Geohydrology of Storage Unit III and a Combined Flow Model of the Santa Barbara and Foothill Ground-Water Basins, Santa Barbara County, California

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Multiply	By	To obtain
acre	0.4047	hectare
acre	4,047	square meter
acre-foot (acre-ft)	1,233	cubic meter
acre-foot (acre-ft)	0.001233	cubic hectometer
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per day (ft^3/d)	0.02832	cubic meter per day
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot per second (ft/s)	0.3048	meter per second
foot per year (ft/yr)	0.3048	meter per year
gallon (gal)	3.785	liter
gallon per day (gal/d)	0.003785	cubic meter per day
gallon per minute (gal/min)	0.06308	liter per second
gallon per minute per foot [(gal/min)/ft]	0.2070	liter per second per meter
gallon per day per square foot [$(gal/d)ft^2$]	0.0407	cubic meter per day per square meter
inch (in.)	25.4	millimeter
inch per year (in/yr)	25.4	millimeter per year
mile (mi)	1.609	kilometer
square foot (ft^2)	929.0	square centimeter
square foot (ft^2)	0.0929	square meter
square foot per second (ft^2/s)	0.0929	square meter per second
foot squared per day (ft^2/d)	0.09290	meter squared per day
square mile (mi^2)	259.0	hectare
square mile (mi^2)	2.590	square kilometer

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

$$°F=1.8(°C)+32$$

Vertical Datum

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.

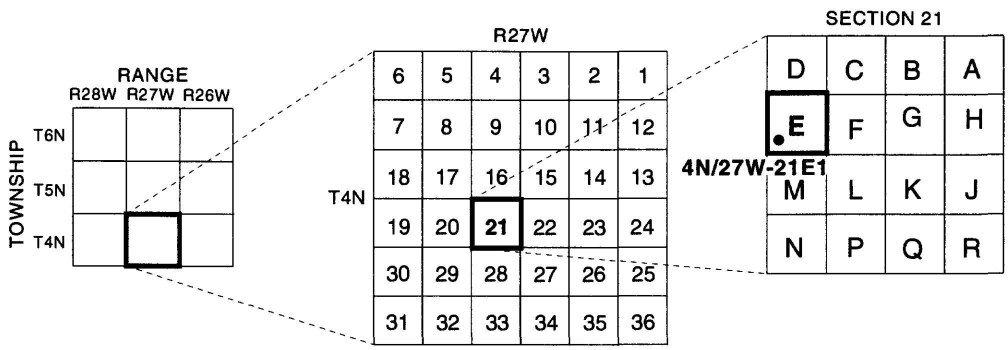
Water-Quality Information

Chemical concentration is given in milligrams per liter (mg/L) or micrograms per liter (µg/L). Milligrams per liter is a unit expressing the solute per unit volume (liter) of water. One thousand micrograms per liter is equivalent to 1 milligram per liter. For concentrations less than 7,000 mg/L, the numerical value is the same as for concentrations in parts per million.

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

Well-Numbering System

Wells are numbered according to their location in the rectangular system for subdivision of public lands. Identification consists of the township number, north or south (N or S); the range number, east or west (E or W); and the section number. Each section is divided into sixteen 40-acre tracts lettered consecutively (except I and O), beginning with "A" in the northeast corner of the section and progressing in a sinusoidal manner to "R" in the southeast corner. Within the 40-acre tract, wells are sequentially numbered in the order they are inventoried. The final letter refers to the base line and meridian. All wells in the study area are referenced to the San Bernardino base line and meridian (S). Well numbers consist of 15 characters and follow the format 004N027W21E001S. In this report, well numbers are abbreviated and written 4N/27W-21E1. Wells in the same township and range are referred to by their section designation, 21E1, only. The following diagram shows how the number for well 4N/27W-21E1 is derived.



Well-numbering diagram

Geohydrology of Storage Unit III and a Combined Flow Model of the Santa Barbara and Foothill Ground-Water Basins, Santa Barbara County, California

By John R. Freckleton, Peter Martin, *and* Tracy Nishikawa

ABSTRACT

The city of Santa Barbara pumps most of its ground water from the Santa Barbara and Foothill ground-water basins. The Santa Barbara basin is subdivided into two storage units: Storage Unit I and Storage Unit III. The Foothill basin and Storage Unit I of the Santa Barbara basin have been studied extensively and ground-water flow models have been developed for them. In this report, the geohydrology of the Santa Barbara ground-water basin is described with a special emphasis on Storage Unit III in the southwestern part of the basin. The purposes of this study were to summarize and evaluate the geohydrology of Storage Unit III and to develop an areawide model of the Santa Barbara and Foothill basins that includes the previously unmodeled Storage Unit III.

Storage Unit III is in the southwestern part of the city of Santa Barbara. It is approximately 3.5 miles long and varies in width from about 2,000 feet in the southeast to 4,000 feet in the northwest. Storage Unit III is composed of the Santa Barbara Formation and overlying alluvium. The Santa Barbara Formation (the principal aquifer) consists of Pleistocene and Pliocene(?) unconsolidated marine sand, silt, and clay, and it has a maximum saturated thickness of about 160 feet. The alluvium that overlies the Santa Barbara Formation has a maximum saturated thickness of about 140 feet. The storage unit is bounded areally by faults and low-permeability deposits and is underlain by rocks of Tertiary age.

The main sources of recharge to Storage Unit III are seepage from Arroyo Burro and infiltration of precipitation. Most of the recharge occurs in the northwest part of the storage unit, and ground water flows toward the southeast along the unit's long axis. Lesser amounts of recharge may occur as subsurface flow from the Hope Ranch subbasin and as upwelling from the underlying Tertiary rocks. Discharge from Storage Unit III occurs as pumpage, flow to underground drains, underflow through alluvium in the vicinity of Arroyo Burro across the Lavigia Fault, evapotranspiration, and underflow to the Pacific Ocean. The faults that bound Storage Unit III generally are considered to be effective barriers to the flow of ground water. Interbasin ground-water flow occurs where deposits of younger alluvium along stream channels cross faults. Ground-water quality in Storage Unit III deposits varies with location and depth. Upward leakage of poor-quality water from the underlying Tertiary rocks occurs in the storage unit, and such leakage can be influenced by poor well construction or by heavy localized pumping. The highest dissolved-solids concentra-

tion (4,710 milligrams per liter) in ground water resulting from this upward leakage is found in the coastal part of the storage unit.

The ground-water system was modeled as two horizontal layers. In the Foothill basin and Storage Unit I the layers are separated by a confining bed. The upper layer represents the upper producing zone and the shallow zone near the coast. The lower layer represents the lower producing zone. In general, the faults in the study area were assumed to be no-flow boundaries, except for the offshore fault that forms the southeast boundary; the southeast boundary was simulated as a general-head boundary. The Storage Unit III model was combined with the preexisting Storage Unit I and Foothill basin models, using horizontal flow barriers, to form an areawide model.

The areawide model was calibrated by simulating steady-state predevelopment conditions and transient conditions for 1978–92. The nonpumping steady-state simulation was used to verify that the calibrated model yielded physically reasonable results for predevelopment conditions. The calibrated areawide model calculates water levels in Storage Unit III that are within 10 feet of measured water levels at all sites of comparison. In addition, the model adequately simulates water levels in the Storage Unit I and Foothill basin areas. A total of 33,430 acre-feet of water was pumped from the study area during the simulation period. Model results indicate that 2,833 acre-feet came from storage and 5,332 acre-feet crossed the general-head boundary from the ocean, thus indicating that seawater intrusion could occur. A sensitivity analysis indicates that, in general, the model is most sensitive to changes in transmissivity and total recharge.

INTRODUCTION

The ground-water supply met the needs of the city of Santa Barbara and outlying areas in the 1800's, but the supply later became inadequate for the expanding population and was largely superseded by water diverted from the Santa Ynez River. In recent years, the Santa Ynez River has continued to be the predominant source of water supply, and ground water has supplied less than 20 percent (about 3,260 acre-ft/yr) of the total demand (about 16,300 acre-ft/yr for water years 1984–88 [Steve Mack, City of Santa Barbara, oral commun., 1994]). Although ground water is a relatively small percentage of the long-term demand, it is an important source of supplemental water during times of surface-water shortages.

Ground water is extracted by the city of Santa Barbara from the Santa Barbara and Foothill ground-water basins (fig. 1). The Santa Barbara basin has been divided into Storage Units I and III for this study (fig. 1). Storage Unit I and the Foothill basin have been the subjects of previous U.S. Geological Survey studies that included the development and calibration of ground-water models (Martin and Berenbrock, 1986; Freckleton, 1989); however, prior to this study Storage Unit III has not been studied thoroughly. Efficient management of the limited ground-water resources of the Santa Barbara area requires a good understanding of the geohydrology of Storage Unit III.

Purpose and Scope

This study was done in cooperation with the city of Santa Barbara. The purposes of the study were to summarize and evaluate the geohydrology of Storage Unit III of the Santa Barbara ground-water basin and to develop an areawide model of the Santa Barbara and Foothill basins that includes the previously unmodeled Storage Unit III and incorporates the preexisting models of Storage Unit I and the Foothill basin.

This report includes a summary of selected geologic and hydrologic information obtained from reports of previous hydrologic studies in the Santa Barbara area and an evaluation of data collected specifically for this study in Storage Unit III. Included are data from drilling and subsequent monitoring at three single-well sites (one outside Storage Unit III) and five cluster-well sites (one outside Storage Unit III) designed and constructed for this study. Evaluated in the study were basin and storage-unit geometry, hydraulic properties of the aquifer materials, historical ground-water levels, ground-water pumping, precipitation, surface-water flow, and ground-water quality.

Analysis of data relating to hydraulic connections between Storage Unit III, Storage Unit I, and the Foothill ground-water basin was facilitated by the development of a numerical flow model (discussed in the last half of this report). The scope of model development consisted of combining, with few conceptual modifications, the existing Storage Unit I (Martin and Berenbrock, 1986) and Foothill basin (Freckleton, 1989) models and the model of Storage Unit III, developed for this study, to form an areawide model. The model aided in conceptualizing the areawide flow system and in estimating ground-water flow rates, recharge, and hydraulic properties for which direct measurements were unavailable.

Previous Investigations

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), with a focus on Storage Unit I of the Santa Barbara ground-water basin (fig. 1). At that time, the city had plans to extract about 10,000 acre-ft of water from the storage unit over a period of 5 to 10 years but was concerned that declines in water levels produced by the extraction might allow seawater to intrude the freshwater aquifer.

During phase 1 of the three-phase study, two coastal monitor-well clusters were completed and used to obtain water-level and water-quality data that could provide an early warning of seawater intrusion. Elevated levels of chloride in water samples from certain zones at the coastal monitor wells did indicate possible seawater intrusion (Hutchinson, 1979, p. 23).

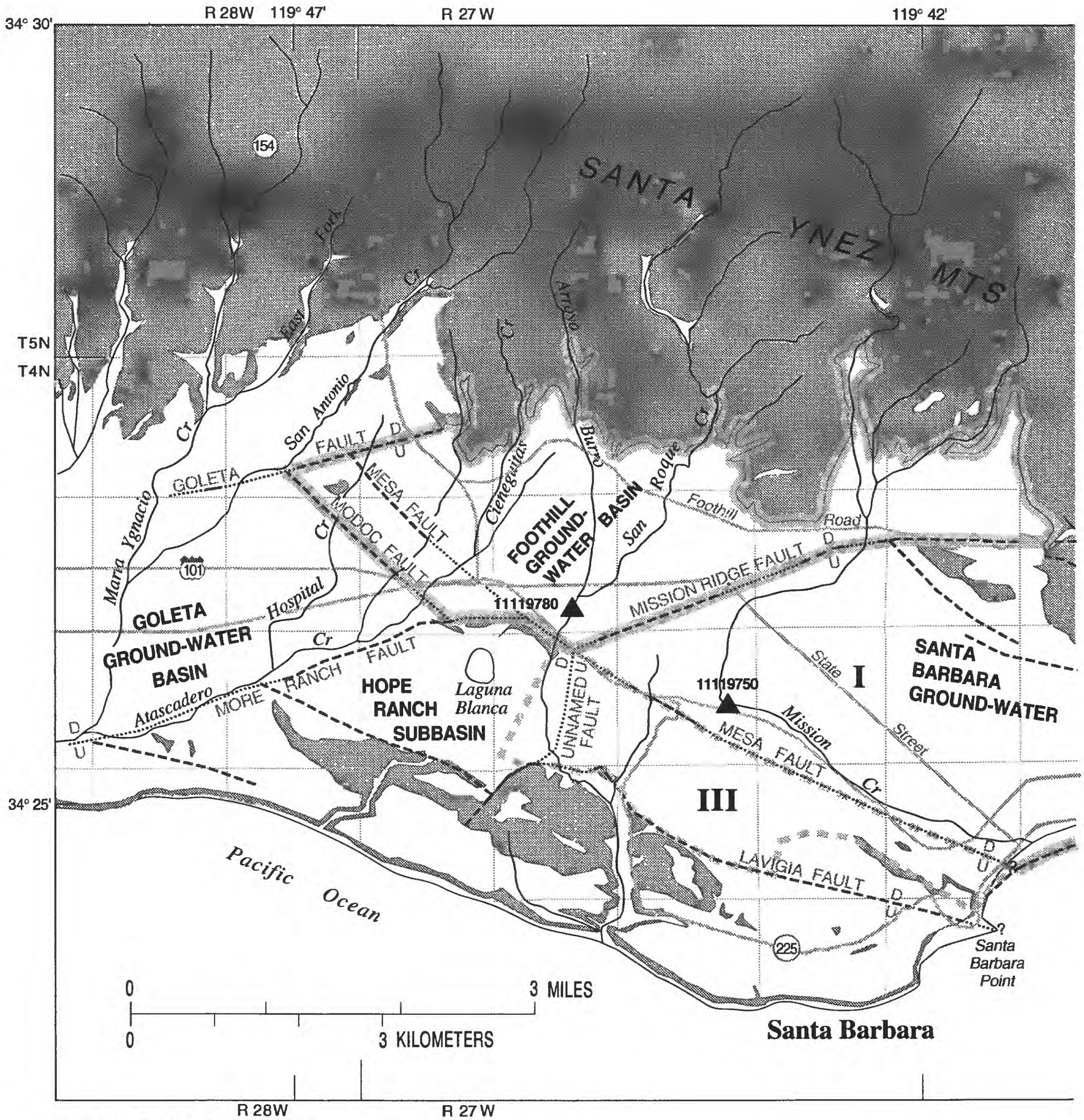
Phase 2 of the study (Martin, 1984) included a description of the geohydrology of the Santa Barbara ground-water basin, with emphasis on Storage Unit I. During the period of the first and second phases of the study, a monthly water-level and water-quality monitoring network (primarily in Storage Unit I) was expanded from 17 to 30 wells. Data from the monitoring network were used in phase 2 to assess vertical variations in ground-water quality and hydraulic head and to determine the effects of pumping on water levels and water quality.

Phase 3 of the study (Martin and Berenbrock, 1986) included evaluation of data collected during phase 2, the development of a numerical flow model of Storage Unit I, and the simulation of a variety of operational conditions using the model.

The study subsequently was extended to include the geohydrologic assessment of the Foothill ground-water basin (consisting of areas formerly known as Storage Unit II of the Santa Barbara ground-water basin and the Goleta East subbasin), the addition of Foothill basin wells to the monitoring network, and the construction of a numerical flow model (Freckleton, 1989).

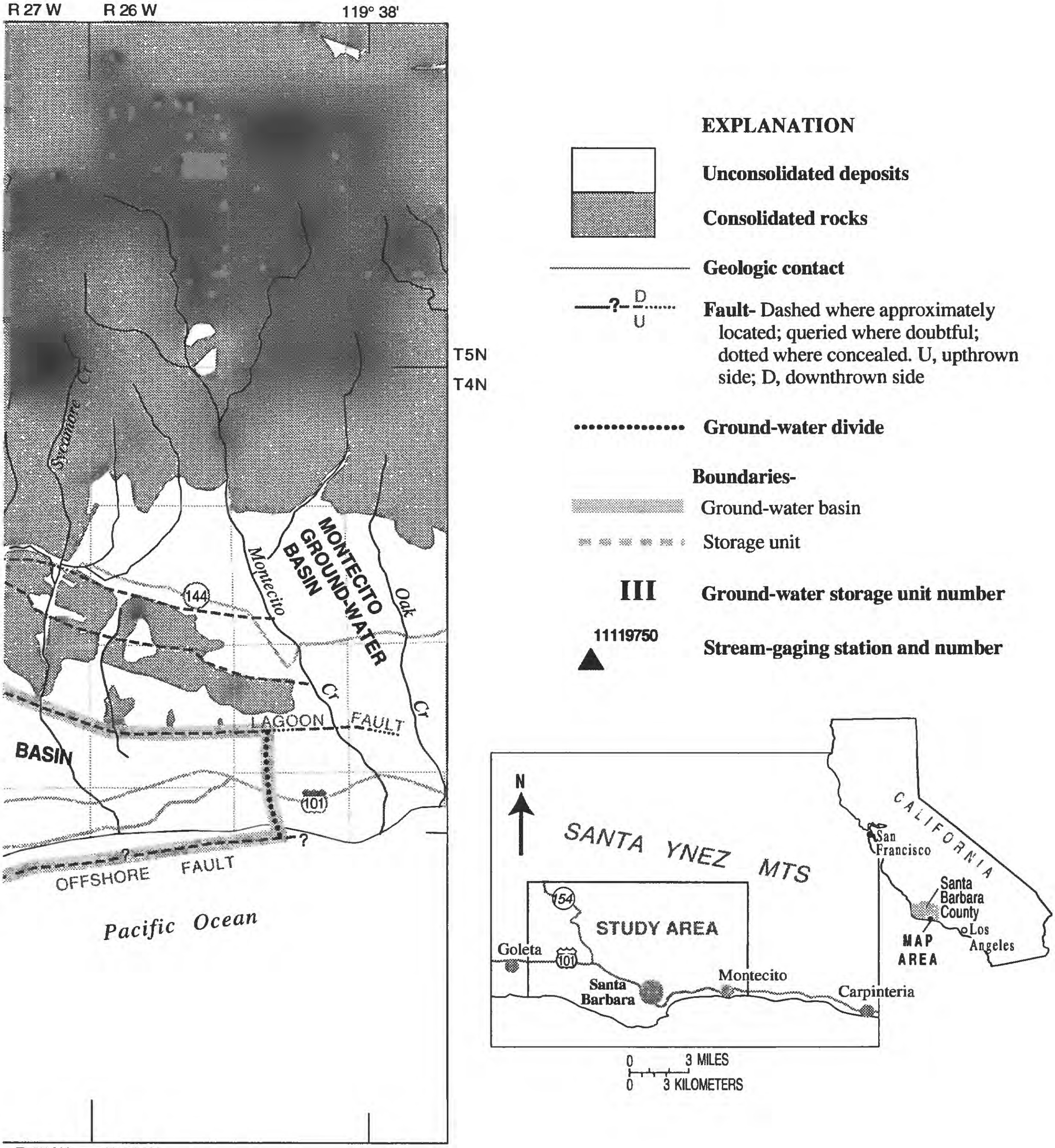
Description of Study Area

The study area includes the Santa Barbara and Foothill ground-water basins located in southwestern Santa Barbara County about 120 mi northwest of Los Angeles (fig. 1). Muir (1968) divided the Santa Barbara ground-water basin into three subbasins—Storage Units I, II, and III—largely on the basis of faults. Storage Unit III, the main focus of this report, underlies the southwest part of the city and is southwest of and adjacent to Storage Unit I, which underlies the main part of the city. The Foothill basin is north of Storage Units I and III and is adjacent to the northwestern end of Storage Unit I. For this report, Storage Units I and III are considered to constitute the Santa Barbara ground-water basin. The Santa Barbara and Foothill ground-water basins are the sources of ground water for the city of Santa Barbara.



Base from U.S. Geological Survey, Santa Barbara 1:24,000,1967 and Goleta 1:124,000, 1988

Figure 1. Location of ground-water subbasins in the Santa Barbara, California, area.



Geology and fault locations modified from J.E. Upson (1951), K.S. Muir (1968), M.F. Hoover (1978), and T.W. Dibblee, Jr. (1986 and 1987)

Figure 1. Continued.

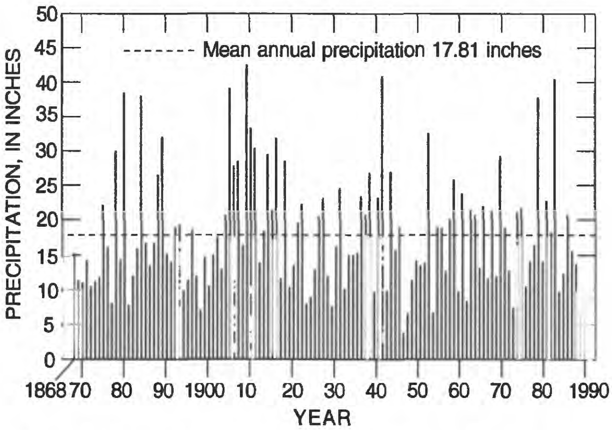


Figure 2. Annual precipitation, city of Santa Barbara, California, 1868–1990. (Data for 1981–85 from Santa Barbara Airport.)

The ground-water basins lie within a narrow lowland along the south foot of the Santa Ynez Mountains, a rugged linear range that rises steeply to crestal altitudes of nearly 4,000 ft. The lowland consists at most places of elevated terraces that generally lie well back from the coast and are separated from it by an alluvial plain. The plain slopes gently to sea level and is about 2 mi wide. The city of Santa Barbara borders the coast and overlies most of the alluvial plain.

The Santa Barbara area is characterized by a Mediterranean-like climate of warm summers and mild winters with little frost hazard. About 95 percent of the rainfall occurs between November and March; in summer, occasional thundershowers occur in the adjacent mountains. The rainfall pattern is not uniform; the bordering foothills typically receive more than 20 in/yr and the mountain crests more than 30 in/yr. Mean annual precipitation at Santa Barbara for the period 1868–1990 was 17.81 in. (fig. 2). Extremes in precipitation in the Santa Barbara area, for the period of record, include 3.99 in. in 1947 and 43.23 in. in 1909. Troxell and others (1942, p. 48-49) estimated that, along the coast of southern California, rainfall increases 3 in. for each 1,000-ft increase in land-surface altitude. Nearly all ground-water recharge and nearly all surface-water flow in the Santa Barbara area are derived directly from rain that falls on the area.

Development in the Santa Barbara and Foothill basins is primarily residential along the peripheral areas and commercial or light industrial along and radiating out from State Street (fig. 1). Prior to urbanization, cattle grazing and then agriculture were the main land uses.

Acknowledgments

Many individuals and organizations aided this study by contributing ideas and data. Special acknowledgment is given to the city of Santa Barbara's Public Works Department, Water Resources Division. Also acknowledged Michael F. Hoover, consulting geologist/hydrologist, for contributing insight, advice, and unpublished data.

REGIONAL GEOHYDROLOGIC SETTING

The Santa Barbara and Foothill ground-water basins (fig. 1) lie within the western Transverse Ranges Province of California. Major structural features in the area are the offshore Channel Islands Ridge (largely submarine, but including local offshore islands known as the Channel Islands—not shown in figure 1) and the anticlinal arch that forms the Santa Ynez Mountains. These features are separated by a structural trough that forms the Santa Barbara Channel, the watercourse between the mainland and the Channel Islands (Staal, Gardner, & Dunne, 1988, p. 7). Rocks and deposits penetrated by wells in the area are Tertiary and Quaternary in age and are almost exclusively sedimentary. These rocks have a maximum thickness of more than 20,000 ft and are locally complexly folded and faulted (Upson, 1951, p. 12). Only a brief summary of the geology of the Santa Barbara area is included here. A more complete description is given by Upson (1951).

The principal source of ground water in the Santa Barbara area is the unconsolidated deposits of Quaternary age and possibly latest Tertiary age. These deposits unconformably overlie consolidated rocks of Tertiary age that form the lower boundary and much of the perimeter of the Santa Barbara and Foothill ground-water basins. These consolidated rocks form continuous outcrops in the foothills of the Santa Ynez Mountains (fig. 3), and also crop out on the ocean floor near Santa Barbara about 0.25 mi offshore (Muir, 1968, p. A8), indicating the probable presence of an east-west-trending fault. Undifferentiated consolidated rocks of Cretacious and Tertiary ages crop out north of the Santa Barbara area (fig. 3) and are not discussed in this report.

Consolidated Rocks

The consolidated rocks in the study area, which are predominantly marine in origin, contain ground water that has a high dissolved-solids concentration (see the "Ground-Water Quality" section of this report), and thus are a potential source of contamination to the overlying and surrounding freshwater aquifers. However, these rocks generally have low permeabilities and are considered not to be a significant source of water, except where highly weathered or fractured. These consolidated rocks include the Sespe Formation of Oligocene and possibly Eocene age, the Vaqueros Sandstone and Rincon Shale of early Miocene age, and the Monterey Formation of early to late Miocene age (fig. 3).

The Sespe Formation consists of alternating layers of reddish-brown to brownish shale, reddish and grayish-green sandstone, bluish silt and clay, and dark-reddish conglomerate—all of continental origin. A zone of coarse-grained conglomerate marks the base of the formation (Upson, 1951, p. 13), and coarse-grained sandstone predominates in the lower part where it alternates with reddish shale. Alternating reddish shale and greenish or greenish-blue sandstone characterize the upper part.

The Vaqueros Sandstone is a fine to coarse, massive calcareous marine sandstone, dirty white to yellowish in color. It is quartzose and locally arkosic, and in places it contains small grains of glauconite. At the base is a fossiliferous conglomerate zone. The Vaqueros Sandstone unconformably overlies the Sespe Formation and is overlain conformably by the Rincon Shale (Upson, 1951, p. 13).

The Rincon Shale consists of massive dark bluish-gray mudstone, which develops a dark greenish-black soil (Upson, 1951, p.14). The Rincon Shale is believed to have low permeability, and in the study area it is not known to be penetrated by water-supply wells. It is conformably overlain by the Monterey Formation.

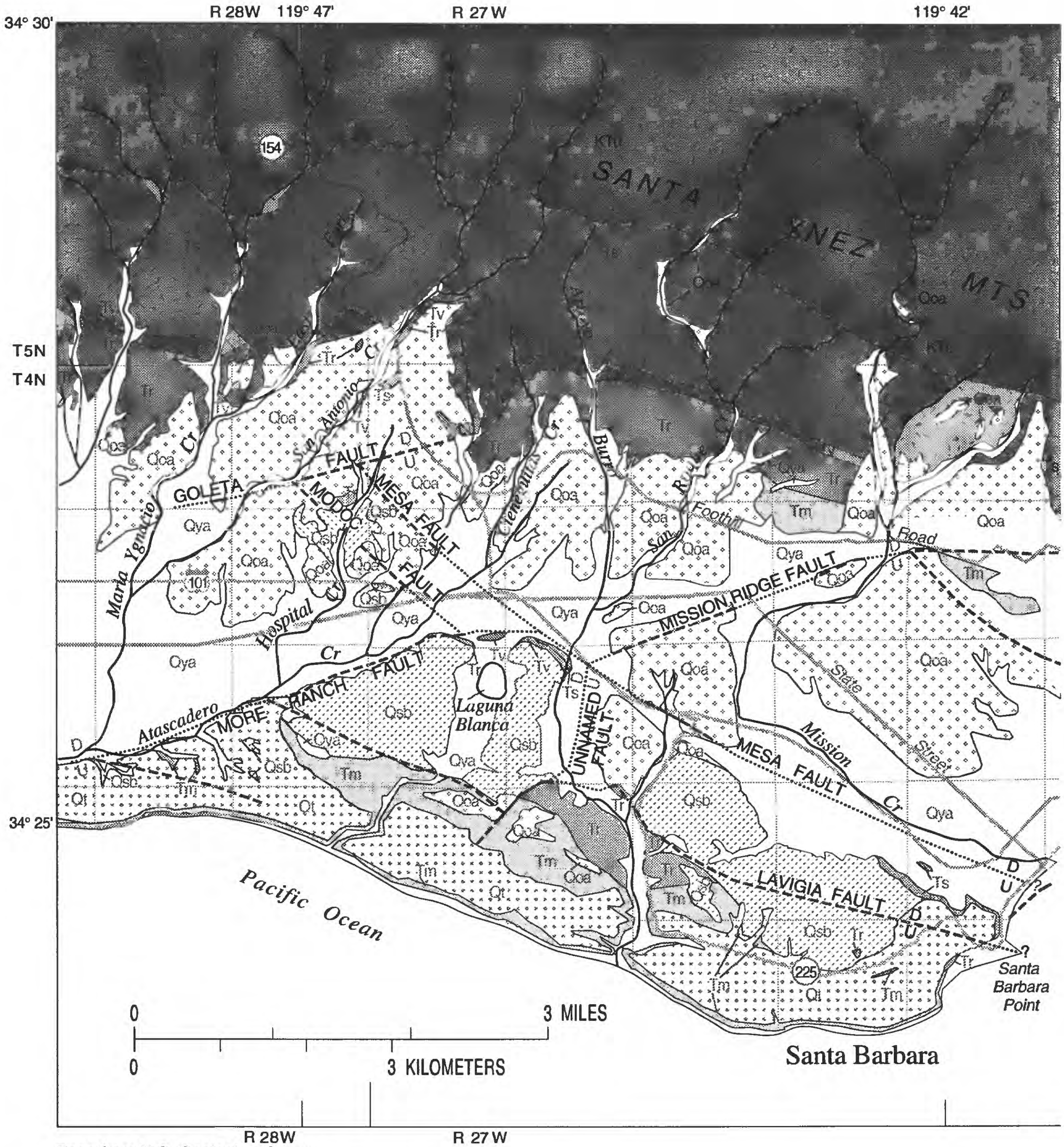
The Monterey Formation consists of thin-bedded locally massive mudstone, diatomaceous shale, and hard siliceous shale. Some limestone and some volcanic material occur locally in the lower part. As encountered in wells in the area and in "fresh deep cuts," the shales are bluish gray, but generally weather to white or cream (Upson, 1951, p. 14). In places, the shales are lightly stained with limonite.

Unconsolidated Deposits

Unconsolidated deposits are the water-bearing units that form the ground-water reservoirs of the area. These deposits are primarily the Santa Barbara Formation of Pleistocene and Pliocene(?) age (Dibblee, 1986) and the overlying older alluvium and younger alluvium of Quaternary age. Terrace deposits of Quaternary age generally are thin and are not considered to be a major source of ground water in the region.

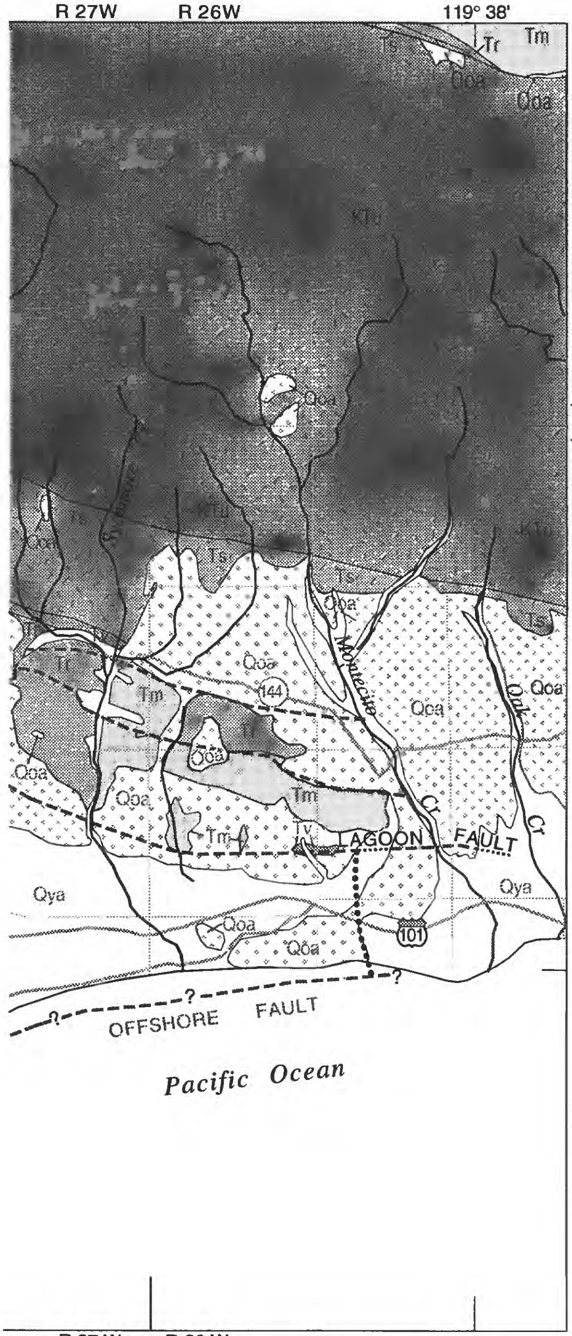
The Santa Barbara Formation (shallow marine deposits) consists primarily of fine to coarse sand, silt, and clay, and it contains sporadic layers of gravel. A layer of fossiliferous sand and gravel occurs near the base of the formation in most areas.

The older alluvium (continental deposits), terrace deposits (partly marine and partly alluvial), and younger alluvium (continental deposits) consist of clay, silt, sand, and gravel. Younger alluvium forms major parts of the alluvial plain in the Santa Barbara area, extends along stream channels, and tongues into adjoining stream canyons.



Base from U.S. Geological Survey,
Santa Barbara 1:24,000,1967 and
Goleta 1:124,000, 1988

Figure 3. Geology of the Santa Barbara area.



Geology and fault locations modified from J.E. Upson (1951), K.S. Muir (1968), M.F. Hoover (1978), and T.W. Dibblee, Jr. (1986 and 1987)

EXPLANATION

Geologic units-

Unconsolidated deposits-

Quaternary and Tertiary (?)

Qya — Younger alluvium- Beach sand, stream channel, and alluvial deposits of Holocene age

Qoa — Older alluvium- Nonmarine deposits of late Pleistocene age

Terrace deposits- Marine and alluvial deposits of late Pleistocene age

Qsb — Santa Barbara Formation- Shallow marine deposits of Pleistocene and latest Pliocene(?)

Consolidated rocks-

Tertiary

Tm — Monterey Formation- Marine shale of early to late Miocene age

Tr — Rincon Shale- Marine shale of early to late Miocene age

Tv — Vaqueros Sandstone- Shallow marine sandstone of early Miocene age

Ts — Sespe Formation- Nonmarine shale or claystone of Oligocene age and possibly Eocene age

KTu — Cretaceous-Tertiary Undifferentiated

Geologic contact

?— D/U — **Fault**- Dashed where approximately located; queried where doubtful; dotted where concealed. U, upthrown side; D, downthrown side

Figure 3. Continued.

Faults and Local Ground-Water Basins

Associated with the anticlinal arch that forms the Santa Ynez Mountains are minor folds and several large faults and adjunctive minor faults. The faults, which are considered to be younger than the folds, have a profound effect on ground water in the area (Upson, 1951, p. 26). The faults have had a considerable effect on determining the areal and vertical distribution of the water-bearing geologic units. Most of the faults within 3 mi of the coast are normal faults that have large vertical displacements of several hundred feet to more than 1,100 ft (Martin and Berenbrock, 1986, p. 8). Where the faults in the Santa Barbara area cut water-bearing units, they function as partial barriers to the movement of ground water.

Ground-water basins adjacent to the Santa Barbara and Foothill basins are the Goleta basin and the Hope Ranch subbasin to the west and the Montecito basin to the east (fig 1). Muir (1968, p. A11) divided the Santa Barbara-Montecito area into "storage units" to be used in the computation of the storage capacity of the water-bearing deposits. The boundaries of the storage units are determined in part by the faults that impede the movement of ground water. In Muir's (1968) arrangement, the city of Santa Barbara overlies most of Storage Units I, II, and III, and the Montecito area overlies Storage Units IV and V. Hutchinson (1979) used the term "Santa Barbara ground-water basin" to denote Storage Units I, II, and III (it is unknown if there was an earlier equivalent description). Martin (1984) refers to Storage Units IV and V as the Montecito ground-water basin. Freckleton (1989) considered Storage Unit II and the East subbasin of the Goleta ground-water basin to be a single hydrologic entity, on the basis of geologic and hydrologic data, and named it the Foothill ground-water basin. Thus, the Santa Barbara ground-water basin is considered in this report to consist of Storage Units I and III. The Santa Barbara and Foothill ground-water basins are the sources of ground water for the city of Santa Barbara.

GEOHYDROLOGY OF STORAGE UNIT III

The geohydrology of Storage Unit III is discussed in this section. The discussion includes boundaries, definition of the aquifer system, aquifer properties, ground-water levels and movement, water-level changes, recharge and discharge, and ground-water quality.

Boundaries

Storage Unit III of the Santa Barbara ground-water basin (fig. 1) trends southeast-northwest. Its width is about 2,000 ft in the southeast and 4,000 ft in the northwest, and its length is about 3.5 mi (fig. 4). For purposes of this report, the lateral storage-unit boundaries will be referred to as "northern," "southern," "eastern," and "western" instead of "northeastern," "southwestern," and so forth. This convention follows that used in other studies (BCI Geonetics, Inc., 1990, p. 1; Hoover and Associates, Inc., 1992, p. 7). In addition, for this study, Storage Unit III is divided informally into a "coastal" part, which extends inland from the coast to just northwest of cluster well 4N/27W-21F1 and 21F2 (fig. 4, section *D-D'*), and an "inland" part, which is the remaining part of the storage unit.

The northern boundary of the storage unit is the Mesa Fault (fig. 3). The western boundary is the geologic contact between younger alluvium and the Santa Barbara Formation west of a north-south-trending unnamed fault. The southern boundary is the Lavigia Fault in the inland part of the storage unit and the contact between the younger alluvium and the consolidated rocks (and, in part, the Santa Barbara Formation) in the coastal part. The eastern boundary is the offshore fault. The lower boundary is the relatively impermeable consolidated rocks of Tertiary age.

The location of the southern boundary has been modified from previous reports as a result of information obtained from test-hole drilling during this study. Specifically, the location of part of the suspected trace of the Lavigia Fault—and therefore part of the southern storage-unit boundary—was mapped 400 ft northward in the vicinity of cluster well 4N/27W-19A1,A2,A3 (fig. 4). This new location was based on the encountering of Tertiary rocks (generally bluish clay, silt, and shale alternating with generally brownish shale and clay) in the test hole. The Tertiary rocks were encountered at 96 ft and they persisted to 360 ft below land surface, the full depth of the well.

The locations of the Mesa and Lavigia Faults, and the unnamed and offshore faults—where they form the northern, southern, western, and eastern boundaries (respectively) of Storage unit III—are considered to be approximate (fig. 4). Martin and Berenbrock (1986) mapped the trace of the Mesa Fault approximately 1,000 to 1,500 ft south of the location defined by Muir (1968) and Hoover (1978), but they did not redefine the location of the Lavigia Fault or the unnamed fault. Although Upson (1951, pl. 2) mapped the trace of the unnamed fault, it was Muir (1968, p. A11) who considered this fault as the western boundary of Storage Unit III. Geologic mapping by a Santa Barbara area geologic and hydrologic consulting firm has verified the presence of this fault (Hoover and Associates, Inc., 1992, p. 9).

Dibblee (1986) mapped the trace of the Mesa Fault in approximately the same location as did Martin and Berenbrock (1986, p. 4-5), but he mapped the trace of the southeastern part of the Lavigia Fault about 2,000 ft south of the location depicted by Martin and Berenbrock (1986, p. 4-5). He did not extend the trace of the Lavigia Fault to the coast. Anecdotal information presented to the authors of this report suggests that Dibblee's placement of the southern part of the fault may be correct (Barry Keller, Metcalf & Eddy, Inc., Santa Barbara, written commun., 1994); the placement, however, is not critical to subsequent geohydrologic interpretations presented in this report. Dibblee (1986) did not map the trace of the unnamed fault.

Vertical displacement across the Mesa Fault (upthrown south of the fault) from Storage Unit I to Storage Unit III is greatest, about 800 ft, in the eastern end of Storage Unit III near well 4N/27W-22Q1 (fig. 5, section *E-E'*). The vertical displacement of the Mesa Fault is less in the northwest, where the relative offset, as estimated from geologic section *B-B'* (fig. 5), is about 100 ft. Vertical displacement across the Lavigia Fault (upthrown south of the fault) in the vicinity of well 4N/27W-18Q1 is estimated from geologic section *B-B'* (fig. 5) to be at least 300 ft. The amount of vertical displacement across the southern end of the Lavigia Fault is unknown. The vertical displacement of the unnamed fault (upthrown east of the fault) is estimated from geologic section *A-A'* (fig. 5) to be about 160 ft. Few data are available to estimate vertical displacement where the unnamed fault intersects the Lavigia Fault. However, on the basis of the orientation and degree of slope of the hydrogeologic units depicted in geologic sections *A-A'* and *B-B'* (fig. 5), vertical displacement could be 200 ft or greater in this area.

Definition of the Aquifer System

Lithologic units mapped by Dibblee (1986) and Muir (1968) are shown in the outcrop pattern in figure 3, and their stratigraphic, structural, and hydrogeologic relations are shown in figure 5. For purposes of this report, the consolidated Tertiary rocks that form the lower boundary of Storage Unit III are undifferentiated (shown in fig. 5 as "Tu").

Unconsolidated deposits of the Santa Barbara Formation and younger and older alluvium compose the main water-bearing units in Storage Unit III. From the coast to cluster well 4N/27W-21F1,2 about 1.5 mi inland, the deposits of Storage Unit III include only the younger and older alluvium and are about 60 ft thick. About 0.5 mi farther northwest at cluster well 4N/27W -21E1,2,3, the deposits include the Santa Barbara Formation, in addition to the younger and older alluvium, and are about 280 ft thick (fig. 5, section *A-A'*). These abrupt changes indicate the possible presence of faulting or folding between these two sites. From cluster well 4N/27W-21E1,2,3, the unconsolidated deposits thicken slightly to about 300 ft at well 4N/27W -17L2,3,4 and then thin northwestward to about 160 ft at an unnamed fault. West of the unnamed fault (downthrown side) in the Hope Ranch subbasin the deposits are about 330 ft thick. The maximum saturated thicknesses of the Santa Barbara Formation and the alluvium are about 160 ft and 140 ft, respectively. In general, the unconsolidated southwest-dipping

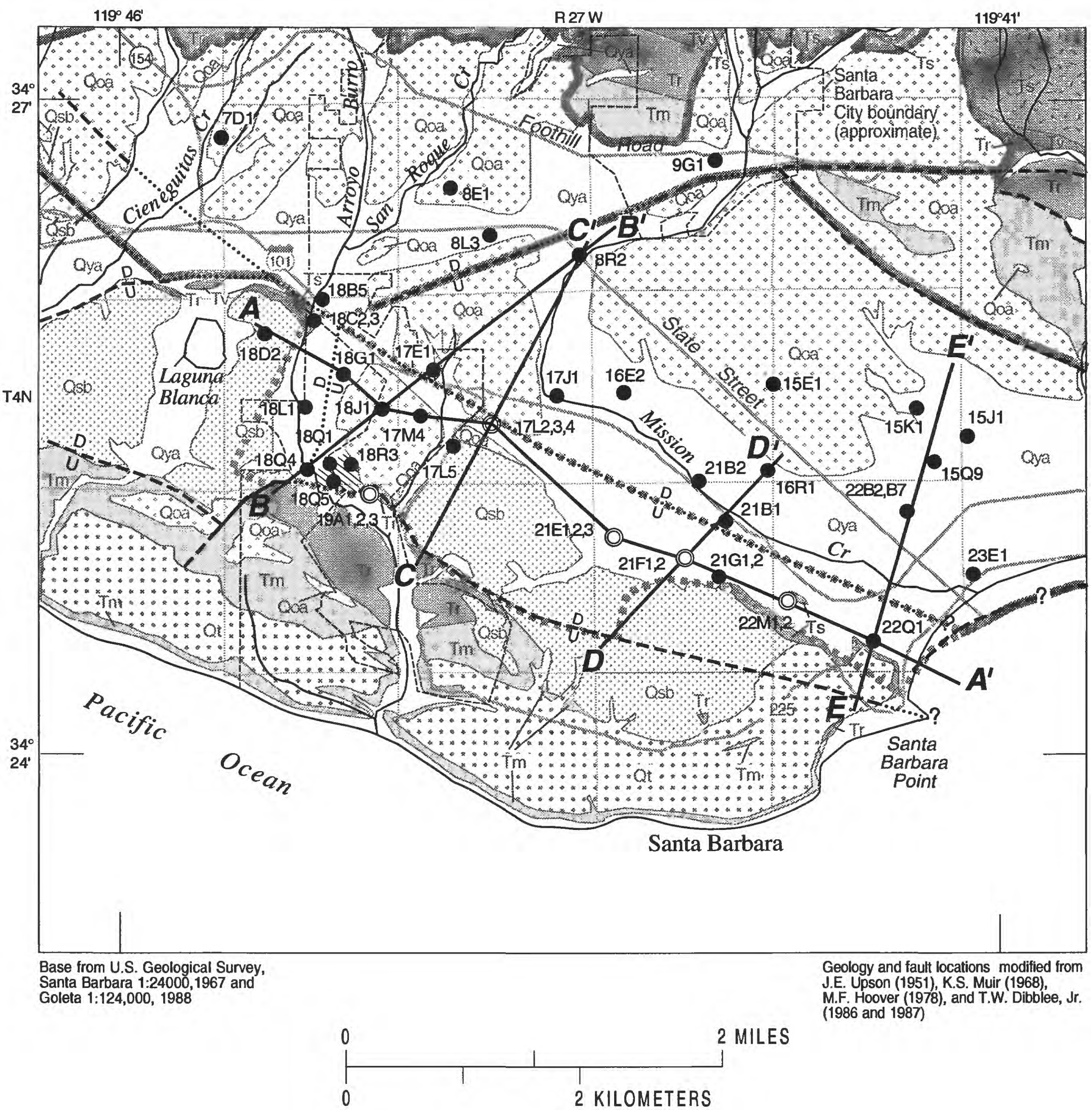


Figure 4. Geology and location of geologic sections and selected wells in Storage Unit III and vicinity, Santa Barbara County, California. (Names of faults are shown in figures 1, 3, and 5.)

EXPLANATION

Geologic units-

Unconsolidated deposits-

Quaternary and Tertiary (?)

Qya — Younger alluvium-
Beach sand, stream channel, and alluvial deposits of Holocene age

Qoa — Older alluvium-
Nonmarine deposits of late Pleistocene age

Qt — Terrace deposits-
Marine and alluvial deposits of late Pleistocene age

Qsb — Santa Barbara Formation-
Shallow marine deposits of Pleistocene and latest Pliocene(?)

Consolidated rocks-

Tertiary

Tm — Monterey Formation-
Marine shale of early to late Miocene age

Tr — Rincon Shale-
Marine shale of early to late Miocene age

Tv — Vaqueros Sandstone-
Shallow marine sandstone of early Miocene age

Ts — Sespe Formation-
Nonmarine shale or claystone of Oligocene age and possibly Eocene age

Geologic contact

?, D, U — **Fault-** Dashed where approximately located; queried where doubtful; dotted where concealed. U, upthrownside; D, downthrown side

A — A' — **Line of geologic section-** (Sections shown in figure 5)

Boundaries-

Ground-water basin

Storage unit

22Q1 — **Well and number**

21F1,2 — **Cluster well and number**

Open grassland receiving recharge from precipitation

Figure 4. Continued.

deposits increase slightly in thickness from the Mesa Fault to the Lavigia Fault (fig. 5, sections *B-B'* and *C C'*).

On the basis of data from borehole geophysical and lithologic logs of selected wells (wells shown in fig. 5) and lithologic logs of wells drilled for this study (table 1, at back of report), the unconsolidated deposits in Storage Unit III have been subdivided into five stratigraphic zones: the shallow zone (zone 1), the upper producing zone (zone 2), the middle zone (zone 3), the lower producing zone (zone 4), and the deep zone (zone 5). These zones correspond to those in the adjacent Storage Unit I described by Martin (1984, p. 5). The relations of these zones between Storage Units I and III can be seen in the geologic sections in figure 5.

The shallow zone (zone 1) includes younger and older alluvium from land surface to the top of the upper producing zone (fig. 5) and is generally less than 100 ft thick. Throughout most of Storage Unit III, the shallow zone consists of fine-grained water-bearing deposits of low permeability that confine or partly confine the underlying upper producing zone. High-permeability water-bearing deposits are present, but they are continuous only for short distances and are not considered an important source of ground water in most of the storage unit. In the coastal part of the storage unit, however, the shallow zone and the younger alluvium constitute the only water-bearing deposits (fig. 5, sections *A-A'*, *D-D'*, *E-E'*).

The upper producing zone (zone 2) near the base of the older alluvium consists of medium to coarse sand and some fine gravel. This zone is about 40 to 60 ft thick and is present throughout the inland part of Storage Unit III.

The middle zone (zone 3) overlies the lower producing zone (fig. 5, section *C-C'*) throughout the southeastern part of the inland area of Storage Unit III and is as much as 300 ft thick. It consists of the upper part of the Santa Barbara Formation and is composed of mainly fine-grained deposits interspersed with sporadic coarse-grained water-bearing deposits. The fine-grained deposits yield virtually no water to wells, but the interbedded coarse-grained deposits may supply some water to wells (Martin and Berenbrock, 1986, p. 7).

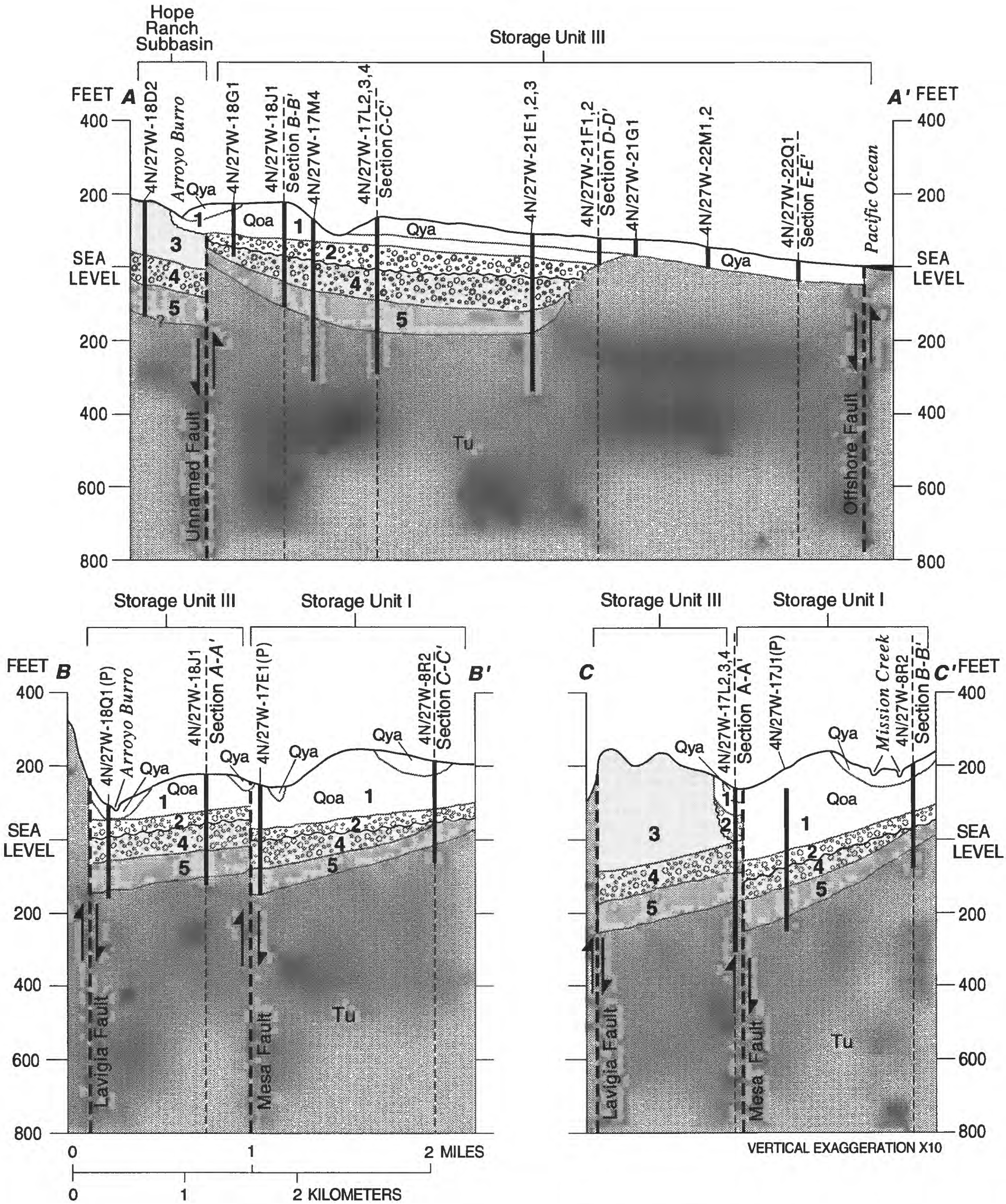
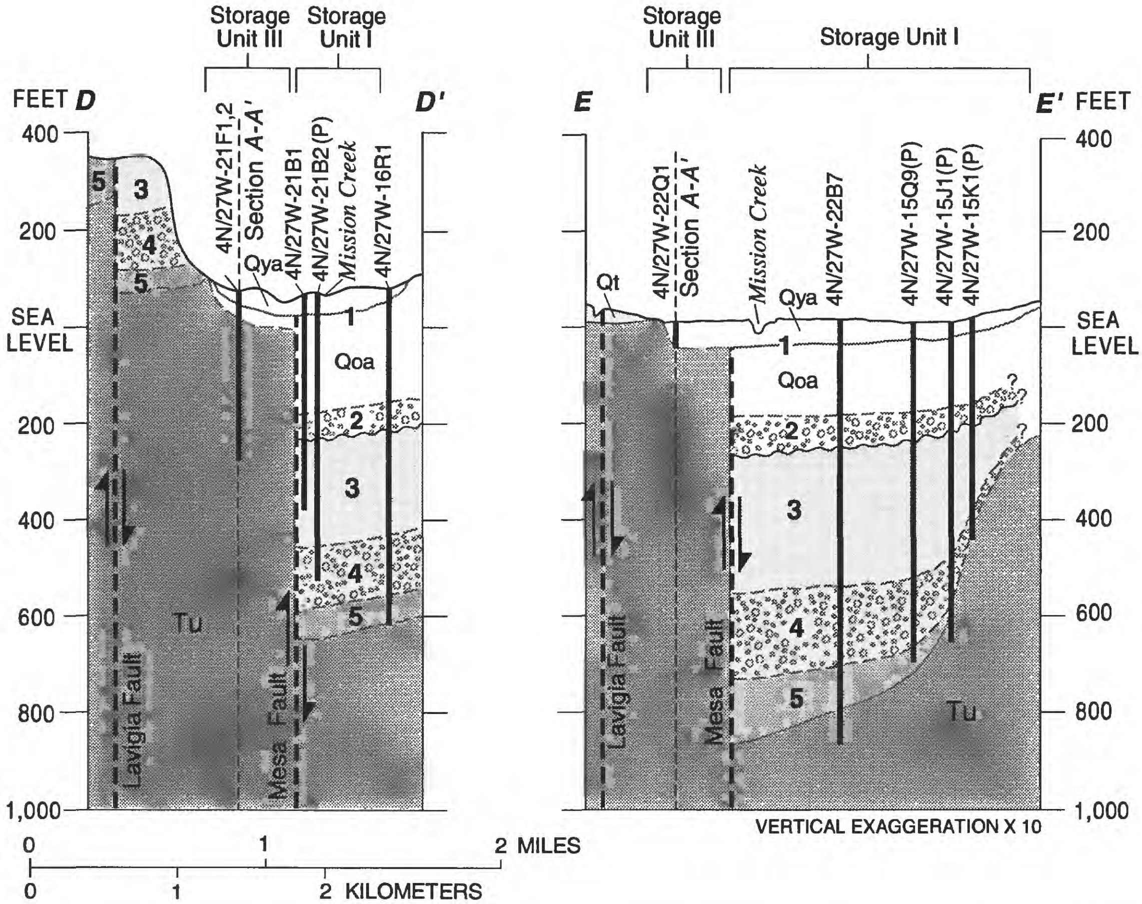


Figure 5. Geologic sections and hydrogeologic units of Storage Unit III, Santa Barbara County, California. (Location of sections shown in figure 4.)



EXPLANATION

Hydrogeologic Units

Unconsolidated deposits-

1 Qya / Qoa	Shallow zone (younger and older alluvium)
2	Upper producing zone (older alluvium)
Qt	Alluvial and marine deposits (terrace deposits)
3	Middle zone (Santa Barbara Formation)
4	Lower producing zone (Santa Barbara Formation)
5	Deep zone (Santa Barbara Formation)

Consolidated rocks-

Tu — Undifferentiated rocks (undifferentiated on sections only)

— — -? **Geologic contact-** Dashed where uncertain, queried where doubtful

~~~~ **Unconformity**

Fault- Approximately located; arrows indicate relative direction of movement

4N/27W-15K1(P) **Well bore and number-** (P) indicates that location is projected. Depth of hole may be greater than depth of installed well(s)

Figure 5. Continued.
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The lower producing zone (zone 4), near the base of the Santa Barbara Formation, is present only in the inland part of the storage unit and consists of medium to coarse sand with fine gravel and shell fragments. In Storage Unit III, the lower producing zone is as much as 100 ft thick at cluster well 4N/27W-21E1,2,3 (fig. 5, section *A-A'*), but it generally thins to the northwest and is about 20 ft thick at the unnamed fault. The lower producing zone probably is the main source of water to wells in Storage Unit III.

The deep zone (zone 5), which is about 40–80 ft thick, separates the lower producing zone from the consolidated rocks throughout the inland part of Storage Unit III (fig. 5, section *A-A'*). This zone consists of fine-grained deposits and contains water of poor quality (high dissolved-solids concentration). Because of its low permeability (Martin and Berenbrock, 1986, p. 10), the deep zone probably is not an important source of supply water; however, it is important because of its potential to degrade the quality of the overlying aquifer zones. For example, leakage from the deep zone may occur over time owing to excessive pumping from or reduced recharge to the overlying zones in the aquifer system.

Aquifer Properties

The deposits of the shallow zone (older and younger alluvium) and of the upper producing zone (the older alluvium) have similar water-bearing properties (Muir, 1968, p. A10). Transmissivity of the shallow and upper producing zones probably is no more than about 550 ft^2/d on the basis of a maximum saturated thickness of about 140 ft and a measured hydraulic conductivity of 3.88 ft/d (Williams, 1981, p. 11). In most areas of Storage Unit III, the alluvium is confined or partly confined. On the basis of a typical confined-aquifer specific storage of 1×10^{-6} per foot and a saturated thickness of 140 ft, the storage coefficient of the shallow and upper producing zones is about 1.4×10^{-4}. Along Arroyo Burro in the western part of the storage unit, the younger alluvium is unconfined (owing to steeper depositional gradients and, therefore, less extensive or missing confining clay layers) and the specific yield is assumed to be less than 0.2.

Transmissivities calculated from aquifer-test data are available for two wells in Storage Unit III: 790 ft^2/d at well 4N/27W-18Q4, which is perforated in the upper and lower producing zones and the deep zone; and about 1,260 ft^2/d at well 4N/27W-17M4, which is perforated in the same zones (transmissivity values from BCI Geonetics, Inc., 1990, Appendix 1). Transmissivity of these zones at cluster wells 4N/27W -17L2,3,4 and -21E1,2,3, is about 1,300 ft^2/d, assuming that the aquifer material and the saturated thickness are similar to those at well 4N/27W-17M4.

Few data are available to estimate storativity (storage coefficient for confined aquifers and specific yield for unconfined aquifers) of the Santa Barbara Formation (the middle, lower producing, and deep zones) in Storage Unit III, but values estimated for Storage Unit I and the Foothill basin are assumed to be representative of the Santa Barbara Formation where it is composed of similar materials. A storage coefficient of approximately 1.0×10^{-4} was calculated from aquifer-test data for the lower producing zone of Storage Unit I (Martin and Berenbrock, 1986, p. 20), and values of specific yield range from 0.05 to about 0.10 where the Santa Barbara Formation is unconfined (Freckleton, 1989, p. 7).

The specific capacity at well 4N/27W-17M4, which has a perforated interval of 270 ft in the upper and lower producing zones and deep zone, is 4.7 (gal/min)/ft of drawdown on the basis of a pumping rate of 203 gal/min (BCI Geonetics, Inc., 1990). The specific capacity at well 4N/27W-18Q4, which has a perforated interval of 140 ft in the upper and lower producing zones and deep zone, is 3.0 (gal/min)/ft on the basis of a pumping rate of 250 gal/min (BCI Geonetics, Inc., 1990). The specific-capacity values for well 4N/27W-17M4 and well 4N/27W-18Q4 approximately convert to transmissivity values of 1,260 ft^2/d and 800 ft^2/d, respectively, using a conversion factor of 270 $(ft^3/d)/(gal/min)$ (Driscoll, 1986).

Ground-Water Levels and Movement

Fourteen wells were installed at eight sites in the study area to better understand the current ground-water conditions. The depth to water in wells during this study in Storage Unit III ranged from about 5 ft above land surface at 4N/27W-21E3 (flowing well) to about 60 ft below land surface at 4N/27W-17L3 (fig. 6).

Hydraulic head in the ground-water system varies with depth. The hydraulic head and resulting water levels (fig. 6) in cluster wells generally decreased with increased depth in the system. For example, in cluster wells 4N/27W-21E1,2 and 3, water levels were generally highest in the well tapping the upper producing zone, slightly lower in the well tapping the lower producing zone, and lowest in the well primarily tapping the deep zone. These results indicate the potential for downward movement of water at the cluster well sites.

Potentiometric-surface maps are useful in defining the horizontal component of ground-water flow. The potentiometric surface and directions of horizontal movement shown in figure 7 represent shallow-zone hydraulic conditions in the coastal part and upper-producing-zone hydraulic conditions in the inland part of Storage Unit III and the upper-producing-zone hydraulic conditions in Storage Unit I based on 1990–91 water-level measurements. The potentiometric contour lines are based on water levels in tightly cased wells that tapped either the shallow zone or upper producing zone. The upper producing zone in the inland part, and the shallow zone in the coastal part of Storage Unit III are in good hydraulic connection, and these zones are modeled as a single layer in Storage Unit III (see section on flow model "Assumptions"). The horizontal component of flow through the two zones was from the northwest to the southeast along the long axis of the storage unit, roughly parallel to the Mesa and Lavigia Faults, indicating limited flow across the faults. The barrier effect of the Mesa Fault is further supported by shallow-zone hydraulic-head differences between Storage Unit III and Storage Unit I that range from about 5 ft near the coast at well 4N/27W-22Q1 to about 55 ft near cluster well 4N/27W-21F2 (fig. 7).

The potentiometric surface of the lower producing zone, based on 1990–91 water-level measurements, is shown in figure 8. In the inland part of Storage Unit III during 1990–91, water moved through the lower producing zone toward well 4N/27W-18Q4 and other nearby pumped wells. Prior to pumping in Storage Unit III, ground water probably moved horizontally through the lower producing zone from the northwest to the southeast (Martin, 1986, fig. 4). Water levels in wells in Storage Unit III indicate that head differences in the lower producing zone across the Mesa Fault range from less than 10 ft to about 50 ft. Flow through the lower producing zone probably is generally parallel to the Mesa Fault in both Storage Units I and III.

Water-Level Changes

The longest period of record for water-level measurements in Storage Unit III is 1946–91. During this period, five water-level measurements made at well 4N/27W-17M1 (perforated in the shallow, upper and lower producing, and deep zones) indicate a water-level decline of about 13 ft. Other relatively long-term water-level data were collected at wells 4N/27W-18Q1 and -18Q4, which are perforated in the upper and lower producing zones and deep zone. Well 4N/27W-18Q4 is the main production well in Storage Unit III and is measured only when it is not pumped; therefore, the water levels shown in figure 9 do not reflect maximum declines at this location. Water levels in well 4N/27W -18Q1 declined to a maximum depth of about 40 ft below land surface in 1990 (fig. 9) in response to pumping at well 4N/27W-18Q4. The pattern of rapid water-level response (decline and recovery) at well 4N/27W -18Q1 (fig. 9) is indicative of the confined or partly confined conditions in the upper and lower producing zones in Storage Unit III.

Short-term water-level fluctuations (periods of months rather than years) are evident in selected hydrographs for Storage Unit III wells (fig. 6). Water-level fluctuations at these wells are relatively small, generally less than a few feet, and probably represent response to cyclic short-term pumping and recharge in Storage Unit III. In general, these short-term water-level fluctuations are slightly more pronounced in cluster wells 4N/27W-17L2,3 and 4N/27W-21E1; these wells are perforated in the lower producing zone, which is the main pumping zone. In addition, the short-term fluctuations are greater in magnitude at cluster wells 4N/27W-17L2,3 owing to their proximity to the main pumping area.

Recharge and Discharge

The sources of ground-water recharge in Storage Unit III include seepage from Arroyo Burro (which is not hydraulically connected to the aquifer system),

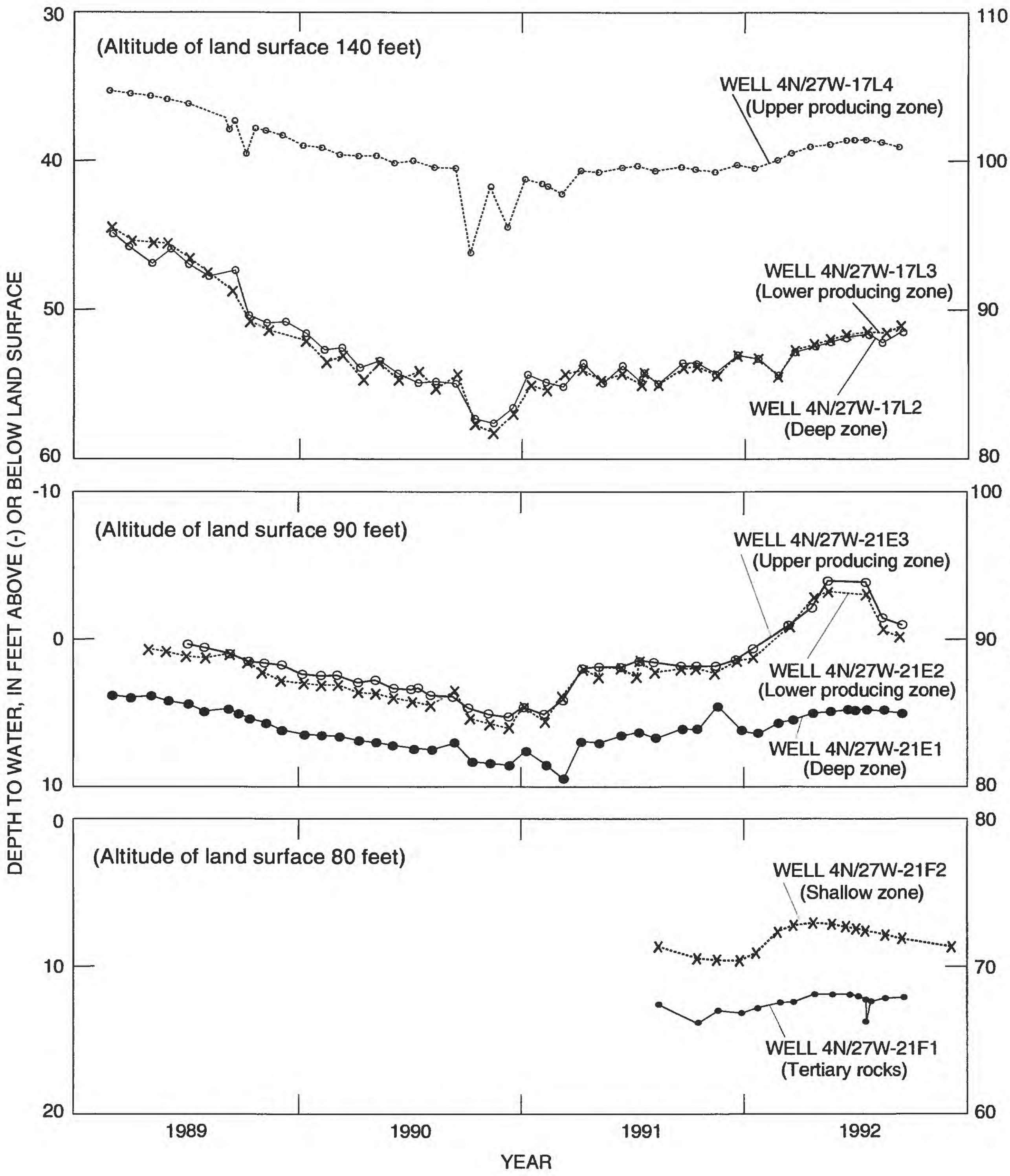
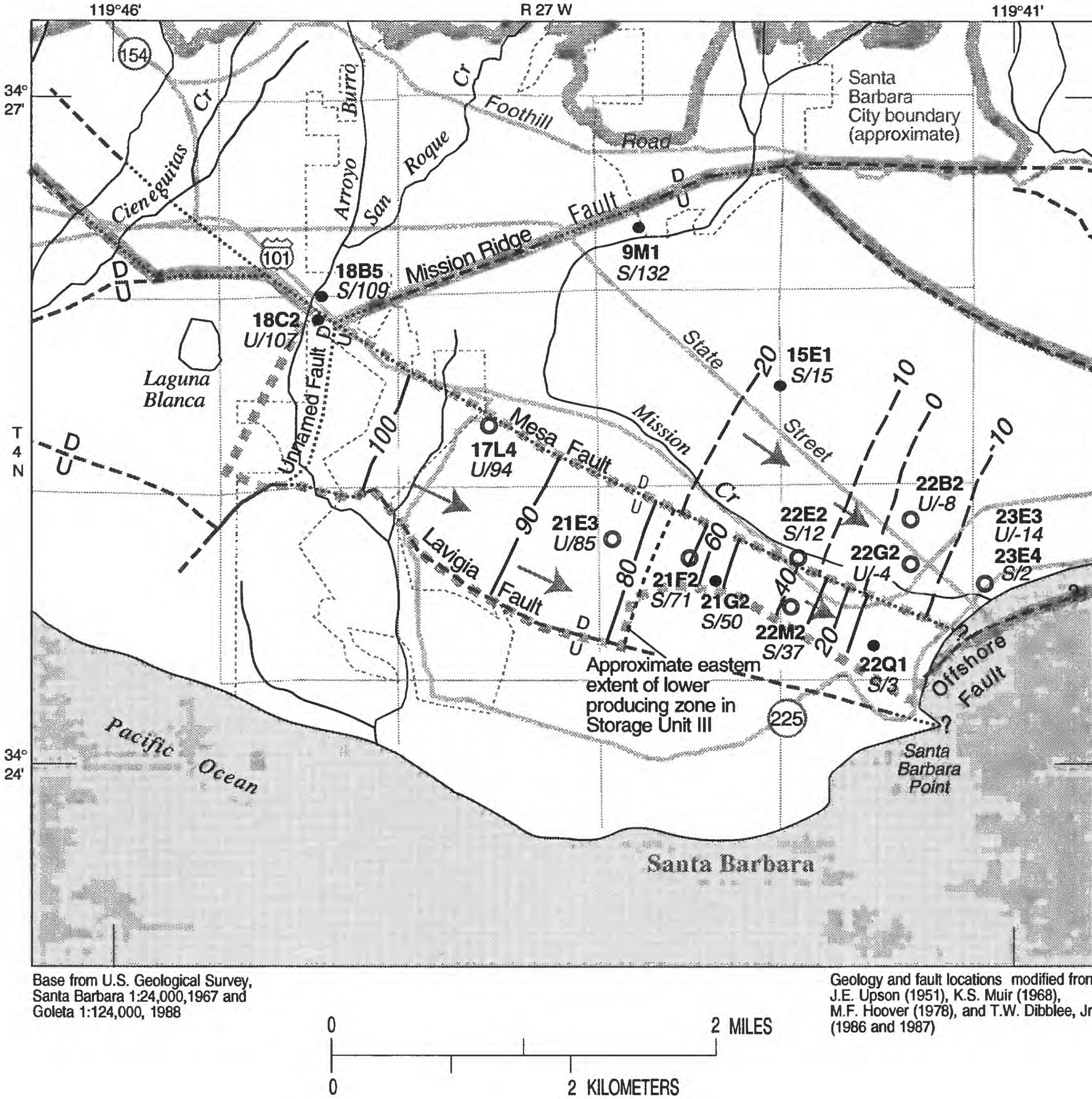


Figure 6. Depth to water in selected cluster wells, Santa Barbara County, California.



EXPLANATION

—?— D/U ······ **Fault-** Dashed where approximately located; queried where doubtful; dotted where concealed. U, upthrown side; D, downthrown side

— — —80 **Potentiometric contour-** Shows altitude at which water level would have stood in tightly cased wells. Dashed where approximately located. Contour interval 10 feet. Datum is sea level

→ **Direction of ground-water movement**

Boundaries-

Ground-water basin

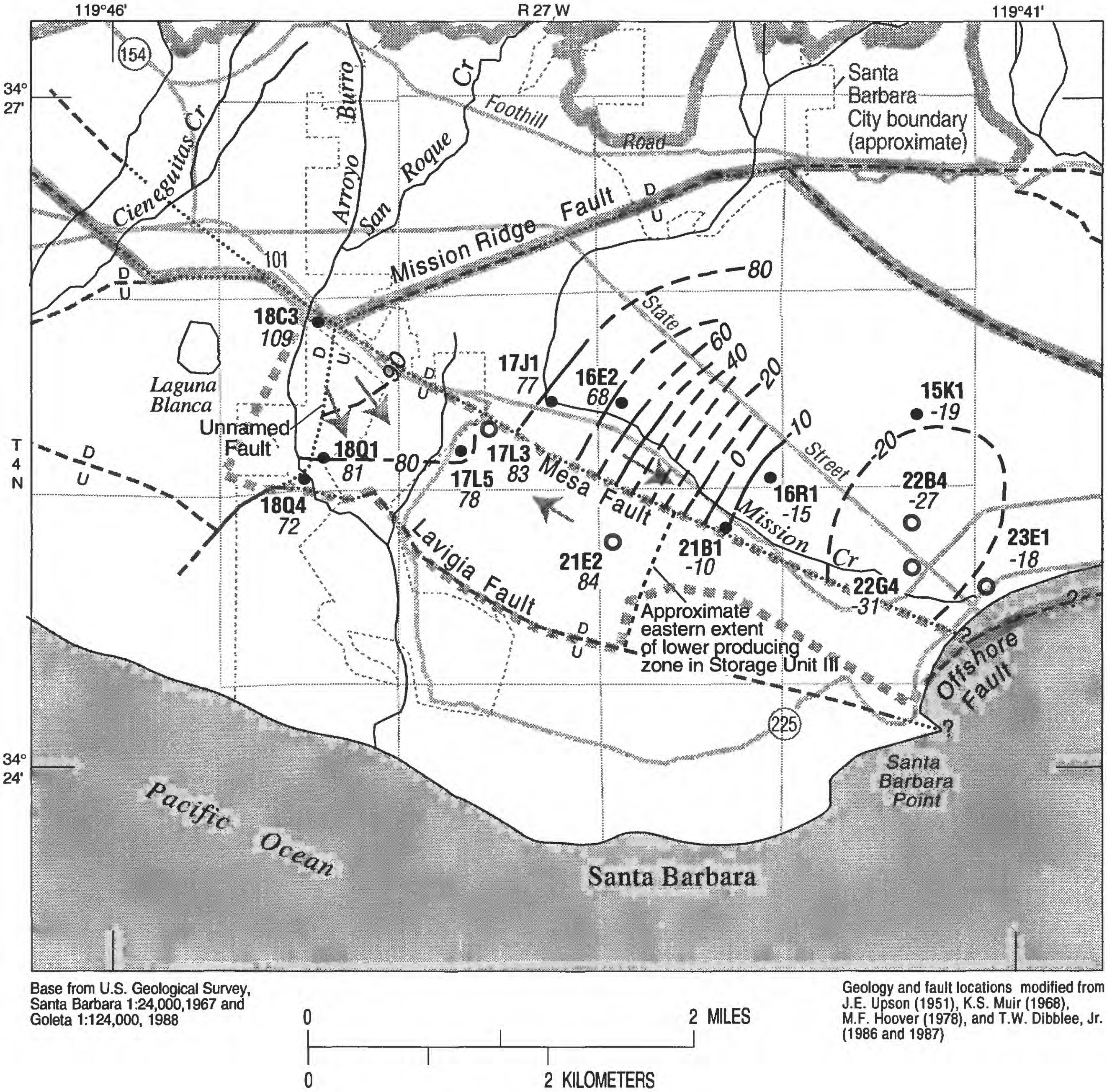
Storage unit

21G2 S/50 ● **Well and number-**

21E3 U/85 O **Cluster well and number-**

(Bottom number is water-level altitude, in feet above or below (-) sea level (S/, shallow zone; U/, upper producing zone)

Figure 7. Potentiometric surface and movement of water in the shallow and upper producing zones, Santa Barbara, California, area, based on 1990–91 water-level measurements.



EXPLANATION

Fault- Dashed where approximately located; queried where doubtful; dotted where concealed. U, upthrown side; D, downthrown side

80 **Potentiometric contour-** Shows altitude at which water level would have stood in tightly cased wells. Dashed where approximately located. Contour interval 10 feet. Datum is sea level

Boundaries-

Ground-water basin

Storage unit

15K1 -19 **Well and number-**

21E2 84 **Cluster well and number-** Water-level altitude, in feet above or below (-) sea level

Direction of ground-water movement

Figure 8. Potentiometric surface and movement of water in the lower producing zone, Santa Barbara, California, area, based on 1990–91 water-level measurements.

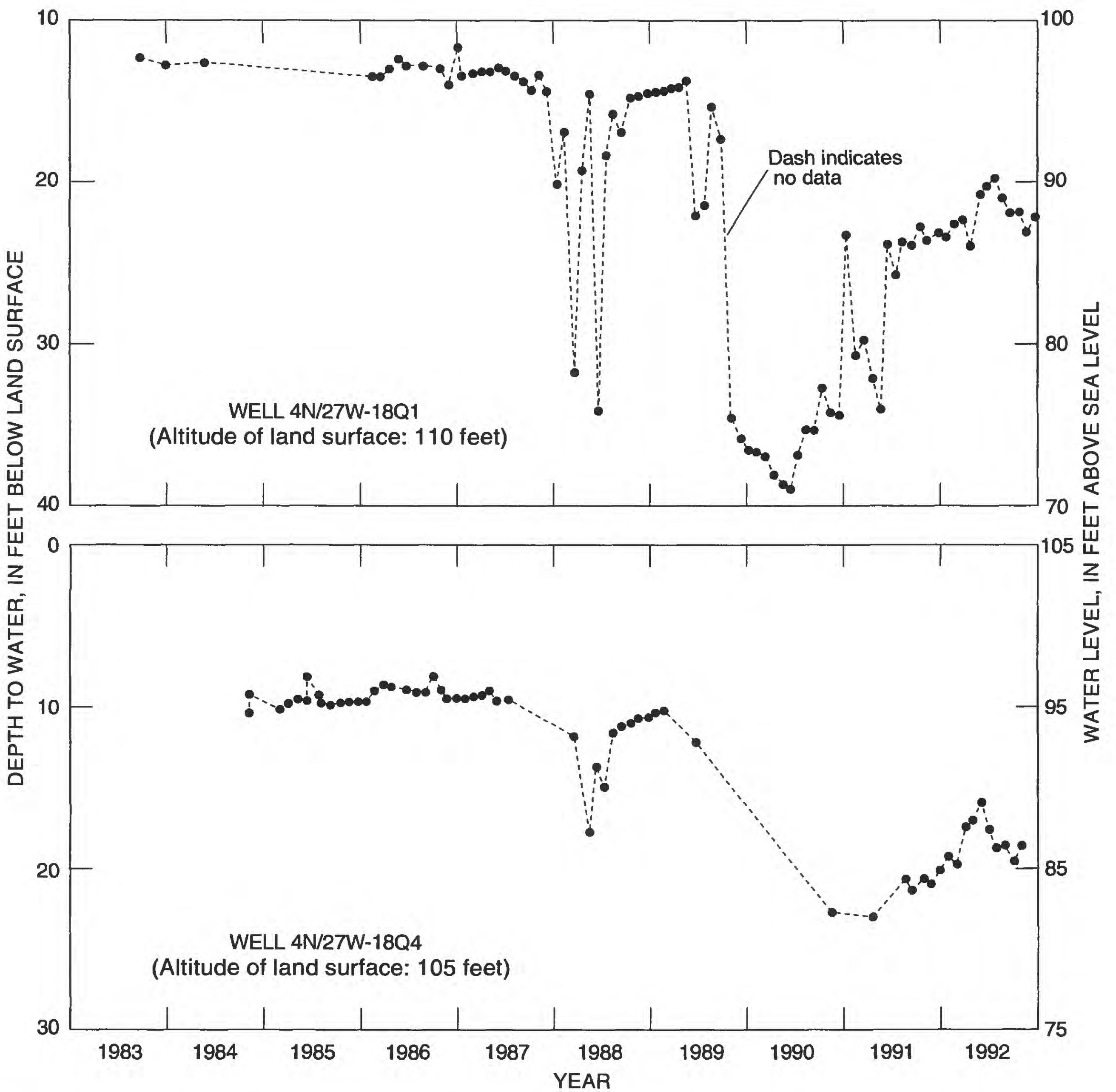


Figure 9. Depth to water in wells 4N/27W-18Q1 and 4N/27W-18Q4 in Storage Unit III, Santa Barbara County, California.

subsurface flow from the Foothill basin, possibly subsurface flow from the shallow zone in Storage Unit I, and infiltration of precipitation. Small quantities of recharge also may occur as subsurface flow from the Hope Ranch subbasin, flow from south of the Lavigia Fault, and as upwelling from the Tertiary rocks underlying the storage unit.

The permeable length of Arroyo Burro in Storage Unit III is about 3,000 ft and the width is about 8 to 10 ft. Measurable flow occurred an average of 267 days per year (during 1971–78) at Arroyo Burro gaging station 11119780; however, this flow is not considered to reflect natural conditions because of the influence of urban runoff and air conditioner effluent from a large shopping center. Therefore, the average number of days of flow is assumed to be the same as in Mission Creek (90 days per year) about 1 mi to the east. The quantity of water neglected by this assumption amounts to no more than 3.5 percent of the median annual flow for the period of record (Freckleton, 1989, p. 14). On the basis of an infiltration rate of 4.8 (gal/d) /ft^2 (Todd, 1978, p. 37), an assumed average 90 days of flow per year, and a stream width of 10 ft, stream recharge is estimated to be 40 acre-ft/yr. In a streamflow-infiltration study of Mission Creek in the adjacent Storage Unit I (McFadden and others, 1991, p. 13), infiltration rates more than double those reported by Todd (1978) were measured. If one assumes that these higher rates are applicable to Arroyo Burro in Storage Unit III, then infiltration may be about 80 acre-ft/yr.

Recharge from subsurface flow occurs mainly through unfaulted younger alluvium along Arroyo Burro at the northwestern end of the storage unit when water levels in the adjacent Foothill basin and Storage Unit I are high. Some recharge also may occur by subsurface flow through younger alluvium along the Mesa Fault. However, in the area of the Mesa Fault, such recharge likely is small because ground water probably flows parallel to the fault in both Storage Units I and III (Martin and Berenbrock, 1986, p. 42).

The rate of infiltration of precipitation probably is greatest in the undeveloped northwestern part of Storage Unit III where there is a small area (about 28 acres) of open grassland (fig. 4). Muir (1968, p. A17-19) estimated recharge from precipitation to be 0.138 ft/yr for land covered with grass and weeds above an altitude of 100 ft in Storage Unit III. Below that altitude, storm sewers (which drain water to the ocean), city streets, and buildings prevent significant infiltration of rain. Using a recharge area of about 1,200 acres above an altitude of 100 ft and a recharge value of 0.138 ft/yr, one obtains an estimate of about 160 acre-ft/yr. However, urban and commercial development subsequent to Muir's (1968) study has reduced the amount of acreage available for infiltration recharge.

The quantity of subsurface flow entering Storage Unit III from the Hope Ranch subbasin is unknown. Also unknown is the quantity of flow owing to upwelling from the Tertiary rocks underlying the storage unit, and flow that may originate south of the Lavigia Fault. It is unlikely that flow from south of the Lavigia Fault would occur in the western end of Storage Unit III owing to the natural land-surface gradients, which are toward the south.

Discharge from Storage Unit III occurs as pumpage, underflow through alluvium in the vicinity of Arroyo Burro across the Lavigia Fault, underflow across the eastern boundary to the Pacific Ocean, flow to underground sewer drains, and evapotranspiration. In addition, although bounding faults are considered relatively impermeable, and thus relatively effective barriers, some flow undoubtedly occurs through these boundaries.

The main pumper in Storage Unit III is the city of Santa Barbara (Valle Verde well, 4N/27W-18Q4). In addition, the Las Positas Mutual Water Company well (4N/27W-17M4) and two privately owned wells (4N/27W-18Q5 and -18R3) currently (1992) are pumped in the storage unit (Hoover and Associates, Inc., 1992, p. 12). Pumpage in Storage Unit III ranged from about 46 to 65 acre-ft/yr during 1978–86 to as much as 281 acre-ft/yr in 1990 (table 2, at back of report).

The quantity of underflow discharging from Storage Unit III along Arroyo Burro across the Lavigia Fault is unknown, but it probably is only a few tens of acre-feet per year. Discharge by evapotranspiration is not considered to be significant owing to the depth to ground water, which generally is greater than 20 ft.

Ground-Water Quality

To determine the areal and vertical variations in ground-water quality in Storage Unit III, water samples were collected from 14 wells at 8 sites. Eleven of the sampled wells, located at five sites, are test wells constructed by the U. S. Geological Survey during this study. The test wells at four of these sites are cluster wells, which consist of two or three small-diameter wells perforated at different depths in the same borehole. The perforated intervals of the wells are separated by a low-permeability bentonite grout to prevent flow through the borehole. Two wells, 4N/27W-17M4 and -18Q4, are active production wells. The remaining well, 4N/27W-22Q1, is a test well logged by the U.S. Geological Survey during a previous study (Martin, 1984, p. 31).

The quality of ground water in Storage Unit III varied areally within individual water-bearing zones. The distribution of dissolved-solids concentration (sum of chemical constituents) and the chemical quality of the samples from selected wells, based on available water-quality data collected from 1968–93, are shown in figure 10 for the shallow and upper producing zones, lower producing zone, and the deep zone and Tertiary rocks. Note that most of the data presented in figure 10 were collected in 1993. No water-quality data are available for the middle zone because this zone is not tapped by any sampled wells in Storage Unit III. Water-quality data from wells sampled outside Storage Unit III are presented in this report to help determine possible ground-water interaction with adjacent storage units or ground-water basins.

Representative chemical analyses of ground water are shown in figure 10 for the different water-bearing zones using a method suggested by Stiff (1951). The water-quality diagrams show the general quality of the water at specific years (as designated in figure 10), and their locations in the figure give an indication of the areal differences in chemical character of ground water. Analyses with similarly shaped diagrams represent ground water of similar characteristics, and the differing widths of the diagrams are indications of the differences in the concentrations of dissolved constituents.

Shallow and Upper Producing Zones

Six of the sampled wells in Storage Unit III are in the shallow or upper producing zones (zones 1 and 2): 4N/27W-17L4, -21E3, -21F2, -21G2, -22M2, and -22Q1 (table 3, at back of report, and fig. 10*A*). Data from the two water-bearing zones are combined because there are no available data representative of the shallow zone in the inland part of Storage Unit III, and the upper producing zone is not present in the coastal part. Concentrations of dissolved solids in samples from the shallow zone ranged from 708 mg/L at well 4N/27W-21F2 near the western end of the coastal part of Storage Unit III to 2,520 mg/L at well 4N/27W -22M2 in the middle of the coastal part (fig. 10*A*). Samples from the two remaining wells in the coastal area had dissolved-solids concentrations of about 1,500 mg/L. Martin (1984) concluded that the Tertiary rocks that directly underlie the shallow zone in the coastal part of Storage Unit III (fig. 5) are the source of the high dissolved-solids concentrations on the basis of comparisons of the sulphate and barium concentrations, chloride-to-sulphate ratio, and chloride-to-barium ratio for ocean water and water yielded by well 4N/27W-22Q1. Low dissolved-solids-concentration water in the upper and lower producing zones in the inland part of Storage Unit III probably is the primary source of water to well 4N/27W-21F2.

Samples from the shallow and upper producing zones in Storage Unit I near the coastal part of Storage Unit III (wells 4N/27W-22E2, -22G2, and -23E4) have relatively low dissolved-solids concentrations and different chemical characteristics (fig. 10*A*), indicating the absence of significant ground-water flow across the Mesa Fault in the shallow zone. In general, areal variability of water quality is influenced by factors such as proximity to recharge areas or pumping centers, proximity to Tertiary rocks, and well construction.

Samples from wells 4N/27W-17L4 and -21E3 in the upper producing zone of Storage Unit III had dissolved-solids concentrations of 705 and 828 mg/L, respectively (table 3 and fig. 10*A*). These samples are similar in chemical character to samples from the shallow zone along Arroyo Burro in the Foothill basin (well 4N/27W-18B5) and the Hope Ranch subbasin (well 4N/27W-18C2). However, the dissolved-solids concentration of samples from the upper producing zone in

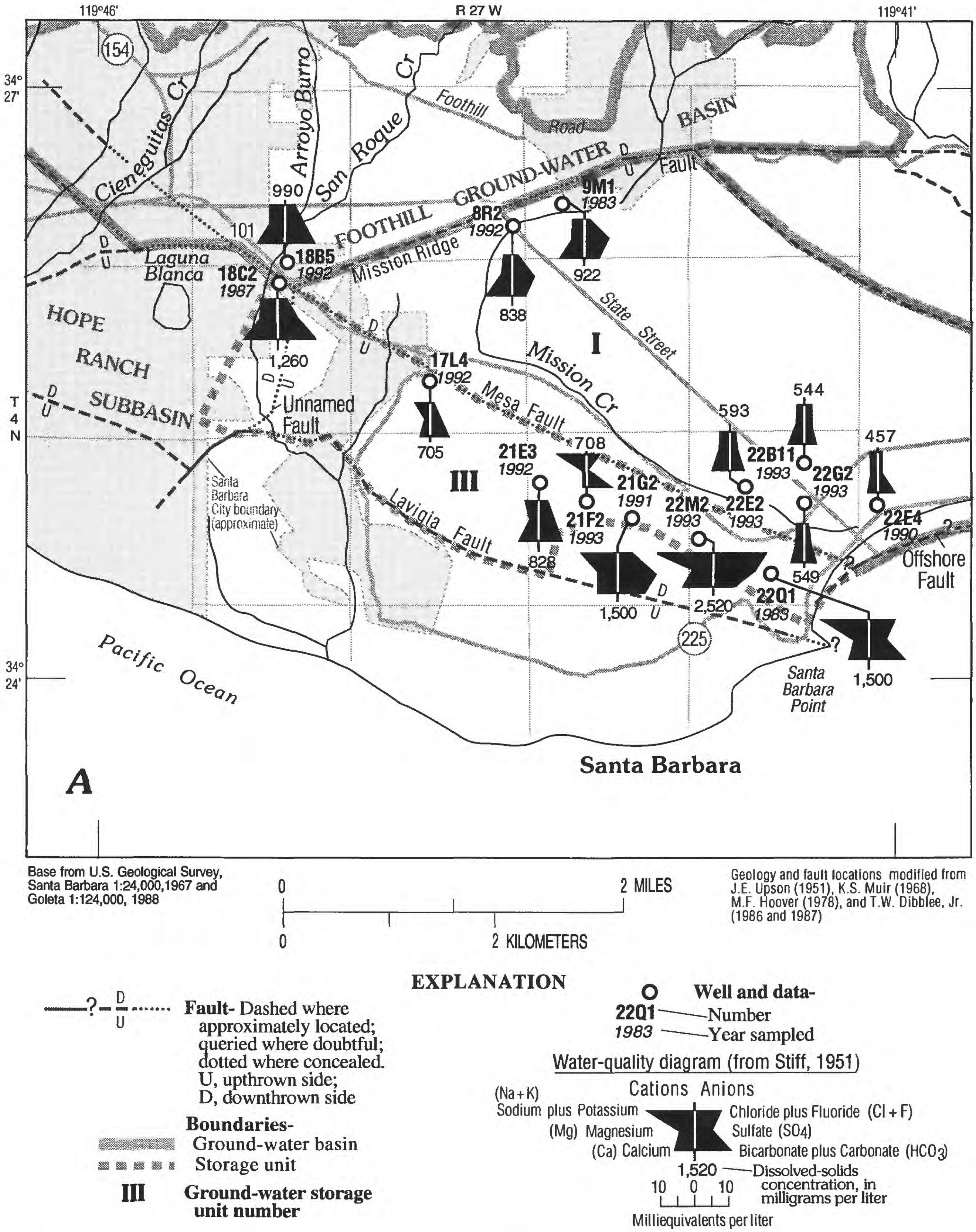


Figure 10. Chemical quality of water from selected Storage Unit III, Storage Unit I, Hope Ranch subbasin, and Foothill basin wells in the shallow and upper producing zones *(A)*; the lower producing zone *(B)*; and, the deep zone and Tertiary rocks *(C)*.

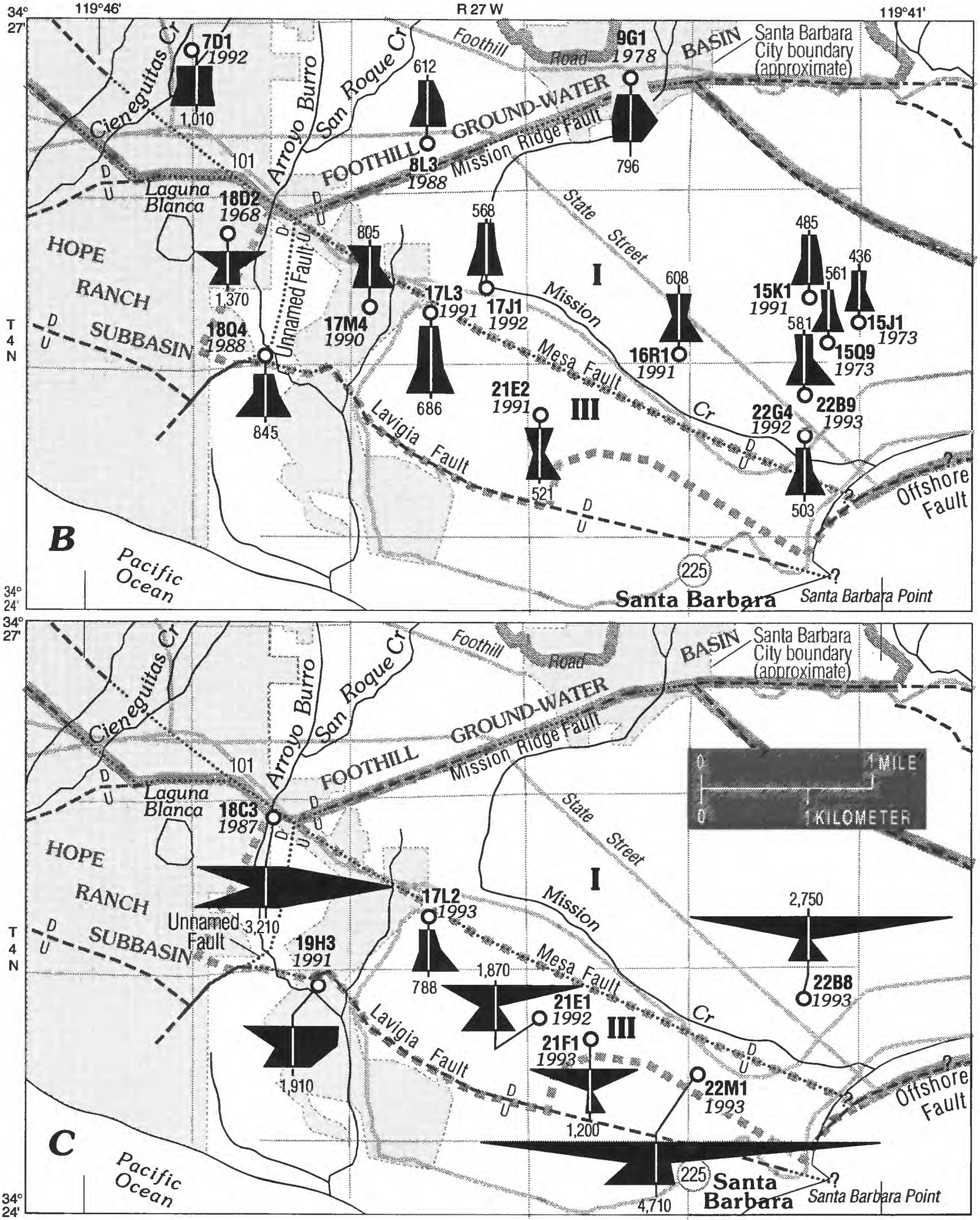


Figure 10. Continued.

Storage Unit III was lower than that in all available samples from the shallow and upper producing zones in surrounding upgradient areas (fig. 10*A*). These results indicate that underflow from adjacent storage units or basins cannot be the sole source of recharge to Storage Unit III.

Lower Producing Zone

Four of the sampled wells in Storage Unit III (4N/27W-17L3, -17M4, -18Q4, and -21E2) (fig. 10*B*) are in the lower producing zone. Dissolved-solids concentrations in samples from these wells ranged from 521 to 845 mg/L (table 3). The highest dissolved-solids concentrations were in samples from production wells 4N/27W-17M4 and -18Q4 (805 and 845 mg/L, respectively), which are perforated opposite most of the saturated thickness of the aquifer (see table 3 for zones) and undoubtedly obtain some water from other water-bearing zones. Wells 4N/27W-17L3 and -21E2 are monitor wells that are perforated solely opposite the lower producing zone, and samples from these wells best describe the water-quality characteristics of the lower producing zone in Storage Unit III. This major water-producing zone potentially may be degraded by upward migration of poor-quality water from the underlying deep zone and Tertiary rocks caused by poor well construction or heavy localized pumping.

The sample from well 4N/27W-17L3 in the northwestern part of Storage Unit III is similar in chemical character and dissolved-solids concentration (686 mg/L) to samples from the upper producing zone in this part of the storage unit, indicating similar sources of water. The dissolved-solids concentration of a sample from well 4N/27W-17J1 in Storage Unit I, less than 0.5 mi northeast of well 17L3, was 568 mg/L. The difference in dissolved-solids concentration suggests that ground water does not move freely across the Mesa Fault. The sample from well 4N/27W-21E2 in the eastern edge of the upper producing zone in Storage Unit III, however, is more similar in chemical character and dissolved-solids concentration (521 mg/L) to samples from the lower producing zone in Storage Unit I. Runoff along Arroyo Burro probably is not the source of water to this part of Storage Unit III.

Deep Zone and Tertiary Rocks

Prior to this study, no wells were perforated solely opposite the deep zone or the underlying Tertiary rocks in Storage Unit III because well yields are relatively low and the water quality is generally poor. As part of this study, four monitor wells (4N/27W-17L2, -21E1, -21F1, and -22M1) at separate cluster well sites (fig. 10*C*) were constructed opposite the deep zone or Tertiary rocks in Storage Unit III, and three wells (4N/27W-19A1, A2, A3) were constructed at a single cluster site (fig. 4) south of the storage unit .

The deep zone is monitored at two of the cluster-well sites (4N/27W-17L2, and -21E1) in the inland part of Storage Unit III. The dissolved-solids concentrations of samples from these wells were higher than the concentrations in samples from the overlying lower producing zone at the same sites. The concentration of dissolved-solids in the sample from well 4N/27W -17L2 was 788 mg/L, about 100 mg/L higher than the concentration in the sample from well 4N/27W-17L3, and the samples were similar in chemical character. The dissolved-solids concentration of the sample from well 4N/27W-21E1 was 1,870 mg/L, more than 1,000 mg/L higher than the concentration in the sample from the lower producing zone at the same site. Sodium and chloride are the predominant ions in the sample from the deep zone (fig. 10*C*), indicating that water from the underlying Tertiary rocks may be a source of water to the deep zone in this part of the storage unit.

Water level and water quality in the Tertiary rocks are monitored at two cluster-well sites (4N/27W -21F1 and -22M1) in the coastal part of Storage Unit III (fig. 10*C*). The logs from both wells indicate that the wells are perforated opposite shale. The dissolved-solids concentration in the samples ranged from 1,200 mg/L in well 21F1 to 4,710 mg/L in well 22M1. Sodium and chloride were the predominant ions in the samples from both wells.

Hydraulic Effects of Faults

Vertical displacement along the faults in Storage Unit III probably has offset the older permeable water-bearing strata (older alluvium and the Santa Barbara Formation), possibly juxtaposing them opposite less permeable deposits (fig. 5). This displacement, along with cementation, can create low-permeability zones that greatly retard the interbasin flow of ground water across the faults as well as basin discharge across the faults. Other factors contributing to the barrier effect of faults are compaction and extreme deformation of the water-bearing deposits adjacent to the faults. All these factors may affect the water-transmitting properties of faults in the study area. Although some water can be transmitted across these relatively impermeable fault zones, appreciable quantities can be transmitted only where steep hydraulic gradients exist (Upson, 1951, p. 95). Younger alluvium, which probably is unfaulted along stream channels such as Arroyo Burro, is thought to serve as a means for ground water to flow freely across fault boundaries into and out of Storage Unit III.

In the Santa Barbara area, faults also are inferred on the basis of lack of transmission of pumping effects (Upson, 1951, p. 27) and on differences in water quality among Storage Unit I, Storage Unit III, and the Foothill basin (Freckleton, 1989, p. 19). Although well 4N/27W-18L1 west of the unnamed fault (fig. 4) is known to have been in operation during 1987, pumping effects are not apparent in the hydrographs (fig. 9) for well 4N/27W-18Q1 about 1,800 ft to the southeast (east of the fault) and well 4N/27W-18Q4 about 1,800 ft to the south (also east of the fault) in Storage Unit III.

From July 1978 to January 1980, water levels and water quality were monitored as part of a basin-testing program to evaluate the effects of pumping in Storage Unit I. Results of the testing indicate that the Mesa Fault is a barrier to ground-water movement between Storage Units I and III (Martin, 1984, p. 13). However, additional aquifer tests could provide data to better estimate both fault location and fault conductance. In addition, in this and other studies (Martin and Berenbrock, 1986, Freckleton, 1989), numerical models have been used to evaluate the effects of faults on the horizontal flow of ground water. Results of the model evaluation done in this study are described in the "Flow Model" section of this report, which follows.

FLOW MODEL

The mathematical representation of Storage Unit III has been incorporated into an areawide numerical flow model that includes the Foothill basin model (Freckleton, 1989, p. 24) and the Storage Unit I model (Martin and Berenbrock, 1986, p. 16) using horizontal flow barriers (Hsieh and Freckleton, 1993) discussed later in this report. A numerical flow model—which is based on known and estimated physical and hydrologic characteristics for a ground-water system, including system stresses—calculates the approximate hydraulic-head distribution and fluxes in the flow system. The physical characteristics of the study area are the boundaries of the basin, the initial hydraulic-head distribution (for the transient model), and the types, location, and quantities of recharge and discharge (system stresses). Hydrologic characteristics simulated for the study area include those that reflect the ability of the system to transmit water (transmissivity); to store and release water (storage coefficient and specific yield); to conduct water in drains simulating head-dependent boundaries (drain conductance); to allow for the vertical passage of water between model layers (vertical conductance); and to control the flow of water across fault boundaries (hydraulic characteristic and general-head boundary conductance).

The FORTRAN-based modular computer code used for this study was developed by McDonald and Harbaugh (1988). In this code, a governing partial differential equation for ground-water flow is approximated by finite-difference equations that are solved over a network composed of rectangular blocks (or cells) 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. Major options required for simulation and for solution in the numerical model are referred to as "packages" (McDonald and Harbaugh, 1988, p. 3–20) and, for this study, include the Basic (includes input and output procedures), Block-Centered Flow, Well, Recharge, Drain, General-Head Boundary, and Strongly Implicit Procedure Packages. An additional package (not included by McDonald and Harbaugh, 1988) is the Horizontal-Flow-Barrier Package (Hsieh and Freckleton, 1993), which is used to simulate faults that form boundaries between components of the flow system.

Assumptions

A numerical model is only an approximation of the natural system because not all the characteristics of the natural system can be included in sufficient detail for an exact representation. Simplifying assumptions are required to make the problem manageable. Some of the more important simplifying assumptions made for the areawide numerical model are:

- The aquifer system can be represented by two model layers. Although there are numerous layers, with widely varying hydraulic properties, in the formations that compose the principal aquifers in the Santa Barbara area, the separate layers generally are too thin and discontinuous to simulate individually. Therefore, for the basin-scale analysis, it was assumed that the combined effect of the numerous actual physical layers could be grouped into one or two model layers, each representing a homogeneous porous medium. In the Foothill basin and Storage Unit I, two model layers are used where a locally thick, extensive, low-permeability zone separates the major water-bearing units. In Storage Unit III, two model layers are used to simulate the upper (layer 1) and lower (layer 2) producing zones (zones 2 and 4, respectively) in the inland part of the storage unit. In addition, layer 1 in Storage Unit III is used to model the shallow zone of the coastal part. These discretizations were based on examination of drillers' logs and geophysical logs obtained for this study, and on data from previous studies (Freckleton, 1989, p. 25; Martin and Berenbrock, 1986, p. 16-17). Extrapolation of existing data to areas lacking data was done on the basis of geohydrologic interpretation.
- Ground-water movement within a layer is horizontal, and movement between layers is vertical. This assumption is a consequence of the gross vertical discretization used in the model (McDonald and Harbaugh, 1988, chap. 2, p. 31). Although ground-water flow generally is neither fully horizontal nor fully vertical in the actual system, this assumption is adequately representative of the large-scale flow regime.
- The water-bearing layers are horizontally isotropic. Isotropy refers to the property of a medium to exhibit no directional preference in a physical process, such as the conductance of flowing water. Isotropic characteristics are difficult to determine in real-world systems owing to the complex nature of aquifer geometry and possible effects that can mask isotropy or emulate anisotropy (for example, antecedent potentiometric surfaces, or boundary effects). At present there are no data to suggest that large-scale anisotropies exist in the ground-water system of the area.
- Changes in ground-water storage in the model layers occur instantaneously with changes in hydraulic head. In most real-world systems there is a delayed response to storage changes as the various materials that make up an aquifer system release water at differing rates. The above assumption is a consequence of the numerical model used for this study, and within the time discretization used in this study it does not contribute significant error to this simulation.
- Transmissivity and storage coefficient do not change with water-level changes. In the study area the greatest water-level changes occur where there are confined conditions; therefore, the transmissivity in these areas does not change because the saturated thickness of the aquifer material does not change. In the unconfined areas of Storage Unit I, water-level changes are small in comparison with the total saturated thickness of the aquifer (Martin and Berenbrock, 1986, p. 20); therefore, there is little effect on transmissivity. In the unconfined areas of the Foothill basin and Storage Unit III, the most transmissive aquifer material lies near the bottom of the unconfined zones, and water-level changes near the tops of these zones do not significantly affect the aquifer transmissivity (Freckleton, 1989, p. 43). Historical data indicate that water levels had not declined below the low-permeability units that confine the aquifer system during periods when pumpage was greater than is expected for future basin operation. For this reason, it is assumed that storage coefficient in the model need not be changed in response to changing water levels.
- Recharge occurs instantaneously. This is a consequence of the numerical model, and it does not

significantly affect model-calculated heads for long-term simulations.

- The assumption that seawater intrusion has little or no effect on hydraulic head, which was adequate for the Storage Unit I model (Martin and Berenbrock, 1986, p. 16), has been superseded in this study. Specifically, freshwater-equivalent seawater heads have been placed along the coastal boundary at the offshore fault where it bounds Storage Units I and III. Density differences between freshwater and seawater cause seawater to have a greater hydraulic head, for a given elevation, than does freshwater. For example, to balance a seawater-freshwater interface at a depth of 400 ft below sea level, a freshwater head of 10 ft above sea level would be required.
- In Storage Unit I, specific-yield values, as well as stream-drain and recharge distributions, can be changed to reflect recent recalibration values and distributions (Peter Martin, U.S. Geological Survey, oral commun.,1991). The old values and distributions are given by Martin and Berenbrock (1986, fig. 5), and the current values and distributions are given (in fig. 12) in the "Boundaries" section of this report.
- Faults internal to the flow system (that is, not on boundaries) can be simulated adequately by horizontal-flow barriers (Hsieh and Freckleton, 1993) that impede the flow of ground water between Storage Unit III, Storage Unit I, and the Foothill basin. Faults in the area are steeply dipping or vertical and are known to affect both water levels and the transmission of pumping effects. These conditions, and the assumption of horizontal flow (second assumption), conform to the criteria described by Hsieh and Freckleton (1993) for modeling with horizontal-flow barriers.

Discretization

Discretization is the segmentation of a "continuous" medium, such as an aquifer or time, into a number of discrete parts. In this report, the aquifers are discretized spatially on the basis of data and geohydrologic interpretation (including simplification), and time is discretized on the basis of a monthly reporting schedule for water levels and pumpage. The backward finite-difference formulation used in this model is unconditionally stable in both space and time.

The areawide model is represented by a rectangular grid of 1,596 cells in 42 rows and 19 columns (fig. 11). Each side of a cell represents a distance of 1,000 ft in the physical system. The point at the geometric center of a model cell is referred to as a "node." Nodes are the locations at which the model calculates hydraulic heads. Cells and nodes are referenced by their location in the model network or "grid." For example, the designation 26,7,2 refers to the cell or node located at row 26, column 7, in layer 2. Layer 1 contains 300 active cells and layer 2 contains 365 active cells. In most areas, the active cells in the two layers overlap. The layering, cell spacing, and orientation of the areawide model correspond to those used by Martin and Berenbrock (1986, p. 17) for Storage Unit I and by Freckleton (1989, p. 32) for the Foothill basin.

Storage Unit III was discretized vertically as two layers: an upper layer and a lower layer (see first assumption in flow model "Assumptions" section). The upper layer (layer 1, representing the upper producing zone in the inland part and the shallow zone in the coastal part) consists of 48 active cells, and the lower layer (layer 2, representing the lower producing zone) consists of 45 active cells. Each cell in the model network that represents an active part of the flow system is assigned values of transmissivity and storage coefficient (or specific yield) for transient simulations and, where appropriate, drain conductance, vertical hydraulic conductivity, hydraulic characteristic of faults, and general-head boundary conductance. Model cells outside the flow system are inactive and are not assigned parameter values.

The geologic, hydraulic, and water-quality data indicate that little hydraulic communication occurs among Storage Unit I, Storage Unit III, and the Foothill basin. The communication is simulated by horizontal-flow barriers (Hsieh and Freckleton, 1993) which are used to combine the three areas into an areawide model. Horizontal-flow barriers are discussed in detail later in this report.

Temporal discretization consists of stress-period intervals 1 month in length. Stress period length refers

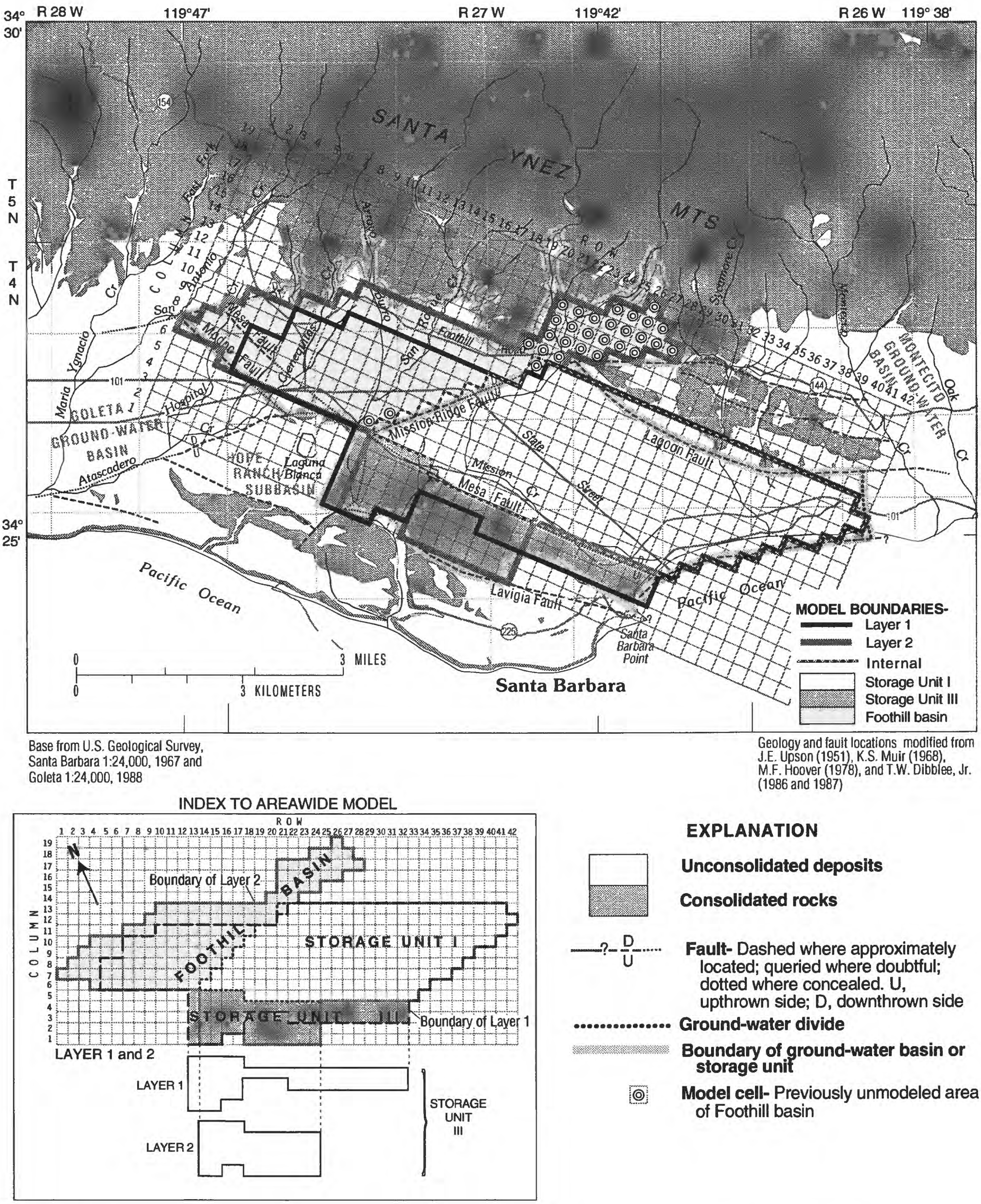


Figure 11. Model grid and generalized geology for the Santa Barbara and Foothill ground-water basins, California.

to the simulated period during which a model input, such as recharge quantity or discharge quantity, is held constant. The model calculates hydraulic heads at the end of each of the stress periods used in a simulation. A 1-month stress period was chosen to correspond to both the water-level monitoring network measurement interval and the period used by the major pumpers to report ground-water extractions.

Boundary Conditions

The following is a discussion of the types of boundary conditions used in the areawide model. These boundaries are described with respect to the modeled basin and subbasins. Special emphasis is placed on the boundaries of Storage Unit III. Additional information is given by Martin and Berenbrock (1986) for Storage Unit I and by Freckleton (1989) for the Foothill ground-water basin.

General Discussion of Boundary Conditions

The model boundaries were modeled as either specified flux or head dependent. Specified-flux boundaries include no-flow, stream-recharge, and areal-recharge boundaries. Head-dependent boundaries include drains, general-head boundaries, and horizontal-flow barriers. The boundaries are shown in figure 12, in which all boundaries are no-flow type, unless otherwise stated. The model boundaries coincide with physical boundaries of the flow system and were determined through analysis and interpretation of geologic and hydrologic data.

A no-flow boundary indicates that there is no exchange of water between the model cell and the domain outside the model. No-flow boundaries were used to simulate the lateral and bottom surfaces of the model that are in contact with consolidated rocks or barrier faults.

A specified-flux boundary indicates that water flows into or out of the model domain at a specified rate that remains constant for the entire stress period. Specified-flux boundaries were used to simulate flow into the model domain by stream and areal recharge.

Drain boundaries indicate that water is removed from the model domain at a rate proportional to the difference between the head in the domain and some fixed head or elevation, so long as the head in the domain is above that elevation; drain boundaries have no effect if head in the domain falls below that level (McDonald and Harbaugh, 1988). The constant of proportionality is termed the drain conductance whose value is determined during the calibration process. Drain boundaries were used to simulate outflow of ground water to streams or to dewatering drains installed by the city, and subsurface flow out of the basins.

A general-head boundary simulates a source of water outside the model area that either supplies to, or receives water from, adjacent cells at a rate proportional to the hydraulic-head differences between the source and the model cells (McDonald and Harbaugh, 1988). The constant of proportionality is the hydraulic conductance whose value is determined during the calibration process. A general-head boundary was used to simulate the coastal boundary of the model.

The horizontal-flow-barrier boundary simulates thin, vertical low-permeability geologic features that impede the horizontal flow of ground water. These geologic features are approximated as a series of horizontal-flow barriers conceptually situated on the boundaries between pairs of adjacent cells in the finite-difference grid (Hsieh and Freckleton, 1993). The flow across this boundary is proportional to the hydraulic-head difference between adjacent cells. The constant of proportionality is the hydraulic characteristic whose value is determined during the calibration process. This boundary type is used to simulate the Mission Ridge and Mesa Faults, and thus provides a method to combine model areas.

Lateral Boundaries

The northern boundary of Storage Unit I and of most of the Foothill basin is the contact between the unconsolidated, water-bearing deposits and the consolidated rocks of the Santa Ynez Mountains; this boundary is treated as a no-flow boundary (fig. 11). This definition includes an area of the Foothill basin not previously modeled by Freckleton (1989) (fig. 11). The northwestern boundary of the Foothill basin is the Goleta Fault (fig. 1); this boundary also is treated as a no-flow boundary. The southwestern boundary of the Foothill basin is formed by the Modoc, More Ranch, and Mesa Faults; these faults are treated as no-flow boundaries. The northwestern boundary of model layer 1 in Storage Unit III is the contact between the allu-

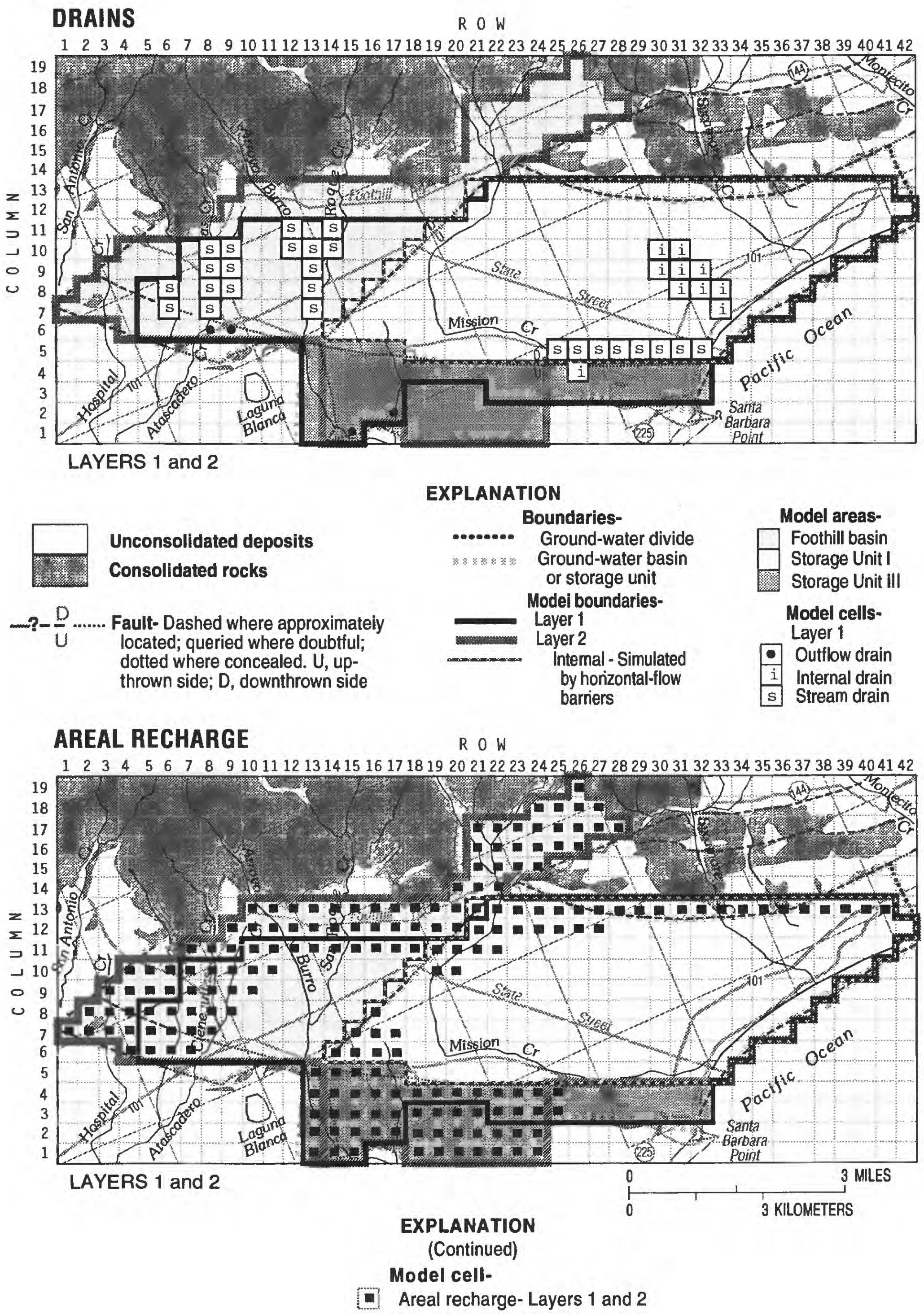


Figure 12. Drains, areal recharge, stream recharge, general-head boundary, and pumpage in layers 1 and 2, Santa Barbara County, California.

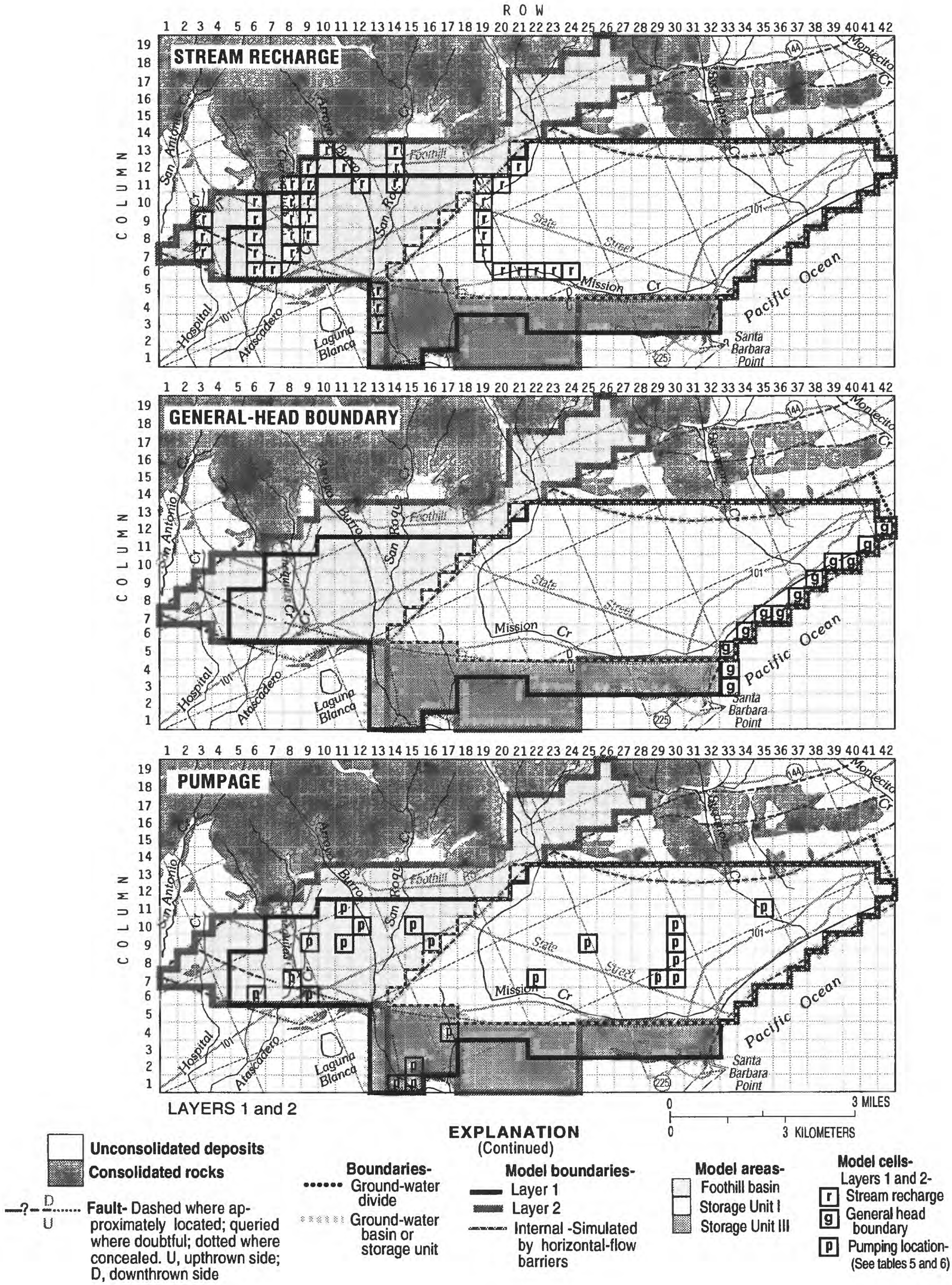


Figure 12. Continued.

vium and zone 3 (middle zone) of the Santa Barbara Formation in the Hope Ranch subbasin (section *A-A'* in fig. 5). This boundary is treated as a no-flow boundary because of the differences in permeability of these formations across the discontinuity. The northwestern boundary for model layer 2 in Storage Unit III is an unnamed fault (figs. 1 and 11) and is treated as no-flow boundary. The southern boundary of Storage Unit III is the Lavigia Fault and also is treated as a no-flow boundary. The southeastern boundary coincides with the offshore fault (figs. 1 and 11); this boundary is treated as a general-head boundary for layers 1 and 2 in Storage Unit I (Martin and Berenbrock, 1986) and for layer 1 in Storage Unit III. The external heads of this boundary are the freshwater equivalents of the seawater heads. The eastern boundary of Storage Unit I is the ground-water divide between Storage Unit I and the Montecito ground-water basin (fig. 1); this boundary is treated as a no-flow boundary in accordance with Martin and Berenbrock (1986).

The bottom boundary of the model is treated as a no-flow boundary. This boundary is formed by the contact between the aquifer and the underlying relatively impermeable deep zone of the Santa Barbara Formation or Tertiary rocks.

Horizontal-Flow-Barrier Boundaries

The Mission Ridge and Mesa Faults are modeled with the horizontal-flow-barrier boundary (figs. 11 and 12). The hydraulic characteristics for both faults were set to zero, thereby allowing zero flow across the faults. The barriers are not present for the part of the Mesa Fault in the Foothill basin and at the intersection of Arroyo Burro and both faults (the common boundary of the three modeled basins in layer 1) (fig. 12). The Mesa Fault is not modeled in the Foothill basin because analyses of water-level data indicated that the fault in this basin is not a barrier to flow. The barriers are not present at the intersection of Arroyo Burro and both faults reflecting the erosion, and subsequent deposition of permeable materials, across the fault boundary.

Specified-Flux Boundaries

Stream recharge was simulated as specified-flux boundaries for Hospital, Cieneguitas, and Atascadero Creeks, and for the upper reaches of Arroyo Burro and San Roque Creek in the Foothill basin; for the upper reach of Mission Creek in Storage Unit I; and for the lower reach of Arroyo Burro in Storage Unit III (fig. 12). Direct infiltration of precipitation and runoff from the surrounding hills is simulated as areal recharge. Areal recharge is distributed over areas of low urbanization in Storage Unit I and the Foothill basin as determined by Martin and Berenbrock (1986) and Freckleton (1989). Areal recharge in Storage Unit III is distributed over areas whose elevations are greater than 100 ft above sea level in accordance with Muir (1968).

Drain Boundaries

Stream drains were used to simulate ground-water discharge to the Hospital, Cieneguitas, Atascadero, and San Roque Creeks and Arroyo Burro in the Foothill basin; the lower reach of Mission Creek in Storage Unit I; and the lower reach of Arroyo Burro in Storage Unit III (fig. 12). Internal drains were used to simulate flow into manmade drains installed by the city of Santa Barbara in Storage Unit I (fig 12). An additional internal drain installed by the city of Santa Barbara (fig. 12) is located about 1,000 ft south of the Mesa Fault in Storage Unit III. Outflow drains are located at the confluence of Cieneguitas and Atascadero Creeks in the Foothill basin and at the places where Arroyo Burro and an unnamed stream leave Storage Unit III; these drains simulate ground-water underflow from the model domain.

Calibration

Calibration is a procedure by which selected model variables are adjusted within a reasonable range—under steady-state or transient-state conditions (or both)—in order to minimize the differences between simulated (computed) hydraulic heads and measured water levels and between simulated and measured fluxes. In this study, a transient calibration was done. In this calibration, model parameters were adjusted and values of recharge and discharge were estimated using a trial-and-error approach in Storage Unit III and additional areas not addressed by the previously developed Foothill basin and Storage Unit I models (Freckleton, 1989; Martin and Berenbrock, 1986). Details regarding the calibration procedure, including information on the specific model variables that were adjusted, and the historical periods chosen for the comparison of simulated and measured water levels, are discussed in subsequent sections of this report.

Calibration Procedure

Transient calibration of the areawide model involved adjusting transmissivity, vertical conductance, storage coefficient, distribution and quantities of recharge and natural discharge, general-head boundary conductance, drain conductance, and horizontal-flow-barrier hydraulic characteristic using a trial-and error approach. These adjustments were made primarily in the Storage Unit III area of the model and in the previously unmodeled area of the Foothill basin (fig. 11). The calibration method used for this report is the matching of simulated and measured hydrographs at selected wells. In addition, simulated potentiometric maps and measured heads for July 1990 (a period of relatively high pumpage) are used for calibration purposes. The period that was selected for transient calibration for the areawide model is 1978–92. The parameters resulting from the transient calibration were then tested under steady-state predevelopment conditions to ensure that the resulting steady-state water levels were physically reasonable.

The initial conditions that were chosen for the transient calibration were simulated steady-state hydraulic heads for Storage Unit I (Martin and Berenbrock, 1986), simulated 1978 hydraulic heads for the previously modeled areas of the Foothill basin (Freckleton, 1989), and measured and extrapolated hydraulic heads for Storage Unit III and the previously unmodeled area of the Foothill basin (fig. 13).

Pumpage data are available for the 1978–92 calibration period and generally are considered to be accurate; the data from metered supply wells such as 4N/27W-18Q4, which is operated by the city of Santa Barbara, are considered to be especially accurate. The monthly pumpages used in the transient model for 1978–92 are shown graphically in figure 14. Pumpage for each well in the model was assigned to the model node closest to the well's location. For those wells open to deposits represented by both model layers, pumpage was distributed to the layers in proportion to the perforated interval and to the transmissivity of the layers at the well nodes (table 4, at back of report).

Transmissivity values for Storage Unit I and the Foothill basin were unchanged from those of Martin and Berenbrock (1986) and Freckleton (1989). Transmissivities for the previously unmodeled area of the Foothill basin were assigned by extrapolation of nearby data values and by calibration. Transmissivity distributions for Storage Unit III were constructed using values estimated from aquifer tests, estimates of saturated thickness and hydraulic conductivity, and estimates made by extrapolating data (on the basis of geologic concepts, such as depositional environment) to areas lacking test data. For Storage Unit III, measured transmissivity values were available for only two wells (4N/27W-17M4 [model cell 17,4] and -18Q4 [model cell 14,1]); these measured values were 1,260 and 790 ft^2/d, respectively (Hoover and Associates, Inc., 1992). Model-calibrated transmissivities for these two well locations were about 1,200 and 800 ft^2/d, respectively (sum of transmissivities for layers 1 and 2). The calibrated distribution of transmissivities for the areawide model is shown in figure 15.

Vertical leakage between layers 1 and 2 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 the bed. The hydraulic conductivity, bed thickness, and cell area are typically lumped together into a single parameter termed vertical conductance. The vertical-conductance values for Storage Unit I and the Foothill basin are unchanged from those of Martin and Berenbrock (1986) and Freckleton (1989). In these basins the vertical conductance is proportional to the vertical hydraulic conductivity of the middle zone (confining unit) divided by the thickness of this zone. The middle zone, as a confining member, is absent in Storage Unit III (fig. 5); therefore, the vertical conductance is proportional to the harmonic mean of the hydraulic conductivity values of vertically adjacent nodes (MacDonald and Harbaugh, 1988). Vertical-conductance values for the previously unmodeled area of the Foothill basin were assigned by extrapolation of nearby data values and by calibration.

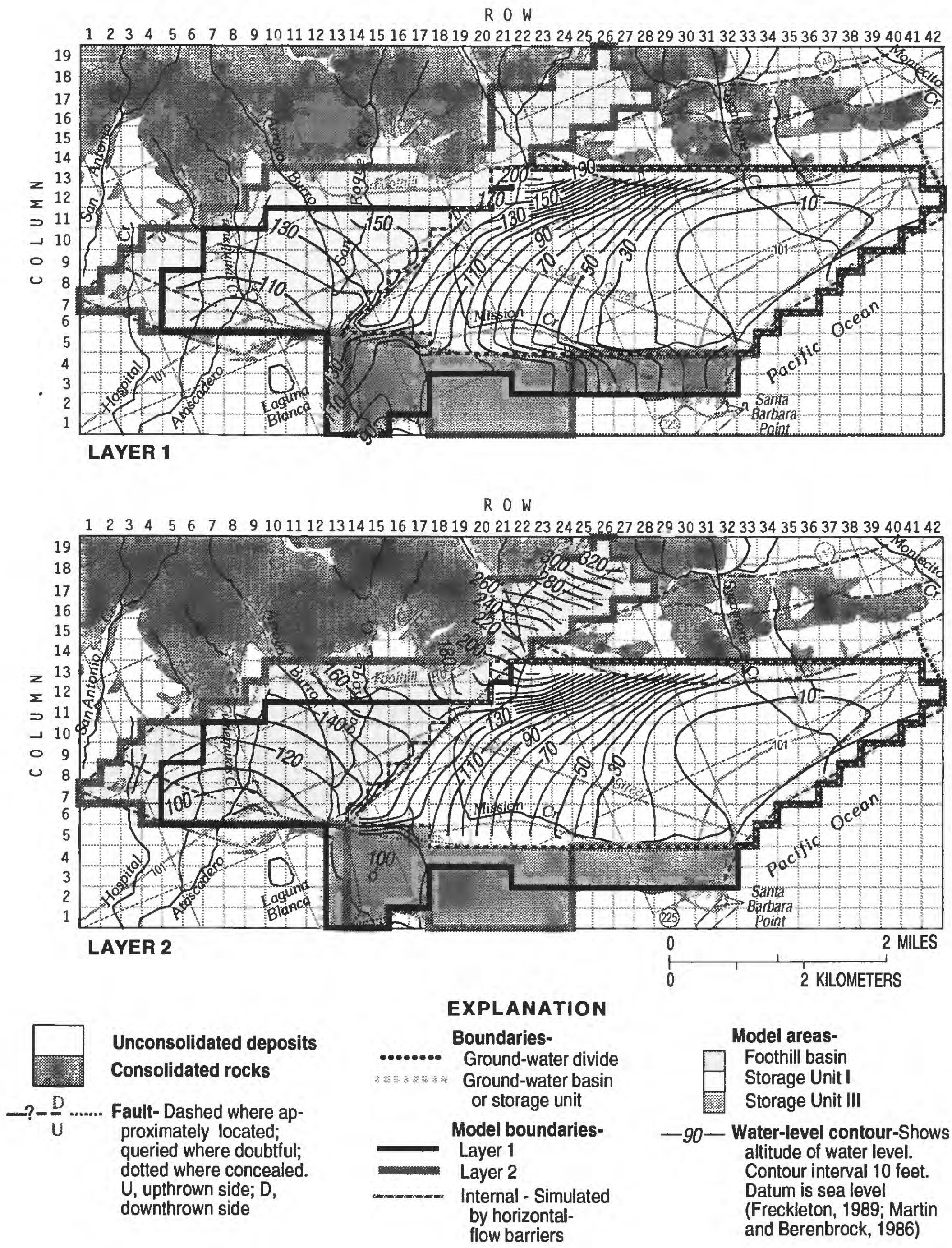


Figure 13. Simulated initial water-level contours, January 1978, Santa Barbara areawide model.

Vertical conductance in Storage Unit III was determined by estimating the thickness between model-layer nodes using geophysical and geologic logs and geologic sections (fig. 5), along with estimates of vertical hydraulic conductivity (initially one-tenth to one-hundredth of the horizontal hydraulic conductivity of 3.88 ft/d cited earlier in this report). The model uses the quantity "Vcont" or "vertical leakance" as input. Vcont is the vertical conductance divided by the cell area. The calibrated distribution of Vcont values for the areawide model is shown in figure 16.

Storage-coefficient values for Storage Unit I and the Foothill basin were relatively unchanged from those of Martin and Berenbrock (1986) and Freckleton (1989). Storage-coefficient data are sparse for Storage Unit III and for the previously unmodeled area of the Foothill basin; therefore, estimates of storage coefficient were derived mainly by geohydrologic interpretation (such as analysis of the depositional environment), by extrapolation of nearby data values, and by calibration. The calibrated distribution of storage-coefficient values used in the areawide model is shown in figure 17.

Constant recharge is used throughout the transient calibration because the ground-water system in the Santa Barbara area is more sensitive to the temporal distribution of pumping than to the temporal distribution of recharge (Martin and Berenbrock, 1986, p. 44). The ground-water system's relative insensitivity to the temporal distribution of recharge probably is due to a combination of the vertical distance recharge must travel through the unsaturated zone and the particle size of the material traversed, both of which tend to dampen individual recharge pulses into a steady rate at depth. This behavior is consistent with the work of Bouwer (1982), who found that deep percolation reaches virtually steady uniform flow in a distance on the order of 50 to 100 ft and that downward velocities in the vadose zone decrease with decreasing particle size of the materials.

The simulated stream-recharge values at the end of the transient simulation for Storage Unit I, the Foothill basin, and Storage Unit III are presented in table 5 (at back of report) and the boundary is shown in figure 12. The stream recharge for Storage Unit I was increased by 46 acre-ft/yr from the value used by Martin and Berenbrock (1986) to reflect new data collected by McFadden and others (1991). The stream recharge

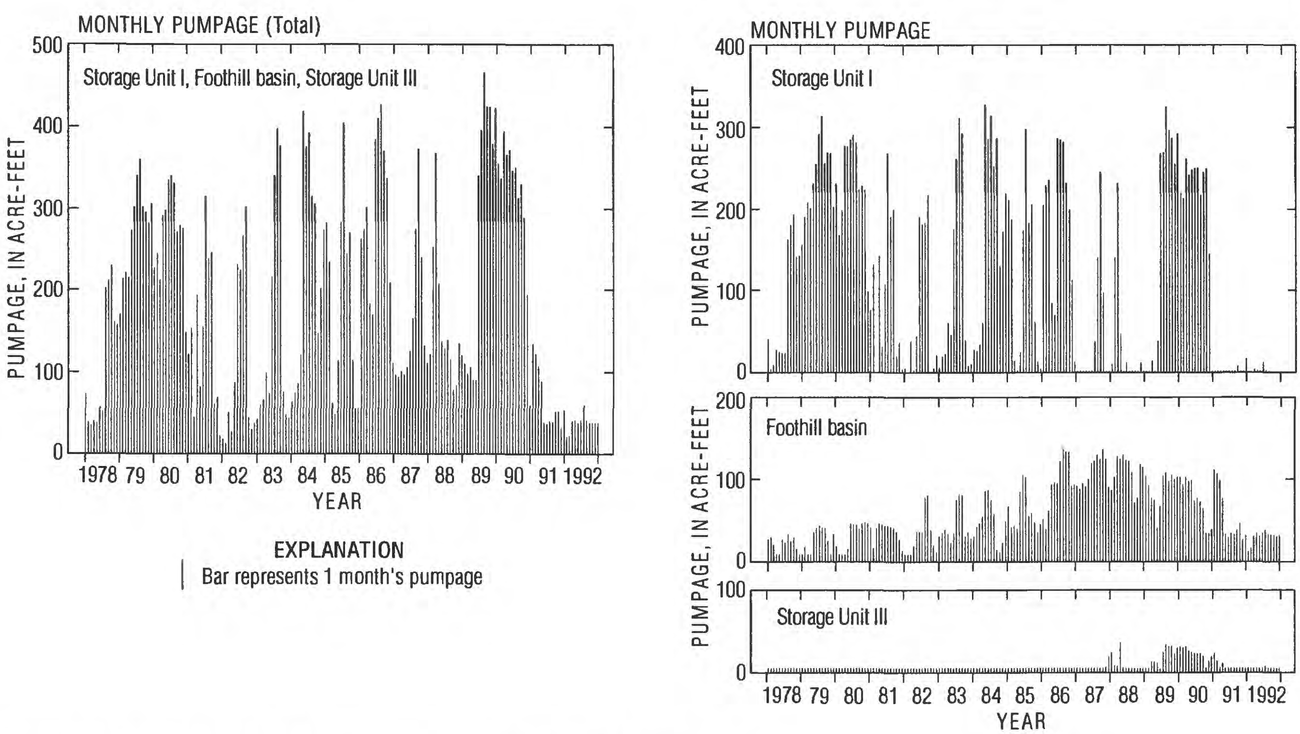


Figure 14. Pumpages used in the Santa Barbara areawide model, 1978–92.

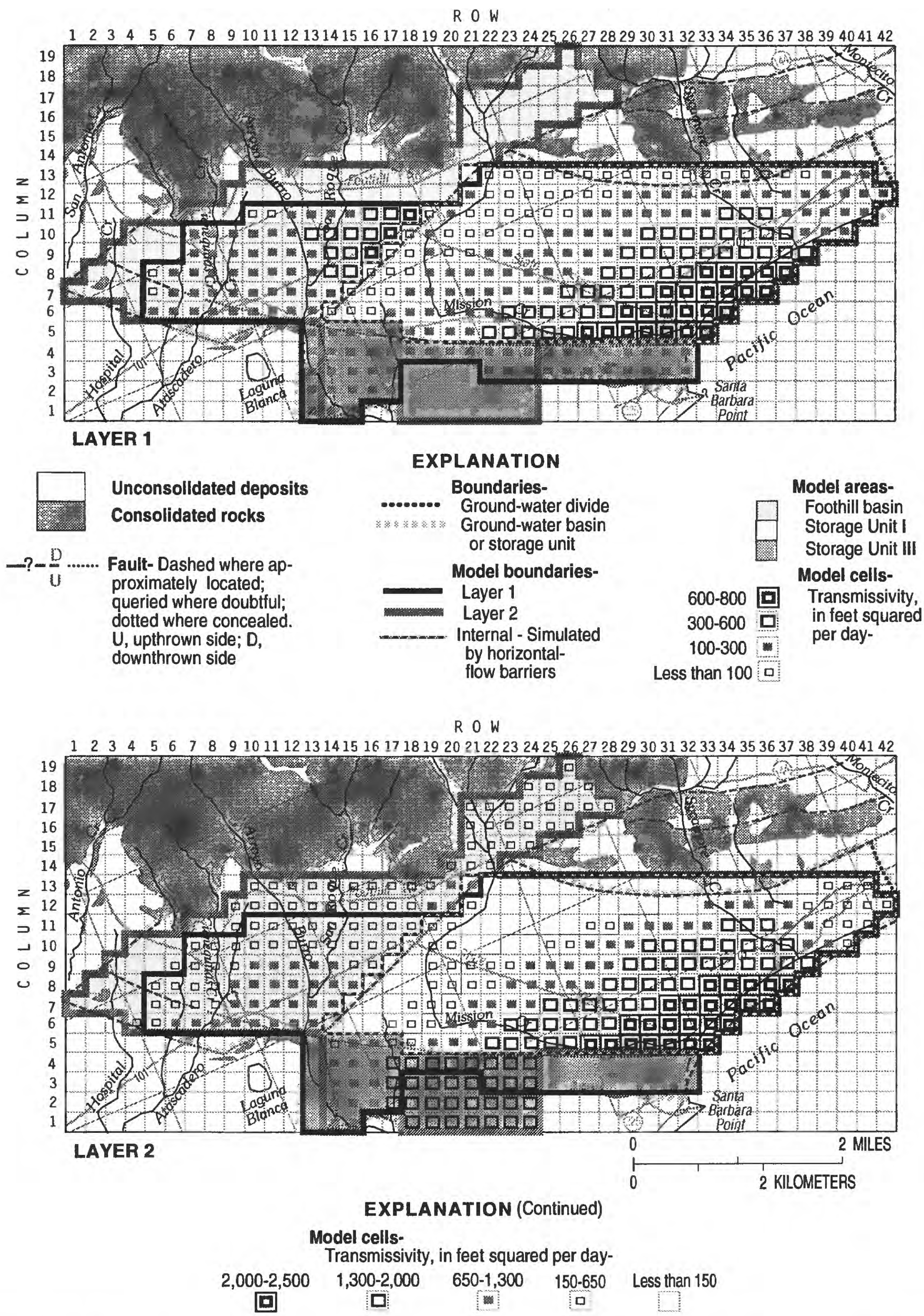


Figure 15. Transmissivity distribution for layers 1 and 2 in the calibrated Santa Barbara areawide model.

for Foothill basin was reduced by 18 acre-ft/yr from the value used by Freckleton (1989) to reflect the concrete lining of the lower reach of Arroyo Burro. Stream-recharge values for Storage Unit III presented earlier in this report were used as initial values for the calibration procedure. A total of 60 acre-ft/yr was used for layer 1 in the Storage Unit III area of the model.

The simulated areal recharge from the direct infiltration of precipitation and runoff from the surrounding hills at the end of the transient simulation is presented in table 5 and the boundary is shown in figure 12. The areal-recharge value for Storage Unit I was increased by 20 acre-ft/yr from the value used by Martin and Berenbrock (1986). The areal-recharge value for Foothill basin was increased by 73 acre-ft/yr from the value used by Freckleton (1989) to account for the previously unmodeled area. The calibrated average annual areal recharge in Storage Unit III for layers 1 and 2 was estimated to be 124 acre-ft/yr. Although this is less than that estimated in the recharge and discharge section of this report (160 acre-ft/yr), it is consistent with an expected reduction of recharge owing to increased urban and commercial development in the area subsequent to the study (Muir, 1968) on which the 160 acre-ft/yr estimate is based.

The offshore fault is modeled as a general-head boundary. As stated earlier, a general-head boundary simulates a source of water outside the model area that either supplies water to, or receives water from, adjacent cells at a rate proportional to the hydraulic-head differences between the source and model cell (McDonald and Harbaugh, 1988). The simulated inflow/outflow values for the general-head boundary at the end of the transient simulation are presented in table 5 and the boundary is shown in figure 12. The Storage Unit I conductance of 0.4×10^{-2} ft²/s was unchanged from that of Martin and Berenbrock (1986). The model-calibrated conductance in Storage Unit III is 0.4×10^{-1} ft²/s. The difference in values reflects the differences in materials and thickness of the formation at this boundary—that is, differences between the shallow zone in Storage Unit III and the upper and lower

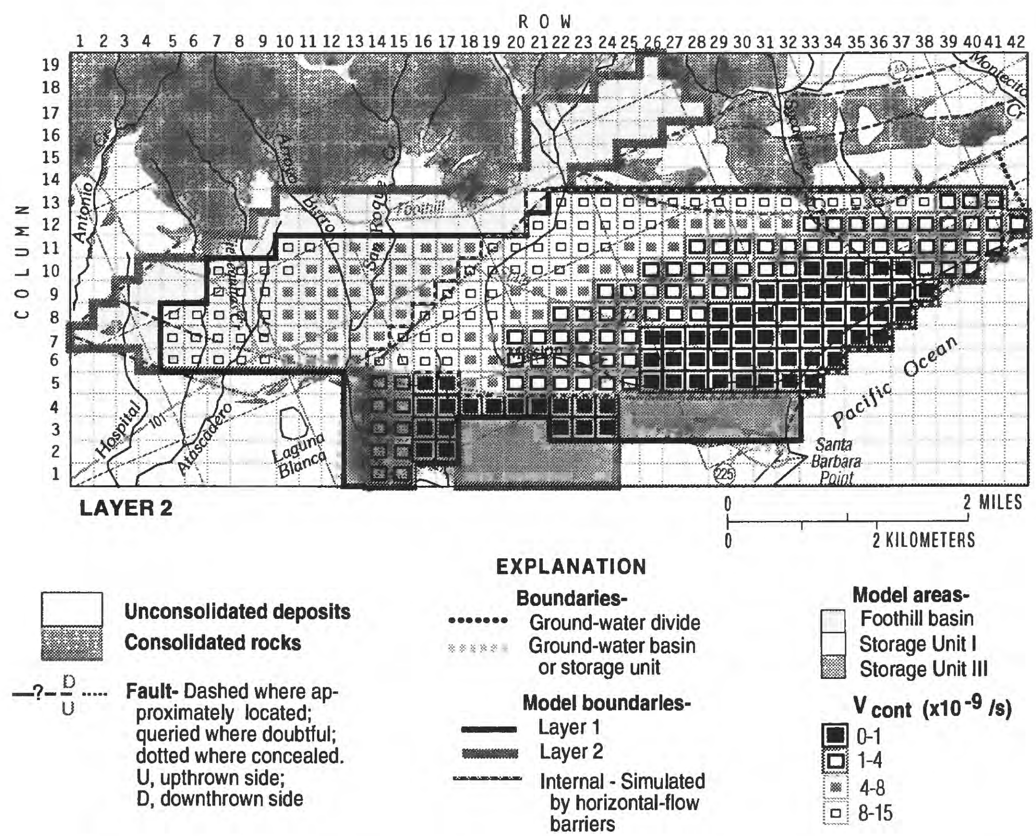


Figure 16. Calibrated distribution of Vcont (vertical conductance divided by the cell area) in the Santa Barbara areawide model.

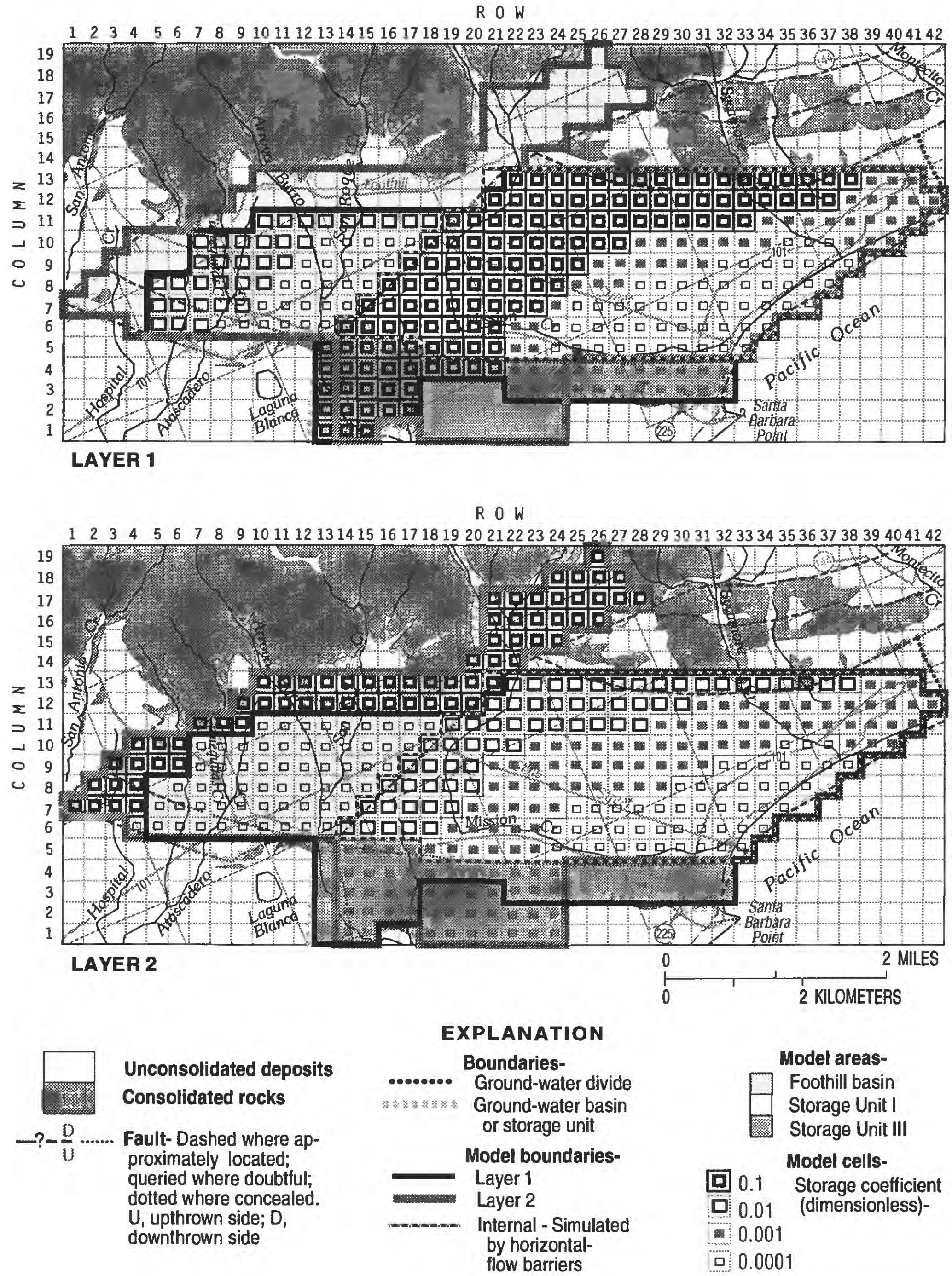


Figure 17. Storage-coefficient distribution for layers 1 and 2 in the calibrated Santa Barbara areawide model.

producing zones in Storage Unit I. The hydraulic head external to the boundary (seawater) is set equal to its freshwater-equivalent value. The freshwater-equivalent head for this study was calculated by dividing the depth below sea level to the centers of the upper and lower producing zones (model layers 1 and 2, respectively) by 40 (Bear, 1979, p. 384-385) at each of the general-head boundary cells (table 6, at back of report).

The simulated drain discharges at the end of the transient simulation from Storage Unit I, the Foothill basin, and Storage Unit III are presented in table 5 and the boundary is shown on figure 12. Recall that flow from drains is dependent on the drain conductance and head differences between the drain and the aquifer. Drain-conductance values and elevations for Storage Unit I and the Foothill basin were unchanged from those of Martin and Berenbrock (1986) and Freckleton (1989). However, eight stream drains were added to Storage Unit I to simulate ground-water discharge to the lower reach of Mission Creek (fig. 12). In addition, a drain previously used to simulate discharge from the Foothill basin [current model cell (13,6,1)] is now removed from the model. Drains were used in Storage Unit III to simulate subsurface outflow through unfaulted younger alluvium at the points where Arroyo Burro and the channel of an unnamed stream cross the Lavigia Fault (nodes 15,1,1 and 17,2,1, respectively, fig. 12). An internal drain (not on a boundary) at node 26,4,1 was used to simulate an underground sewer drain that captures ground water. Stream drain elevations were determined from contour maps (interval 5 feet) and represent the creekbed altitudes at the model nodes. Elevation values for the internal sewer drain were provided by the city of Santa Barbara (John Henry, oral commun., 1995). Drain conductances of the outflow drains were adjusted during calibration to control the quantity of outflow, which in turn affects basinwide water levels. Calibrated drain conductance is 5.0×10^{-3} ft^2/s for the outflow drains in Storage Unit III and 0.10 ft^2/s for the internal drain; these values are the same as those for similar drains in Storage Unit I and the Foothill basin.

The simulated interbasin flow between Storage Unit I and the Foothill basin and between the Foothill basin and Storage Unit III at the intersections of Arroyo Burro with the Mission Ridge and Mesa Faults at the end of the transient simulation is given in table 5. Recall that these faults are simulated using horizontal-flow barriers, and that the flow is controlled by the hydraulic characteristic. The hydraulic characteristics of the barriers were set equal to 0.0 ft/s at all locations—except on the boundary between model cells 13,6,1 and 14,6,1 for the Mission Ridge Faults and 13,6,1 and 13,5,1 for the Mesa Fault, where the flow barriers are not present and ground-water flow in this area is governed in part by the conductances between these pairs of cells. This condition reflects the erosion, and subsequent deposition of permeable materials, across the fault boundary in this location.

Calibration Results

The simulated hydraulic heads and the corresponding measured water levels at selected wells in Storage Unit III, Storage Unit I, and the Foothill basin are shown in figure 18. The Storage Unit I and Foothill basin hydrographs show a reasonable fit, for the most part within 10 ft, between the simulated and measured water levels. In some cases, however, greater differences may be caused by using average monthly pumpage. Martin and Berenbrock (1986) reported that the Storage Unit I model was very sensitive to pumpage and that using average weekly pumpage may be more appropriate than using average monthly values. In Storage Unit III, simulated water levels follow the trends of the measured water levels (fig. 18), and the differences between simulated and measured water levels generally are less than 10 ft. Note, however, the downward "spikes" in the measured water levels at wells 4N/27W-21G1 and -21G2 in Storage Unit III; the spikes are due to pumping that results in water-level decline at these wells during sampling for water quality.

The simulated July 1990 and measured water levels at selected wells are shown in figure 19. These data reflect the effects of the greatest amount of pumping for the simulation period (fig. 14). The effects of this pumping are shown clearly in figure 19 by the low water levels in the vicinity of the city's major pumping wells in Storage Unit I and the Foothill basin. The simulated water levels in the Foothill basin show the effects of the drain-simulated outflow from this basin between Cieneguitas and Atascadero Creeks (fig. 19) at the Modoc Fault (fig. 11). A comparison of the water-level contours, for layers 1 and 2, indicates that flow is lower than for the initial conditions because of greater pumping in this basin. In addition, the flow in the areas where Arroyo Burro crosses the Mesa and Mission Ridge Faults, as indicated by the lower elevations of the water-level contours (fig. 11), can be clearly seen in figure 19; discharge in this area is lower than for the initial conditions because the pumping in this simulation has changed the flow field. This pumpage directs local flow away from this discharge area. It should be noted that these simulated water levels are a "snapshot" in time and do not reflect the transient nature of the

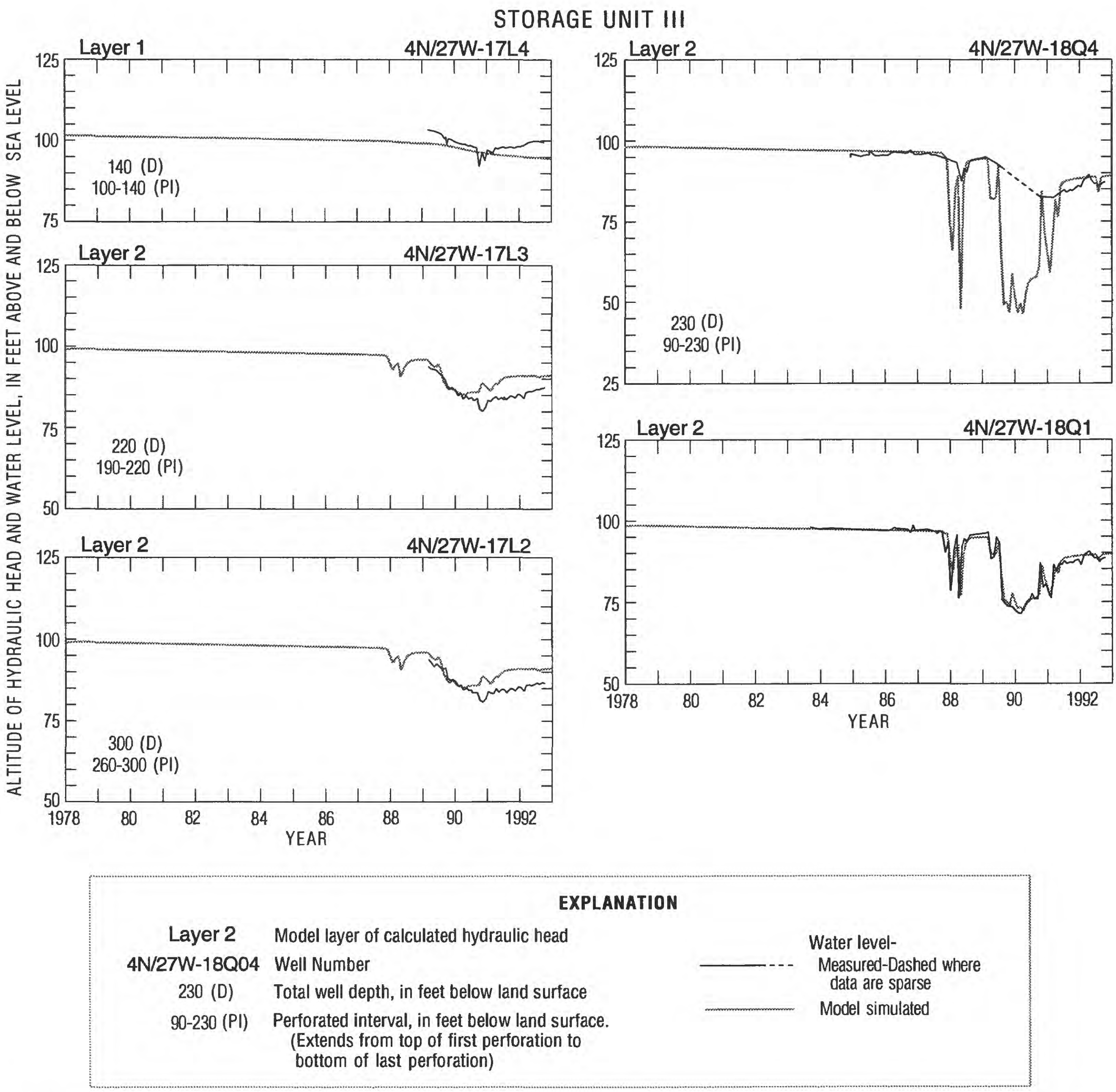
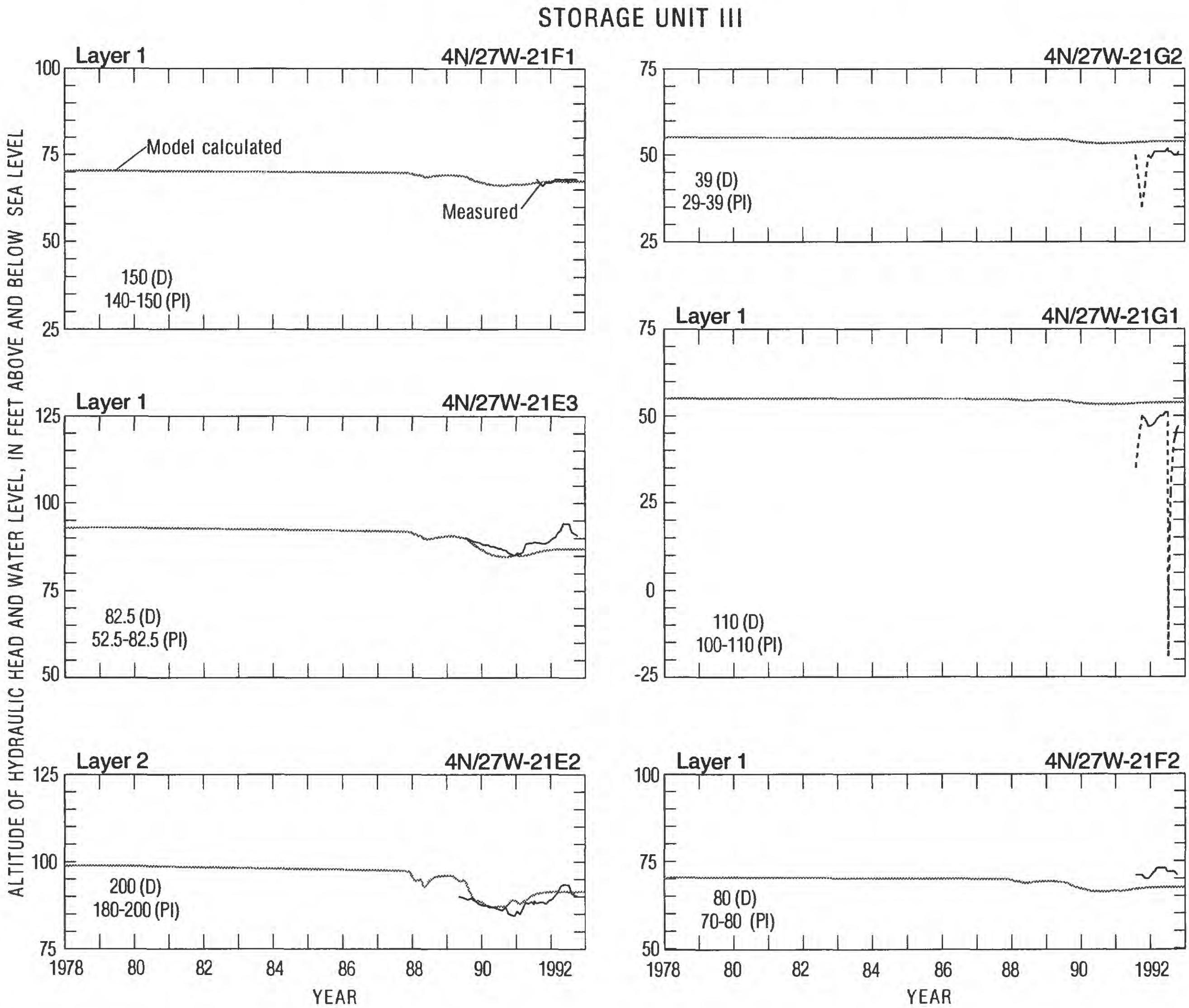


Figure 18. Model-calculated hydraulic heads and measured water levels for selected Storage Unit III, Storage Unit I, and Foothill basin wells, Santa Barbara County.

stresses on the systems; therefore, these data should be analyzed in conjunction with the previously mentioned hydrographs (fig. 18).

Although water levels in 1978 were selected as initial conditions (fig. 13), it also was recognized that pumping was occurring during 1978 in all three component basins of the areawide flow system. Furthermore, because the calibration of certain model parameters was based on that time period (1978–90), it was necessary to assess the model's response to the nonpumping conditions that would exist during a steady-state condition. Observing the model's response during nonpumping conditions (turning pumpage off in the model) ensures that model parameters obtained by calibration adjustments for 1978 conditions do not cause water levels to rise above land surface in areas where the shallow aquifer is unconfined.

The simulated steady-state water levels under nonpumping conditions and historical high water levels (pre-1992) at selected wells are shown in figure 20. The use of historical high levels may be misleading



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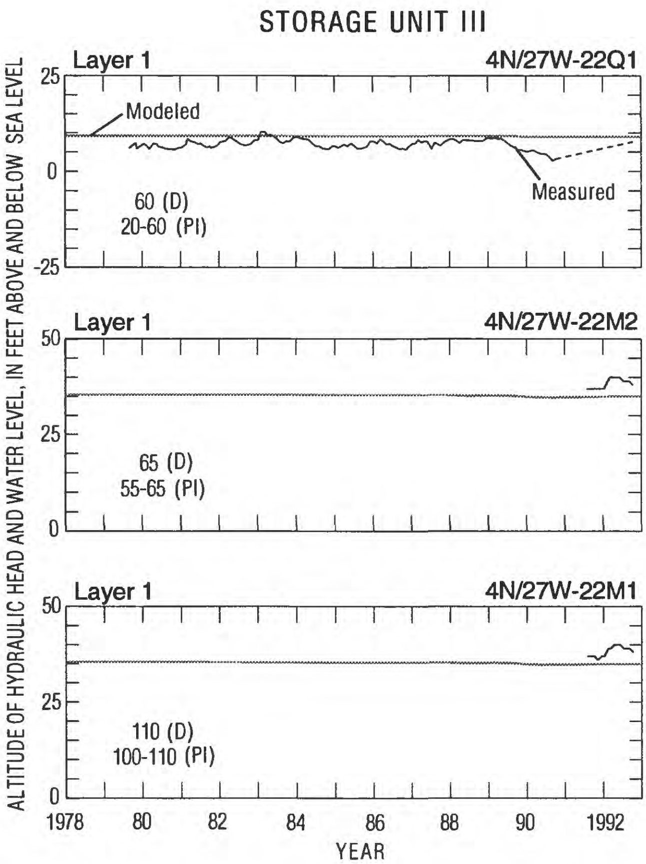

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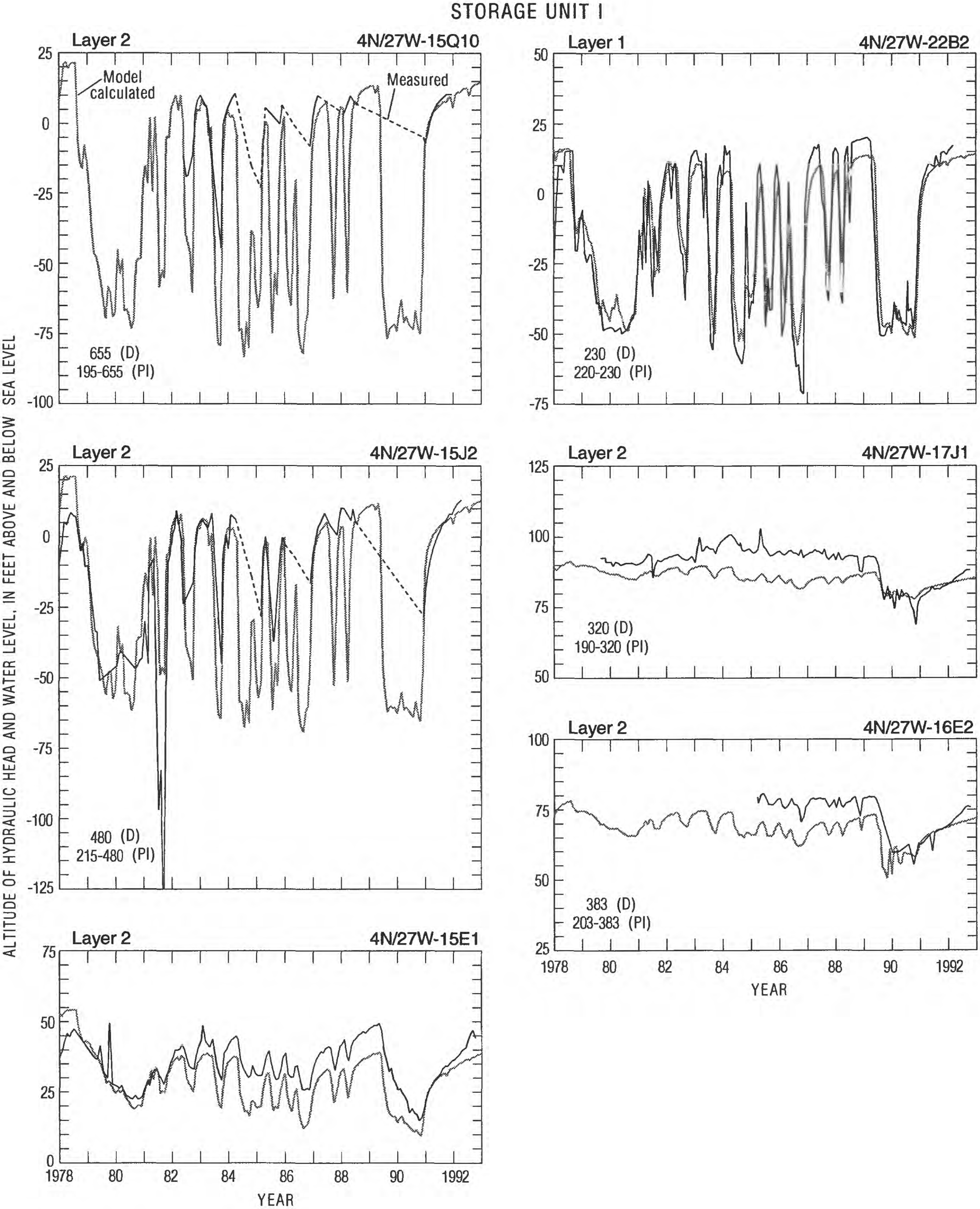
because, in many cases, these water levels reflect the influence of pumping conditions in the aquifers and, therefore, the aquifers may not have recovered fully from any pumping that might have occurred. In general, this leads to simulated water levels that are higher than the measured historical high levels in both model layers (fig. 20). In Storage Unit I, the simulated water levels are higher than the measured historical high levels in both model layers. The fit is better upgradient of well 4N/27W-15E2 because of the relative lack of pumping in this area. In the Foothill basin, the simulated water levels are higher than the measured historical high levels in both model layers. In Storage Unit III, the fit is fairly good in both layers, reflecting the lack of significant pumping in this subbasin until later in time.

Simulated Hydrologic Budgets

The simulated water budgets are presented for steady-state conditions (table 7, at back of report) and for two transient periods: stress period 151 (July 1990), a period of heavy pumping, and stress period 180 (December 1992), the end of the transient simulation (tables 8, at back of report and 5, respectively). Recall that for all simulations, stream and areal recharge are input parameters and are held constant and that pumpage is based on historical data. The model simulates the inflows to and outflows from the general-head boundary, interbasin flow, flow to drains, and flow to and from storage.

For the steady-state simulation, the total recharge is 2,031 acre-ft and the total discharge is 2,032 acre-ft (table 7); these values should be equal under steady-state conditions. The small difference is a result of roundoff error. The simulated steady-state water budget indicates that a total of 1,699 acre-ft is discharged from drains and 311 acre-ft is discharged from the general-head boundary. The simulated steady-state recharge and discharge values will be compared with the values resulting from the transient simulation.

The total pumpage for stress period 151 (table 8, July 1990) is 4,234 acre-ft/yr (2,999 acre-ft/yr from Storage Unit I, 946 acre-ft/yr from the Foothill basin, and 289 acre-ft/yr from Storage Unit III). Stress period 151 (July, 1990) is a period of relatively high pumpage. This pumpage has resulted in decreased discharge from the drains and has reversed the net flow across the general-head boundary at the coast in comparison with steady-state conditions. The simulated water budget indicates that a total of 196 acre-ft/yr is discharged from drains (an 88-percent decrease from steady state); with no discharge occurring in Storage Unit I, 124 acre-ft/yr is discharged from the Foothill basin (an 87-percent decrease), and 72 acre-ft/yr is discharged from Storage Unit III (a 59-percent decrease). The simulated water budget further indicates that a net 884 acre-ft/yr is recharging Storage Unit I through the general-head boundary from the Pacific Ocean, whereas 287 acre-ft/yr is discharging through this boundary during steady-state conditions. Overall, these results indicate



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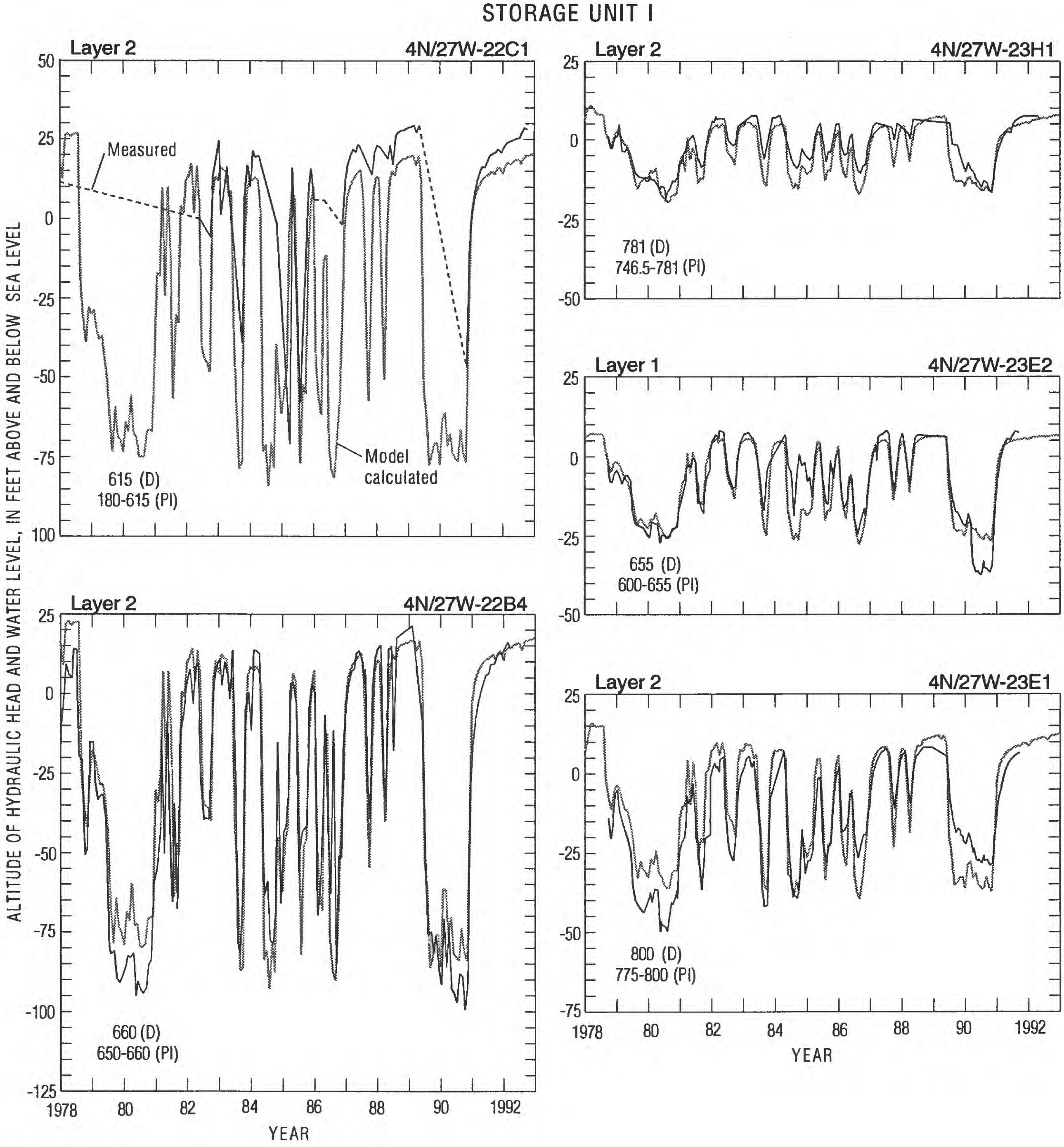

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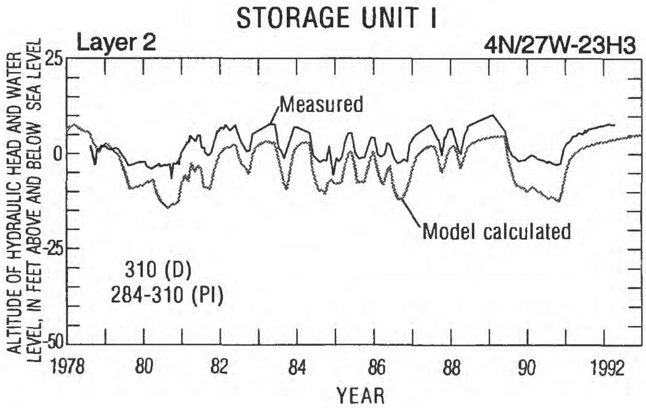
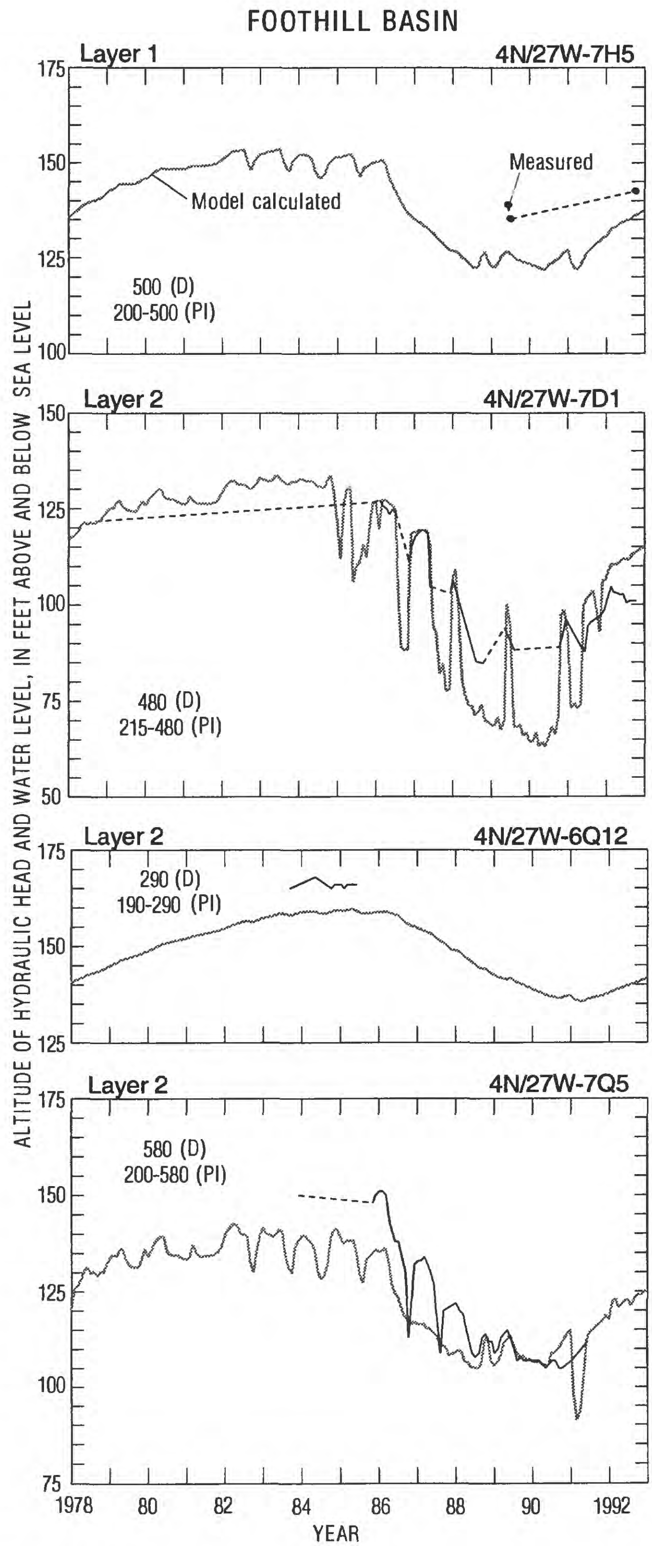


Figure 18. Continued.

that seawater intrusion may occur under this pumping condition in Storage Unit I. The simulated water discharge through the general-head boundary in Storage Unit III is a net flow of 23 acre-ft/yr, a reduction of 4 percent from steady-state conditions. Approximately 1,560 acre-ft/yr is derived from depletion of storage, indicating that storage supplies 37 percent of the pumpage (42 percent of the pumpage from Storage Unit I, 9 percent of the pumpage from Foothill basin, and 73 percent of the pumpage from Storage Unit III).

The total pumpage for stress period 180 (table 5, December 1992) is 474 acre-ft/yr (5 acre-ft/yr from Storage Unit I, 405 acre-ft/yr from the Foothill basin, and 64 acre-ft/yr from Storage Unit III) (table 5). Decreased pumpage in stress period 180 has allowed water levels to recover, resulting in increased discharge from the drains and a reversal in the net flow across the general-head boundary at the coast in comparison with the period of high pumping (stress period 151). However, the drain discharge and net flow across the general-boundary are less than in the simulated steady-state conditions. The simulated water budget for December 1992 indicates that a total of 430 acre-ft/yr is discharged from drains (a 75-percent decrease from steady state); 185 acre-ft/yr is discharged from Storage Unit I (a 68-percent decrease from steady state), 157 acre-ft/yr is discharged from the Foothill basin (an 83-percent decrease), and 88 acre-ft/yr is discharged from Storage Unit III (a 50-percent decrease). The sim-



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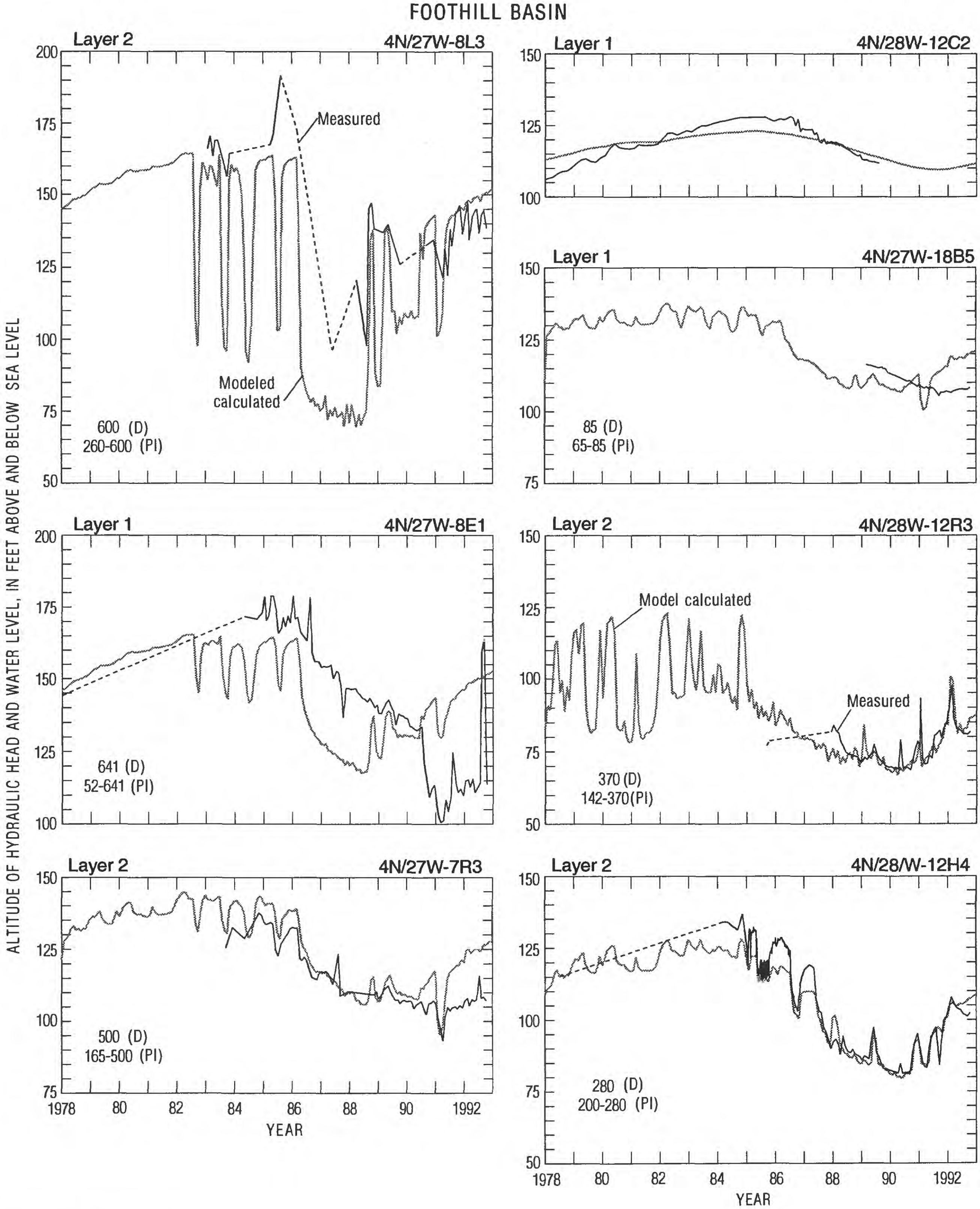

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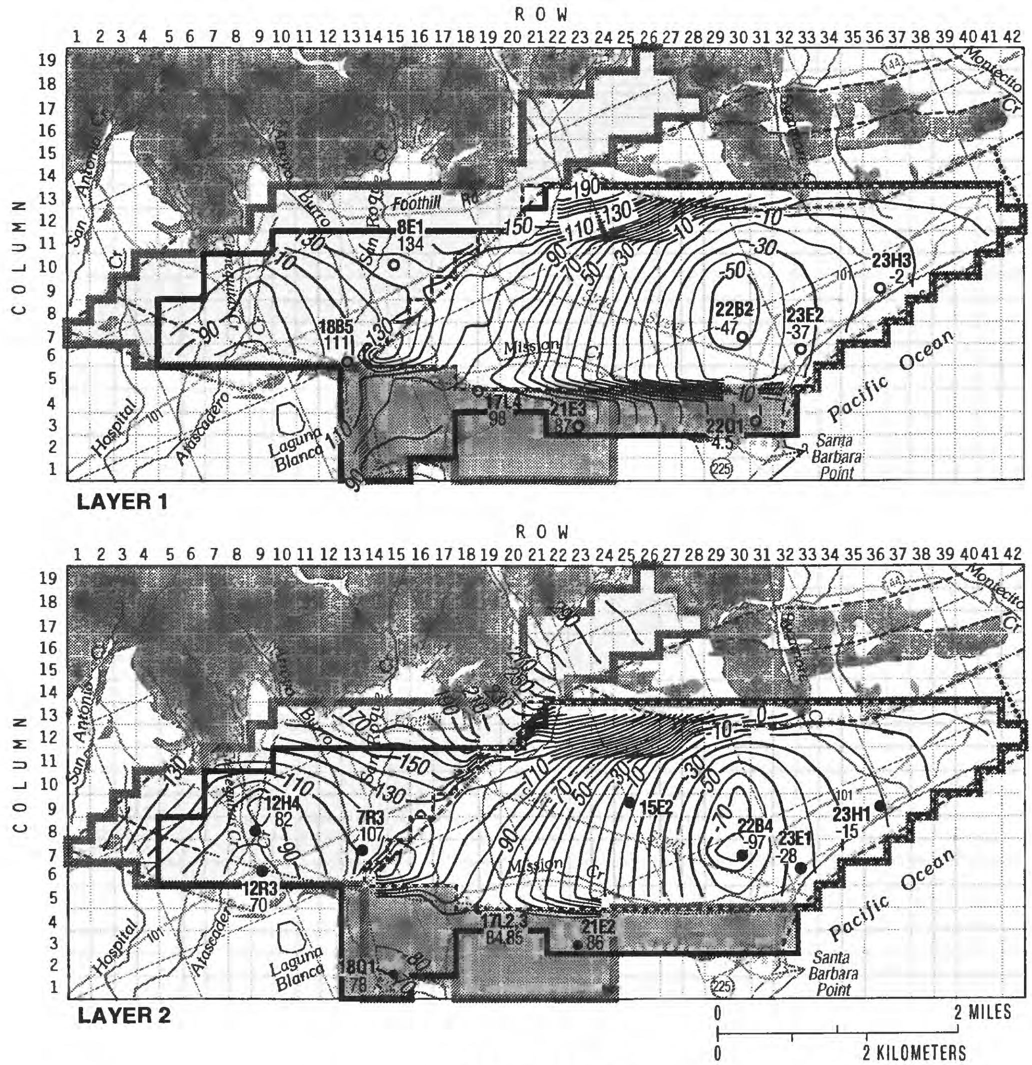


EXPLANATION

Unconsolidated deposits

Consolidated rocks

Fault- Dashed where approximately located; queried where doubtful; dotted where concealed. U, upthrown side; D, downthrown side

Boundaries-

Ground-water divide

Ground-water basin or storage unit

Model boundaries-

Layer 1

Layer 2

Internal - Simulated by horizontal-flow barriers

Model areas-

Foothill basin

Storage Unit I

Storage Unit III

—90— **Water-level contour-** Shows altitude of water level. Contour interval 10 feet. Datum is sea level

Well and number- Bottom number is water level, in feet above or below (-) sea level

23E2 -37 o Layer 1

23E1 -28 • Layer 2

Figure 19. Simulated water-level contours and measured water levels, July 1990, Santa Barbara areawide model.

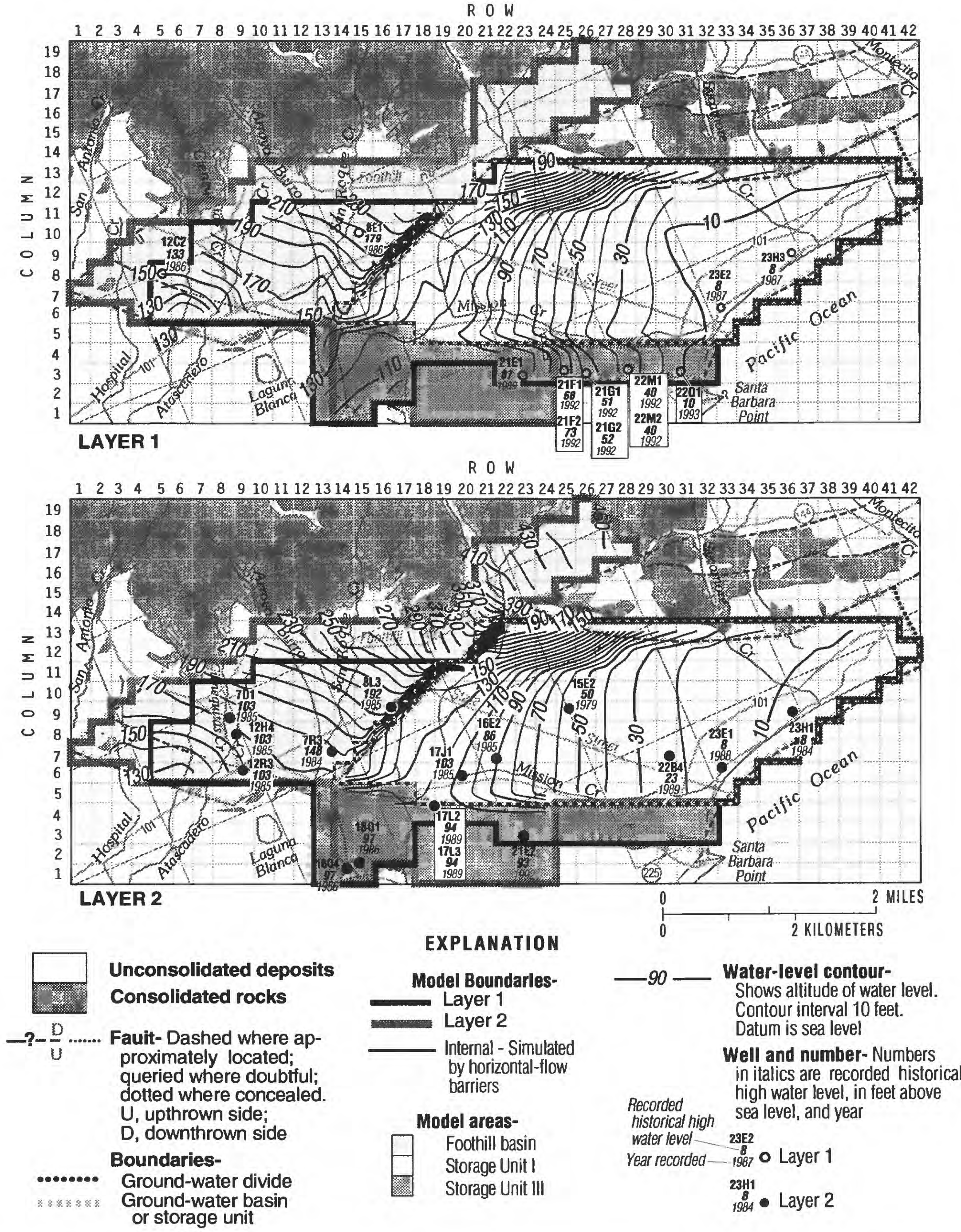


Figure 20. Simulated steady-state water-level contours and recorded historical high water levels in the ground-water basins in the Santa Barbara area, California.

ulated water budget further indicates that a net 42 acre-ft/yr is discharged from Storage Unit I through the general-head boundary to the Pacific Ocean, whereas 287 acre-ft/yr is discharged through this boundary during steady-state conditions. These results indicate that seawater intrusion may not occur under this pumping condition in Storage Unit I; however, a net 36 acre-ft/yr recharges model layer 2 from the Pacific Ocean, indicating that seawater intrusion may occur in layer 2. The simulated water discharged through the general-head boundary in Storage Unit III is a net flow of 23 acre-ft/yr, a decrease of 4 percent from steady-state conditions. Approximately 1,039 acre-ft/yr is returned to storage as a result of rising water levels owing to the decreased pumping. Storage provides 42 percent of the pumpage from Storage Unit I, 9 percent of the pumpage from the Foothill basin, and 73 percent of the pumpage from Storage Unit III.

The cumulative volumes of recharge and discharge for the simulation period January 1978 to December 1992 are presented in table 9, at back of report. A total of 33,430 acre-ft of water was pumped from the study area. During the simulation period, 2,833 acre-ft (8.5 percent of the total) is removed from storage. A total of 5,332 acre-ft entered the study area through the general-head boundary at the coast, indicating that seawater intrusion may occur during the simulation period. In fact, available water-quality data indicate that there are high chloride concentrations in Storage Unit I coastal monitoring wells (Johnson and Fong-Frydendal, 1993). A density-dependent groundwater flow and transport model would be required to fully investigate the potential for seawater intrusion.

Sensitivity Analysis

The sensitivity of the areawide model was determined for changes in recharge (areal, stream, or combined), conductance of the outflow drains, transmissivity, storage coefficient, vertical conductance, general-head boundary conductance, and horizontal-flow-barrier hydraulic characteristic. These model parameters (subsequently referred to as "inputs") were varied individually while holding the remaining inputs at their calibrated values. In general, the amount of variation for a particular input was based on reasonable ranges of values that would be expected in the natural system. Vertical conductance and general-head boundary conductance were varied at 0.1 and 10 times their calibrated values. Drain conductance, recharge, storage coefficient, and transmissivity were varied at 0.5 and 2 times calibrated values. Horizontal-flow-barrier hydraulic characteristic was set to represent no-flow conditions. Sensitivity to changes in pumpage were not investigated owing to a high degree of confidence in the pumpage data for the main pumped wells.

A sensitivity analysis was performed on an ongoing basis during the calibration process in order to determine the model areas, as well as inputs, that were most important in affecting model-generated hydraulic heads at the calibration wells. In addition, considerable calibration effort was placed on determining reasonable values for those items that were both the most sensitive and the least well known. Results presented here are those from the final sensitivity analysis of the calibrated transient model. The sensitivities of hydraulic head, fluxes through drains, and fluxes through the general-head boundary of the areawide model to changes in inputs are presented in tables 10–12 at back of report, respectively. Sensitivity is ranked from 1 to 15 in tables 10–12 whereby the lowest rank indicates the most sensitive input and the highest rank indicates the least sensitive input. The hydraulic heads in the areawide model are most sensitive to changes in total recharge and transmissivity, and to the removal of faults (table 10). The drain fluxes in the areawide model area most sensitive to changes in total recharge, transmissivity, and drain conductance (table 11). The general-head boundary fluxes in the areawide model are most sensitive to changes in transmissivity, general-head boundary conductance, and total recharge (table 12).

Hydraulic-head results of the recharge and transmissivity sensitivity analyses are presented in figure 21. Shown in figure 21 is the range of changes in hydraulic head at the end of the transient simulation (December 1992) between the calibrated areawide model and the model with a varied sensitivity input. When total recharge was doubled, the most sensitive areas were the stream and areal recharge areas (fig. 21*C*). The greatest changes in hydraulic head (40 to 100 ft) were in the Foothill basin for both model layers (fig. 21). When transmissivity was halved, the most sensitive areas were the areas of low transmissivity (the northern parts of Storage Unit I and the Foothill basin) (fig. 21*B*). The greatest changes in hydraulic head were 40 to 100 ft along Mission Creek in Storage Unit I (fig. 21*B*). When transmissivity was doubled, the most sensitive area was the Foothill basin where changes in hydraulic head ranged from 40 to 100 ft (fig. 21). When total recharge was halved, water levels declined by as much as 47 ft in layer 1 and 52 ft in layer 2 (table 10). The sensitivities to changes in total recharge are not symmetric because the ocean acts as a buffer (source of water) to decreases in areal and stream recharge. When all the faults were removed, hydraulic heads rose as much as 38 ft in layer 1 and 40 ft in layer 2 and declined as much as 43 ft in layer 1 and 42 ft in layer 2 (table 10); these results indicate that the faults retard ground-water movement in the areawide model.

Limitations

Numerical models have known limitations in representing real-world systems. For example, the deviation of simulated hydraulic heads from measured water levels results from simplifications associated with the system conceptualization; errors in estimated aquifer characteristics and model parameters; errors of estimated or measured recharge, discharge, and historical water levels; and errors associated with the numerical-solution procedure. Simplifications described in the flow model "Assumptions" section of this report can contribute to errors that might affect the model's accuracy.

The use of estimated values of aquifer characteristics (such as transmissivity, storage coefficient, and vertical hydraulic conductivity) and model parameters (drain conductance, conductance of the general-head boundary at the offshore fault, and fault hydraulic characteristic) will introduce error into the model. However, error introduced as a result of the deviation of the aquifer characteristics probably is small, especially in the areas where the values are based on measured data. The effects of uncertainty in model parameters are more difficult to quantify because the parameter values were obtained, for the most part, through model calibration.

Recharge, discharge, and water levels generally are considered to have been measured or estimated correctly. However, errors in these values can be a serious concern because they directly affect model values of aquifer characteristics and (or) model parameters determined in the calibration process. For example, recharge and transmissivity used in the model are strongly connected in that they are the most sensitive model inputs. This means that, in general, when recharge or transmissivity is varied with the objective of matching a hydrograph, then a correction in the other sensitive input may be necessary to compensate for the changes caused by the varied input. Thus, a greater certainty in the values of one input will generally translate into a lessening of the uncertainty in the values of the other.

The numerical model is based on the "ground-water flow" equation, which is an approximation used to characterize ground-water flow systems, and the equation describes the time-varying hydraulic-head configuration in three dimensions for ground water of constant density in a porous earth material. The equation takes into account major influencing factors and neglects others. Analytical solutions to the ground-water flow equation are valid through continuous space and time intervals, but solutions to the equations used in the numerical model (approximations to the ground-water flow equation) are valid only at discrete locations at specified times. The numerical model can calculate flow rates from the hydraulic-head information it generates, but they are not a direct solution result.

As the number of model-grid cells is increased and the length of model stress periods is reduced, results calculated by the numerical model will approach the exact solution to the ground-water flow equation. In general, the numerical model is an approximation, but experience has shown that it is a good one. Nonetheless, a certain amount of error is introduced by these approximations. Additional error is introduced by assuming that hydraulic conductivity (or transmissivity) and specific storage (or storage coefficient) are strictly functions of location and not of both location and time. Other errors result from trun-

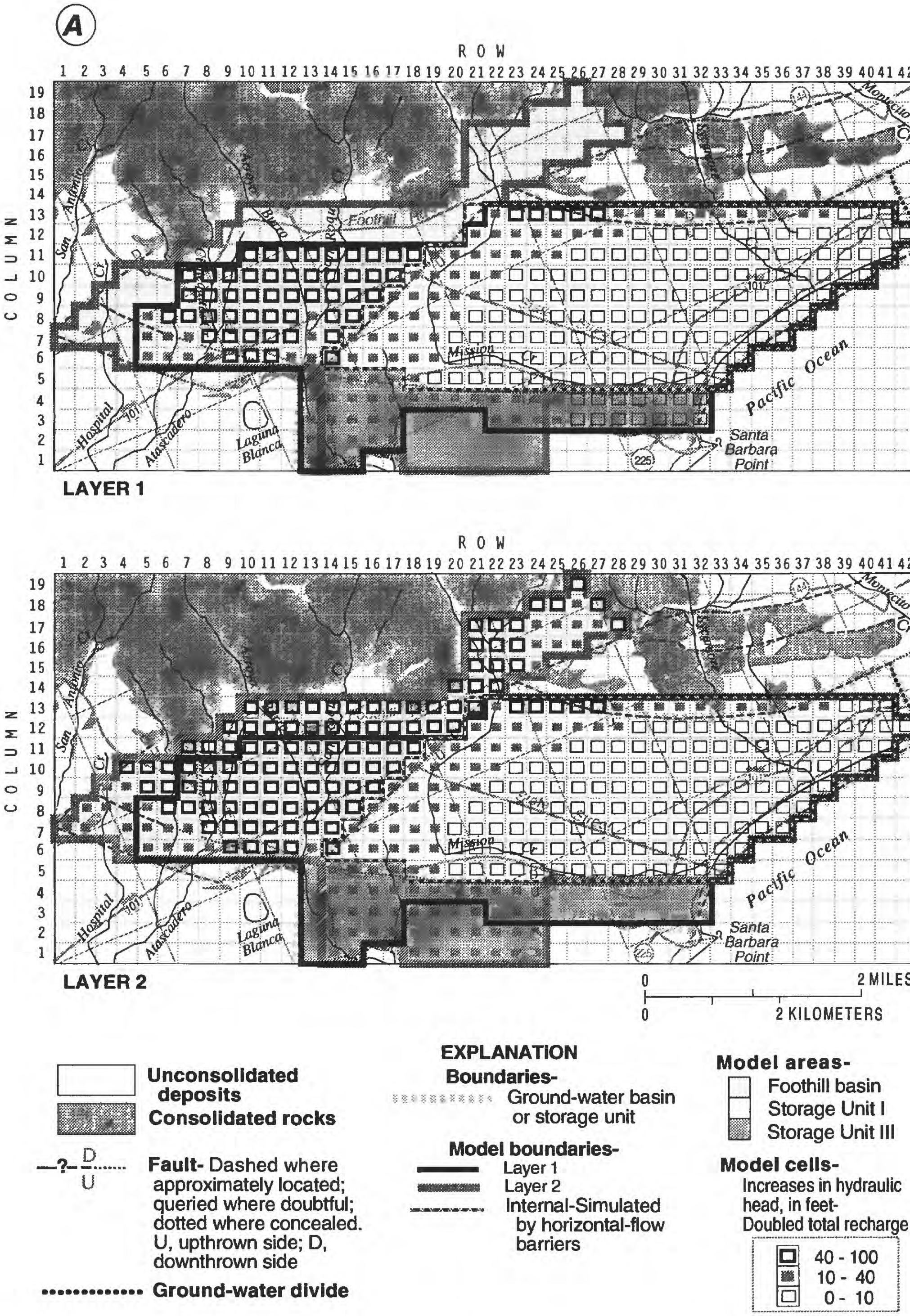
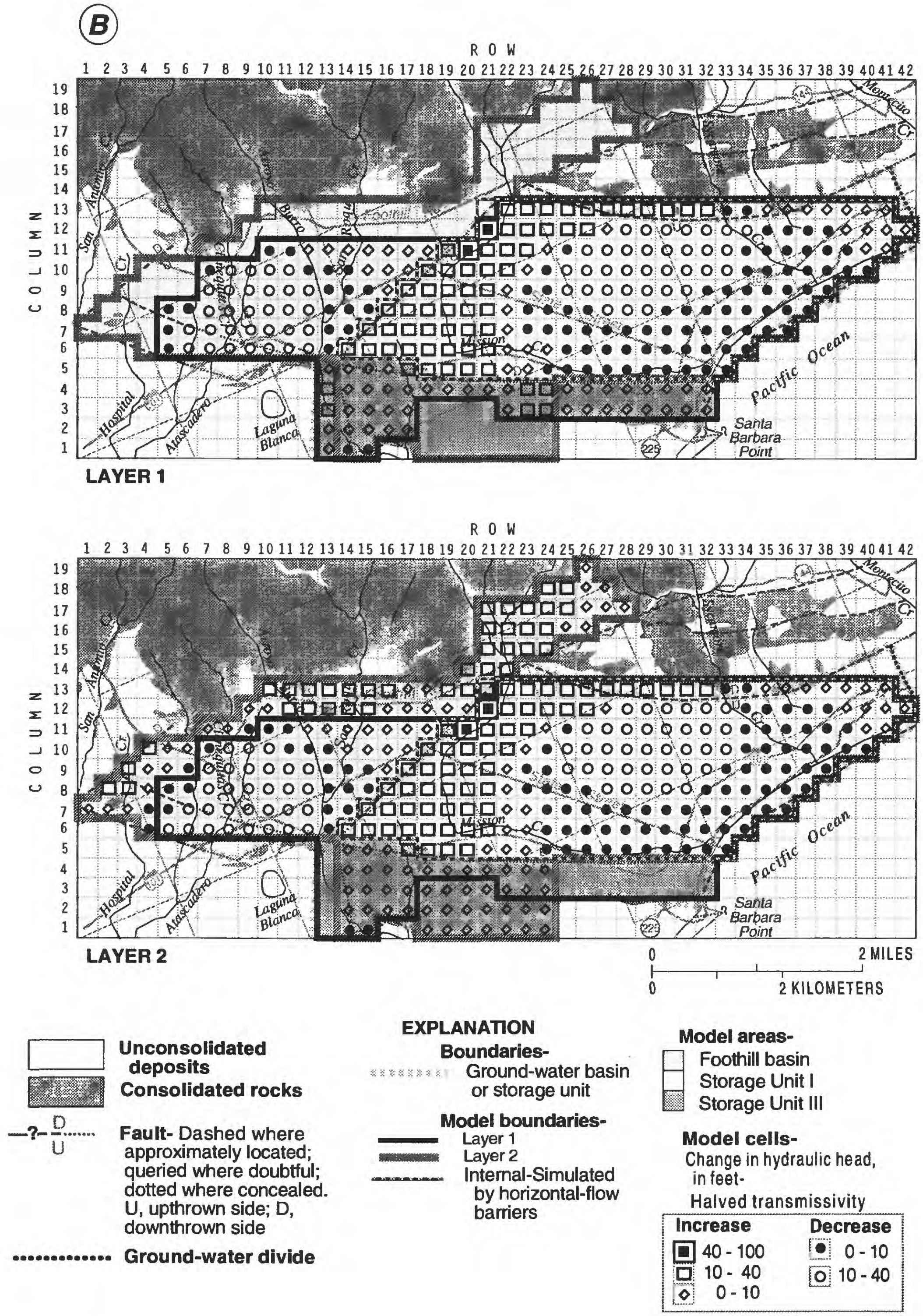


Figure 21. Changes in hydraulic head in layers 1 and 2 of the areawide model and Storage Unit III. Areawide model: areal plus stream ***(A)***; halved transmissivity ***(B)***; doubled transmissivity ***(C)***; Storage Unit III: doubled total recharge ***(D)***; doubled stream recharge ***(E)***; doubled transmissivity ***(F)***.



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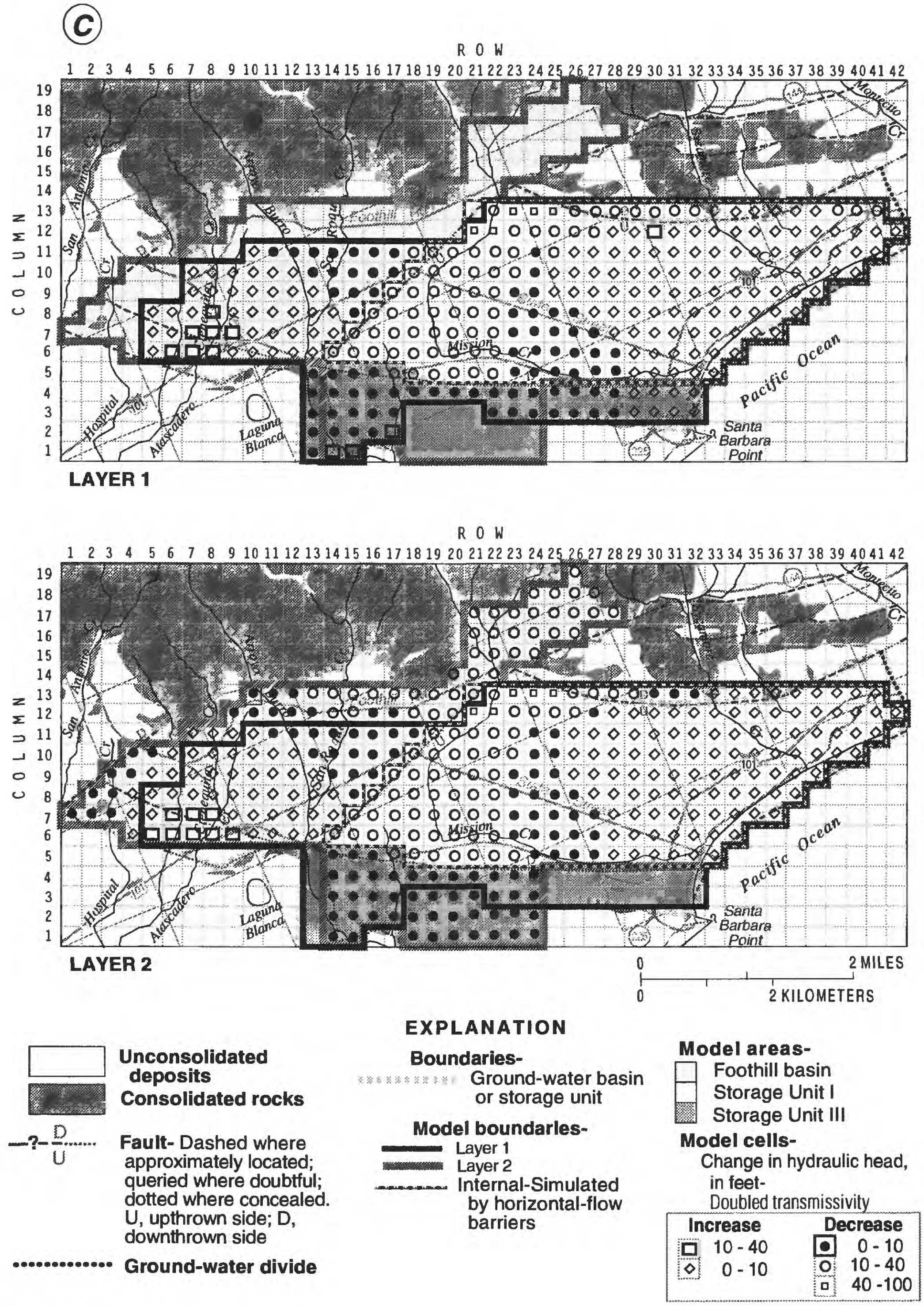

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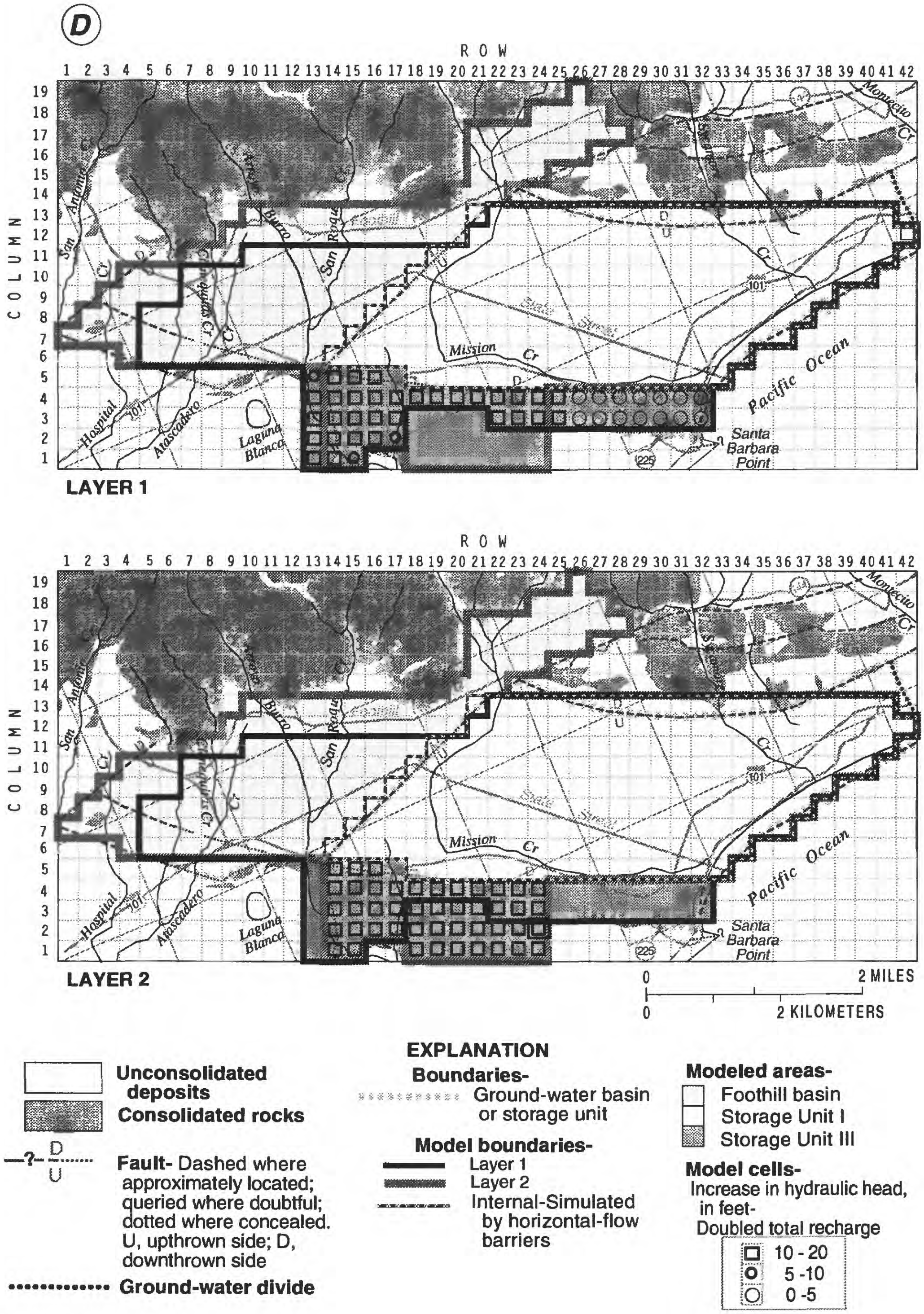

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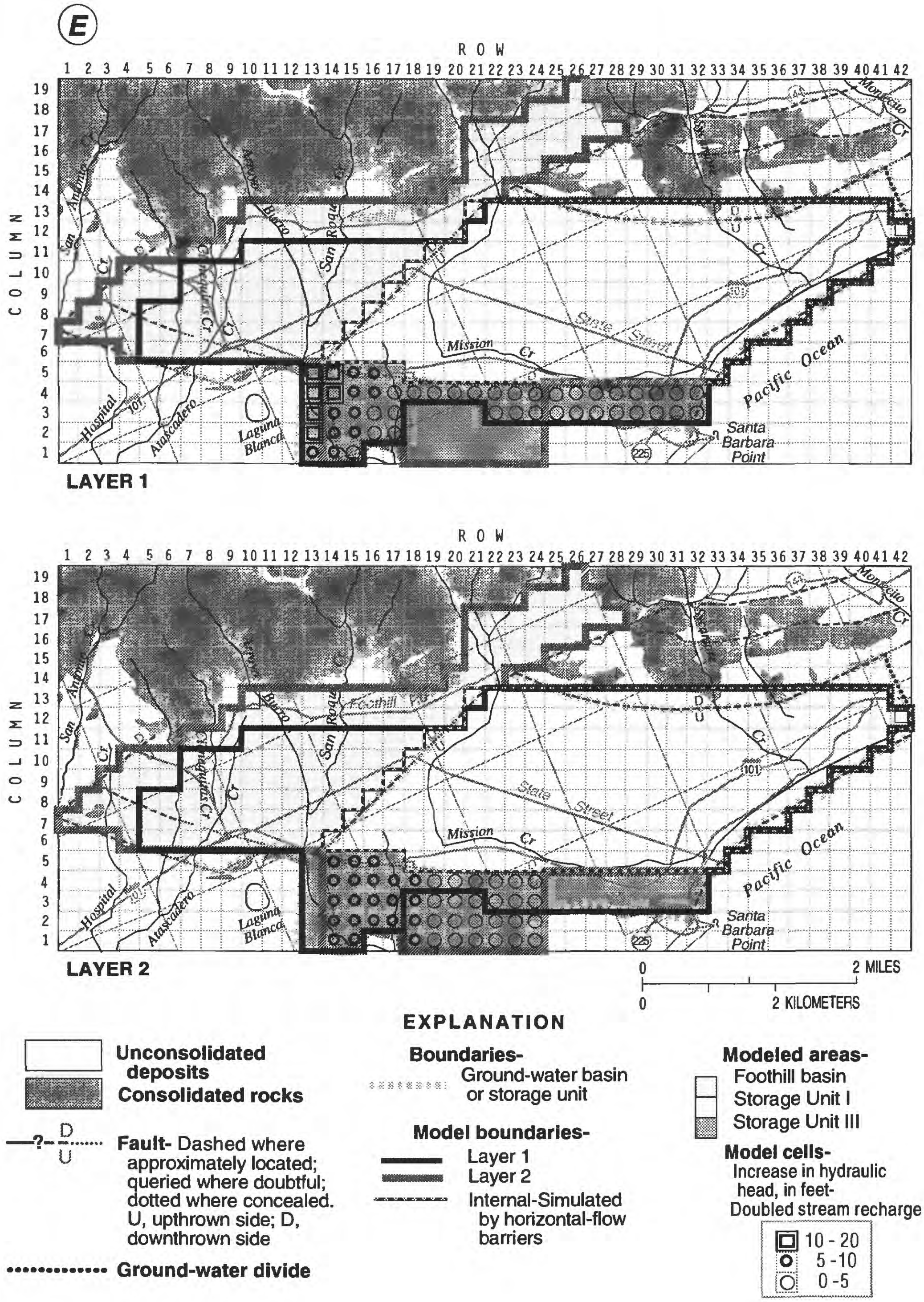

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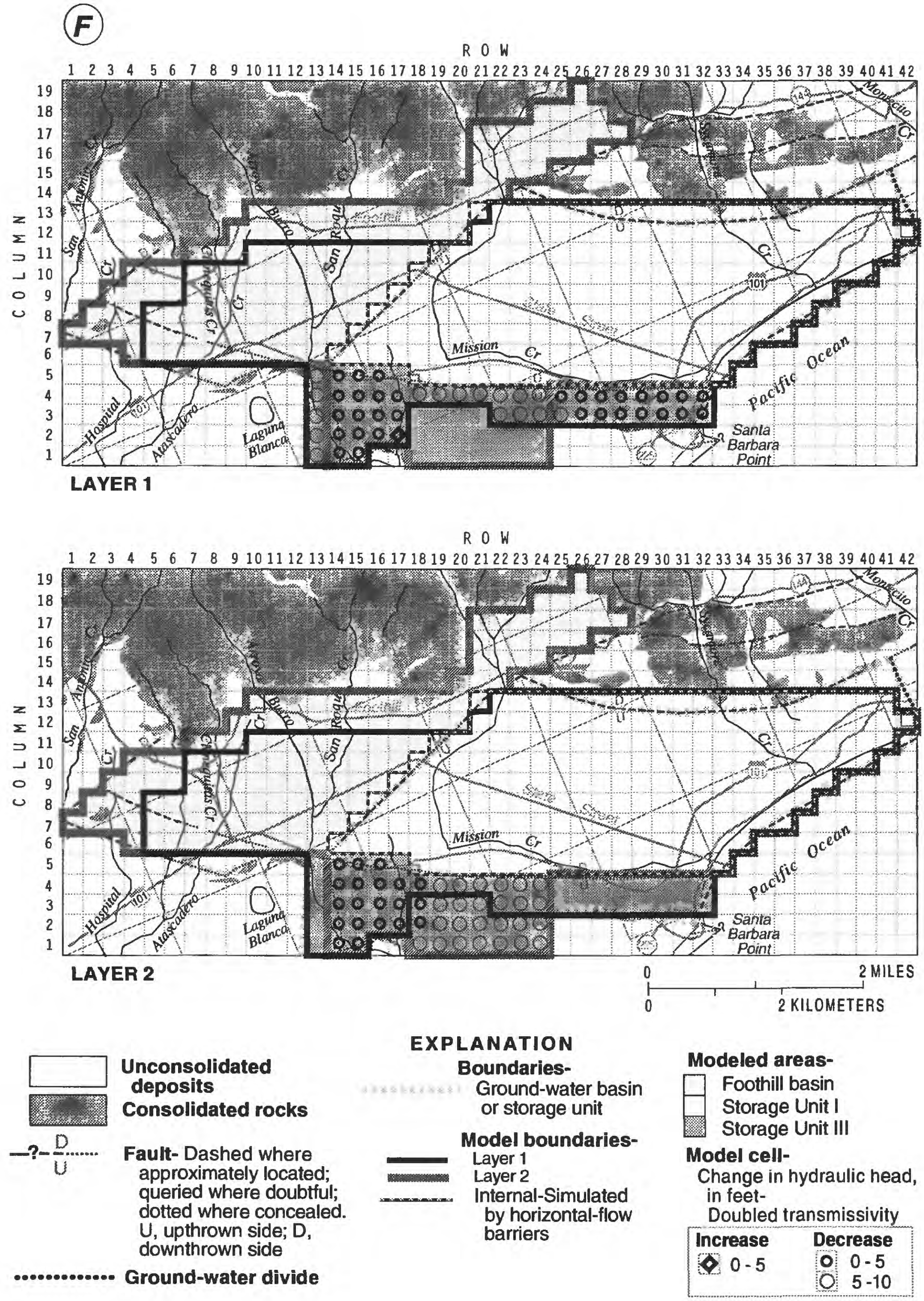

Figure 21. Continued.

cation of numeric values or selection of convergence criterion or are associated with the particular numerical procedure used to solve the model equations. Usually these errors are not serious.

There are limitations and errors specific to the use of horizontal-flow barriers in simulating the internal fault boundaries linking Storage Units III and I and the Foothill basin. The main limitation is uncertainty as to the degree of hydraulic connection between the storage units and the Foothill basin as reflected in the number and locations of the horizontal-flow barriers and the estimated hydraulic characteristic assigned to each barrier. In addition, the fact that the model does not account for storage effects in the horizontal-flow barriers could result in small errors for calculated hydraulic heads near the barriers. Errors in the number, location, and estimated hydraulic characteristics of the horizontal-flow barriers can affect both steady-state and transient-state simulations. Errors introduced by omission of the storage properties of the barriers will be manifested only during transient simulations.

The predictive accuracy of the model will be governed in part by the cumulative effect of the previously discussed sources of error. Additional error will be introduced by simulating conditions that differ significantly from those used in the model calibration. As an example, it would be inappropriate to simulate major pumping stresses in the northeast, north, and northwest parts of the Foothill basin where no major pumping stress was simulated in the calibrated model. Also, uncertainty in the numerical representation of the boundary conditions requires that interpreting model results near boundaries be done with care. Similar care must be exercised in evaluating long-term simulations, for which the effects of uncertainty in storage-coefficient values will be manifested.

SUMMARY

The purposes of this study were to summarize and evaluate the geohydrology of Storage Unit III of the Santa Barbara ground-water basin and to develop an areawide model of the Santa Barbara and Foothill basins that includes the previously unmodeled Storage Unit III and incorporates the pre-existing models of Storage Unit I and the Foothill basin.

Storage Unit III and Storage Unit I compose the Santa Barbara ground-water basin. Storage Unit III trends southeast-northwest; its width is about 2,000 ft in the southeast and 4,000 ft in the northwest, and its length is about 3.5 miles. Storage Unit III is in the southwestern part of the city of Santa Barbara north of the coastal zone. The storage unit is bounded by the Mesa Fault on the north, the contact between younger alluvium and the Santa Barbara Formation on the west, the Lavigia Fault on the south, and an offshore fault on the east. Sedimentary rocks of Tertiary age underlie the storage unit and form its lower boundary. These boundary conditions and locations vary somewhat from those determined in other studies. Under natural conditions ground-water flow within the storage unit is to the southeast, parallel to the basin axis.

In Storage Unit III the Tertiary rocks generally have low permeabilities and are considered non-water bearing. Where cut by faults and fractures, the rocks commonly yield water, but the quantity yielded is relatively small and the quality is generally poor (high dissolved-solids concentration). The unconsolidated water-bearing deposits that make up the ground-water system include the Santa Barbara Formation of Pleistocene and Pliocene(?) age, older alluvium and terrace deposits of Pleistocene age, and younger alluvium of Holocene age. The Santa Barbara Formation, in Storage Unit III, has a maximum saturated thickness of about 240 ft. The alluvium is as much as 140 ft thick.

Unconsolidated deposits of the Santa Barbara Formation and younger and older alluvium compose the main water-bearing units in Storage Unit III. The thickness of the unconsolidated deposits is about 60 ft in the area from the coast to about 1.5 miles inland and ranges from 160 to 300 ft in the rest of the basin. In general, the southwest-dipping unconsolidated deposits increase slightly in thickness from the Mesa Fault in the north to the Lavigia Fault in the south.

On the basis of data from borehole geophysical and lithologic logs of selected wells and lithologic logs of wells drilled for this study, the unconsolidated deposits in Storage Unit III have been subdivided into five main zones: the shallow zone (zone 1), the upper producing zone (zone 2), the middle zone (zone 3), the lower producing zone (zone 4), and the deep zone (zone 5). These zones correspond to those in the adjacent Storage Unit I.

Transmissivities calculated from aquifer-test data range from about 790 to 1,260 ft^2/d. Transmissivity of the alluvium is probably no more than 550 ft^2/d on the basis of maximum saturated thickness. Storativity probably ranges from about 0.0001 (storage coefficient, where the aquifer is confined) to 0.10 (specific yield, where the aquifer is unconfined).

A water-level monitoring network consisting of 14 wells at 8 sites was installed for this study. This network was used to determine areal and vertical variations in water levels, to determine possible ground-water interactions, and to construct potentiometric-surface maps of the upper and lower producing zones. Water levels declined 13 ft during 1946-91, the longest period of record.

Sources of recharge to Storage Unit III are seepage from Arroyo Burro, subsurface flow from the Foothill basin and Storage Unit I, and infiltration of precipitation. Lesser amounts of recharge may occur as subsurface flow from the Hope Ranch subbasin and as upwelling from the Tertiary rocks underlying the storage unit. Estimates of recharge from stream seepage range from about 40 to 80 acre-ft/yr. The amount of subsurface flow entering the Hope Ranch subbasin, and the amount of upwelling from Tertiary rocks underlying the storage unit are unknown. Infiltration of precipitation probably is less than 160 acre-ft/yr.

Discharge from Storage Unit III occurs as pumpage, flow to underground drains, underflow across the Lavigia Fault, underflow to the Pacific Ocean, and evapotranspiration. The greatest historical pumpage in Storage Unit III is about 280 acre-ft/yr. The drain discharge and underflow discharge quantities are unknown but are probably on the order of a few tens of acre-feet per year. Evapotranspiration is not considered to be a significant source of discharge because the depth to water generally is greater than 20 ft.

The 14 monitoring wells were also sampled to determine ground-water quality. The water-quality data were used to help determine possible ground-water interaction with adjacent basins. Water-quality data indicate that little hydraulic communication occurs between Storage Unit III and Storage Unit I. Poor-quality water (high in dissolved-solids concentration) is associated with the proximity of a sampled well to fault boundaries and to Tertiary rocks that underlie the storage unit. Upward leakage of poor-quality water from rocks of Tertiary age can be influenced by poor well construction or heavy localized pumping.

The fault boundaries generally are considered to be effective barriers to ground-water flow. However, ground water is believed to flow into and out of Storage Unit III through unfaulted younger alluvium along stream channels.

The preexisting Storage Unit I and Foothill basin models have similar areal and vertical spatial discretization and share a similar grid orientation. The previously unmodeled Storage Unit III was discretized to correspond with the preexisting models, thus easing the combining of the three models. The three models were combined using horizontal-flow barriers based on geologic, hydraulic, and water-quality data.

A transient calibration of the areawide model was performed. In Storage Unit III, hydrographs of simulated water levels generally follow the trends of the measured water levels, and differences between simulated and measured water levels are less than 10 ft. The model also adequately simulates water levels on a regional basis (Foothill basin and Storage Unit I areas). In addition, a nonpumping, steady-state simulation was done to verify that the calibrated model yielded reasonable results under non-stress conditions.

Steady-state model results indicate that the total recharge is 2,031 acre-ft and is balanced by 1,699 acre-ft that is discharged through the drains and 311 acre-ft that is discharged through the general-head boundary at the ocean. Transient model results indicate that the total pumpage was 33,430 acre-ft during the simulation period of January 1978 to December 1992. During the simulation period 2,833 acre-ft (8.5 percent of the total) is removed from storage. A total of 5,332 acre-ft entered the study area through the general-head boundary at the coast, indicating that seawater intrusion may occur during the simulation period.

A sensitivity analysis was done to determine the model areas, as well as inputs, that were most important in affecting model-generated hydraulic heads at the calibration wells. In addition, considerable calibration effort was placed on determining reasonable values for those items that were both the most sensitive and least well known. The hydraulic heads in the areawide model are most sensitive to changes in total recharge, transmissivity, and the removal of faults. The drain fluxes in the areawide model are most sensitive to changes in total recharge, transmissivity, and drain conductance. The general-head boundary fluxes in the areawide model are most sensitive to changes in transmissivity, general-head boundary conductance, and total recharge.

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Table 1. Driller's logs of test holes drilled in Storage Unit III and vicinity, Santa Barbara County, California

	Thickness	Depth
4N/27W-17L2,3,4. Cluster-well site. Drilled and logged by U.S. Geological Survey. Altitude of land-surface datum 140.02 feet; Three 2-inch polyvinyl chloride casings; depth of hole 410 feet. Depth of well 17L2, 300 feet; perforated interval 260-300 feet. Depth of well 17L3, 220 feet; perforated interval 190–220 feet. Depth of well 17L4, 140 feet; perforated interval 100-140 feet. Drilling completed 2-3-89.		
Sand, light tan-yellow	20	0–20
Sand, silty very fine to medium reddish-tan, and clay	10	20–30
Sand, silty very fine to fine reddish-tan, and clay, and black fragments (plant roots?)	6	30–36
Clay, silty sandy tan	2	36–38
Sand, very fine to medium reddish-tan, and clay	1	38–39
Clay, reddish-brown, and sand, very fine to medium	1	39–40
Sand, very fine to medium, brown, and clay, silty	3	40–43
Gravel, fine to medium, and sand, very fine to medium, and clay, silty	5	43–48
Clay, reddish-brown, and sand, very fine to medium	2	48–50
Gravel, pea, and sand, very coarse	10	50–60
Sand, very fine to very coarse, and gravel, pea	3	60–63
Clay, silty reddish-brown, and sand, very fine to medium	2	63–65
Sand, very coarse to very fine, and clay, grayish-red	3	65–68
Clay, silty sandy reddish-brown, and sand, very coarse to very fine	2	68–70
Clay, silty sandy reddish-brown, and sand, very fine to fine	3	70–73
Shale, yellow-brown	9	73–82
Clay, blue-green	13	82–95
Shale, dark blue-gray, and clay, blue-gray	2	95–97
Clay, blue-gray	13	97–110
Clay, blue-gray, and sand, very fine to medium	13	110–123
Sand, silty fine blue-green	7	123–130
Sand, silty fine to medium, and clay, and shale dark, blue-gray	15	130–145
Clay, blue-green, and sand, very fine to medium	5	145–150
Sand, very fine to medium blue-green, and clay	15	150–165
Sand, very fine to medium	25	165–190
Sand, very fine blue-green	15	190–205
Sand, very fine to fine, and shells	20	205–225
Sand, very fine to fine blue-gray, and clay	5	225–230
Sand, very fine to coarse blue-gray, and clay, blue-gray	20	230–250
Sand, silty very fine to fine blue-green	10	250–260
Sand, silty very fine to fine blue-green, and clay	10	260–270
Sand, silty very fine to fine blue-green	5	270–275
Sand, very fine to fine blue-green, and shells	1	275–276
Sand, very fine to fine blue-green	4	276–280
Sand, silty very fine to fine blue-green	3	280–283
Sand, very fine to fine blue-green, and shells	7	283–290
Sandstone, and shells	4	290–294
Sand, very fine to fine, and shells	6	294–300
Sand, silty very fine to fine blue-green	6	300–306

Table 1. Driller's logs of test holes drilled in Storage Unit III and vicinity, Santa Barbara County, California—Continued

	Thickness	Depth
4N/27W-17L2,3,4—Continued		
Sand, very fine to fine, and sandstone	4	306–310
Sand, silty very fine to fine blue-green	13	310–323
Sand, very fine to fine, and shells	1	323–324
Sandstone	6	324–330
Sand, very fine to fine blue-green, and clay, blue-green, and sandstone, and shells	35	330–365
Sand, silty very fine to fine blue-green, and clay, blue-green and shells	25	365–390
Sand, silty very fine to fine blue-green, and clay, blue-green and sand, coarse, and shells	9	390–399
Clay, blue-green, and silt, and sand	2	399–401
Shale, brown	9	401–410
4N/27W-18B5. Drilled and logged by U.S. Geological Survey. Altitude of land-surface datum, 170.11 feet. Six-inch polyvinyl chloride casing. Depth of hole, 100 feet. Depth of well, 85 feet.; perforated interval, 65–85 feet. Drilling completed 2-7-89.		
Sand	12	0–12
Clay, reddish-brown, and sand, silty-clayey	3	12–15
Gravel, very fine to pea	2	15–17
Gravel, very fine to medium,	1	17–18
Clay, reddish-brown, and sand, very fine to fine	2	18–20
Clay, reddish-brown, and sand, silty	10	20–30
Gravel, pea, and sand, very fine to medium	5	30–35
Gravel, pea, and gravel, very fine to medium	5	35–40
Gravel, medium to pea, and sand, very fine to medium	3	40–43
Sand, silty yellow-brown, and clay, and gravel, very fine to medium	7	43–50
Clay, yellow-brown, and sand very fine to coarse and gravel, very fine to medium	10	50–60
Sand, very fine to medium, and clay, silty yellow-brown	3	60–63
Sand, very fine to medium, and shells	6	63–69
Clay, silty yellowish, and sand, very fine to medium	1	69–70
Clay, silty sandy yellowish	5	70–75
Sand, silty yellowish	3	75–78
Clay, silty reddish-brown	4	78–82
Clay, blue-green	1	82–83
Sandstone, fine grained decomposed blue-green	7	83–90
Clay, silty sandy reddish-brown	7	90–97
Clay, silty sandy light blue, and clay, brown	3	97–100
4N/27W-19A1,2,3. Cluster-well site. Drilled and logged by U.S. Geological Survey. Altitude of land-surface datum, 86.1 feet. Three 2-inch polyvinyl chloride casings; depth of hole, 360 feet. Depth of well 19A1, 360 ft; perforated interval, 320–360 feet. Depth of well 19A2, 180 feet; perforated interval 160–180 ft. Depth of well 19A3, 110 feet, perforated interval, 70–110 feet. Drilling completed 2-1-89.		
Sand, and sandstone boulder, yellow-tan	14	0–14
Sandstone, decomposed boulder, medium to fine grained gray-yellow	4	14–18
Sandstone, medium to fine grained gray-yellow	2	18–20
Sandstone, medium to fine grained tan-yellow	6	20–26

	Thickness	Depth
4N/27W-19A1,2,3—Continued		
Sandstone, medium to fine grained blue-gray-white	9	26–35
Sandstone, medium to fine grained tan-yellow	5	35–40
Sandstone, medium to fine grained tan-yellow with dark specks	18	40–56
Sandstone, medium to fine grained blue-gray-white	10	56–68
Sandstone, medium to fine grained gray-white	11	68–79
Sand, lightly cemented coarse to fine grained; light blue-white	7	79–86
Clay, blue-gray, and sand, fine	4	86–90
Sand, lightly cemented coarse to very fine grained; light blue-white	6	90–96
Silstone, blue-green, and shells	1	96–97
Clay, silty light blue-gray	13	97–110
Clay, light blue-gray	10	110–120
Clay, light blue-gray, and shale, brown	1	120–121
Shale, brown	4	121–125
Clay, light blue-gray	5	125–130
Silt, clayey blue	6	130–136
Clay, gray-blue	4	136–140
Clay, gray-blue	1	140–141
Silt, clayey gray	6	141–147
Silt, clayey blue-gray	1	147–148
Shale, brown	5	148–153
Clay, silty light blue	4	153–157
Sandstone, fine grained blue-white	1	157–158
Shale, brown	14	158–172
Clay, silty blue-gray	3	172–175
Shale, brown	5	175–180
Shale, brown with blue-green specks	6	180–186
Clay, light brown to tan	7	186–193
Shale, brown	4	193–197
Shale, reddish-brown	1	197–198
Clay, blue-green, and sand, fine, and silt	5	198–203
Shale, brown	5	203–208
Shale, reddish-brown	1	208–209
Shale, brown with blue-green specks	1	209–210
Shale, brown	10	210–220
Shale, brown	10	220–230
Shale, brown, and clay, blue-gray	10	230–240
Clay, light gray-blue	7	240–247
Clay, blue-gray, and shale, blue-gray	3	247–250
Shale, soft blue-gray	2	250–252
Shale, brown	4	252–256

	Thickness	Depth
4N/27W-19A1,2,3—Continued		
Shale, soft blue-gray, and clay, silty blue-gray	6	256–262
Clay, silty blue-gray, and shale, soft blue-gray	3	262–265
Shale, brown	5	265–270
Clay, silty sandy blue-gray	6	270–276
Silstone, blue-gray	2	276–278
Shale, blue-gray	2	278–280
Clay, fine sandy blue-gray	1	280–281
Shale, brown	2	281–283
Shale, reddish-brown	5	283–288
Clay, fine sandy blue-green	1	288–289
Shale, brown	1	289–290
Clay, silty to sandy reddish-brown	1	290–296
Clay, blue-green, and sand, medium, and silt	2	296–298
Shale, soft reddish-brown	6	298–304
Sand, silty very fine	1	304–305
Clay, silty blue-green, and sand, very fine to medium	8	305–313
Shale, brown	4	313–317
Shale, reddish-brown	3	317–320
Shale, soft brown	5	320–325
Shale, hard brown	3	325–328
Shale, soft brown	2	328–330
Shale, soft brown with blue-green specks	3	330–333
Clay, blue-green, and sand, very fine to fine	3	333–336
Shale, brown	4	336–340
Shale, reddish-brown with green specks	5	340–345
Silstone, greenish-brown	1	345–346
Sand, silty fine, and shale, soft brown	2	346–348
Clay, silty blue-green, and sand, very fine	2	348–350
Clay, silty blue-green	2	350–352
Shale, reddish-brown	7	343–359
Shale, soft brown	1	359–360
4N/27W-21E1,2,3. Cluster-well site. Drilled and logged by U.S. Geological Survey. Altitude of land-surface datum, 90.21 feet. Three 2-inch polyvinyl chloride casings; depth of hole, 410 feet. Depth of well 21E1, 290 feet; perforated interval, 250–290 ft. Depth of well 21E2, 200 feet; perforated interval, 180–200 feet. Depth of well 21E3, 82.5 feet; perforated interval, 52.5–82.5 feet. Drilling completed 2-6-89.		
Sand, silty sand brown	20	0–20
Gravel, very fine to pea, and sand, coarse to fine, and clay, dark reddish-brown	3	20–23
Clay, silty dark brown, and sand, very fine to fine	4	23–27
Sand, silty very fine to fine light tan-brown	3	27–30
Sand, silty light reddish-brown, and clay, and gravel, very fine	2	30–32

Table 1. Driller's logs of test holes drilled in Storage Unit III and vicinity, Santa Barbara County, California—Continued

	Thickness	Depth
4N/27W-21E1,2,3—Continued		
Gravel, very fine, and sand, silty, and sandstone	3	32–35
Gravel, very fine to medium	5	35–40
Gravel, very fine to coarse, and sand, silty, and clay, and pebbles	7	40–47
Gravel, very fine to medium, and sand, very coarse, and sand, silty	3	47–50
Gravel, very coarse, and pebbles, and sand, very coarse	2	50–52
Gravel, pea, and gravel, very fine to medium, and sand, very fine to fine	8	52–60
Gravel, coarse, and pebbles, and sand, very fine to coarse	4	60–64
Silstone, reddish-brown-tan	1	64–65
Sand, very fine to very coarse, and clay	5	65–70
Sand, very fine to fine blue-green	5	70–75
Sand, very fine to fine blue-green, and shells	2	75–77
Clay, sand, very fine to fine blue-green	12	77–89
Clay, sand, silty very fine to fine blue-green	1	89–90
Clay, sand, very fine to fine	7	90–97
Sandstone, very fine grained blue-black	3	97–100
Sand, silty very fine to fine	10	100–110
Sand, silty very fine to fine blue-green, and clay	10	110–120
Sand, very fine to fine blue-green, and rock chips	7	120–127
Sand, very fine to fine, and shells	3	127–130
Sand, very fine to fine blue-green	1	130–131
Sand, very fine to fine, and shells	2	131–133
Sand, very fine to fine blue-green	13	133–146
Sand, very fine to fine, and shells	1	146–147
Sand, very fine to coarse, and clay, brown, and clay, blue-green	3	147–150
Sand, very fine to coarse blue-green	10	150–160
Sand, very fine to fine blue-green	12	160–172
Gravel	3	172–175
Sand, very fine to fine blue-green	19	175–194
Clay, dark green, and sand, very fine to fine blue-green	6	194–200
Sand, silty very fine to fine blue-green	1	200–201
Sand, very fine to fine, and shells	1	201–202
Sand, silty very fine to fine	6	202–208
Shale, yellow-brown	2	208–210
Sand, silty very fine to fine blue-green	1	210–211
Sandstone, yellow-brown	9	211–220
Sand, very fine to fine blue-green	5	220–225
Sandstone, lightly cemented brown-yellow	2	225–227
Sand, silty very fine to fine blue-green, and clay	3	227–230
Sand, silty clayey very fine to fine, and siltstone	5	230–235
Sand, very fine to fine blue-green, and clay, silty brown	8	235–243

Table 1. Driller's logs of test holes drilled in Storage Unit III and vicinity, Santa Barbara County, California—Continued

	Thickness	Depth
4N/27W-21E1,2,3—Continued		
Clay, blue-green, and sand, very fine to fine blue-gray	2	243–245
Clay, brown, and clay silty, blue-green	2	245–247
Clay, silty sandy blue-green-brown	23	247–270
Clay, silty blue-green, and sand, very fine to fine, and shells	10	270–280
Silt, brown, and sand, silty very fine to fine, and clay	3	280–283
Sand, very fine to fine, and shells	14	283–297
Sand, very fine to fine, and clay, silty brown, and shells	13	297–310
Sand, silty very fine to fine, and shells	10	310–320
Sand, very fine to fine, and shells	3	320–323
Siltstone, gray-tan, and sand, very fine to fine	1	323–324
Sand, very fine to fine	1	324–325
Sand, silty very fine to fine, and shells	10	325–335
Sand, lightly cemented, and shells	10	335–345
Sand, silty very fine to fine	1	345–346
Sand, silty very fine to fine, and shells	9	346–355
Sand, silty very fine to fine, and clay, tan-gray, and shells	10	355–365
Sand, very fine to fine	8	365–373
Sand, cemented light blue-gray	5	373–378
Sand, very fine to fine	12	378–390
Sand, lightly cemented	3	390–393
Clay, light blue-white	7	393–400
Shale, soft brown	7	400–407
Shale, brown	3	407–410
4N/27W-21F1,2. Cluster-well site. Drilled and logged by U.S. Geological Survey. Altitude of land-surface datum, 80 feet. Two 2-inch polyvinyl chloride casings; depth of hole 180 feet. Depth of well 21F1, 150 feet, perforated interval, 140–150 feet. Depth of well 21F2, 80 feet; perforated interval, 70–80 feet. Drilling completed 6-21-91.		
Sand	10	0–10
Sand, medium; clay, and silt, with wood; dark yellowish brown	13	10–23
Clay, with some silt and sand; olive black	7	23–30
Sand, medium to fine, and clay; dark greenish gray	11	30–41
Gravel, sand, medium, and clay; olive gray to moderate brown	7	41–48
Clay and sand, medium to fine; moderate brown to olive gray	32	48–80
Shale and clay; moderate brown to dusky yellow brown	100	80–180
4N/27W-21 G1, G2. Individual wells drilled 5 feet apart. Drilled and logged by U.S. Geological Survey. Altitude of land-surface datum, 66 feet. Two-inch polyvinyl chloride casings. Depth of hole (21G1), 120 feet. Depth of well 21G1, 110 feet; perforated interval, 100–110 feet.		
Sand, medium to fine, with silt and wood; moderate brown	10	0–10
Sand, fine silt, and clay; moderate brown	20	10–30
Sand, medium to coarse, and gravel, with clay; dark yellowish brown	8	30–38
Sand, fine to medium, and clay; dark yellowish brown	32	38–70

Table 1. Driller's logs of test holes drilled in Storage Unit III and vicinity, Santa Barbara County, California—Continued

	Thickness	Depth
4N/27W-21 G1, G2—Continued		
Clay and sand, medium to fine; blue gray to moderate brown	10	70–80
Clay and silt, with some wood; moderate brown to grayish blue green	20	80–100
Shale and clay; grayish brown	20	100–120
4N/27W-22M1,2. Cluster-well site. Drilled and logged by U.S. Geological Survey. Altitude of land-surface datum, 53 feet. Two 2-inch polyvinyl chloride casings. Depth of hole, 120 feet. Depth of well 22M1, 110 feet; perforated interval, 100-110 feet. Depth of well 22 M2, 65 feet; perforated interval, 55–65 feet. Drilling completed 6-18-91.		
Clay, brown	10	0–10
Sand, fine to medium, with silt; moderate brown	8	10–18
Sand, medium to coarse, with gravel; moderate brown	17	18–35
Sand, fine to medium, and clay; moderate brown	5	35–40
Sand, fine to medium; moderate brown	13	40–53
Dand, medium to fine, with some clay and gravel; light olive gray	5	53–58
Gravel, and sand, medium to coarse; light olive gray	7	58–65
Sand, fine, clay, and silt; moderate brown	15	65–80
Clay and some fine sand; pale blue to grayish green	13	80–93
Clay and some silt; moderate brown	7	93–100
Sand, fine to medium, with silt and some clay; moderate brown	10	100–110
Clay and silt; moderate brown	10	110–120

Table 2. Storage Unit III pumpage, Santa Barbara County, California, 1978–92

[Pumpage, in acre-feet. —, no pumpage]

State well No.	Owner	Pumpage						
		[1]1978–86	1987	1988	1989	1990	1991	1992
4N/27W-17M4	Las Positas Mutual Water Company	30–45	30–45	30–45	30–45	30–45	30–45	30–45
4N/27W-18Q4	City of Santa Barbara	—	17	61	169	216	37	3
4N/27W-18Q5	Private	8–10	8–10	8–10	8–10	8–10	8–10	8–10
4N/27W-18R3	Private	8–10	8–10	8–10	8–10	8–10	8–10	8–10
	Total	46–65[1]	63–82	107–126	215–234	262–281	83–102	49–68

[1]1978–86 yearly average.

Table 3. Water quality in samples from selected wells in Storage Unit III and vicinity, Santa Barbara County, California

[Constituents and hardness are in milligrams per liter except where noted. Constituents are dissolved. <, less than; —, no data. Perforated interval; depths producing zone; 3, middle zone; 4, lower producing zone; 5, deep zone; SH, shale; S, sandstone. µS/cm, microsiemens per centimeter (at 25 degrees

State well No.	Date of sample	Well depth (feet)	Perforated interval (feet)	Zone or material perforated	Specific conducance (µS/cm)	pH (Standard units)	Hardness, as CaCO3	Calcium	Magnesium
				Storage Unit III					
4N/27W-17L2	07-20-93	300	260–300	5	1,110	7.3	410	110	34
4N/27W-17L3	07-09-91	220	190–220	4	1,030	7.4	430	110	37
4N/27W-17L4	06-24-92	140	100–140	2	1,030	7.0	300	88	20
4N/27W-17M4	07-17-90	370	100–370	4,5,SH	1,220	7.3	390	100	33
4N/27W-18Q4	06-15-88	240	90–230	2,4,5	1,210	7.2	576	160	43
4N/27W-21E1	06-24-92	290	250–290	5,SH	3,400	7.3	670	190	47
4N/27W-21E2	07-09-91	200	180–200	4	872	7.6	260	76	16
4N/27W-21E3	07-20-93	82.5	52.5–82.5	2	1,210	7.0	460	130	33
4N/27W-21F1	08-19-93	150	140–150	SH	2,220	8.2	45	12	3.6
4N/27W-21F2	08-19-93	80	70–80	1,SH	1,270	7.8	85	20	8.4
4N/27W-21G2	08-06-91	39	29–39	1	2,140	7.4	610	120	76
4N/27W-22M1	08-19-93	110	100–110	SH	8,150	7.2	1,200	300	99
4N/27W-22M2	08-19-93	65	55–65	1,SH	3,580	7.4	920	230	83
4N/27W-22Q1	09-20-83	60	20–60	1	2,400	8.6	540	130	52
				Storage Unit I					
4N/27W-8R2	07-06-92	205	155–205	2,5	1,210	6.8	570	160	41
4N/27W-9M1	10-11-83	120	30–110	1	1,330	6.9	560	150	45
4N/27W-15J1	07-26-73	629	83–629	1,2,3,4	755	7.0	290	71	27
4N/27W-15K1	07-16-91	464	280–464	4	764	7.5	320	89	24
4N/27W-15Q9	08-08-73	667	91–667	1,2,3,4	748	7.1	290	84	20
4N/27W-16R1	07-17-91	625	545–625	4	989	7.8	350	100	24
4N/27W-17J1	07-09-92	320	190–320	2,4,5	860	8.2	370	100	29
4N/27W-22B6	08-06-84	670	210–670	4	847	7.2	350	97	25
4N/27W-22B8	07-22-93	780	760–780	5	4,830	7.6	390	110	29
4N/27W-22B9	07-22-93	670	650–670	4	849	7.4	310	90	21
4N/27W-22B11	07-22-93	220	200–220	2	878	6.9	340	93	27
4N/27W-22E2	08-19-93	70	60–70	1	917	7.0	380	95	35
4N/27W-22G2	07-21-93	200	180–200	2	845	6.8	330	87	27
4N/27W-22G4	07-07-92	690	650–690	4	755	7.6	300	85	22
4N/27W-23E1	10-25-88	805	775–800	4	12,500	7.0	3,700	970	310
4N/27W-23E3	07-20-90	385	355–380	2	517	8.3	160	42	14
4N/27W-23E4	07-30-90	180	150–175	1	777	7.2	280	69	26
				Foothill Basin					
4N/27W-7D1	07-09-92	490	215–480	3,4	1,590	7.2	610	140	62
4N/27W-8L3	06-15-88	610	260–600	4	936	6.9	380	98	32
4N/27W-9G1	03-16-78	273	179–273	4	1,170	6.5	470	95	57
4N/27W-18B5	07-06-92	85	65–85	1	1,470	7.3	640	160	59
				Hope Ranch Subbasin					
4N/27W-18C2	11-10-87	88	78–88	1	1,790	8.4	830	220	68
4N/27W-18C3	11-10-87	257	237–257	5	3,550	7.3	1,300	440	48
4N/27W-18D2	04-23-68	315	57–315	3,4,5	2,490	8.2	580	150	51
				South of Storage Unit III					
4N/27W-19A1	02-05-91	360	320–360	SH	19,000	7.6	1,809	590	82
4N/27W-19A3	02-05-91	110	70–110	S, SH	2,860	7.2	733	190	63

of topmost and bottommost perforations; casing may not be perforated throughout the interval. Zone or material perforated: 1, shallow zone; 2, upper Celsius); µg/L,micrograms per liter. Location of wells shown in figure 4]

Sodium	Alkalinity as $CaCO^3$	Sulfate	Chloride	Fluoride	Silica	Solids, sum of constituents	Nitrite plus nitrate as N	Barium (µg/L)	Boron (µg/L)
				Storage Unit III					
83	496	180	50	0.6	28	788	<0.05	—	210
65	340	200	39	.6	24	686	<.05	37	120
120	330	190	47	.4	38	705	<.05	—	70
150	360	150	130	.1	25	805	<.10	60	150
72	375	220	91	.4	30	845	<.10	—	130
410	340	33	920	1.1	34	1,870	<.05	—	4,600
79	255	50	110	.8	28	521	<.05	76	450
86	363	230	92	.3	25	828	2.1	—	200
450	263	17	530	5.5	12	1,200	<.05	—	14,000
240	413	3.1	160	1.3	14	708	<.05	—	2,600
280	446	570	160	1.5	17	1,500	.057	<100	2,400
1,300	287	200	2,600	1.0	16	4,710	<.05	—	8,100
460	440	760	690	.6	22	2,520	<.05	—	3,700
370	—	250	310	.3	19	1,500	.16	300	2,400
				Storage Unit I					
53	—	320	73	.3	32	838	2.9	—	80
81	—	390	81	.3	25	922	—	68	300
53	185	100	70	.5	—	436	—	—	100
37	188	140	49	.3	30	485	.31	27	50
39	205	120	41	.4	—	—	—	—	<100
79	321	87	92	.4	31	608	<.05	260	50
46	—	140	71	.4	35	568	.099	—	70
48	235	110	67	.3	34	528	.86	—	110
860	318	16	1,500	1.4	28	2,750	<.05	—	8,900
61	354	100	58	.3	34	581	<.05	—	200
41	189	110	82	.4	37	544	8.8	—	50
56	255	150	61	.5	27	593	2.9	—	180
50	219	130	59	.4	34	548	5.7	—	60
54	—	110	27	.2	30	503	<.05	—	50
1,700	187	760	4,900	<.1	31	8,800	<.1	—	410
48	222	<1.0	42	.3	13	—	<.10	32	70
49	263	64	55	<.10	31	457	<.10	71	190
				Foothill Basin					
120	—	260	190	.5	26	1,010	4.5	—	190
60	237	190	43	.4	40	612	1.1	—	80
77	140	340	98	.2	27	796	3.8	—	250
100	439	270	94	.5	22	990	3.6	—	240
				Hope Ranch Subbasin					
110	580	310	110	.4	24	1,260	16.0	—	230
490	204	1,900	190	.4	3.7	3,210	<.10	—	1,100
290	254	210	510	.5	—	1,370	—	—	100
				South of Storage Unit III					
3,500	39	2.1	7,000	1.1	9.2	12,000	<.10	6,200	10,000
340	248	660	510	.6	24	1,910	<.10	<100	1,800

Table 4. Distribution of pumpage to model layers in Storage Unit I, Foothill basin, and Storage Unit III, Santa Barbara areawide model

[Row: model row location of pumping node; Column: model column location of pumping node. Asterisk (*) in well number indicates pumpage distributed to two nodes (50 percent to each) as shown]

State well No.	Local name	Location in model		Pumpage fraction to model layer	
		Row	Column	Layer 1	Layer 2
		Storage unit I			
4N/27W-14R1	Soledad	35	11	0.2	0.8
4N/27W-15E2	Alameda	25	9	.2	.8
4N/27W-15J2*	Ortega	30	10	.1	.9
		30	9	.1	.9
4N/27W-15Q10*	Corporation	30	9	.3	.7
		30	8	.3	.7
4N/27W-16E2	Padre	22	7	.2	.8
4N/27W-22B6	Vera Cruz	30	7	.05	.95
4N/27W-22C1	City Hall	29	7	.1	.9
		Foothill basin			
4N/27W-6Q12	Pueblo Properties	11	11	0.0	1.0
4N/27W-7A7	Lincolnwood 1	12	10	.0	1.0
4N/27W-7D1	Los Robles	9	9	.0	1.0
4N/27W-7G7	Sunset Mutual	11	9	.3	.7
4N/27W-7H5	Lincolnwood 2	12	10	.5	.5
4N/27W-7K6	Calvary Cemetery	12	8	.3	.7
4N/27W-7K8	Santa Barbara Savings	12	8	1.0	.0
4N/27W-7K9	Westpac Shelter	13	8	.6	.4
4N/27W-7Q5	Hope	13	7	.1	.9
4N/27W-8E1	Chupparosa	15	10	.5	.5
4N/27W-8L3	McKenzie	16	9	.3	.7
4N/28W-12H3	San Vincente 2	8	7	.3	.7
4N/28W-12K4	San Vincente 1	8	7	.0	1.0
4N/28W-12L6	El Sueno	6	6	.0	1.0
4N/28W-12R3	La Cumbre Mutual	9	6	.0	1.0
		Storage unit III			
4N/27W-17M4	Las Positas	17	4	0.1	0.9
4N/27W-18Q4	Valle Verde	14	1	.1	.9
4N/27W-18Q5	Parks 2	15	1	.1	.9
4N/27W-18R3	Parks 1	15	2	.1	.9

Table 5. Water budget for end of transient simulation, Santa Barbara areawide model, December 1992

[Values in acre-feet, na, not applicable]

Recharge	Model subarea					
	Storage unit I		Foothill basin		Storage unit III	
	Layer 1	Layer 2	Layer 1	Layer 2	Layer 1	Layer 2
Storage	42	3	0	8	8	0
Streams	446	na	176	243	60	na
Areal	420	na	135	405	82	42
General-head boundary	0	38	na	na	0	na
Interbasin	0	0	7	0	12	0
Subarea totals by layer	908	41	318	656	162	42
Subarea totals	949		974		204	
Model total	2,127					
Discharge						
Storage	650	22	186	214	28	<0.5
Wells	1	4	36	369	6	58
Drains	185	na	147	10	88	na
General-head boundary	78	2	na	na	23	na
Interbasin	7	0	12	0	0	0
Subarea totals by layer	921	28	381	593	145	58
Subarea totals	949		974		203	
Model total	2,126					

Table 6. Model locations and hydraulic heads at general-head boundary cells, Santa Barbara areawide model

{ft, foot]

Layer	Row	Column	Hydraulic head (ft)
1	32	3	0.5
1	32	4	.5
1	33	5	10.8
1	34	6	9.6
1	35	7	8.4
1	36	7	8.4
1	37	8	7.8
1	38	9	7.2
1	39	10	5.6
1	40	10	5.6
1	41	11	5.4
1	42	12	4.8
2	33	5	21.6
2	34	6	19.2
2	35	7	16.8
2	36	7	16.8
2	37	8	15.6
2	38	9	14.4
2	39	10	13.8
2	40	10	13.8
2	41	11	13.2
2	42	12	9.6

Table 7. Simulated steady-state water budget, Santa Barbara areawide model
[Values in acre-feet, na, not applicable]

Recharge	Model subarea					
	Storage unit I		Foothill basin		Storage unit III	
	Layer 1	Layer 2	Layer 1	Layer 2	Layer 1	Layer 2
Streams	446	na	176	243	60	na
Areal	420	na	135	405	82	42
General-head boundary	0	0	na	na	0	na
Interbasin	0	0	5	0	17	0
Subarea totals by layer	866	0	316	648	159	42
Subarea totals	866		964		201	
Model total	2,031					
Discharge						
Drains	575	na	891	56	177	na
General-head boundary	171	116	na	na	24	na
Interbasin	5	0	17	0	0	0
Subarea totals by layer	751	116	908	56	201	0
Subarea totals	867		964		201	
Model total	2,032					

Table 8. Simulated water budget, July 1990, Santa Barbara areawide model

[Values in acre-feet, na, not applicable]

Recharge	Model subarea					
	Storage unit I		Foothill basin		Storage unit III	
	Layer 1	Layer 2	Layer 1	Layer 2	Layer 1	Layer 2
Storage	1,211	48	45	181	212	<0.5
Streams	446	na	176	243	60	na
Areal	420	na	135	405	82	42
General-head boundary	289	608	na	na	0	na
Interbasin	0	0	23	0	0	0
Subarea totals by layer	2,366	656	379	829	354	42
Subarea totals	3,022		1,208		396	
Model total	4,626					
Discharge						
Storage	<0.5	<0.5	78	60	0	<0.5
Wells	341	2,658	63	883	29	260
Drains	.0	na	112	12	72	na
General-head boundary	13	0	na	na	23	na
Interbasin	10	0	0	0	13	0
Subarea totals by layer	364	2,658	253	955	137	260
Subarea totals	3,022		1,208		397	
Model total	4,627					

Table 9. Cumulative water budget for the transient simulation (1978–92), Santa Barbara areawide model

	Volume of water, in acre-feet				
	Storage	Wells	Drains	Recharge	General-head boundary
In	15,439	0	0	30,170	6,126
Out	12,606	33,430	4,905	0	794
Change	2,833	–33,430	–4,905	30,170	5,332

Mass balance 2,833-33,430-4,905+30,170+5,332 = 0

Table 10. Sensitivity of hydraulic head in the Santa Barbara areawide model (December 1992) to changes in areawide model inputs

[Range of change is in feet, and range numbers are separated by slash (/); unsigned numbers in range of change are positive or zero and indicate increases or no change (zero) from values in the calibrated model, negative numbers indicate declines; rank (in parentheses) from most sensitive (1) to least sensitive (15). —, barrier either on or off]

Model input	Factor of change from calibrated model	Range of change in hydraulic head in model layer, and rank			
		Layer 1		Layer 2	
Total recharge	2.0	76/0	(1)	96/2	(1)
Transmissivity	.5	53/-26	(2)	53/-26	(2)
Transmissivity	2.0	14/-49	(3)	14/-49	(3)
Total recharge	.5	0/-47	(4)	-1/-52	(4)
All faults are not barriers	—	38/-43	(5)	40/-42	(5)
No layer 1 Mesa Fault	—	6/-19	(6)	4/-12	(6)
Vertical conductance	.1	15/-18	(7)	16/-14	(7)
Storage coefficient	2.0	18/-6	(8)	17/-10	(8)
Storage coefficient	.5	4/-17	(9)	14/-17	(9)
General-head boundary conductance	.1	3/-16	(10)	0/-16	(10)
All faults are barriers	—	16/-1	(11)	16/4	(11)
Drain conductance	.5	12/0	(12)	9/-4	(12)
Drain conductance	2.0	0/-10	(13)	0/-8	(13)
Vertical conductance	10.0	4/-8	(14)	2/-6	(14)
General-head boundary conductance	10.0	6/0	(15)	6/0	(15)

Table 11. Sensitivity of the Santa Barbara areawide model cumulative flux through drains (1978-92) to changes in model inputs

[Flux values are normalized relative to the calibrated model values (for example, a flux value of 1.00 represents flux equivalent to the value in the calibrated model); rank (in parentheses) from most sensitive (1) to least sensitive (15). —, barrier either on or off]

Model input	Factor of change from calibrated model	Cumulative relative flux in model layer, and rank			
		Layer 1		Layer 2	
Total recharge	2.0	1.99	(1)	5.48	(1)
Transmissivity	2.0	1.65	(2)	.85	(10)
Transmissivity	.5	.61	(3)	1.22	(7)
Total recharge	.5	.66	(4)	.00	(2)
Drain conductance	.5	.77	(5)	1.45	(3)
Drain conductance	2.0	1.18	(6)	.60	(4)
Vertical conductance	10.0	1.17	(7)	.84	(9)
Vertical conductance	.1	.84	(8)	1.24	(6)
No layer 1 Mesa Fault	—	.93	(9)	.99	(13)
All faults are not barriers	—	.98	(10)	.95	(11)
General-head boundary conductance	10.0	.98	(11)	.98	(12)
Storage coefficient	.5	1.01	(12)	1.26	(5)
Storage coefficient	2.0	1.01	(13)	.78	(8)
All faults are barriers	—	.99	(14)	.99	(14)
General-head boundary conductance	.1	1.00	(15)	1.00	(15)

Table 12. Sensitivity of the Santa Barbara areawide model cumulative flux through general-head boundaries (1978-92) to changes in model inputs

[Flux values are normalized relative to the calibrated model values (for example, a flux value of 1.00 represents flux equivalent to the value in the calibrated model); rank (in parentheses) from most sensitive (1) to least sensitive (15). —, barrier either on or off]

Model input	Factor of change from calibrated model	Cumulative relative flux in model layer, and rank			
		Layer 1		Layer 2	
Transmissivity	2.0	2.38	(1)	3.50	(2)
General-head boundary conductance	10.0	1.49	(2)	3.73	(1)
Transmissivity	.5	.51	(3)	.41	(7)
Total recharge	2.0	1.46	(4)	2.19	(4)
General-head boundary conductance	.1	.64	(5)	.07	(5)
No layer 1 Mesa Fault	—	.71	(6)	1.29	(11)
Storage coefficient	2.0	1.18	(7)	1.56	(8)
Total recharge	.5	.84	(8)	.61	(9)
Vertical conductance	.1	1.14	(9)	2.56	(3)
All faults are not barriers	—	.86	(10)	1.67	(6)
Storage coefficient	.5	.93	(11)	.82	(12)
Drain conductance	.5	1.01	(12)	1.01	(13)
Vertical conductance	10.0	1.00	(13)	.66	(10)
Drain conductance	2.0	1.00	(14)	1.00	(14)
All faults are barriers	—	1.00	(15)	1.00	(15)