and shell fragments. In Storage Unit I, the lower producing zone ranges in thickness from less than 10 feet near Sycamore fault to more than 200 feet beneath the city of Santa Barbara. The lower producing zone is probably the major source of water to wells in the Santa Barbara ground-water basin (Martin, 1984, p. 5).

In most of Storage Unit I the deep zone separates the lower producing zone from the consolidated rocks. The deep zone consists of fine-grained deposits reported to contain water of poor quality (Martin, 1984, p. 5). Because of the reported low permeability and lack of information, the deep zone was not simulated in the mathematical model of Storage Unit I.

Ground-Water Movement

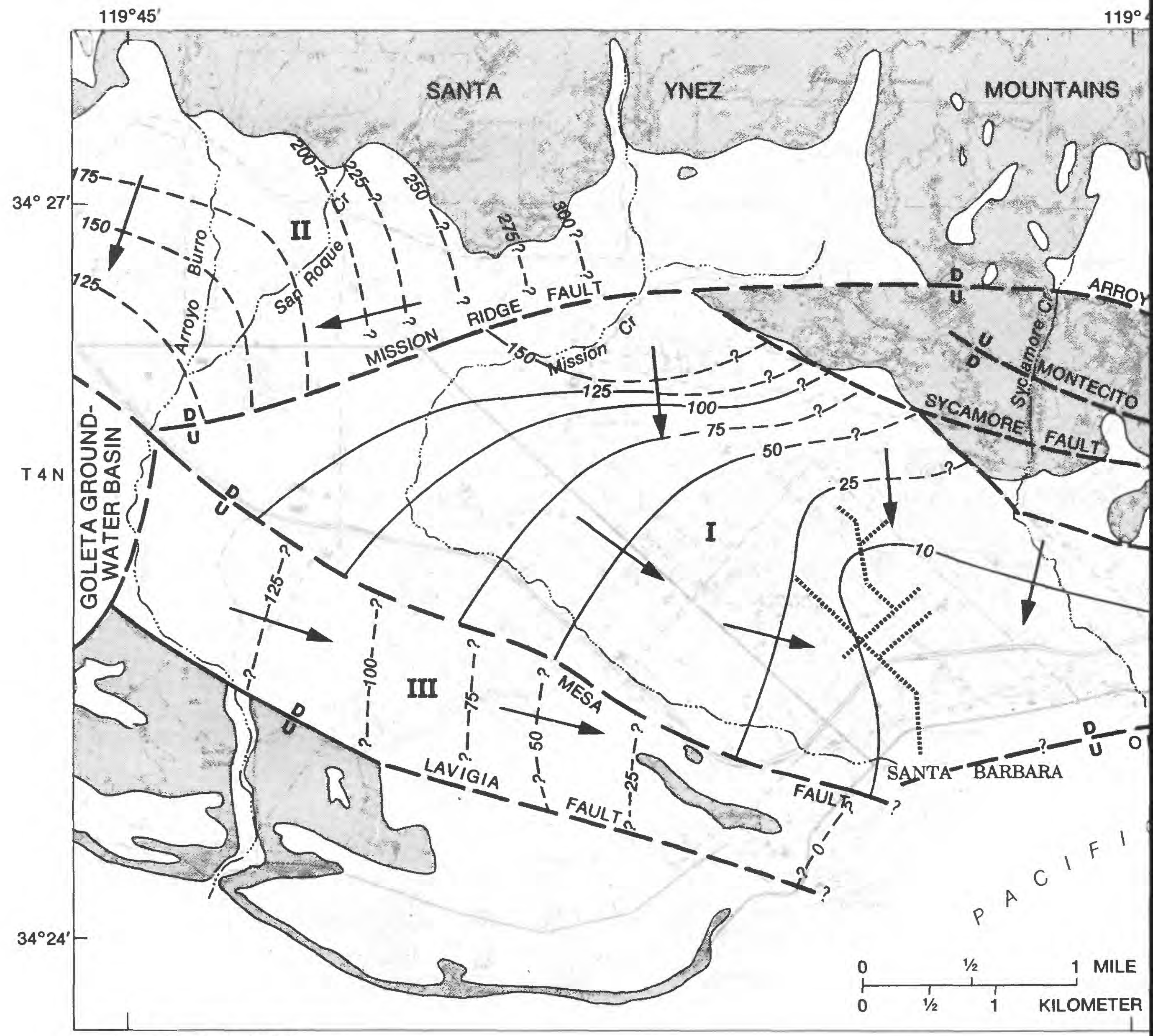
During nonpumping periods, ground-water movement in Storage Unit I, in both the upper and lower producing zones, generally is from the northwest and northeast toward the Pacific Ocean. Ground-water recharge occurs mainly by direct infiltration of precipitation and runoff from the surrounding highlands onto the northern and northwestern perimeter of Storage Unit I and by seepage of streamflow in Mission Creek. Ground-water discharge occurs by upward leakage into drains in the area of the former Santa Barbara Estero (fig. 1) and by leakage across the unnamed offshore fault into the Pacific Ocean. (See fig. 3.) The potentiometric contours of the lower producing zone (fig. 3), constructed from July 1978 and February 1983 water-level measurements, are representative of ground-water conditions during nonpumping periods. Combining the measurements from these two periods is justified because the difference in water levels measured in the same well during both periods is generally less than 1 foot.

During pumping periods potentiometric contours of both the upper and lower producing zone show a distinct cone of depression related to municipal pumping near the southern part of Storage Unit I. The January 1980 potentiometric contours of the lower producing zone are representative of ground-water conditions during pumping periods (fig. 4). In January 1980, annual municipal pumpage was about 3,000 acre-ft. The pumping, centered in the city less than 1 mile from the coast, caused water-level declines to altitudes below sea level in the southern part of Storage Unit I and reversed the direction of ground-water movement in the area between the pumping center and the Pacific Ocean. (See fig. 4.)

Leakage of ground water between the upper and lower producing zones occurs through the middle zone. Along the northern perimeter of Storage Unit I, the direction of leakage is downward from the upper producing zone to the lower producing zone. In the area of the former Santa Barbara Estero, the direction of leakage is upward from the lower to the upper producing zone during nonpumping periods, and it is downward from the upper to the lower producing zone during pumping periods (Martin, 1984, p. 12).

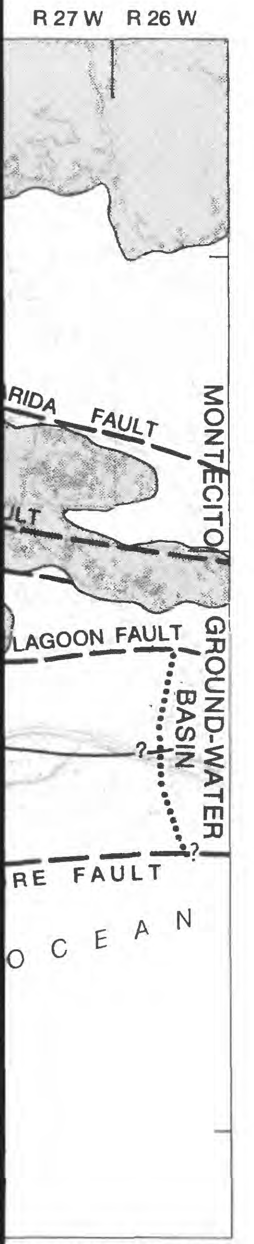
Water-level data from Storage Units II and III indicate that the Mission Ridge and Mesa faults are partial barriers to ground-water movement during both nonpumping and pumping periods (Martin, 1984, p. 13). Geologic section A-A' (fig. 2) shows that consolidated rocks are uplifted to within 300 feet of the land surface on the south side of the Mission Ridge fault, and there is a 500-foot displacement between the tops of the consolidated rocks on the north and south sides of the fault. The Mesa fault is probably an effective barrier to ground-water movement near the ocean, where consolidated rocks are uplifted to near land surface on the west side of the fault. (See fig. 2.) Flow lines in the lower producing zone of Storage Units I and III are parallel to Mesa fault (figs. 3 and 4), suggesting that there is little flow across the fault.

The unnamed offshore fault (fig. 2) is also a partial barrier to ground-water movement. The offshore fault truncates the water-bearing deposits so that they lie against consolidated rocks on the seaward side of the fault. The presence of saltwater in the lower producing zone of Storage Unit I indicates, however, that the offshore fault is not an effective barrier to ground-water movement (Martin, 1984, p. 23).



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

FIGURE 3. – Potentiometric contours and water movement in the lower producing zone based on July 1978 and February 1983 water-level measurements.



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(1968) and M.F. Hoover
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EXPLANATION

UNCONSOLIDATED DEPOSITS

CONSOLIDATED ROCKS

FAULT – Dashed where approximately located, queried where doubtful. U, upthrown side; D, downthrown side

GROUND-WATER DIVIDE

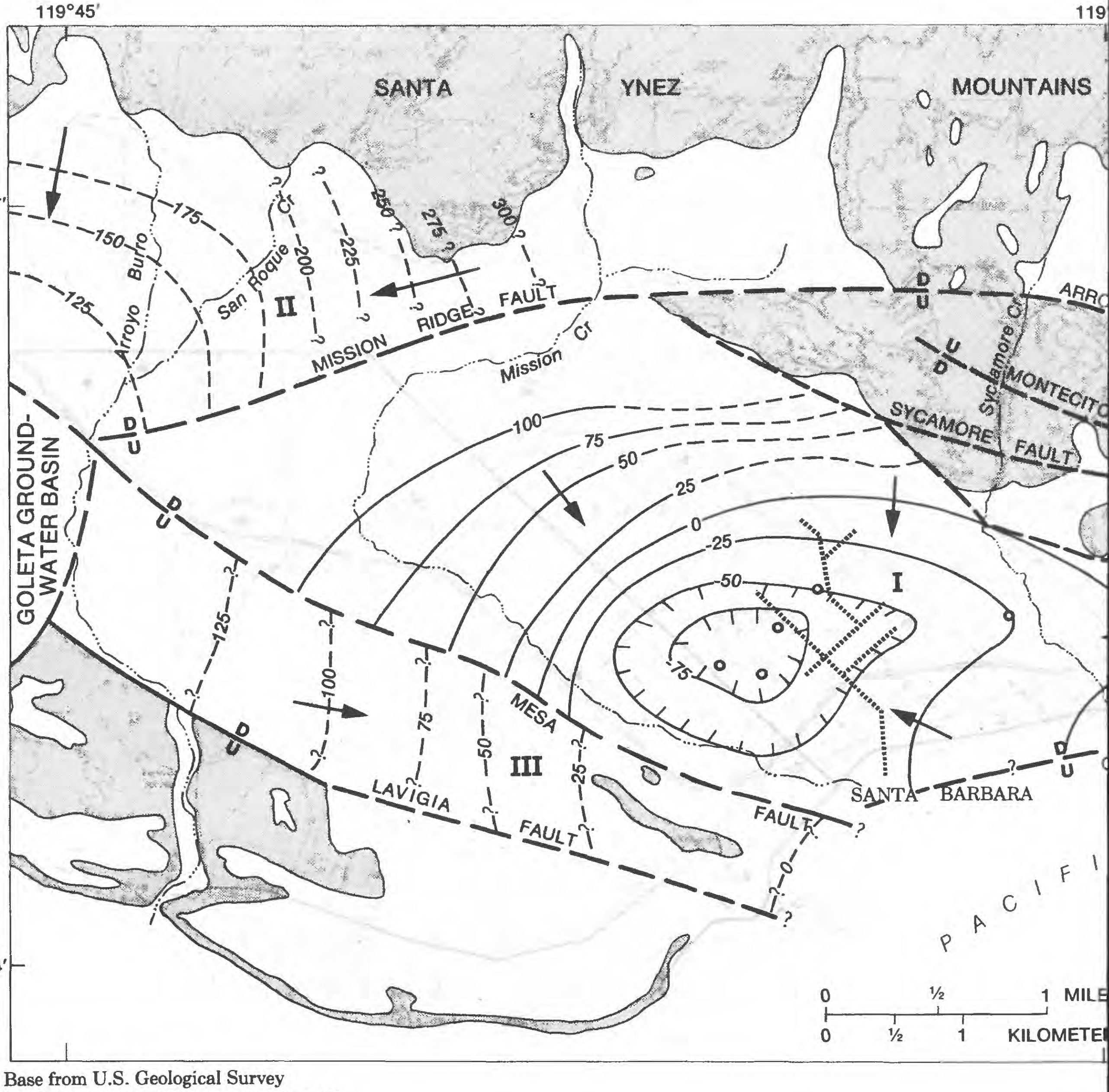
I GROUND-WATER STORAGE UNIT -- Faults control storage-unit boundaries

UNDERGROUND DRAIN

10 POTENTIOMETRIC CONTOUR – Shows altitude, in feet above sea level, at which water level would have stood in tightly cased wells. Dashed where approximately located, queried where doubtful. Contour interval variable

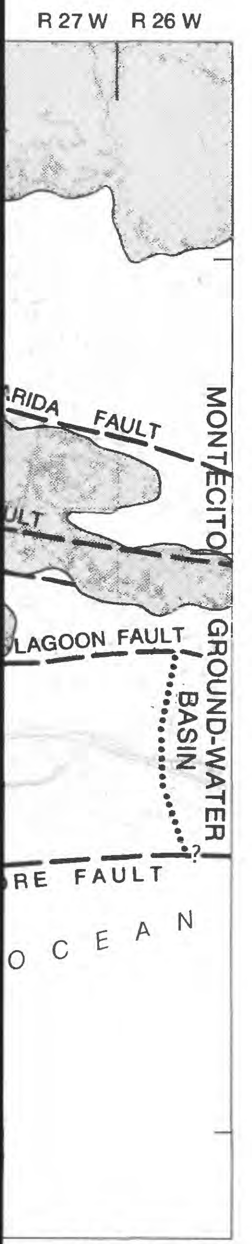
DIRECTION OF GROUND-WATER MOVEMENT

FIGURE 3. – Continued.



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

FIGURE 4. – Potentiometric contours and water movement in the lower producing zone based on January 1980 water-level measurements.



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EXPLANATION

UNCONSOLIDATED DEPOSITS

CONSOLIDATED ROCKS

FAULT – Dashed where approximately located, queried where doubtful. **U**, upthrown side; **D**, downthrown side

GROUND-WATER DIVIDE

GROUND-WATER STORAGE UNIT -- Faults control storage-unit boundaries

UNDERGROUND DRAIN

POTENTIOMETRIC CONTOUR – Shows altitude at which water level would have stood in tightly cased wells. Dashed where appproximately located, queried where doubtful. Contour interval 25 feet. Datum is sea level. Contours modified from Martin (1984)

MUNICIPAL SUPPLY WELL – (Municipal pumpage in Storage Unit I averaged 6.3 acre-feet per day from May 1978 through December 1979)

DIRECTION OF GROUND-WATER MOVEMENT

FIGURE 4. – Continued.

THE GROUND-WATER FLOW MODEL

The objective in constructing a mathematical ground-water flow model of Storage Unit I was to test conceptions about the hydraulics of the ground-water flow system and to develop a tool that could be used to estimate changes in hydraulic heads on the basis of projected water-use requirements. However, the mathematical model cannot exactly duplicate the actual aquifer system because of the complex geohydrologic relations in Storage Unit I. Model development requires the use of assumptions and approximations that simplify the physical system.

Model Assumptions

The mathematical model used in this study was developed by McDonald and Harbaugh (1984) and utilizes the block-centered finite-difference numerical method of solution. A full explanation of the theoretical development, the solution technique used, and the mathematical treatment of each simulated condition is included in McDonald and Harbaugh (1984).

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 can be represented by two water-bearing layers separated by a confining bed.
2. Ground-water movement in both water-bearing layers is horizontal.
3. The water-bearing layers are isotropic.
4. Ground-water movement within the middle zone (the confining bed) is vertical.
5. Changes in hydraulic head within the middle 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.
9. Saltwater intrusion has little or no effect on hydraulic head.

Model Construction

The aquifer system was simulated as two horizontal layers separated by a confining bed. Layer 1, the upper layer, represents the upper producing zone. Layer 2, the lower layer, represents the lower producing zone. The middle zone is the confining bed that separates the two layers. Horizontal flow and storage in the confining bed were not simulated.

In order to numerically define this aquifer system, it is necessary to divide the aquifer system into a grid, determine the boundary conditions for the aquifer, estimate the aquifer properties within the model area, and estimate the rates and distribution of recharge and discharge to the aquifer system.

Model Grid

The finite-difference techniques used in the model require that the ground-water system be divided into a grid of rectangular blocks. The model grid consists of 252 blocks that are 1,000 feet on a side. The finite-difference grid used for layers 1 and 2 is identical and is shown in figure 5. Average values for aquifer characteristics are assigned to each grid block, and average hydraulic head for each block is assigned at the center, or node, of each block.

Model Boundaries

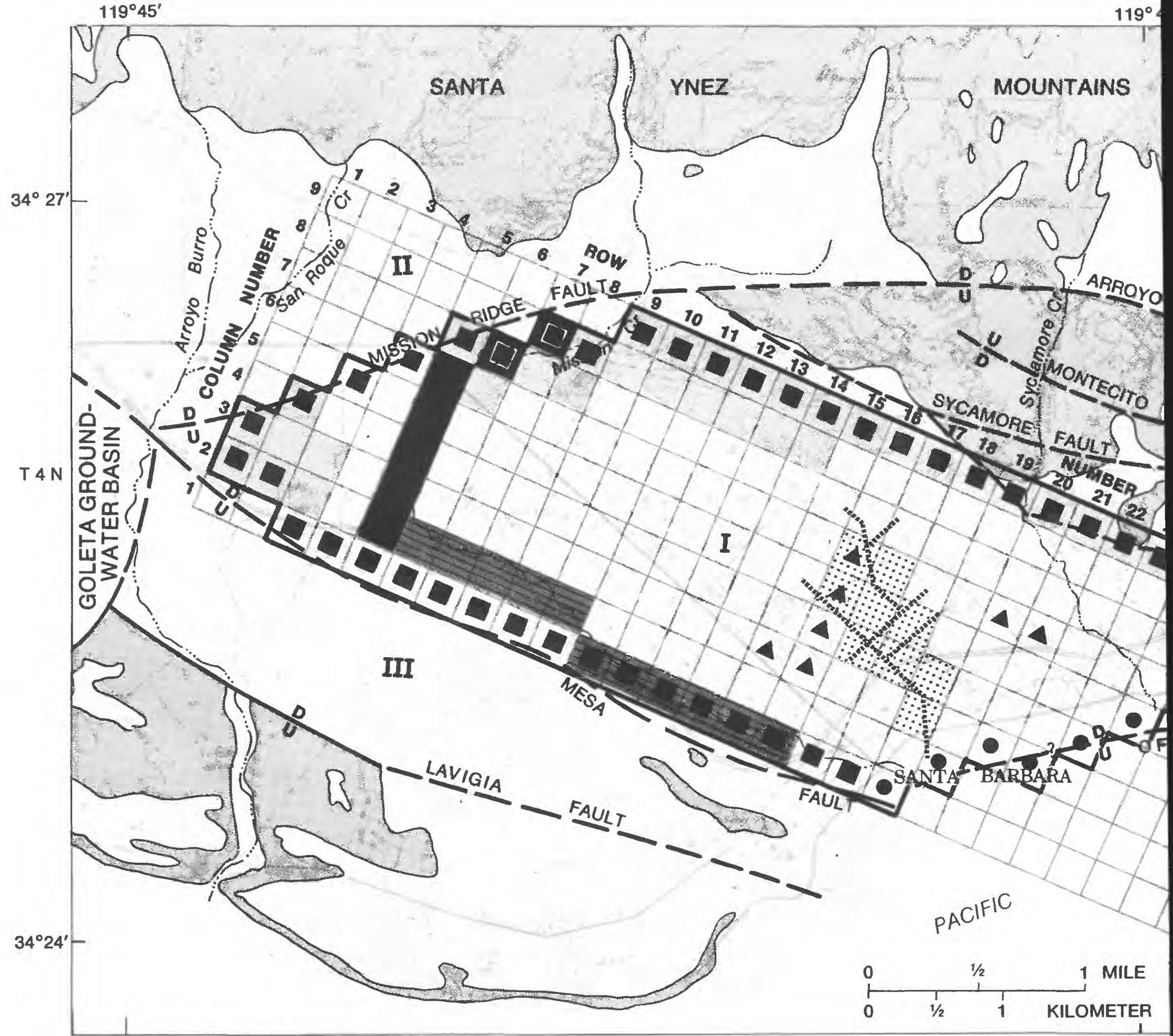
All model boundaries (fig. 5) coincide with the aquifer limits defined by geohydrologic interpretations. The model boundaries of layers 1 and 2 are identical and include the Mesa, Mission Ridge, Sycamore, and Lagoon faults. Although there is undoubtedly some flow across these faults, it is probably slight. For modeling purposes, the faults were considered as no-flow boundaries. A no-flow boundary indicates that no water enters or leaves across the boundary.

An unnamed offshore fault is also one of the model boundaries. (See fig. 5.) This boundary is simulated as a general-head boundary. A general-head boundary simulates a source of water outside the modeled area that supplies water at a rate proportional to the hydraulic-head difference between the source and a model block (McDonald and Harbaugh, 1984, p. 343). The rate at which water is supplied to a model block is given by the expression:

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

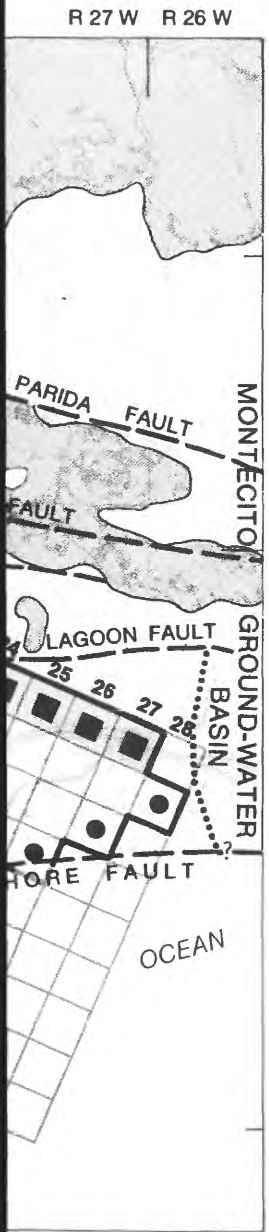
where

Q is the rate at which water is supplied to the block from the boundary $[L^3T^{-1}]$,
C is the constant of proportionality for the boundary $[L^2T^{-1}]$,
HB is the hydraulic head at the source boundary [L], and
h is the hydraulic head in the block [L].



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

FIGURE 5. – Grid network with model boundaries and recharge and discharge blocks.



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EXPLANATION

UNCONSOLIDATED DEPOSITS

CONSOLIDATED ROCKS

BOUNDARY OF MODELED AREA

FAULT – Dashed where approximately located, queried where doubtful. **U**, upthrown side; **D**, downthrown side

GROUND-WATER DIVIDE

I GROUND-WATER STORAGE UNIT -- Faults control storage-unit boundaries

UNDERGROUND DRAIN

NO-FLOW BOUNDARY (Layers 1 and 2)

GENERAL-HEAD BOUNDARY (Layers 1 and 2)

AREAL-RECHARGE BLOCK (Layers 1 and 2)

STREAM-RECHARGE BLOCK (Layer 1)
- Upper subreach
- Lower subreach

DRAIN BLOCK (Layer 1)

MUNICIPAL PUMPAGE (Layers 1 and 2)

FIGURE 5. – Continued.

In this model HB was set equal to sea level. Therefore, during nonpumping conditions when the head in the aquifer is above sea level, ground water moves from the aquifer across the fault to the ocean. During pumping conditions when the head in the aquifer is below sea level, ground water moves from the seaward side of the fault toward the aquifer. The value of C represents primarily the hydraulic conductance of the fault and was determined during the steady-state and transient-state calibration of the model.

The lower boundary of the model was assumed to be the top of the deep zone. (See fig. 2.) Although the deep zone is not impermeable, the amount of water that is contributed from the deep zone was considered negligible for modeling purposes.

Aquifer Properties

Data on the transmissivity and storage coefficient for the two layers and vertical leakage between the layers are required to simulate ground-water flow in Storage Unit I.

Transmissivity

The initial distribution of transmissivity used in the model was derived from aquifer tests, specific-capacity tests, and drillers' logs. Measured values ranged from about 700 ft^2/d in the northwestern part of Storage Unit I to about 4,000 ft^2/d beneath the city of Santa Barbara. These values were then modified during the steady-state calibration of the model until the final distribution of transmissivity was derived. The transmissivity of the total thickness of the water-bearing deposits was proportioned to the two layers of the model on the basis of thickness of the water-bearing deposits above and below the confining bed. The model-calibrated transmissivity distributions for layers 1 and 2 are shown in figures 6 and 7.

The transmissivity values used in the model do not change with time. Beneath the city of Santa Barbara, where the greatest water-level changes occur, both layers are confined. Where layer 1 is unconfined, water-level changes are small compared to the total thickness of the aquifer and have little effect on transmissivity.

Storage coefficient

Transient-state model simulations were used to estimate storage coefficients. The calibration procedure was started by using initial estimates of storage coefficient based on analyses of lithologic logs and available aquifer tests. The average specific yield of the upper 250 feet of saturated materials in Storage Unit I was estimated from lithologic logs to be 10 percent (Muir, 1968, p. A13). On the basis of this estimate, a storage coefficient of 0.10 was assumed representative of the unconfined areas. An aquifer test in the southern part of Storage Unit I indicated a storage coefficient of 0.00013 (Brown and Caldwell, 1973, p. 65), which is representative of confined areas. The model-calibrated storage coefficients for each layer are shown in figures 8 and 9.

The storage coefficients in layer 1 are generally typical of unconfined aquifers, except beneath the city of Santa Barbara in the southern part of the ground-water basin. (See fig. 8.) In this area, clay beds near the land surface cause some confinement, and the upper layer has storage coefficients typical of confined aquifers. The storage coefficients in layer 2 are typical of confined aquifers, except along the north and northwest edges of Storage Unit I where clay beds are thin or absent and unconfined conditions prevail at depth. In general, storage coefficients in both layers decrease from the Mission Ridge fault toward the ocean. The decrease in storage-coefficient values is caused by increased thickness of overlying clay beds. (See fig. 2.)

Vertical leakage between layers

The confining bed that separates layers 1 and 2 is a semipermeable zone through which ground-water leakage occurs when there is a difference in hydraulic head between the layers. The rate at which this leakage occurs is controlled by the thickness and vertical hydraulic conductivity of the confining bed and by the hydraulic-head difference across this bed.

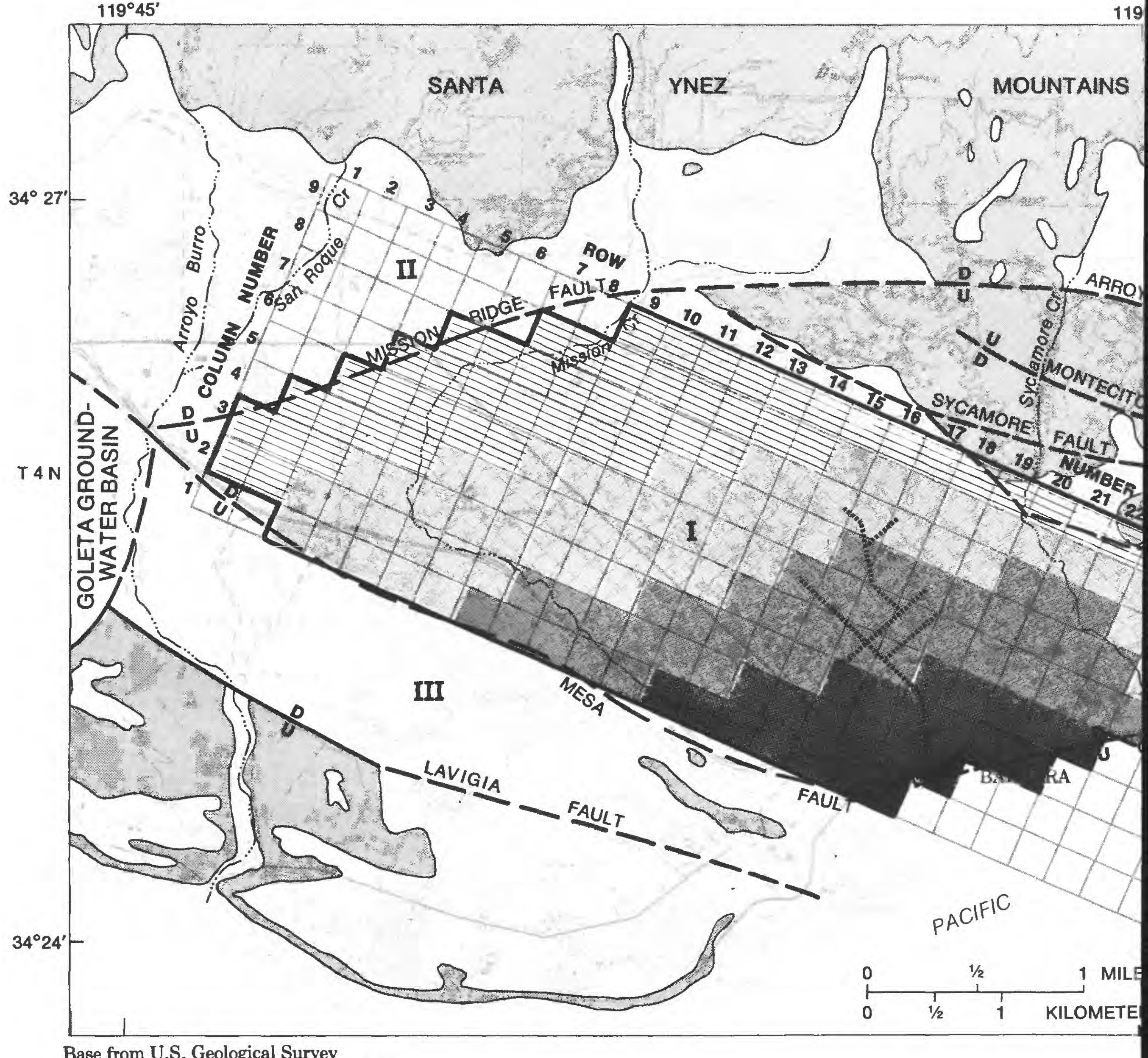
For modeling purposes, the thickness of the confining bed was considered to be equal to the total thickness of the middle zone. The thickness of the middle zone, as estimated from numerous electric and geologic logs in the study area, ranges from less than 100 feet in the northwestern part of Storage Unit I near the Mission Ridge fault to 400 feet near the Pacific Ocean. (See fig. 10.) The vertical hydraulic conductivity of the confining bed was assumed to be uniform throughout Storage Unit I and was calibrated during steady-state and transient-state model simulations to be 0.03 ft/d, which is reasonable for the fine-grained sand, silt, and clay that compose the middle zone.

Natural Recharge and Discharge

Natural recharge and discharge simulated in the model include areal recharge, stream recharge, drains, and a general-head boundary. (See fig. 5.) Each of these sources or sinks is discussed below--except for the general-head boundary, which was discussed earlier in the report. (See section on "Model Boundaries.")

Areal recharge

In this model the areal-recharge term is the average direct infiltration of precipitation and runoff from the surrounding hills. The area of direct infiltration and runoff, about 920 acres, includes the part of Storage Unit I that is not heavily urbanized and the part directly adjacent to the hills on the northeast boundary of the model (fig. 5). In all other parts of Storage Unit I, storm sewers, city streets, and buildings prevent significant infiltration of rainfall (Muir, 1968, p. A17). An estimated uniform areal recharge rate of 0.43 ft/yr (Muir, 1968, p. A18) was verified during the steady-state calibration procedure. Total areal recharge used in the steady-state model simulations was 400 acre-ft/yr.



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

FIGURE 6. – Areal distribution of transmissivity of layer 1, as simulated in the model.

ology modified from K.S.
ir (1968) and M.F. Hoover
78)

EXPLANATION

UNCONSOLIDATED DEPOSITS

CONSOLIDATED ROCKS

BOUNDARY OF MODELED AREA

FAULT – Dashed where approximately located, queried where doubtful. **U**, upthrown side; **D**, downthrown side

GROUND-WATER DIVIDE

I — GROUND-WATER STORAGE UNIT -- Faults control storage-unit boundaries

UNDERGROUND DRAIN

TRANSMISSIVITY, IN FEET SQUARED PER DAY

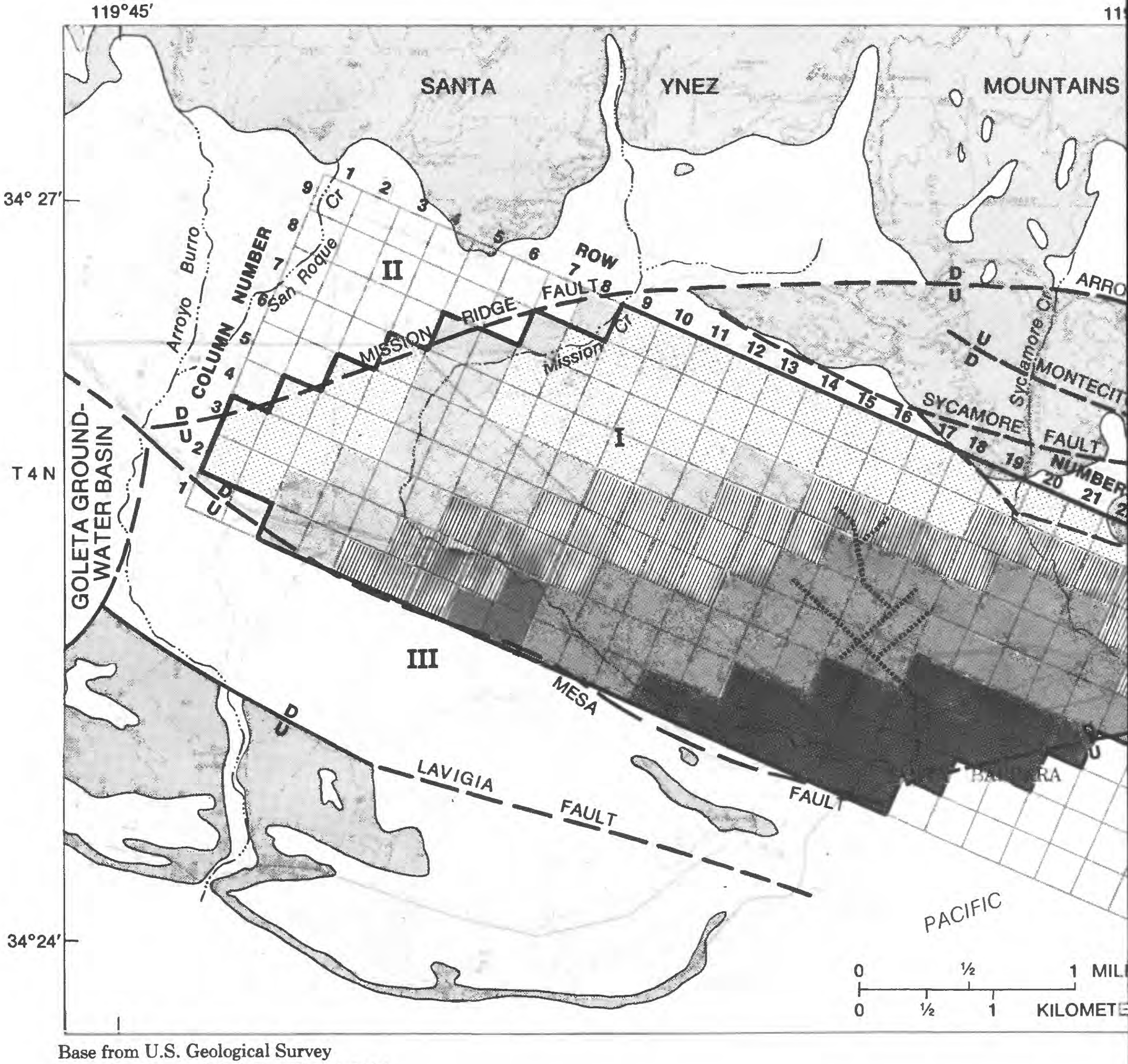
Less than 100

100-300

300-600

600-800

FIGURE 6. – Continued.



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

FIGURE 7. – Areal distribution of transmissivity of layer 2, as simulated in the model.

eology modified from K.S.
uir (1968) and M.F. Hoover
978)

EXPLANATION

UNCONSOLIDATED DEPOSITS

CONSOLIDATED ROCKS

BOUNDARY OF MODELED AREA

FAULT – Dashed where approximately located, queried where doubtful. **U**, upthrown side; **D**, downthrown side

GROUND-WATER DIVIDE

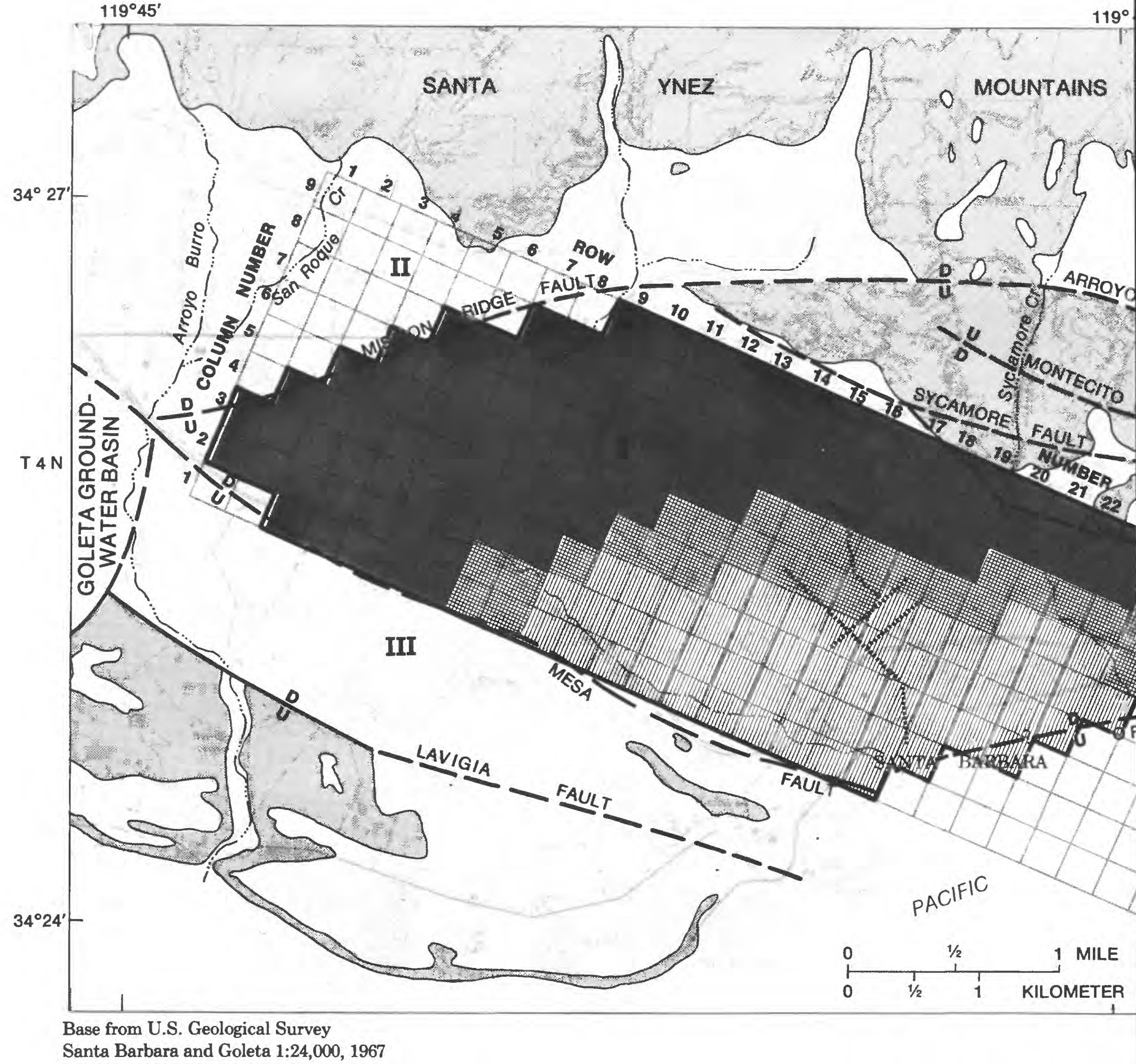
I GROUND-WATER STORAGE UNIT -- Faults control storage-unit boundaries

UNDERGROUND DRAIN

TRANSMISSIVITY, IN FEET SQUARED PER DAY

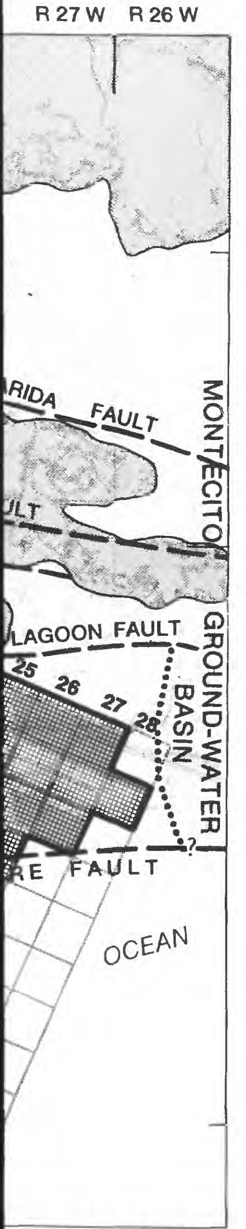
- Less than 150
- 150– 650
- 650–1300
- 1300–2000
- 2000–2500

FIGURE 7. – Continued.



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

FIGURE 8. – Areal distribution of storage coefficient of layer 1, as simulated in the model.



ogy modified from K.S.
(1968) and M.F. Hoover
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EXPLANATION

UNCONSOLIDATED DEPOSITS

CONSOLIDATED ROCKS

BOUNDARY OF MODELED AREA

D U ?
FAULT – Dashed where approximately located, queried where doubtful. **U**, upthrown side; **D**, downthrown side

GROUND-WATER DIVIDE

I GROUND-WATER STORAGE UNIT -- Faults control storage-unit boundaries

UNDERGROUND DRAIN

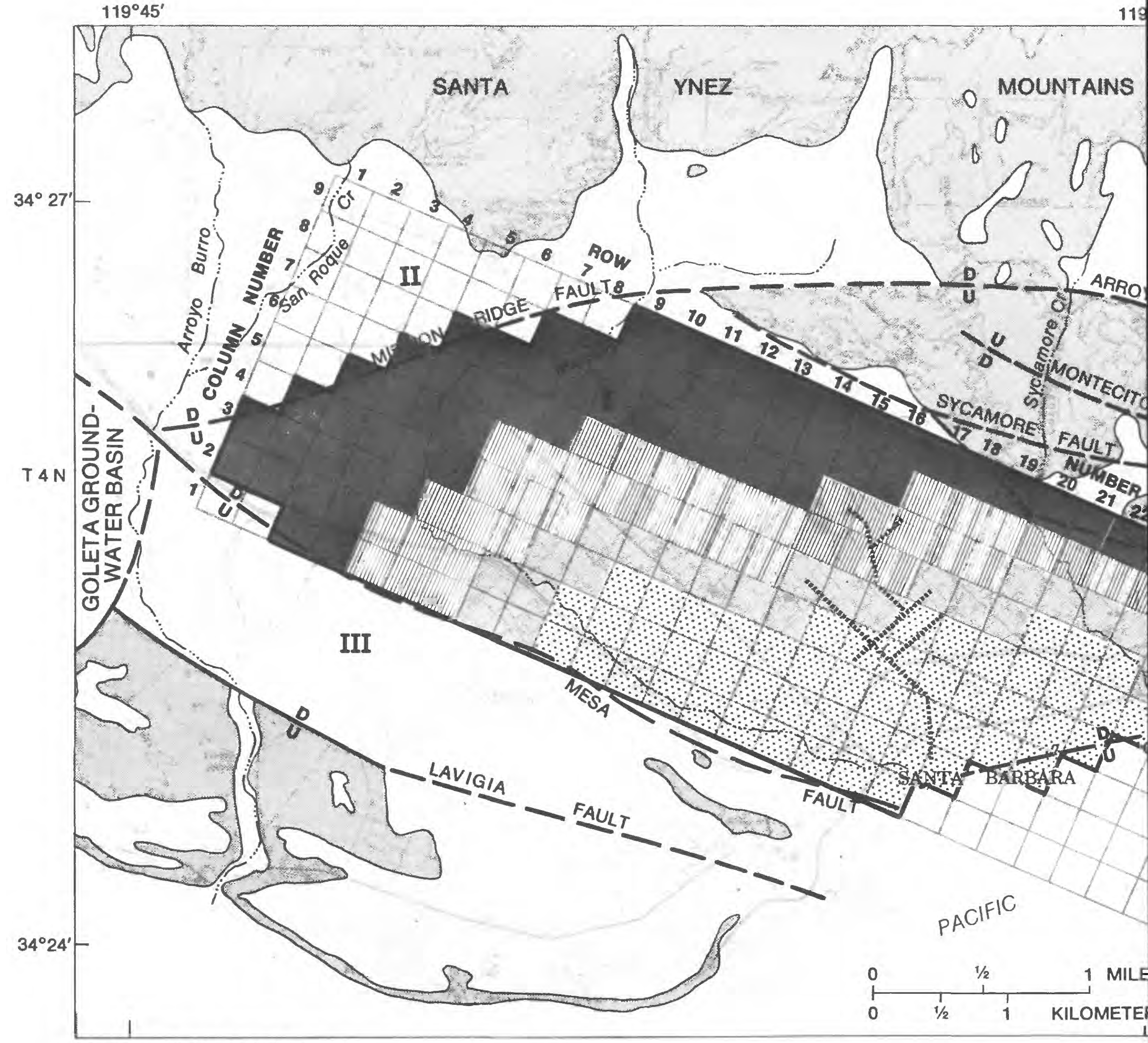
STORAGE COEFFICIENT

0.001

0.01

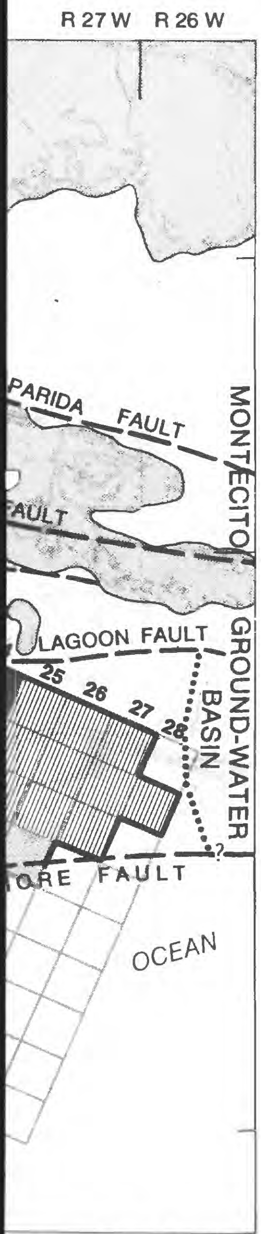
0.1

FIGURE 8. – Continued.



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

FIGURE 9. – Areal distribution of storage coefficient of layer 2, as simulated in the model



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luir (1968) and M.F. Hoover
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EXPLANATION

UNCONSOLIDATED DEPOSITS

CONSOLIDATED ROCKS

BOUNDARY OF MODELED AREA

FAULT – Dashed where approximately located, queried where doubtful. **U**, upthrown side; **D**, downthrown side

GROUND-WATER DIVIDE

I GROUND-WATER STORAGE UNIT -- Faults control storage-unit boundaries

UNDERGROUND DRAIN

STORAGE COEFFICIENT

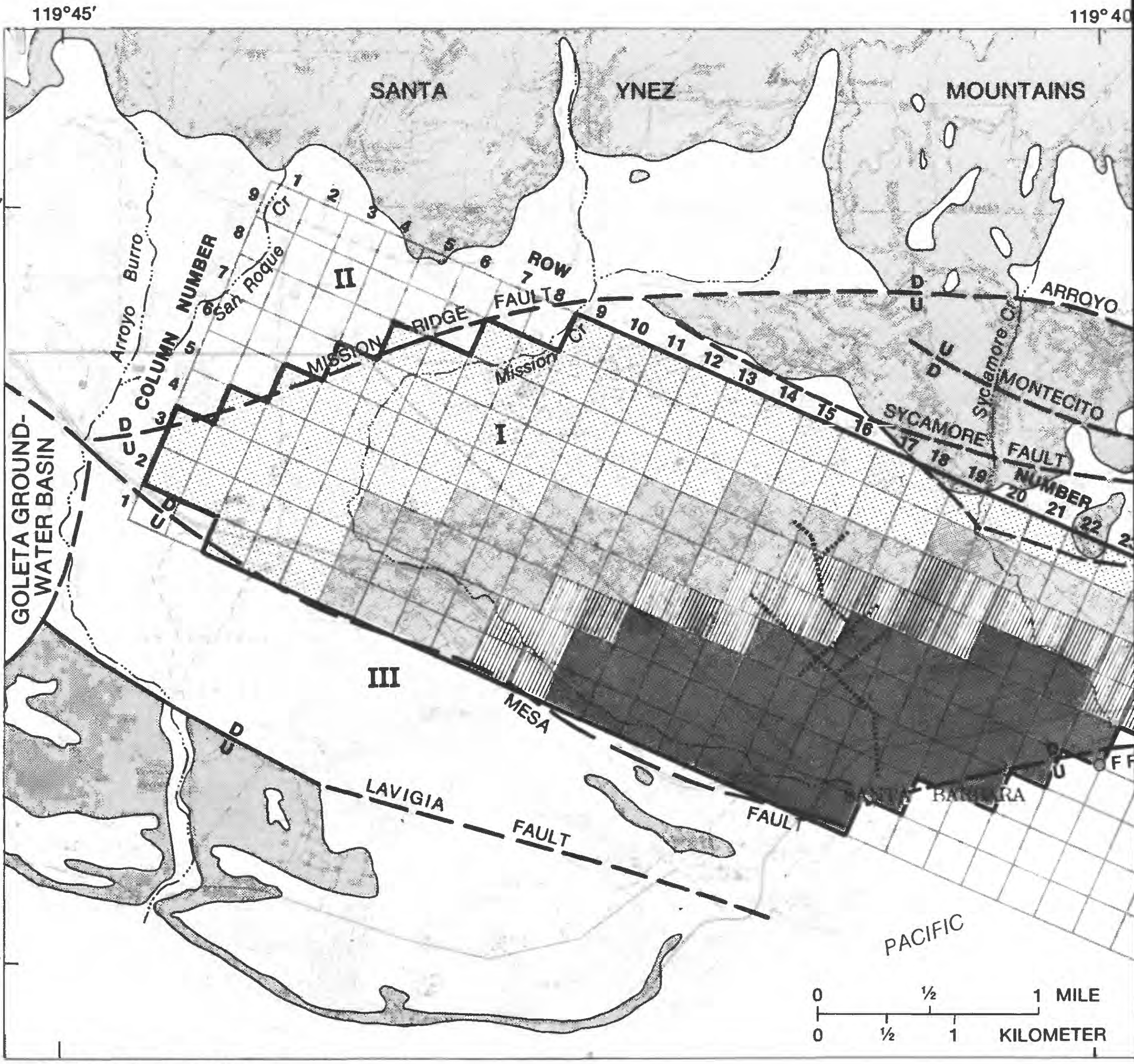
0.0001

0.001

0.01

0.1

FIGURE 9. – Continued



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

FIGURE 10. – Areal distribution of thickness of confining bed between layers 1 and 2, as simulated in the model.

eology modified from K.S.
luir (1968) and M.F. Hoover
978)

EXPLANATION

UNCONSOLIDATED DEPOSITS

CONSOLIDATED ROCKS

BOUNDARY OF MODELED AREA

FAULT – Dashed where approximately located, queried where doubtful. **U**, upthrown side; **D**, downthrown side

GROUND-WATER DIVIDE

I GROUND-WATER STORAGE UNIT -- Faults control storage-unit boundaries

UNDERGROUND DRAIN

THICKNESS OF CONFINING BED, IN FEET

Less than 100

100-200

200-300

300-400

FIGURE 10. – Continued.

Stream recharge

Stream recharge from Mission Creek was simulated by recharge wells in layer 1 along the stream channel. Recharge from Sycamore Creek, the other major stream in the modeled area, was considered negligible (Martin, 1984, p. 8) and was not simulated.

Martin (1984, p. 7) estimated stream recharge to be 376 acre-ft/yr on the basis of seepage-loss measurements along Mission Creek. This initial estimate of stream recharge was adjusted to 400 acre-ft/yr during the steady-state calibration. For modeling purposes, Mission Creek was divided into two reaches on the basis of seepage-loss characteristics measured by Martin (1984, p. 7). The simulated stream recharge was divided such that about 60 percent of the modeled stream recharge was input equally into the seven model blocks representing the upper reach of Mission Creek, and about 40 percent was input into the 11 model blocks representing the lower reach (fig. 5).

Drains

During prolonged nonpumping periods, ground water discharges naturally into drains (see fig. 5) in the area of the former Santa Barbara Estero. The rate at which water seeps into a drain is approximated in the model using the equation (McDonald and Harbaugh, 1984, p. 288):

$$Q_D = CD(H_a - H_D), \quad (2)$$

where

Q_D is the rate water flows into the drain $[L^3T^{-1}]$,

CD 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 head in the drain [L].

The head in the drain (H_D) is assumed to be the altitude of the drain. When the head in the aquifer (H_a) is less than the altitude of the drain, there is no flow into the drain. The coefficient CD may be affected by the size and frequency of openings in the drains, chemical precipitation around a drain, and the difference in permeability between the aquifer material and the backfill around the drain (McDonald and Harbaugh, 1984, p. 288). In this model the coefficient CD represents predominantly the vertical hydraulic conductivity of the shallow zone divided by the thickness of this zone. As a result of model calibration, the coefficient CD was set equal to about 0.9 ft^2/d for all the modeled drains. Ground-water discharge into the drains is not measured; therefore, the coefficient CD could not be accurately determined. The coefficient CD determined by model calibration should only be considered as an order-of-magnitude estimate.

Pumpage

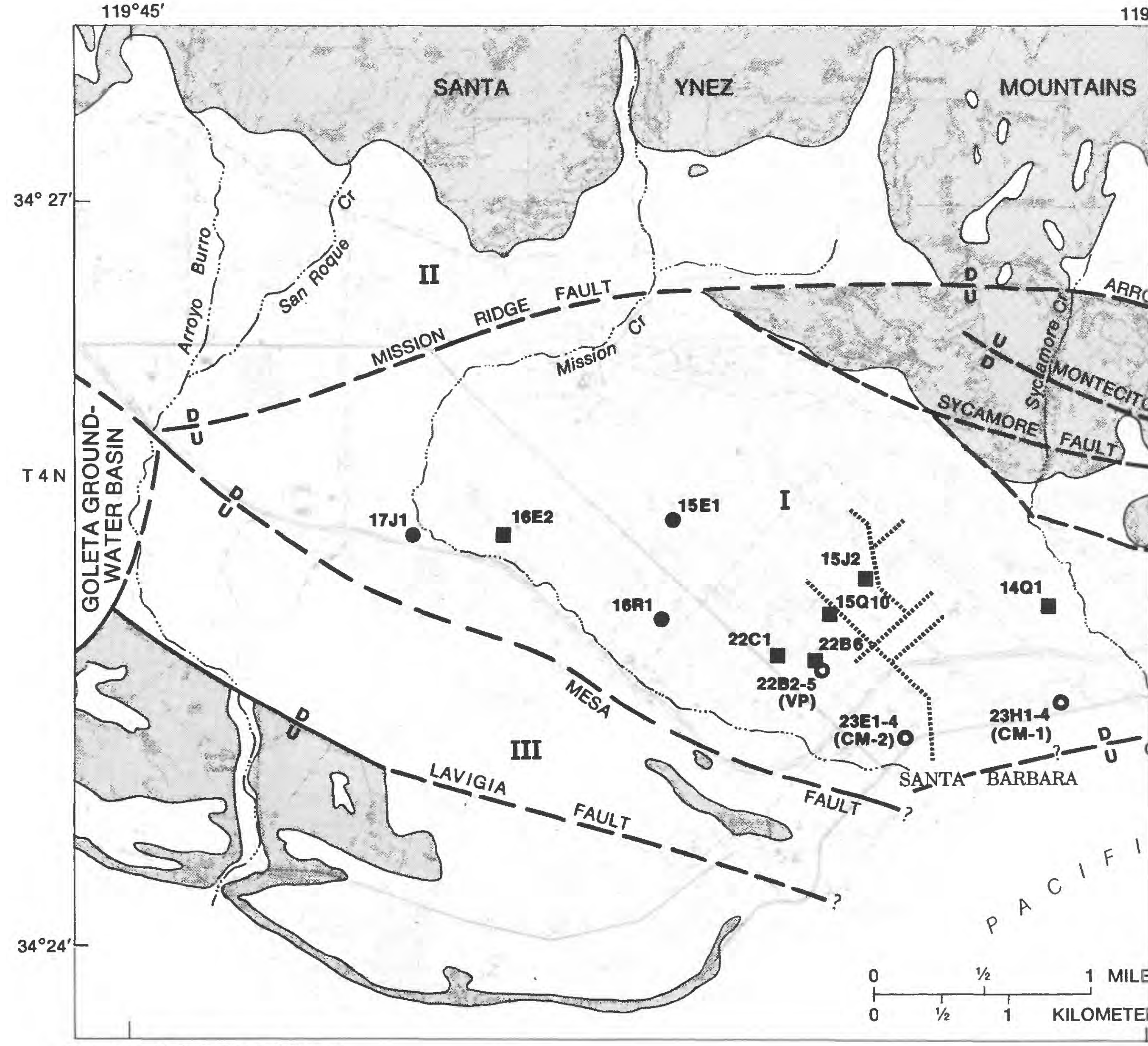
Ground-water pumping in Storage Unit I began in the early 1800's to supplement local surface-water sources. During years of low rainfall, when surface water is scarce, pumping is intensified. During years of high rainfall, when surface water is abundant, pumping is significantly reduced or suspended. The principal use of ground water is for municipal supply. Private pumpage for domestic, agricultural, and industrial uses was considered negligible for modeling purposes.

During the study period, the city of Santa Barbara pumped from five wells in Storage Unit I: Soledad well (4N/27W-14Q1), Ortega Park well (4N/27W-15J2), Corporation Yard well (4N/27W-15Q10), Vera Cruz Park well (4N/27W-22B6), and City Hall well (4N/27W-22C1) (fig. 11). The pumpage is metered, and municipal pumpage was used in the model without modification because it was assumed that none of the water returned to the aquifer system. The pumpage for each of the municipal supply wells and total municipal pumpage in Storage Unit I for the model simulation period, 1978-83, are shown in figure 12. The total municipal pumpage ranged from 0 acre-ft/yr to more than 3,500 acre-ft/yr. The measured pumpage was divided into month-long pumping periods in the transient-state and verification simulations.

The pumpage from each well was assigned to the grid node closest to the well. If a well was nearly equidistant from two nodes, the pumpage was equally distributed between the nodes. The nodes used to simulate municipal pumpage are shown in figure 5.

Municipal supply wells obtain water from both layers simulated by the model. The quality of water from the supply wells represents a composite of water from the two layers, and the chemistry of the composite is controlled by the relative production rate for each layer. With the chemistry of water from each layer and the chemistry of the composite water known, the amount of water contributed from each layer was determined by mass-balance calculations.

In this study, nitrate-nitrogen (nitrate reported as nitrogen) concentrations were used to determine the pumpage from each layer. Representative nitrate-nitrogen samples were collected from the two layers at the Vera Cruz Park monitor site (4N/27W-22B2-5), less than 200 feet from the Vera Cruz Park supply well (4N/27W-22B6) (fig. 11). The mean nitrate-nitrogen concentration was about 14 mg/L in three samples collected in layer 1 and about 0.20 mg/L in three samples collected in layer 2 during 1978-83. Mean nitrate-nitrogen concentrations in samples collected from the different municipal supply wells during this same period ranged from 0.86 to 4.4 mg/L (table 1). Mass-balance calculations indicate that layer 1 contributes from 5 to 30 percent of the water and about 99 percent of the nitrate-nitrogen, and layer 2 contributes from 70 to 95 percent of the water and about 1 percent of the nitrate-nitrogen in water from the municipal supply wells (table 1).



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

FIGURE 11. – Location of municipal supply wells and selected monitor wells in Storage Unit I of the Santa Barbara ground-water basin.

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EXPLANATION

UNCONSOLIDATED DEPOSITS

CONSOLIDATED ROCKS

FAULT – Dashed where approximately located, queried where doubtful. **U**, upthrown side; **D**, downthrown side

GROUND-WATER DIVIDE

GROUND-WATER STORAGE UNIT -- Faults control storage-unit boundaries

UNDERGROUND DRAIN

WELL AND NUMBER
- 14Q1 — Municipal supply well
- 16R1 — Monitor well
- 23H1-4 — Nested monitor-well site
  - (CM-1) Coastal Monitor Site 1
  - (CM-2) Coastal Monitor Site 2
  - (VP) Vera Cruz Park Monitor Site

FIGURE 11. – Continued.

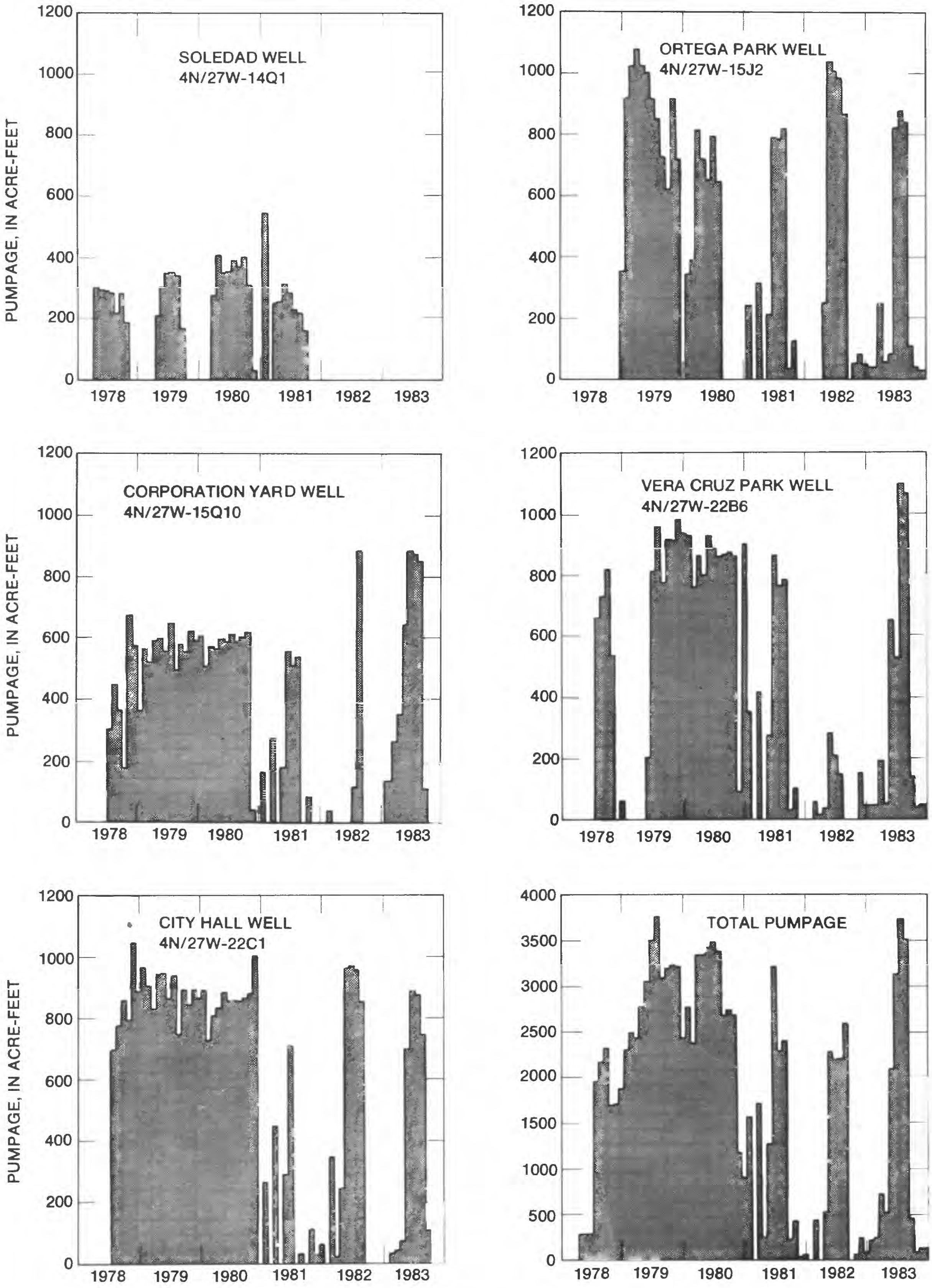


FIGURE 12. – Municipal pumpage in Storage Unit I, 1978-83.

TABLE 1.--Mean nitrate-nitrogen concentration in samples collected at the Vera Cruz Park monitor site and from municipal supply wells, 1978-83, and calculated ground-water contribution from producing zones (layers 1 and 2 of model)

Well location	Number of samples	Mean nitrate-nitrogen concentration (mg/L)	Ground-water contribution[1] (percent)	
			Layer 1	Layer 2
Vera Cruz Park monitor site				
4N/27W-22B2 (Layer 1)	3	14	100	0
4N/27W-22B4 (Layer 2)	3	0.20	0	100
Municipal supply wells				
4N/27W-14Q1	3	2.8	20	80
4N/27W-15J2	2	1.6	10	90
4N/27W-15Q10	4	4.4	30	70
4N/27W-22B6	4	.86	5	95
4N/27W/22C1	4	1.5	10	90

[1]Measured at Vera Cruz Park monitor site; calculated at municipal supply wells.

Steady-State Calibration

The ground-water flow model of Storage Unit I was calibrated in part by simulating steady-state conditions. A steady-state condition exists when recharge equals discharge, and ground-water levels remain unchanged with time. In the Santa Barbara area, seasonal pumpage has caused cyclical variations in water levels since ground-water pumping began in the early 1800's. During prolonged nonpumping periods, however, water levels recover to near steady-state conditions. For this study, water-level measurements made in July 1978 and February 1983 were assumed to approximate steady-state conditions (fig. 3). Water levels during these two periods were not affected by pumping; therefore, they were the highest or close to the highest of record for most of the wells measured. The combined measurements from these periods provided sufficient data to permit reasonable simulation of steady-state conditions.

Steady-state water levels are dependent on the quantity and distribution of recharge to layer 1, the hydraulic conductance of the offshore fault, the hydraulic conductance of the interface between layer 1 and the drains, the transmissivity of layers 1 and 2, and the vertical hydraulic conductivity of the confining bed between the layers. These parameters were adjusted during numerous calibration runs until model-calculated water levels matched measured water levels.

A series of steady-state simulations was used to determine the sensitivity of the model to variations in the hydraulic parameters. The sensitivity analysis involved holding all input parameter values constant except the one being studied, and then varying that parameter from 0.5 to 2.0 times the calibrated value of the parameter (fig. 13). The sensitivity of the calculated hydraulic heads to the different hydraulic parameters is presented in figure 13 as the mean relative change in hydraulic head for both layers of the model. The mean relative change in hydraulic head was also determined for the individual layers, but because the results were almost the same as those for both layers combined, they were not included in figure 13. The simulation indicated that the model-calculated heads were most sensitive to changes in transmissivity and recharge. Calculated heads were relatively insensitive to changes in the conductance of the offshore fault, the conductance of the drains, and the vertical hydraulic conductivity of the confining bed. The model-calculated distribution of ground-water discharges to the drains and across the offshore fault was most sensitive to changes in the conductance of the offshore fault; moderately sensitive to the conductance of the drains, vertical hydraulic conductivity of the confining bed, and transmissivity; and relatively insensitive to recharge.

Because the model-calculated heads were the most sensitive to changes in transmissivity and recharge, most of the steady-state calibration runs involved adjusting these parameters. The final model-calibrated transmissivities are generally close to values estimated from aquifer tests, as shown in table 2. No aquifer tests were available along the northern perimeter of Storage Unit I; however, the low transmissivity values calibrated by the model for this area are probably reasonable. Inspection of geologic logs from wells in this area indicates that the aquifer is very thin and consists predominantly of fine-grained sand, silt, and clay of low permeability. Only minor changes in the initial estimates of recharge were necessary to adequately simulate steady-state conditions.

Few adjustments were made during steady-state calibration to initial estimates of the conductance of the drains, the conductance of the offshore fault, and the vertical hydraulic conductivity of the confining bed because steady-state water levels were relatively insensitive to these parameters and few data were available for calibration. Considerable adjustments to conductance of the offshore fault and the vertical hydraulic conductivity of the confining bed were made during the transient-state calibration.

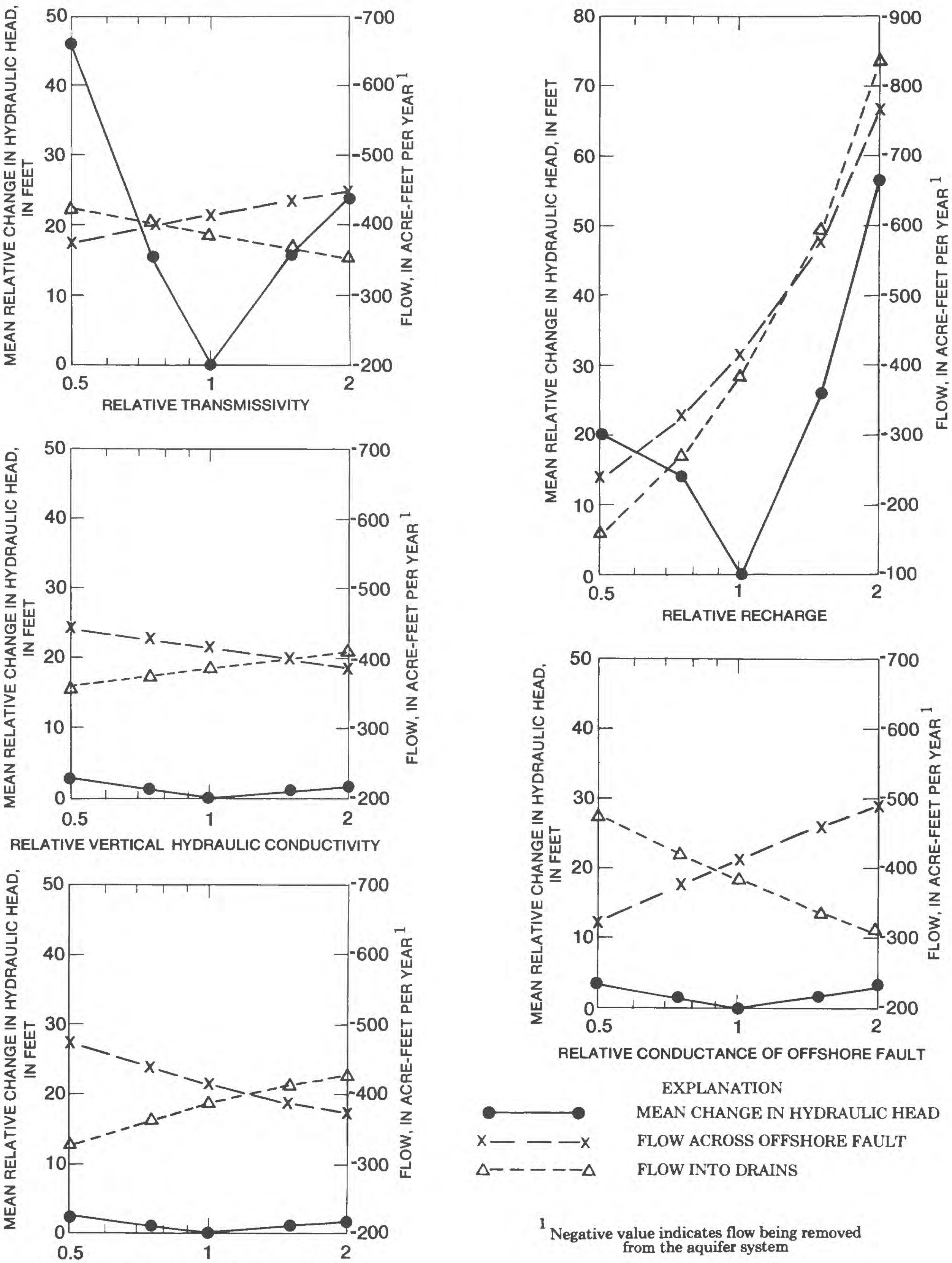


FIGURE 13. – Sensitivity of model-calculated hydraulic heads and flow to changes in transmissivity, recharge, vertical hydraulic conductivity, conductance of the drains, and conductance of the offshore fault during steady-state conditions.

TABLE 2.--Comparison of estimated and model-calibrated transmissivity values

Model node (row/column)	Well location	Estimated transmissivity (ft^2/d)	Model-calibrated transmissivity of layers 1 and 2 combined (ft^2/d)
7/5	4N/27W-16E2	[1]708	936
9/4	4N/27W-16P2	[2]1,203	1,604
15/5	4N/27W-22L1	[3]2,139	2,205
16/7	4N/27W-15Q8	[4]1,257	1,872
16/7	4N/27W-15Q9	[4]4,251	1,872
16/7	4N/27W-15R1	[4]2,005	1,872
16/8	4N/27W-15J1	[4]1,751	1,872
19/9	4N/27W-14P1	[4]882	936
20/9	4N/27W-14Q1	[4]1,604	1,872
21/9	4N/27W-14R1	[4]2,166	1,872

[1]Analysis from Geotechnical Consultants (1983).
[2]Analysis from U.S. Geological Survey data files, San Diego, California.
[3]Analysis from Peter Martin (written commun., 1983).
[4]Analysis from Brown and Caldwell (1973).

Model-calculated potentiometric surfaces for layers 1 and 2 generally approximate the measured water levels, as shown in figure 14. The calculated potentiometric contours are generally within about 5 feet of measured water-level altitudes in both layers. The largest discrepancies were in layer 2 in the area of the former Santa Barbara Estero. A possible explanation for these discrepancies is that selected municipal wells are pumped occasionally during prolonged "nonpumping" periods solely to maintain water levels below land surface to prevent damage from rising water. The amount of this pumpage is unrecorded and was not simulated in the model. The water budget generated by the model for steady-state conditions is presented in column 1 of table 3. Both the potentiometric contours and the water budget were calculated using parameters that were initially adjusted during the steady-state calibration and then further adjusted during the transient-state calibration.

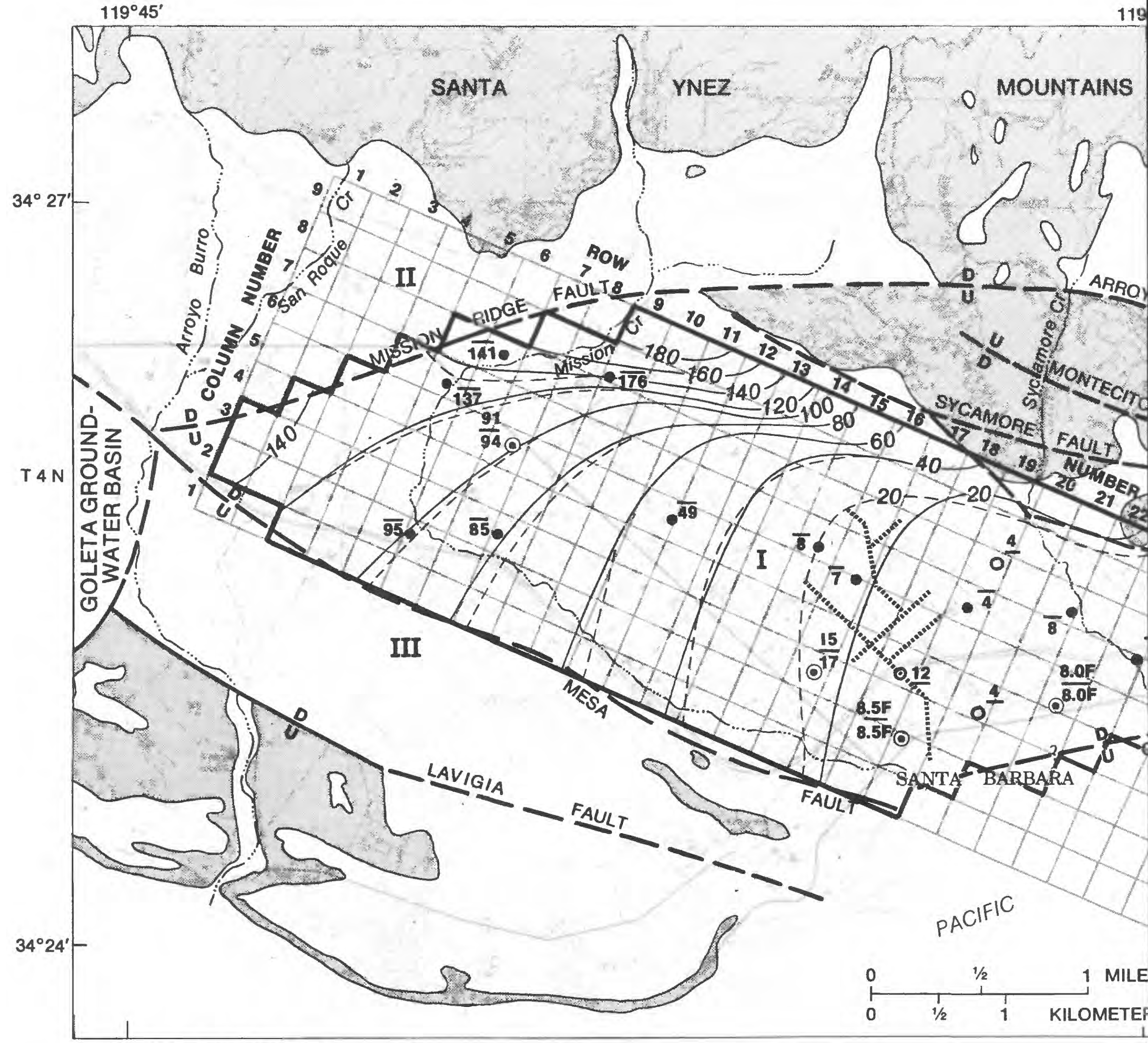
TABLE 3.--Model-simulated water budget

[Negative sign indicates water being removed from the aquifer system]

	Steady-state simulation (acre-feet per year) (1)	May 1978 through December 1979 simulation (cumulative volume, in acre-feet) (2)	May 1978 through December 1983 simulation (cumulative volume, in acre-feet) (3)
Recharge from Mission Creek	400	670	2,270
Areal recharge	400	670	2,270
Water derived from storage	0	2,310	4,180
Pumpage	0	-3,810	-9,980
Head-dependent boundary (offshore fault)	-330	270	1,380
Drains	-470	-110	-120

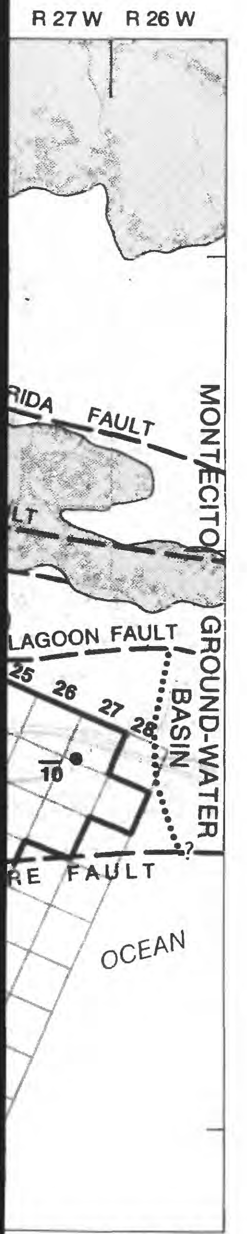
Transient-State Calibration

Ground-water conditions in Storage Unit I during the period May 1978 through December 1979 were used to calibrate the model to transient or time-dependent conditions. Transient conditions in Storage Unit I are the result of stress on the system imposed by municipal pumpage. During this transient period the city of Santa Barbara increased pumping in Storage Unit I to determine the usable quantity of ground water in storage. Municipal pumpage increased from about 150 acre-ft/yr in the 3 months prior to the transient period to as much as 3,700 acre-ft/yr during the period. The average pumpage was about 2,300 acre-ft/yr, which is significantly in excess of the natural recharge to Storage Unit I. As a result, water levels in the lower producing zone declined by as much as 100 feet near the pumping center. (See figs. 3 and 4.)



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

FIGURE 14. – Comparison of measured water levels and model-calculated potentiometric contours for steady-state conditions.



gy modified from K.S.
(1968) and M.F. Hoover
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EXPLANATION

UNCONSOLIDATED DEPOSITS

CONSOLIDATED ROCKS

BOUNDARY OF MODELED AREA

D U ——?—— FAULT – Dashed where approximately located, queried where doubtful. **U**, upthrown side; **D**, downthrown side

GROUND-WATER DIVIDE

I GROUND-WATER STORAGE UNIT -- Faults control storage-unit boundaries

UNDERGROUND DRAIN

– – 20 – – Layer 1
—— 20 —— Layer 2
MODEL-CALCULATED POTENTIOMETRIC CONTOUR – Shows altitude, in feet above sea level, at which water level would have stood in tightly cased wells as calculated by the steady-state model. Contour interval 20 feet

MEASURED WATER LEVEL, JULY 1978 OR FEBRUARY 1983 – In feet above sea level

4 — Well in layer 1 – Number above line is altitude of water level

8 — Well in layer 2 – Number below line is altitude of water level

8.0F / 8.0F — Well in layers 1 and 2 – Number above line is altitude of water level in layer 1, number below line is altitude of water level in layer 2. The letter F indicates that the well was flowing

FIGURE 14. – Continued.

The magnitude of water-level declines is dependent on natural recharge, ground-water pumpage, the storage coefficient and transmissivity of the aquifer, the vertical hydraulic conductivity of the confining bed, the conductance of the offshore fault, and the conductance of the drains. For the transient-state calibration the natural recharge, transmissivity, and conductance of the drains were presumed to be the same as those used in the steady-state calibration. Ground-water pumpage was measured and was entered into the model without modification (fig. 12). Therefore, the calibration procedure for transient-state conditions required modification of prior estimates of storage coefficients and refinement of vertical hydraulic conductivities and the conductance of the offshore fault until model-simulated declines in head matched observed declines.

Hydraulic heads that were computed for steady-state conditions were used as initial conditions for the transient-state calibration. For the transient-state calibration, the period May 1978 through December 1979 was divided into 20 monthly stress periods. Natural recharge was assumed to be constant throughout the transient-state period.

The transient-state calibration was started by adjusting initial estimates of storage coefficient while keeping the other parameters the same as determined during the steady-state calibration. The storage coefficient was adjusted throughout the model until computed water-level declines approximated measured declines.

A series of transient-state simulations were then made to determine the sensitivity of the model to variations in recharge, storage coefficient, vertical hydraulic conductivity of the confining bed, and conductance of the offshore fault. The recharge and storage-coefficient values were varied from 0.5 to 2.0 times those determined during the steady-state and transient-state calibrations. The sensitivity of the calculated hydraulic heads to variations in recharge and storage is presented in figure 15 as the mean relative change in hydraulic head for both layers of the model. Both the model-calculated hydraulic head and flow across the offshore fault are relatively insensitive to changes in recharge and storage coefficient over the simulated range. For example, the mean change in calculated hydraulic head throughout the modeled area was less than 4 feet when either recharge or storage coefficient was doubled (fig. 15). Doubling the recharge or storage coefficient resulted in less than a 3-foot change in hydraulic head at the pumping center (not shown in fig. 15). Using the calibrated recharge and storage-coefficient values results in a calculated change in hydraulic head during the transient simulation of more than 100 feet at the pumping center. Therefore, doubling the recharge or storage coefficient results in only a 3-percent change in calculated hydraulic head at the pumping center.

Results of model simulations to determine the sensitivity to variations in the vertical hydraulic conductivity of the confining bed and the conductance of the offshore fault are presented in figure 16, along with measured hydraulic-head data from nested wells at the Vera Cruz Park monitor site and coastal monitor site 2. The Vera Cruz Park monitor site is near the center of municipal pumping, and coastal monitor site 2 is about half a mile from the closest municipal supply well and about a quarter of a mile from the offshore fault. (See fig. 11.) These monitor sites provide the most accurate information on the hydraulic head in both model layers because the wells at each site are perforated solely in the individual layers. Measurements from these monitor sites were used to calibrate the vertical hydraulic conductivity and the conductance of the offshore fault.

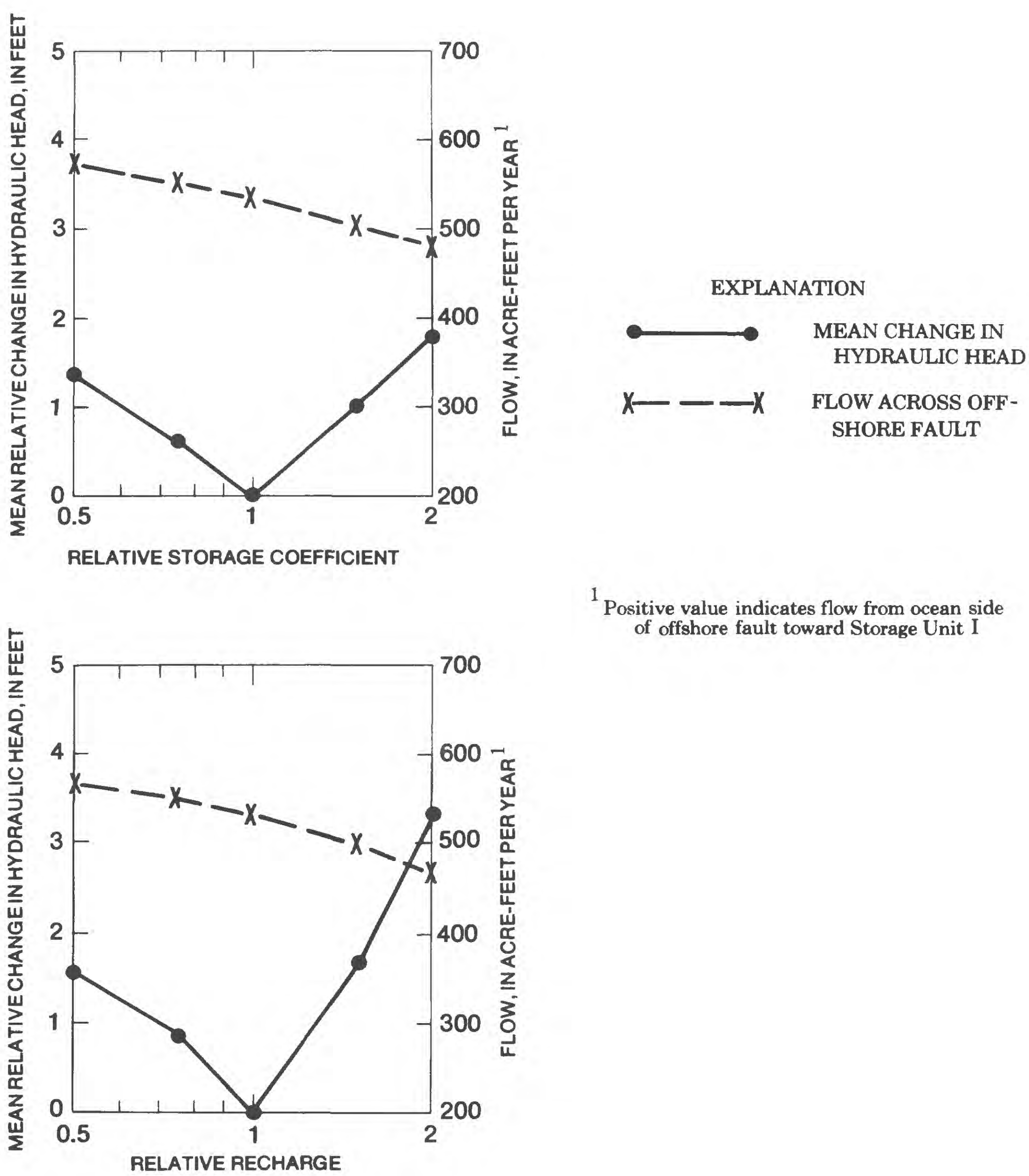


FIGURE 15. – Sensitivity of model-calculated hydraulic heads and flow to changes in storage coefficient and recharge during transient-state conditions.

As shown in figure 16, the model-calculated declines in hydraulic head are sensitive to changes in both the vertical hydraulic conductivity of the confining bed and the conductance of the offshore fault. The model-calculated differences in hydraulic head between layers are also sensitive to the vertical hydraulic conductivity of the confining bed, but are relatively insensitive to the conductance of the offshore fault (fig. 16). The sensitivity of the model to the vertical hydraulic conductivity decreases with distance from the pumping center, and the sensitivity of the model to the conductance of the offshore fault decreases progressively with distance inland from the fault.

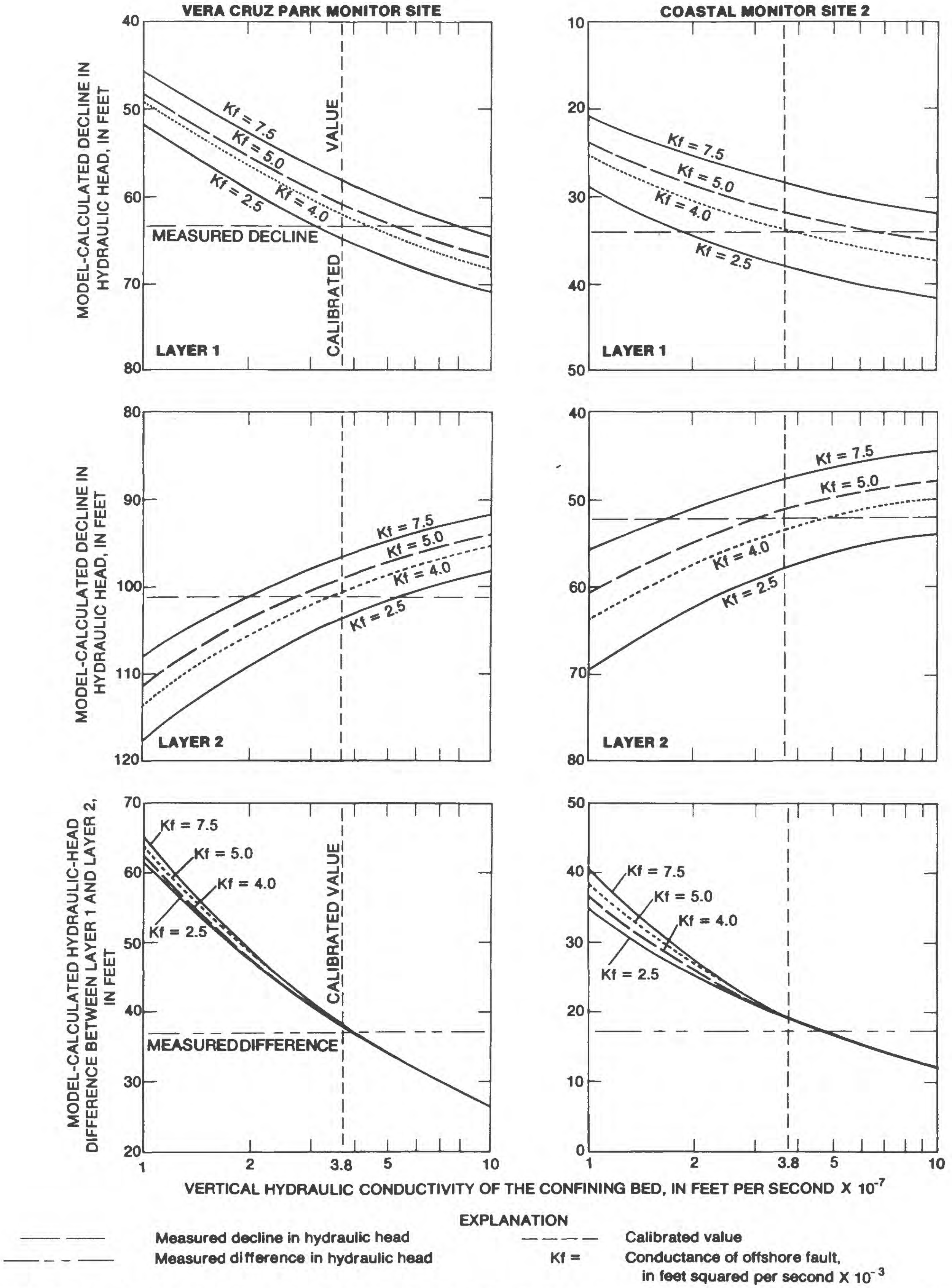


FIGURE 16. – Sensitivity of model-calculated decline in hydraulic head and model-calculated difference in hydraulic head between layers to changes in the conductance of the offshore fault and the vertical hydraulic conductivity of the confining bed during transient-state conditions.

The vertical hydraulic conductivity of the confining bed was assumed to be the same throughout Storage Unit I. The final calibrated value, 3.8×10^{-7} ft/s (0.03 ft/d), was selected because the computed differences in hydraulic head between layers closely approximated measured data at the Vera Cruz Park monitor site and coastal monitor site 2 (fig. 16). The conductance of the offshore fault was then estimated to be 4.0×10^{-3} ft^2/s (350 ft^2/d) by inputting the calibrated value for vertical hydraulic conductivity into the model and adjusting the fault conductance until model-calculated declines in hydraulic head closely matched measured declines at both monitor sites (fig. 16).

Figure 17 shows representative hydrographs, after transient-state calibration, that illustrate the final match between calculated and measured water-level trends. Figure 18 shows a comparison between measured water-level declines in layer 2 and those calculated by the model during the transient-state calibration period. The similarity between measured and calculated drawdowns in both figures indicates that the model closely approximates the hydraulic response of the ground-water system to pumping.

The results of the transient-state simulation indicate that by the end of the simulation period (December 1979) increased municipal pumpage caused ground water to flow across the offshore fault toward Storage Unit I at a rate of about 580 acre-ft/yr; whereas, during steady-state conditions ground water flowed from Storage Unit I toward the ocean at a rate of about 330 acre-ft/yr. The increased municipal pumpage during the simulation period also caused ground-water discharge to drains to cease by the end of the simulation period. The model indicated (as shown in table 3, column 2) that 2,310 acre-ft, or 61 percent of the 3,810 acre-ft of water pumped from the system during the simulation period, was withdrawn from storage. The remainder was derived from changes in flow across the offshore fault (about 22 percent) and a decrease in ground-water discharge to drains (about 17 percent).

Verification Simulation

An acceptable fit of water levels from May 1978 through December 1979 was generated by adjusting model parameters during the steady-state and transient-state calibrations. The model was then used to simulate conditions from January 1980 through December 1983 using the monthly measured municipal pumpage (fig. 12). None of the model parameters were adjusted during this simulation. The purpose of this run was to verify the model and the calibrated parameter values.

Water-level changes calculated by the model during the verification period are compared to measured values on the latter parts of the hydrographs in figure 17. As shown in the hydrographs, the model closely matches the system. In most cases, however, calculated water-level changes are not as great as measured changes. This is due in part to the averaging of monthly municipal pumpage. The model is very sensitive to pumpage, and to match the measured water levels exactly would require weekly or possibly even daily pumpage data.

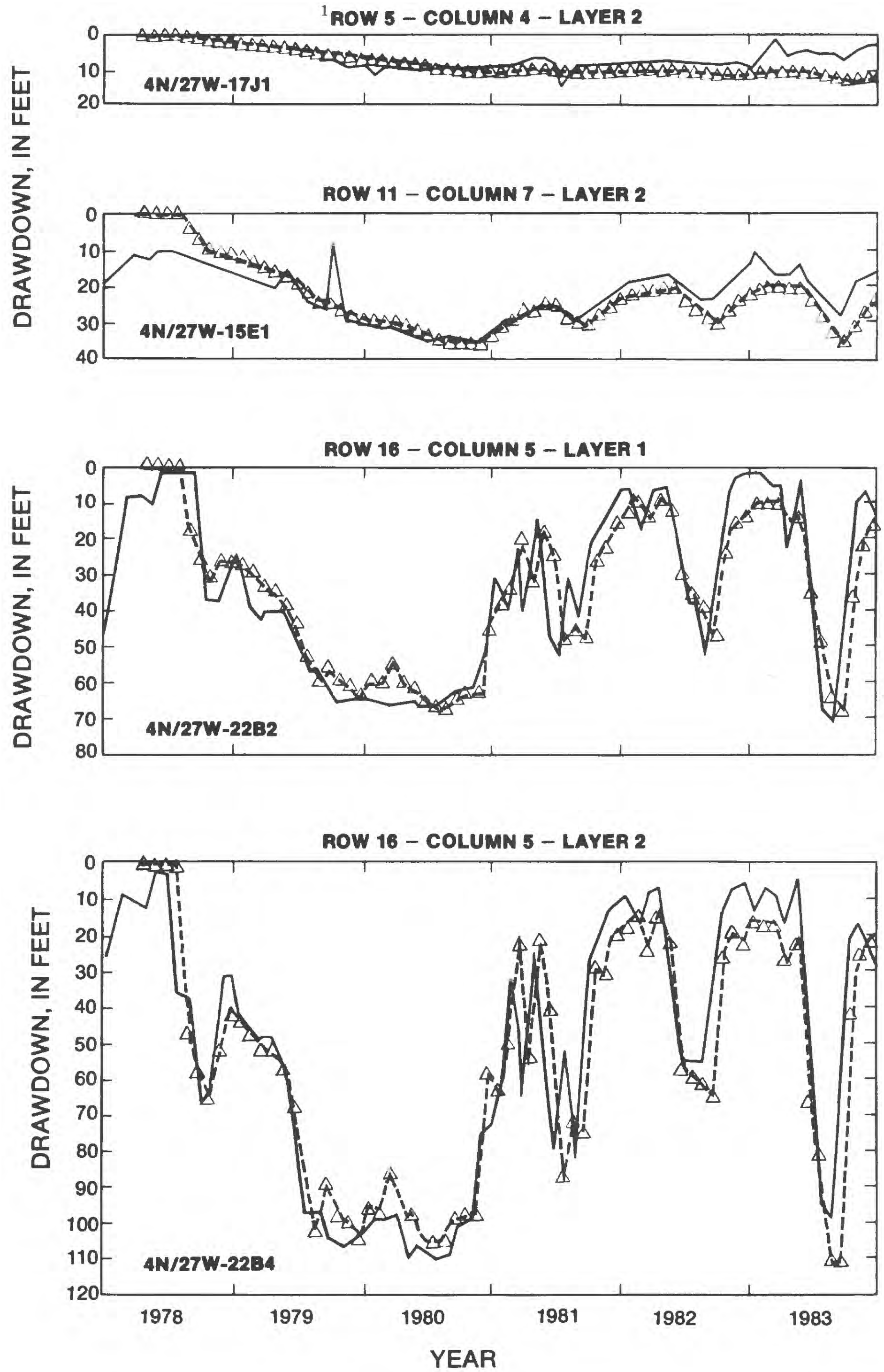
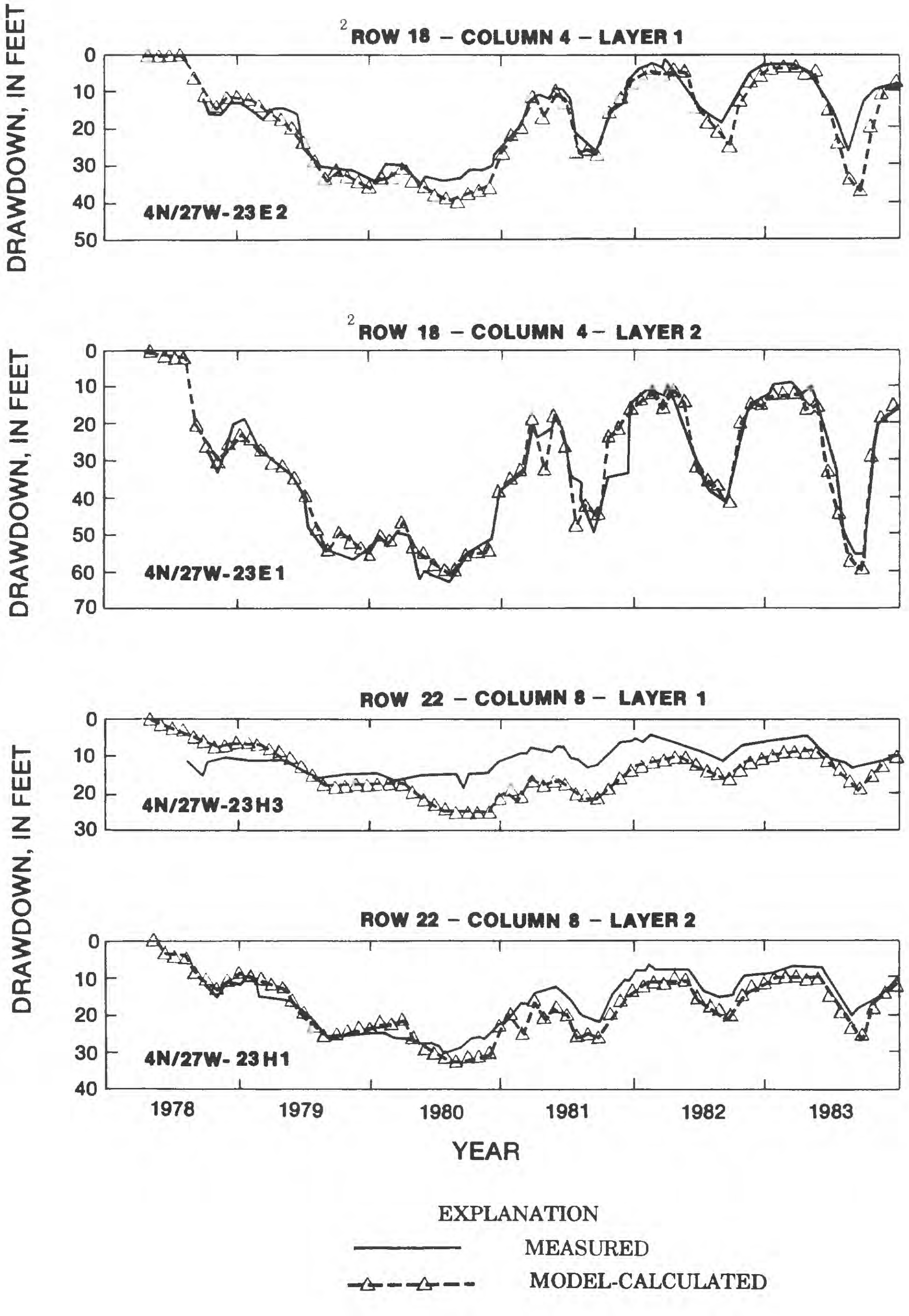


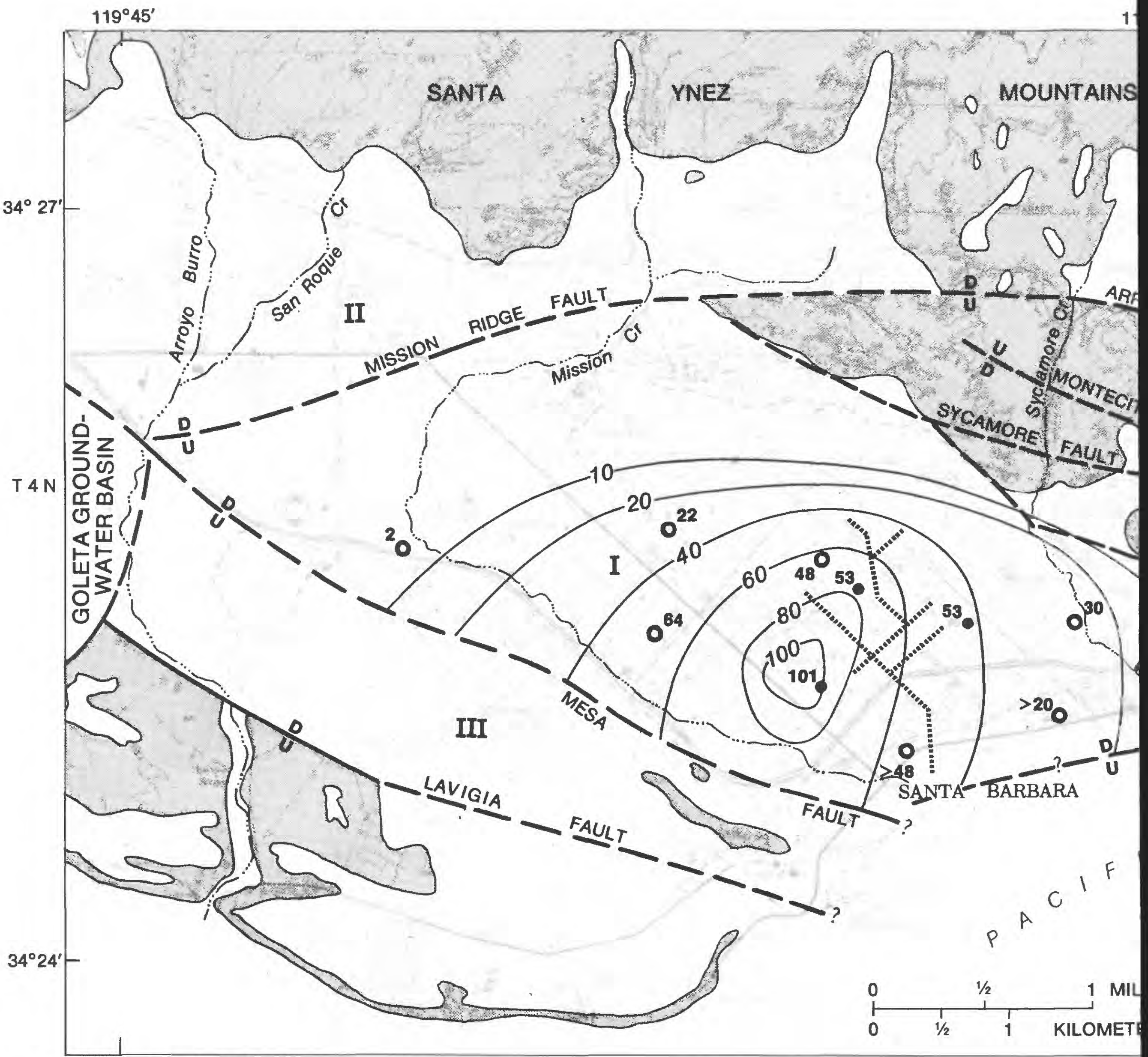
FIGURE 17. – Comparison of model-calculated and measured water-level trends, 1978-83.



[1]Hydrograph shows average of model-calculated drawdown at nodes of two blocks: row 5-column 4 and row 6-column 4.

[2]Hydrograph shows average of model-calculated drawdown at nodes of four blocks: row 18-column 4, row 18-column 5, row 19-column 4, and row 19-column 5.

FIGURE 17. – Continued.



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

FIGURE 18. – Comparison of measured and model-calculated declines in hydraulic head from steady-state conditions to the end of the transient- state simulation.

logy modified from K.S.
ir (1968) and M.F. Hoover
8)

EXPLANATION

UNCONSOLIDATED DEPOSITS

CONSOLIDATED ROCKS

FAULT – Dashed where approximately located, queried where doubtful. **U**, upthrown side; **D**, downthrown side

GROUND-WATER DIVIDE

GROUND-WATER STORAGE UNIT -- Faults control storage-unit boundaries

UNDERGROUND DRAIN

LINE OF EQUAL MODEL-CALCULATED DECLINE IN HYDRAULIC HEAD–Interval variable, in feet

MEASURED DECLINE IN HYDRAULIC HEAD, IN FEET–Number shows measured decline in hydraulic head from steady-state conditions represented by July 1978 measurements to the end of the transient-state period represented by January 1980 measurements

MEASURED DECLINE IN HYDRAULIC HEAD, IN FEET–Number shows measured decline in hydraulic head from steady-state conditions represented by February 1983 measurements to the end of the transient-state period represented by January 1980 measurements. (> indicates value is greater than that shown but is not known because well was flowing)

FIGURE 18.–Continued.

During the transient-state and verification simulations (May 1978 through December 1983), 9,980 acre-ft of water was pumped from Storage Unit I for municipal use. Results of the model simulation (column 3 in table 3) indicate that 42 percent (4,180 acre-ft) of the water pumped from the system was withdrawn from storage. The remainder was derived from changes in flow across the offshore fault (about 33 percent) and a decrease in ground-water discharge to drains (about 25 percent).

Model simulations indicate that the municipal pumpage from May 1978 through December 1983 induced about 1,380 acre-ft of water to move across the offshore fault toward Storage Unit I (table 3). The inflow of water from the ocean side of the fault is verified by increased chloride concentrations in samples from coastal monitor wells (Martin, 1984, p. 23). For example, chloride concentrations in samples from well 4N/27W-23E1 (fig. 19) increased from less than 1,000 mg/L in October 1978 to more than 4,000 mg/L in January 1983. From January 1983 to January 1984, chloride concentrations declined to less than 1,500 mg/L. The decline is probably in response to decreased municipal pumping since January 1981 (fig. 12). The delay in the decline of chloride concentration may be attributed to the slow leakage of saltwater entrapped in low-permeability confining beds.

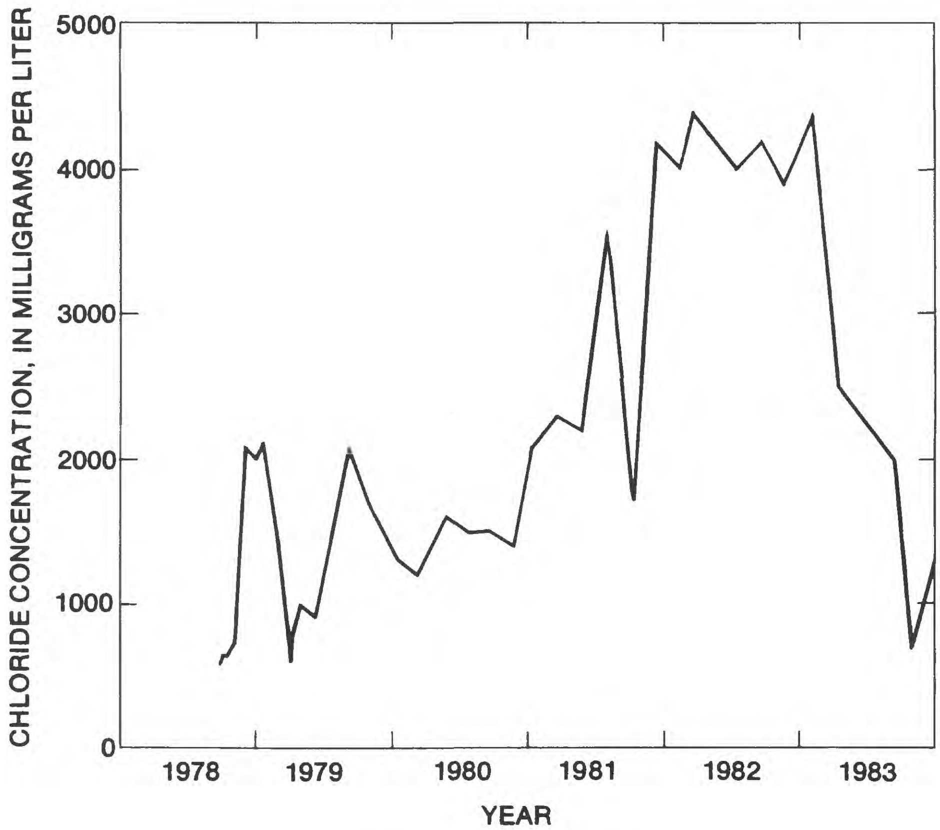


FIGURE 19. – Chloride concentrations in water from well 4N/27W-23E1, 1978-83.

Simulations of Aquifer Response to Management Alternatives

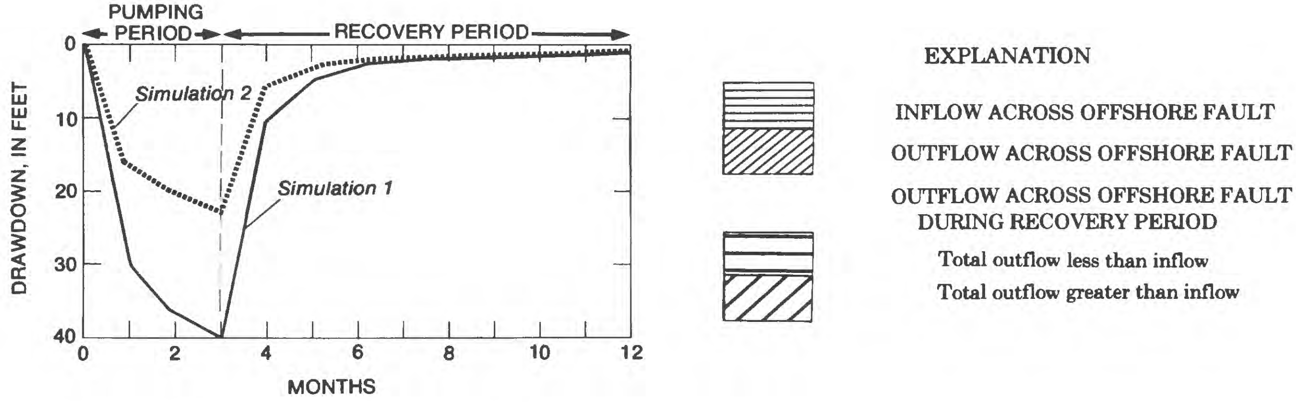
Having been verified as capable of simulating the hydraulic-head response of the aquifer due to pumping, the model can be used to estimate changes in hydraulic head due to proposed management alternatives such as changing the quantities and distribution of pumpage and (or) artificial recharge.

For this study, several simulations were made to determine the aquifer response to different municipal pumpage patterns. Determining the quantity of ground-water flow across the offshore fault during the different simulations was of particular importance because of saltwater-intrusion problems. In all the management simulations, the model-calculated steady-state hydraulic heads were used as the initial hydraulic heads. Ground-water recharge was assumed to be constant and the same as in steady-state conditions.

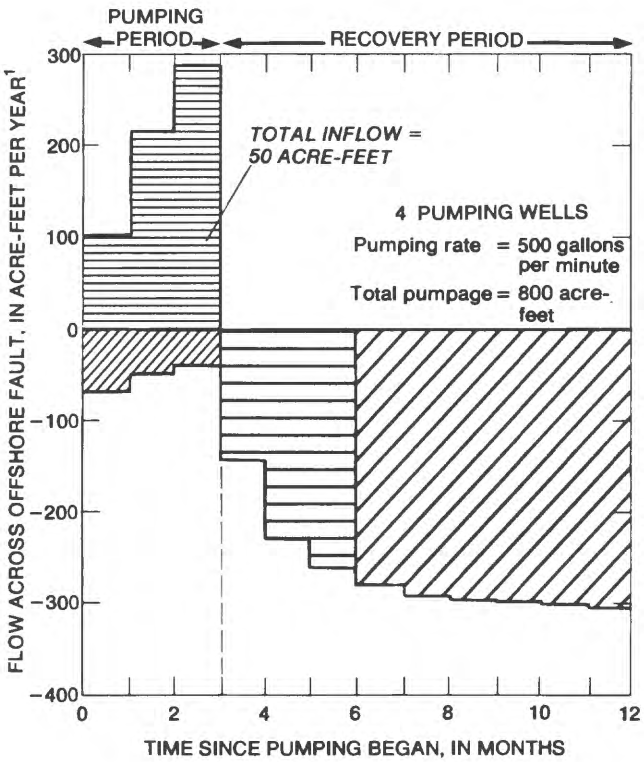
The first and second management simulations were used to determine the response of the aquifer to seasonal pumpage. In Santa Barbara, ground-water pumping usually occurs during the peak-demand summer months when ground water is used to minimize the impact on surface-water-treatment facilities; during the remainder of the year, pumpage is minimal.

In the first management simulation, it was assumed that four municipal supply wells near the coast (4N/27W-15J2, -15Q10, -22B6, -22C1) (fig. 11) would each be pumped at a rate of 500 gal/min for a 3-month period, and then the system would be allowed to recover for 9 months. The total pumpage was 800 acre-ft, which is equal to the estimated steady-state annual recharge to Storage Unit I. During the simulation period, water levels declined by more than 40 feet near the coast, and about 50 acre-ft of water flowed across the offshore fault toward the pumping center (figs. 20A and 20B). Water levels recovered to near steady-state conditions by the end of the simulation period (fig. 20A). After pumping ceased, it took about 3 months for total outflow across the offshore fault to exceed the quantity of inflow that had occurred during the 3-month pumping period.

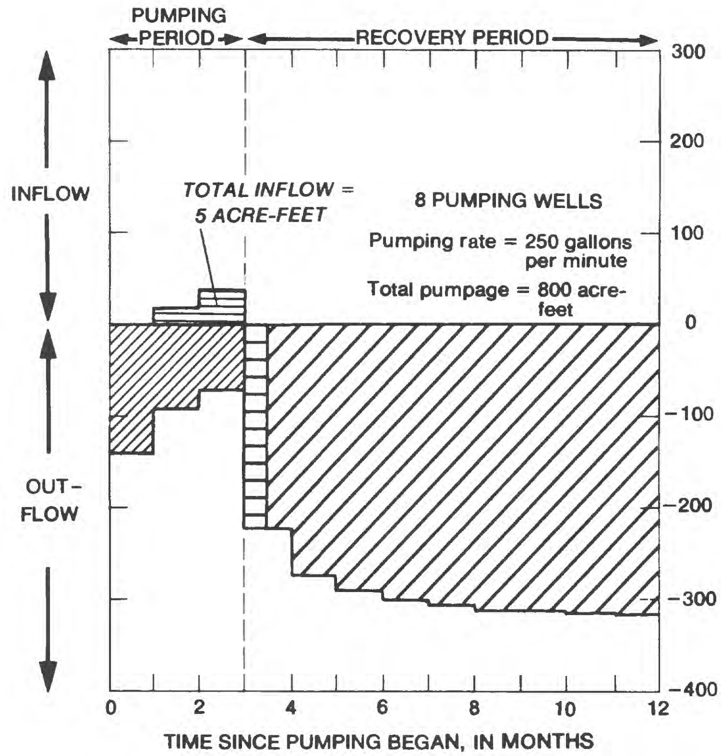
The second management simulation was the same as the first, except that eight wells were pumped at a rate of 250 gal/min each for the 3-month pumping period. The total pumpage remained at 800 acre-ft. The pumping sites included the four municipal wells used in management simulation 1 and four other wells farther from the coast (4N/27W-15E1, -16E2, -16R1, -17J1) (fig. 11). Except for one of the additional sites (well 4N/27W-16E2), municipal supply wells do not exist at any of the selected sites. Observation wells do exist at these sites, however, and municipal supply wells could be constructed at these sites in the future.



A. Drawdown near coast in Simulations 1 and 2



B. Flow across offshore fault in Simulation 1



C. Flow across offshore fault in Simulation 2

[1]Positive value (inflow) indicates flow from ocean side of offshore fault toward Storage Unit I; negative value (outflow) indicates flow from Storage Unit I across fault toward ocean.

FIGURE 20. – Results of management simulations 1 and 2.

During the second simulation, water levels near the coast declined about 25 feet, and only 5 acre-ft of water was induced to flow across the offshore fault toward the pumping center (figs. 20A and 20C). Water levels recovered to near steady-state conditions by the end of the 1-year simulation. The quantity of inflow across the offshore fault that occurred during the pumping period was balanced by outflow across the fault in less than 1 month after pumping ceased.

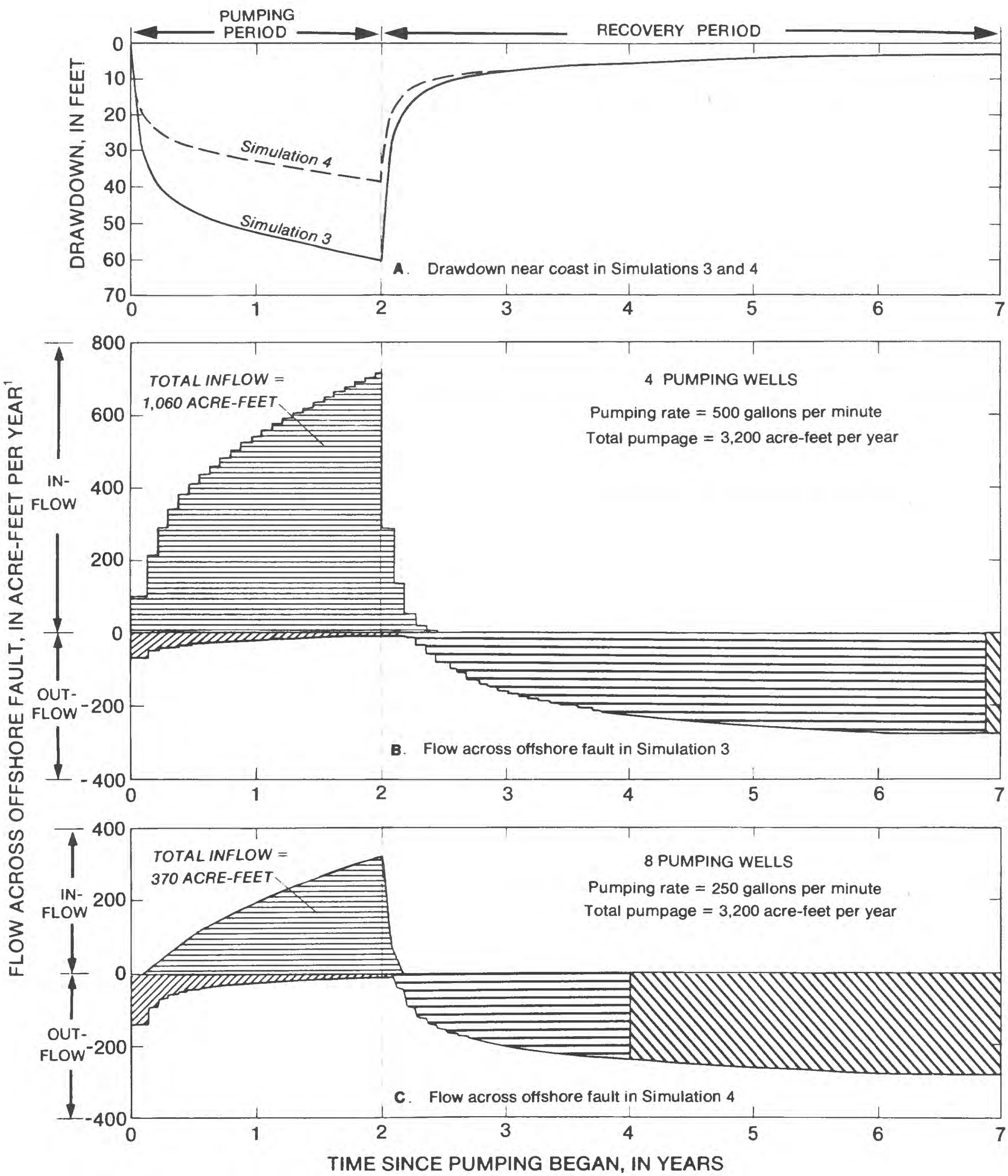
Results of the second management simulation show that spreading the municipal supply wells throughout Storage Unit I and reducing the pumping rate at the individual wells significantly reduces the water-level declines near the coast, and correspondingly reduces the quantity of ground-water inflow across the offshore fault during the simulation period.

The third and fourth management simulations were used to determine the response of the aquifer to a 2-year drought period. During a drought, surface-water supplies are scarce and ground water would be used throughout the year.

The third simulation assumed that four municipal supply wells near the coast (4N/27W-15J2,-15Q10,-22B6,-22C1) (fig. 11) would each be pumped at a rate of 500 gal/min for the 2-year drought period, and then the system would be allowed to recover for 5 years. The total pumpage was equal to 6,400 acre-ft, or 3,200 acre-ft/yr. During the simulation, water levels declined by more than 60 feet near the coast (fig. 21A), and about 1,060 acre-ft of water flowed across the offshore fault toward the pumping center (fig. 21B). By the end of the 5-year recovery period, water levels recovered to within 5 feet of steady-state conditions, and total ground-water inflow across the offshore fault was balanced by outflow (fig. 21B).

The fourth management simulation was the same as the third, except that eight wells were each pumped at a rate of 250 gal/min. The eight wells were the same as those used in the second management simulation. During the fourth simulation, water levels declined by more than 40 feet near the coast (fig. 21A), and about 370 acre-ft of water flowed across the offshore fault toward the pumping center (fig. 21C). As in the previous simulation, water levels recovered to within 5 feet of steady-state conditions by the end of the 5-year recovery period; however, it took only 2 years for total outflow across the offshore fault to exceed the inflow that occurred during the pumping period (fig. 21C).

The results of the fourth simulation also show that spreading municipal pumpage throughout Storage Unit I and reducing the pumpage at the individual wells significantly reduces water-level declines near the coast. Because the water-level declines near the coast are less, the quantity of ground-water inflow across the offshore fault is significantly reduced.



[1]Positive value (inflow) indicates flow from ocean side of offshore fault toward Storage Unit I; negative value (outflow) indicates flow from Storage Unit I across fault toward ocean.

EXPLANATION

INFLOW ACROSS OFFSHORE FAULT

OUTFLOW ACROSS OFFSHORE FAULT

OUTFLOW ACROSS OFFSHORE FAULT DURING RECOVERY PERIOD

Total outflow less than inflow

Total outflow greater than inflow

FIGURE 21. – Results of management simulations 3 and 4.

SUMMARY

The ground-water system of Storage Unit I of the Santa Barbara ground-water basin was simulated with a three-dimensional finite-difference model. The objective of the model was to evaluate present knowledge and conceptions of the ground-water system, and to develop a tool capable of estimating ground-water conditions resulting from current and proposed pumpage in the study area. Data required for calibrating the model were obtained primarily from phase 1 (Hutchinson, 1979) and phase 2 (Martin, 1984) of the study.

Water-level measurements collected in July 1978 and February 1983 were considered representative of steady-state conditions. Sources of recharge during steady-state conditions include direct infiltration of precipitation and runoff from surrounding hills (400 acre-ft/yr) and seepage along Mission Creek (400 acre-ft/yr). The model-simulated steady-state discharge includes ground-water outflow across the offshore fault (330 acre-ft/yr) and leakage to drains in the area of the former Santa Barbara Estero (470 acre-ft/yr).

Transient-state conditions during the period May 1978 through December 1979 were used to calibrate the model. During the transient period, municipal pumpage averaged 2,300 acre-ft/yr, which is significantly in excess of the natural recharge. The pumping, centered in the city less than 1 mile from the coast, has caused water-level declines to altitudes below sea level. From the model simulation it is estimated that by December 1979, ground water flowed across the offshore fault toward Storage Unit I at a rate of about 580 acre-ft/yr; whereas, during steady-state conditions ground water flowed from Storage Unit I toward the ocean at a rate of about 330 acre-ft/yr. The increased municipal pumpage also caused ground-water leakage to drains to cease throughout most of the simulated period.

After the model was considered to be calibrated, it was used to simulate the period January 1980 through December 1983 to verify the calibrated input parameters. During the verification period, model-calculated water-level changes closely matched measured values throughout Storage Unit I. By closely matching the response of the aquifer, the model and calibrated input parameters were considered to be verified.

During the transient-state and verification simulations, 9,980 acre-ft of ground water was pumped from Storage Unit I for municipal use. Calculations made with the model indicate that the pumpage induced about 1,380 acre-ft of water to move across the offshore fault toward Storage Unit I. The inflow of water from the ocean side of the fault is verified by increased chloride concentrations in samples from coastal monitor wells.

Several model simulations were used to estimate the aquifer response to different municipal pumpage patterns. Results of the simulations show that spreading the pumpage throughout Storage Unit I and reducing the pumpage at individual wells significantly reduces water-level declines near the coast. The reduction of water-level declines correspondingly reduces the quantity of ground-water inflow across the offshore fault. For example, if the city's four municipal supply wells (centered near the coast) are pumped continuously for 2 years at a rate of 500 gal/min for a total pumpage of 6,400 acre-ft, it is estimated that 1,060 acre-ft of ground water will flow across the offshore fault toward Storage Unit I. However, if eight wells are spread throughout Storage Unit I and each pumped at a rate of 250 gal/min to obtain the same total pumpage, it is estimated that only 370 acre-ft of ground water will be induced to flow across the fault toward Storage Unit I.

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