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Hydrogeology, Water Quality, Water Budgets, and Simulated Responses to Hydrologic Changes in Santa Rosa and San Simeon Creek Ground-Water Basins, San Luis Obispo County, California

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations
Report 98-4061

Prepared in cooperation with the
SAN LUIS OBISPO COUNTY FLOOD
CONTROL AND WATER CONSERVATION DISTRICT

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By Eugene B. Yates and Kathryn M. Van Konyenburg

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4023-09

Sacramento, California
1998

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

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Denver, CO 80225

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CONVERSION FACTORS, VERTICAL DATUM, ABBREVIATIONS, AND WELL- AND SPRING-NUMBERING SYSTEM

Multiply	By	To obtain
acre	0.4047	hectare
acre-foot (acre-ft)	1,223	cubic meter
acre-foot per month (acre-ft/mo)	1,223	cubic meter per month
acre-foot per year (acre-ft/yr)	1,223	cubic meter per year
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot per foot (ft/ft)	1.000	meter per meter
foot per month (ft/mo)	0.3048	meter per month
foot per year (ft/yr)	0.3048	meter per year
foot squared per day (ft^2/d)	0.0929	meter squared per day
gallon per day (gal/d)	0.06308	liter per day
gallon per minute (gal/min)	0.06308	liter per minute
inch (in.)	25.4	millimeter
inch per year (in/yr)	25.4	millimeters per year
kilowatt-hour per acre-foot (kWh/acre-ft)	0.002919	joule per cubic meter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
pound per square inch (lb/in^2)	703.1	kilogram per square meter

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—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

Abbreviations

mg/L milligram per liter
µS/cm microsiemen per centimeter at 25 degrees Celsius

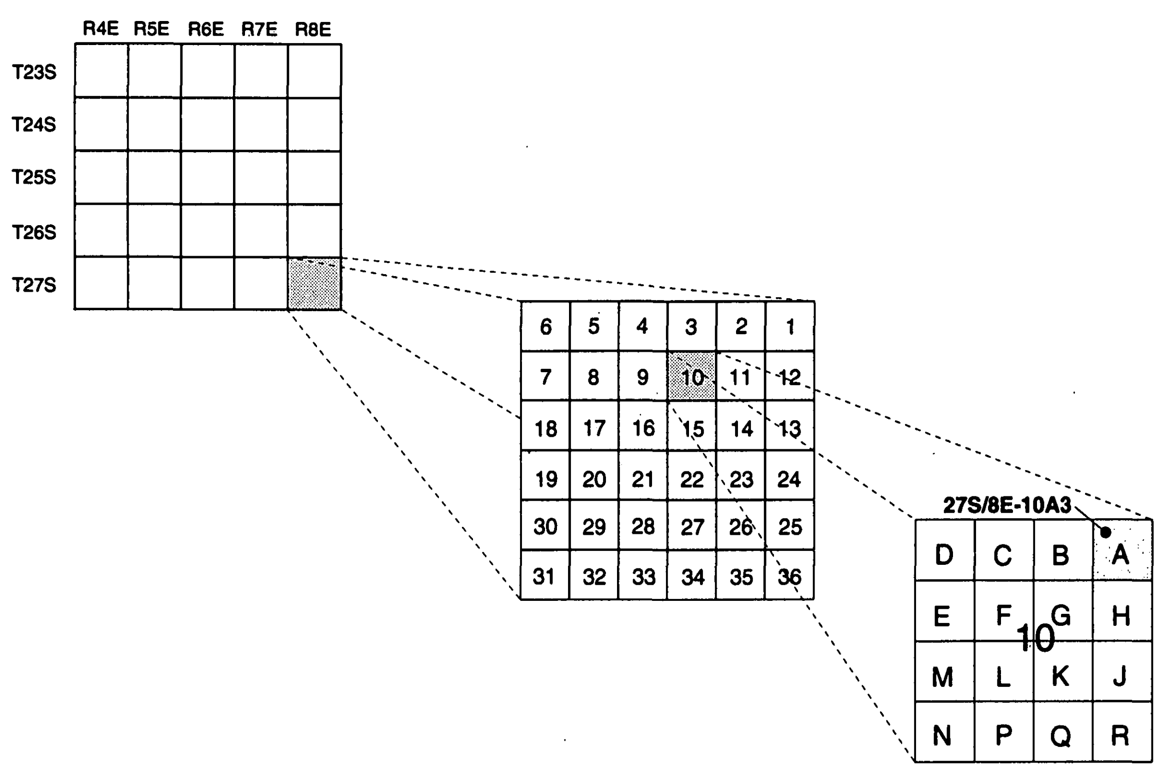
AET actual evapotranspiration
ET_0 reference evapotranspiration

CCSD Cambria Community Services District
CIMIS California Irrigation Management Information System

Water year: A water year is a 12-month period, October through September, designated by the calendar year in which it ends. In this report, years are water years unless otherwise noted.

Well- and Spring-Numbering System

Wells and springs are identified and numbered according to their location in the rectangular system for the subdivision of public lands. Identification consists of the township number, north or south; the range number, east or west; 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 letter "S" inserted before the sequence number indicates a spring. The final letter refers to the base line and meridian. In California, there are three base lines and meridians; Humbolt (H), Mount Diablo (M), and San Bernardino (S). All wells and springs in the study area are referenced to the Mount Diablo base line and meridian (M). Numbers consist of 15 characters and follow the format 027S008E10A003M. In this report, well numbers are abbreviated and written 27S/8E-10A3. Wells in the same township and range are referred to only by their section designation, 10A3. The following diagram shows how the number for well 27S/8E-10A3 is derived.



Hydrogeology, Water Quality, Water Budgets, and Simulated Responses to Hydrologic Changes in Santa Rosa and San Simeon Creek Ground-Water Basins, San Luis Obispo County, California

By Eugene B. Yates *and* Kathryn M. Van Konynenburg

ABSTRACT

Santa Rosa and San Simeon Creeks are underlain by thin, narrow ground-water basins that supply nearly all water used for local agricultural and municipal purposes. The creeks discharge to the Pacific Ocean near the northwestern corner of San Luis Obispo County, California. The basins contain heterogeneous, unconsolidated alluvial deposits and are underlain by relatively impermeable bedrock. Both creeks usually stop flowing during the summer dry season, and most of the pumpage during that time is derived from ground-water storage. Annual pumpage increased substantially during 1956–88 and is now a large fraction of basin storage capacity. Consequently, dry-season water levels are lower and the water supply is more vulnerable to drought.

The creeks are the largest source of ground-water recharge, and complete basin recharge can occur within the first few weeks of winter streamflow. Agricultural and municipal pumpages are the largest outflows and cause dry-season water-level declines throughout the San Simeon Basin. Pumping effects are more localized in the Santa Rosa Basin because of subsurface flow obstructions. Even without pumpage, a large quantity of water naturally drains out of storage at the upper ends of the basins during the dry season.

Ground water is more saline in areas close to the coast than in inland areas. Although seawater intrusion has occurred in the past, it probably was not the cause of high salinity in 1988–89. Ground water is very hard, and concentrations of dissolved solids, chloride, iron, and manganese exceed drinking-water standards in some locations.

Probability distributions of streamflow were estimated indirectly from a 120-year rainfall record because the periods of record for local stream-gaging stations were wetter than average. Dry-season durations with recurrence intervals between 5 and 43 years are likely to dry up some wells but not cause seawater intrusion. A winter with no streamflow is likely to occur about every 32 years and to result in numerous dry wells, seawater intrusion, and subsidence.

Digital ground-water-flow models were used to estimate several items in the ground-water budgets and to investigate the effects of pumpage and drought. The models also were used to investigate the hydrologic effects of selected water-resources management alternatives. Selection of alternatives was not constrained by issues related to water rights, which were under dispute during the study. Increases in the area and intensity of irrigation could increase agricultural water demand by 26 to 35 percent, an increase that would lower water levels by as much as 10 feet and possibly cause subsidence in the lower Santa Rosa Basin. An additional municipal well in the lower Santa Rosa Basin could withdraw 100 acre-feet per year without causing seawater intrusion, but subsidence might occur. Transferring 270 acre-feet per year of treated wastewater from a percolation area near the coast to an area about 0.5 mile upstream of the

municipal well field in the San Simeon Basin could raise upstream water levels by as much as 12 feet without causing significant water-table mounding or seawater intrusion. Decreases in agricultural pumping after a winter without streamflow could prevent seawater intrusion while allowing municipal pumping to continue at normal rates.

INTRODUCTION

Agricultural and municipal water users along Santa Rosa and San Simeon Creeks rely almost entirely on a limited ground-water resource. Ground water occurs in the alluvial deposits beneath the creeks, which drain the western flanks of the Santa Lucia Range in San Luis Obispo County and empty into the Pacific Ocean (fig. 1). The alluvial deposits form flat valley floors, which are used for irrigated agriculture. The town of Cambria is in the Santa Rosa Creek valley about 1 mi from the coast. Municipal water is supplied by the Cambria Community Services District (CCSD), which operates wells in the Santa Rosa and the San Simeon Creek valleys.

The quantity of fresh ground water stored in the thin alluvial deposits is small relative to the overall water demand. During an average winter rainy season, ground-water recharge from streamflow is more than sufficient to meet demand and maintain high ground-water levels. The creeks usually stop flowing during the dry summer season, and users rely on the quantity of ground water in storage until the following winter.

Rapid population growth in Cambria resulted in a fourfold increase in municipal pumpage between 1960 and 1988. In the early 1980's, agricultural pumping increased abruptly as many farmers switched to vegetable crops. These increases in pumping resulted in larger seasonal water-level declines during summer. Rural landowners in the valleys became concerned about the effects of the declines and the potentially devastating consequences of droughts. On several occasions in the mid-1980's, they protested Cambria Community Services District's appropriative water-rights permits before the California State Water Resources Control Board. The quantity of ground water pumped by the District is limited by detailed terms and conditions in their permits.

Purpose and Scope

The purpose of this report is to document the results of a 3-year study of ground-water resources in the Santa Rosa and the San Simeon Creek ground-water basins. During the study, the hydrogeology and water quality of the basins were investigated, quantitative water budgets were developed, and selected water-resources management alternatives

EXPLANATION

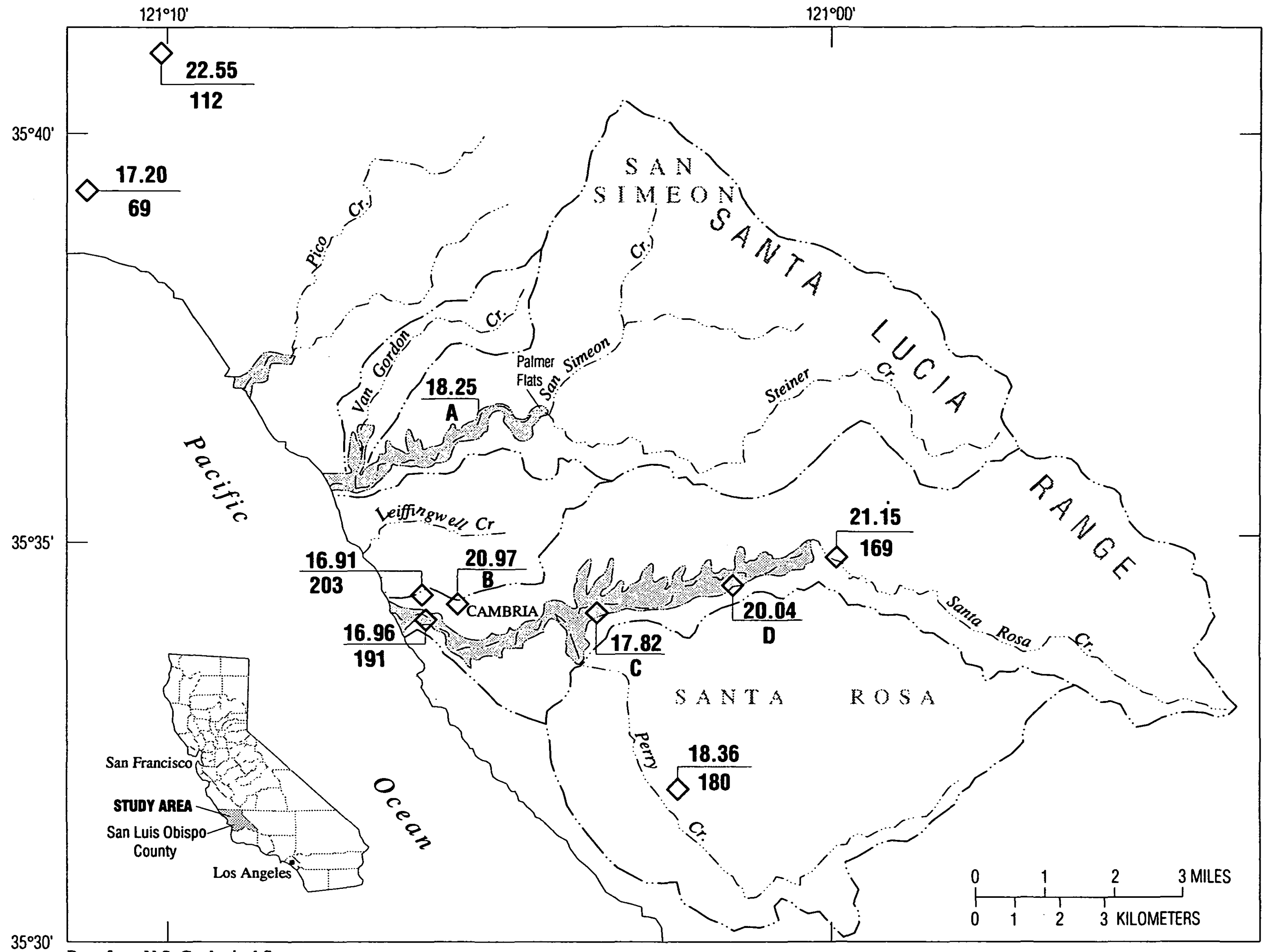
GROUND-WATER BASIN

BOUNDARY OF DRAINAGE BASIN

21.15
169
RAINFALL STATION - Location of daily rainfall measurement. Upper number is annual rainfall, in inches, during water year 1988. Lower number is station identifier. Numerical identifiers are station numbers of permanent gages operated by San Luis Obispo County. Alphabetical identifiers indicate temporary gages used for this study

69 San Simeon (Hearst Ranch)
112 Hearst Castle (fire station)
169 Santa Rosa Creek (Soto Ranch)
180 Cambria (CalTrans)
191 Cambria (wastewater plant)
203 Cambria (Division of Forestry)
A Jon Pedotti
B John Olson
C James Fiscalini
D Scooter Rhoades

Figure 1. Locations of creeks, drainage-area boundaries, ground-water basins, and rainfall stations in the Cambria area, San Luis Obispo County, California.



Base from U.S. Geological Survey
Adelaide 1:62,500, 1961, and San
Simeon 1:62,500, 1959

Figure 1. Locations of creeks, drainage-area boundaries, ground-water basins, and rainfall stations in the Cambria area, San Luis Obispo County, California—Continued.

were evaluated. The study was a cooperative effort between the U.S. Geological Survey and the San Luis Obispo County Flood Control and Water Conservation District.

Field activities undertaken for the study included measurement of rainfall, streamflow, temperature, reference evapotranspiration, land use, well efficiency, electricity use at wells, ground-water levels, aquifer characteristics, and surface- and ground-water quality. Observation wells were installed at several locations. Data analysis included preparation of maps, sections, and graphs showing geology, rainfall, water levels, and water quality. Analytical and numerical models were used to simulate ground-water flow, and patterns of rainfall and streamflow were statistically analyzed. The study focused on Santa Rosa and San Simeon Creeks, although some consideration also was given to ground-water conditions along Pico Creek.

Description of Study Area

The study area includes the drainage areas of Santa Rosa and San Simeon Creeks, including major tributaries such as Perry, Steiner, and Van Gordon Creeks (fig. 1). Pico Creek, about 2 mi north of San Simeon Creek, was included in the analysis of water quality. Near the headwaters, the creek valleys form steep, narrow canyons. Along the final 3 to 5 mi before reaching the ocean, the valleys widen and have relatively flat bottoms a few thousand feet wide. These flat-bottomed areas are underlain by ground-water basins and are flanked by steep hillslopes that rise 200 to 800 ft above the valley floor.

Figure 2 shows cultural features, wells, springs, and streamflow and climate measurement stations used in this study. The town of Cambria is adjacent to the lower end of Santa Rosa Creek and had a population of about 5,300 people in 1990. The commercial district of Cambria is along Main Street between the Main Street bridge and the coast. Residential areas are on the hillsides above the commercial district and on the slopes facing the ocean south of the outlet of Santa Rosa Creek.

The water supply for Cambria is obtained from three wells in the CCSD well field on San Simeon Creek about 1 mi from the coast and from two wells near the Burton Avenue bridge over Santa Rosa Creek. Municipal wastewater receives a secondary level of treatment and is discharged to a sprayfield in the San Simeon Creek valley about 0.5 mi downstream of the CCSD well field.

The remaining parts of the valley floors are occupied by agricultural fields and a few rural residences. Native vegetation consists of trees, grass, and shrubs that grow along the creeks and field borders. Grassy hillslopes along the sides of the valleys are used for grazing. Other land uses include a State park campground at the mouth of San Simeon Creek and an in-stream gravel mining operation and processing plant along San Simeon Creek near well 27S/8E-10G2.

EXPLANATION

—··— BOUNDARY OF GROUND-WATER BASIN

WELL OR TEST HOLE

- ● Private domestic
- Irrigation
- ○ Municipal
- ○ Unused
- Test hole
- Spring used for domestic water supply
- Spring used for stock water supply

\ Indicates observation well

R2 Last letter and digit of well number

▲ STREAM-GAGING STATION

Continuous-record gaging station and identifier

- A Santa Rosa Creek near Cambria (11142200)
- B Santa Rosa Creek at State Highway 1
- D Perry Creek at Cambria (11142240)
- E San Simeon Creek at Palmer Flats
- F San Simeon Creek near Cambria (11142300)

△ Site of occasional discharge measurement

CLIMATE MEASUREMENT STATION

◆ Evapotranspiration measurement station

Temperature measurement station and identifer

- A Cambria Community Services District plant
- B James Fiscalini
- C Scooter Rhoades

Figure 2. Locations of cultural features, wells, springs, and streamflow and climate measurement stations in (*A*) the Santa Rosa and (*B*) the San Simeon ground-water basins, San Luis Obispo County, California.

Acknowledgments

The Cambria Community Services District provided logistical support for well drilling, measured water levels at numerous wells, and freely offered access to their library and historical water-level and water-quality records. Dennis Kunkel of Pacific Gas and Electric Company did more than 20 well-efficiency tests and provided records of monthly agricultural electricity consumption. Numerous farmers and residents voluntarily contributed to the study by recording temperature and rainfall, providing crop and land-use information, allowing access to electric meters, wells, and fields, adjusting irrigation schedules to accommodate well-efficiency and aquifer tests, and providing information and insight. They include the following:

A. Santa Rosa Basin

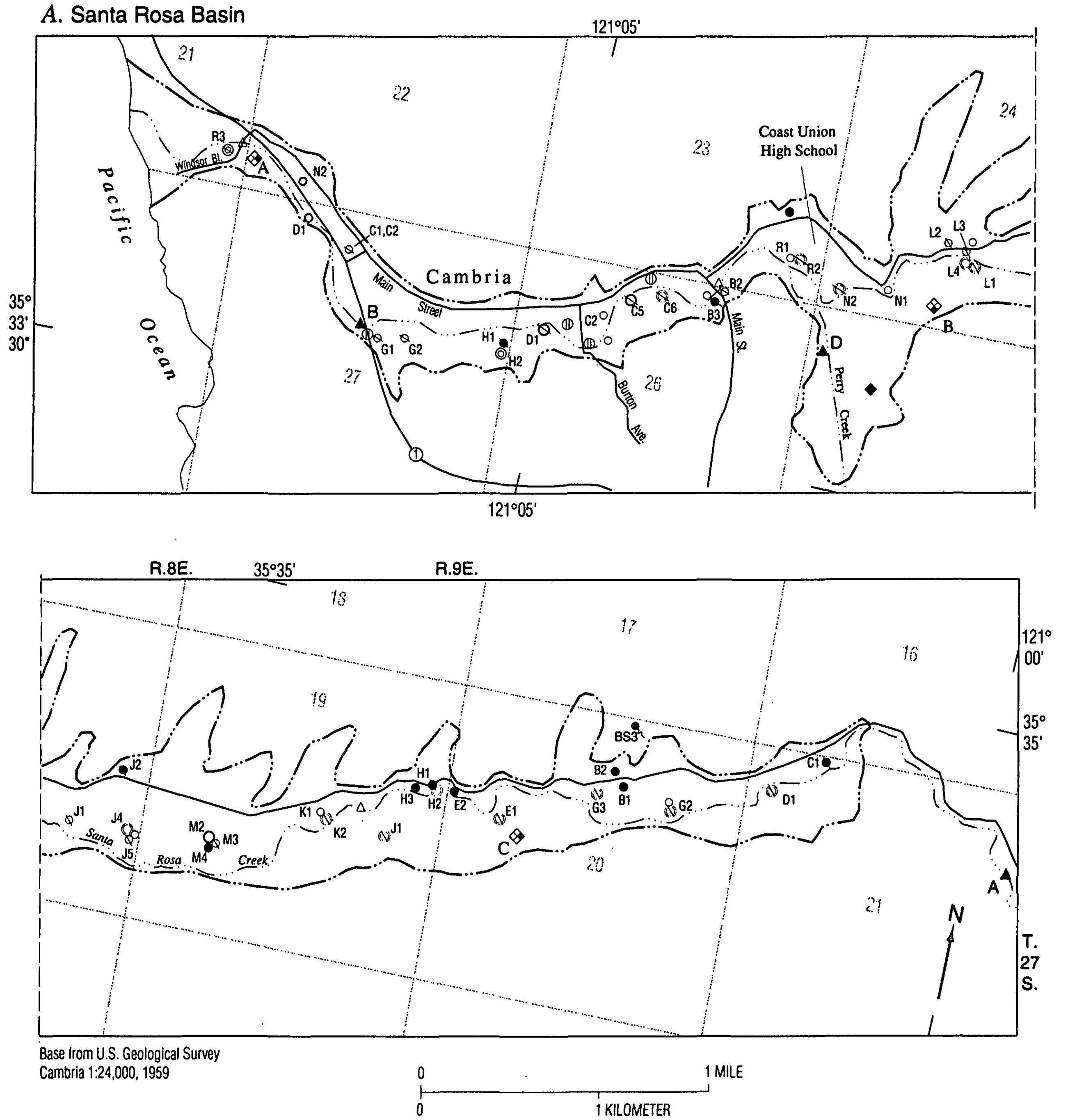


Figure 2. Locations of cultural features, wells, springs, and streamflow and climate measurement stations in (*A*) the Santa Rosa and (*B*) the San Simeon ground-water basins, San Luis Obispo County, California—Continued.

William Bianchi, Alfred Fiscalini, James Fiscalini, Larry Fiscalini, Louis Fiscalini, Olympio Fiscalini, William Hanna, Lloyd Junge, Edward Kalin, Peter Manuele, Lawrence Molinari, John Olson, Alvaro Pantoja, Jon Pedotti, Rosalie and Sterling Rhoades, Scooter Rhoades, Gary Silveira, Leslie Taylor, Jerry Veith, Clyde Warren, and Walter Warren.

HYDROGEOLOGY

Regional Geology and Geologic History

The Santa Rosa and the San Simeon Creek ground-water basins lie just to the west of the southern end of the Santa Lucia Range (fig. 1). The geology of the area is similar to that of other parts of the California Coast Ranges in that Cenozoic and uppermost

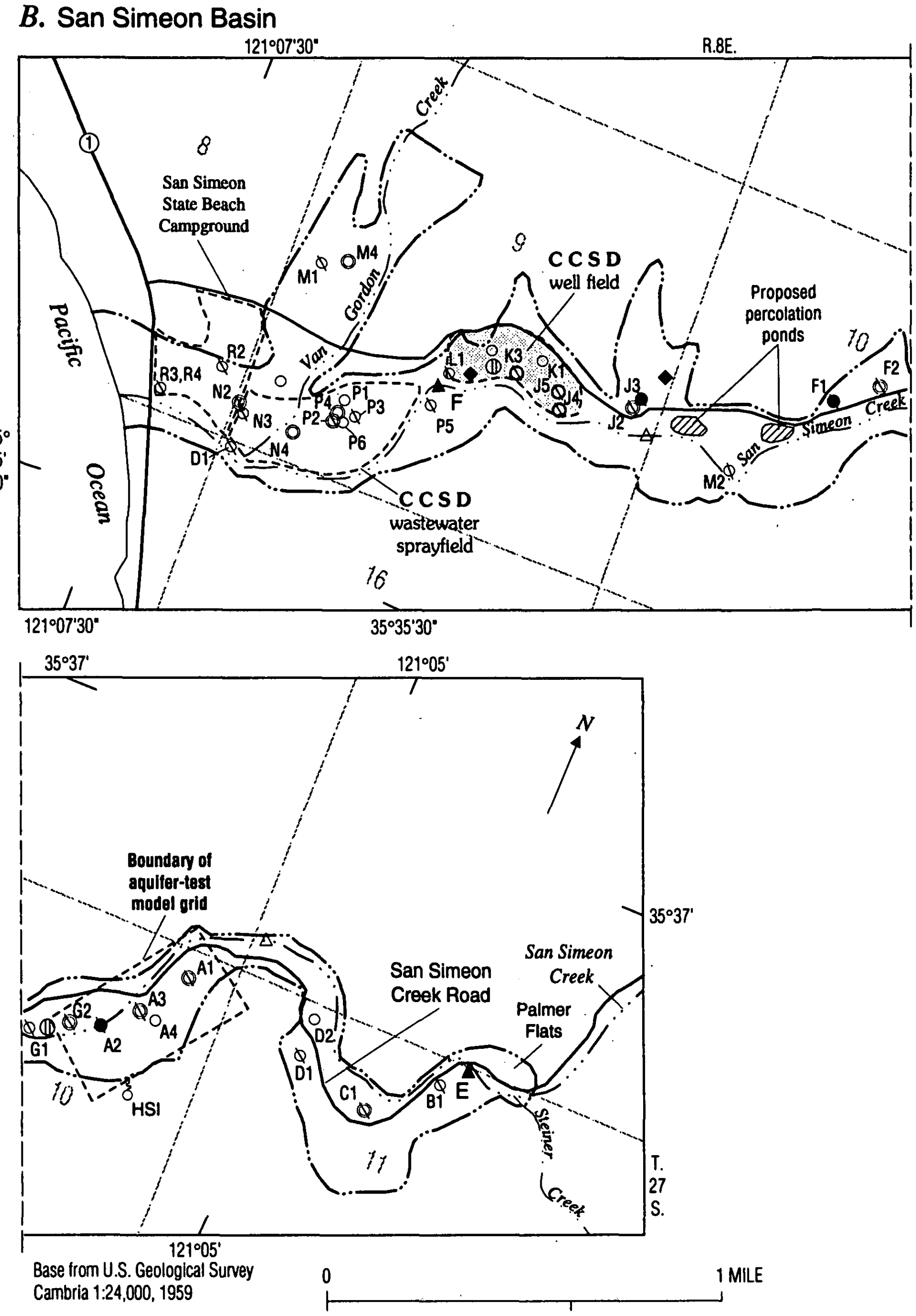


Figure 2. Locations of cultural features, wells, springs, and streamflow and climate measurement stations in (*A*) the Santa Rosa and (*B*) the San Simeon ground-water basins, San Luis Obispo County, California—Continued.

Mesozoic marine sedimentary rocks unconformably overlie the Mesozoic eugeosynclinal rocks of the Franciscan Complex. In this area, the marine sediments were thrust over the Franciscan Complex.

Surficial geology along Santa Rosa and San Simeon Creeks near Cambria is shown in figure 3. Geologic sections along the axes of the two creek valleys are shown in figure 4. Most of the area is underlain at depth by bedrock of the Franciscan Complex, an aggregation of rocks that were tectonically fragmented and mixed during the Late Cretaceous period. The Franciscan Complex is exposed on hillsides near Cambria and throughout the mountainous terrain to the east.

Numerous northwest-trending normal faults (Hall and others, 1979) cross the basins. These old faults resulted in widespread shearing and fracturing of the Franciscan rocks but do not appear to affect Quaternary deposits in the creek valleys. The Hosgri fault zone parallels the coastline about 2 mi west of the ground-water basins. The Hosgri fault zone is seismically active and could generate an earthquake of magnitude 7.0 along the segment closest to Cambria (Pacific Gas and Electric Company, 1988). An earthquake of this magnitude could cause a slight decrease in basin storage or an increase in stream base flow. Such changes were observed following the 1989 Loma Prieta earthquake about 110 mi northwest of Cambria; the terrain in these areas is similar (Wendell Ayers and Scott Hamlin, U.S. Geological Survey, oral commun., 1991).

Although the marine sedimentary rocks near the coast are nearly the same age as the rocks of the Franciscan Complex, the unnamed sandstones and shales have not undergone the tectonic disruption evident in the Franciscan Complex (Hsü, 1969).

EXPLANATION

Quaternary	Holocene	Qal	**ALLUVIAL DEPOSITES**
	Holocene and Plesistocene	Qt	**STREAM-TERRACE DEPOSITS**
		Qtu	**UNDIFFERENTIATED TERRACE DEPOSITS** - Slightly consolidated. Marine and nonmarine
Tertiary		Tu	**UNDIFFERENTIATED CONSOLIDATED ROCKS** - Crystalline felsite and marine sediments
Cretaceous	Upper Cretaceous	Ks	**SANDSTONE** - Marine, with interbedded shale
Cretaceous and Jurassic		KJf	**FRANCISCAN COMPLEX** - Consolidated rocks including melange (m) and metavolcanics (mv)

—?– – **CONTACT** - Dashed where approximately located. Queried where inferred

—?—··· **FAULT** - Dashed where approximately located. Dotted where concealed. Queried where approximately located

▲ ▲ **THRUST FAULT** - Sawteeth on upper plate

A A' **LINE OF GEOLOGIC SECTION**

K3● **WELL AND NUMBER**

⊕ **TEST HOLE**

Figure 3. Surficial geology of (*A*) the Santa Rosa and (*B*) the San Simeon ground-water basins, San Luis Obispo County, California. (See figure 4 for location of sections.)

Howell and others (1977) refer to the marine sedimentary rocks as the Cambria slab. The slab is relatively intact because it moved *en bloc* during a later episode of deformation in the Late Cretaceous period, after the episode of overthrusting and gravity sliding that deformed the Franciscan Complex.

Stream-terrace deposits, primarily of marine origin, accumulated during a high stand of sea level in the middle to late Pleistocene. These slightly consolidated deposits (unit Qtu in fig. 3) now cover much of the unnamed marine sedimentary rocks in the study area near the coast. More recent unconsolidated

A. Santa Rosa Basin

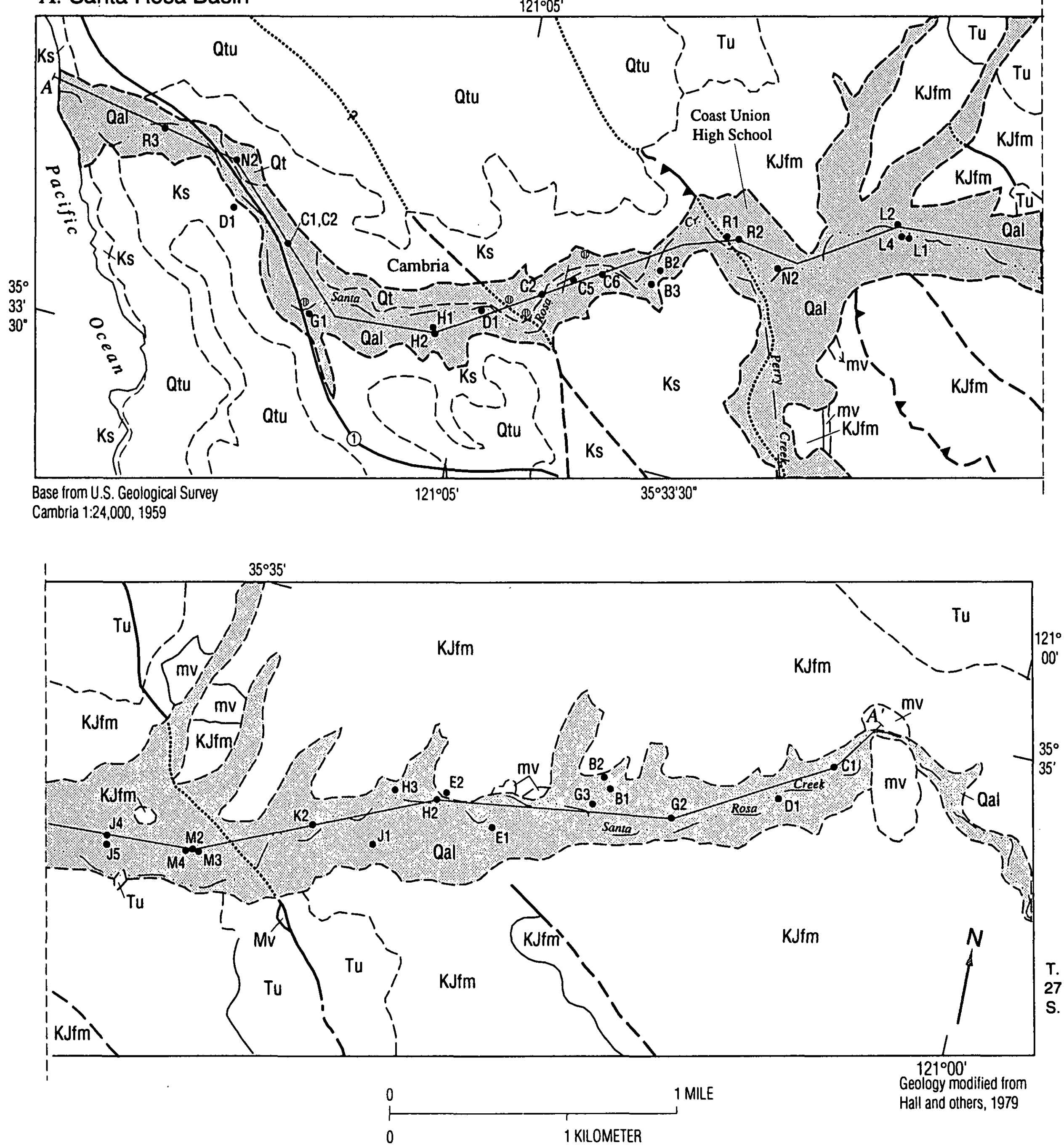


Figure 3. Surficial geology of (*A*) the Santa Rosa and (*B*) the San Simeon ground-water basins, San Luis Obispo County, California. (See figure 4 for location of sections.)—Continued.

B. **San Simeon Basin**

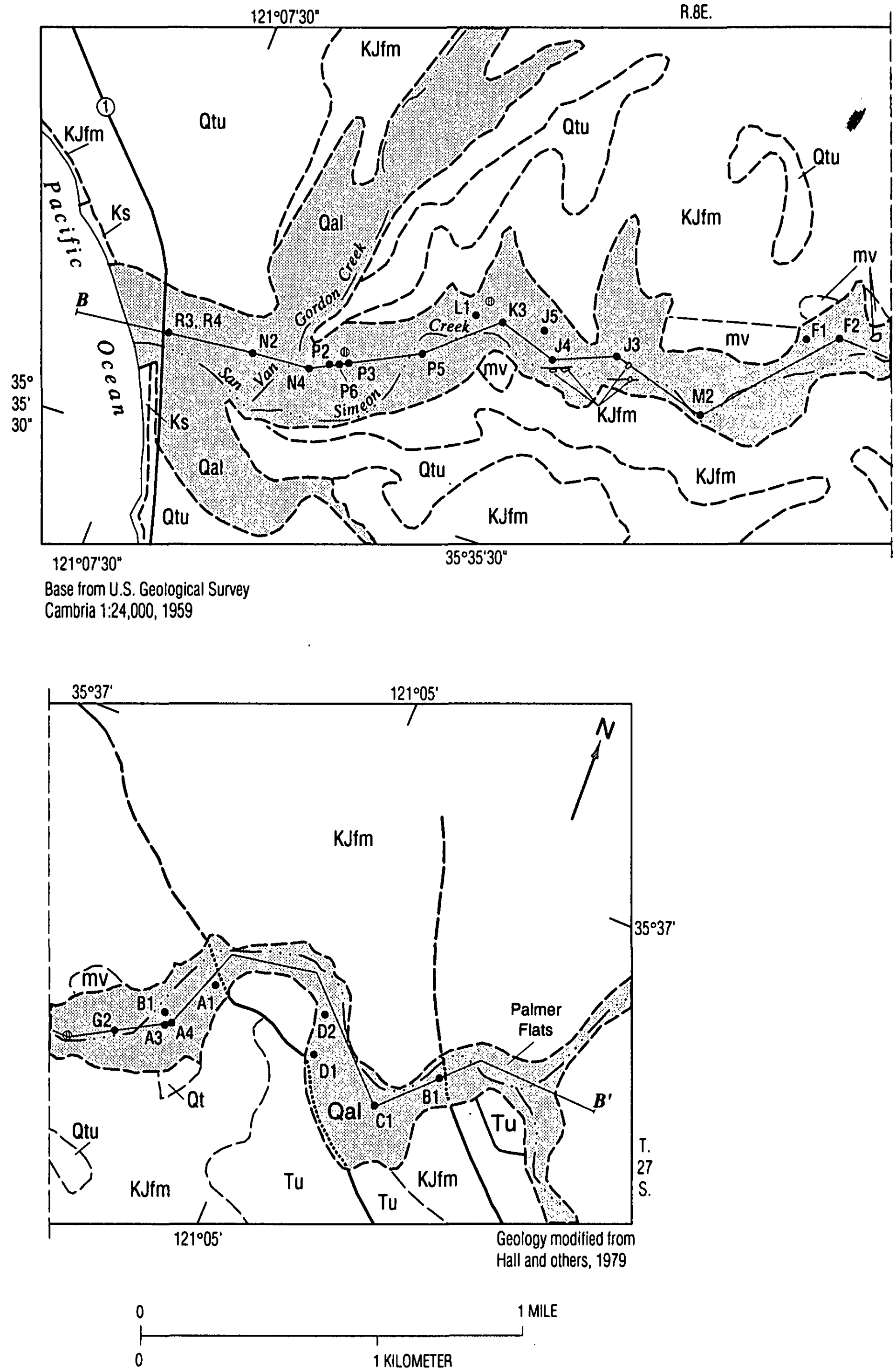
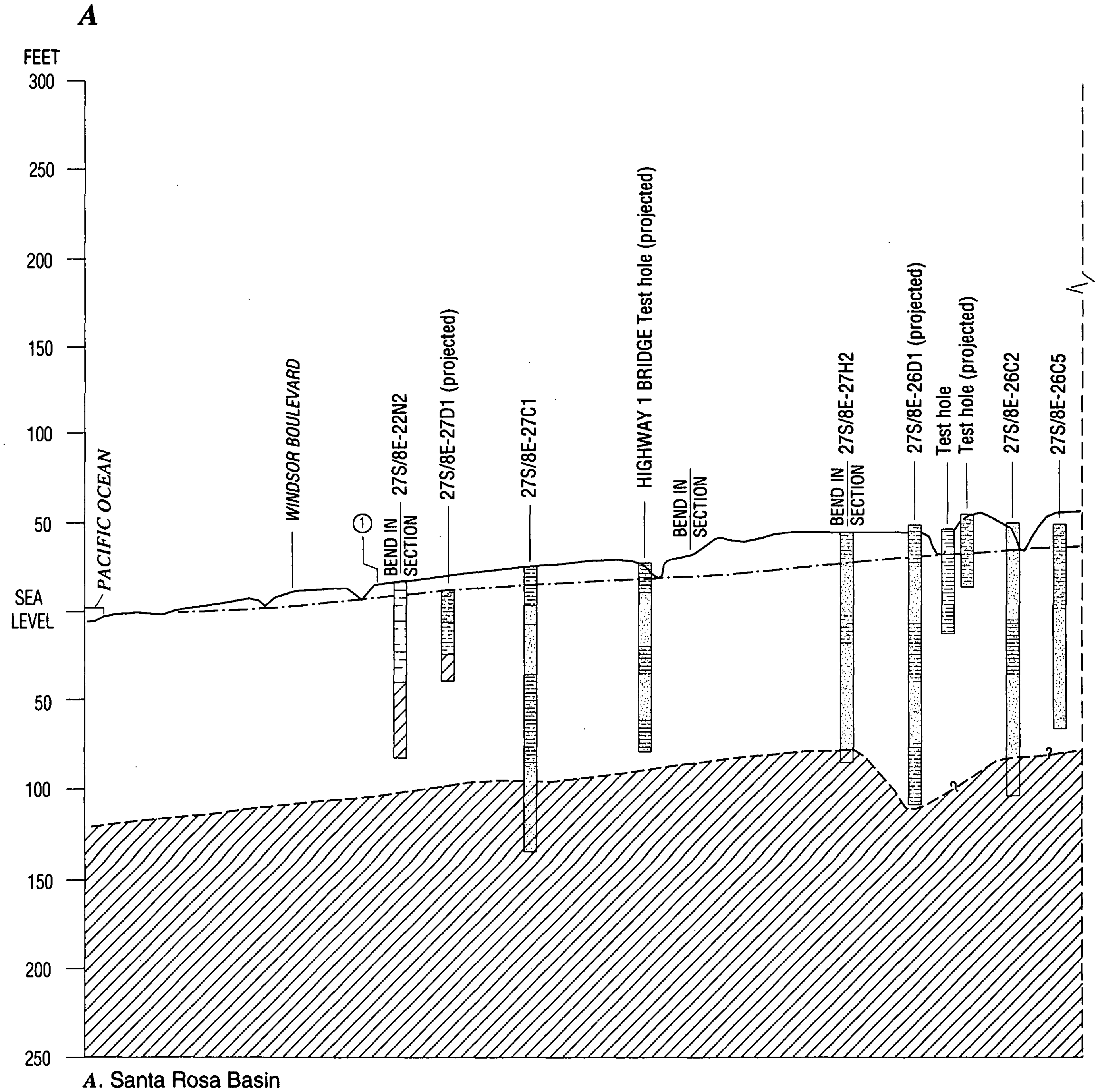


Figure 3. Surficial geology of (*A*) the Santa Rosa and (*B*) the San Simeon ground-water basins, San Luis Obispo County, California. (See figure 4 for location of sections.)—Continued.



A. Santa Rosa Basin

Figure 4. Geologic sections *A–A′* and *B–B′* along (*A*) the Santa Rosa and (*B*) the San Simeon Creek valleys, San Luis Obispo, California. (Location of sections are shown in figure 3.)

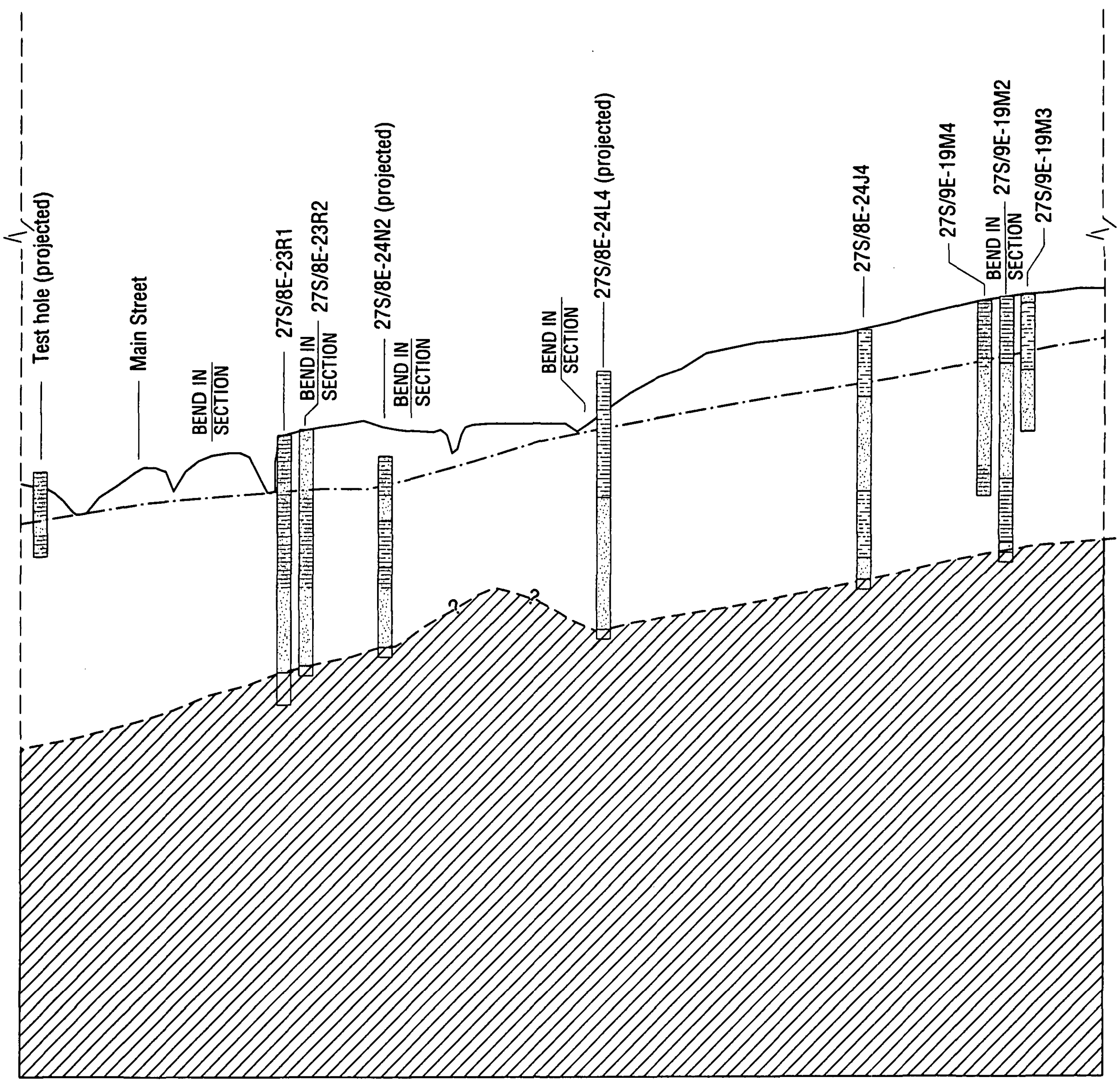


Figure 4. Geologic sections *A–A'* and *B–B'* along (*A*) the Santa Rosa and (*B*) the San Simeon Creek valleys, San Luis Obispo, California. (Location of sections are shown in figure 3.)—Continued.

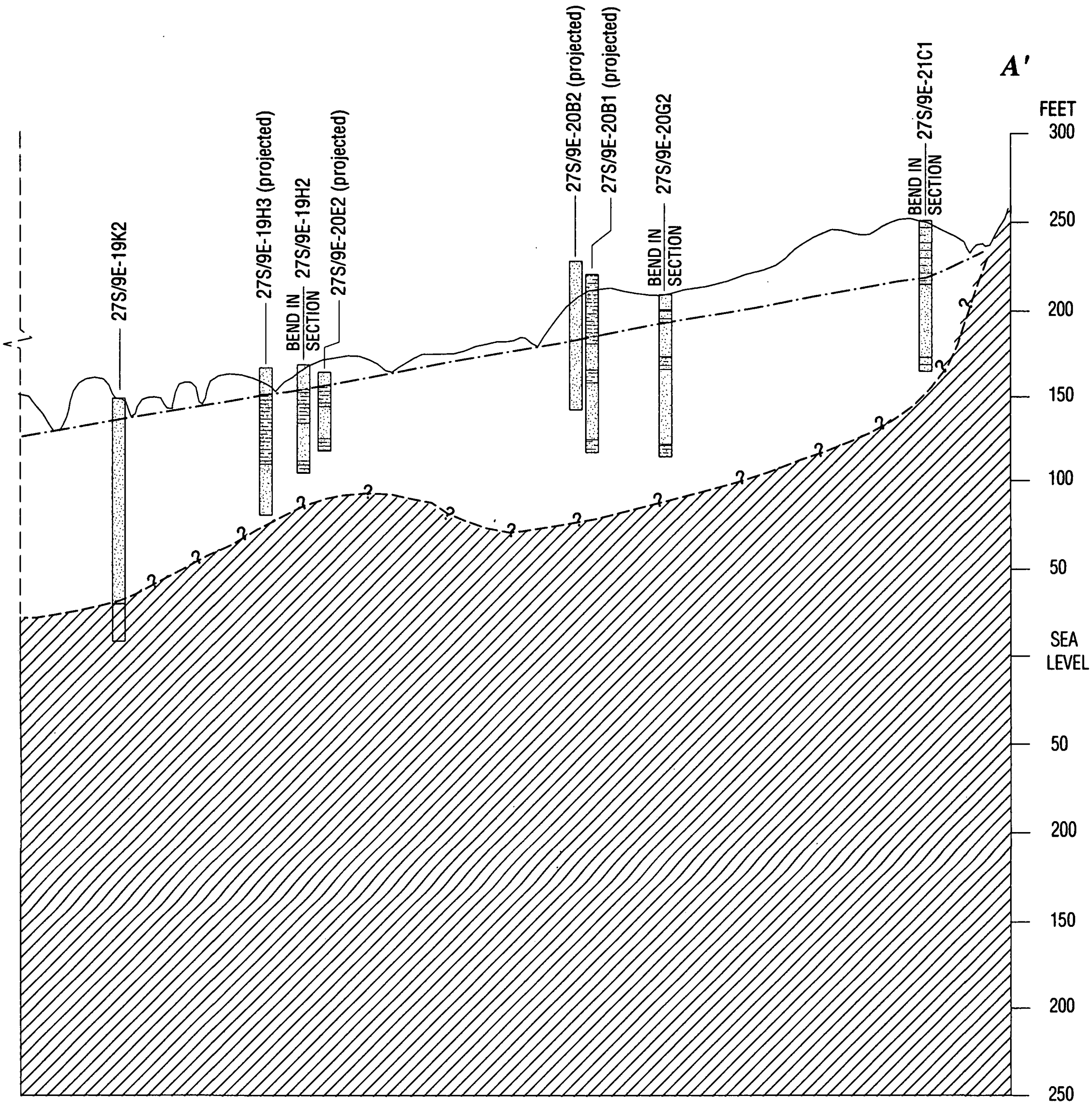
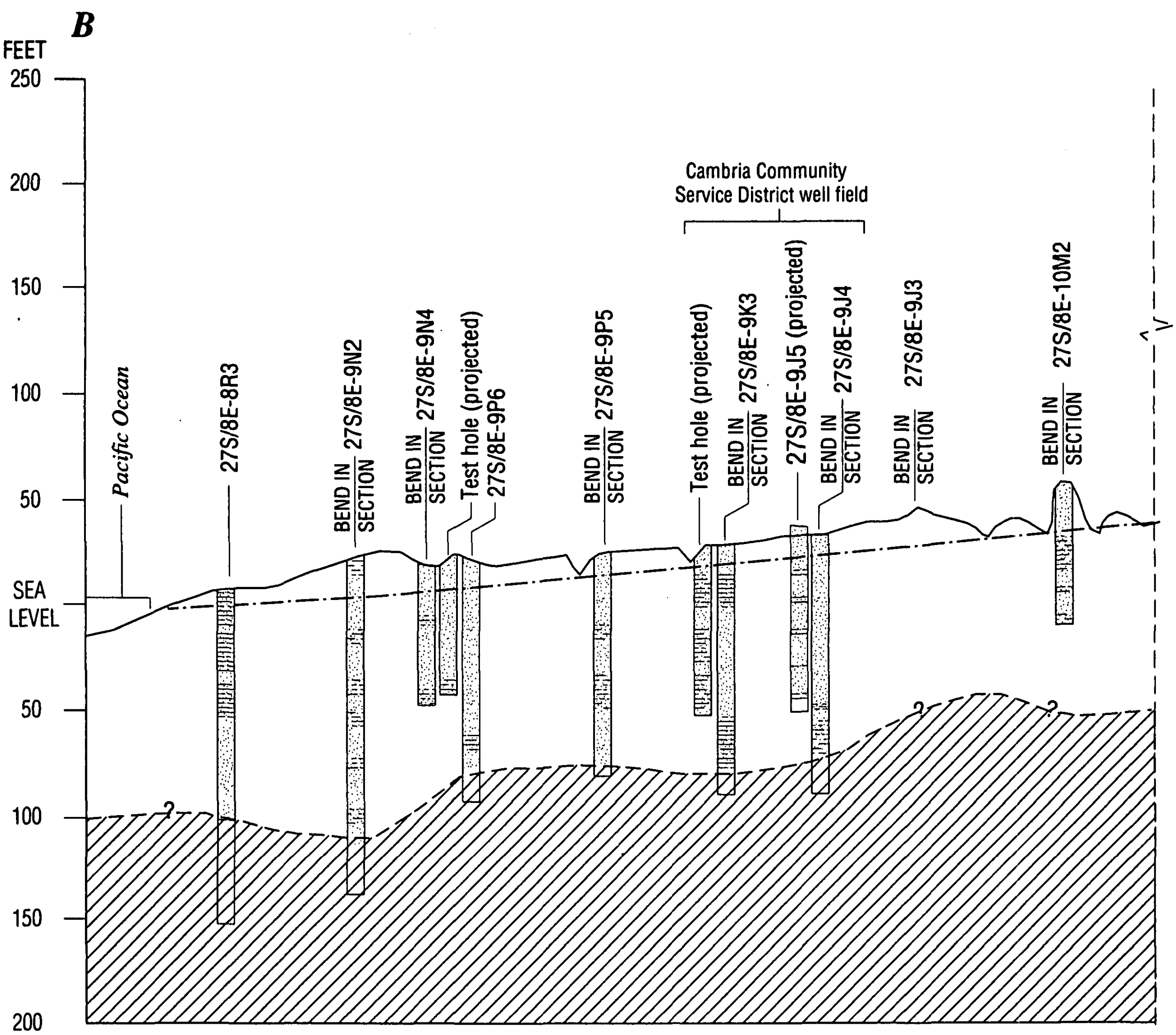


Figure 4. Geologic sections *A–A'* and *B–B'* along (*A*) the Santa Rosa and (*B*) the San Simeon Creek valleys, San Luis Obispo, California. (Location of sections are shown in figure 3.)—Continued.



B. San Simeon Basin

Figure 4. Geologic sections *A–A′* and *B–B′* along (*A*) the Santa Rosa and (*B*) the San Simeon Creek valleys, San Luis Obispo, California. (Location of sections are shown in figure 3.)—Continued.

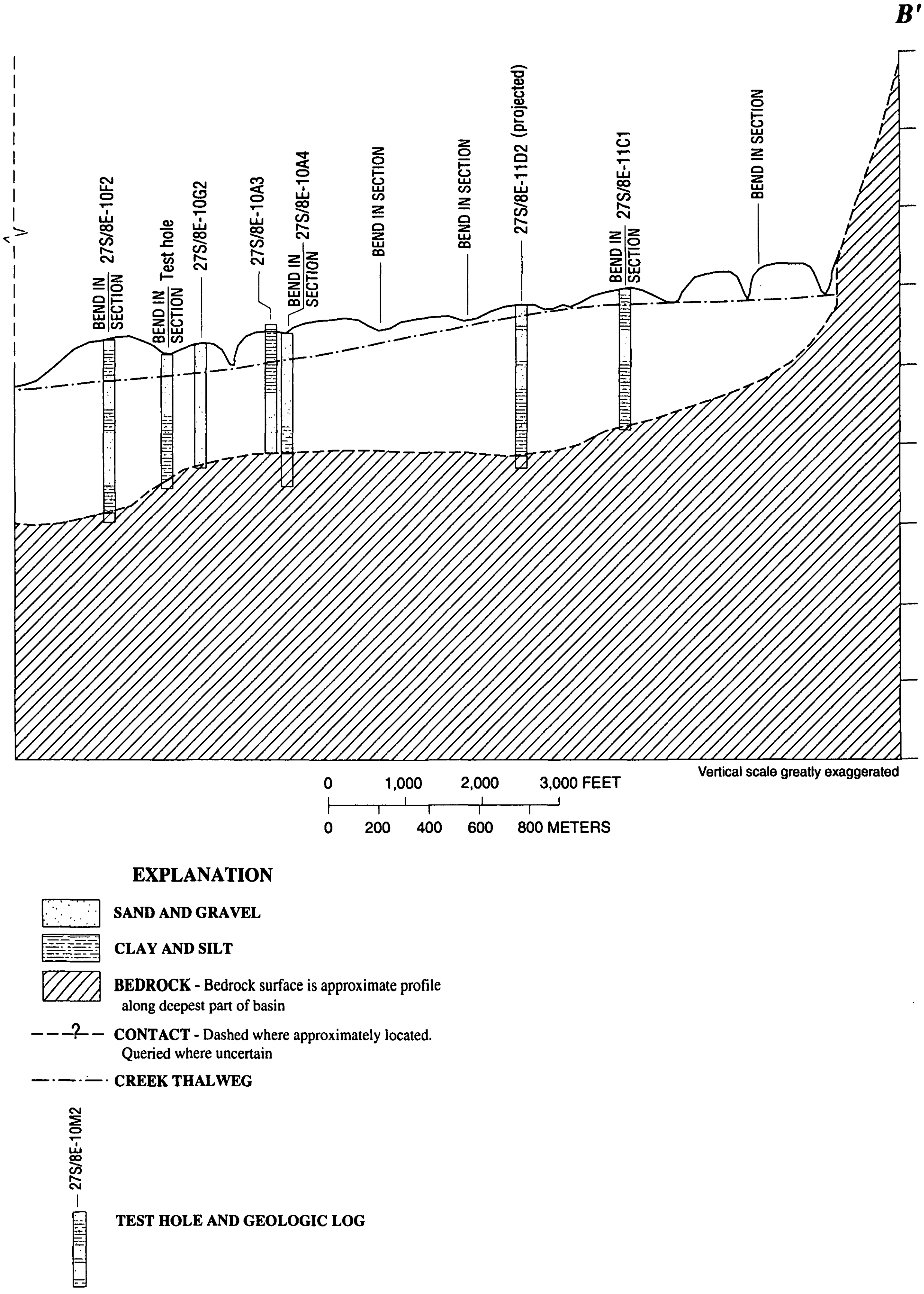


Figure 4. Geologic sections *A–A'* and *B–B'* along (*A*) the Santa Rosa and (*B*) the San Simeon Creek valleys, San Luis Obispo, California. (Location of sections are shown in figure 3.)—Continued.

alluvial and stream-terrace deposits (units Qal and Qt in fig. 3) are along the valley floors.

Ground-Water Basins

The unconsolidated alluvial and stream-terrace deposits in the Santa Rosa and the San Simeon Creek valleys form ground-water basins extending 3 to 5 mi inland from the coast. Pores between the grains of these deposits can store water. Because the pores are interconnected, this water can flow slowly from one location to another. The bottom and sides of the basins are bounded by relatively impermeable bedrock. Two principal ground-water basins underlie the Cambria area, one underlying Santa Rosa Creek downstream of well 27S/9E-21C1 and one underlying San Simeon Creek downstream of the confluence with Steiner Creek (fig. 2). A similar but much smaller basin exists beneath the final mile of Pico Creek (fig. 1) before it enters the ocean. All the basins extend an unknown distance offshore. In this report, Santa Rosa Creek, San Simeon Creek, and Pico Creek ground-water basins will be referred to as Santa Rosa Basin, San Simeon Basin, and Pico Basin, respectively.

The onshore boundaries of the basins as defined for this study are shown in figure 2. They generally follow the contact between basin fill and bedrock (fig. 3). The upper parts of several small side valleys are excluded because the basin fill is thin and does not significantly affect ground-water storage or flow in the main valleys. The basin boundaries occasionally deviate slightly into the bedrock areas in order to include most agricultural fields entirely within the basin. Contours of the bedrock surface that form the base of the ground-water basins are shown in figure 5. The total volume of unconsolidated sediments in the onshore part of the Santa Rosa Creek Basin is 66,000 acre-ft, of which 55,000 acre-ft is above sea level. The total volume of unconsolidated sediments in the onshore part of the San Simeon Creek Basin is 30,000 acre-ft, of which 16,700 acre-ft is above sea level.

Geologic Units

The geologic units of the Santa Rosa and the San Simeon Basins can be divided into two broad categories: relatively impermeable, consolidated bedrock and poorly consolidated to unconsolidated alluvial deposits. Bedrock is considered relatively impermeable because it stores and transmits much smaller quantities of water than do the more porous and permeable basin-fill deposits.

Bedrock

Bedrock in the study area consists primarily of Jurassic and Cretaceous sedimentary and low-grade metamorphic rocks of the Franciscan Complex. West of Coast Union High School in the Santa Rosa Basin, bedrock consists of an unnamed sequence of Upper Cretaceous marine sandstones and shales (fig. 3*A*). Some sedimentary and partly metamorphosed volcanic rocks of Tertiary age also are exposed but are less often in contact with the basin-fill deposits. The slightly consolidated undifferentiated terrace deposits form a relatively thin surficial layer over the Franciscan Complex and marine sediments adjacent to the basins. For this study, these also were grouped as bedrock.

The Franciscan Complex in the Cambria area generally consists of a melange of torn and sheared lenticular masses composed of graywacke, greenstone, diabase, gabbro, serpentine, chert, shale, tuff, blue schist, and other metamorphic rocks. This melange varies spatially, allowing tectono-stratigraphic units, known as the melange units, to be established (Hsü, 1969).

The predominant melange unit in the study area is composed of various size blocks and slabs of chert, greenstone, and graywacke, with the smaller blocks surrounded by a ductily deformed matrix. Larger slabs, as much as 5,000 ft in their maximum dimension, usually exhibit brittle deformation (Hsü, 1969).

In addition to the melange units, the Franciscan Complex contains large outcrops of metavolcanic rocks. These rocks commonly are associated with red chert, locally are dark red, and often are extensively sheared. Outcrops of these metavolcanic rocks form prominent hills at the eastern end of the Santa Rosa Basin and east of the confluence of Santa Rosa and Perry Creeks. Along the San Simeon Basin, metavolcanic rocks are exposed east of Palmer Flats and on the northern side between wells 27S/8E-10G2 and 9P5 (fig. 3*B*). These rocks usually are brittle and highly fractured and therefore are able to transmit some ground water. Evidence of this is confirmed by the numerous springs in the Franciscan Complex; some springs discharge enough water to meet the domestic needs of a single household.

The unnamed Upper Cretaceous sandstone is not highly deformed, and the original strata usually are preserved. Occasionally, graded bedding and laminations are disrupted by extensional shears as observed along the beach at the mouth of Leffingwell Creek (fig. 1) (Hsü, 1969). The interbedded shales in this sequence are partly fractured and show less ductile deformation than the matrix of the Franciscan melange units. These shale interbeds and their associated fractures probably are the conduits for the springs in this sequence. Overall, spring discharge in the unnamed sandstone probably is less than spring discharge in the Franciscan Complex because the unnamed sandstone is less fractured and deformed.

A. Santa Rosa Basin

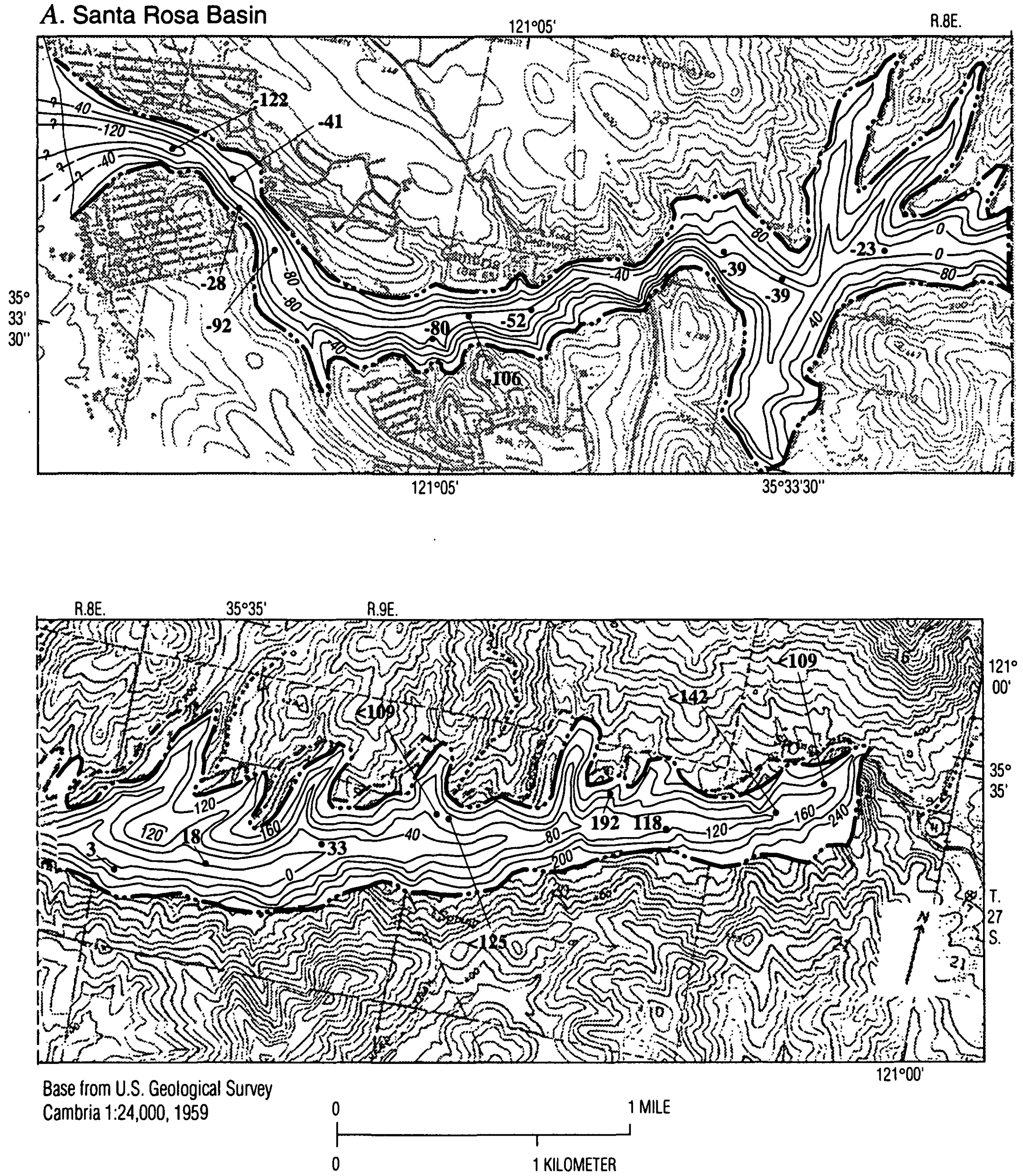


Figure 5. Altitude of the bedrock surface beneath (*A*) the Santa Rosa and (*B*) the San Simeon ground-water basins, San Luis Obispo County, California.

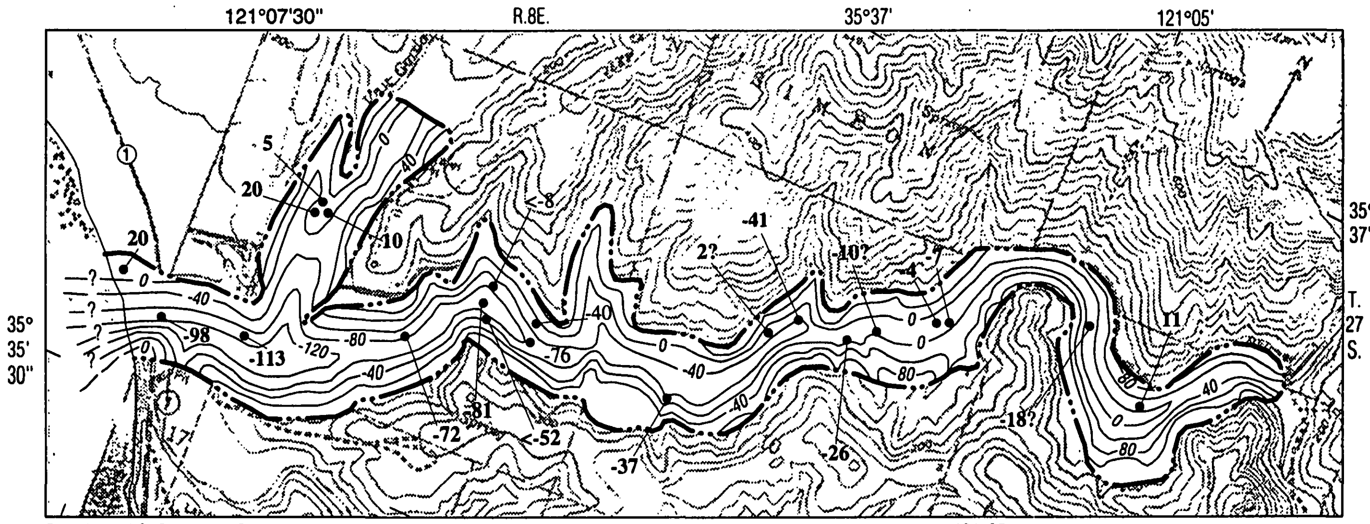
Basin Fill

Basin fill in the Santa Rosa and the San Simeon Basins consists of unconsolidated alluvial and stream-terrace deposits. Additional Quaternary sediments, primarily of marine origin, come in contact with the basin boundaries near the coast.

The alluvial and stream-terrace deposits are similar in that each consists of cobble- and pebble-size gravel, sand, silt, and clay. The stream-terrace deposits, however, are slightly older than the alluvial deposits and generally are less than 10 ft thick. The only extensive stream-terrace deposit in the study area is on the northern side of Santa Rosa Creek between wells 27S/8E-23R2 and 27C1 (fig. 3*A*). The more common alluvial deposits are often about 100 ft thick near the center of the valleys and more than 120 ft thick at the coast.

Geologic logs of wells drilled in the alluvial deposits show alternating layers of coarse- and fine-grained sediments, indicative of cyclic fluvial deposition. Layering of the basin fill is evident in the geologic sections shown in figure 4. Typically, fine-grained sediments are deposited on the flood-plain

B. San Simeon Basin



Base from U.S. Geological Survey
Cambria 1:24,000, 1959

0 — 1 MILE
0 — 1 KILOMETER

EXPLANATION

— -80 — **BEDROCK CONTOUR**-Shows estimated altitude of bedrock surface beneath the ground-water basin. Queried where uncertain. Contour interval 40 feet. Datum is sea level

—··—— **BOUNDARY OF GROUND-WATER BASIN**

-72● **WELL OR TEST HOLE**-Number indicates altitude of bedrock, in feet above or below (-) sea level estimated from well log. <, indicates well did not reach bedrock. Queried where uncertain

Topographic contour not shown inside ground-water basin boundaries

Figure 5. Altitude of the bedrock surface beneath (*A*) the Santa Rosa and (*B*) the San Simeon ground-water basins, San Luis Obispo County, California—Continued.

surfaces adjacent to the creek channel and coarse-grained sediments are deposited within the channel. Over geologic time, the channel meanders across the flood plain and produces interfingered coarse- and fine-grained deposits of varying thicknesses.

Continuity of individual layers in the basin fill greatly affects ground-water movement. Continuous coarse-grained channel deposits can allow rapid downvalley ground-water flow, and continuous fine-grained deposits can greatly impede lateral and vertical ground-water flow. Geologic logs of wells and test holes generally indicate that individual layers are variable and discontinuous. For example, logs of well 27S/8E-27H2 and two test holes in the Santa Rosa Creek valley drilled about 100 ft upstream and downstream of the well indicate that only one, upper gravel layer can be correlated among the three holes with any certainty. At depths greater than 40 to 50 ft, the layers differ remarkably (Robert Miller, driller, oral commun., Nov. 6, 1987).

Similarly, a cluster of three wells farther up the Santa Rosa Creek valley (27S/9E-19M2, 19M3, and 19M4) has a large degree of spatial variability (fig. 4*A*). The wells are within 25 ft of each other, but well logs indicate that the top 30 to 40 ft in each well varies from clay to an interbedded mixture of clays, sand, and gravel. The logs indicate there is a continuous gravel layer at greater depths, but it changes in thickness from 60 to 40 ft over a distance of less than 20 ft. In the San Simeon Basin, a similar pattern is observed. Wells 27S/8E-10A3 and 10A4 are separated by a distance of only 95 ft along a line perpendicular to the valley axis, yet only about one-half of the geologic strata seem to be correlated. For example, well 27S/8E-10A3 penetrates 27 ft of clay and gravel between the depths of 10 and 40 ft, whereas well 27S/8E-10A4 encountered no clay at this depth.

Continuity of individual layers is evident in some locations and seems to be greater in the direction parallel to the valley axis. This is the result of deposition by the creeks, which generally flow in this direction. For example, wells 27S/9E-19H3, 19H2, and 20E2 in the Santa Rosa Basin are within 450 ft of each other (fig. 4*A*), and all but one clay layer can be correlated among their respective driller's logs. In the San Simeon Basin, wells 27S/8E-9K3 and 9J4 are 630 ft apart along a line parallel to the valley axis. Their logs are much more similar than the logs for wells 27S/8E-9J4 and 9J5; these wells are only 250 ft apart, but along a line nearly perpendicular to the valley axis.

An exception to this pattern can be seen in drillers' logs of wells near Coast Union High School in the Santa Rosa Basin. Two wells at the high school (27S/8E-23R1 and 23R2) are about 150 ft apart along a line nearly parallel to the valley axis, yet only a 35-foot basal gravel layer can be correlated between them. The upper 90 ft of sediments in well 27S/8E -23R1 consists almost entirely of clays with only small amounts of sand. In contrast, the upper 90 ft of sediments in well 27S/8E-23R2 consists of alternating layers of sand and gravel, sandy clay, and sand with only 35 ft of sandy clay. Perhaps the sediments deposited by Perry Creek disrupt the normal patterns of continuity in this area.

An extensive, continuous clay layer might be present near the high school. Previous investigations by Envicom Corporation (1981) indicated an apparent correlation of geologic logs for wells 27S/8E-23R1 and 24J1. However, logs for newer wells in the same area (27S/8E-23R2 and 24N2) contain significantly higher percentages of coarse-grained deposits. When the additional logs are incorporated into the geologic section (fig. 4*A*), the clay layer is not as continuous or extensive as previously thought. However, the 30- to 35-foot-thick basal gravel seems to be continuous between the wells and downstream as far as well 27S/8E-27H2.

In the San Simeon Basin, drillers' logs do not show any obviously continuous clay layers. At the upper end of the basin, alluvial deposits at depths greater than about 50 ft are finer grained than shallow deposits. The pattern is similar near the CCSD well field, where several well logs show fine-grained deposits near the bottom of the basin. Fine-grained deposits appear at various depths between the well field and the coast and cannot be correlated with certainty between wells.

Water Levels

Seasonal water-level fluctuations can be used to infer the location and relative magnitude of inflows and outflows to and from the ground-water basins. Seasonal fluctuations are evident in monthly water-level data collected since 1978 by the Cambria Community Services District at about 36 wells, most of which are in the San Simeon Basin. For this study, water levels were measured monthly between March 1988 and April 1989 at an additional 26 wells, most of which are in the Santa Rosa Basin. Water levels at 31 wells were measured as often as daily during and shortly after a major storm on December 23–26, 1988. Measuring-point altitudes were surveyed from local bench marks.

Water-level hydrographs for eight wells in the Santa Rosa Basin and eight wells in the San Simeon Basin for January 1988 through March 1989 are shown in figure 6. Most of the hydrographs show a large seasonal drawdown beginning in spring and increasing steadily until early November. Hydrogeologic sections of ground-water levels along the length of the valleys are shown in figure 7. These sections follow the same lines as the geologic sections presented earlier (fig. 4). Seasonal water levels were highest in March 1988 and lowest at different times between mid-October and mid-December 1988, depending on location. Water levels from the latter dates are combined to form a single profile representing the minimum seasonal water level.

Seasonal water-level declines are caused by a combination of increased pumping and decreased streamflow during the summer dry season. At the upper ends of the basins, natural downvalley drainage of ground water causes large dry-season declines. Rapid water-level declines begin when the total basinwide pumping rate becomes larger than the rate of streamflow entering the basin. This occurred between March and April 1988 in the Santa Rosa Basin and between April and May 1988 in the San Simeon Basin when streamflow entering the basin was about 1.3 ft^3/s. During February through April, water levels declined less than about 1 ft/mo in both basins. During June through August, the rate of water-level decline increased to between 3 and 7 ft/mo in most areas.

During November and early December 1988, the rate of water-level decline slowed or even reversed slightly at most wells. The creeks were still dry during that period, and water levels reflected the balance between decreased pumping rates and the small but relatively steady inflow of ground water from bedrock along the sides of the valleys.

After a few days of small sporadic flows, streamflow began with a large flow peak on December 24, 1988. Water-level response to the onset of streamflow was immediate, and water levels recovered as much as 19 ft in 4 days. In most wells, more than 90 percent of the winter water-level recovery was during the first 2 weeks of streamflow.

Dry-season drawdown during 1988 was small at several locations. Seasonal drawdown within about 2,000 ft of the coast was less than 5 ft in both basins because of the absence of nearby pumping and because the creek and ocean limit the range of natural water-level fluctuations (see, for example, well 27S/8E-16D1, fig. 6*A*). Drawdown was less than about 2 ft at two inland locations along Santa Rosa Creek near wells 27S/9E-19H2 and 27S/8E-24L2. The lack of drawdown at these locations probably is caused by subsurface obstructions to ground-water flow downstream of the wells. The relatively impermeable obstructions act like dams, causing a stairstep in the downvalley water-level profile (fig. 7) and forcing ground water to emerge as surface flow in the creek. Water levels in the uppermost part of the valley, upstream of well 27S/9E-19H2, rise nearly to the level of the thalweg when the creek flows in winter, then gradually recede in summer to a nearly flat profile level with the obstruction (fig. 7*A*). The obstruction near well 27S/8E-24L2 prevents the dry-season pumping depression near municipal wells 27S/8E-26C5 and 26D1 from significantly affecting wells upstream of the obstruction. The creek probably serves as the principal means by which ground water moves past the obstructions.

The obstructions conceivably could be caused by thick, localized clay deposits, faults, or buried bedrock ridges that decrease the cross-sectional area of the basin. The valley probably always has been too steep and narrow to favor deposition of clay materials by Santa Rosa Creek; however, a landslide from an adjacent hillslope could have created a thick, localized deposit of fine-grained sediments. Previous geologic investigations did not identify any faults young enough to have affected the basin-fill deposits (Hall and others, 1979; Pacific Gas and Electric Company, 1988). The shape of the hillsides near the obstructions indicates that shallow, buried bedrock ridges are a possible cause of the obstructions. These ridges could be more pronounced than indicated in the bedrock contour map (fig. 5) and geologic sections (fig. 4).

Bedrock constrictions in two locations along San Simeon Creek steepen the downvalley water-level profile but do not force ground water to emerge as surface flow in the creek. The first location is along the narrow canyon between wells 27S/8E-10A1 and 11D1. The water-level profile upstream of the canyon shows a pattern of seasonal filling and recession similar to, but less pronounced than, the one at the upper end of the Santa Rosa Basin (fig. 7*A*). The second location, locally known as "Holland Gap," is between wells 27S/8E-9J3 and 9J4 at the upstream end of the CCSD

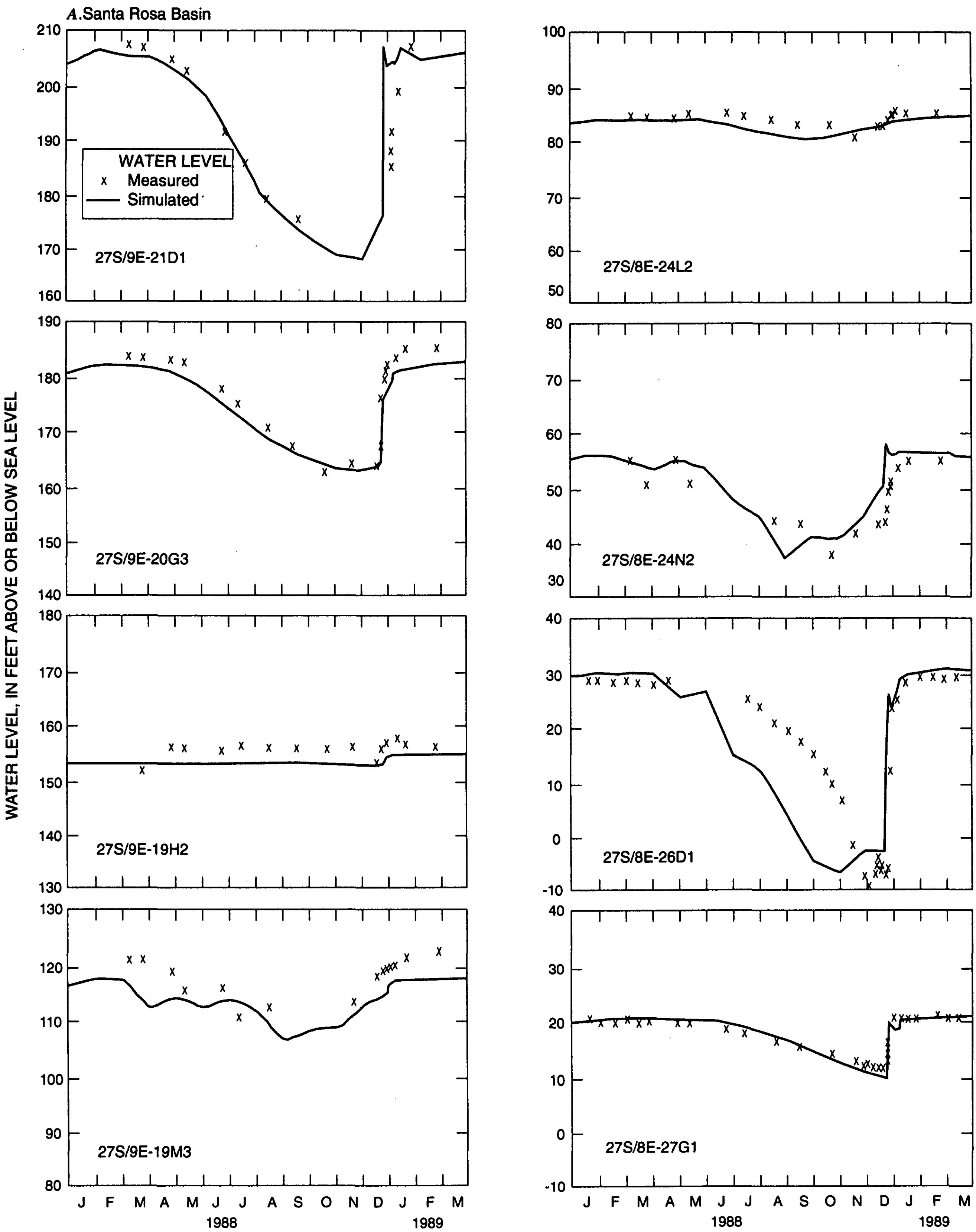


Figure 6. Measured and simulated water levels for selected wells in (*A*) the Santa Rosa and (*B*) the San Simeon ground-water basins, San Luis Obispo, California, January 1988 through March 1989.

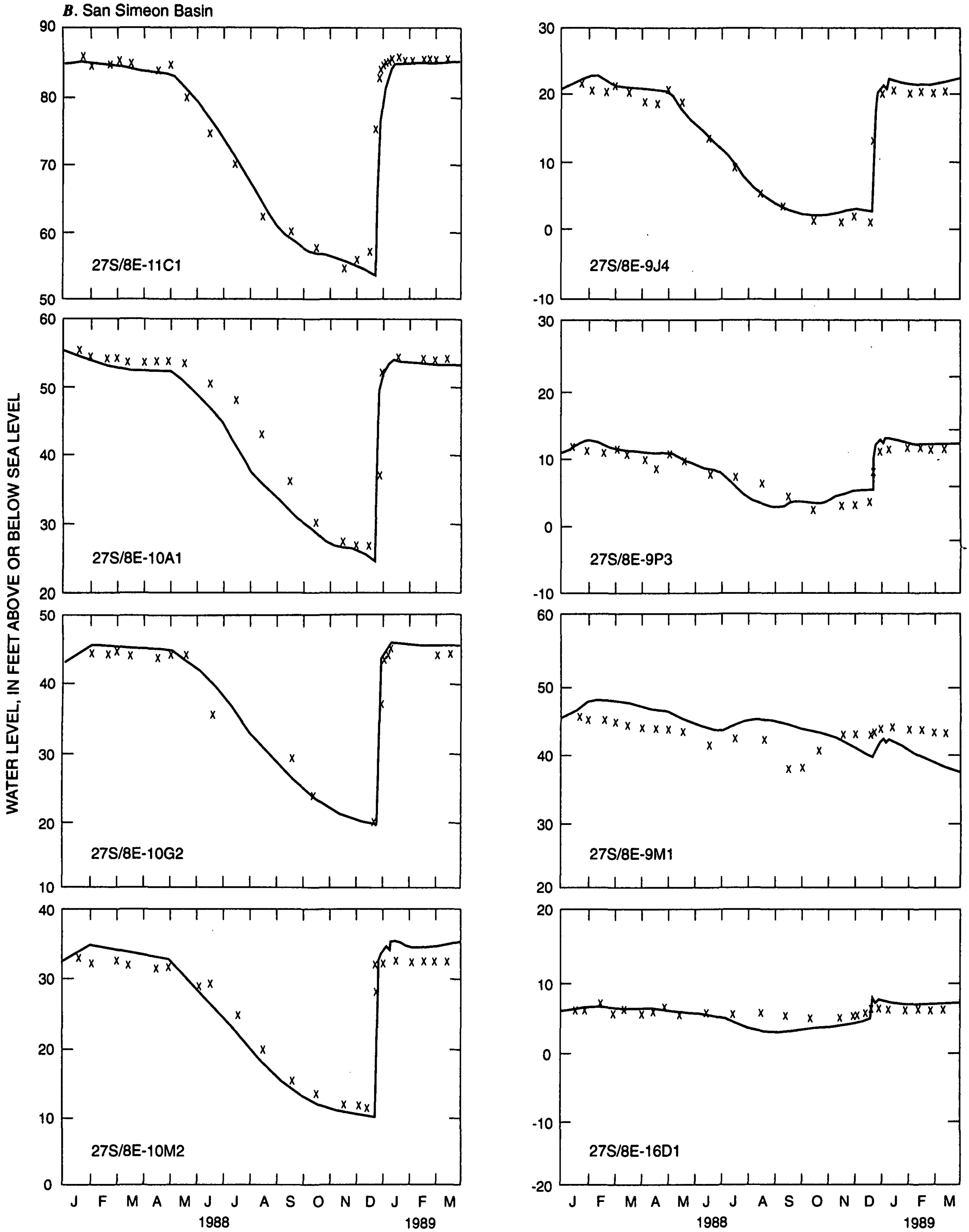
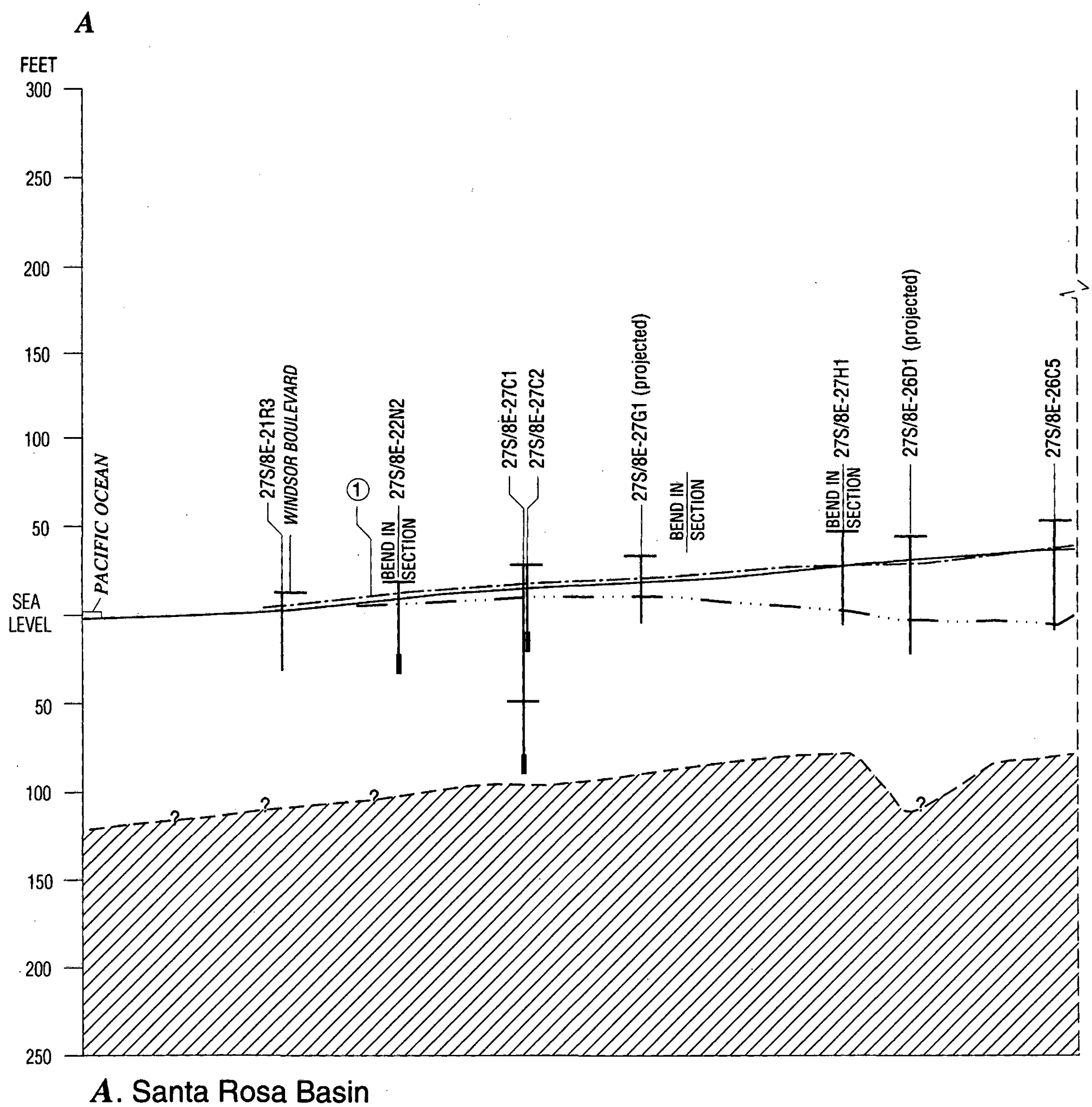


Figure 6. Measured and simulated water levels for selected wells in (*A*) the Santa Rosa and (*B*) the San Simeon ground-water basins, San Luis Obispo, California, January 1988 through March 1989—Continued.



A. Santa Rosa Basin

Figure 7. Ground-water levels for wells along the length of (*A*) the Santa Rosa and (*B*) the San Simeon ground-water basins, San Luis Obispo, California. (Location of sections are shown in figure 3.)

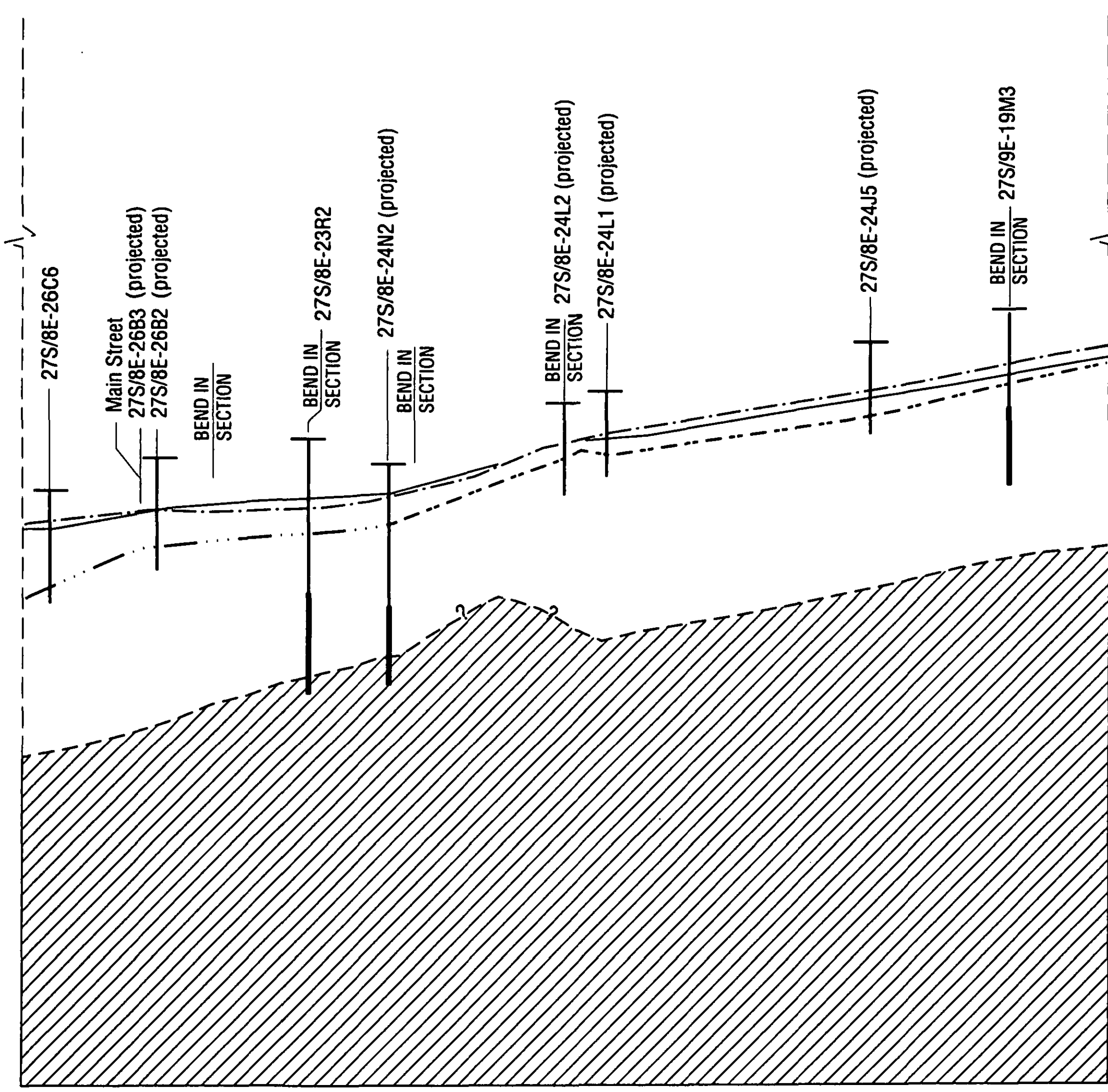


Figure 7. Ground-water levels for wells along the length of (*A*) the Santa Rosa and (*B*) the San Simeon ground-water basins, San Luis Obispo, California. (Location of sections are shown in figure 3.)—Continued.

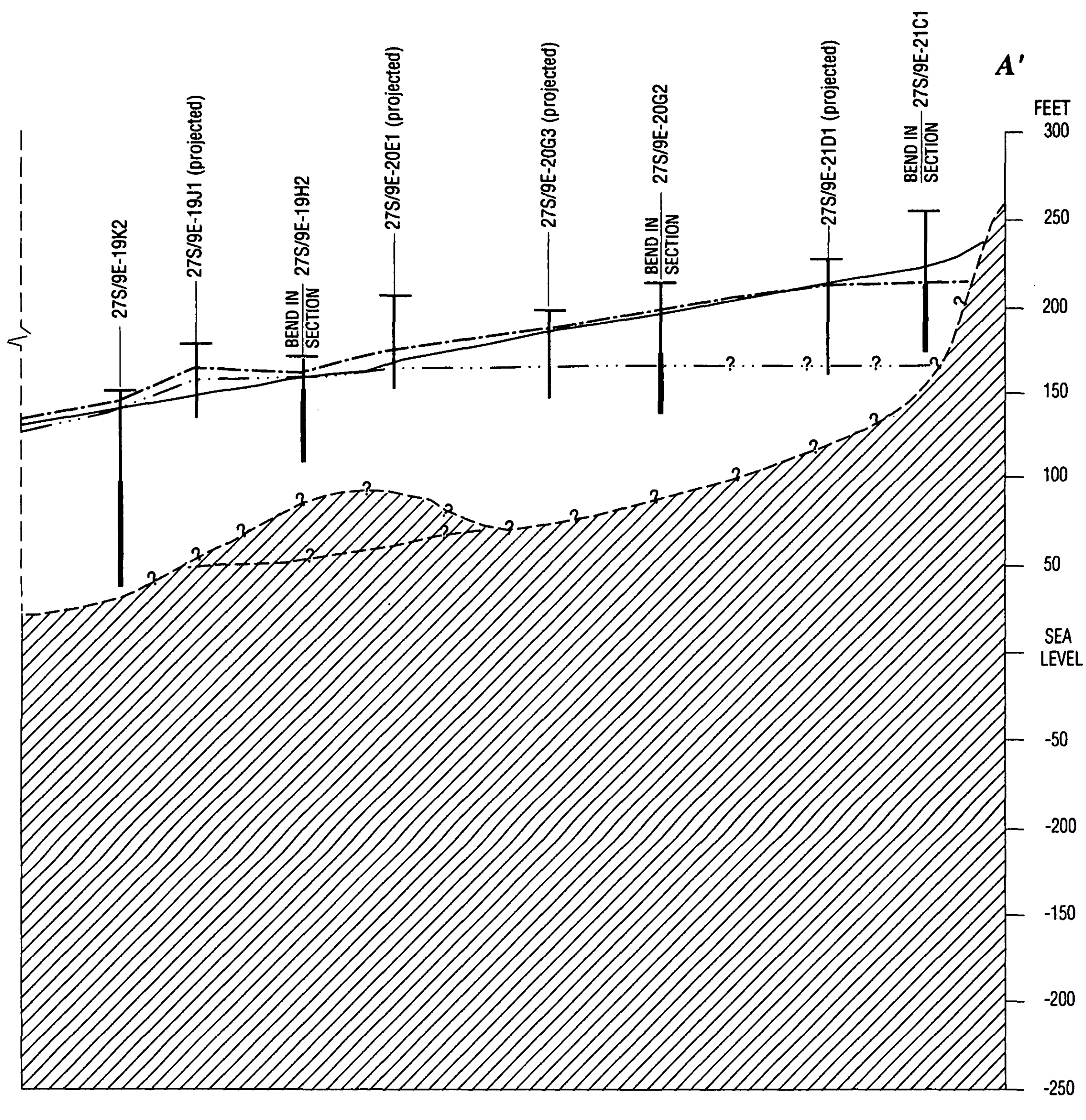
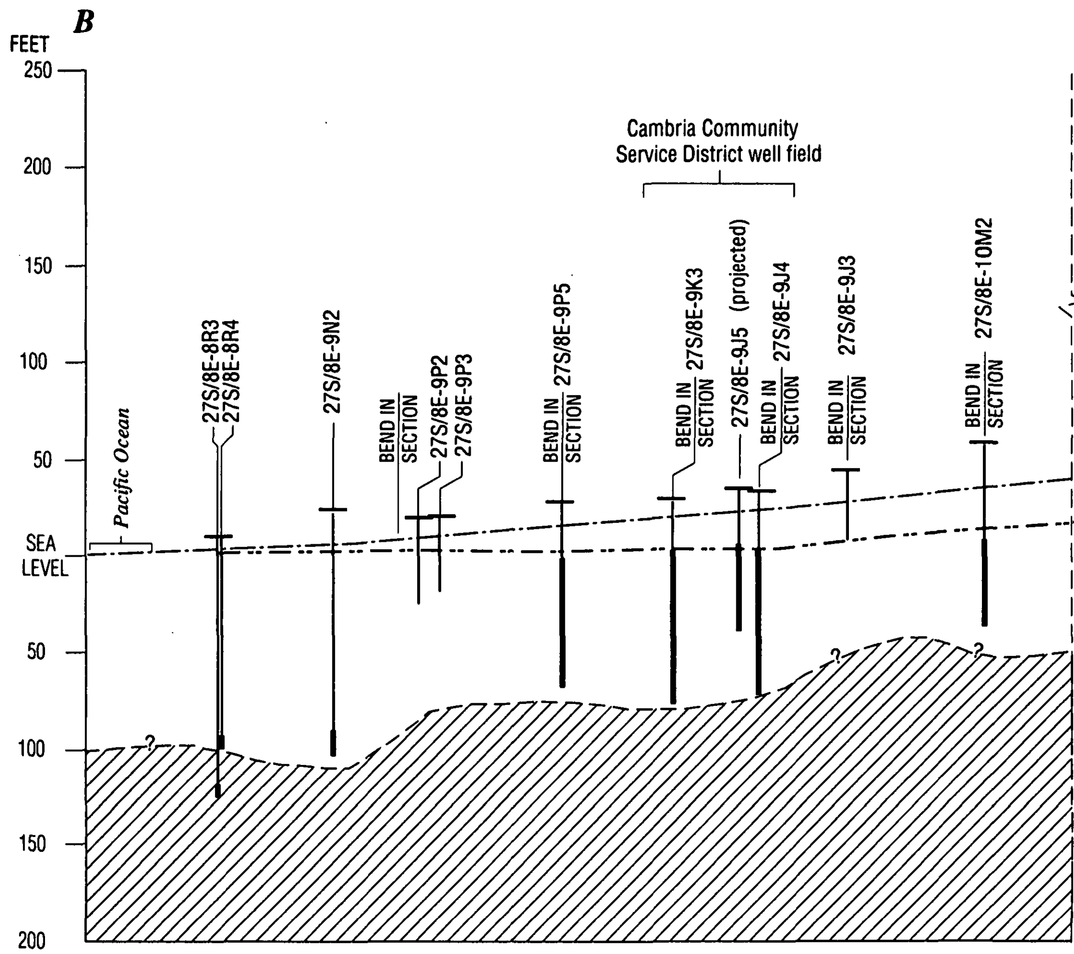
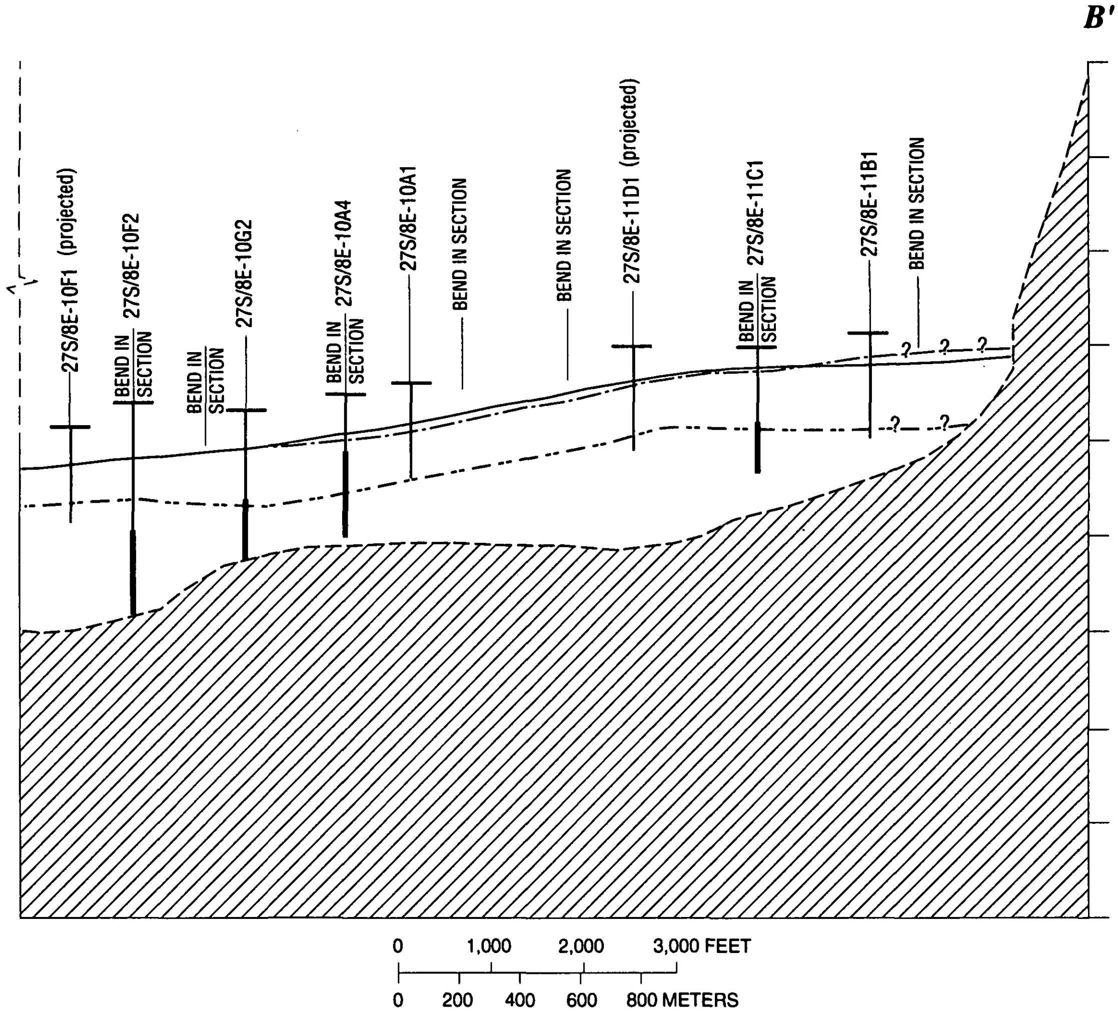


Figure 7. Ground-water levels for wells along the length of (*A*) the Santa Rosa and (*B*) the San Simeon ground-water basins, San Luis Obispo, California. (Location of sections are shown in figure 3.)—Continued.



B. San Simeon Basin

Figure 7. Ground-water levels for wells along the length of (*A*) the Santa Rosa and (*B*) the San Simeon ground-water basins, San Luis Obispo, California. (Location of sections are shown in figure 3.)—Continued.



EXPLANATION

BEDROCK - Bedrock surface is approximate profile along deepest part of basin

CONTACT - Dashed where approximately located. Queried where uncertain

CREEK THALWEG

MINIMUM WATER LEVEL DURING 1988

March 14,1988 (San Simeon Basin) and March 22-23, 1988 (Santa Rosa Basin). Queried where uncertain

November 15,1988 (San Simeon Basin) and October 18-21, 1988 (Santa Rosa Basin). Queried where uncertain

December 13-16, 1988 (Santa Rosa Basin). Queried where uncertain

27S/8E-10A1

WELL AND PERFORATED INTERVAL-Horizontal line is land surface. Heavy line is perforated interval

Figure 7. Ground-water levels for wells along the length of (*A*) the Santa Rosa and (*B*) the San Simeon ground-water basins, San Luis Obispo, California. (Location of sections are shown in figure 3.)—Continued.

well field (fig. 7*B*). Small bedrock outcrops in the creekbed and near the road indicate that ground water must flow through a relatively narrow notch in the buried bedrock surface.

A large seasonal pumping depression occurred in 1988 near municipal wells 27S/8E-26C5 and 26D1 in the Santa Rosa Basin. The combined discharge from these wells was fairly constant from June through December 22, 1988, and was equivalent to a continuous pumping rate of 235 gal/min. Effects of the pumping were evident as far upstream as well 27S/8E-24N2 and as far downstream as well 27S/8E-21R3 (fig. 7*A*). Although static water levels at the pumping wells declined as much as 11.6 ft below sea level in late autumn, water levels between those wells and the coast remained higher. The lowest water level in well 27S/8E-27G1 was about 10 ft above sea level (fig. 6*A*).

A pumping depression was similar but smaller at the CCSD well field in the San Simeon Basin. Water levels in the well field declined to a minimum of about 1.5 ft above sea level. Water levels between the well field and the coast are elevated by recharge from the CCSD wastewater sprayfield. However, regulatory constraints limit the buildup of the recharge mound to no more than about 1 ft above water levels in the well field.

Water-level gradients across the valleys generally are steeper than those along the valleys. There are few wells along the sides of the valleys, but cross-valley gradients can be estimated by comparing water levels in wells with the water surface in the creek. During the winter flow season, the creek surface and the adjacent water table are at about the same altitude. By this method, cross-valley water-level gradients in March 1988 ranged from almost 0 to 0.958 and averaged about 0.027. Downvalley water-level gradients were smaller, ranging from about 0.002 to 0.008 and averaging less than 0.006. When the creeks are flowing, downvalley gradients are controlled by the slope of the creek channels.

Vertical water-level gradients within the basin-fill deposits are small in most locations because most municipal and irrigation wells penetrate virtually the entire basin thickness. The wells draw water from all depths and, consequently, do not tend to create vertical water-level gradients. Vertical gradients could be measured accurately only at three locations where multiple-depth monitoring wells were installed for this study. Wells 27S/8E-8R3 and 8R4 in the San Simeon State Beach campground (fig. 2*B*) are perforated at depths of 130 to 140 ft and 85 to 95 ft, respectively. Water levels in both wells show pronounced tidal fluctuations with a maximum amplitude of about 1 ft. The fluctuations at the two depth intervals are slightly out of phase, so that the vertical gradient alternates from upward to downward. The wells are 500 ft from the ocean and only 25 ft from a ponded area where San Simeon Creek reaches the beach. Water levels in both wells are consistently higher than the water level in the pond, with upward gradients ranging from about 0.001 to 0.010 ft/ft. The upward gradient probably results from fresh ground water flowing upward over the wedge of relatively dense seawater that is at the base of the aquifer near the coast.

Slightly farther upstream, a large downward vertical gradient is created by the CCSD wastewater sprayfield operation. In 1988, the water level in a 20-foot-deep piezometer well (27S/8E-9N3) was within 2 ft of the land surface and was 13 to 16 ft higher than the water level in nearby well 27S/8E-9N2, which is perforated at a depth of 117 to 127 ft below land surface. The downward gradient resulted from a combination of high recharge rates at the land surface and deep pumping from wells several hundred feet upstream.

A small upward vertical gradient also is evident at wells 27S/8E-27C1 and 27C2 in the Santa Rosa Basin. The wells are perforated at depths of 105 to 115 and 40 to 50 ft below land surface, respectively. The wells are 4,500 ft from the coast, but water levels are not noticeably influenced by tides. The vertical gradient was consistently upward with a magnitude of about 0.009 ft/ft. The gradient reversed for a few days following a flood peak on December 24, 1988. At this location, the upward gradient might not result from discharge of fresh ground water over a saltwater wedge. Digital simulation of the ground-water-flow system indicated that ground water is forced upward and into the creek by a constriction in the aquifer downstream of the wells. Between the constriction and the coast, the gradient reverses and water tends to seep from the creek back into the aquifer.

Long-term water-level hydrographs for four locations are shown in figure 8. Winter water levels are about the same every year because even a small quantity of streamflow is sufficient to recharge the ground-water basins fully. After the rapid recovery of ground-water levels during the first few weeks of the streamflow season, additional recharge from the creek is rejected. Water levels near the creek stabilize at about the level of the creek surface, which remains fairly constant except during storms. Water year 1977 was an exception; total annual creek discharge was only about 5 percent of normal. Semiannual water-level measurements in spring 1977 indicated that water levels at many wells did not fully recover during the winter.

The Santa Rosa and the San Simeon Basins differ from larger or less developed basins in that annual inflows and outflows are a large part of the total quantity of ground water in storage. Thus, the basins could not sustain a significant excess of outflow over inflow without going completely dry in a few years.

Two long-term water-level trends have occurred in recent years, but neither is necessarily indicative of a long-term imbalance between inflow and outflow. The first is a small, gradual decline in winter water levels in the middle part of the San Simeon Basin between wells 27S/8E-10A1 and 9L1 (see, for example, well 27S/8E -10G1, fig. 8). During 1978–87, the average rate of long-term decline in winter water levels at five wells was 0.35 ft/yr. The most likely cause of the decline was increased winter pumping rates at the CCSD well field. Total pumpage for January through March increased an average of 8.4 acre-ft/yr during 1979–88. The trend was greater than zero at the 0.05 level of significance. Increased pumping in winter induces increased seepage from the creek, but water levels are lowered slightly in the process. This relation was confirmed by model simulations described later in the report.

The second trend is a steady increase in the dry-season water-level decline near the CCSD well field on San Simeon Creek (27S/8E-9L1, fig. 8). This trend is caused largely by the steady increase in dry-season pumpage at the well field since the late 1970's. Agricultural pumpage also increased rapidly in the

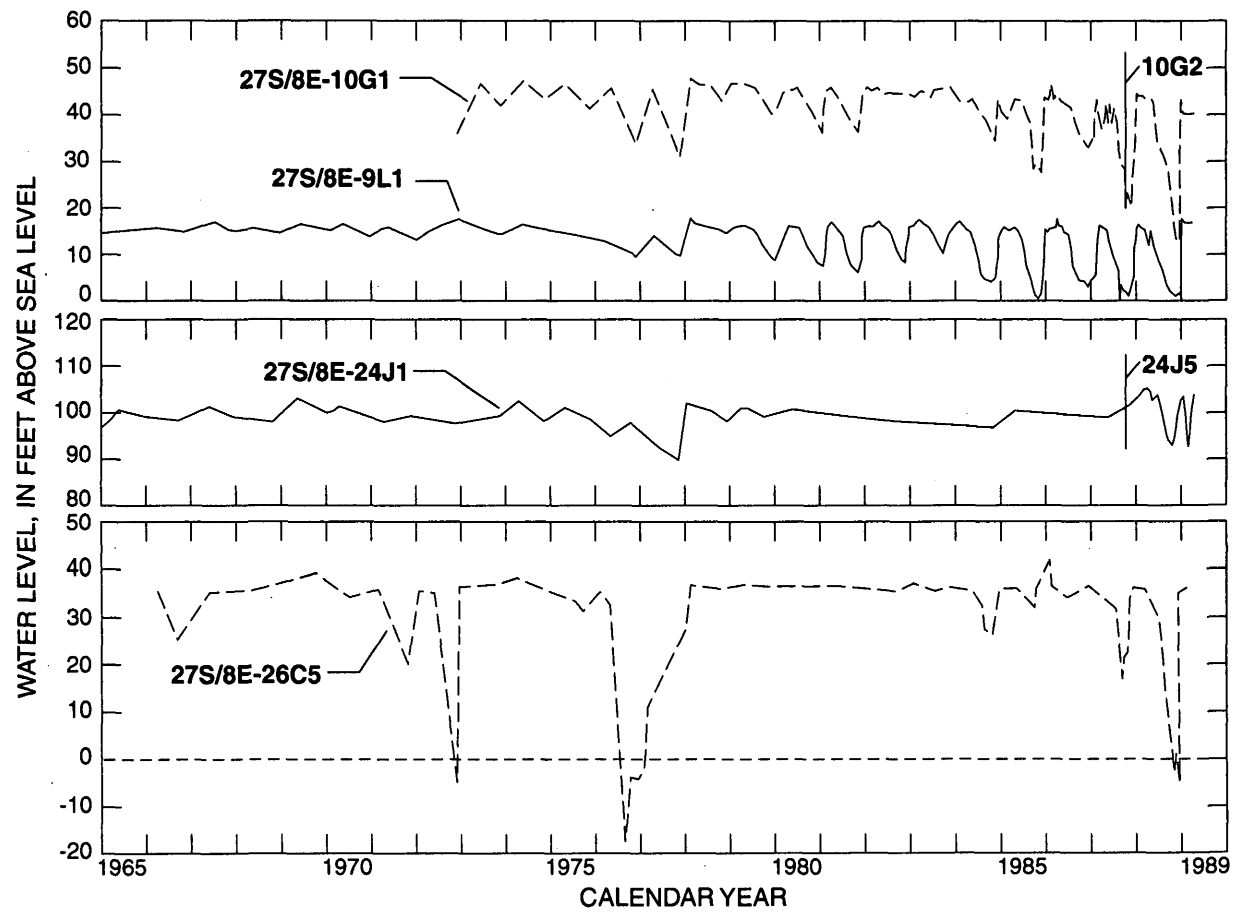


Figure 8. Water levels in four wells in the Santa Rosa and the San Simeon ground-water basins, San Luis Obispo County, California, 1965–89.

early 1980's because of a shift from dry-farmed to irrigated crops. This contributed to the increase in dry-season water-level declines since that time (27S/8E -10G1, fig. 8).

Transmissivity and Storage Coefficient

Transmissivity (*T*) describes the ease with which ground water flows through an aquifer and equals the product of aquifer thickness and hydraulic conductivity. Hydraulic conductivity (*K*) in units of feet per day is the quantity of water that will flow through 1 ft^2 of cross-sectional area of an aquifer under a water-level gradient of 1 ft/ft. The storage coefficient (*S*) of an aquifer is a dimensionless ratio equal to the quantity of water that would be released from an aquifer, per square foot of aquifer area, following a 1-foot decline in water level. In unconfined aquifers, water is released by drainage of pore spaces at the water table. The corresponding storage coefficients (specific yields) are much larger than in confined aquifers where water is released by elastic expansion of the water and geologic materials.

Estimates of *T* and *S* were obtained by several methods. Single-well drawdown tests analyzed using the straight-line method (Lohman, 1972) were done at eight wells and yielded estimates of *T*. Multiple-well drawdown tests analyzed using the Theis curve for confined aquifers yielded estimates of *T* and *S* at seven wells. Results of the tests are shown in table 1. Estimates of *T* were highly variable and ranged from 718 to 44,200 ft^2/d with a median value of 10,000 ft^2/d. Estimates of *S* ranged from 0.0022 to 0.0400 with a median value of 0.0097. The response of water levels in wells to the onset of winter streamflow were evaluated to estimate aquifer diffusivity, which is the ratio *T/S*.

These values of *S* are between the ranges commonly associated with confined and unconfined aquifers (Lohman, 1972; Freeze and Cherry, 1979). These measurements of *S* represent relatively short-term storage responses to stresses lasting from minutes to hours. As described in a later section of this report, larger estimates of *S* (0.045 to 0.10) resulted from digital simulation of longer term storage responses (days to years) using a ground-water-flow model. These larger values are in the low end of the range commonly associated with unconfined aquifers. Thus, most parts of the basins are slightly confined, probably as a result of discontinuous fine-grained layers.

Results of the multiple-well drawdown test at well 27S/8E-10A3 did not conform to theoretical patterns for homogeneous, isotropic aquifers. Drawdown at the more distant observation wells (27S/8E-10A1 and 10A2) was large relative to the drawdown at a closer well (27S/8E-10A4). Possible causes of the anomalous drawdowns include horizontally anisotropic hydraulic conductivity and the influence of nearby bedrock boundaries. Because these causes are difficult to evaluate using analytical methods, they were investigated using a digital, finite-difference ground-water-flow model (McDonald and Harbaugh, 1988). The model grid included a 59-acre rectangular area (fig. 2). The long sides of the area approximately coincided with the contact between bedrock and the basin fill and were designated as no-flow boundaries. The upstream end of the area was across a narrow part of the valley where underflow in summer is small. The downstream end of the area was arbitrarily drawn across the valley but was located far enough from the observation wells so that storage effects from aquifer materials downstream of the boundary would be negligible for a drawdown test lasting only 12 hours. The one-layer model contained 2,120 cells ranging in size from 4×4 to 50×150 ft.

The aquifer-test model was unable to duplicate the measured drawdowns exactly, but anomalies similar to those in the measured data could be achieved by adjusting the locations of the model boundaries or by assuming an anisotropic distribution of *K*. Drawdowns at the distant observation wells were insensitive to boundary location except when the buried bedrock sides of the basin were assumed to be within about 100 ft of the wells, which is unlikely. Anisotropy was introduced into the model by assuming that *K* is greater along the axis of the valley than perpendicular to it. *T* was even more anisotropic than *K* because basin thickness decreases toward the sides of the valley but is relatively constant along the valley axis. Anisotropy resulted in increased drawdown at the distant observation wells, which are aligned with the pumping well along the valley axis, and decreased drawdown at the closest observation well, which is aligned in a perpendicular direction. The best match between simulated and measured drawdowns was with K=720 ft/d in the axial direction, K=300 ft/d in the transverse direction, and S=0.05.

Anisotropy also was evident in the response of water levels in 19 wells to the onset of winter streamflow in December 1988. Equations describing

Table 1. Hydraulic characteristics determined from drawdown tests and streamflow-response tests for selected wells in the Santa Rosa and the San Simeon ground-water basins, San Luis Obispo County, California

[Location: See well-numbering system in text. Wells listed in downstream order. Analysis method: 1, straight line; 2, Theis curve. Streamflow-response test: Response to a period of streamflow beginning December 22, 1988, at 1500 hours and peaking on December 24, 1988. Effective thalweg: Effective thalweg indicates level to which water levels recovered, in feet above (+) or below (–) the altitude of the thalweg at the point where the creek is closest to the well. h, hour; ft^2/d, foot squared per day; ft, foot; —, no data]

Location	Drawdown test						Streamflow-response test		
	Duration (h)	Analysis method	Transmissivity (*T*) (ft^2/d)	Hydraulic conductivity (*K*) (ft^2/d)	Storage coefficient (*S*)	Diffusivity (*T/S*) (ft^2/d)	Distance from creek (ft)	Effective thalweg (ft)	Diffusivity (*T/S*) (ft^2/d)
Santa Rosa Basin									
27S/9E-20G3	—	—	—	—	—	—	151	+1.64	1.3×10^4
20E1	3	1	18,000	301	—	—	225	+6.82	2.0×10^4
19K2	—	—	—	—	—	—	128	+.32	1.7×10^3
19M3	.8	2	2,940	48	0.0113	2.60×10^5	742	+6.79	1.3×10^4
27S/8E-24J4	.6	1	1,000	17	—	—	—	—	—
24L4	8	2	718	14	.0022	3.26×10^5	—	—	—
24L2	—	—	—	—	—	—	150	+2.30	3.6×10^3
24N2	—	—	—	—	—	—	80	–.85	1.7×10^3
23R2	—	—	—	—	—	—	80	+2.00	2.7×10^3
26C6	12	2	44,200	631	.0097	4.56×10^6	50	+1.26	1.8×10^3
26C5	12	1	10,000	143	—	—	37	+1.50	1.0×10^3
27H1	—	—	—	—	—	—	—	–.68	1.3×10^4
27H2	[1]12	[1]1	[1]5,750	[1]77	—	—	330	+.68	2.0×10^3
27G1	—	—	—	—	—	—	79	+.12	3.3×10^3
27C1	—	—	—	—	—	—	341	–2.62	3.3×10^4
21R3	8	1	19,100	383	—	—	—	—	—
San Simeon Basin									
27S/8E-11C1	—	—	—	—	—	—	150	–2.20	1.0×10^5
10A1	9	2	7,070	177	0.0050	3.54×10^4	—	—	—
10A3	9	1	16,500	413	—	—	165	–1.22	4.0×10^4
10A4	9	2	13,500	338	.0400	3.38×10^5	265	–.72	6.8×10^4
10A2	9	2	7,500	188	.0120	6.25×10^5	—	—	—
10G2	—	—	—	—	—	—	30	–1.00	2.7×10^3
10F2	—	—	—	—	—	—	200	+2.20	1.0×10^5
10M2	12	1	5,620	99	—	—	—	—	—
9J3	—	—	—	—	—	—	275	–2.90	1.5×10^5
9P3[2]	24	2	16,702	185	.0072	2.32×10^6	—	—	—
9P2[2]	24	1	26,474	294	—	—	—	—	—

[1]Test by Robert Miller Drilling Company in 1984, reported in McClelland Engineers (1986).

[2]Test done in 1978. Raw data from Cambria Community Services District (John Stratford, written commun., 1988). Hydraulic conductivity calculated from transmissivity assuming saturated thickness of 90 ft.

the theoretical response of ground-water levels to sudden changes in stream stage were presented by Cooper and Rorabaugh (1963) and Hall and Moench (1972). The equations assume that the initial water table is flat, the aquifer is homogeneous, the creek fully penetrates the aquifer, and the change in stream stage is instantaneous. If these assumptions are met, measured water-level responses can be compared with theoretical responses to estimate aquifer diffusivity (T/S). When compared with results of drawdown tests, streamflow-response tests can reveal aquifer anisotropy because drawdown tests measure T in all directions. Streamflow-response tests are affected only by T in the direction perpendicular to the creek, which generally follows the valley axis.

The creek channels at the test sites do not fully penetrate the aquifer and therefore do not fit one of the assumptions used to develop the theoretical equations. If the error caused by this discrepancy is large, it would result in a delay between the instantaneous change in streamflow and the onset of the water-level response. None of the tests indicated an obvious measured delay, so the error was assumed to be negligible.

For this study, measured stream-stage hydrographs were discretized into 2-hour increments to approximate instantaneous changes. The theoretical responses to these incremental changes were superimposed using the convolution method. Results of the streamflow-response tests (table 1) indicate diffusivities ranging from 1.0×10^3 to 1.5×10^5 ft^2/d, with a median value of 1.3×10^4 ft^2/d. These values generally are smaller than those calculated using T and S values from drawdown tests, which ranged from 3.54×10^4 to 4.56×10^6 ft^2/d, with a median value of 3.38×10^5 ft^2/d. Assuming that S is the same for both types of tests, the differences can be attributed to relatively low T perpendicular to the valley axis. However, S might be larger for the streamflow-response tests because of their longer durations, and this could be the cause of the relatively small diffusivities.

WATER QUALITY

Surface-Water Quality

Surface-water samples were collected at the six sites shown in figure 9. Samples were collected on March 8–9, 1988, and February 23–24, 1989, and analyzed for concentrations of major ions, nitrate, and selected trace elements. Results of these analyses are shown in table 2. Flow was less than 6 ft^3/s in both creeks for all sampling dates.

Surface water generally is of better quality in San Simeon Creek than in Santa Rosa or Perry Creeks. For instance, the concentration of dissolved solids ranged from 280 to 292 mg/L (milligram per liter) along San Simeon Creek, whereas it ranged from 469 to 530 mg/L along Santa Rosa and Perry Creeks (table 2). Likewise, the concentrations of hardness, calcium, magnesium, sodium, potassium, sulfate, chloride, and manganese in San Simeon Creek were equal to or less than the concentrations of these ions in either Santa Rosa or Perry Creeks. Of the constituents tested, none had significantly lower concentrations in Santa Rosa or Perry Creeks than in San Simeon Creek.

Ion concentrations at the two sites on San Simeon Creek differed by less than 10 percent. In contrast, concentrations of several ions increased by 12 to 64 percent along Santa Rosa Creek. Some of these increases resulted from flow from Perry Creek into Santa Rosa Creek. Perry Creek seems to be the source of increased concentrations of sodium, potassium, chloride, bromide, and manganese. The high concentrations of these ions in Perry Creek probably result from weathering and from release of connate seawater trapped in the Tertiary marine deposits along Perry Creek. The effect of mixing water from Santa Rosa and Perry Creeks can be seen in the trilinear diagram in figure 10*A*. The diagram indicates that the composition of Perry Creek water is intermediate between Santa Rosa Creek water and seawater, and the composition of Santa Rosa Creek water below the confluence with Perry Creek results from mixing of upstream Santa Rosa Creek water with Perry Creek water.

Increased sulfate concentrations measured in the water from Santa Rosa Creek below the confluence with Perry Creek cannot be attributed to mixing of upstream Santa Rosa Creek water with Perry Creek water. The source of the sulfate might be the Upper Cretaceous marine sandstone that borders Santa Rosa Creek valley below the confluence with Perry Creek or the sediments in the part of the ground-water basin below the confluence.

Surface-water quality in Santa Rosa, San Simeon, and Perry Creeks is affected by the rate of streamflow. Specific conductance measured during different months of the year varies by as much as 36

Table 2. Surface- and ground-water quality near Cambria, San Luis Obispo County, California, 1988–89

[Location: See well-numbering system in text. Wells are in downstream order. Constituents are given in milligrams per liter unless otherwise noted. ft^3/s,

Location (fig. 9)	Date	Flow, instantaneous (ft^3/s)	Specific conductance (µS/cm)	pH (standard units)	Water temperature (°C)	Hardness, total (as $CaCO_3$)	Calcium, dissolved	Magnesium, dissolved	Sodium, dissolved	Percent sodium	Sodium adsorption ratio
Drinking-water standard		*na*	*na*	[1]*6.5-8.5*	*na*	*na*	*na*	*na*	*na*	*na*	*na*
				Surface water							
Santa Rosa Creek	3-09-88	3.0	722	8.2	15.5	--	66	48	20	--	--
near Cambria	2-24-89	--	737	8.1	13.0	--	72	51	22	--	--
Santa Rosa Creek at	3-09-88	5.0	848	8.2	13.0	--	71	57	30	--	--
State Highway 1	2-24-89	--	822	8.3	13.0	--	71	57	31	--	--
Santa Rosa Creek at	3-08-88	5.0	865	8.2	16.5	--	69	56	33	--	--
Windsor Boulevard	2-24-89	--	838	7.9	--	--	70	57	32	--	--
Perry Creek at Cambria	3-09-88	.40	931	8.1	15.0	--	56	58	58	--	--
	2-24-89	.37	867	8.1	13.0	--	51	55	58	--	--
San Simeon Creek at	3-08-88	5.1	493	8.2	15.5	--	42	30	16	--	--
Palmer Flats	2-23-89	--	468	8.0	14.5	--	41	29	15	--	--
San Simeon Creek	3-08-88	3.3	518	8.2	12.0	--	45	32	16	--	--
near Cambria	2-23-89	3.6	495	8.2	17.0	--	44	31	16	--	--
				Ground water							
Santa Rosa basin											
27S/9E-20G2	12-13-88	na	712	7.7	15.5	380	70	49	25	13	0.6
	2-23-89	na	709	7.2	15.5	370	69	48	24	12	.5
20BS3	2-23-89	na	618	7.9	14.5	290	54	38	33	20	.8
19H3	12-12-88	na	833	7.6	15.0	430	77	57	37	16	.8
	2-22-89	na	821	7.8	17.5	390	72	52	33	15	.7
27S/8E-24L1	12-13-88	na	1,050	8.0	15.0	610	110	82	38	12	.7
	2-24-89	na	1,080	7.9	16.0	610	110	82	37	12	.7
27C1	12-13-88	na	2,270	7.5	16.0	880	120	140	230	36	3
	2-22-89	na	2,430	7.1	17.5	940	130	150	230	35	3
27C2	12-13-88	na	1,580	7.9	16.0	810	110	130	73	16	1
	2-22-89	na	1,620	7.2	17.5	840	120	130	68	15	1
San Simeon basin											
27S/8E-11C1	12-14-88	na	734	7.5	15.5	360	63	48	33	17	.8
	2-22-89	na	571	7.5	16.0	280	51	38	20	13	.5
10A3	12-14-88	na	608	7.8	15.5	290	54	38	20	13	.5
	2-22-89	na	535	7.5	17.0	270	50	35	18	13	.5
10HS1	2-22-89	na	1,230	7.0	12.0	450	89	55	110	34	2
9M4	12-14-88	na	960	7.6	15.0	400	83	48	73	28	2
	2-23-89	na	978	7.6	18.0	400	84	47	72	28	2
9N2	12-14-88	na	1,390	7.8	15.5	680	120	92	64	17	1
	2-22-89	na	1,420	7.4	17.0	680	120	93	68	18	1
8R3	12-13-88	na	2,320	8.3	17.0	460	74	66	340	61	7
	2-21-89	na	2,010	7.8	18.0	570	95	80	250	49	5
8R4	12-13-88	na	816	7.8	16.5	230	39	33	99	48	3
	2-21-89	na	426	7.5	18.0	96	17	13	54	54	2

[1]Secondary maximum contaminant level (Title 22, California Code of Regulations, 1986, sections 64401-64473).
[2]Primary maximum contaminant level (Title 22, California Code of Regulations, 1986, sections 64401-64473).

cubic foot per second; µS/cm, microsiemen per centimerer at 25°C; °C, degrees Celsius; na, not applicable; --, no data; <, actual value is less than value shown]

Potassium, dissolved	Alkalinity, total (as $CaCO_3$)	Sulfate, dissolved	Chloride, dissolved	Fluoride, dissolved	Bromide, dissolved	Silica, dissolved	Dissolved solids, residue at 180°C	Dissolved solids, sum of constituents	Nitrite plus nitrate, dissolved (as N)	Boron, dissolved	Iron, dissolved	Manganese, dissolved
na	*na*	[1]*250*	[1]*250*	[1]*2.0*	*na*	*na*	[1]*500*	[1]*500*	[2]*10*	*na*	[1]*0.3*	[1]*0.05*
					Surface water--*Continued*							
1.7	347	110	25	0.3	--	18	--	--	--	0.160	0.011	--
1.6	328	100	24	.2	0.022	12	520	--	<0.010	.150	.009	0.008
1.4	306	95	14	.3	--	20	--	--	--	.130	.009	--
1.4	304	110	14	.2	<.010	19	469	--	<.010	.130	.007	.003
1.8	343	110	7.5	.3	--	18	--	--	--	.160	.009	--
1.7	326	120	30	.3	.037	12	530	--	<.010	.150	.006	.009
3.1	376	52	65	.4	--	7.4	--	--	--	.150	.009	--
2.5	328	58	72	.4	.079	5.6	502	--	<.010	.130	.008	.043
1.1	216	41	13	.2	--	15	--	--	--	.200	.009	--
1.0	202	42	12	.2	<.010	14	280	--	<.010	.200	.006	.001
1.1	229	42	14	.2	--	15	--	--	--	.180	.003	--
1.1	216	44	13	.1	<.010	14	292	--	<.010	.180	.005	.003
					Ground water--*Continued*							
Santa Rosa basin--*Continued*												
1.3	308	95	15	0.3	--	21	473	470	2.00	0.150	0.012	0.002
1.2	287	97	15	.3	--	21	445	454	1.40	.130	.006	.003
.5	264	63	17	.2	--	23	373	393	1.30	.050	.005	.002
1.0	376	78	15	.3	--	27	547	518	<.010	.180	.014	.350
.8	348	85	24	.3	--	27	496	503	.013	.170	.046	.330
1.2	536	97	27	.3	--	30	730	708	<.010	.240	.022	.470
1.1	563	100	27	.2	--	31	711	727	<.010	.230	.030	.490
3.4	516	66	550	.5	--	34	1,520	1,460	.020	.220	.110	1.60
2.4	517	59	650	.5	--	36	1,470	1,570	<.010	.190	.070	1.70
1.4	618	96	210	.3	--	32	1,080	1,020	<.010	.180	.021	.910
.8	635	88	210	.4	--	33	1,030	1,030	<.010	.170	.200	1.00
San Simeon basin--*Continued*												
1.2	264	76	40	.1	--	20	461	453	2.90	.200	.033	.020
.9	258	50	16	.2	--	19	342	354	.939	.170	.008	.003
1.0	250	51	15	.1	--	21	357	353	.531	.170	.004	.002
.8	243	45	15	.2	--	20	320	333	.697	.170	.009	.002
5.0	211	290	150	.6	--	54	892	881	.036	.150	.016	.190
1.6	446	18	81	.5	--	32	594	606	<.010	.310	.018	.910
1.4	448	19	82	.5	--	32	596	608	<.010	.310	.030	.920
1.0	500	77	180	.4	--	32	889	868	.018	.190	.012	1.40
.7	494	80	190	.5	--	33	873	884	<.010	.160	.870	1.60
6.7	250	140	580	.3	--	18	1,400	1,380	.014	1.40	.010	.190
4.4	298	100	540	.2	--	27	1,240	1,280	<.010	.560	.060	.330
3.2	270	63	77	.2	--	24	495	501	.011	.240	.009	.180
4.2	157	31	30	.2	--	13	270	257	<.010	.170	.370	.230

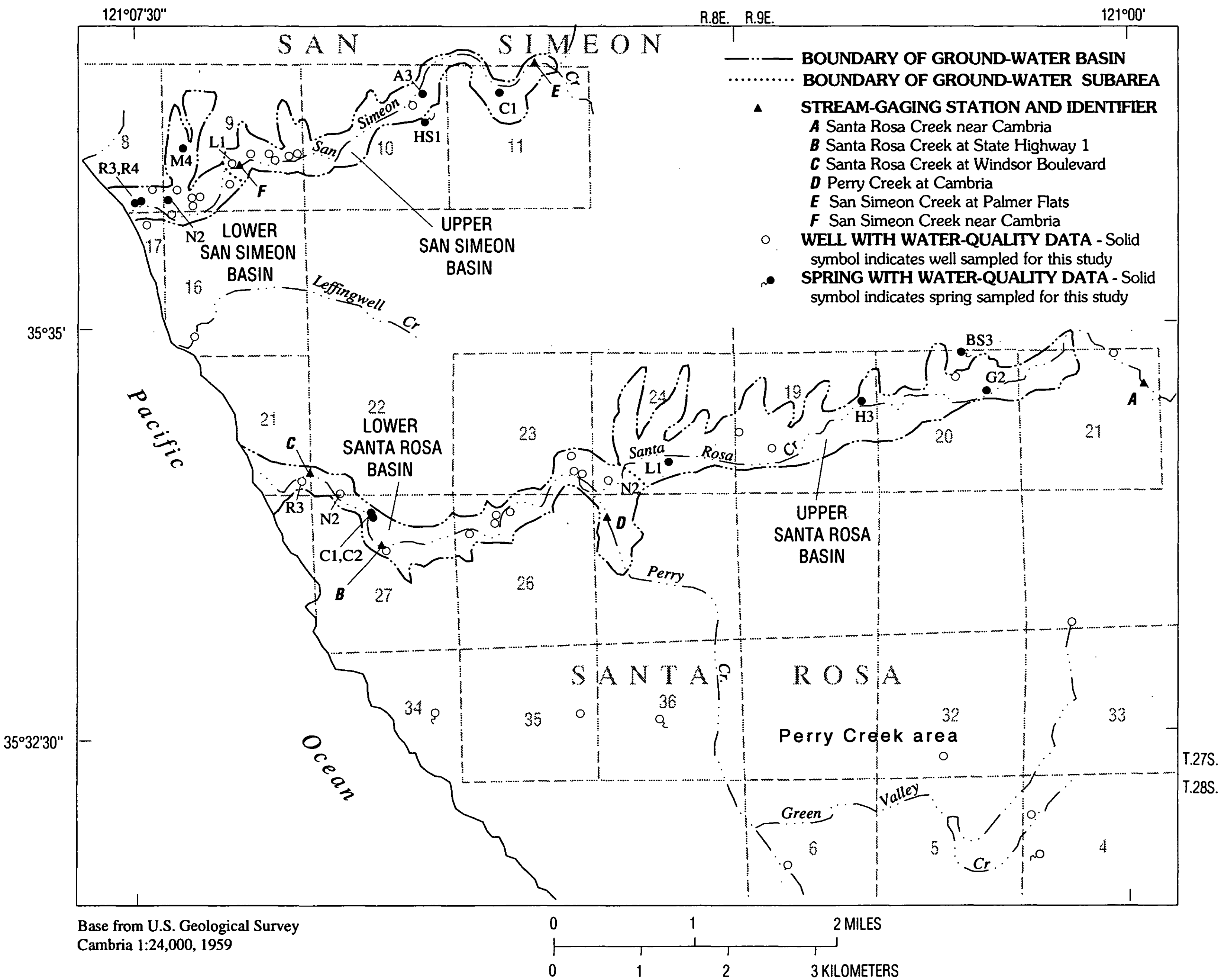


Figure 9. Locations of surface- and ground-water-quality measurement sites, San Luis Obispo County, California.

percent at a single site. The variations tend to be inversely related to streamflow. Specific conductance, measured on the approximate date of the onset of winter streamflow, indicated that there is no increase in dissolved minerals associated with the first period of runoff of the winter season.

Specific conductance of San Simeon Creek at Palmer Flats ranged from 472 µS/cm (microsiemen per centimeter at 25 degrees Celsius) on December 20, 1988, the approximate date of the first winter flow, to 556 µS/cm on May 10, 1988. The stream discharges on these dates were 6.0 and 0.98 ft^3/s, respectively. Specific conductance at the gaging station on Perry Creek, just above the confluence with Santa Rosa Creek, ranged from 867 µS/cm on February 24, 1989, when the stream discharge was 0.37 ft^3/s to 1,360 µS/cm on November 17, 1988, when discharge was 0.04 ft^3/s. These data illustrate the inverse relation between discharge and specific conductance.

Ground-Water Quality

Ground-water samples were collected for this study from 11 wells and 2 springs along the San Simeon Creek and Santa Rosa Creek ground-water basins (fig. 9). Samples were collected in December 1988 and February 1989, when ground-water levels were near their minimum and maximum seasonal levels, respectively. Analyses of these samples (table 2) were combined with historical data for a more complete evaluation of ground-water quality. The historical data are of unknown accuracy although samples that did not exhibit a cation-anion balance were omitted. In cases where multiple samples were available for a well, the median concentration of a given ion was used in the spatial analysis of water quality.

Ground-water quality does not meet drinking-water standards in all parts of the basins. California State drinking-water standards for the constituents measured in this study are shown in table 2 and fall into two categories. Primary maximum contaminant levels are enforceable standards to protect public health. Of the constituents discussed here, only nitrate is regulated by a primary maximum contaminant level. Secondary maximum contaminant levels regulate aesthetic characteristics of drinking water, such as taste, odor, and color. Concentrations of pH, sulfate, chloride, fluoride, dissolved solids, iron, and manganese are regulated by secondary maximum contaminant levels. For the constituents listed in table 2, California State drinking-water standards (Title 22, California Code of Regulations, sections 64401-64473) are the same as Federal standards, except that secondary maximum contaminant levels are enforceable.

Identification of Subareas

Five subareas within the study area were identified on the basis of water-quality differences (fig. 9). The San Simeon and the Santa Rosa Basins were each divided into an upper and lower basin, and ground water in the Perry Creek drainage area was grouped as the fifth subarea. Pico Creek was not included in the delineation of subareas. Along San Simeon Creek, the boundary between the upper and lower basins is near well 27S/8E-9L1 at the downstream end of the CCSD well field. Along Santa Rosa Creek, the boundary is between wells 27S/8E-24N2 and 24L1, about 2,000 ft upstream of the confluence with Perry Creek. The boundary in the Santa Rosa Basin coincides with the location of one of the subsurface flow obstructions.

The differences in water quality among the five subareas are most clearly indicated by the concentrations of sodium, sulfate, chloride, and dissolved solids. The relative concentrations of sodium, sulfate, and chloride, in each subarea can be seen in the trilinear diagrams in figures 10*B* through 10*D*. In these figures, the range of historical data for each subarea is enclosed by a line, and data from samples collected for this study are plotted as individual points. Quantitative differences in concentrations of sodium, sulfate, chloride, and dissolved solids are indicated by the boxplots shown in figure 11. The boxplots schematically show the sample distribution of ion concentrations in the subareas.

The lower basins have higher concentrations of sodium, chloride, and dissolved solids than the upper basins. The difference between the upper and lower basins along San Simeon Creek is larger and more abrupt than along Santa Rosa Creek. Sodium and chloride increase equally, so that the relative concentrations of ions in wells near the coast approaches that of seawater (fig. 10*C*). Ground water in the Perry Creek Basin also is high in sodium, chloride, and dissolved solids (fig. 10*D*), but it is lower in sulfate than water in the lower Santa Rosa Basin to which it is tributary. Overall, water quality is best in the upper San Simeon Basin.

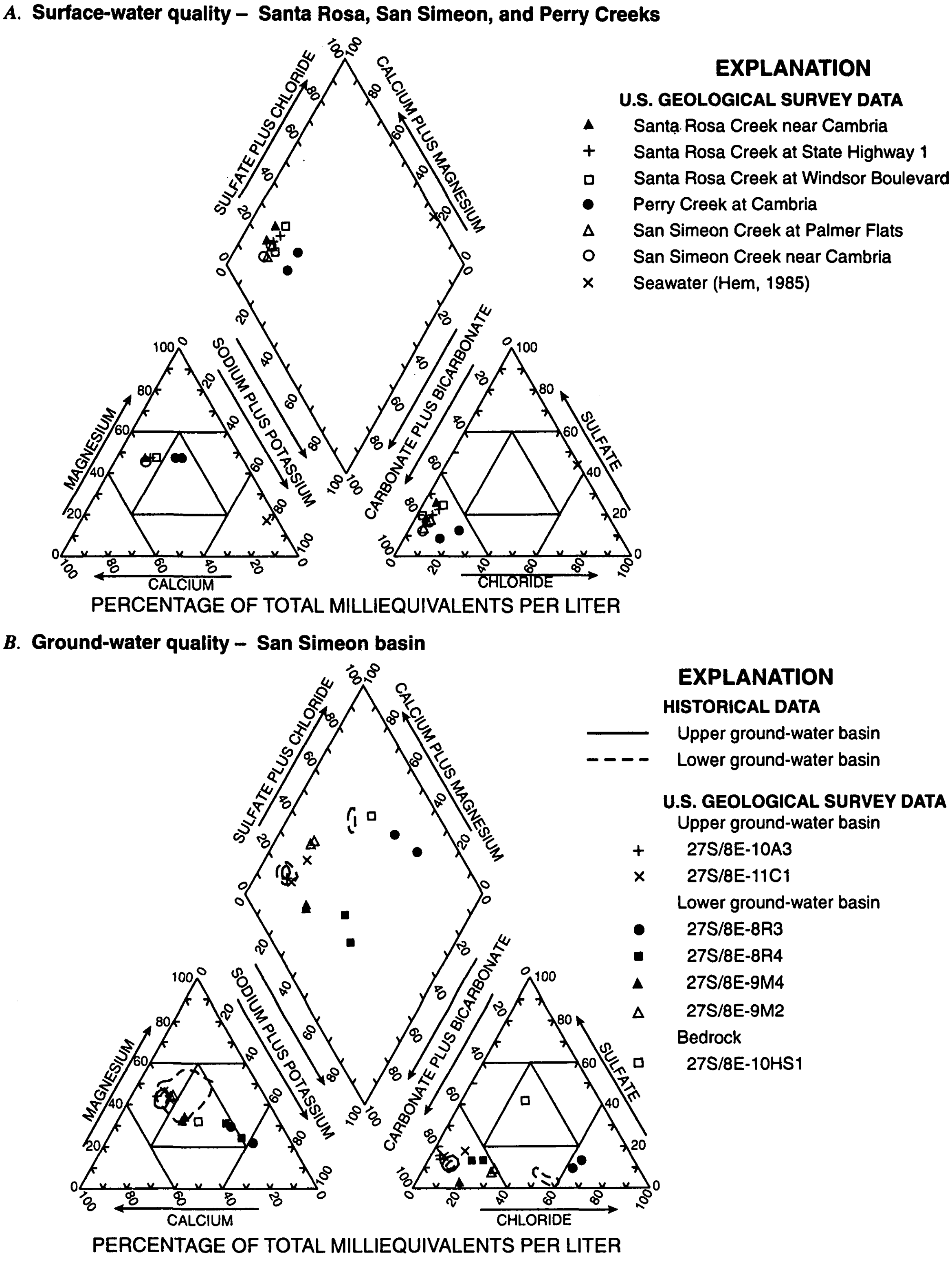
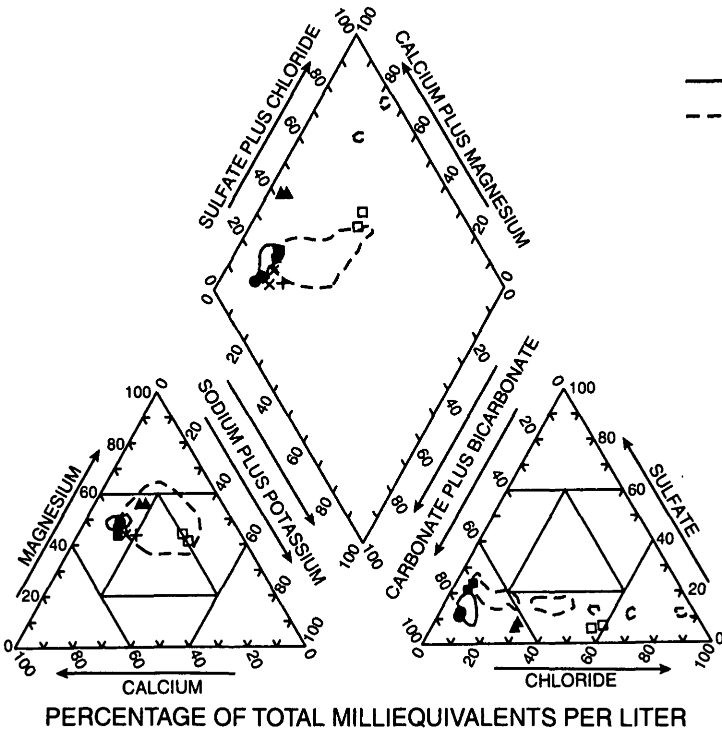


Figure 10. Quality of surface water of (*A*) Santa Rosa, San Simeon, and Perry Creeks and quality of ground water of (*B*) the San Simeon Basin, (*C*) the Santa Rosa Basin, and (*D*) the Perry Creek area, San Luis Obispo County, California. Historical data from STORET (U.S. Environmental Protection Agency, written commun., 1987) San Luis Obispo County (Glenn Britton, written commun., 1988, and John Stratford, Cambria Community Services District, written commun., 1988).

C. **Ground-water quality – Santa Rosa basin**



EXPLANATION

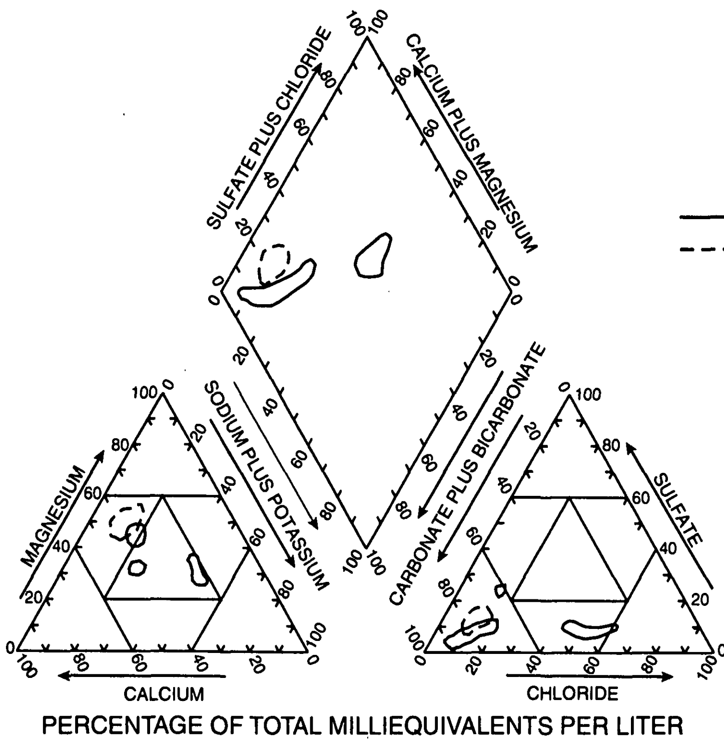
HISTORICAL DATA

—— Upper ground-water basin
– – – – Lower ground-water basin

U.S. GEOLOGICAL SURVEY DATA

Upper ground-water basin
× 27S/9E-19H3
■ 27S/9E-20G2
● 27S/9E-24L1
Lower ground-water basin
□ 27S/8E-27C1
▲ 27S/8E-27C2
Bedrock
+ 27S/9E-20BS3

D. **Ground-water quality – Pico basin and Perry Creek area**



EXPLANATION

HISTORICAL DATA

—— Perry Creek basin
– – – – Pico Creek basin

Figure 10. Quality of surface water of (*A*) Santa Rosa, San Simeon, and Perry Creeks and quality of ground water of (*B*) the San Simeon Basin, (*C*) the Santa Rosa Basin, and (*D*) the Perry Creek area, San Luis Obispo County, California. Historical data from STORET (U.S. Environmental Protection Agency, written commun., 1987) San Luis Obispo County (Glenn Britton, written commun., 1988, and John Stratford, Cambria Community Services District, written commun., 1988)—Continued.

Salinity

Sources of Salinity

In this discussion, the term "salinity" refers to the concentrations of sodium, chloride, and dissolved solids. The source of salinity in the lower basins is of interest because water from some wells in those areas does not meet the secondary maximum contaminant levels for dissolved solids and chloride. The concentration of dissolved solids in wells 27S/8E -27C1 and 8R3 was between 1,240 and 1,520 mg/L in December 1988 and February 1989 (table 2). The secondary maximum contaminant level is 1,000 mg/L. The concentration of chloride in the two wells was between 540 and 650 mg/L; the secondary maximum contaminant level is 500 mg/L, but for taste reasons, the maximum concentration recommended is 250 mg/L (Title 22, California Code of Regulations, sections 64401-64473). Brackish water is water that is less saline than seawater but substantially more saline than fresh ground water. For this discussion, water with a dissolved-solids concentration greater than about 1,000 mg/L is considered brackish.

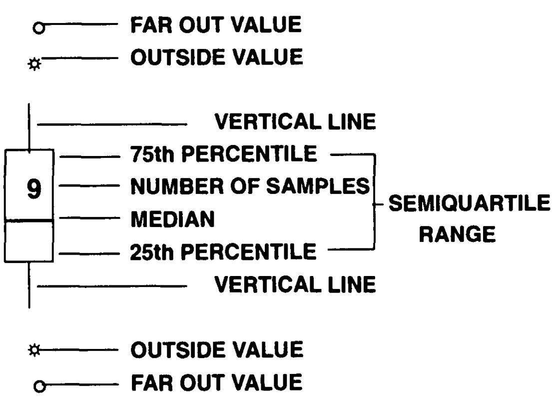
Possible sources of salinity in the lower basins and coastal areas include Perry Creek, the Cretaceous marine sandstone (unit Ks in fig. 3), other bedrock materials, municipal wastewater, irrigation-return flow, and the ocean. Although more than one of these sources might be significant in some locations, the ocean is the only source that can account for all the observed salinity effects.

Ground water in the Perry Creek area is more saline than ground water in the lower Santa Rosa Basin, but it has a lower sulfate concentration. Unless there is a separate source of sulfate, Perry Creek could not be the source of the salinity in the lower basin. Inflow from the Perry Creek area is small because the transmissivity of alluvial deposits in that area is too small relative to surface- and ground-water inflow from the upper Santa Rosa Creek Basin to account for the salinity increase. Also, because of its location, the Perry Creek area could not be the source of salinity in the lower San Simeon and the Pico Basins.

The Cretaceous marine sandstone that is exposed on the hillslopes surrounding the lower Santa Rosa Basin could contribute some saline water to that basin. However, it could not be a significant source of salinity in the lower San Simeon and the Pico Basins because it does not occur extensively in those areas.

Two springs in the upper basin areas were sampled to determine the quality of ground water moving through fractures in Franciscan bedrock. The springs had quite different water-quality types, so it is difficult to generalize about bedrock water quality. Spring 27S/8E-10HS1 near the south side of the upper San Simeon Basin had a dissolved-solids concentration of 892 mg/L, which is higher than the concentration in wells in that basin but lower than the concentration measured in some wells in the lower San Simeon Basin. That spring also had a higher proportion of sulfate than ground water in any of the basins in the study area (fig. 10, table 2). In contrast, spring 27S/9E-20BS3 near the north side of the upper Santa Rosa Basin had a water type similar to that of ground water in the basin, but its dissolved-solids concentration (373 mg/L) was lower. In spite of this variability, Franciscan bedrock probably is not a likely cause of high salinity in the lower basins. It is remotely conceivable that upland bedrock areas could have been flushed of brackish connate water by infiltration and through flow of meteoric waters. The spring water could originate from recent meteoric

EXPLANATION



Far out values are more than 3.0 times the semiquartile range from the top or bottom of the rectangle

Outside values are between 1.5 and 3.0 times the semiquartile range from the top or bottom of the rectangle

Vertical lines extend a distance equal to 1.5 times the semiquartile range away from the top or bottom of the rectangle or the limit of the data, whichever is least

Figure 11. Concentrations of sodium, sulfate, chloride, and dissolved solids in ground-water subareas, San Luis Obispo County, California.

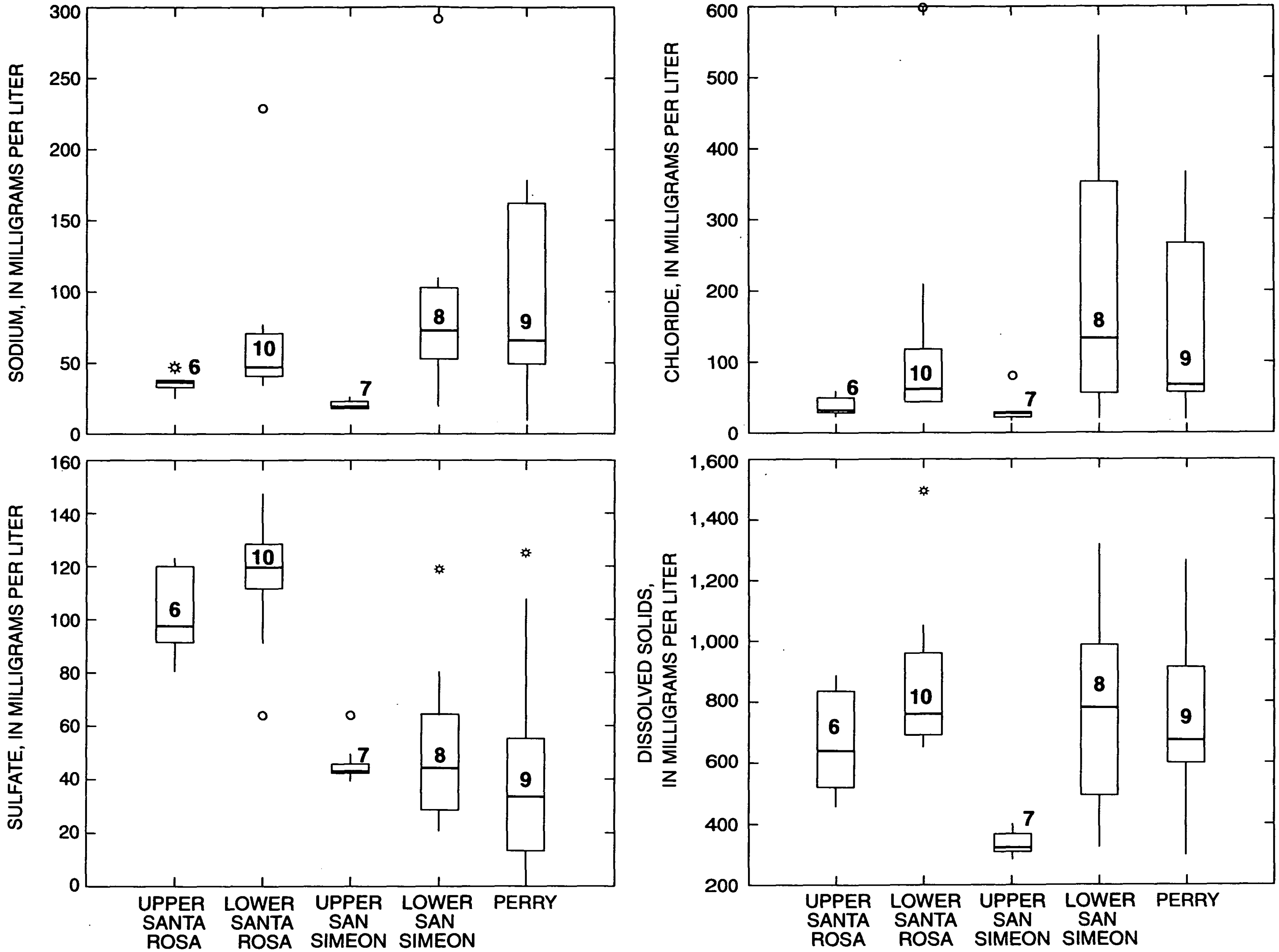


Figure 11. Concentrations of sodium, sulfate, chloride, and dissolved solids in ground-water subareas, San Luis Obispo County, California—Continued.

sources, and older, denser connate water gradually could have migrated downward to deeper parts of the ground-water system, including the lower basins.

Wastewater from old septic systems, leaking sewer pipes, or the CCSD wastewater sprayfield could contribute some salinity to the lower basins, but these probably are not major sources. Use of septic systems in the lower Santa Rosa Basin was largely discontinued when the municipal sewer system was installed in 1972. Because the annual turnover of ground water in the basin is fairly high, significant quantities of old septic leachate probably are not still present. High salinity in the lower San Simeon Basin existed prior to the wastewater sprayfield operation, so wastewater cannot be the source of all salinity in that area. A comparison of the quantity of municipal water delivered to customers with the quantity of treated wastewater disposed of at the sprayfield in 1987 did not indicate that large quantities of wastewater are leaking from the sewer system. Finally, nitrate concentrations are not elevated in the lower basins, which commonly is the case in areas contaminated with wastewater.

Evaporative concentration of irrigation water could explain some of the downvalley increase in dissolved solids. Data from six wells between wells 27S/9E-20G2 and 27S/8E-24N2 in the upper Santa Rosa Basin indicate that the concentration of dissolved solids increases fairly consistently by 30 mg/L per thousand feet down the valley (correlation coefficient, r, = 0.87). Because ground water flows down the valley, water at the lower end has had more opportunity to be pumped to the surface and exposed to evaporation. However, this mechanism would not cause the observed shift in relative concentrations of anions (fig. 10).

The ocean is the probable source of high salinity in the lower basins and in the nearby Pico Creek Basin. Seawater could enter the ground-water basins by infiltration of salt spray, infiltration of storm waves that reach beyond the beach or up the creek, or lateral flow into the aquifers from offshore extensions of the basin-fill deposits. The first two mechanisms would add seawater at the water table, and salinity consequently would tend to decrease with depth. These mechanisms might occur in the Pico Creek Basin, where salinity is higher above the clay confining layer than below the confining layer (Cleath, 1986). However, differing quantities of lateral seawater inflow into the shallow and deep aquifers might produce the same result. Ordinarily, lateral inflow of seawater causes an increase in salinity with depth.

Seawater Intrusion

Seawater can enter onshore parts of a fresh ground-water basin as a result of (1) the density difference between seawater and freshwater, (2) ground-water overdraft—an excess of pumping over recharge—in onshore areas, and (3) local pumping near the coast causing water levels to drop below sea level. In the former case, a seawater wedge tapering inland will naturally form at the base of the basin near the coastline. The wedge often remains relatively stationary while fresh ground water flows up along the top of the wedge and discharges to the ocean. The Ghyben-Herzberg equation states that in isotropic sediments with static ground water the distance from sea level to the top of the seawater wedge is about 40 times the altitude of the water table above sea level (Bear and Dagan, 1964). In the case of overdraft or ground-water or local coastal pumping, the interface between seawater and freshwater tends to move inland when onshore water levels are at or below sea level. This phenomenon is called seawater intrusion.

In the lower Santa Rosa Basin, salinity increases with depth. Well 27S/8E-27C1, which has high salinity, is perforated near the base of the ground-water basin at an altitude of 80–90 ft below sea level (fig. 7*A*). Well 27S/8E-27C2 at the same location is perforated at an altitude of 15–25 ft below sea level. The dissolved-solids concentration was 440 mg/L less than in well 27S/8E-27C1, and the chloride concentration was 340 to 440 mg/L less (table 2).

Brackish water in well 27S/8E-27C1 might not be related to a natural seawater wedge or to seawater intrusion. Although an upward water-level gradient exists between this well and well 27S/8E-27C2, the gradient seems to be caused by a bedrock constriction. These wells, which are 4,500 ft from the coast, had minimum seasonal water levels in 1988 of more than 9 ft above sea level. These water levels indicate a theoretical interface altitude of 280 ft below sea level, which is far below the bottom of the basin. The theoretical interface altitude might not be accurate because conditions in the lower Santa Rosa Basin do not conform exactly to the assumptions of the Ghyben-Herzberg equation. In particular, the basin-fill deposits probably are not isotropic. Preferred grain orientation and interbedding of clay with sand and silt probably decrease vertical permeability relative to horizontal permeability, and this can flatten the interface profile relative to isotropic deposits (Meisler and others, 1985). This effect probably is not strong enough to extend the top of the wedge inland as far as these wells. The high water levels in these wells and in well 27S/8E-21R3, closer to the coast, eliminate seawater intrusion as a cause of the salinity. An alternative possibility is that the brackish water in well 27S/8E-27C1 is from a pocket of seawater left over from a previous high stand of sea level.

Historical water-quality data indicate that seawater intrusion might have occurred in the lower Santa Rosa Basin in the past. The chloride concentration in water from well 27S/8E-21R3 was 1,925 mg/L in November 1961. Background chloride concentrations typically ranged from 30 to 270 mg/L as shown in figure 12 (Glenn Britton, San Luis Obispo County Engineering Dept., written commun., 1988). Water-level data are not available for November 1961, but rainfall during the preceding 3 years was only 72 percent of average. An associated decrease in ground-water recharge could have allowed the seawater-freshwater interface to move inland. A similar salinity increase (to 933 mg/L) was measured in December 1969; however, the water level in well 27S/8E-21R3 was not unusually low at that time (Glenn Britton, San Luis Obispo County Engineering Dept., written commun., 1987). The salinity increase in 1969 could have been related to temporary changes in the creek outlet. A major flood occurred during the preceding winter, and it could have caused a breach in the beach large enough to allow a greater-than-normal advance of seawater up the creek during the summer. This could have increased ground-water salinity near well 27S/8E-21R3, which is only about 50 ft from the creek and about 1,900 ft inland.

In the lower San Simeon Basin, salinity also increases with depth. Well 27S/8E-8R3 is perforated at an altitude of 122 to 132 ft below sea level and has high salinity. Well 27S/8E-8R4 at the same location is

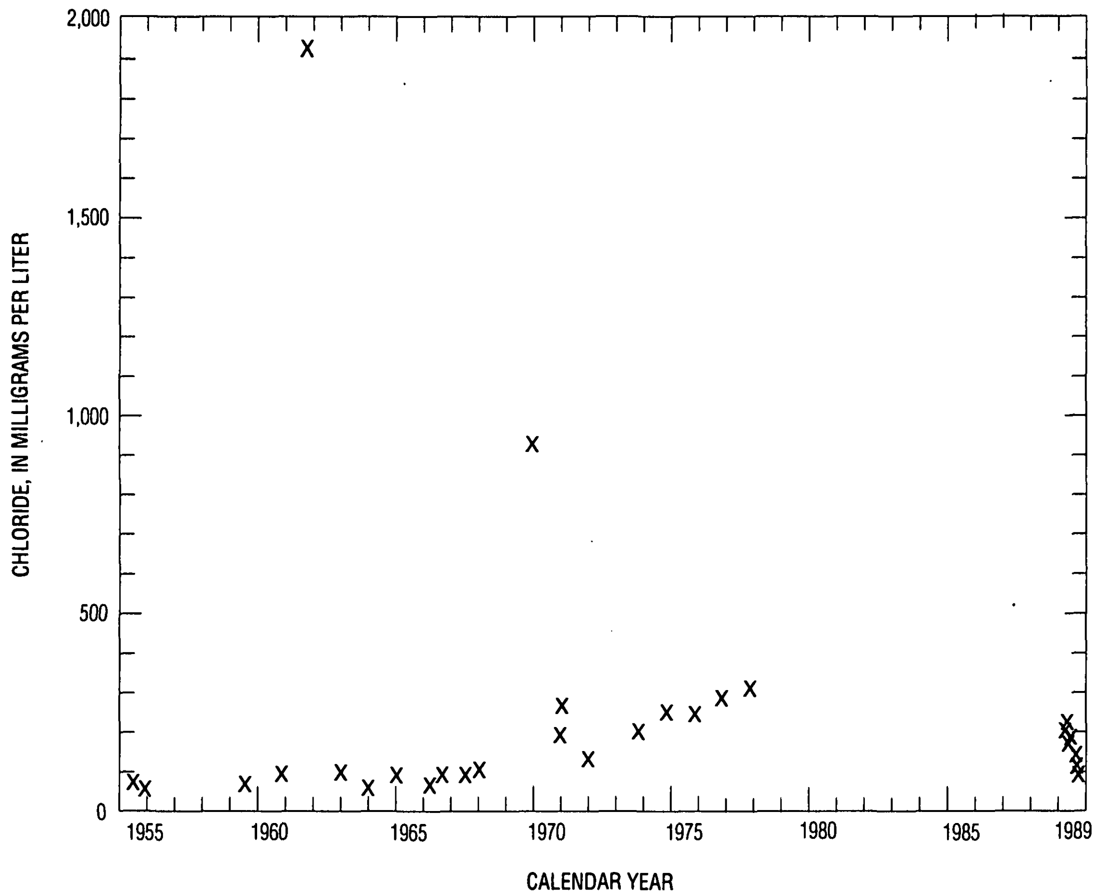


Figure 12. Chloride concentrations in ground water at well 27S/8E-21R3 in the Santa Rosa Basin, San Luis Obispo County, California, 1955–89.

perforated at 76 to 86 ft below sea level, and the dissolved-solids concentration is 905 to 970 mg/L less than the dissolved-solids concentration in well 27S/8E-8R3 (table 2). The chloride concentration was 503 to 510 mg/L less than the chloride concentration in well 27S/8E-8R3.

Water levels indicate that the salinity gradient between wells 27S/8E-8R3 and 8R4 results from a natural, relatively stable seawater wedge. The minimum water level in well 27S/8E-8R3 during 1988–89 was about 3.4 ft above sea level. The Ghyben-Herzberg relation indicates that for this water level, the top of the seawater wedge would be at an altitude of 136 ft below sea level, which is close to the altitude of the well screen (122 to 132 ft below sea level). Also, the discharge of fresh ground water over a saltwater wedge theoretically will create upward flow of ground water. This is confirmed by water-level data for wells 27S/8E-8R3 and 8R4 next to San Simeon Creek. Water levels decrease progressively from the deeper well up to the creek, indicating an upward gradient of 0.001 to 0.010 ft/ft.

Brief salinity increases concurrent with low ground-water levels have occurred in the Pico Basin and almost certainly resulted from pumping which caused water levels temporary to drop below sea level. During November and December 1984, chloride concentrations in several wells in the Pico ground-water basin increased from background chloride concentrations of less than 45 mg/L to concentrations as high as 460 mg/L within 2 weeks after water levels in those wells declined below sea level (Stephen Havlicek, San Simeon Acres Community Services District, written commun., 1985; Cleath, 1986). Concentrations returned to background levels within 4 months after water levels rose back above sea level. Similar but less well-documented events occurred in 1981 and possibly 1982 (Cleath, 1986).

Chemistry of Brackish Water

Differences in proportional concentrations of calcium, magnesium, sodium, sulfate, and chloride in brackish water can be used to indicate the extent to which the seawater component has fully reacted with clays in the basin-fill deposits. If the interface is advancing, these differences qualitatively indicate how recently the interface reached the well location. If the interface is stationary, the differences indicate how close the well is to the interface. Table 3 shows the percentage of seawater in coastal wells in the lower Santa Rosa, the lower San Simeon, and the Pico Basins. The percentage of seawater is calculated assuming nonreactive mixing of seawater and fresh, inland ground water. Separate estimates of the percentage of seawater are calculated using data for each ion. Chloride is the most conservative of the five ions and probably gives the best estimate of percentage of seawater.

In all three basins, the percentage of seawater estimated using the calcium and magnesium ions is greater than or equal to the chloride estimate, and the sodium estimate is lower than the chloride estimate. This effect is caused by cation exchange between seawater and clays in the basin-fill deposits. Prior to intrusion, the cations adsorbed to the clays were predominantly calcium and magnesium. Although calcium and magnesium adsorb more tightly than sodium, seawater contains seven times as many sodium ions as calcium and magnesium ions combined. The effect of mass action is to replace adsorbed calcium and magnesium with sodium. The result in the solution phase is to create a relative increase in calcium and magnesium and a relative decrease in sodium, compared with mixing without cation exchange. These increases and decreases have a corresponding effect on the estimated percentage of seawater. This effect is greatest in the Pico Basin, where intrusion was recent at the time the samples were collected. The percentage of seawater estimated from the chloride concentration was 1.7 percent. The calcium and magnesium estimates were much larger (17 and 4.2 percent, respectively), and the sodium estimate was much lower (0.21 percent) (table 3).

If seawater continues to flow through a previously fresh aquifer, the adsorbed phase equilibrates with the composition of the brackish water. Cation-exchange reactions diminish, and estimates of the percentage of seawater calculated from cation concentrations approach the estimate calculated from chloride concentration. This indicates that the brackish water at well 27S/8E-8R3 in the lower San Simeon Basin is the most fully equilibrated of the samples investigated. The chloride estimate was 2.8 percent, and the calcium, magnesium, and sodium estimates were 8.7, 2.8, and 2.6 percent, respectively (table 3). The water at well 27S/8E-27C1 in the lower Santa Rosa Basin showed an intermediate amount of equilibration.

Factors Affecting Use

In addition to salinity, several other water-quality characteristics potentially might affect ground-water use in the Cambria area. These include hardness and the concentrations of sulfate, nitrate, boron, iron, manganese, and trihalomethanes. Historical and present land-use practices also might affect water quality.

The calculated percentages of seawater (table 3) indicate that sulfate is not a conservative ion. Although sulfate is relatively unaffected by cation-exchange processes, it can be removed from solution by reduction to sulfide. This effect is not evident in the lower San Simeon Basin and is small in the Pico Basin. In the lower Santa Rosa Basin, however, reduction is so strong that the sulfate concentration is lower in brackish water than in either seawater or fresh ground water. This results in an unrealistic (negative) value for the percentage of seawater. The reduction was confirmed by the odor of hydrogen sulfide at wells 27S/8E-27C1 and 22N2. The odor of hydrogen sulfide is unpleasant even in small concentrations. The reduction process probably is associated with organic matter in fine-grained beds in the basin-fill deposits. The concentration of sulfate in water from spring 27S/8E-10HS1 exceeded the secondary maximum contaminant level of 250 mg/L given in Title 22, California Code of Regulations, 1986, sections

Table 3. Percentage of seawater in coastal wells in the lower Santa Rosa, lower San Simeon, and Pico ground-water basins, San Luis Obispo County, California

[Chemical analyses of ground water are in milligrams per liter]

Basin	Item	Calcium	Magnesium	Sodium	Sulfate	Chloride
Lower Santa Rosa	Fresh ground water[1]	71	74	46	125	58
	Brackish ground water[2]	125	145	230	62	600
	Percentage of seawater[3]	15.9	5.6	1.8	−2.4	2.9
Lower San Simeon	Fresh ground water[4]	53	36	20	42	20
	Brackish ground water[5]	84	73	295	120	560
	Percentage of seawater[3]	8.7	2.8	2.6	2.9	2.8
Pico	Fresh ground water[6]	72	55	35	52	145
	Brackish ground water[7]	130	110	56	85	460
	Percentage of seawater[3]	17	4.2	.21	1.2	1.7
Seawater (mg/L)[8]		410	1,350	10,500	2,700	19,000

[1]Average composition of four samples from wells 27S/8E-26C5 and 26D1 between 1967 and 1972.

[2]Average composition of two samples from well 27S/8E-27C1 in December 1988 and February 1989.

[3]Percentage of seawater calculated from a mixing-model equation:

$$x = \frac{100(C_{BW} - C_{FW})}{(C_{SW} - C_{FW})},$$

where x is percentage of seawater, and C_{BW}, C_{FW}, and C_{SW} are the concentrations of an ion in brackish water, freshwater, and seawater, respectively.

[4]Average composition of four samples from wells 27S/8E-9J1, 9L1, and 9J4 between 1965 and 1981.

[5]Average composition of two samples from well 27S/8E-8R3 in December 1988 and February 1989.

[6]Average composition of samples from San Simeon Acres Community Services District Wells #1 and #2 in December 1984 (data from Stephen Havlicek, San Simeon Acres Community Services District, written commun., 1985).

[7]Average composition of samples from two private wells (Cavalier Motel and Silver Surf Motel) in November 1984 (data from Stephen Havlicek, San Simeon Acres Community Services District, written commun., 1985).

[8]Average composition of seawater (Hem, 1985).

64401-64473 (table 2). Unless removed, ground water in parts of the lower Santa Rosa Basin could become unacceptable for potable purposes.

Iron and manganese concentrations in ground water exceed the secondary maximum contaminant levels in many locations throughout the study area but especially in the lower basins. Seventeen of the 24 manganese analyses done for this study exceeded the secondary maximum contaminant level of 0.05 mg/L, whereas only 2 of the 24 iron analyses exceeded the secondary maximum contaminant level of 0.3 mg/L (table 2). Manganese concentrations in ground water along the Santa Rosa Basin increased downstream and ranged from 0.002 at well 27S/9E-20G2 to 1.70 mg/L at well 27S/8E-27C1. The median value for that basin was 0.470 mg/L. Manganese concentrations also increased downstream in the San Simeon ground-water basin, ranging from 0.002 mg/L at well 27S/8E-10A3 to 1.60 mg/L at well 27S/8E-9N2. The median concentration for that basin was 0.190 mg/L. The two samples with iron concentrations in excess of the standard were from wells 27S/8E-11C1 and 8R4 in the lower San Simeon Basin (table 2). Iron and manganese are more soluble in a reduced state, and the high concentrations in the lower basins probably result from low oxidation potential in those areas.

Manganese concentrations in surface-water samples were less than 0.010 mg/L for Santa Rosa Creek and San Simeon Creek and was 0.043 mg/L for Perry Creek (table 2). The relatively low concentrations in surface water result partly because the creek water is oxidized. Manganese concentration in seawater is only 0.002 mg/L (Hem, 1985). The source of the manganese in ground water probably is the basin-fill deposits.

Nitrate concentrations met the primary maximum contaminant level of 10 mg/L as nitrogen in all surface- and ground-water samples collected for this study. Eleven of 24 samples had concentrations less than the detection limit of 0.010 mg/L as nitrogen. The highest concentration was 2.90 mg/L at well 27S/8E -11C1 (table 2). Historical data of unknown accuracy indicate that nitrate concentrations exceeded the primary maximum contaminant level twice in wells in the CCSD wastewater sprayfield. However, both samples were collected before 1976 and pre-date the sprayfield operation.

Historical nitrate data indicate that concentrations are highly variable in space and time. The distribution of concentrations does not indicate an obvious source, such as fertilizers, leaking sewers, or residual effects of old septic systems in residential areas. The ocean has a nitrate concentration of only 0.67 mg/L as nitrogen, so it cannot be the source of high nitrogen concentrations. Relatively high concentrations might result from inadequate surface seals on wells near pastures, barnyards, rural septic systems, or fertilizer handling areas. Buried organic material in the basin-fill deposits also could contribute nitrogen to ground water.

Historical ground-water data indicate that boron concentrations were high, 1.0 to 1.4 mg/L, in a cluster of three wells near Perry Creek about 5 mi southeast of Cambria. The source of this boron might be a marine graywacke unit of the Franciscan Complex that is exposed near these wells (Hall and others, 1979). A boron concentration of 1.4 mg/L was measured in brackish water from well 27S/8E-8R3 (table 2). Other coastal wells with high salinity have much lower boron concentrations, which indicate that the source of the boron in well 27S/8E-8R3 might be local bedrock. Boron concentrations less than 1.0 mg/L—which include all other samples in the study area—are not likely to affect crops grown in the area. Several crops could be adversely affected by boron concentrations between 1.0 and 2.0 mg/L. These crops in order of decreasing sensitivity are beans, bell peppers, oats, peas, and tomatoes (Bohn and others, 1979).

Hardness concentrations in the ground-water samples are consistently greater than 180 mg/L (as $CaCO_3$). Hence, ground water throughout the study area is hard (Hem, 1985). Hardness concentrations in ground water tend to increase downstream, with historical values ranging from 250 to 400 mg/L in the upper basins and from 300 to 1,000 mg/L in the lower basins. Concentrations in the Perry Creek area generally are between 400 and 500 mg/L.

Trihalomethanes are carcinogenic organic compounds containing bromine or chlorine that can occur naturally or from chlorination of water containing organic carbon. Bromide was detected in surface-water samples collected for this study. The municipal water supply is chlorinated prior to delivery; however, trihalomethane concentrations measured by the Cambria Community Services District (1990) were less than 0.01 mg/L. The primary maximum contaminant level is 0.1 mg/L.

Seasonal and Long-Term Trends

Ground water at the 11 wells sampled for this study became more dilute between December 1988 and

February 1989. The concentration of dissolved solids decreased in 10 of 11 wells; the average decrease was 76 mg/L (12 percent). The increase at the remaining well was only 2 mg/L (0.3 percent). The dilution resulted from ground-water recharge during the 2 months between sampling dates. The principal source of recharge was flow in San Simeon and Santa Rosa Creeks. Near the upper ends of the upper basins, the concentration of dissolved solids in ground water in February was nearly the same as the concentration in the creeks, indicating little dissolution of aquifer minerals during the recharge process. The gradual increase in dissolved solids during spring, summer, and autumn could result from gradual dissolution of aquifer minerals or from the evaporative concentration of ground water as it is used and reused for irrigation.

The composition of ground water in wells near the coast did not show a consistent trend away from the composition of seawater as a result of basin recharge between December 1988 and February 1989. This indicates that salinity in those wells is not a transient response to seasonal water-level fluctuations but rather is the result of more stable long-term processes.

Although ground water generally became more dilute during the winter of 1989, concentrations of iron and manganese increased at many wells. Manganese concentrations increased an average of 0.076 mg/L (11 percent) at 8 of 11 wells, decreased an average of 0.018 mg/L (10 percent) at 2 wells, and did not change in the remaining well (table 2). Increases in iron concentrations were even more dramatic. Iron concentration increased an average of 0.188 mg/L (1,370 percent) at 8 of 11 wells. Decreases at the remaining three wells averaged only 0.024 mg/L (46 percent). These increases suggest that ground water became more reduced during recharge because iron and manganese are more soluble in their reduced state. The transition of iron from the ferric to the ferrous state occurs at a lower oxidation potential than the analogous transition in manganese, which could explain the larger changes in iron concentrations. The seasonal variations in oxidation potential could be caused by the seasonal cycles in pumping and water levels. Pumping water from deep, reduced strata tends to draw relatively aerated water down from shallower strata. Seasonal variations in pumping can thus cause seasonal variations in the movement of dissolved oxygen into reduced strata.

With one possible exception, historical ground-water-quality data do not indicate any long-term trends in water quality. The possible exception is evident in water-quality samples collected from well 27S/8E-21R3 in the lower Santa Rosa Basin between 1955 and 1977. In addition to the previously described transient intrusion in 1962 and 1969, the data might indicate a slight increasing trend in salinity between 1970 and 1977. This trend can be seen in the plot of chloride concentrations for 1955–89 shown in figure 12. The slope of the chloride trend for 1971–77 (29.7 mg/L per year) was significantly greater than zero at the 95-percent confidence level. On a trilinear diagram (not shown), the anion composition of ground water for 1971–77 shows a trend toward the composition of seawater, indicating that the increasing chloride concentrations did not result from a simple evaporative process. However, 17 samples collected in 1989 (Bryan Bode, Cambria Community Services District, written commun., 1990) indicated that the chloride concentration had not continued to steadily increase since 1977. The chloride concentration during 1989 was highly variable, which could indicate that the apparent trend during the early 1970's is not accurately defined by the small number of data points.

WATER BUDGETS

Water budgets provide a quantitative means of comparing various processes that affect a hydrologic system. They can also reveal opportunities and constraints for water-supply development. Ground-water budgets for the Santa Rosa and the San Simeon Basins are presented in this section. Climatic and surface-water processes that influence flows to and from the ground-water basins also are described. Although field data were used to develop the estimates for each budget item, some estimates were revised using ground-water-flow models documented later in this report. Model calibration indicated that some of the initial estimates of flows and aquifer characteristics were inaccurate or mutually inconsistent. The revised estimates are briefly mentioned in this section for completeness. They are described more fully in the section on "Digital Simulation of Hydrologic System."

Annual ground-water budgets for each basin for April 1988 through March 1989 are shown in table 4. Nonzero budget items range from 4 to 1,175 acre-ft/yr. Model results are precise in that small changes in input result in small, predictable changes in output. Accuracy of the water budgets is limited primarily by the accuracy of the assumptions and data used in the model and probably is not greater than two significant digits. To retain small items in the budgets while giving a reasonable indication of accuracy for large items, all values in the table and text are rounded to the nearest 10 acre-ft/yr. Only head-dependent flows, which include seepage to and from the creek, ground-water outflow to the ocean, phreatophyte transpiration, and net storage change, are simulated by the models. The remaining budget items are estimated from field data and are specified as input to the models. Some inflows are directly offset by related outflows. From a management standpoint, a more useful picture of the water budgets emerges when related flows are combined into a net flow. For example, flow losses from Santa Rosa Creek are a large budget item, but so is ground-water flow into the creek. The actual quantity of streamflow captured as ground-water recharge is best indicated by the net flow loss from the creek. Net flow losses for the creeks and net pumpage are shown in the table 4.

The budget period was chosen to begin and end in late winter when the basins are virtually full. Ground-water levels tend to recover during winter to a level that is in equilibrium with the level of the water surface in the creek. This level usually is within a few feet of the same level every year. High creek stages could result in high ground-water levels, but high stages occur only briefly during storms. Similarly, if ground-water levels rise because of rainfall recharge or inflow from bedrock, the water tends to drain fairly quickly into the creek until levels return to equilibrium with the creek stage. Thus, although some budget items

Table 4. Simulated annual water budgets for the Santa Rosa and the San Simeon ground-water basins, San Luis Obispo County, California, April 1988 through March 1989

[All values rounded to nearest 10 acre-feet per year. Positive net flow indicates flow into basin; negative net flow indicates flow out of basin. CCSD, Cambria Comumunity Services District. <, actual value is less than value shown]

Budget item	Santa Rosa Basin			San Simeon Basin		
	Inflow	Outflow	Net flow	Inflow	Outflow	Net flow
Rainfall recharge	140	0	140	50	0	50
Creek seepage	1,120	650	470	950	410	540
Subsurface inflow and outflow:						
Onshore boundaries	370	0	370	150	0	150
Ocean boundary	0	60	-60	0	320	-320
Agricultural water use:						
Pumpage	0	890	-570	0	450	-280
Irrigation-return flow	320	0		170	0	
Nonagricultural water use:						
Municipal pumpage	0	250	-240	0	550	-120
Rural pumpage[1]	0	10		0	<10	
Wastewater recharge:						
CCSD sprayfield[2]	0	0		440	0	
Septic tanks	10	0		<10	0	
Irrigation-return flow	10	0		0	0	
Phreatophyte transpiration	0	160	-160	0	30	-30
Total inflows and outflows			-50			-10
Net storage change			-30			-10
Mass-balance error			20			0

[1]Includes domestic and industrial pumpage.

[2]Recharge at sprayfield equals applied wastewater plus rainfall minus ET_0.

vary from dry years to wet years, these variations usually are offset by compensating changes in other budget items so that late-winter water levels remain about the same. Exceptions occur in extremely dry years (drier than 1988–89) when ground-water levels do not fully recover in winter.

Rainfall

Rainfall distribution in the study area was estimated by combining measurements from six permanent rainfall stations and measurements from four temporary stations operated during 1987–89. The temporary stations were operated to better define local variations in rainfall distribution. Average annual rainfall at the temporary stations was estimated by correlation with measurements at the permanent stations during water year 1988. Locations of the gaging stations and annual rainfall during water year 1988 are shown in figure 1.

Rainfall distribution during 1988 was consistent with the patterns of average rainfall for 1936–67 shown on a map developed by the San Luis Obispo County Flood and Water Conservation District (Glenn Britton, written commun., 1989). The additional stations did not reveal any obvious local anomalies in rainfall distribution. In particular, local orographic effects were not evident, although only two stations were located on hillsides above the valley floor. Generally, average annual rainfall increased uniformly from 20 in. at the coast to about 26 in. at the inland ends of the Santa Rosa and the San Simeon Basins. Average annual rainfall at the headwaters of the creek drainages is about 40 to 50 in.

Records for local rainfall stations are fairly short. The Hearst Ranch station (fig. 1) has been in operation since 1939, but most of the other stations have been in operation for a much shorter time. A better indicator of long-term climatic trends and variability is the 120-year rainfall record for the station at the California Polytechnic State University Institute in San Luis Obispo, 30 mi southeast of Cambria. Annual rainfall at the San Luis Obispo-Poly station correlates well with rainfall at stations in the Cambria area (r between 0.85 and 0.96).

Cumulative departure of annual rainfall at the San Luis Obispo-Poly station during 1870–1989 is shown in figure 13. Using the period 1957–72 as representative of long-term average climatic conditions, average annual rainfall at Hearst Castle, San Simeon, and CalTrans stations is 31.6, 23.4, and 21.1 in., respectively. The CalTrans station was moved in January 1969. A double-mass plot indicated that rainfall at the old location averaged 85 percent of rainfall at the new location, and the historical data were adjusted accordingly. The cumulative departure

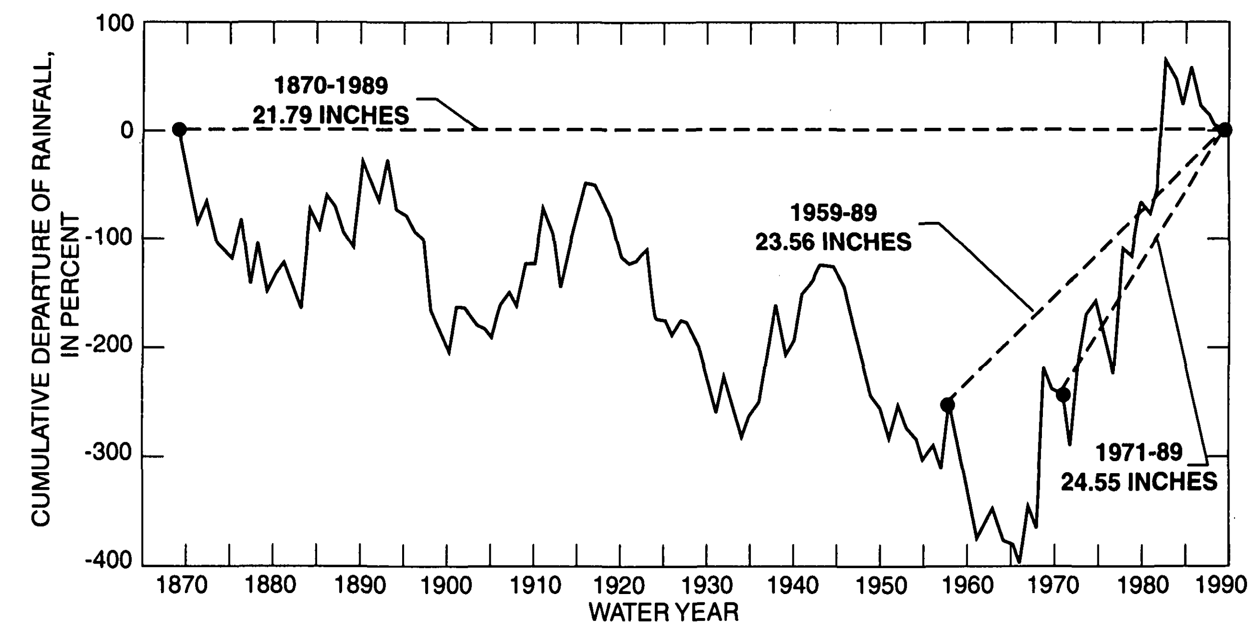


Figure 13. Cumulative departure of annual rainfall at the San Luis Obispo-Poly station, San Luis Obispo County, California, 1870–1989.

diagram also indicates that water years 1988 and 1989 were drier than normal. Rainfall at the three stations during water year 1988 was between 71 and 87 percent of the long-term average. Rainfall at the three stations during water year 1989 was between 55 and 66 percent of the long-term average.

Typically, about 93 percent of annual rainfall occurs between November and April. Winter storm systems bring periods of rainy weather lasting several days. A large storm on December 23–26, 1988, brought 2.0 to 3.8 in. of rainfall to the valley floors and resulted in large streamflow peaks.

Streamflow

Flow Entering Ground-Water Basins

The drainage areas of Santa Rosa and San Simeon Creeks extend inland to the crest of the Santa Lucia Range (fig. 1), which reaches altitudes of 3,400 ft above sea level. Runoff from the areas upstream of the ground-water basins and from the Perry Creek drainage area was measured with continuous-record stream-gaging stations (fig. 2). Because of the steep terrain in the upstream areas, streamflow responds markedly to rainfall. Some water is retained in the soil and fractured rock, however, and reemerges as base flow in the creeks. In most years, base flow gradually decreases in spring and ceases or becomes a trickle of several gallons per minute by early summer.

The drainage area of San Simeon Creek is 26.2 mi^2 of which 3.2 percent is occupied by the ground-water basin, 86.2 percent is upstream of the upper end ground-water basin, and 10.6 percent is in small drainage on the hillslopes along the sides of the basin. Van Gordon Creek enters San Simeon Creek about 0.5 mi east of the Pacific Ocean and has a drainage area of 2.6 mi^2. The drainage area of Santa Rosa Creek is 24.5 mi^2, and the distribution among basin, upstream, and hillslope areas is 7.7, 60.2, and 32.1 percent, respectively. Perry Creek enters Santa Rosa Creek about 1 mi east of Cambria and has a drainage area of 22.7 mi^2.

Streamflow has been measured since 1959 at the upstream gaging station on Santa Rosa Creek (Santa Rosa Creek near Cambria) and since 1971 at the upstream gaging station on San Simeon Creek (San Simeon Creek at Palmer Flats) (fig. 2). Streamflow during occasional periods of missing record was estimated by correlation with flow in Santa Rita Creek near Templeton, about 15 mi east of Cambria (outside of study area). Santa Rita Creek is similar to San Simeon and Santa Rosa Creeks in terms of drainage area, terrain, and rainfall.

The downstream gaging station on Santa Rosa Creek (Santa Rosa Creek at State Highway 1) (fig. 2) has been in operation since 1976, although it may soon be discontinued because a new gaging station was installed at the Main Street bridge. The downstream gaging station on San Simeon Creek and the gaging station on Perry Creek were installed for this study and were operated during water years 1988–89.

Flow-duration curves for daily mean flows at the upstream gaging stations on Santa Rosa and San Simeon Creeks for the period of record for each gaging station are shown in figure 14. The curves indicate that peak flows in San Simeon Creek tend to be larger and that smaller flows are less persistent. Flow is virtually 0 about 47 percent of the time at the San Simeon Creek gaging station and about 25 percent of the time at the Santa Rosa Creek gaging station. The curves do not represent long-term average conditions because the periods of record for both gaging stations were wetter

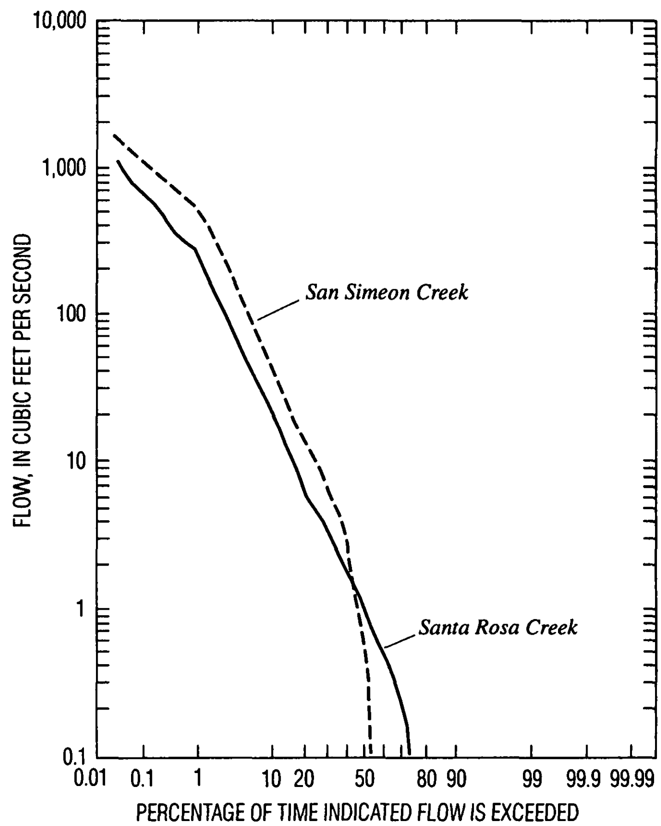


Figure 14. Flow-duration curves for daily mean flow in San Simeon Creek at Palmer Flats (1971–89) and Santa Rosa Creek near Cambria (1959–89), San Luis Obispo County, California.

than average. This issue is described more fully in the section "Occurrence and Effects of Drought."

The persistence of base flow in late spring and summer is affected by evapotranspiration in the upper parts of the drainage areas. A long-time Cambria resident observed that summer base flow in Van Gordon Creek was much more persistent for several years following large brush fires along the upper reaches of the creek (Clyde Warren, oral commun., 1989). Controlled brush-removal experiments in small semiarid drainage areas with similar vegetation have demonstrated that shrubs close to the creekbed can consume as much as 40 percent of annual streamflow (Hibbert and others, 1982).

Flow in Perry Creek is not closely related to flow in Santa Rosa Creek. A tiny trickle of base flow (less than 0.1 ft^3/s) persists throughout the summer and probably is supported by emerging ground water. After omitting flows of less than 0.03 ft^3/s, a least-squares regression of daily mean flows in the two creeks during 1988–89 indicated that flow in Perry Creek was generally about 0.18 times as large as flow in Santa Rosa Creek (r=0.80). Streamflow during some storms was distinctly different, however. For example, the largest mean daily flow in Perry Creek during a storm on December 23–26, 1988, was only one-half as large as the largest flow during a storm on January 17–19, 1988. This is exactly opposite of the relative flow magnitudes in Santa Rosa Creek during the same two storms.

Annual stream discharge during 1959–89 at the upstream gaging station on Santa Rosa Creek ranged from 244 to 27,800 acre-ft, with a mean value of 7,840 acre-ft and a median value of 5,010 acre-ft. Annual discharge during 1971–89 at the upstream gaging station on San Simeon Creek ranged from 475 to 42,600 acre-ft, with a mean value of 16,200 acre-ft and a median value of 13,100 acre-ft.

The flow-duration curves and annual discharge statistics for Santa Rosa and San Simeon Creeks probably are not representative of the long-term average because the periods of record for the stream-gaging stations were wetter than usual, based on long-term rainfall records. Better estimates of long-term mean and median annual discharges were obtained by relating annual discharge in Santa Rosa and San Simeon Creeks to annual rainfall at San Luis Obispo, as shown in figure 15. The data indicate that the relation of discharge and rainfall is approximately linear. Correlation coefficients of ordinary least-squares regression lines were 0.91 and 0.96 for Santa Rosa and San Simeon Creeks, respectively.

Mean and median rainfall in San Luis Obispo during 1870–1989 were 21.79 and 19.76 in., respectively. The regression equations indicate that the corresponding mean and median annual discharges in Santa Rosa Creek are 6,800 and 5,700 acre-ft, respectively. In San Simeon Creek, the mean and median are 13,100 and 10,900 acre-ft, respectively. These means are 13 to 19 percent smaller than the means calculated for the period of streamflow record. The medians are about the same for both periods. The mean exceeds the median because wet-year outliers create a positive skew to the annual rainfall distribution.

Daily mean flow at the upstream gaging stations on Santa Rosa and San Simeon Creeks during water years 1988–89 is shown in figure 16. Peak instantaneous flow on December 24, 1988, was 1,870 ft^3/s at the upstream gaging station on Santa Rosa Creek and 2,280 ft^3/s at the upstream gaging station on San Simeon Creek. Annual discharge in Santa Rosa, San Simeon, and Perry Creeks during 1988–89 was 1,925, 4,320, and 304 acre-ft, respectively. The drainage areas of the creeks are of nearly equal size. The differences in annual discharge result primarily from differences in rainfall and land slope. Perry Creek drains foothill areas where rainfall and land slopes are much less than in the other two drainage areas.

Runoff from small drainages in the hills along the sides of the ground-water basins occurs only during brief periods of intense rainfall. On December 23–26, 1988, between 1.4 and 2.4 in. of rain fell on the

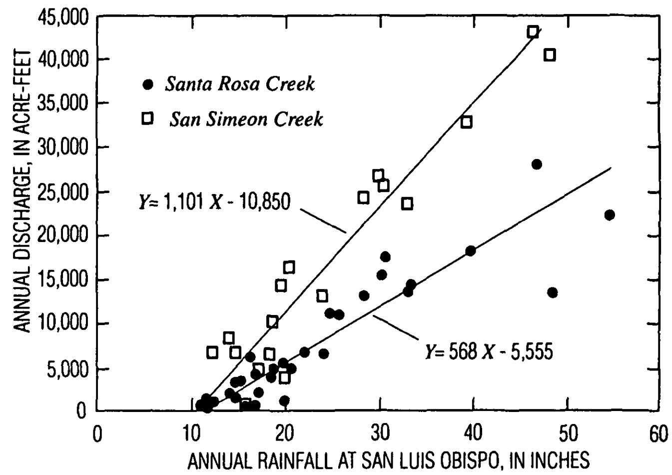


Figure 15. Relation of annual rainfall at San Luis Obispo and annual discharge in San Simeon and Santa Rosa Creeks, San Luis Obispo County, California.

hillslopes, and flows of less than 0.5 ft³/s were measured in several small drainages. Rainfall intensity tapered off to a drizzle, and by the next day flow in most of the small drainages had stopped. The combined runoff from all the small drainages along the hillslopes was less than 1 percent of the flow in the main creeks at that time. Likewise, runoff from the valley floors was negligible. Local runoff could contribute a larger percentage of flow if rainfall intensity for a particular storm was relatively high in the small drainage.

Gains and Losses Within Ground-Water Basins

As the creeks flow across the ground-water basins, they can gain or lose water through the creekbeds. In winter, seepage from the creeks provides the largest source of recharge to the ground-water basins. In summer, movement of ground water into the creeks creates flow along some stream reaches. Streamflow gains and losses were measured using three methods: (1) instantaneous streamflow measurements, (2) continuous records of streamflow at gaging stations, and (3) estimates of storage changes in the ground-water basin.

Flow measurements were made at four locations (fig. 2) along San Simeon Creek and at four locations along Santa Rosa Creek during the recession phase of the storm on December 23–26, 1988. The measurements indicated a loss of streamflow along all reaches of San Simeon Creek. The rate of loss between the upstream and downstream gaging stations decreased from 15.6 ft³/s on December 25 to 2.2 ft³/s on December 27. A similar pattern was observed on Santa Rosa Creek after accounting for inflow from Perry Creek and from an unnamed tributary near the northeast corner of sec. 21, T.27S., R.9E. The rate of loss along Santa Rosa Creek was highest along the reach between the upstream gaging station and a point near well 27S/9E-19J1. These flow loss measurements probably underestimate the average loss rate for the storm because they were made after the flow peak. As flow receded, some of the water stored in streambanks during the peak probably moved back into the creek, thereby offsetting losses through the bottom of the creekbed.

Estimating flow gains and losses on the basis of continuous records of streamflow at gaging stations can minimize errors caused by transient bank storage. This

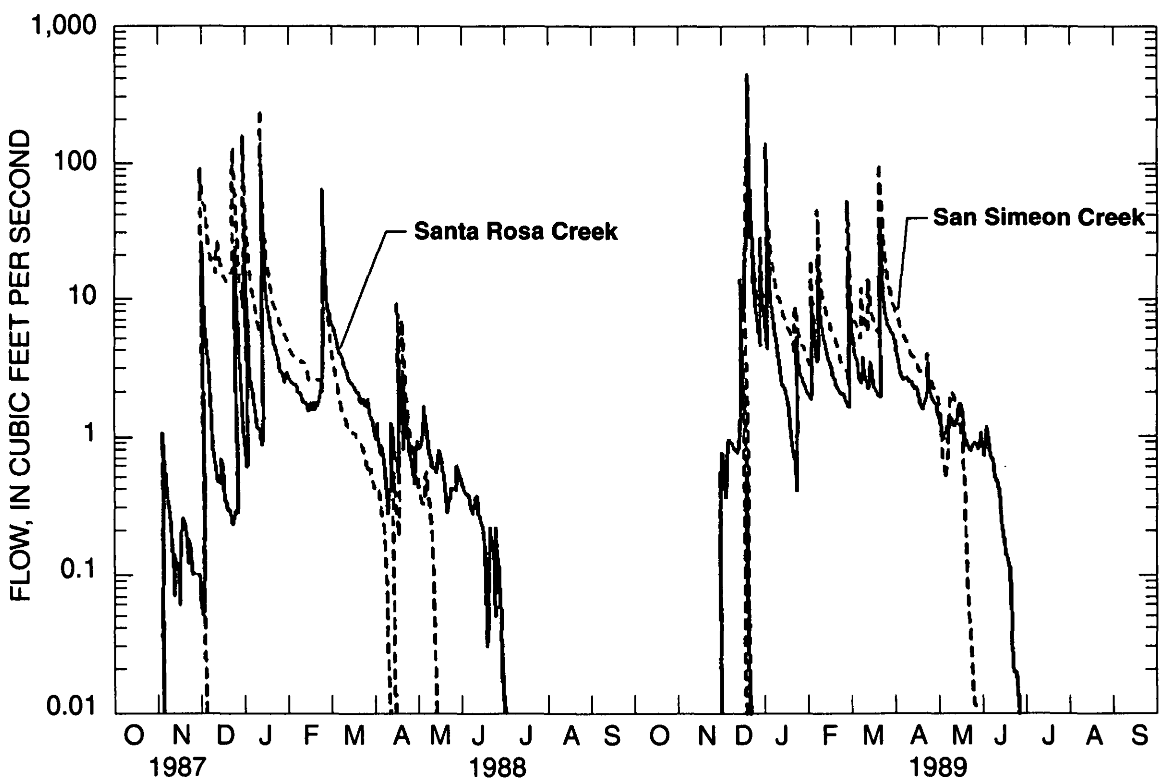


Figure 16. Daily mean flow in Santa Rosa Creek (Santa Rosa Creek near Cambria) and San Simeon Creek (San Simeon Creek at Palmer Flats), San Luis Obispo County, California, water years 1988–89.

was done by comparing cumulative discharges at the upstream and downstream gaging stations on each creek for a period of several days or weeks. This method is accurate only when flows for the gaging stations on Santa Rosa and San Simeon Creeks are less than about 50 ft^3/s. As flows increase, gains and losses become a smaller percentage of total flow and become smaller than the uncertainty in the flow measurements. Also, there are discrepancies between the rating curves used to calculate flow from stream stage at each gaging station. The accuracy of these curves is poor at high flow because few data are available to define the curve. Errors in the rating curve result in a consistent bias in calculated flow. For example, the upstream gaging station on San Simeon Creek gives a low reading at high flows relative to the downstream gaging station. As a result, flow gains are unrealistically large (as much as 323 ft^3/s) along the intervening reach when total flow exceeds about 100 ft^3/s. These gains are too large to be attributable to ground-water inflow, and there is little, if any, surface inflow.

Rating curves are more accurate for flows less than 50 ft^3/s, and in this range continuous streamflow records can be used to estimate net gains or losses in flow as the creeks cross the ground-water basins. Generally, calculated gains and losses along Santa Rosa and San Simeon Creeks are consistent with instantaneous flow data and indicate that the rate of flow to or from ground water is controlled by adjacent ground-water levels. Daily mean flow loss rates of 20 to 40 ft^3/s are common during the first few weeks of streamflow when ground-water levels are low. Net losses in mid-winter are small when ground-water levels rise to the level of the thalweg. An exception occurs near municipal wells which operate all year and induce flow losses from the channel even after nearby ground-water levels have fully recovered.

Because flow losses could not be estimated accurately at high flows, continuous streamflow records could not be used to estimate total annual ground-water recharge from the creeks.

A third estimate of seepage losses was obtained from estimates of storage changes in the aquifer. Water levels rose rapidly during and after the storm on December 23–26, 1988. Nearly all the rise was attributable to stream recharge because rainfall during the month prior to the onset of streamflow had little or no effect on water levels and because water levels abruptly ceased rising once they reached the approximate level of water in the creek. Water-level rises were multiplied by area and specific yield for local areas within the basins. These were summed to obtain the total storage change for each basin. The calculations indicated that aquifer storage in the San Simeon Creek Basin increased about 480 acre-ft during the first week after the onset of streamflow and about 40 acre-ft during the following week. At that point, the basin was virtually full and storage did not continue to increase. In the Santa Rosa Creek Basin, storage increased about 360 acre-ft during the first week after the onset of streamflow, 90 acre-ft the following week, and 130 acre-ft during the subsequent 11 weeks.

Streamflow and water-level data indicate that most of the recharge from the creek occurs early in the winter flow season. Once water levels rise to the level of the creek, further recharge is rejected. A comparison of manual flow measurements in March and December 1988 confirmed that net flow losses are relatively small when the basins are full at end of the flow season.

In summer, Santa Rosa Creek acts locally as a drain for ground water. Because of subsurface flow obstructions, the water table intersects the creekbed near well 27S/9E-19H2 and emerges as flow in the creek. During the summer of 1988, this flow was several cubic feet per second and continued downstream as far as well 27S/8E-24N2. During the summer of 1989, flow eventually receded to the vicinity of well 27S/8E-24J4.

The first reach of the creeks to dry up during streamflow recession is important for fisheries management. After each of two streamflow peaks in December 1988, one of the first reaches of Santa Rosa Creek to go dry was the reach adjacent to well 27S/8E -27H1. The first reach to go completely dry on San Simeon Creek during the summer of 1988 was between the CCSD well field and the wastewater sprayfield. Pools persisted all summer between the sprayfield and the coast, but flow in that reach was too small to detect visually.

On several occasions during low-flow conditions, flow in Santa Rosa Creek at the Windsor Boulevard bridge was greater than flow at the State Highway 1 bridge (fig. 2) but by less than 1 ft^3/s. This gain in flow probably is caused by ground water that is forced to the surface by a bedrock constriction in the aquifer.

All three methods used to estimate seepage losses from the creeks indicate that seepage rates are highest at the beginning of the streamflow season when rates in both basins average 400 acre-ft per week.

These rates decrease rapidly as ground-water levels rise to the levels of the creeks. The calibrated ground-water-flow models indicated that net seepage losses during the first week of streamflow following the storm on December 23–26, 1988, were 300 acre-ft in the Santa Rosa Basin and 410 acre-ft in the San Simeon Basin. Net seepage losses for April 1988 through March 1989 were 470 and 540 acre-ft in the Santa Rosa Basin and the San Simeon Basin, respectively (table 4).

Areal Recharge

Deep percolation of rainfall and irrigation water past the root zone of plants is another source of ground-water recharge. This type of recharge occurs throughout the ground-water basin wherever soils are not covered by impervious materials. The amount of deep percolation is affected by rainfall, irrigation, evaporative demand, plant type, and soil-moisture conditions. These factors were all accounted for in one-dimensional soil-moisture budgets developed for areas of uniform land use and vegetation type. Rainfall and irrigation are described in other sections of this report. The remaining factors and the budget calculations are described in this section.

Evaporative Demand

Evaporative demand refers to the humidity gradient that causes water to move in the vapor phase from plants, soils, and surface-water bodies, which are relatively moist, to the atmosphere, which is relatively dry. Evaporative demand in the study area during water years 1988 and 1989 was estimated from temporary local climate stations and permanent climate stations elsewhere on the coast.

A commonly used measure of evaporative demand is called reference evapotranspiration (ET_0). This is the amount of evapotranspiration that occurs from an areally extensive plot of irrigated short-cropped grass. The California Department of Water Resources (1988) operates a network of climate stations under a program called the California Irrigation Management Information System (CIMIS). ET_0 at each station is calculated using the modified Penman equation, which requires measurements of net solar radiation, temperature, windspeed, relative humidity, and soil heat flux. The CIMIS program uses empirical coefficients to adjust the raw Penman calculations to match measured consumptive water use by irrigated short-cropped grass.

A climate station similar to the ones used in the CIMIS program was operated at the CCSD well field (fig. 2*B*) during July through October 1988. In addition, measurements of actual evapotranspiration were made using the eddy-correlation method (Duell, 1990) during 3- to 4-day periods in July and October. These measurements were made at the well-field site, in a tomato field in July, and in a sugar pea field in October. Actual evapotranspiration can differ from ET_0, depending on vegetative characteristics and the availability of soil moisture. Data collected for the eddy-correlation measurements also were used to calculate ET_0 using the Penman equation. However, the humidity measurements of the eddy-correlation stations were made using a wet-bulb psychrometer rather than the dry-bulb psychrometer used at the Penman and CIMIS stations.

Monthly ET_0 measured at the well field was compared with the average of monthly ET_0 at CIMIS stations at Castroville, 90 mi north of the study area, and at Betteravia, 60 mi south of the study area. These stations were selected because they are both within a few miles of the coast, as is the study area. Coastal fog is common in summer, and consequently, ET_0 at the coastline can be as little as 65 percent of ET_0 at stations 10 to 20 mi inland (California Department of Water Resources, 1975).

Monthly ET_0 during 1988 is shown in table 5 including the measured values at the well field, the average of the two CIMIS stations, and two published estimates of long-term average ET_0. ET_0 at the well field is consistently higher than the CIMIS values. The discrepancy decreases from 34 percent in July to 13 percent in October. The difference probably results largely from differences in site characteristics. Dry site conditions can result in ET_0 measurements that are 15 percent too high (William Pruitt, University of California, Davis, oral commun., 1988). Instead of irrigated short-cropped grass, the well-field site is in an open field of nonirrigated, unmown wild grass with scattered native shrubs. The grass was dry and brown in July. In October, it had started to resprout in response to early winter rains and more closely approximated conditions at the CIMIS stations. This could explain the decreasing discrepancy between the ET_0 measurements. Daily ET_0 calculated using the Penman equation at the tomato and sugar pea sites was consistently less than at the well-field site, which

Table 5. Estimates of monthly reference evapotranspiration (ET_0) near Cambria during calendar year 1988 and for long-term average climatic conditions, San Luis Obispo County, California

[Well field: U.S. Geological Survey data, using CIMIS version of Penman equation. CIMIS: Average of values for CIMIS stations at Castroville and Betteravia. Cambria: Values for Cambria from Pruitt and others (1987). Central Coast: Values for central coast coastal valleys and plains (California Department of Water Resources, 1975). CIMIS, California Irrigation Management Information System. All values in inches. —, no data]

Month	1988		Long-term average	
	Well field	CIMIS	Cambria	Central Coast
January	—	1.91	1.86	1.8
February	—	3.00	2.22	2.1
March	—	4.74	2.93	3.1
April	—	4.50	3.54	3.9
May	—	5.68	4.15	4.7
June	—	4.88	4.49	4.9
July	6.61	4.94	4.76	5.3
August	5.95	4.57	4.27	4.8
September	4.39	3.39	3.54	3.8
October	2.79	2.46	3.05	3.2
November	—	2.06	2.03	2.2
December	—	1.86	1.64	1.5
Total	—	43.99	38.48	41.3

further indicates that the relatively hot, dry conditions at the well-field site might have resulted in an overestimate of ET_0. Use of the wet-bulb psychrometer at the crop sites also might have contributed to the difference.

Temperatures during 1988 might have been slightly higher than normal, which also would tend to increase ET_0. The average annual ET_0 for the two CIMIS stations at Castroville and at Betteravia in 1988 was 43.99 in., which is higher than the long-term average for those stations (39.42 in.) and higher than both of the published estimates of long-term average ET_0 (table 5).

The presence of a climatic gradient near the coast was evident in the daily temperature data collected at three locations along the Santa Rosa Creek valley. The stations were 0.4, 2.5, and 4.5 mi from the coast. Monthly averages of maximum, mean, and minimum daily temperatures at the stations are shown in figure 17. The influence of marine air is evident in the data for the station closest to the coast (CCSD wastewater plant), which has the narrowest range of daily temperature fluctuations in almost all months. The station farthest from the coast (Scooter Rhoades) generally has the largest range. Although the range of

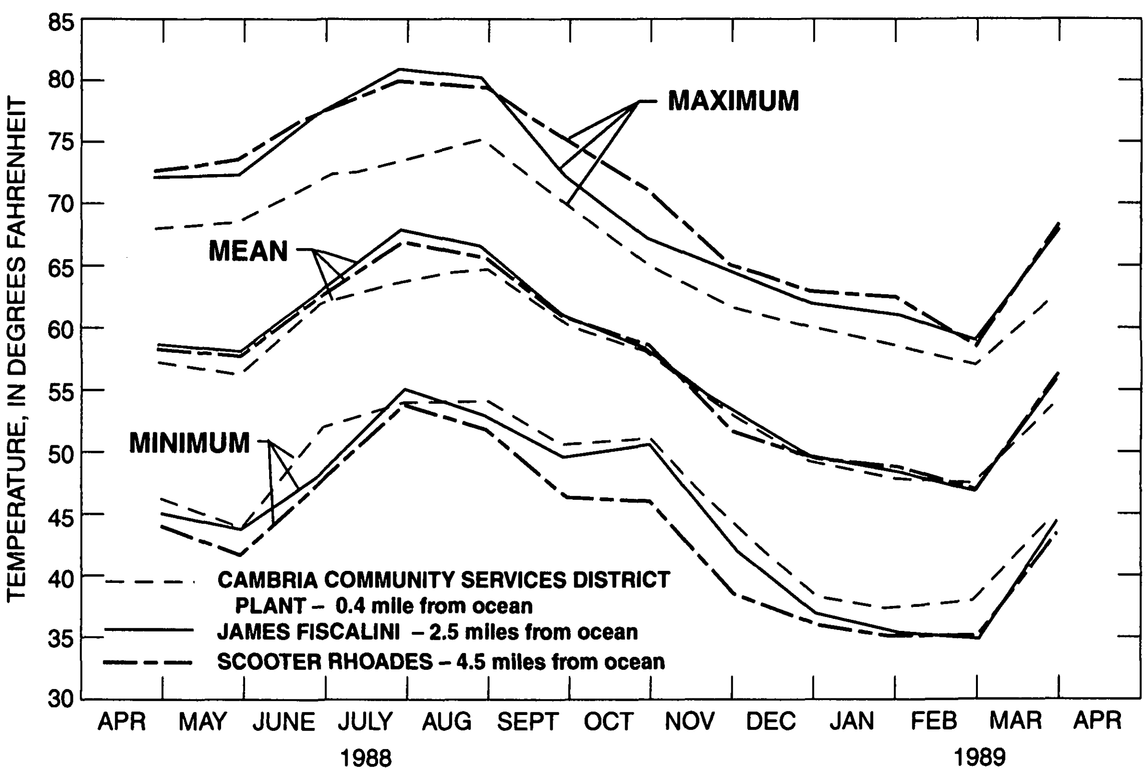


Figure 17. Monthly averages of maximum, mean, and minimum daily temperatures at three distances from the coast in the Santa Rosa Basin, San Luis Obispo County, California, 1988–89. (See figure 2 for location of climate measurement stations.)

daily temperature fluctuations increases inland, the daily mean temperature is similar for all stations in every month except July, when the mean temperature at the station closest to the coast was about 4°F lower than at the other two stations. The coastal station might have been heavily influenced by fog, which is common in summer.

Estimates of ET_0 were not adjusted to account for the coastal climatic gradient. ET_0 is related to daily mean temperature (U.S. Soil Conservation Service, 1967), which in this case does not vary significantly with distance from the coast. Fog can decrease solar radiation near the coast, but the corresponding decrease in ET_0 was assumed to be small relative to the overall

A. Santa Rosa Basin

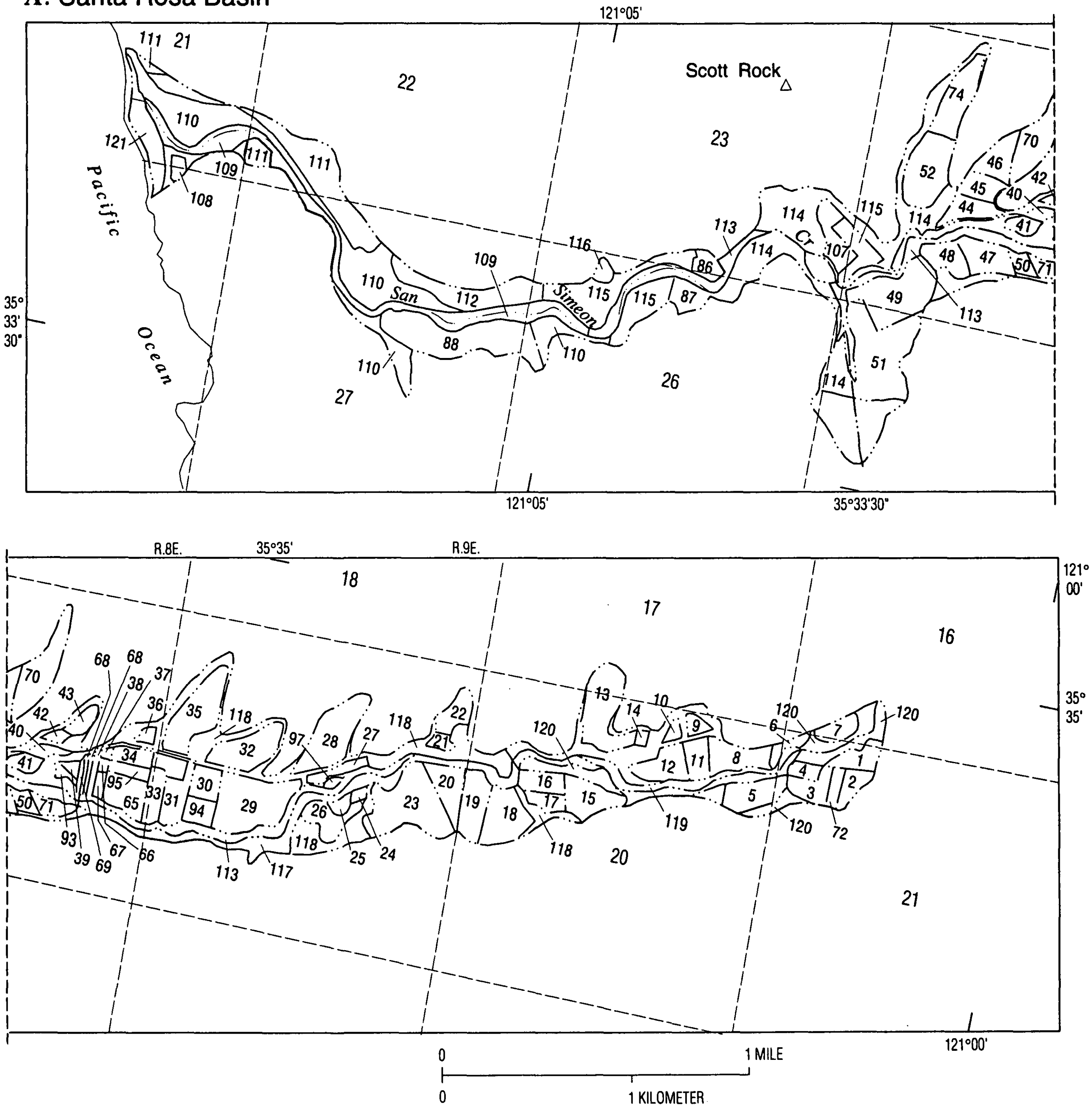


Figure 18. Fields and zones of uniform vegetation type in (*A*) the Santa Rosa and (*B*) the San Simeon ground-water basins, San Luis Obispo County, California.

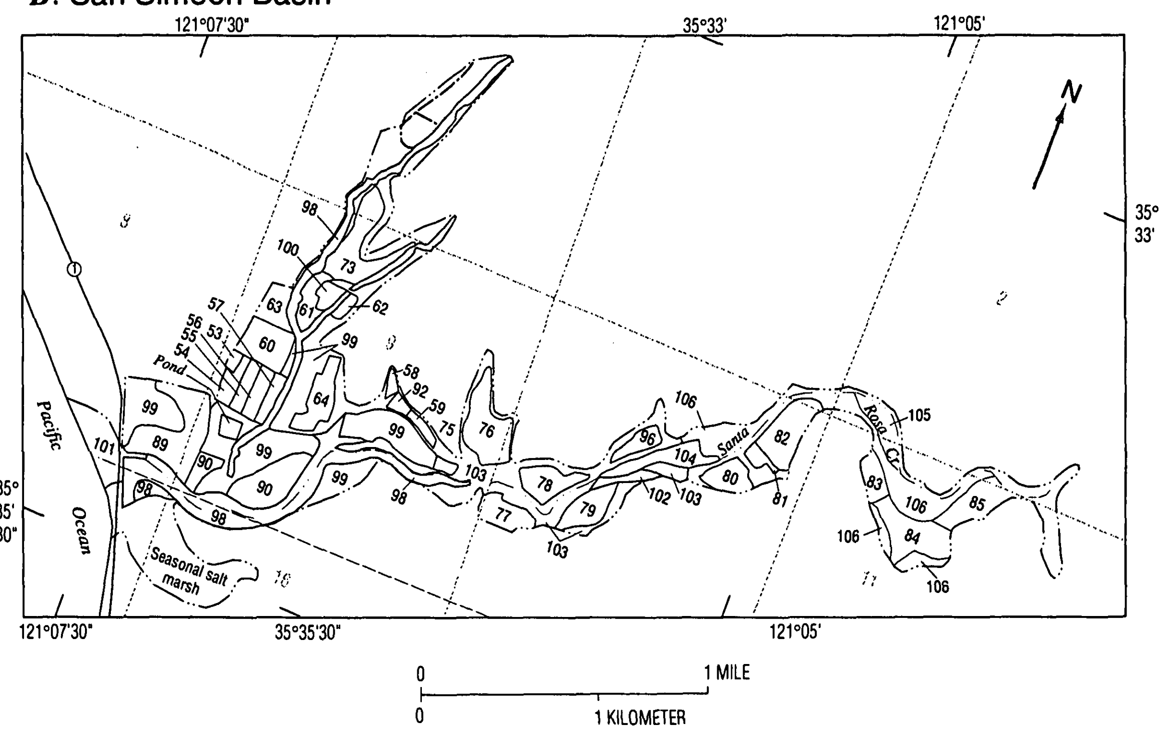
uncertainty in estimating ET_0 and crop evapotranspiration. Also, an analysis of water use at individual irrigation wells did not indicate an obvious inland increase in quantities of applied water, which would be expected if ET_0 increased inland.

Eddy-correlation measurements in the tomato and sugar pea fields were used to calculate crop coefficients, which are the ratio of actual evapotranspiration (AET) to ET_0. The tomato crop was measured in July; measurement began 2 days after an irrigation. The plants were one-half grown (staked to 3 ft tall) with about 30 percent canopy coverage. The crop coefficient was 0.82. Other estimates of the crop coefficient for half-grown tomatoes at the peak of their growing season generally are in the range of 0.76 to 0.95 (U.S. Soil Conservation Service, 1967; California Department of Water Resources, 1975; Doorenbos and Pruitt, 1977). The sugar pea field was measured in October starting the day after an irrigation. The vines were fully mature and strung to a height of about 6 ft in rows 3 ft apart. The calculated crop coefficient was 1.05. Published estimates of crop coefficients for sugar peas are not available, but the calculated values seem reasonable given the height of the crop and the damp soil conditions.

Land Use

Land use in the Santa Rosa and the San Simeon ground-water basins was mapped to determine the distribution of areal recharge. Land use was systematically observed every 1 to 3 months during 1988, and areas of uniform vegetation type were identified. A map of individual fields and zones of uniform vegetation type is shown in figure 18. A

***B.* San Simeon Basin**



EXPLANATION

—··— **BOUNDARY OF GROUND-WATER BASIN**-Dashed where approximately located

(80) **FIELD OF UNIFORM VEGETATION** - Numbers correspond to table 6

Figure 18. Fields and zones of uniform vegetation type in (*A*) the Santa Rosa and (*B*) the San Simeon ground-water basins, San Luis Obispo County, California—Continued.

tabulation of vegetation type, applied irrigation water, and ground-water recharge for each field and land-use zone is shown in table 6. A summary tabulation, grouped into irrigated and nonirrigated categories, is shown in table 7.

In 1988, 43 percent (519.5 acres) of the Santa Rosa Basin was crop land. About 36 percent of the basin area was irrigated at least once during the year. Residential, commercial, and industrial uses accounted for 8.5 percent (104 acres) of the basin area.

The relative amounts of agricultural and irrigated land in the San Simeon Basin in 1988 were similar to those in the Santa Rosa Basin. However, the cropping intensity was slightly greater. Cropping intensity is the ratio of cropped area or harvested acreage to total crop land. An intensity greater than 1.0 indicates that some fields produce more than one crop during the year. The cropping intensities in the Santa Rosa and the San Simeon Basins were 1.5 and 1.8, respectively. Assuming irrigation rates for each crop type are similar in both basins, the average quantity of irrigation water applied to each acre of crop land was greater in the San Simeon Basin.

Land use in the Santa Rosa and the San Simeon Creek valleys has changed significantly over the past several decades. Information regarding land use was obtained from interviews with local farmers (Jon Pedotti, Larry Fiscalini, and Scooter Rhoades), the California Department of Water Resources (Mark VanVlack, written commun., 1987), and from field surveys done during 1987–89 for this study. Sugar beets were the principal crop in the Santa Rosa Creek valley in the 1950's and 1960's. There was a shift toward dry-farmed crops such as garbanzo beans and oat hay in the 1970's, although about one-half of the crop land continued to be irrigated for alfalfa, pasture, and sudan grass. In the early 1980's, there was a rapid change to irrigated vegetable crops including cherry tomatoes, sugar peas, squash, and fava beans. Many fields were double-cropped in winter with dry-farmed hay and grains. These continued to be the principal crops at the time the surveys were done for this study.

The evolution of cropping patterns in the San Simeon Creek valley was similar. The San Simeon Creek valley was part of the William Hearst ranch until the 1930's and probably was used to raise fodder crops. From the 1930's to 1960's, there was some irrigation for sugar beets and flowers. During 1970–81, the principal crops were dry-farmed garbanzo beans, oat hay, and barley. The only significant irrigation during 1974–77 was for pasture at the present site of the CCSD wastewater sprayfield and for 60 acres of alfalfa. As in the Santa Rosa Basin, there was a rapid conversion to irrigated vegetable crops beginning in 1981.

Soil-Moisture Budget

A one-dimensional daily soil-moisture budget was calculated for 119 zones of uniform vegetation during January 1988 through March 1989. Zones consisted of individual agricultural fields or areas of natural vegetation and ranged in size from 0.5 to 152 acres (table 6). Rainfall was interpolated linearly to each zone using long-term rainfall patterns and daily rainfall at Soto Ranch and the CCSD wastewater plant. Surface runoff of rainfall was assumed to occur if daily rainfall exceeded 3.0 in. Irrigation was estimated from crop water demand and agricultural energy use, as described in a later section of this report.

Evapotranspiration of soil moisture was divided into two components. Evaporation of recent rainfall from the soil surface was assumed to occur at the ET_0 rate. This evaporation occurred from a hypothetical surficial soil layer with a storage capacity of 0.5 in. Evaporation of irrigation water from the soil surface was accounted for in the crop coefficients used to estimate crop water use. The second component of evapotranspiration was actual evapotranspiration by plants and was calculated by multiplying ET_0 by a monthly crop coefficient. Crop coefficients reflect plant type, growth stage, and season. Coefficients for agricultural crops were obtained from previous studies of crop water use (U.S. Soil Conservation Service, 1967; California Department of Water Resources, 1975; and Doorenbos and Pruitt, 1977) and ranged from 0.35 for oats just before harvest to 1.21 for fully mature and staked sugar peas in midsummer. Other coefficients used were 0.25 for bare soil and 1.00 for riparian vegetation and native brush and grass.

In nonirrigated areas, AET is limited by the amount of soil moisture available to plants. Available water capacity is the quantity of water that can be stored in the plant root zone between soil-moisture tensions corresponding to field capacity and wilting point. Available water capacity for each zone was calculated from water-retention characteristics of the local soils (U.S. Soil Conservation Service, 1984) and plant root depths. AET was adjusted by a multiplier which decreased sigmoidally according to soil type from 1.0 at field capacity to 0.0 at the wilting point (Dunne and Leopold, 1978, p. 142). For example,

Table 6. Vegetation type, applied irrigation water, and ground-water recharge for April 1988 through March 1989 and for average rainfall conditions for individual fields and land-use zones in the Santa Rosa and the San Simeon ground-water basins, San Luis Obispo County, California

[Location of fields shown in figure 18. Double-cropping with the same type of crop indicated by 2. acre-ft, acre-foot]

Field or zone number	Area (acres)	Vegetation type	April 1988—March 1989		Average rainfall	
			Applied irrigation water (acre-ft)	Ground-water recharge (acre-ft)	Applied irrigation water (acre-ft)	Ground-water recharge (acre-ft)
			Santa Rosa Basin			
1	6	Peas (2)	19.6	11.84	19.3	15.38
2	3	Peas, squash, lettuce	7.6	4.66	7.5	6.62
3	6	Peas (2)	23.3	12.40	22.9	15.91
4	3	Squash, lettuce	8.1	4.70	8.1	6.78
5	10	Oats, irrigated pasture	18.4	10.11	15.4	13.25
6	3	Peas	5.5	3.96	5.2	5.45
7	4	Peas, squash, lettuce	13.5	7.33	13.5	10.14
8	10	Oat hay, irrigated pasture	18.2	9.70	18.1	15.76
9	2	Oat hay, irrigated pasture	3.8	2.20	3.7	36
10	1	Oat hay, irrigated pasture	1.8	12	1.8	1.42
11	6	Alfalfa	17.5	76	17.6	10.97
12	10	Oat hay, irrigated pasture	17.5	8.78	17.5	15.57
13	15	Peas, tomatoes	28.5	11.44	28	192
14	1	Domestic orchard	0	.20	0	.74
15	10	Peas	26	13.99	22.1	186
16	6	Peas	6.7	4.45	4.5	6.93
17	4	Peas	12.2	6.61	12.3	90
18	12	Oat hay, squash	34	19.22	30.7	24.44
19	12	Oat hay, tomatoes	28.3	15.63	27.9	22.50
20	9	Peas, irrigated pasture	20.3	11.90	17.1	13.74
21	2	Irrigated pasture	6.3	3.63	4.7	3.24
22	5	Irrigated pasture	15.8	96	11.8	8.10
23	22	Irrigated pasture	53.4	24.14	53.5	38.52
24	1	Peas	1.1	.73	1.1	1.15
25	2.5	Peas	2.8	1.84	2.8	2.90
26	8	Nonirrigated pasture, peas	9.1	5.88	8.9	9.75
27	4	Peas	7.1	3.86	6.9	5.76
28	17	Nonirrigated pasture	0	1.24	0	8.17
29	26	Oat hay, squash	35.7	18.96	35.1	29.80
30	6.5	Oat hay, squash	7.2	5.22	7.1	7.95
31	8	Peas, oat hay	7.6	4.24	4.9	7.94
32	16	Irrigated pasture	45.3	21.79	40	26.36
33	6	Peas, oat hay	13.1	5.59	13.2	8.54
34	5	Lettuce, peas	10.5	4.94	8.8	6.51
35	20	Nonirrigated pasture	0	15	0	8.70
36	2	Nonirrigated pasture	0	.10	0	.87
37	.5	Tomatoes, peppers	1.2	.49	1	.63
38	2	Oat hay, tomatoes	2.7	.73	2.6	1.40
39	2.5	Fallow	0	.02	0	.92
40	3	Peas	5.5	2.33	5.4	3.38
41	4	Oat hay, squash	5.8	2.55	5.7	4.37
42	1.5	Nonirrigated pasture	0	.01	0	.54

Table 6. Vegetation type, applied irrigation water, and ground-water recharge for April 1988 through March 1989 and for average rainfall conditions for individual fields and land-use zones in the Santa Rosa and the San Simeon ground-water basins, San Luis Obispo County, California—Continued

Field or zone number	Area (acres)	Vegetation type	April 1988—March 1989		Average rainfall	
			Applied irrigation water (acre-ft)	Ground-water recharge (acre-ft)	Applied irrigation water (acre-ft)	Ground-water recharge (acre-ft)
			Santa Rosa Basin—Continued			
43	4	Nonirrigated pasture	0	0.02	0	1.45
44	6	Peas, oat hay	4.7	1.97	3.1	4.85
45	6	Peas, oat hay	10.5	2.96	8.9	5.78
46	8	Peas, oat hay	14.7	68	14.4	9.74
47	10	Peas, oat hay	16.9	8.26	13.4	11.92
48	7	Peas, oat hay	16	7.68	16	11.27
49	24	Oat hay, peas	24.2	10.94	15.9	176
50	3	Squash and zucchini	5.7	28	5.4	3.33
51	33	Peas, oat hay	98.7	48.99	97	65.46
52	14	Oat hay, squash	19	9.86	18.8	165
65	11	Peas (2)	25.8	9.80	22.6	14.32
66	1	Tomatoes (2)	2.3	.97	2.2	1.39
67	1.5	Tomatoes, squash	3.6	1.63	3.6	2.39
68	1.5	Tomatoes, oat hay	1.9	.52	1.9	1.22
69	.5	Peppers, oat hay	.8	.30	.8	.54
70	14	Irrigated pasture	34.4	127	26.7	14.21
71	4	Peas	8.8	36	7.7	47
72	3	Peas, squash	9.8	5.40	8.7	6.28
74	13	Oat hay, squash	23.6	8.23	20.2	12.74
86	4	Nonirrigated pasture	0	0	0	1.14
87	6	Irrigated pasture	20.4	9.84	15.8	9.82
88	33	Nonirrigated pasture	0	0	0	7.52
93	1.5	Peas	2.4	1.20	2.4	1.74
94	4.5	Oat hay, peas	8.8	4.95	7.7	6.51
95	3	Squash, lettuce	5.9	2.86	5.1	3.57
97	1	Fallow	0	.04	0	.45
107	8	Turf	32.1	16.27	26.6	166
108	1	Turf and shrubs	3.5	1.72	2.8	1.65
109	22	Riparian vegetation	0	0	0	0
110	102	Upland vegetation	0	0	0	0
111	33	Commercial	0	0	0	51
112	23	Residential	0	4.15	0	17.66
113	43.5	Riparian vegetation	0	0	0	0
114	152	Upland vegetation	0	0	0	0
115	38	Commercial	0	.17	0	7.96
116	1.5	Residential	0	.45	0	1.47
117	45	Riparian vegetation	0	0	0	0
118	86.5	Upland vegetation	0	0	0	0
119	18.8	Riparian vegetation	0	0	0	1.98
120	115	Upland vegetation	0	0	0	5.82
121	10	Beach	0	2.55	0	5.47
Total........	1,214.3		935.5	470.62	854.4	718.14

Table 6. Vegetation type, applied irrigation water, and ground-water recharge for April 1988 through March 1989 and for average rainfall conditions for individual fields and land-use zones in the Santa Rosa and the San Simeon ground-water basins, San Luis Obispo County, California—Continued

Field or zone number	Area (acres)	Vegetation type	April 1988—March 1989		Average rainfall	
			Applied irrigation water (acre-ft)	Ground-water recharge (acre-ft)	Applied irrigation water (acre-ft)	Ground-water recharge (acre-ft)
			San Simeon Basin			
53	1	Christmas trees	2	0.64	2	1.13
54	5	Squash, fava beans	10.1	48	8.6	5.23
55	5	Peas, fava beans	13.2	5.68	11.8	7.24
56	6	Peas, squash	11.5	5.4	10	7.52
57	5	Zucchini, peas	12.9	5.7	11.8	6.71
58	.8	Peas, Christmas trees	1.6	.71	1.6	12
59	3.9	Christmas trees	9.7	4.5	7.2	4.14
60	22	Peas, oat hay	53.8	22.86	53.6	323
61	9	Peas, oat hay	20.7	8.29	20	11.25
62	2.6	Peas, oat hay	5.8	2.43	5.8	3.46
63	6	Oat hay	0	0	0	1.54
64	14	Peas	40.8	162	35.8	19
73	24	Nonirrigated pasture	0	0	0	6.8
75	1.5	Fava beans, oat hay	4.5	1.94	4.2	2.52
76	17	Tomatoes, oat hay	37.3	14.98	30.3	17.34
77	9	Fava beans, oat hay	17.4	81	17.3	12.69
78	12	Zucchini, oat hay	22.8	12.28	21.1	159
79	12	Fava beans, oat hay	24.5	12.86	24.3	18.92
80	6.5	Zucchini, fava beans	17	9.31	15	10.21
81	1.5	Irrigated pasture	5.1	2.41	4.6	2.72
82	15	Squash, fava beans	37.4	20.14	37.4	20.14
83	5.5	Zucchini, oat hay	16.8	9.15	16.8	9.15
84	16	Squash, oat hay	43.5	27.53	43.5	27.53
85	12	Zucchini, fava beans	34.7	21.57	31.4	21.3
89	24	Campground (nonirrigated)	0	0	0	0
90	22	Wastewater sprayfield[1]	0	0	0	0
92	1.1	Christmas trees	2.7	1.3	2	1.17
96	7	Peas	7	4.69	7	7.2
98	46	Riparian vegetation	0	0	0	0
99	118.2	Upland vegetation	0	0	0	0
100	4	Equipment yard	0	0	0	1.42
101	16.1	Beach	0	4.11	0	8.8
102	15	Riparian vegetation	0	0	0	0
103	68.9	Upland vegetation	0	0	0	0
104	10	Gravel plant	0	11	0	5.24
105	10.2	Riparian vegetation	0	0	0	.55
106	50.5	Upland vegetation	0	0	0	0
Total........	605.3		452.8	227.6	423.1	289.06

[1]Applied water and ground-water recharge at the municipal waste were estimated separately using a different method.

Table 7. Land use in the Santa Rosa and the San Simeon ground-water basins, San Luis Obispo County, California, calendar year 1988

[Irrigated: Includes all fields and crops that were irrigated at least once during the year. All values in acres. CCSD, Cambria Community Services District]

Type of land use	Santa Rosa Basin		San Simeon Basin	
	Irrigated	Nonirrigated	Irrigated	Nonirrigated
Crop land	[1]438.0	81.5	[2]189.3	[3]37.0
Campground	0	0	0	18.8
CCSD well field	0	0	0	20.0
CCSD wastewater sprayfield	0	0	54.2	0
Residential[4]	.5	23.5	0	0
Commercial[4]	1.8	78.2	0	0
Industrial	0	0	0	14.0
Native vegetation				
Riparian	0	100.0	0	78.0
Nonriparian[5]	0	473.5	0	163.7
Rural impervious[6]	0	20.0	0	5.0
Total	[1]440.3	776.7	[2]243.5	[3]336.5
Cropped area				
Alfalfa	18.5	0	0	0
Christmas trees	0	0	4.9	0
Fava beans	0	0	66.0	0
Leafy vegetables	16.0	0	0	0
Oat hay	146.5	0	100.4	6.0
Pasture	100.0	81.5	1.5	31.0
Peppers	1.0	0	0	0
Squash	83.0	0	83.0	0
Sugar peas	247.5	0	72.4	0
Tomatoes	48.5	0	17.0	0
Total	661.0	81.5	345.2	37.0
Cropping intensity[7]	1.5	1.0	1.8	1.0

[1]Includes 3 acres of crop land outside the ground-water basin boundaries.
[2]Includes 14 acres of crop land outside the ground-water basin boundaries.
[3]Includes 28 acres of crop land outside the ground-water basin boundaries.
[4]Proportion of irrigated to nonirrigated acreage estimated from monthly distribution of municipal water use.
[5]Includes beach areas.
[6]Includes rural roads and buildings.
[7]Cropping intensity is the ratio of total cropped area to total area of cropped land. Values greater than 1.0 are possible when more than one crop is grown per year.

decreases in available soil moisture cause the AET of native brush and grass to decline rapidly during spring and early summer. The soil-moisture budget calculations indicate that there is little AET in summer, which is consistent with observations in other areas (Miller and others, 1983).

In irrigated areas, irrigation was assumed to occur as soon as soil-moisture depletion caused a decrease of 20 percent in AET. This resulted in irrigation frequencies of 14 to 21 days for sugar peas and tomatoes in summer, which are consistent with local farming practice (Larry Fiscalini and Gary Silveira, farmers, oral commun., 1989).

Deep percolation was assumed to occur when the amount of soil moisture in storage exceeded field capacity after adding inflows from rainfall and irrigation and subtracting evapotranspiration. In irrigated fields, most of the deep percolation is from excess applied irrigation water. During 1988–89, for example, deep percolation on typical irrigated fields consisted of about 8 in. of irrigation-return flow and 4 in. of rainfall recharge. No rainfall recharge occurred on nonirrigated fields or in areas of native vegetation (except the beach) during 1988–89. Total rainfall recharge from April 1988 through March 1989 was 140 acre-ft in the Santa Rosa Basin and 50 acre-ft in the San Simeon Basin (table 4). Agricultural irrigation-return flow was 320 and 170 acre-ft in the two basins, respectively. These totals differ from those shown in table 6 because of adjustments made to implement variable time-step durations in the ground-water-flow model.

Irrigation tends to increase rainfall recharge by leaving the soil in a relatively moist condition at the beginning of the winter rainy season. Smaller amounts of rainfall are then needed to bring the soil to field capacity and initiate deep percolation. The absence of deep percolation in nonirrigated areas during 1988–89 is not surprising because rainfall was only about 68 percent of the long-term average. In the central coast region, most deep percolation occurs during relatively wet years (Blaney and others, 1963; Yates, 1988).

To illustrate the threshold-type relation between annual rainfall and areal recharge, areal recharge during 1988–89 was recalculated assuming average rainfall. This was done by increasing daily rainfall by 46 percent, resulting in a twofold to threefold increase in rainfall recharge to about 410 acre-ft in the Santa Rosa Basin and 130 acre-ft in the San Simeon Basin. Agricultural pumpage and irrigation-return flow decreased by 7 to 9 percent. Total recharge from rainfall and irrigation-return flow under normal rainfall conditions was about 720 acre-ft in the Santa Rosa Basin and 290 acre-ft in the San Simeon Basin (table 6).

Subsurface Inflow and Outflow

Ground water enters the ground-water basins as subsurface inflow from bedrock areas along the sides of the basins. Infiltrated rainfall that percolates beneath the root zones of plants growing on the hillslopes gradually flows downward toward the valley floor through fractures in the bedrock. Some of this water emerges in springs, but the remainder seeps directly into the ground-water basins. Although fractured bedrock generally is much less permeable than alluvial aquifers, the total quantity of inflow is potentially large in this case because the thin, narrow basins have a large surface area in contact with bedrock.

An estimate of subsurface inflow from bedrock areas was obtained by multiplying the long-term average rainfall recharge rate by the area of hillslopes along the sides of the basin (fig. 19; table 8). Ridgetops were assumed to coincide with ground-water-flow divides. An estimate of the rainfall recharge rate was obtained from a 6-year study of soil-moisture profiles for a coastal area with similar vegetation about 80 mi south of Cambria (Blaney and others, 1963). The reported long-term average recharge rate for grassy areas was about 1.7 in/yr. This rate would correspond to 720 and 290 acre-ft/yr of inflow into the Santa Rosa and the San Simeon Creek Basins, respectively.

Rainfall on the Cambria hillslopes (21 to 27 in/yr) is greater than in the area where the soil-moisture study was done (13 in/yr), so one might expect inflow to be larger in the Cambria area. However, calibration of the ground-water models indicated that even the original estimates are too large because they cause unrealistic water-level recovery in late autumn. The calibrated estimates of inflow were about 370 and 150 acre-ft/yr for the Santa Rosa and the San Simeon ground-water basins, respectively (table 8). Subsurface inflow for some of the larger tributary areas, such as Van Gordon Creek, was estimated by applying Darcy's law to conditions at the basin boundary. Most of the deep percolation in these drainage basins was assumed to emerge as streamflow in the tributary creek rather than as subsurface inflow into the ground-water basin.

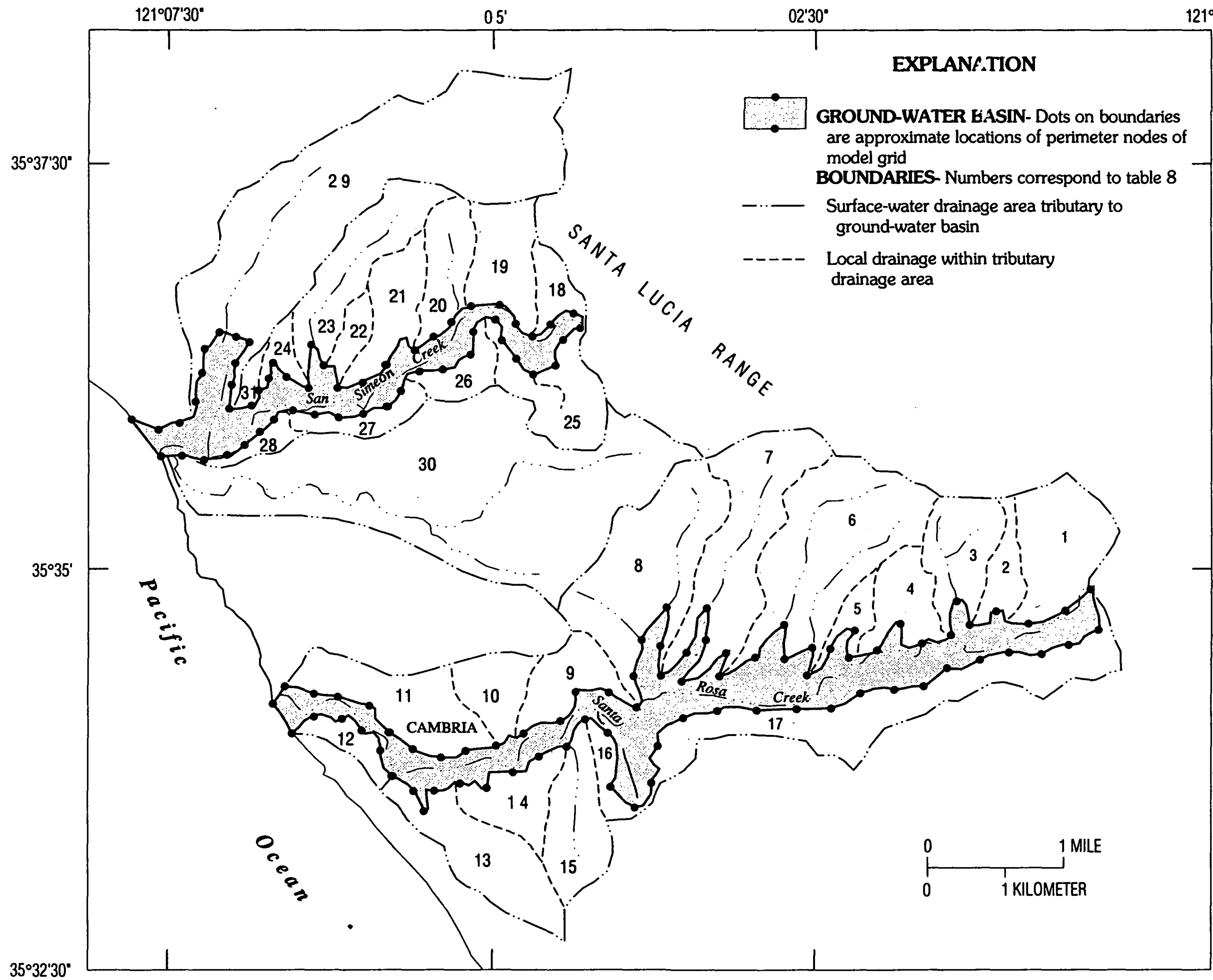


Figure 19. Tributary drainage basins contributing subsurface inflow to the Santa Rosa and the San Simeon ground-water basins, San Luis Obispo County, California.

Table 8. Drainage area and estimated subsurface inflow from tributary drainage basins adjacent to the Santa Rosa and the San Simeon ground-water basins, San Luis Obispo County, California

[Location of drainage basins shown in figure 19. acre-ft/yr, acre-foot per year]

Drainage basin No.	Drainage area (acres)	Subsurface inflow (acre-ft/yr)
	Santa Rosa Basin	
1	349	27
2	108	8
3	248	19
4	185	14
5	73	5
6	705	52
7	541	36
8	622	39
9	184	11
10	163	10
11	344	30
12	87	7
13	340	31
14	190	14
15	256	19
16	73	5
17	588	44
Total	5,056	371
	San Simeon Basin	
18	130	9
19	243	17
20	207	14
21	203	14
22	67	5
23	340	23
24	98	7
25	269	20
26	121	10
27	107	7
28	54	3
29	1,652	12
30	1,820	5
31	50	3
Total	5,361	149

Subsurface outflow occurs at the coast where the basin-fill deposits extend offshore beneath the ocean. Fresh ground water can reach the ocean by discharging directly through the ocean floor or by seeping into the creek and flowing to the ocean as surface-water outflow. The proportion of outflow that occurs as subsurface outflow depends on water-level gradients, aquifer transmissivity, and streambed leakances near the coast. A maximum estimate of subsurface outflow can be obtained by assuming that all outflow is subsurface, in which case it equals the product of hydraulic conductivity, cross-sectional flow area, and water-level gradient. For the Santa Rosa Basin, hydraulic conductivity was about 50 ft/d; the average water-level gradient in 1988 was about 0.00267, and the calculated outflow was 140 acre-ft/yr. Corresponding values for the San Simeon Basin were 400 ft/d for hydraulic conductivity, 0.00303 for average water-level gradient, and 790 acre-ft/yr for calculated outflow. The calibrated ground-water-flow models estimated that the rates of outflow for the two basins during 1988–89 were 60 and 320 acre-ft/yr, respectively. The rates of subsurface outflow probably do not vary substantially from year to year because the presence of the creek channel and the small amount of pumping near the coast tend to maintain relatively constant water-level gradients.

Transpiration by Phreatophytes

In areas where the water table is shallow, deep-rooted plants can use ground water in addition to soil moisture. In the Cambria area, this occurs primarily along creek channels, which are bordered by dense thickets of shrubs and trees. This riparian vegetation covers about 129 acres along Santa Rosa Creek and 71 acres along San Simeon Creek (table 6). The quantity of ground water transpired decreases rapidly with increasing depth to the water table. Few measurements of actual evapotranspiration by riparian vegetation on the central California coast have been done. A maximum estimate of the quantity of water consumed can be calculated by assuming that riparian vegetation obtains all its water from ground water and transpires at a rate equal to ET_0. These assumptions yield estimates of 330 acre-ft/yr for the Santa Rosa Basin and

260 acre-ft/yr for the San Simeon Basin. Estimates calculated by the ground-water models for 1988–89 were smaller: 160 and 30 acre-ft/yr (table 4). The smaller estimates result because depth to the water table limits phreatophyte transpiration in some of the areas mapped as riparian vegetation.

Water Use

Agricultural

Agricultural water use was estimated from crop water demand and from records of electricity use by wells and ditch pumps. Crop water use (AET), described earlier in the section, "Areal Recharge," gives an estimate of the consumptive water use by crops. Electricity use gives an estimate of agricultural pumpage. The ratio of AET to pumpage is the irrigation efficiency. Estimates of AET and pumpage were calculated independently and then compared to see if the resulting irrigation efficiency was reasonable.

With the permission of the well owners, records of monthly electricity use were obtained for the 18 principal irrigation wells in the Santa Rosa and the San Simeon Basins. Almost all irrigation water is supplied by wells, most of which have individual electric meters. Water occasionally is pumped out of the creek at two locations, but in both cases, the ditch pumps are electric and are connected to the same meter as a nearby well. Unit electricity use is the number of kilowatt-hours (kWh) used to pump 1 acre-ft of water. It is a function of well efficiency and total pumping lift. The efficiency of each well was measured for this study at least once during 1988 (Dennis Kunkel, Pacific Gas and Electric Company, written commun., 1988). The results of 23 well-efficiency tests indicated that unit electricity use ranged from 178 to 401 kWh/acre-ft with a median value of 323 kWh/acre-ft. Pumping efficiency ranged from 27 to 80 percent, with a median value of 56 percent. For some of the tests, water was discharged to waste at low pressure. This would result in lower total pumping lift and possibly lower pumping efficiency than under normal operating conditions.

Total pumping lift is the sum of the static depth to water in the well, the drawdown of water in the well when the pump is operating, the difference in altitude between the wellhead and the discharge point, and the discharge pressure at the discharge point (converted from units of pounds per square inch to feet of water). In the Cambria area, estimating pumpage from electricity use is complicated because most wells serve fields at different altitudes, the static depth to water gradually increases during the irrigation season, and discharge pressure for furrow irrigation is different from that for sprinkler irrigation. Variations in the first two factors were relatively small and could be estimated fairly accurately. The largest source of uncertainty stemmed from the irrigation method. The discharge pressure for furrow irrigation is less than 5 lb/in^2, and the discharge pressure for sprinklers typically is about 60 lb/in^2. This pressure difference corresponds to a difference in pumping lift of 127 ft, which is much larger than variations typically associated with static depth to water or field altitude. A sample of 18 sprinkler set-ups indicated a wide range of operating pressures, from 25 to 72 lb/in^2 with a median pressure of 58 lb/in^2.

Estimating total pumping lift is further complicated by the fact that many farmers irrigate a single crop by both sprinkler and furrow methods, depending on the maturity of the crop. Other farmers irrigate the same crops entirely by sprinkler. Thus, in any given month, a well is likely to serve several different crops at different stages of maturity using different irrigation methods. The irrigation method for each field in each month was estimated from observations of crop maturity and from information provided by individual farmers.

An increase in total pumping lift causes an increase in unit electricity use. The proportional increase was calculated for six wells where efficiency tests were done for several values of total pumping lift. The results were highly variable but averaged 1.4 kWh/acre-ft per foot of increase in total pumping lift. This value was assumed to apply to the remaining 12 irrigation wells.

A final source of uncertainty in calculating agricultural pumpage from electricity use arose where the electricity meter for a well was not functioning correctly or where the service connection supplied electricity for uses other than pumpage. In these cases, the magnitude of the error was estimated and the electricity record adjusted accordingly.

The pumpage at each well was calculated by allocating the amount of electricity used in a given month among the fields served by the well. The allocation for each field was then divided by the unit electricity use calculated from the total pumping lift conditions at that field during that month. The allocations were based on the irrigation water demand calculated by the soil-moisture budget algorithm described earlier. Total agricultural pumpage from April 1988 through March 1989 was 890 acre-ft in the Santa Rosa Basin and 450 acre-ft in the San Simeon Basin (table 4). Monthly agricultural pumpage during that period is shown in figure 20 for each basin.

Irrigation efficiency is the ratio of AET to the quantity of irrigation water applied to a crop. Irrigation efficiencies were calculated for each well by comparing total crop water demand in all fields served by a well with the pumpage at that well. Crop water demand is calculated by the soil-moisture budget algorithm as the quantity of irrigation water needed to avoid water stress caused by soil-moisture depletion. This was converted to electricity demand using the total pumping lift at each field and the pumping efficiency of the well. When compared on a monthly basis, there was often a considerable discrepancy between the calculated and the measured amount of electricity use. Much of the error resulted from slight miscalculations of the timing of periods of irrigation. For example, if irrigation occurred at the end of a month and the soil-moisture budget algorithm predicted that it was near the beginning of the following month, a discrepancy between calculated and measured electricity use would result for both months.

Irrigation efficiency was assumed to be constant for each well and was selected so that total calculated energy use equaled total measured energy use from April 1988 to March 1989. Irrigation efficiencies ranged from 53 to 80 percent, with a median value of 66 percent. Some of the high values probably result from under irrigation of low-value forage crops such as pasture, alfalfa, and oat hay.

Municipal and Industrial

More than 98 percent of the households in the Cambria area receive water from the five CCSD municipal wells. Two of these wells are along Santa Rosa Creek (27S/8E-26C5 and 26D1) and three are in the CCSD well field along San Simeon Creek (27S/8E-9J4, 9J5, and 9K3) (fig. 2). The San Simeon wells generally are used in preference to the Santa Rosa wells, so pumpage from the Santa Rosa wells typically varies depending on streamflow patterns and ground-water levels in the San Simeon Basin. Municipal pumpage for Cambria during 1956–88 (John Stratford, General Manager, written commun., 1989) is shown in figure 21.

Municipal pumpage has increased substantially in recent years from about 130 acre-ft in 1956 to about 820 acre-ft in 1988 (fig. 21). Long-term municipal pumpage trends indicate a greater yearly average increase in pumpage from 1982 to 1988 than from 1967 to 1976. From 1967 to 1976, pumpage increased an average of 6.0 percent per year. During the 1977–78 drought and the 5 years immediately following, production increased an average of only 2.2 percent per year. This lower rate probably is attributable to successful water conservation efforts and to extensive water main repairs done in the late 1970's. From 1982 to 1988, pumpage increased at an average of 8.4 percent per year.

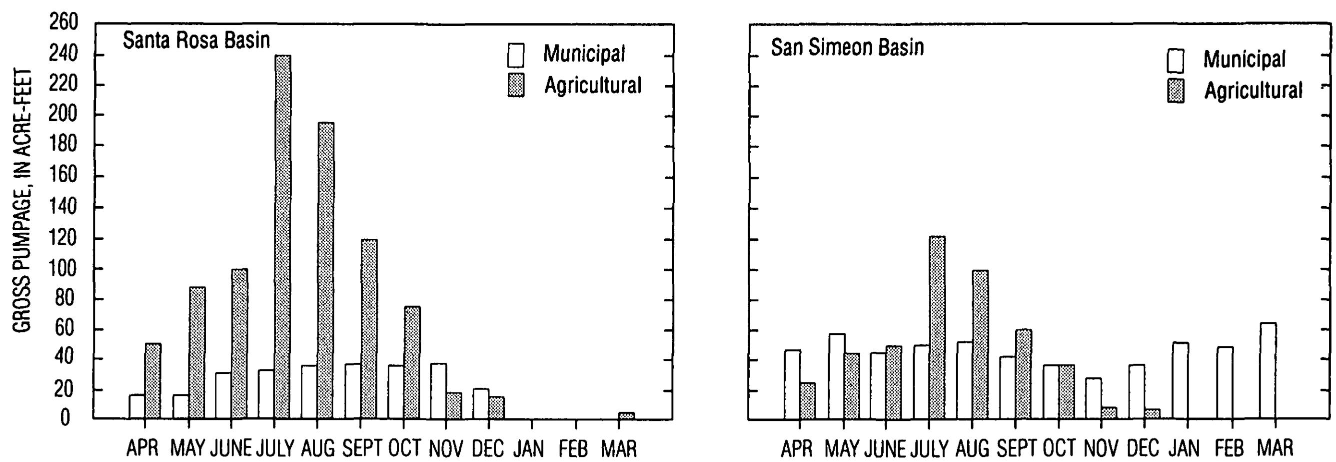


Figure 20. Monthly municipal and agricultural pumpage for the Santa Rosa and the San Simeon ground-water basins, San Luis Obispo County, California, April 1988 through March 1989.

Monthly municipal pumpage from April 1988 through March 1989 is shown in figure 20 for each basin. The absence of municipal pumpage from the Santa Rosa Basin for January and February 1989 reflects the preferential use of San Simeon water, which is of higher quality than water from the Santa Rosa Basin, when the San Simeon supply is adequate.

Comparison of metered consumption and metered pumpage indicates that in 1988 about 10 percent of the water pumped in the distribution system was unaccounted for. Water losses that are unaccounted for result from leaks, underrecording by meters, and unmetered uses such as flushing water mains, firefighting, and water supply for the wastewater-treatment plant and the San Simeon Beach campground. System losses have decreased substantially in recent years. About 30 percent of the water pumped into the system was unaccounted for during 1966–79, whereas only about 15 percent was unaccounted for during 1980–84.

The average monthly distribution of municipal pumpage during calendar years 1979–88 is shown in figure 22. Outdoor water use was estimated by a curve separation procedure in which indoor use is subtracted from total use. Indoor water use was assumed to equal total municipal water use in January. Seasonal fluctuations in indoor water use were estimated by comparing San Luis Obispo County's population estimate for Cambria of 3,900 in January 1985 with the CCSD's maximum seasonal population estimate for Cambria of 5,000 (McClelland Engineers, Inc., 1986). On the basis of these estimates, the peak seasonal population is about 28 percent greater than the population in January. A similar curve separation of municipal wastewater flows for 1984–88 indicated a peak summer population about 17 percent greater than the minimum winter population. For this analysis, a 10-percent average increase in indoor water use was assumed for May and September and a 20-percent average increase for June through August. Outdoor water use was calculated by subtracting indoor use from total use for each month. Annually, about 83 percent of municipal pumpage is used indoors and the remaining 17 percent is used outdoors.

A complete water-use budget was calculated for calendar year 1987. It indicated that 9.7 percent of the 777 acre-ft of water pumped in 1987 was lost from the system before delivery. On the basis of a municipal water-use curve separation for water delivered in 1987, 74 percent was used indoors and 26 percent was used outdoors. About 98 percent of the water used indoors enters the sewer system and the remaining 2 percent is

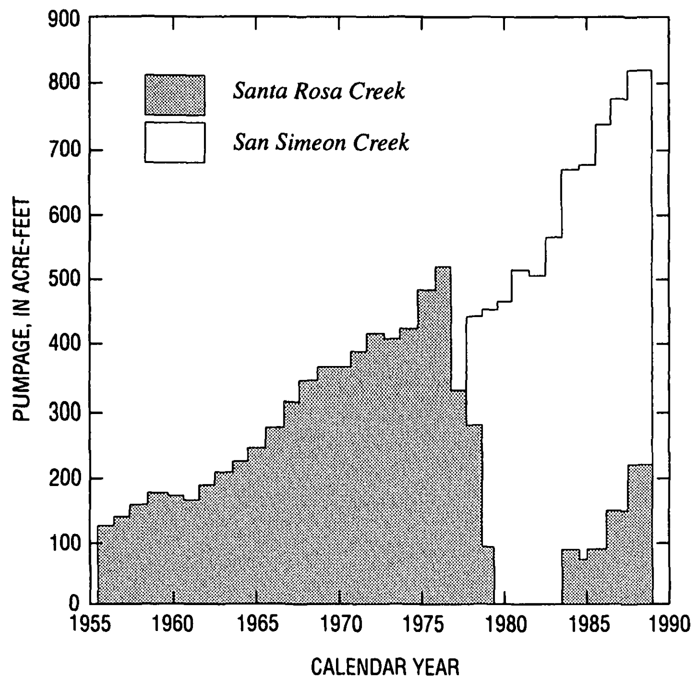


Figure 21. Annual municipal pumpage for Cambria, San Luis Obispo County, California, 1956–88.

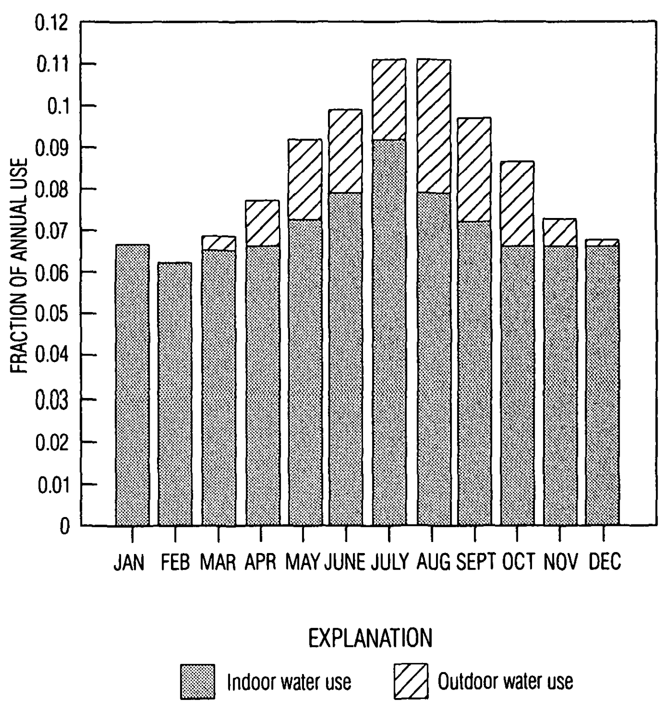


Figure 22. Average monthly distribution of municipal pumpage, San Luis Obispo County, California, 1979–88.

consumed (California Department of Water Resources, 1983). On the basis of the preceding calculations, about 570 acre-ft of water entered the sewer system in 1987. By comparison, the measured quantity of wastewater reaching the CCSD sprayfield was 530 acre-ft. The 7-percent discrepancy may be the result of sewer main losses or of errors in the estimates of indoor and outdoor water use.

Average annual per capita water consumption is about 140 gal/d. This amount was calculated using population estimates for 1985 and consumption data for July 1985 through June 1986. Total water consumption was 640 acre-ft from July 1985 to June 1986, and the average annual population in 1985 was 4,200 people.

Individual domestic wells and springs provided water for about 90 permanent residents and an approximately equal number of migrant field workers in 1988. Rural domestic pumpage was about 12 acre-ft/yr in the Santa Rosa Basin and 5 acre-ft/yr in the San Simeon Basin. These estimates are based on the assumption that per capita domestic water use is the same for permanent rural residents as it is for residents within the CCSD service area. Per capita water use by migrant field workers was assumed to be one-third that of permanent rural residents.

Overview of Budgets

In 1988–89, the creek was the largest source of inflow to the Santa Rosa and the San Simeon Basins, followed by subsurface inflow and rainfall recharge. Rainfall recharge would be significantly larger in a year with above-average rainfall, but there would be a corresponding decrease in seepage from the creek. In both basins, net pumpage was the largest outflow; net agricultural pumpage was about twice as large as net municipal and rural nonagricultural pumpage. However, these lumped, basinwide budgets mask significant differences in the distribution and quality of return flow from municipal and agricultural uses. Most irrigation-return flow occurs in the middle or upstream parts of the valleys and contributes to the supply for agricultural and municipal wells farther down the valley. Treated municipal wastewater is returned to the basins at only one location, the CCSD sprayfield. Water-quality regulations prohibit direct use of the recharged wastewater for potable purposes, and reuse for irrigation is limited by the downstream location of the sprayfield.

There are several differences between the water budgets for the two basins. Net municipal pumpage is larger in the Santa Rosa Basin even though gross municipal pumpage is smaller because all treated wastewater is returned to the San Simeon Basin. Ground-water inflow is relatively large in the Santa Rosa Basin because areas of tributary ground-water inflow along the sides of the basin are much larger. Ground-water outflow to the ocean is a much larger percentage of total outflow in the San Simeon Basin than in the Santa Rosa Basin where ground water tends to reach the ocean by the creek instead. This tendency also partly explains why net creek seepage is a smaller percentage of total inflow in the Santa Rosa Basin than in the San Simeon Basin (48 percent compared with 73 percent).

The nonzero net storage change does not imply that there is a significant or long-term imbalance between inflow and outflow. Both basins were virtually full at the beginning and end of the budget period. The small net storage change simply reflects slight differences in streamflow, rainfall, and cropping patterns between the first and last months of the budget period. Similarly, the mass-balance error is an artifact of the precision specified for solving the equations in the models. It is negligible in both basins.

The budgets for 1988–89 reflect dry climate and streamflow conditions. Ground-water budgets and model simulations were not done for periods of average or wet climatic conditions. However, the response of the system to wetter conditions can be inferred from sensitivity analyses of the models and the configuration of head-dependent boundaries.

If ground-water levels fully recover in winter—which happens in all but extremely dry years—additional recharge from deep percolation, flow losses, or subsurface inflow is largely rejected and simply contributes to increased streamflow to the ocean. Additional rainfall in summer and autumn could significantly decrease agricultural pumpage but would have little effect on municipal pumpage. Increasing the rate and, more importantly, the duration of streamflow in summer would greatly decrease dry-season water-level declines by providing a large source of recharge to offset ground-water pumping.

DIGITAL SIMULATION OF HYDROLOGIC SYSTEM

Digital models were developed to provide an integrated analysis of ground- and surface-water flow in the Santa Rosa and the San Simeon Basins. Separate models were developed for each basin. The models accounted for spatial variations in aquifer characteristics and interactions among inflows, outflows, and water levels. They also provided a means to estimate flows and basin characteristics for which direct measurements were inaccurate or unavailable. The models were calibrated to simulate accurately the hydrologic systems under present-day conditions. They were then used to simulate the effects of hypothetical streamflow and pumping conditions.

The digital models are mathematical representations of the conceptualized hydrologic system and are not as detailed or complex as the real system. The accuracy and precision of model results are limited by the validity and accuracy of the assumptions and data used in the model.

Model Design

Ground-water flow in the basin-fill deposits was simulated using a three-dimensional finite-element model (FEMFLOW3D) developed by Durbin and Bond (1998). The model code simulates a linearized three-dimensional free-surface ground-water system with a fixed grid. A complete description of the background, the mathematical basis, and the structure of FEMFLOW3D is presented in Durbin and Bond (1998).

The model code was applied to the Santa Rosa and the San Simeon Basins by preparing separate sets of input data for each basin. Plan views of the model grids are shown in figure 23. The Santa Rosa model has 910 nodes and 678 triangular prismatic elements. The San Simeon model has 768 nodes and 595 triangular prismatic elements. Small node spacings were chosen to achieve a high level of spatial resolution in simulated results, particularly between the creeks and nearby wells.

Values of hydraulic conductivity (K) and storage coefficient (S) are assigned to each element. An algorithm presented by Glover (1988) is used to include horizontal anisotropy of K. In these models, anisotropy is the ratio of K perpendicular to the major valley axis to K parallel to the major valley axis.

Transmissivity is adjusted according to the saturated thickness of the aquifer in each time step, which is consistent with unconfined conditions. For comparison, several simulations were done assuming confined conditions (constant saturated thickness). Results were better using the unconfined assumption, which is consistent with the absence of extensive confining layers in most parts of the basins. Measured and calibrated storage coefficients also indicated that conditions are unconfined or only slightly confined.

Onshore boundaries of the basins are represented in the models as no-flow or specified-flow boundaries. The ocean boundary coincides with the coastline in both basins and is represented as a head-dependent flow boundary. Seawater is assumed to have the same density as freshwater, and the boundary head is equal to sea level. For comparison, simulations also were done with a static saltwater wedge acting as a no-flow boundary.

Some flows into and out of the ground-water basins are not influenced by ground-water levels. These include pumpage and recharge from rainfall and irrigation-return flow. These flows are calculated prior to each simulation and are included in the model as specified flows at appropriate nodes (fig. 18, table 6). The timing of agricultural pumpage, irrigation-return flow, and rainfall recharge is determined by the soil-moisture budget algorithm.

Ground-water inflow also is assumed to be independent of ground-water levels in the basins. Although this is not strictly true, the permeability of bedrock is small enough that inflow probably changes slowly in response to water-level fluctuations in the basins. Also, those fluctuations are small compared to the total gradient from the hilltops to the valleys. Furthermore, seasonal fluctuations in recharge on adjacent hillsides are diminished as the recharge water percolates slowly toward the basin. However, inflow from bedrock probably decreases during several consecutive dry years. In early 1991 after 4 consecutive years of below-average rainfall, three springs along the Santa Rosa Creek valley went dry and flow in three others was less than one-half of normal (Scooter Rhoades, local resident, oral commun., 1991). For simulations of 1 to 2 years the assumption of constant inflow from bedrock is reasonable. In the 1988–89 simulation, inflow from each drainage area was distributed along the boundary of the ground-water basin so that inflow was concentrated at the node closest to the point where the surface-water drainage entered the valley floor (fig. 19).

Other flows into and out of the ground-water basins are influenced by ground-water levels. These head-dependent flows include ground-water flow to

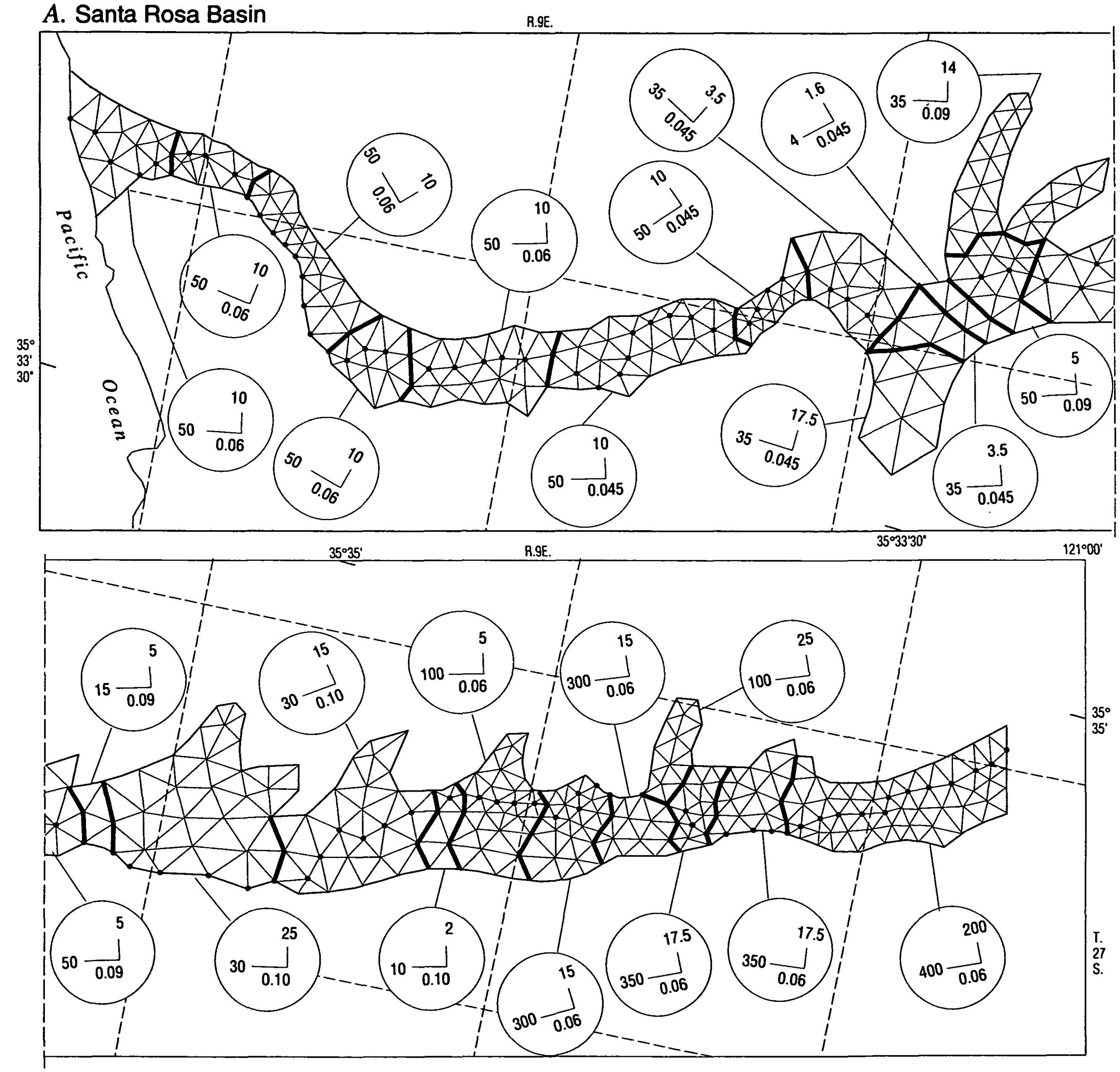
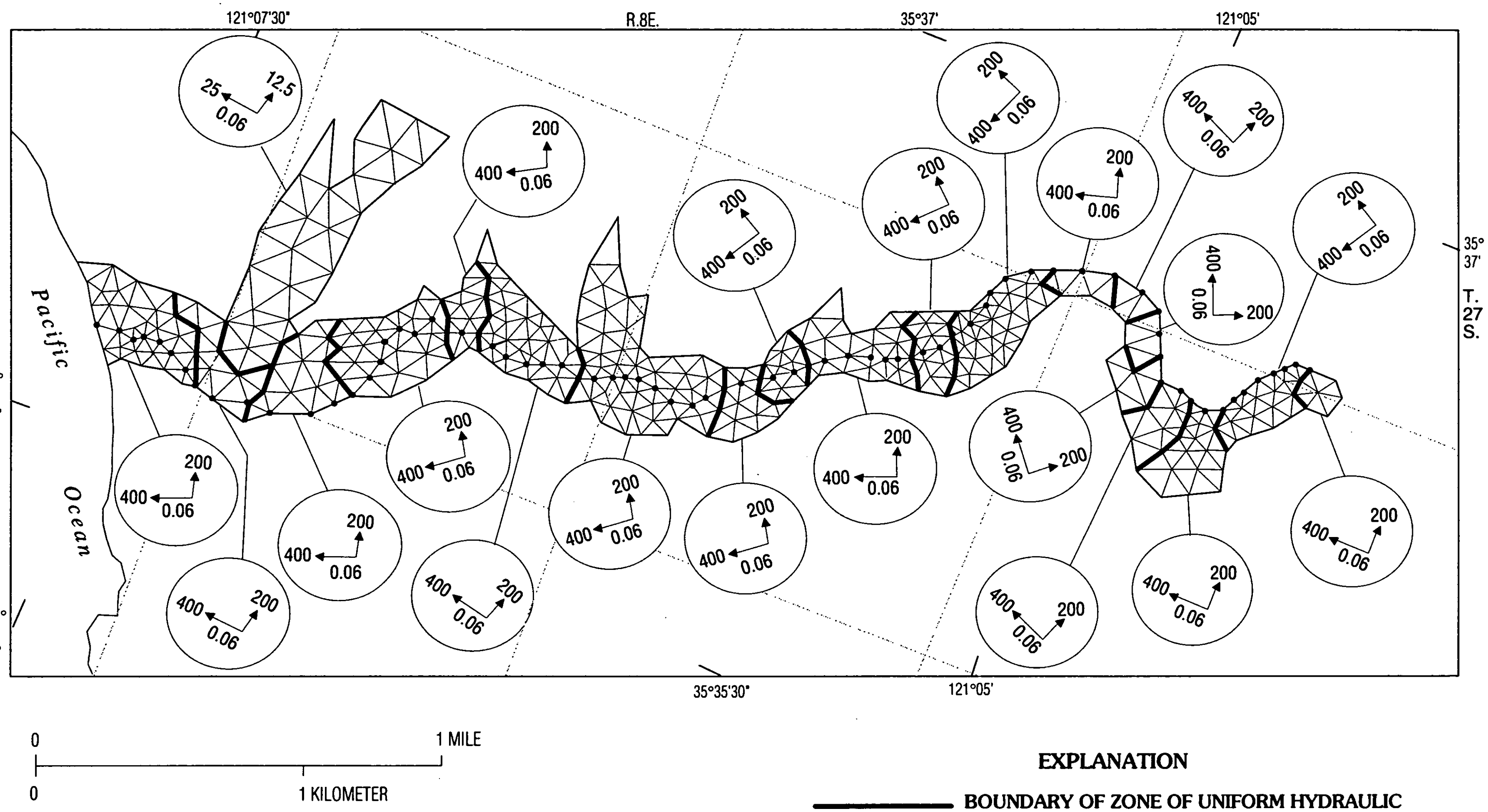


Figure 23. Nodal grids and zones of uniform hydraulic characteristics for the ground-water-flow models of the Santa Rosa and the San Simeon ground-water basins, San Luis Obispo County, California.

B. San Simeon Basin



EXPLANATION

BOUNDARY OF ZONE OF UNIFORM HYDRAULIC CHARACTERISTICS

HYDRAULIC CHARACTERISTICS - Long and short arrows indicate directions and magnitude of maximum and minimum hydraulic conductivity, in feet per day. Bottom number is the storage coefficient (dimensionless)

STREAM NODE

Figure 23. Nodal grids and zones of uniform hydraulic characteristics for the ground-water-flow models of the Santa Rosa and the San Simeon ground-water basins, San Luis Obispo County, California—Continued.

and from the creeks, transpiration by phreatophytes, and flow across the ocean boundary.

Seepage to and from the creeks is calculated as a linear function of streambed leakance, wetted area, and the difference in water level between the stream surface and nearby ground water. Streambed leakance is the vertical hydraulic conductivity of the streambed divided by a length term that theoretically represents the distance from the streambed to the point where ground-water level is measured. Calibrated leakances range from 0.5 to 0.7 per day in the Santa Rosa model and are 0.7 per day in the San Simeon model.

The altitude of the stream surface in each reach in each model time step is obtained by adding stream stage to the thalweg altitude. Stream stage and width are calculated from streamflow using power functions fitted to rating curves for stream-gaging stations in the study area. The functions are

$$S = 0.1471Q^{0.5136} \qquad (1)$$

where

S is stream stage, in feet; and

Q is stream discharge, in cubic feet per second;

$$W = \begin{cases} 7.25\ Q^{0.3934}, \text{ if } h_s > h_{gw} \\ 7.25\ Q_{gw}^{\ 0.3934}, \text{ if } h_s < h_{gw} \end{cases} \qquad (2)$$

where

W is wetted perimeter, in feet;

h_s is the altitude of the stream surface, in feet;

h_{gw} is the altitude of the ground-water level next to the creek, in feet; and

Q_{gw} is the stream discharge, in cubic per second, that would occur if h_s were equal to h_{gw}.

Streamflow entering the upper ends of the basin areas is routed reach-by-reach in a downstream direction. Each reach is associated with a particular model node, resulting in a total of 106 reaches in the Santa Rosa model and 82 reaches in the San Simeon model. Inflow to each reach equals outflow from the preceding reach, and stream stage and seepage are calculated from local streamflow and ground-water levels. In this way, mass balance is presented for streamflow and ground water.

Transpiration of ground water by phreatophytes is calculated for areas of riparian vegetation, which cover about 129 acres in the Santa Rosa Basin and 71 acres in the San Simeon Basin (fig. 18, table 6). The transpiration rate is adjusted according to the depth of the simulated water table at nodes in those areas, decreasing linearly from a maximum rate equal to residual ET_0 when the water table is at land surface to zero when the water table is at a depth of 18 ft or more. Residual ET_0 is the amount of evaporative demand that cannot be supplied by soil moisture and was calculated using the soil-moisture budget algorithm described earlier for field soils. Residual ET_0 varies by month and land-use zone. Water-table altitude varies for each model node and time step, and the extinction depth of 18 ft is constant for all nodes in all time steps.

Flow across the ocean boundary is assumed to be possible in both directions, depending on whether water levels at nodes along the coastline are above or below sea level. The rate of flow is regulated by a conductance value assigned to each boundary node. Conductance equals a leakance term multiplied by the cross-sectional area of flow. The leakance term includes a hypothetical length representing the effective distance from the coastline to the point where the aquifer crops out on the ocean floor. Because this distance is highly speculative, boundary conductances were selected primarily on the basis of model calibration.

Model Calibration

The models were calibrated by adjusting selected input variables until simulated water levels and streamflow matched measured values. Calibration provides a means of estimating variables that are difficult to measure directly, such as streambed leakances and aquifer storage coefficients. It also offers a means of checking the accuracy of prior estimates of other input variables, and it ensures that the estimates for all variables are mutually consistent. Calibration and sensitivity analysis also indicate the variables to which model results are most sensitive. In sensitivity analysis, variables are systematically adjusted within their ranges of uncertainty to determine the relative contribution of individual variables to overall model uncertainty.

The principal period used for model calibration was from April 1988 through March 1989. Simulations were transient, with time steps ranging from 1 day during the first week of winter streamflow to 1 month during the summer dry season. Initial water levels equaled measured water levels at the beginning of April 1988. Steady-state simulations were used to estimate water levels in areas for which measured data were not available.

Model results were compared with 548 water-level measurements at 32 wells in the Santa Rosa Basin and 396 water-level measurements at 21 wells in the San Simeon Basin. Simulated seepage gains and losses along the creeks were compared with gaged flows for 2 downstream locations and with 66 manual flow measurements for 9 other locations.

Additional simulations for January 1976 through March 1977 were done using measured rainfall, streamflow, and municipal pumpage and estimated agricultural pumpage. Soil-moisture budgets and areal recharge were recalculated to reflect the smaller quantity of irrigated area at that time. These simulations were used to verify that model variables calibrated for 1988–89 would correctly simulate the incomplete recovery of ground-water levels during the winter of 1977.

Generally, the San Simeon model proved easier to calibrate than the Santa Rosa model because of the greater variability of aquifer characteristics and the observed emergence of summer streamflow in the Santa Rosa Basin. Abrupt discontinuities in hydraulic conductivity were necessary to simulate subsurface-flow obstructions, and a large degree of anisotropy was necessary to simulate large transverse water-level gradients at some locations in the Santa Rosa Basin. In contrast, the San Simeon Basin was accurately simulated with a nearly homogeneous distribution of aquifer characteristics and only a small degree of anisotropy. Simulating the emergence of ground water into Santa Rosa Creek during the dry season was difficult because it creates two avenues of downvalley water movement. These avenues interact in a complex manner and had to be correctly balanced to achieve an acceptable calibration.

The distributions of calibrated hydraulic conductivity and storage coefficient are shown in figure 23. The calibrated values of *K* parallel to the valley axis are within the range of measured values. The calibrated value for most of the San Simeon Basin (400 ft/d) is higher than most of the measured values. Possible reasons for the discrepancy are that measured values represent an average of *K* along the longitudinal and transverse axes of the valley or that drawdowns inside pumping wells increased at a different rate than in the adjacent aquifer because of partially clogged well screens. Like the measured values, calibrated values of *K* are more variable in the Santa Rosa Basin than in the San Simeon Basin.

Model calibration indicated that *K* is anisotropic in most areas although to different degrees. This is consistent with the results of the drawdown and streamflow-response tests and with the anisotropic continuity of individual layers in the basin fill. Conceptually, the basin fill probably consists of braided strands of highly permeable channel deposits preferentially oriented parallel to the valley axis and embedded in fine-grained, less permeable overbank deposits. High yields result where wells happen to penetrate one of the permeable strands. The exact location and extent of the permeable strands cannot be detected accurately from the land surface. Thus, for practical purposes, the basin fill functions as a locally homogeneous but anisotropic porous medium.

Calibrated storage coefficients are 0.06 throughout the San Simeon Basin and range from 0.045 to 0.10 in the Santa Rosa Basin (fig. 23). These values are larger than those obtained from drawdown tests (table 1) and are at the low end of the range commonly found in unconfined aquifers (Freeze and Cherry, 1979). The smallest calibrated storage coefficients are between the high school and the State Highway 1 bridge in the Santa Rosa Basin, which is the area most likely to have an extensive confining layer. The difference between the measured and calibrated *S* values probably results from delayed-yield storage effects.

Delayed-yield storage effects have been observed in other stream-dominated ground-water systems (Loeltz and Leake, 1983; Yates, 1988). These effects become evident when a larger storage coefficient is needed to simulate long-term storage changes than to simulate short-term ones. Delayed yield probably results from gradual movement of water into and out of fine-grained strata and from vertical movement of water between aquifer layers and the perforated interval of the well casing. Calibrated storage coefficients are larger than the ones calculated from drawdown tests because the models simulate storage responses for periods of days to years, whereas the drawdown tests measured storage responses for periods of minutes to hours. By providing additional water to wells during extended dry periods, delayed yield potentially could be a significant source of water in the Cambria area. However, model results indicate that the additional quantity of water is small for time intervals between 1 week and as much as 1 year. The single set of calibrated storage coefficients adequately simulated the rapid water-level recovery following the onset of winter streamflow and the gradual water-level decline during the 7-month dry season.

Model Results

Water Levels

Hydrographs of simulated water levels for January 1988 through March 1989 are shown with the measured water levels presented earlier (fig. 6). Measured and simulated water levels are for nonpumping conditions, when the well pump has been off for at least several hours.

With several exceptions, the models were able to closely simulate measured water levels. One exception was water levels in well 27S/8E-8R2, which were anomalously high compared with the regional trends indicated by nearby wells. Simulated water levels were still too low when reasonable local variations in hydraulic conductivity and recharge were introduced into the model. Whatever the reason for the anomaly, water levels in the well clearly are not representative of regional conditions, which the model otherwise simulates well. A second exception occurs at a few scattered wells (for example, 27S/8E-10A1 and 26D1), where simulated water levels declined too rapidly at the beginning of the dry season (fig. 6). Finally, simulated water levels at some irrigation wells (for example, 27S/8E-24N2 and 27S/9E-19M3) are irregular in summer. This is an artifact of the process of converting periods of irrigation (calculated on a daily basis) into average monthly pumping rates.

The difference between simulated and measured water levels in the Santa Rosa Creek Basin ranged from -28.6 to 19.9 ft. The median difference for 548 measurements was 0.6 ft; 84 percent of the differences were less than 5 ft. In the San Simeon Creek Basin, differences ranged from -6.0 to 9.0 ft, with a median value of 0.02 ft. For 396 measurements, 83 percent of the differences were less than 2 ft. The absolute value of the mean error was less than 0.3 ft for both basins, which further indicates that simulated water levels are not biased. The accuracy of the model results is good, considering that seasonal water-level fluctuations exceed 30 ft in some locations and that basinwide variation in water levels ranges from -12 to 210 ft.

Flows

Seepage to and from creeks, phreatophyte transpiration, and ground-water flow to the ocean are head-dependent flows that are calculated by the model. The annual quantities of each of these flows during the calibration period were presented earlier in the section "Water Budgets" (see table 4).

The model calculated seepage losses of 91 and 150 acre-ft from Santa Rosa and San Simeon Creeks, respectively, on December 22, 1988, the first day of substantial streamflow in the winter runoff season. These losses correspond to daily average rates of 46 and 76 ft^3/s, respectively, and were the highest rates of the season.

Net seepage loss during the first week of streamflow was 300 and 410 acre-ft for the Santa Rosa and the San Simeon Basins, respectively. The amounts are 82 and 95 percent of estimated ground-water storage increase during that period in the respective basins. These large percentages are consistent with measured water levels. At almost all wells, a large, rapid water-level recovery began abruptly on the first day of streamflow and ceased when the water level reached the approximate altitude of the water surface in the creek. Seepage from the creek is the only plausible source of recharge for this recovery pattern. In terms of surface flow in the creeks, the loss rates are consistent with observed flow losses described earlier in the section "Gains and Losses Within the Ground-Water Basins." These data indicate that the model simulates stream-aquifer interactions reasonably well.

In the Santa Rosa Basin, the model correctly simulated gaining flow during the dry season for three locations. In June 1988, a simulated flow of 0.26 ft^3/s emerged into the creek near well 27S/9E-19H2. Influent seepage of about the same amount emerged into the creek at the narrows upstream of the high school, and a flow of about 0.03 ft^3/s emerged into the creek in the lower part of the basin where the valley becomes narrow upstream of the Windsor Boulevard bridge. Flow gains have been observed at all of these locations. In June, simulated flow was continuous between the upper two locations, which also is consistent with field observations. By August, simulated gains ceased at the lowermost location, and a short dry reach had formed above the middle location. The rate of emerging flow gradually decreased at the upper location to 0.07 ft^3/s in early December 1988.

In the San Simeon Basin, seepage into the creek during the dry season was limited to the reach between the wastewater sprayfield and the ocean, which is consistent with field observations.

About 78 percent of transpiration by phreatophytes was during May through September. Transpiration rates were low in other months because of low residual ET_0 demand in winter and spring and low ground-water levels in autumn at some locations. Transpiration constituted 15 percent of net outflow from the Santa Rosa Basin and 4 percent of net outflow from the San Simeon Basin. Measurements of phreatophyte transpiration are not available to compare with simulated transpiration.

The rate of subsurface outflow to the ocean varied by a factor of only about 2 during the calibration period. Rates were high in late winter when water levels were highest, and rates were low in late autumn. Subsurface outflow was 60 acre-ft (table 4), or about 6 percent of annual net outflow from the Santa Rosa Basin. Subsurface outflow was 320 acre-ft (table 4), or about 43 percent of annual net outflow in the San Simeon Basin. The higher absolute and percentage values in the San Simeon Basin resulted from higher hydraulic conductivity of the alluvial deposits and steeper water-level gradients caused by the wastewater sprayfield.

Sensitivity Analysis

Sensitivity analysis is a systematic evaluation of the effect of small changes in individual variables on model results. Model calibration and sensitivity analysis often provide a great deal of insight into the nature of the hydrologic system. Significant hydrologic effects of the main model variables are discussed below. Unless otherwise noted, the response of both models to input variations is similar, and all changes are with respect to the fully calibrated simulations.

The general effect of hydraulic conductivity (*K*) is to control the downvalley water-level gradient, with smaller values steepening the gradient. At a given location, changes in *K* tend to shift the water-level hydrograph up or down without significantly altering its shape. An exception is near large pumping wells, where a decrease in *K* tends to increase slightly the amount of dry-season drawdown by localizing the cone of depression. Because *K* is a factor of transmissivity (*T*) and hence diffusivity (*T*/*S*), decreases in *K* tend to retard the rate of water-level recovery following the onset of winter streamflow.

The only noticeable effect of mild anisotropy (ratio of transverse to axial *K* between 1.0 and 0.1) is to slow the rate of recovery following the onset of streamflow. More extreme anisotropy (ratio less than 0.1) tends to create noticeable transverse water-level gradients by rising water levels along the sides of the basin throughout the year. A value of 0.05 was needed near well 27S/9E-20E1 in the Santa Rosa Basin to simulate the 8-foot difference in winter water levels between the well and the creek, which is only 225 ft away. Simulation results generally are better when the direction of anisotropy is aligned with the valley axis rather than the local orientation of the creek channel. Finally, by decreasing the overall *K* near a pumping well, anisotropy tends to increase slightly the amount of dry-season drawdown near large wells.

Storage coefficients strongly affect the magnitude of dry-season water-level declines and the rate of water-level recovery in winter. However, they have no effect on the level to which water levels recover. For example, an increase in *S* from 0.09 to 0.12 throughout the area upstream of well 27S/8E-24L1 on Santa Rosa Creek decreases the dry-season drawdown by as much as 5 ft. The increase in storage coefficient also increases the persistence of dry-season streamflow downstream of well 27S/9E-19H2 because base flow is supported by a larger volume of stored ground water. These effects constrain the range of calibrated *S* values. Storage coefficients significantly affect local water supplies because they strongly influence the quantity of ground water available during the dry season.

Streambed leakance strongly affects the rate of seepage between the creek and the ground-water system. Because it affects seepage in both directions, a uniform change in leakance has a relatively small effect on net seepage. For example, decreasing the streambed leakance along Santa Rosa Creek downstream of well 27S/9E-20G3 from 0.5 to 0.3 per day decreases seepage to the creek by 63 acre-ft/yr (10 percent) and decreases seepage from the creek by 57 acre-ft/yr (5 percent). Net seepage from the creek decreases only 6 acre-ft/yr (1 percent).

The effect of streambed leakance on seepage is similar to the effect of diffusivity. A decrease in either variable noticeably retards the rate of water-level recovery following the onset of winter streamflow and makes a more uniform distribution of seepage rates during the first week of recovery. These effects were the primary factors used to calibrate streambed leakance.

Streambed leakance is important to water-resources management because it potentially could limit the percentage of annual stream discharge captured as ground-water recharge during exceptionally dry years. This possibility was investigated using simulations of the 1976–77 drought. When calibrated streambed leakances were decreased by a factor of two, all streamflow during the winter of 1977 was still captured as recharge. This indicates that the calibrated values are not so small that they significantly limit seepage during low-flow periods. Consequently, they probably are not a significant source of error in simulations of drought conditions.

The proportion of ground-water outflow to the ocean that occurs as subsurface underflow instead of as seepage into the creek is largely determined by the balance between streambed leakances and the ocean boundary conductance. Associated changes in water levels and streamflow are too small to allow accurate estimation of the proportion. For example, coastal water levels tend to remain in a narrow range between sea level and the creek thalweg (except, perhaps, if leakances or boundary conductance is very small). Likewise, if all subsurface outflows in the calibrated models were forced into the creeks by decreasing the ocean boundary conductance, streamflow at the coast would increase by an annual average of only 0.08 ft^3/s in Santa Rosa Creek and 0.44 ft^3/s in San Simeon Creek. These increases amount to small changes in streamflow and would be nearly undetectable.

Conductance of the ocean boundary is important to water-resources management because it strongly influences the potential for seawater intrusion. If the conductance is large, high rates of intrusion will occur when ground-water levels near the coast decline below sea level. If the conductance is small, coastal water levels could be drawn down below sea level without incurring large quantities of seawater intrusion. In effect, a low boundary conductance creates a one-way outlet valve for fresh ground water. Ground water can still discharge to the ocean through the creek, but the ocean cannot flow up the creek to intrude the basin.

The effect of a saltwater-freshwater interface near the coast was tested by including a stationary saltwater wedge at the base of the San Simeon Basin near the coast. The wedge was assumed to form a no-flow boundary of the fresh ground-water system. The top of the wedge decreased from a depth of 30 ft at the coastline to a depth of 130 ft near well 27S/8E-9N2, where the wedge was assumed to pinch out against bedrock. The effect of the wedge was to shunt 15 acre-ft/yr (6 percent) of subsurface outflow into the creek. Water levels near the coast were higher by less than 2 ft. These small changes indicate that model results are not strongly affected by the omission of the effects of density difference(s) between the ground water and the seawater.

Irrigation efficiency has almost no effect on the model because it affects pumpage and return flow by equal amounts. A change in irrigation efficiency changes the rate of local cycling of water between the aquifer and field soils. This cycling occurs predominantly in the vertical direction and consequently is not considered in a single-layer model. Exceptions occur if an irrigation well is not located near the fields it serves. For example, fields along Van Gordon Creek primarily are served by wells in the CCSD wastewater sprayfield. Irrigation-return flow exceeds pumpage in the immediate vicinity of the fields, which contributes significantly to the relatively steep water-level gradients from that area southward toward the main part of the San Simeon Basin.

Potential evapotranspiration (ET_0) has indirect and direct effects on model results. By affecting the amount of soil moisture used by plants, it indirectly influences the quantity of irrigation, irrigation-return flow, and recharge from rainfall. In terms of quantities and percentages, changes in ET_0 cause greater changes in irrigation than in recharge from deep percolation through soils. For example, a 10-percent change in ET_0 results in a 9- to 18-percent change in irrigation and a 2- to 13-percent change in recharge. The direction of change is the same for all three variables. The change in recharge from deep percolation is relatively small because it consists of recharge from irrigation-return flow and rainfall, which are oppositely affected by a change in ET_0. That is, an increase in ET_0 causes an increase in irrigation-return flow (because of the concomitant increase in pumpage) but a decrease in recharge from rainfall.

By altering crop water demand, changes in ET_0 influence the quantity of irrigation pumpage and recharge in the model and directly affect the rate of transpiration by phreatophytes. The overall effect of a 10-percent decrease in ET_0 year round in the San Simeon model is a decrease in pumpage by 41 acre-ft/yr and a decrease in areal recharge from soils by 15 acre-ft/yr. These decreases result in a net increase in inflow of 26 acre ft/yr. This is largely offset by a decrease in net seepage from the creek (17 acre-ft/yr), an increase in subsurface outflow to the ocean (6 acre-ft/yr), and a slight increase in phreatophyte transpiration (1 acre-ft/yr). All these changes are less than 6 percent of the calibrated reference values. The effect on water levels is a decrease in the amount of dry-season decline of 2 ft or less.

The effect of changes in rainfall on model results is strongly influenced by the season in which the change occurs. Increased rainfall during the winter generally increases the quantity of rainfall recharge, but this is almost entirely offset by a decrease in net seepage from the creek. Rain occurring during the irrigation season results in a nearly equal decrease in net irrigation pumpage. However, as long as the creek is still flowing, the decrease in net pumpage simply causes a corresponding decrease in net seepage from the creek. For this reason, rain in autumn, prior to the onset of streamflow, is of particular value in increasing the overall annual water supply.

If the amount of rain falling on the San Simeon Basin during April 1988 through March 1989 had been greater by 331 acre-ft (46 percent), total annual rainfall would have equaled the long-term average. Including this additional rainfall in the soil-moisture budget algorithm (assuming no change in the daily distribution of rainfall) results in an increase in areal recharge of 71 acre-ft/yr and a decrease in gross agricultural pumpage of 28 acre-ft/yr. In the model, this combined increase of 99 acre-ft/yr in net inflow is largely balanced by a decrease in net seepage from the creek (78 acre-ft/yr) and increases in subsurface outflow to the ocean (10 acre-ft/yr) and to storage (9 acre-ft/yr). The percentage change in all these items is considerably less than the percentage change in rainfall. Thus, model results generally are less sensitive to total annual rainfall than to the seasonal distribution of rainfall.

The effects of ground-water inflow from bedrock tend to be masked by larger or more variable inflows and outflows except in late autumn, after most irrigation has ceased and before the creeks have started to flow. Water levels in most wells change only slightly during this period. If inflow from bedrock is increased, simulated water levels recover more rapidly than measured levels. On an annual basis, a change in the assumed rate of inflow generally results in an equal and opposite change in the simulated quantity of stream recharge.

Inflow from bedrock is important to water-resources management because it is a more reliable source of water supply than recharge from streamflow or rainfall on the valley floor. The latter sources of recharge can decrease to zero as a result of even a single extremely dry year. In contrast, inflow from bedrock decreases gradually over a period of several years during a prolonged drought.

The assumption that inflow from bedrock is at a constant rate year-round was tested by trying an alternative simulation in which the rate varied seasonally. The rate was assumed to equal the calibrated rate in November and December and twice that rate in April and May with gradual transitions in between. This distribution is an attenuated and slightly delayed replication of the rainfall distribution. The additional ground-water inflow is 73 acre-ft/yr and is largely (81 percent) offset by a decrease in net seepage from the creek. The effect on water levels is a slight decrease in dry-season decline throughout the basin. The assumption of constant ground-water inflow has minimal implications for water-resources management because any seasonal variations would probably add inflow during the streamflow season when water is already abundant.

Initial water levels at the beginning of model simulations have little effect on model results because they adjust rapidly to the new set of conditions imposed for each simulation. Except at the edges of the valleys, water levels adjust to new stresses within 1 month. In areas of low hydraulic conductivity or a large degree of anisotropy, simulated water levels in wells near the edge of the valley (for example, wells 27S/8E-9M1 and 24J2) can take more than a year to adjust to a new set of conditions. Only the final 12 months of the 15-month calibration simulations were used for comparison. The first 3 months of simulation provided sufficient time for the effects of initial conditions to become negligible.

The models were calibrated assuming unconfined conditions; that is, transmissivity was adjusted in each time step to reflect the current saturated thickness of aquifer sediments. The sensitivity of the model results to this assumption was tested with two simulations in which saturated thickness and transmissivity were held constant. In one simulation, relatively large values of thickness and transmissivity were calculated using high winter water levels. In the second simulation, relatively small values were calculated using low autumn water levels. Storage coefficients were not changed for this test.

The effect of confinement was similar in both basins. Effects are largest where seasonal water-level fluctuations are greatest, such as at the upper ends of the basins. When winter transmissivity is used throughout the year, much more water drains downvalley during the dry season. Seasonal water-level declines at the upper ends of the basins increased as much as 12 ft. This additional downvalley drainage caused a 1- to 4-foot decrease in dry-season water-level declines at most wells downstream of well 27S/8E-10G2 in the San Simeon Basin and well 27S/9E-20G3 in the Santa Rosa Basin. There also was a large decrease in seasonal drawdown at the municipal wells in the Santa Rosa Basin (27S/8E-26C5 and 26D1) because transmissivity was much greater in summer and autumn than under unconfined conditions.

When autumn transmissivity is used throughout the year, effects are opposite and slightly smaller. Dry-season water-level declines at the upper ends of the basins decrease by as much as 12 ft and increase by as much as 3 ft farther downstream.

The assumption of constant transmissivity had little effect on the annual water budgets. Winter transmissivity results in increased seepage to and from the creek, but the change in net seepage is an increase of less than 18 acre-ft/yr. Autumn transmissivity results in large decreases in seepage to and from the creek, but the change in net seepage is a decrease of less than 16 acre-ft/yr. Changes in annual net seepage were less than 3 percent in both basins.

The final set of calibrated variables is not necessarily unique. In some cases, the effects of adjusting one variable can be offset by adjusting one or more other variables. For example, the rate of water-level recovery following the onset of winter streamflow is fairly sensitive to *K*, *S*, anisotropy, and streambed leakance; all affect the diffusivity of the flow path perpendicular to the creek. At a given well, the effect of greater anisotropy can be offset by a decrease in storage coefficient or an increase in streambed leakance. The hydraulic characteristics of the streambed and the alluvial deposits result from a combination of flow regime and sediment type at the time and the place of deposition. Although the characteristics are somewhat interrelated, local variations in depositional environment result in a range of possible combinations. Other examples of nonunique calibrated values are tradeoffs between streambed leakance and ocean boundary conductance near the coast and between *K* and *S* near the upper ends of the basins. In all cases, tradeoffs among variables were limited to a fairly narrow range by the noncompensating effects of the variables in other locations or seasons and by the range of physically plausible values.

Limitations of Model

The accuracy of model results and the suitability of the models for addressing certain hydrologic questions are limited by simplifications and assumptions inherent in model design and by the sensitivity of model results to some input variables. Following are some of the more significant limitations of the models.

1. Vertical movement of ground water is not simulated because the ground-water system is simulated as a single layer.

2. The calibration simulations were for a period of only 15 months. Climatic conditions during the calibration period were drier than normal. The ability of the model to accurately simulate wet conditions or extremely dry conditions has not been tested.

3. The accuracy of simulated water levels near the edges of the valleys is not well defined and probably is less than the accuracy in midvalley areas.

4. The coarseness of the model grids precludes simulation of highly localized water-level variations. In general, this includes variations that generally occur over distances less than the node spacing, which ranges from about 90 to 600 ft in the San Simeon model and from about 150 to 1,200 ft in the Santa Rosa model. This effect is particularly noticeable near the creeks. Where well nodes coincide with stream nodes, simulated water-level recoveries during the December 1988 storm were noticeably more abrupt at wells one or more nodes away from the creek.

5. The models do not simulate the effects of different fluid densities where freshwater meets seawater near the coast. The effects of density differences on water levels and ground-water budgets were small in 1988–89. The accuracy of model results for conditions of seawater intrusion is unknown, nor does the model indicate the position of the interface between seawater and freshwater.

6. The proportion of ground-water discharge to the ocean that occurs as subsurface outflow as opposed to surface outflow might not be accurately simulated because neither water levels nor streamflow is sensitive to the proportion.

7. The models might not accurately simulate local variations in streamflow and seepage because they assume that stream-channel geometry is the same

in all reaches and that the distribution of streambed leakances is relatively uniform. The models would not be accurate enough to identify critical riffles for fish migration; but generally, they simulate known gaining and losing reaches accurately.

8. The models cannot accurately determine the separate amounts of seepage to and from the creeks because the seepage rates are sensitive to streambed leakance, which is poorly known. However, the simulated amount of net seepage is much more accurate because it is determined largely by the net balance of other inflows and outflows, which are better known.

9. Seepage from the creek to the ground-water system is assumed to be head-dependent even when the water table is far below the thalweg. In reality, an unsaturated zone probably exists beneath the streambed under those circumstances and seepage might not be head-dependent until that zone becomes fully saturated. Errors resulting from the head-dependent assumption are most likely to occur during rapid water-level recovery following the onset of winter streamflow. However, measured recovery rates at wells close to the creek did not exhibit noticeable delays in recovery that could be attributed to the effects of an unsaturated zone. Any errors resulting from the head-dependence assumption were compensated for by the leakance values, which were calibrated to simulate accurately the measured rates of recovery.

10. Simulated amounts of phreatophyte transpiration are only approximate because the model does not include the details of local topography and root depth distribution.

11. Water levels simulated by the models are equivalent to static water levels measured when wells are not pumping. They reflect the general effects of pumping on basinwide water levels but do not accurately indicate the water level in the immediate vicinity of a pumping well or the water level in the well casing. The amount of local drawdown included in the simulated water levels is affected by the coarseness of the model grid with larger node spacing associated with less simulated drawdown.

SIMULATED RESPONSES TO HYDROLOGIC CHANGES

Effects of Agricultural and Municipal Pumpage

The effects of different types of pumpage on water budgets and on water levels in each basin were investigated by selectively eliminating all pumpage or either municipal or agricultural pumpage from the calibration simulation. The simulated water budgets indicated the sources of recharge for each type of pumpage. For the simulation without agricultural pumpage, areal recharge through field soils was recalculated assuming that the fields contained nonirrigated annual grass. For the simulation without municipal pumpage, recharge from reclaimed wastewater at the CCSD wastewater sprayfield was assumed to continue, as if CCSD had simply switched to an imported water supply. Rural domestic and industrial pumpages also were retained in the simulation. The simulation without any pumpage represents predevelopment conditions, and recharge by reclaimed wastewater was omitted. Areal recharge was recalculated assuming the valley floors were covered with deep-rooted native vegetation.

The simulated effects of pumpage on water levels are indicated by the hydrographs shown in figure 24. Four sets of simulated water levels are shown for each of the 16 wells for 1988–89: calibrated water levels (shown for comparison), water levels without agricultural pumpage, water levels without municipal pumpage, and water levels without any pumpage.

The sources of water that supplied each type of pumpage are shown in table 9. The relative magnitude of each source was obtained by comparing water budgets for simulations with and without each type of pumpage. There are consistent patterns in the sources of each type of pumpage. In both basins, a relatively large percentage (43 to 48 percent) of agricultural pumpage was supplied by an increase in areal recharge, about two-thirds of which was from irrigation-return flow and the remainder was from rainfall that percolated to the water table. A slightly smaller percentage (36 to 45 percent) of agricultural pumpage was supplied by an increase in net recharge from the creek. In both basins, 86 percent of municipal pumpage was supplied by increased recharge from the creek. This percentage is much higher than for agricultural

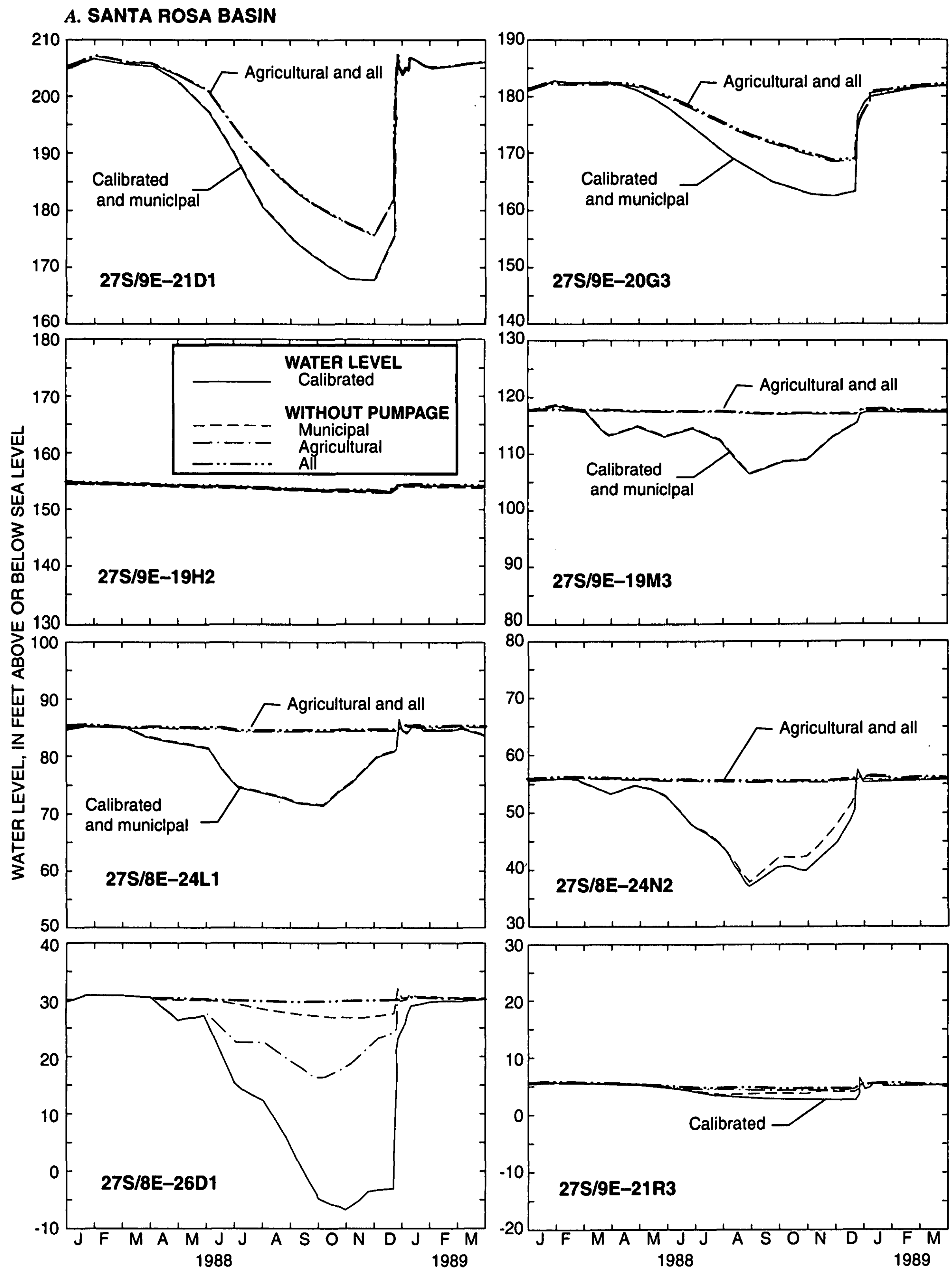


Figure 24. Relative effects of three types of pumpage in (*A*) the Santa Rosa and (*B*) the San Simeon ground-water basins, San Luis Obispo County, California.

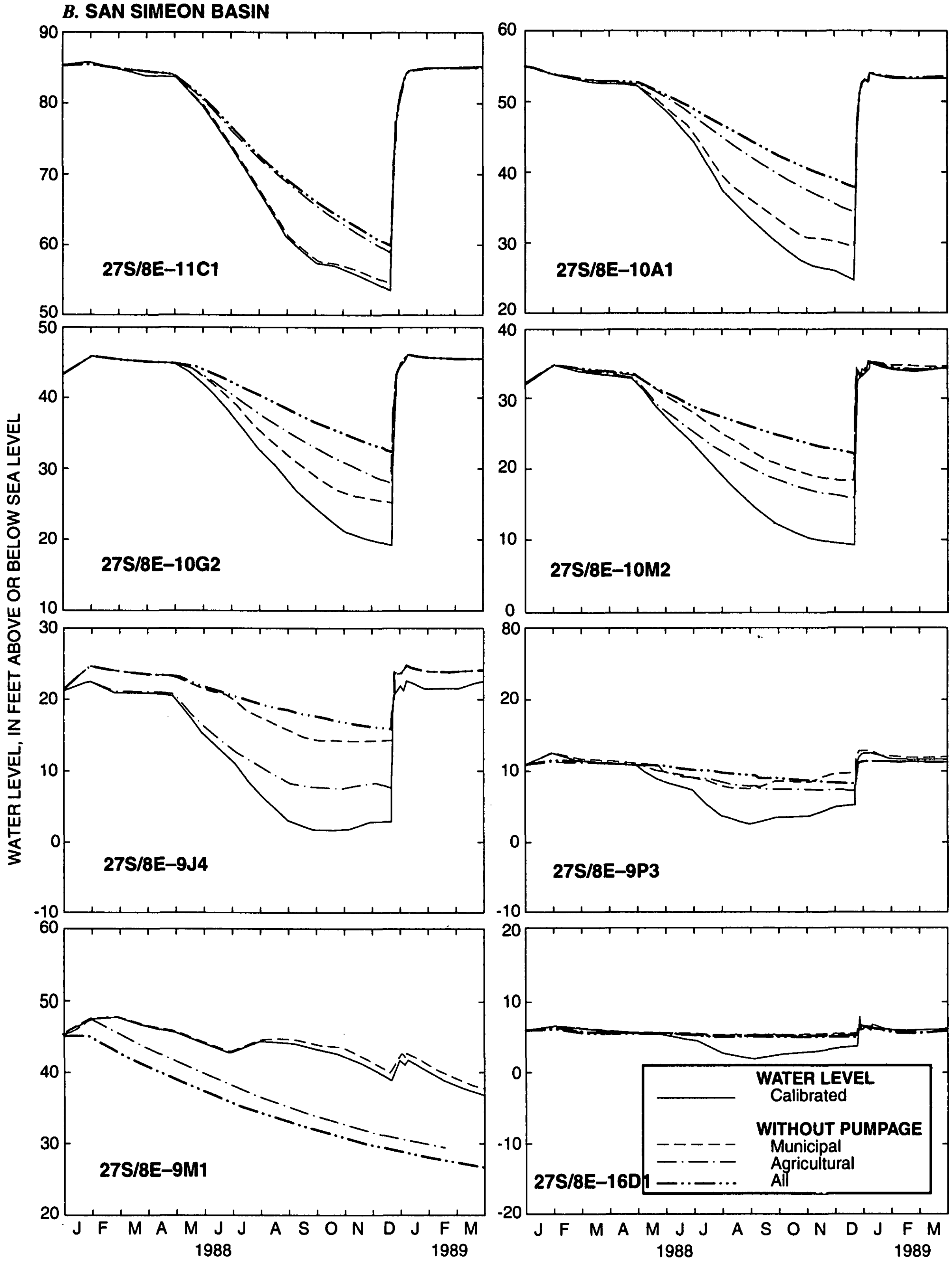


Figure 24. Relative effects of three types of pumpage in (*A*) the Santa Rosa and (*B*) the San Simeon ground-water basins, San Luis Obispo County, California—Continued.

pumpage because the simulations did not count recharge from the CCSD wastewater sprayfield as a source of municipal pumpage. Although sprayfield recharge does offset the effects of municipal pumpage in the context of basinwide ground-water budgets, health regulations prohibit its use as a significant percentage of recharge for municipal pumpage.

Decreased ground-water outflow to the ocean supplied a relatively small percentage (1 to 3 percent) of all types of pumpage in the Santa Rosa Basin. The percentage was slightly greater (5 to 19 percent) in the San Simeon Basin because a larger percentage of ground-water outflow in that basin occurred as subsurface outflow rather than as seepage into the creek.

Decreases in phreatophyte transpiration supplied a larger percentage of pumpage in the Santa Rosa Basin than in the San Simeon Basin because of the larger area of phreatophytic vegetation. In all cases, however, this source of water supplied less than 12 percent of pumpage (table 9).

The amount of dry-season water-level decline caused by agricultural pumpage in the Santa Rosa Basin (in addition to drawdown from natural downvalley drainage) decreased from about 10 ft near well 27S/9E-21D1 to less than 2 ft at the subsurface flow obstruction near well 27S/9E-19H2. It increased again downstream to about 15 ft at well 27S/8E-24L1. Agricultural pumpage caused as much as 25 ft of dry-season water-level decline downstream of the high school even though there was little agricultural pumpage in that area. This drawdown resulted because agricultural pumpage in the upstream areas intercepted ground water that would have flowed downvalley. Most of this downvalley flow would have occurred as streamflow. In the simulation without agricultural pumpage, the trickle of base flow that emerges near well 27S/9E-19H2 flowed continuously to the ocean in all months except October when a short reach near well 27S/8E-27H1 went dry. In the calibration simulation, base flow was much smaller and the creek was dry between the high school and State Highway 1 from July through mid-December.

Agricultural pumpage caused as much as 10 ft of dry-season water-level decline in the San Simeon Basin. This amount decreased downstream from a maximum of 10 ft near well 27S/8E-10A1 to about 6 ft in the CCSD well field (27S/8E-9J4) and about 3 ft near the coast (27S/8E-16D1). Agricultural water use tends to elevate water levels in the Van Gordon Creek area (27S/8E-9M1), where irrigation water is supplied by off-site wells in the CCSD sprayfield. Agricultural pumpage did not significantly affect water levels in winter.

Municipal pumpage in the Santa Rosa Basin had no effect on water levels upstream of well 27S/8E -24L1, but contributed a maximum of about 33 ft of dry-season water-level decline near well 27S/8E-26D1. The drawdown decreased upstream to about 2 ft at well

Table 9. Quantities and sources of three types of ground-water pumpage in the Santa Rosa and the San Simeon ground-water basins, San Luis Obispo County, California, April 1988 through March 1989

Item	Santa Rosa Basin			San Simeon Basin		
	Municipal	Agricultural	All	Municipal	Agricultural	All
Pumpage (acre-feet)	254	893	1,159	556	451	1,013
Source (percent)[1]						
Increase in areal recharge	0	48	41	0	43	23
Increase in net recharge from creek	86	45	53	86	36	25
Decrease in recharge from reclaimed water	0	0	0	0	0	45
Decrease in outflow to ocean	3	1	1	12	19	5
Decrease in phreatophyte transpiration	11	6	5	2	2	2

[1]Source of given type of pumpage is indicated by the change in water budget with respect to a simulation without that pumpage.

27S/8E-24N2 and decreased downstream to about 2 ft at well 27S/8E-21R3.

Municipal pumpage decreased dry-season water levels throughout the San Simeon Basin by quantities ranging from 1 ft at the upper end of the valley (27S/8E-11C1) to 7 ft in the CCSD well field (27S/8E -9J4). Unlike agricultural pumpage, municipal pumpage also affected winter water levels, at least in the well field. Municipal pumping rates that remained high in winter prevented ground-water levels from recovering completely. The water levels remained about 3 ft below the level of the creek throughout the winter of 1989.

A significant amount of dry-season water-level decline is not the result of pumpage but of natural drainage processes. Winter water levels at the upper ends of the valleys cannot be maintained without continued recharge from the creeks. As soon as the creeks dry up in summer, ground water in those areas drains downvalley. In the simulation with no pumpage, these natural dry-season water-level declines were between 21 and 25 ft, or about 75 percent as large as the declines that occurred with pumping in 1988 (fig. 24). In the Santa Rosa Basin, much of the water draining out of the upper end of the valley seeped into the creek and became available to offset dry-season declines in downvalley areas. Consequently, there was almost no dry-season water-level decline under predevelopment conditions downstream of about well 27S/9E-19H2. In the San Simeon Basin, there were natural dry-season water-level declines throughout the valley because water moved downvalley only as subsurface flow.

Occurrence and Effects of Drought

The water supply for the Cambria area is vulnerable to drought because the ground-water basins provide the only supply of water during the dry season and because ground-water storage capacity is small relative to the demand for water. The amount of usable ground-water storage capacity above sea level is about 3,800 acre-ft in the Santa Rosa Basin and 1,000 acre-ft in the San Simeon Basin. Total annual pumpage during 1988–89 was about 30 and 101 percent of the storage capacity in the two basins, respectively. Data for Pico Creek (Cleath, 1986) indicate that total annual pumpage was about 230 percent of storage.

For the purpose of water-supply evaluation, droughts were grouped into three categories: (1) a long dry season between two winters in which the basins are completely recharged, (2) a single winter during which the basins are not fully recharged, and (3) two or more successive winters of incomplete recharge.

Single Long Dry Season

In most years, the creeks stop flowing in summer. When flow stops, the quantity of water available until the following winter is limited to the quantity of ground water stored in the basins plus a slow but steady inflow of ground water from bedrock. The quantity of water in storage at the beginning of the dry season usually is about the same each year, but the length of the dry season is quite variable. If the dry season were exceptionally long and pumping continued unabated, wells could go dry or subsidence or seawater intrusion could occur before recharge begins the following winter. Partly for these reasons, there are legal limitations on annual and seasonal quantities of municipal pumpage for both basins.

The frequency distribution of the duration of the summer dry season was estimated from streamflow records for Santa Rosa Creek near Cambria and San Simeon Creek at Palmer Flats. A persistent trickle of summer base flow in Santa Rosa Creek resulted in a non-normal distribution of dry-season duration. This trickle, which is relatively insignificant from a water-supply standpoint, was omitted from the analysis by counting days in which streamflow was less than 0.5 ft^3/s as days of no flow. The resulting frequency distribution for 1959–89 could be adequately approximated by a normal distribution with a mean of 146 days and a standard deviation of 69 days. Normality was tested using the probability plot correlation coefficient test (Looney and Gulledge, 1985). The probability distribution indicated that the 100-year maximum dry-season duration (that is, the maximum dry-season duration likely to occur once in 100 years) is 307 days. For comparison, the longest dry season in the streamflow record for Santa Rosa Creek (289 days in 1977) has an estimated recurrence interval of about 52 years.

Summer base flow is less persistent in San Simeon Creek and was not omitted from the analysis. For the period of streamflow record (1971–89), the average duration of the dry season was normally distributed with a mean of 164 days and a standard deviation of 64 days. The 100-year dry-season duration is 312 days; the longest dry season on record for San Simeon Creek (269 days in 1977) has an estimated recurrence level of about 20 years.

These estimates almost certainly underestimate the actual mean and 100-year dry-season durations because the periods of record for both stream-gaging stations were wetter than average. This is evident from the cumulative departure diagram for annual rainfall at the San Luis Obispo-Poly station (fig. 13). Average rainfall during the 120-year record was 21.79 in., whereas average rainfall during 1959–89 and 1971–89 was 23.56 and 24.55 in., respectively. Bianchi and Hanna (1988) developed an empirical equation relating the length of the dry season in San Simeon Creek to monthly rainfall in San Luis Obispo. Using 115 years of rainfall data for San Luis Obispo, they estimated that the long-term average duration of the dry season is 200 days, or 36 days longer than the estimate obtained directly from the streamflow data.

The probable duration of the dry season can be estimated as soon as it has begun, allowing water-conservation measures to be implemented if necessary. Figure 25 shows the relation between the duration of the dry season and the date streamflow ceases (or becomes less than 0.5 ft^3/s in the case of Santa Rosa Creek). The relation is not exact because of variability of the date streamflow resumes the following winter. Nevertheless, the relation can give a general indication of probable dry-season duration.

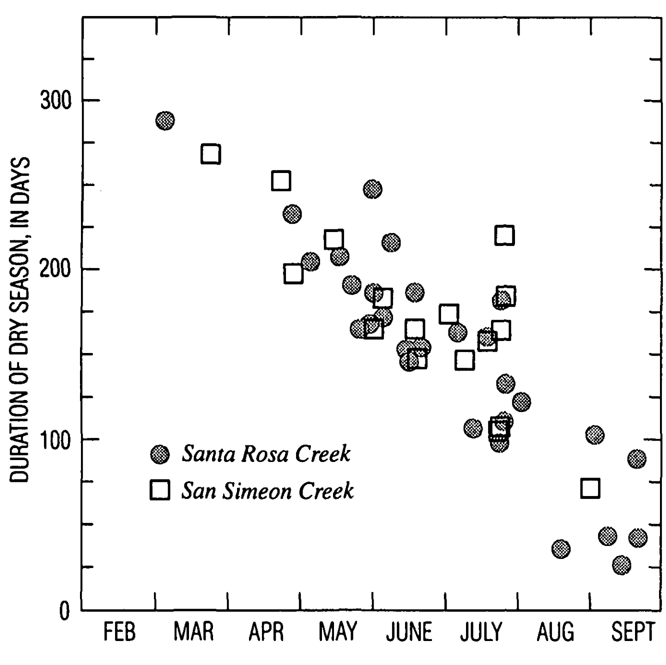


Figure 25. Relation of dry-season duration and date on which streamflow ceases in the Santa Rosa and the San Simeon ground-water basins, San Luis Obispo County, California.

The effect of a prolonged dry season was investigated using the ground-water-flow models. The duration of the summer dry season in the calibrated simulations for 1988–89 was increased to two longer durations by shifting the end of the preceding winter to earlier dates, 1 month at a time. In the Santa Rosa Basin, the duration was increased from 204 to 235 and 266 days, which correspond to estimated recurrence intervals of about 5, 10, and 24 years. In the San Simeon Basin, the duration was increased from 235 to 266 and 296 days, which correspond to estimated recurrence intervals of about 8, 18, and 52 years. Agricultural pumpage was recalculated for the longer dry season using the soil-moisture budget algorithm. Rainfall and ET_0 were adjusted to reflect dry conditions, but cropping patterns and planting dates were left unchanged. Gross pumpage for irrigation increased by about 170 and 43 acre-ft per additional month of dry season in the Santa Rosa and the San Simeon Basins, respectively. This rate of increase became smaller as the dry season became longer because the additional dry days occurred in late winter when the demand for irrigation water was relatively small. Municipal pumpage was assumed to be unaffected by the duration of the dry season because only a small percentage of it is was used for landscape irrigation in late winter.

Figure 26 shows hydrographs for selected wells in the Santa Rosa and the San Simeon Basins for three different dry-season durations. Increasing dry-season duration significantly lowered water levels at the upper ends of the valleys because there was more time for downvalley ground-water flow during the dry season. For example, the minimum water level at well 27S/9E -21D1 decreased about 5 ft for every additional month of dry season. Effects farther down the valley were smaller because the lack of recharge from rainfall and streamflow was partly offset by ground-water flow from farther up the valley. Also, much of the pumping at the lower ends of the valleys is for municipal purposes and does not increase under dry conditions to the extent that agricultural pumping does.

The cumulative dry-season storage deficit increased as the duration of the dry season increased. In the Santa Rosa Basin, the storage deficit increased by about 96 acre-ft for each additional dry-season month. In the San Simeon Basin, the increase was about 28 acre-ft/mo. The percentage increase in storage deficit generally was less than or equal to the percentage increase in dry-season duration.

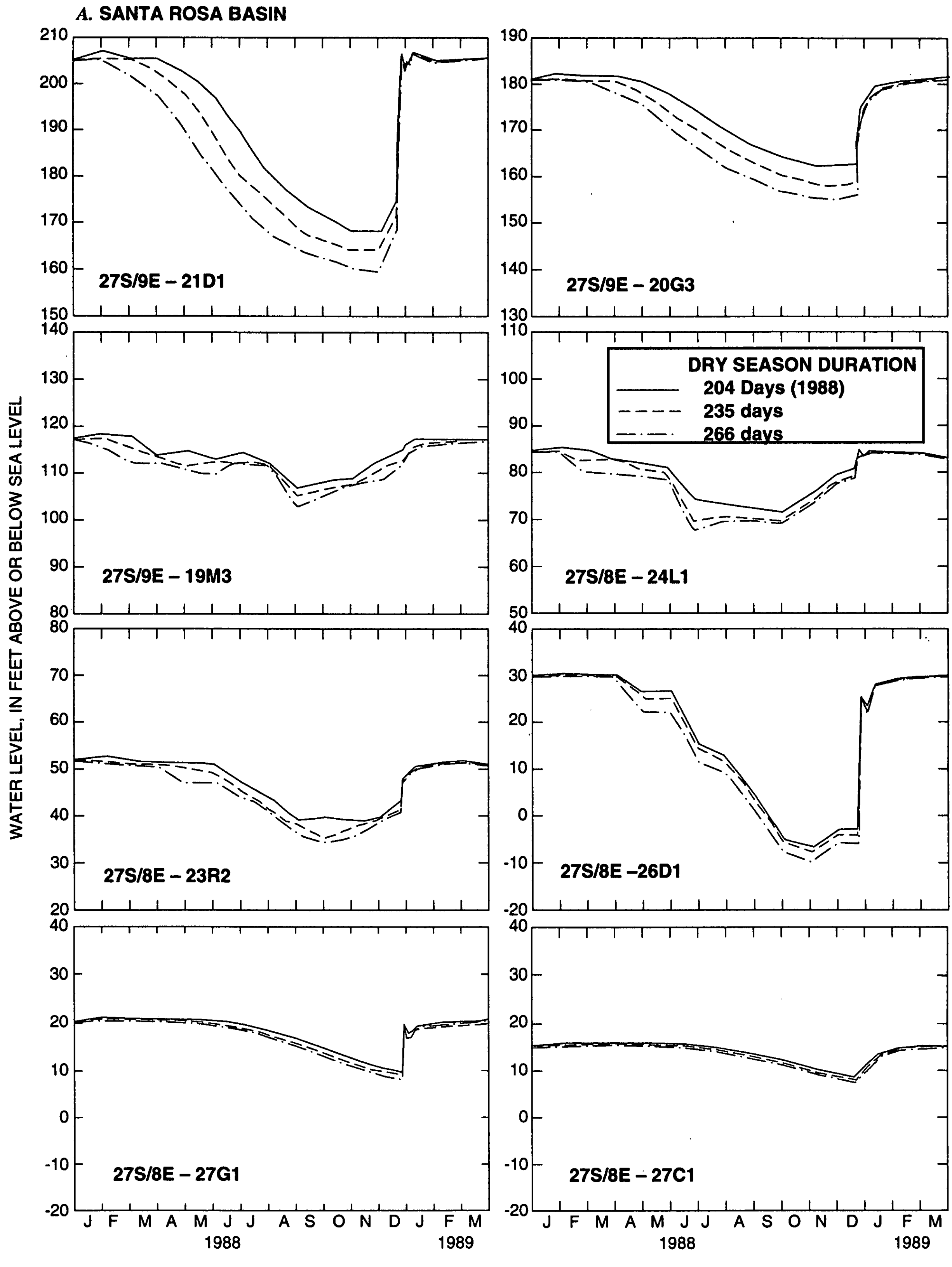


Figure 26. Effects of dry-season duration on simulated ground-water levels for the Santa Rosa and the San Simeon ground-water basins, San Luis Obispo County, California, 1988–89.

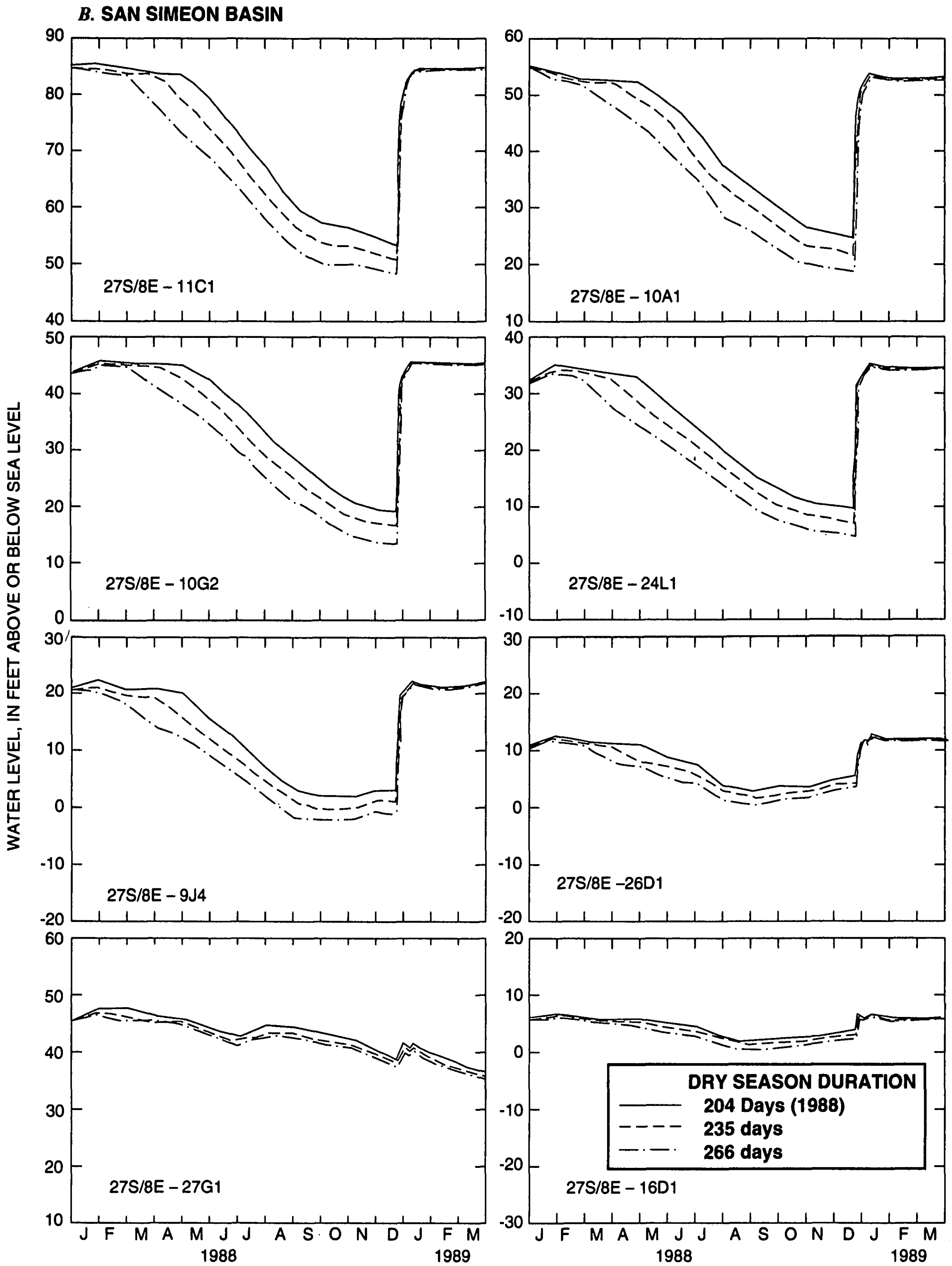


Figure 26. Effects of dry-season duration on simulated ground-water levels for the Santa Rosa and the San Simeon ground-water basins, San Luis Obispo County, California, 1988–89—Continued.

Dry Wells

Some wells are likely to go dry during a long dry season. Wells at greatest risk of going dry are shallow wells and wells at the upper ends of the valleys. Well 27S/9E-21C1 in the Santa Rosa ground-water basin did go dry in mid-September 1988. Similarly, the pumping water level in irrigation well 27S/8E-11C1 in the San Simeon ground-water basin reached the pump intake in October 1988, forcing the farmer to switch to well 27S/8E-10A3. Simulated water levels are not accurate indicators of potential pumping difficulties because they represent static (nonpumping) water levels. Potential difficulties could be evaluated on a well-by-well basis by using the specific capacity of a given well to convert the static water level to a pumping water level. The pumping water level could then be compared with the depth of the pump intake and well screen. Pumping problems are most likely to result when pumping water levels reach the pump intake. Simulated water levels were at depths below the top of the casing perforations at many wells near the upper ends of the valleys in all simulations of long dry seasons. This occurred at wells as far downstream as well 27S/9E-20G3 in the Santa Rosa Basin even for the shortest simulated dry-season duration (calendar year 1988). In the San Simeon Basin, this occurred at wells as far downstream as well 27S/8E-10M2. However, the incremental water-level decline for each additional month of dry season is a small fraction of the total perforated interval of most wells.

Subsidence

Land subsidence and ground deformation occurred in Cambria in the summer of 1976 and could occur again if the minimum dry-season water level is close to or less than the record low level reached that year. A series of ground fractures developed on the north side of Santa Rosa Creek in the commercial district near Burton Avenue (fig. 2). The greatest amount of movement, which probably occurred between early August and mid-September 1976, caused breaks in utility pipelines and cracks as much as 4 in. wide in structures and road surfaces. Cleveland (1980) attributed the subsidence to a trend of increasing water use and below-average recharge in the early 1970's combined with the short-term effects of the drought of 1975–76. No subsidence has ever been reported in the San Simeon Basin.

Other factors might have contributed to the subsidence in 1976. Individual septic systems in Cambria were replaced with a central sewer system in late 1972, which decreased the quantity of local ground-water recharge. Minor amounts of ground settling were noticed in scattered locations each year between 1972 and 1975 (Cleveland, 1980). Some of this movement could have resulted from desaturation of surficial deposits. However, some of the movement also could have resulted from exceptionally low water levels in 1972 (27S/8E-26C5 in fig. 8).

Widespread subsidence in 1976 was more clearly associated with record low water levels. The effect of sewering on subsidence in 1976 might have been largely indirect. By decreasing the quantity of local recharge, sewering caused water levels to decrease faster in response to pumping than they would have otherwise.

Subsidence in alluvial ground-water basins usually is caused by low water levels that decrease the buoyant effect of hydrostatic pressure in the ground-water system. This increases the effective load of the overburden and causes a slight but largely permanent compaction in montmorillonitic clay strata (Lofgren, 1968). In August 1976, water levels in municipal well 27S/8E-26D1 and the now-abandoned well 27S/8E-26C3 reached record low levels of about 60 and 72 ft below land surface (14 and 20 ft below sea level), respectively. The low water levels coincided with the onset of ground deformation.

The potential for additional subsidence in Cambria owing to ground-water pumping can be estimated from studies of subsidence in other areas and from the relation between water levels and pumpage. Ground-water pumping in the San Joaquin and the Santa Clara Valleys in California has caused as much as 29 ft of subsidence over periods of several decades (Poland, 1969; Riley, 1969; and Bull and Poland, 1975). The amount of compaction of clay strata—which is about one-half the total alluvial thickness in these areas—was between 0.00001 and 0.00016 ft per foot of water-level decline per foot of clay thickness. Ground surveys in Cambria were begun too late to record the full amount of subsidence. As much as 0.14 ft of subsidence was measured between late September and December 1976. However, subsidence potential can be estimated by applying the compressibilities measured in other areas to the 140-foot-thick alluvial deposits in Cambria. Assuming 50 percent of the thickness is compressible clay, a 10-foot decrease in the record low water level in Cambria would cause between 0.007 and 0.110 ft of subsidence.

Duration of stress is another factor in subsidence. Compaction can take years to equilibrate to a sudden increase in stress, and subsidence can continue even after water levels rise above their record low levels (Helm, 1978). Similarly, subsidence can resume when water levels are at or slightly above their record low levels if compaction had not fully equilibrated to the amount of stress during the previous period of low water levels. Thus, subsidence near well 27S/8E-26D1 could resume any time water levels are near or below the record low levels of 1976. In 1988, for example, the minimum water level in well 27S/8E-26D1 at the end of the dry season was 12 ft below sea level, which is only 2 ft higher than the minimum level in August 1976. Subsidence could have occurred in 1988, although none was reported.

Minimum water levels during the dry season are determined more by the cumulative quantity of dry-season pumpage than by the duration of the dry season. In 1976, the minimum water level in well 27S/8E-26D1 occurred in late August after a total of about 226 acre-ft of pumpage since the beginning of May. In 1988, the minimum water level did not occur until mid-December, after a total of 238 acre-ft of pumpage since the beginning of May. In both years, streamflow at the gaging station at State Highway 1 ceased in May and a rapid dry-season water-level decline began in June. Although the relation between cumulative pumpage and water-level decline seems similar for both years, other factors could cause changes or variations in the relation. For example, long-term changes could have resulted from the subsidence in 1976 and from decreases in water main leak rates. Subsidence causes an irreversible decrease in the storage capacity of the basin. As a result, less pumpage is needed to return water levels to their previous low levels. The municipal water system leaked about 20 percent less water in 1988 than in 1976 as a result of extensive pipe repairs in late 1970's. Some of the water that leaks from pipes returns to the ground-water basin and offsets pumping withdrawals. Thus, although the gross dry-season pumpages were similar in 1976 and 1978, net pumpages might have been different. Under a permit from the California State Water Resources Control Board (Decision 1624, April 1989), the CCSD is authorized to pump a maximum of 260 acre-ft of water from the Santa Rosa Basin between May 1 and October 31.

In the early 1970's (prior to the occurrence of subsidence in Cambria), the dry-season safe yield of the "downtown area" was assumed to equal 260 acre-ft, apparently for no other reason than that this was the quantity of dry-season pumpage in 1972 (Coastal Valley Engineering, Inc., 1976). Water-level declines in 1988 indicate that 260 acre-ft of pumpage during the dry season can bring water levels close to the threshold at which subsidence will resume. Simulation results indicate that under the pumping conditions that existed in 1988, the minimum dry-season water level in Cambria decreased by 1 to 2 ft for each additional month of dry-season duration.

Single Winter with Incomplete Recharge

If streamflow is insufficient during winter, ground-water recharge will be incomplete and water levels will not return to the levels of the preceding winter. As an extreme example, the hydrographs in figure 27 show simulated water levels for 1988–89 that resulted from omitting all streamflow and rainfall recharge during the winter of 1989. In the Santa Rosa Basin, water levels declined continuously during winter at wells upstream of well 27S/9E-19M3 and downstream of 27S/8E-27G1, but at wells in the intervening reach, water levels recovered as much as 25 ft. The recovery was a result of small storage coefficients, redistribution of water within the basin, and sufficient inflow from bedrock to cause a basinwide storage increase of 57 acre-ft. By the end of the second dry season, all wells upstream of well 27S/9E-20G3 were dry, and water levels in wells 27S/9E-20G3 and 27S/8E-26C5 were low enough to probably cause pumping difficulties.

Seawater intrusion did not occur during the second simulated dry season in the Santa Rosa Basin, but the rate of subsurface outflow to the ocean was only about one-third the rate during the first dry season. Subsidence probably occurred near wells 27S/8E-26C5 and 26D1, where simulated water levels at the end of the second dry season were 2 to 18 ft below the record low levels in 1976.

In the San Simeon Basin, effects were more severe. Water-level recovery was minimal during winter, and basinwide storage did not increase even though inflow from bedrock and recharge from the CCSD wastewater sprayfield were the same as in the calibration simulation. A water-level recovery of 1 to 2 ft in wells in the CCSD well field resulted from ground-water movement from other parts of the basin. One reason winter recovery was much less than in the Santa Rosa Basin is that municipal pumping rates do not

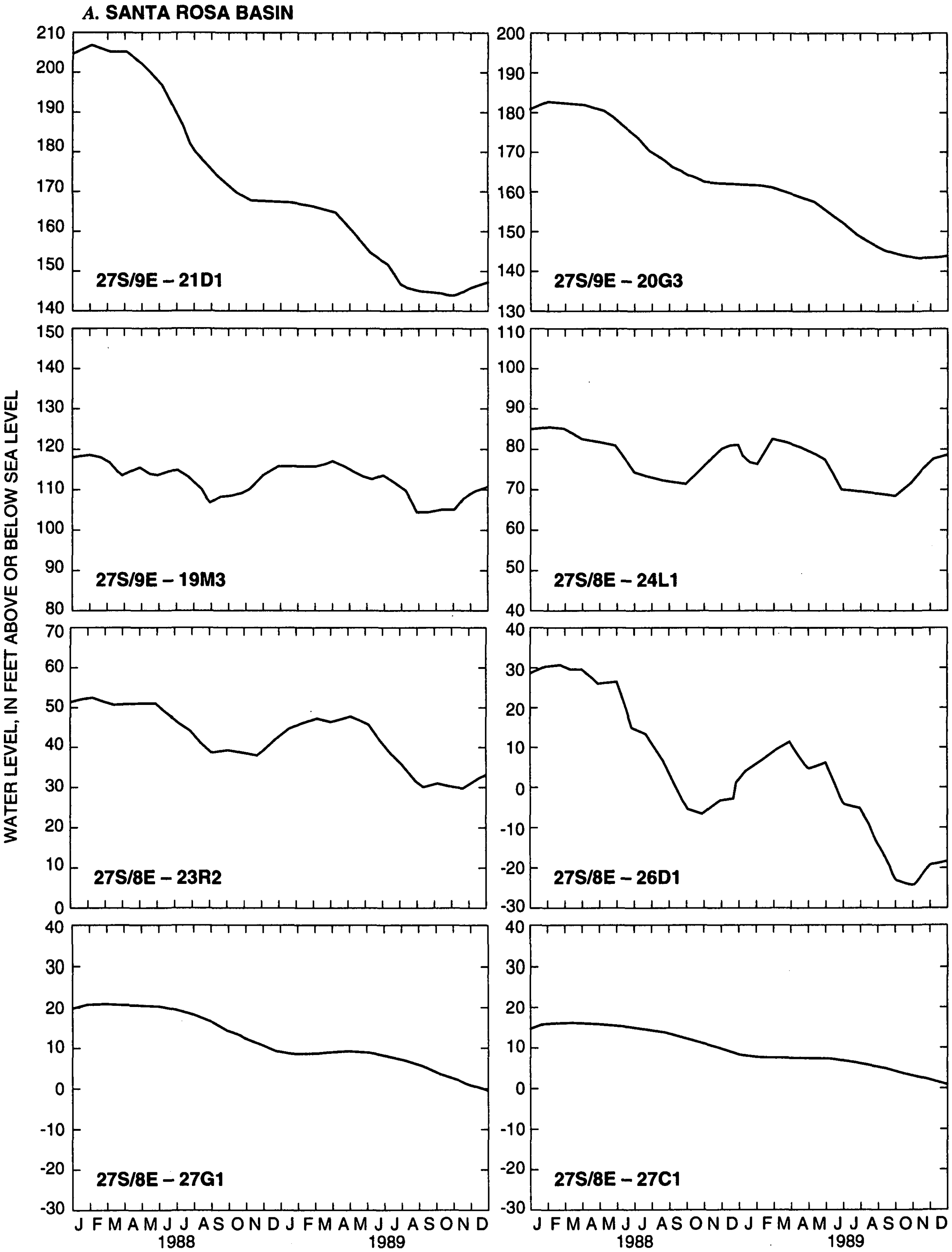


Figure 27. Simulated effects of a single winter without recharge on ground-water levels for 1988–89 for (*A*) the Santa Rosa and (*B*) the San Simeon ground-water basins, assuming normal pumping rates, and effects of selected decreases in agricultural pumping for the San Simeon Basin for 1989, San Luis Obispo County, California.

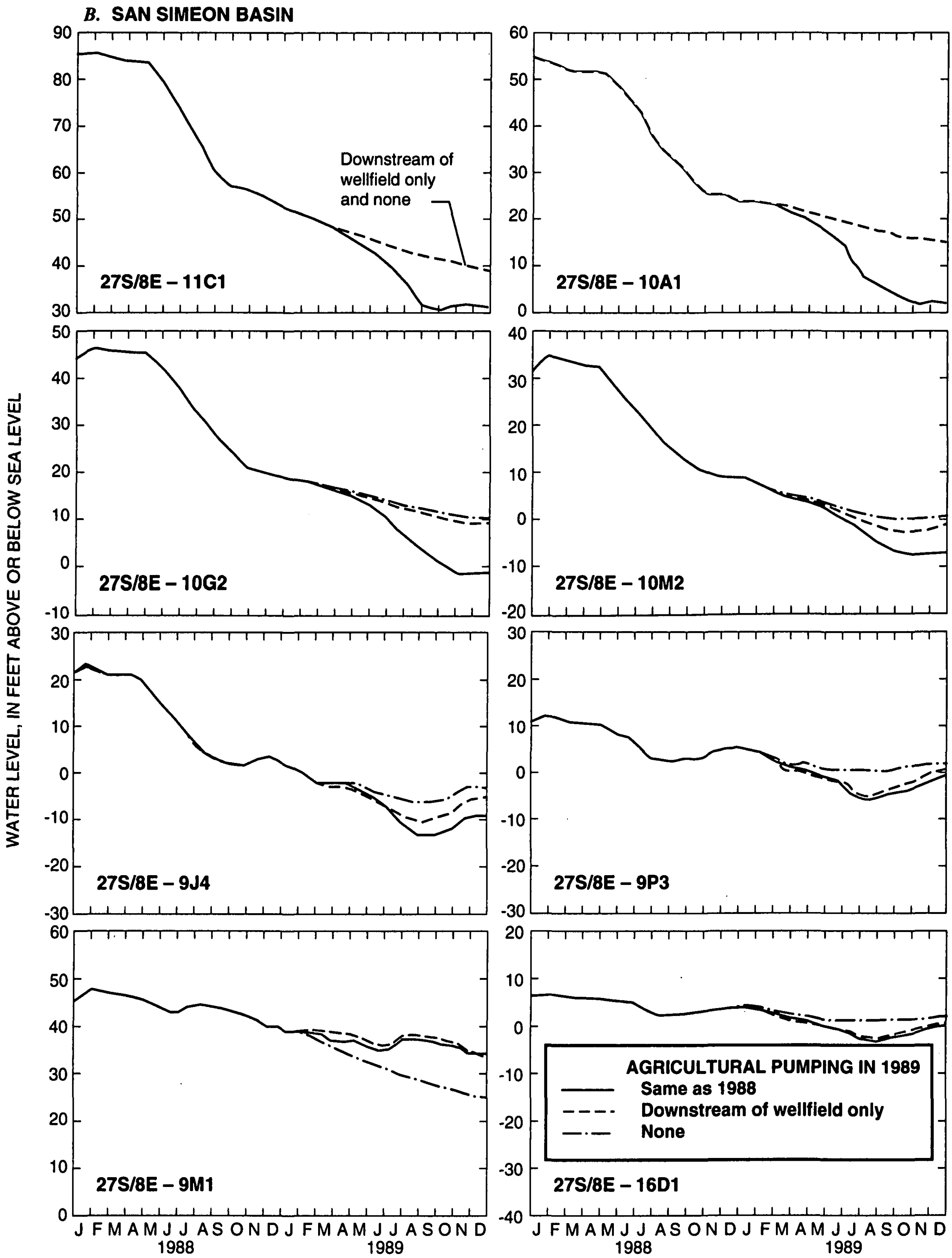


Figure 27. Simulated effects of a single winter without recharge on ground-water levels for 1988–89 for (*A*) the Santa Rosa and (*B*) the San Simeon ground-water basins, assuming normal pumping rates, and effects of selected decreases in agricultural pumping for the San Simeon Basin for 1989, San Luis Obispo County, California—Continued.

decrease in winter as much as do agricultural pumping rates. Water-level declines during the second dry season were about the same as during the first dry season. Water levels in the CCSD well field and wastewater sprayfield declined to below sea level during the second dry season, resulting in 48 acre-ft of seawater intrusion. Static water levels were near or below the pump intake at all wells upstream of well 27S/8E-10F2. By the end of the second dry season, static water levels were below the tops of the perforated intervals at all wells between wells 27S/8E-10F2 and 9K3. These wells might have pumped air or experienced a decline in yield. Simulated conditions during the second dry season were somewhat more severe than those that would actually occur because simulated pumpage was not decreased as wells went dry. If pumpage had been discontinued at dry wells, water-level declines in the middle and lower parts of the valley would not have been as large, but crop losses caused by lack of irrigation water in the upper part of the valley probably would have been large.

Recharge of the ground-water basins will be incomplete if stream discharge during winter is less than the cumulative storage deficit of the preceding dry season. Even if total stream discharge exceeded the deficit, recharge could be incomplete if the daily distribution of streamflow were such that some of it flowed out to the ocean. Dry-season storage deficits have been increasing in recent years because of increases in dry-season pumpage. For the following discussion on stream recharge, the deficit is assumed to equal the deficit from April 1 through December 20, 1988. This deficit was 660 acre-ft in the Santa Rosa Basin and 500 acre-ft in the San Simeon Basin.

These deficits equal the minimum quantity of stream discharge needed for complete basin recharge and are the threshold at which detrimental effects of drought conditions will begin to appear. For quantities of discharge less than this, the severity of the effects increases until the extreme case of zero discharge is reached. These minimum quantities of stream discharge are small compared with the total annual discharge in most years. For the Santa Rosa and the San Simeon Basins, the quantities are only 12 and 5 percent of the long-term median discharge, respectively.

The critical management issue associated with dry winters is the probability of a winter in which streamflow is insufficient to recharge the ground-water basins completely. This occurred most recently during the winter of 1977. The probability of a winter with incomplete ground-water recharge was estimated from the distribution of annual stream discharge and the sequence of daily flows in each year. Using the relation between annual discharge and annual rainfall in San Luis Obispo (fig. 15), the probability of low flows was estimated from the probability of periods of low rainfall. The probability distribution of rainfall at San Luis Obispo for 1870–1989 is shown on a log-normal probability plot in figure 28. The linear pattern formed by the data indicates that annual rainfall is approximately log-normally distributed. The mean and standard deviation are 21.74 and 8.5 in., respectively. For comparison, a log-Pearson Type III distribution also was fit to the data, and the maximum difference

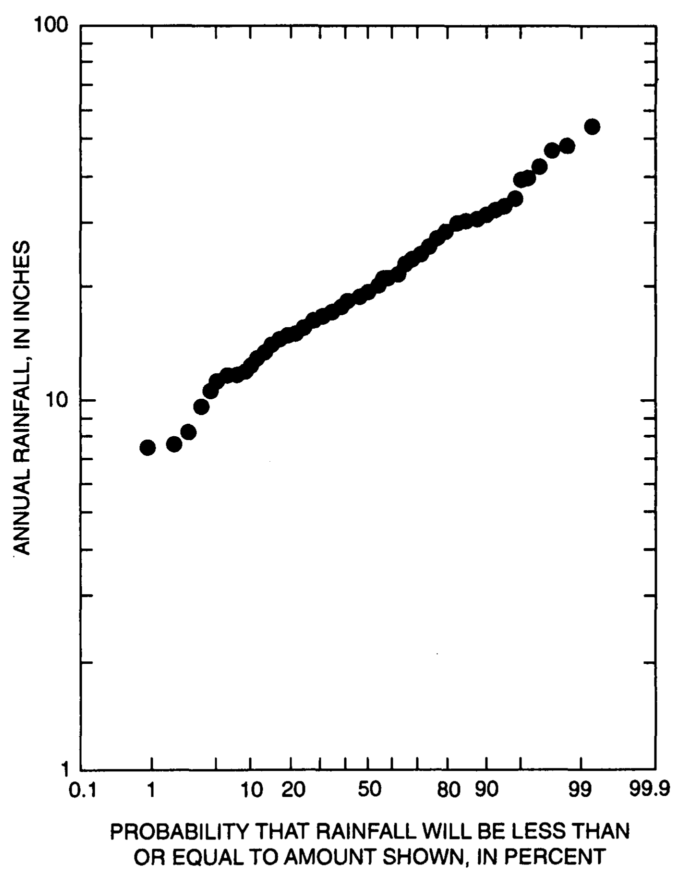


Figure 28. Probability distribution of annual rainfall at the San Luis Obispo-Poly station, San Luis Obispo County, California, 1870–1989.

between the two distributions is about 0.2 in. of rainfall for probabilities in the range 0.01 to 0.99. The log-Pearson Type III distribution is widely used for low flows (Tasker, 1987).

Table 10 shows the recurrence intervals of selected low annual rainfall and stream discharge. The recurrence intervals were calculated using the fitted log-Pearson Type III distribution. Back-transformation of the logarithms to inches of rainfall was done using frequency factors, as explained by Haan (1977). A year with less than the minimum amount of stream discharge necessary to completely recharge the ground-water basin is likely to occur once in 18 years in the Santa Rosa Basin and once in 25 years in the San Simeon Basin. A winter as dry 1976 or 1977, when basin recharge did appear to be incomplete, is likely to occur once in about 25 to 26 years.

The recurrence intervals and stream discharges shown in the table are only approximate because large uncertainties result from scatter in the data. The log-Pearson Type III distribution does not fit the data perfectly. The 95-percent confidence interval for recurrence intervals between 5 and 500 years corresponds to about ±1 in. of rainfall. This in turn corresponds to an uncertainty in annual stream discharge of ±560 acre-ft for Santa Rosa Creek and ±1,100 acre-ft for San Simeon Creek. In terms of recurrence intervals, the 95-percent confidence interval for a winter with incomplete recharge is about +18 years and about −9 years. The uncertainty in the stream discharge is even greater if uncertainties inherent in the regression equations are included. For example, the uncertainties in the expected quantity of stream discharge associated with a 20-year period of rainfall

Table 10. Recurrence intervals of low annual rainfall at San Luis Obispo and stream discharge at upstream gaging stations on Santa Rosa and San Simeon Creeks, San Luis Obispo County, California

[In each row, the underlined item is measured or assumed, and the remaining items are calculated from the rainfall probability distribution (fig. 28) and the rainfall-discharge regressions (fig. 15). na, not applicable]

Item	Recurrence interval (years)	Annual rainfall at San Luis Obispo (inches)	Annual discharge at upstream gaging station (acre-feet)	
			Santa Rosa Creek	San Simeon Creek
Minimum amount likely to occur once in				
100 years	<u>100</u>	8.20	0	0
50 years	<u>50</u>	9.15	0	0
20 years	<u>20</u>	10.80	580	1,040
10 years	<u>10</u>	12.41	1,490	2,810
Zero discharge in				
Santa Rosa Creek	32	9.78	<u>0</u>	0
San Simeon Creek	31	9.85	40	<u>0</u>
Minimum discharge for complete basin recharge in[1]				
Santa Rosa basin	18	10.95	<u>660</u>	1,200
San Simeon basin	25	10.31	300	<u>500</u>
Minimum recorded stream discharge				
Santa Rosa (1977)	26	10.21	<u>240</u>	na
San Simeon (1976)	25	10.29	na	<u>480</u>

[1]Assuming dry-season ground-water storage deficits equal to those in 1988.

become ±1,620 acre-ft for Santa Rosa Creek and 1,880 acre-ft for San Simeon Creek. These large uncertainties result from variations in the data not accounted for by the log-linear model. Nevertheless, the data do not show systematic departures from the assumed distribution and calculated regression lines. For the purpose of water-supply planning, the relations between stream discharge and recurrence interval indicated in table 10 should be considered most likely rather than worst case. Even allowing for uncertainty, the recurrence interval of incomplete recharge is clearly short enough to warrant consideration during water-supply planning.

The recurrence interval for a year with zero discharge is 32 years for Santa Rosa Creek and 31 years for San Simeon Creek (table 10). The linear regressions indicate that discharge is zero in Santa Rosa Creek when annual rainfall in San Luis Obispo is less than 9.78 in. (9.85 in. for San Simeon Creek). Since 1870, rainfall was less than these threshold amounts in 1877, 1898, 1913, and 1924. These were the 4 driest years on record, with rainfall ranging from 7.33 in. in 1898 to 9.52 in. in 1913. For comparison, 1977 was the seventh driest year on record, with 11.53 in. of rainfall. The recurrence interval for the amount of rainfall in 1977 is about 15 years. A longer recurrence interval is indicated in table 10 because the linear regressions predicted that a smaller amount of rainfall would be associated with the measured stream discharges in 1976 and 1977.

Tree-ring data indicate that climatic conditions during the period of record for rainfall for 1870–1989 were similar to those during the preceding several centuries. Growth rings of trees along the central coast of California have been used to estimate rainfall since about 1593 (Michaelson and others, 1987). These data include individual years of more extreme climatic conditions than have occurred during the period of record for rainfall measurements in San Luis Obispo. In the extended record, 1898 is only the third driest year. Furthermore, climatic variability seems to be about as great in recent years as it has been in general throughout the last 400 years. The tree-ring data give no indication that extremely dry years will be any less likely to occur in the future.

Some of the variability in the relation between annual rainfall and annual stream discharge results from different temporal patterns of rainfall within each year. A small number of large storms will generate larger peak flows and greater total discharge than a large number of small storms. Peak flows often exceed the rate at which water can percolate through the creekbed and become ground-water recharge; thus, even in a year when total stream discharge exceeds the dry-season storage deficit, recharge can be incomplete if much of the discharge is during brief periods of peak flows. Test simulations indicated that daily mean flows of as much as 35 ft^3/s in Santa Rosa Creek and 50 ft^3/s in San Simeon Creek could be completely captured as recharge on the first day of the flow season.

The maximum streamflow that can be completely captured as ground-water recharge decreases as the basin gradually fills during the winter. The maximum streamflow (expressed as daily mean flow) during a low-flow year is roughly proportional to total annual discharge. Figure 29 shows the relation for annual discharges of less than 5,000 acre-ft. The relation indicates that in a year with the minimum discharge needed for complete basin recharge (about 662 acre-ft for Santa Rosa Creek and 503 acre-ft for San Simeon Creek), the maximum daily mean flow for any day during the flow season is likely to be between 20 and 80 ft^3/s. This means that even if total annual discharge is low, it is possible that some of the stream discharge will flow out to the ocean and not be captured as recharge. In 1976, for example, annual discharge at the upstream gaging station on Santa Rosa Creek was 323 acre-ft. Discharge at the downstream gaging station

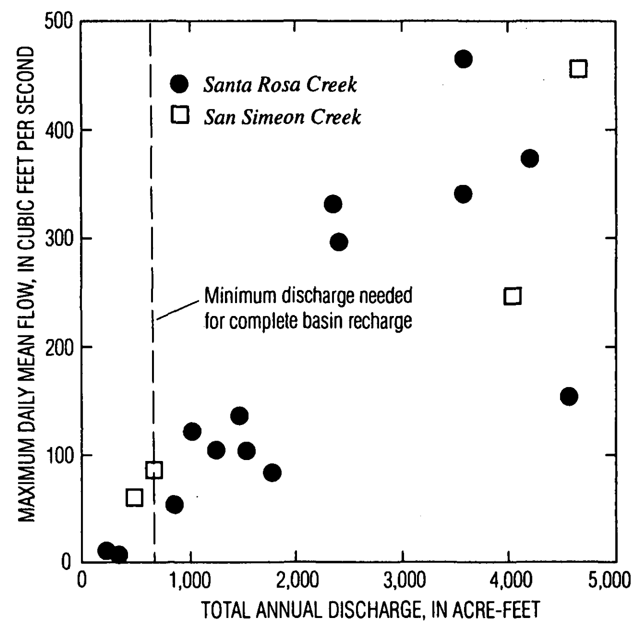


Figure 29. Relation of maximum daily mean flow and annual discharge in Santa Rosa and San Simeon Creeks, San Luis Obispo County, California.

was about one-half that amount, although much of the flow probably was reemerging base flow derived from ground water in the basin rather than through flow of water from the upstream gaging station. In 1977, there was no flow at the downstream gaging station even though discharge at the upstream gaging station was only 25 percent less than in 1976. Because of the variability in the daily sequence of streamflow, annual stream discharge is a good but not perfect indicator of ground-water recharge in dry years.

Successive Winters with Incomplete Recharge

Given that the consequences of even a single winter with incomplete recharge can be fairly severe, the consequences of two successive winters with incomplete recharge could be devastating. The likelihood of this occurrence would be an important factor in designing water storage facilities. Annual stream discharge was tested for serial correlation to determine whether amounts in 1 year are related to amounts in the following year. The 1-year serial correlation coefficients of annual discharge at the upstream gaging stations on Santa Rosa and San Simeon Creeks are less than 0.07, which is not significant according to the a test developed by Anderson (1962). This indicates that the probability of an exceptionally dry year can be assumed to be the same each year and to be independent of streamflow during the previous year.

The periods of record for streamflow in Santa Rosa and San Simeon Creeks are both fairly short for accurate estimation of serial correlation. However, the 120-year record of annual rainfall at San Luis Obispo also does not indicate significant serial correlation. Consequently, the probability of 2 successive years of incomplete recharge is the product of their individual probabilities, or about 0.0028 for Santa Rosa Creek and 0.0014 for San Simeon Creek. These probabilities correspond to recurrence intervals of about 360 and 730 years, respectively. Similarly, the recurrence intervals of 2 successive years of zero discharge are about 1,370 and 1,225 years.

The 400-year tree-ring record analyzed by Michaelson and others (1987) shows a small amount of serial correlation, even after correcting for a large correlation effect related to tree-growth processes. They defined an extremely dry year as having a probability of 0.1 and calculated that the probability of 2 extremely dry years in a row is 0.017. This probability is 1.7 times greater than if there were no serial correlation. If annual stream discharge exhibited the same degree of serial correlation as extremely dry years in the tree-ring record, the recurrence interval for 2 successive years with incomplete recharge would be about 210 years for Santa Rosa Creek and about 430 years for San Simeon Creek.

The driest 2-year drought in the streamflow record was in 1976–77. Average annual rainfall at San Luis Obispo for those 2 years was 13.61 in., which was the sixth driest 2-year period in rainfall record. The driest 2-year period in rainfall record was in 1898–99, which had an average annual rainfall of 12.23 in. This average is greater than the amount of rainfall in the 11 driest single years. Basin recharge would have been complete in at least 1 year of every 2-year drought since 1870. Similarly, 1987–90 was the sixth driest 4-year period since 1870, with an average rainfall of 16.16 in. In summary, recent multiple-year droughts have not been particularly severe, and 2 or more consecutive years of incomplete basin recharge are not likely to occur more often than once in 100 years or more.

Evaluation of Water-Resources Management Alternatives

To help resolve concerns and questions expressed by citizens and public agencies responsible for managing local water resources, ground-water-flow models were used to evaluate the effects of four water-resources management alternatives. The first simulation was of fully irrigated conditions, which could occur as the combined result of management decisions made by individual farmers. The final three simulations explored alternatives that could be pursued by CCSD to augment the municipal water supply under normal or drought conditions.

Increased Agricultural Water Use

The quantity of water available for municipal use could decrease if there were an increase in agricultural water use. Increased agricultural pumping could result from an increase in irrigated area, an increase in cropping intensity, or a conversion to crops with greater irrigation requirements. Hypothetical water-intensive cropping patterns were developed for both basins by modifying the actual cropping patterns of 1988–89. Irrigated crops were substituted for nonirrigated ones and extended fallow periods were filled with additional irrigated crops. Numerous fields throughout both basins were affected by these changes. The number and size of fields were not changed. Many of the irrigated crops presently grown already have moderate or high water requirements, and this crop mix was assumed to continue. Short fallow periods were retained in the hypothetical data set. Overall, the hypothetical cropping pattern and its irrigation requirements represent a high but plausible agricultural water demand.

Agricultural pumping requirements for the hypothetical cropping patterns were estimated using the soil-moisture budget algorithm. These estimates were greater than actual pumpage during 1988–89 by 310 acre-ft (35 percent) in the Santa Rosa Basin and by 120 acre-tt (26 percent) in the San Simeon Basin. The hypothetical pumping rates were substituted into the calibrated simulations for the 1988–89 period by increasing the pumpage at existing wells serving the fields where irrigation demand increases. Municipal pumpage was not changed. In both basins, about 37 percent of the pumpage increase was offset by irrigation-return flow. In the Santa Rosa Basin, almost all the remainder was balanced by an increase in net seepage from the creek. In the San Simeon Basin, the remainder was balanced by increased rainfall recharge, increased net seepage from the creek, and decreased underflow to the ocean. Net storage also increased slightly because of additional irrigation-return flow in the Van Gordon Creek area. Overall, increased agricultural pumpage increased the cumulative dry-season storage deficit and consequently decreased the recurrence interval of a year with incomplete recharge (from 18 to 16 years in the Santa Rosa Basin). No seawater intrusion occurred and stream discharge was sufficient to recharge the basins fully.

Increased agricultural pumping generally increased dry-season water-level declines as shown in figures 30 and 31. The amount varied locally, depending on the amount of pumpage increase at each irrigation well. In the Santa Rosa Basin, dry-season water-level declines increased as much as 10 ft near wells 27S/9E-19M3 and 27S/8E-26D1. The latter well is a municipal well, and the increased water-level decline was largely the result of irrigation at a nearby 33-acre field that was nonirrigated during 1988–89. This well is in the area where subsidence occurred in 1976. In this simulation, the water level at the end of the dry season (18 ft below sea level) was 4 ft lower than the minimum water level in 1976. This low level could result in a small amount of renewed subsidence.

In the San Simeon Basin, the increase in dry-season water-level declines was less than 3 ft in all areas along San Simeon Creek. Water levels were higher by as much as 7 ft along Van Gordon Creek.

Additional Municipal Well in the Santa Rosa Basin

During 1988–89, ground-water pumping was minimal downstream of well 27S/8E-26D1 in the lower part of the Santa Rosa Basin. Although water levels near the well declined to below sea level in 1988, water levels between the well and the coast remained above sea level. One possibility for increasing the municipal water supply would be to install an additional municipal well between well 27S/8E-26D1 and the coast. The effects of this alternative were explored by adding a new well at the present location of well 27S/8E-27G1 (fig. 2). The well arbitrarily was assumed to produce 100 acre-ft/yr, which represents a 12-percent increase in total municipal pumpage. The monthly distribution of this pumpage was assumed to be the same as the monthly distribution of municipal water use and ranged from 6.1 acre-ft in February to 11.0 acre-ft in July and August. All other model input was the same as the input for the calibrated simulation for 1988–89.

The simulated water budget indicated that 90 percent of the additional pumpage was supplied by increased net seepage from Santa Rosa Creek. The remainder was supplied equally by decreased underflow to the ocean and decreased phreatophyte transpiration. No seawater intrusion occurred. The effects of the additional well on ground-water levels are indicated by the hydrographs in figure 30. Water levels upstream of the high school (well 27S/8E-23R2) were unaffected. The minimum dry-season water level near the new well was lower by 13 ft but was above sea level between the well and the coast. The minimum dry-season water level at municipal well 27S/8E-26D1 was lower by 3 ft and was 1 ft below the historical minimum water level. A small amount of renewed subsidence could result from these low levels.

Redistribution of Treated Municipal Wastewater

If municipal wastewater were treated to higher standards, it could be used for artificial ground-water recharge in areas upgradient of the municipal wells. This would increase the quantity of water available for

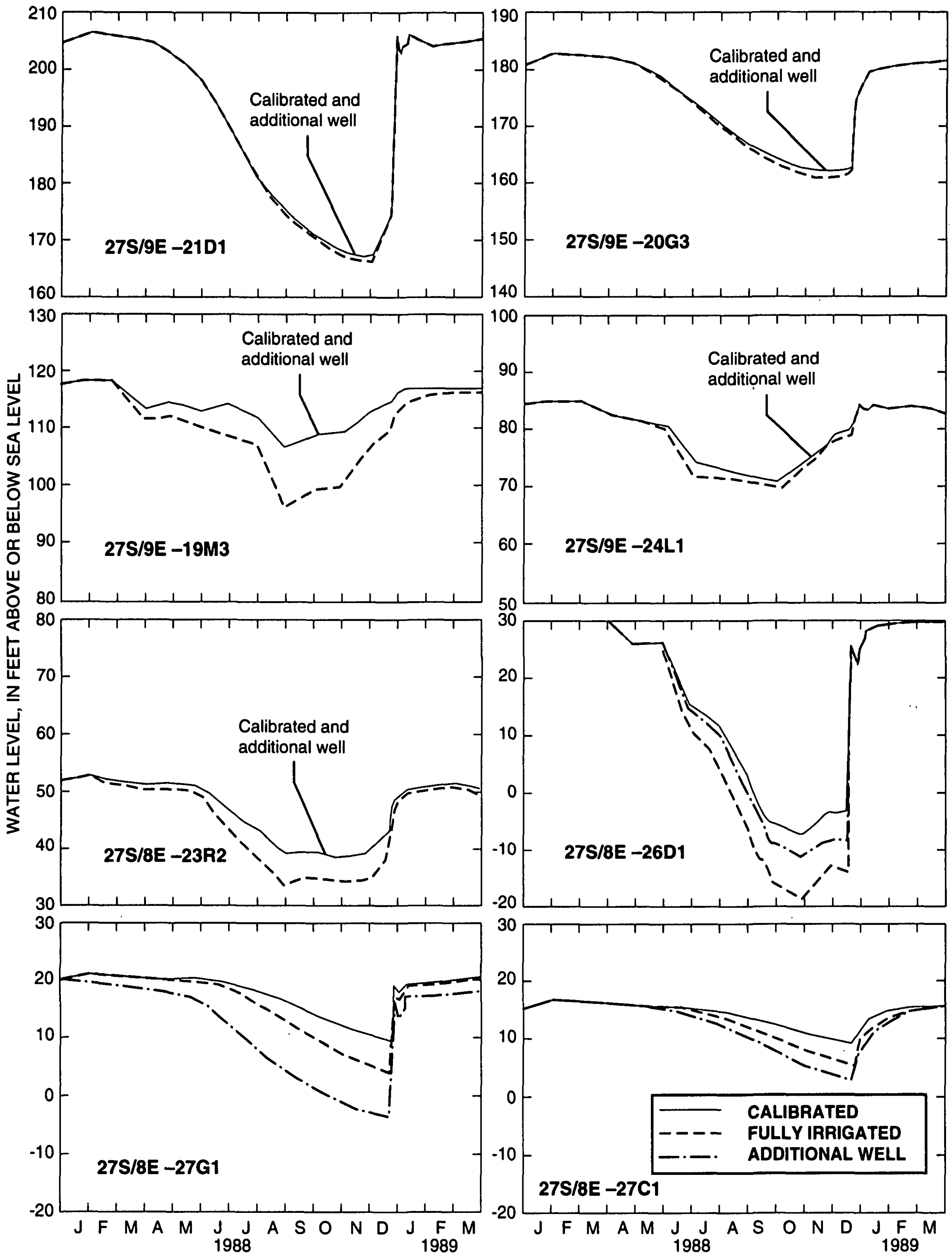


Figure 30. Effects of increased agricultural pumpage and pumpage from an additional municipal well on water levels in the Santa Rosa ground-water basin, San Luis Obispo County, California.

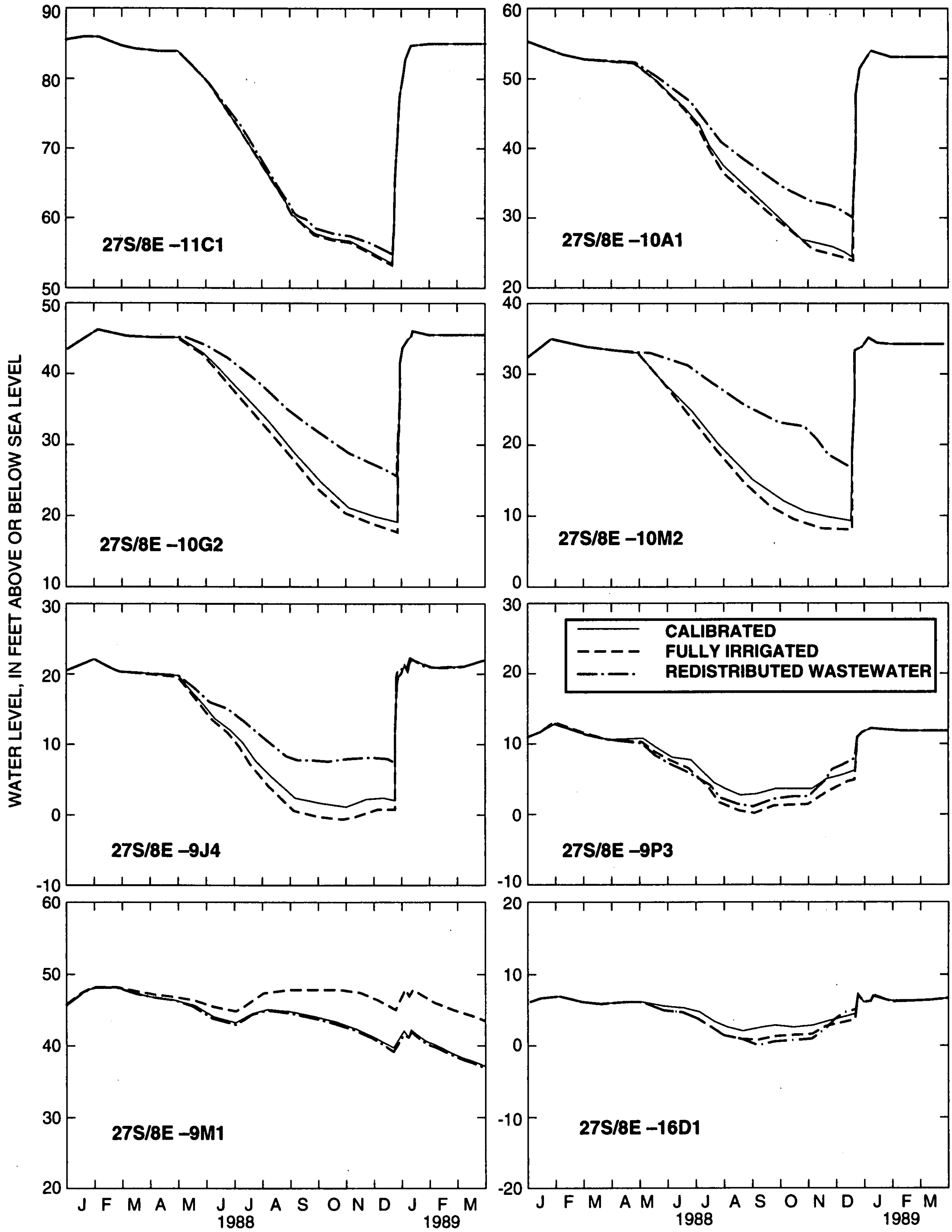


Figure 31. Effects of increased agricultural pumpage and redistributed wastewater recharge on water levels in the San Simeon ground-water basin, San Luis Obispo County, California.

municipal use during the dry season. A project has been proposed to pump ground water from the CCSD wastewater sprayfield, treat it, and deliver it to percolation ponds upstream of the CCSD well field (Steven Swanback, Carollo Engineers, written commun., September 1990). Possible locations for two off-channel percolation ponds with a combined area of 0.80 acre are shown in figure 2. A total of 270 acre-ft of ground water would be transferred at a uniform rate over a 6-month period during the dry season.

The effects of this alternative were simulated by including the proposed wells and percolation ponds in the calibrated simulation for 1988–89 and by assuming that water was transferred during the months of May through October 1988. Pumpage from the sprayfield was assumed to occur at wells 27S/8E-9N2 and 9P2. The ponds were simulated as if they were recharge wells injecting specified quantities of water into the ground-water basins. The transfer operation caused a decrease of 74 acre-ft/yr (23 percent) in ground-water outflow to the ocean, which was largely offset by a decrease of 70 acre-ft/yr (13 percent) in net seepage from the creek. However, simulated water levels in the western part of the sprayfield that declined slightly below sea level during August resulted in a small amount of seawater intrusion (2 acre-ft) during that month. In a second simulation, pumpage in the sprayfield was shifted slightly farther inland, near wells 27S/8E-9N4 and 9P3. Results were similar except that seawater intrusion did not occur.

The effect of the transfer on water levels in the San Simeon ground-water basin is shown in figure 31. Dry-season water-level declines were smaller at all wells upstream of the CCSD wastewater sprayfield. The change in cumulative decline decreased from 12 ft at well 27S/8E-10M2 (located between the two percolation ponds) to about 1 ft at the upper end of the valley (well 27S/8E-11C1). Percolation from the ponds did not create a significant water-level mound even in the first month of the dry season (May 1988). The general water-level gradient was continuously downvalley through the pond area in all months, and there was no emergent seepage into the creek near the ponds. The model grid is too coarse to determine whether water-logged soils or a small water-table mound might occur in the immediate vicinity of the percolation ponds.

Overall, the transfer of 270 acre-ft of ground water from the sprayfield area to the percolation ponds significantly decreased the amount of dry-season water-level decline upstream of the sprayfield without exceeding the capacity of the aquifer to accept or transmit the infiltrated water. A small amount of seawater intrusion occurred when transfer wells were assumed to be located near the western end of the sprayfield.

Water Marketing

The effects of a dry winter on municipal water supply during the following dry season could be lessened if farmers agreed to decrease their pumpage that year by use of a water-marketing agreement. Two simulations representing different arbitrary amounts of farmer participation were made for the San Simeon Basin. The reference simulation was a 2-year simulation of calendar years 1988 and 1989, assuming no rainfall or streamflow recharge during the winter of 1989 and no change in water use from 1988 to 1989. Water budgets and water levels for this simulation were previously described in the section on droughts.

To simulate the first level of farmer participation, agricultural pumpage was omitted for wells upstream of the CCSD well field from February through December 1989, and fields in that area were assumed to lie fallow. Agricultural pumpage in the sprayfield was assumed to be the same as in 1988. The total decrease in agricultural pumpage during 1989 was 265 acre-ft. Water levels resulting from this simulation are shown in figure 27. The largest changes were near the wells where pumping was omitted. Dry-season water-level declines were smaller by as much as 12 ft near well 27S/8E-10A1 (fig. 27*B*). This effect decreases downstream to a change of about 3 ft at the CCSD well field (27S/8E-9J4). Water levels in the CCSD wastewater sprayfield (27S/8E-9P3 and 16D1) were higher by as much as 1 ft but were still below sea level for several months during 1989. The decrease in agricultural pumping resulted in a decrease of only 14 acre-ft (29 percent) in the amount of seawater intrusion.

To simulate the second level of farmer participation, agricultural pumping during 1989 also was omitted for wells in the sprayfield area, where two wells (27S/8E-9N4 and -9P2) commonly are used to irrigate fields farther north along Van Gordon Creek. The additional decrease in agricultural pumpage during 1989 was 206 acre-ft. The resulting water levels are shown in figure 27. The additional decrease in pumpage had minimal effects upstream of the CCSD wastewater sprayfield. In the sprayfield area, however, it elevated summer water levels enough to keep them above sea level and to prevent seawater intrusion.

These simulations show that transfer of water from agricultural to municipal use by means of a water-marketing agreement could allow normal municipal pumping in the San Simeon Basin during an extremely dry year without causing seawater intrusion. The simulations also demonstrated that pumpage decreases near the coast are more effective than pumpage decreases farther inland for preventing seawater intrusion.

SUMMARY

Thin, narrow ground-water basins underlie the final 3 to 5 mi of Santa Rosa and San Simeon Creeks before the creeks reach the Pacific Ocean. The creeks are near the town of Cambria in San Luis Obispo County. The basin fill consists of unconsolidated alluvial and stream-terrace deposits. The bottoms and sides of the basins are bounded by bedrock consisting primarily of the Franciscan Complex and a Cretaceous marine sandstone. Although some ground water is stored in bedrock and transmitted through its fractures, bedrock is much less porous and permeable than the basin fill.

Basin-fill deposits are heterogeneous, with grain sizes ranging from clay to gravel. Individual layers are discontinuous, although continuity generally is greatest in the direction parallel to the valley axis. A continuous clay layer underlain by sand and gravel might exist in the Santa Rosa Basin between Coast Union High School and a point about 1 mi downstream.

Hydraulic characteristics of the basin fill were measured or estimated by several methods and were highly variable. Drawdown tests and streamflow-response tests provided estimates of transmissivity ranging from 718 to 44,200 ft^2/d and estimates of storage coefficient ranging from 0.0022 to 0.0400. Calibration of ground-water-flow models yielded estimates of hydraulic conductivity ranging from 1.6 to 400 ft/d and estimates of storage coefficient ranging from 0.045 to 0.10. The calibrated storage coefficients are more accurate for long-term storage responses (days to years) than for short-term responses. Test results and model results indicated that hydraulic conductivity generally is greatest parallel to the valley axis and that hydraulic conductivity is greater and more uniform in the San Simeon Basin than in the Santa Rosa Basin. Zones of extremely low hydraulic conductivity in the Santa Rosa Basin were used to simulate areas where subsurface flow obstructions block the normal downvalley flow of ground water and force it to emerge as surface flow in the creek. The obstructions probably are caused by buried bedrock ridges that decrease the cross-sectional area of the basin.

Ground-water levels in most parts of the basins follow a seasonal pattern of gradual decline during the summer dry season followed by rapid recovery when the creeks start flowing in winter. In most years, the basins are fully recharged within a few weeks following the onset of streamflow, and additional recharge is rejected. In exceptionally dry years, stream discharge is too small to recharge the basins fully. The most significant long-term trend in water levels has been a gradual increase in the amount of dry-season water-level decline in the San Simeon Basin. This change is the result of increases in municipal and agricultural pumpage during the dry season. Large water-level declines during longer-than-average dry seasons have caused pumping difficulties in wells at the upper ends of the basins and probably were the principal cause of subsidence near Burton Avenue in the Santa Rosa Basin.

Water-quality samples collected for this study indicated that water in San Simeon Creek is of higher quality than water in Santa Rosa and Perry Creeks. Hardness and concentrations of sodium, chloride, dissolved solids were lowest in San Simeon Creek. Connate seawater released from marine sediments decreases the quality of water in Perry Creek. The effect is smaller but measurable in Santa Rosa Creek downstream of the confluence with Perry Creek.

Similar water-quality patterns exist in ground water. Data from samples collected for this study were combined with historical data to identify five subareas of uniform water quality: the Perry Creek area and the upper and lower parts of the Santa Rosa and the San Simeon Basins. Again, concentrations of most ions were lowest in the upper San Simeon Basin. Salinity is higher in the lower basins than in the upper basins. Salinity levels were highest (1,240 to 1,520 mg/L of dissolved solids) in deep observation wells installed near the coast for this study. Salinity in the lower basins is almost certainly derived primarily from the ocean rather than from an onshore source. However, overdraft probably is not the cause of the saline water in the observation wells. In the San Simeon Basin, the saline water seems to be associated with a stable saltwater wedge that forms naturally at the base of the basin near the coast. In the Santa Rosa Basin, the observation well is too far inland and its water level is too high for the brackish water to reasonably be attributed to a natural saltwater wedge or to ground-water overdraft. The cause of the high salinity in that well is not precisely known, but probably is related to historical changes in sea level. Brief occurrences of seawater intrusion previously have been measured in the Santa Rosa and the Pico Basins. In the latter case, the intrusion almost certainly was caused by ground-water overdraft.

Salinity, hardness, and high concentrations of iron and manganese limit the use of ground water in parts of the basins. The concentration of dissolved solids in the aforementioned observation wells exceeded the maximum concentration recommended for drinking water. Concentrations of iron and manganese exceed the drinking-water standards. Available data indicate no gradual, long-term changes in ground-water quality.

Major components of the hydrologic system were investigated to develop accurate ground-water budgets. Budget items were estimated by analysis of new and existing field data. In some cases, estimates were revised during the calibration of digital ground-water-flow models developed for each basin. The three-dimensional, finite-element models each contained several hundred nodes and elements. The models were calibrated to match measured water levels and streamflow for April 1988 through March 1989. The models accounted for anisotropy in aquifer characteristics and mass balance between streamflow and ground-water flow.

Average annual rainfall increases from about 20 in. at the coast to about 26 in. at the inland ends of the ground-water basins and more than 40 in. at the headwaters of the creek drainage areas. Rainfall in 1988 and 1989 was about 71 and 62 percent of the long-term average, respectively.

Streamflow at the upper ends of the ground-water basins has been measured since 1959 on Santa Rosa Creek and since 1971 on San Simeon Creek. Both of these periods of record are wetter than average, as indicated by cumulative departures of annual rainfall in San Luis Obispo during 1870–1989. Annual discharge in Santa Rosa and San Simeon Creeks was related to annual rainfall in San Luis Obispo using ordinary least-squares regression. These relations were used to estimate long-term mean and median discharge in the two creeks. Mean annual discharge in Santa Rosa and San Simeon Creeks is 6,800 and 13,100 acre-ft, respectively. Median annual discharges are 5,700 and 10,900 acre-ft, respectively. Two years of discharge data for Perry Creek indicated that daily mean flow is on average only 18 percent as large as flow in Santa Rosa Creek. Although Santa Rosa and San Simeon Creeks usually dry up in summer, base flow is more persistent in Santa Rosa Creek.

Santa Rosa and San Simeon Creeks gain and lose water as they flow across the ground-water basins. In winter, seepage from the creeks provides the largest source of ground-water recharge. Net seepage loss rates of 20 to 40 ft^3/s between the upstream and downstream gaging stations are common during the first few weeks of streamflow. As ground-water levels rise, these rates decrease and eventually approach zero. In summer, ground water emerges into Santa Rosa Creek near well 27S/9E-19H2 and creates surface flow of several cubic feet per second along about a 2-mile reach of the creek. Both creeks gain a small quantity of water near the coast. The best estimates of annual net ground-water recharge from the creeks were obtained from the ground-water-flow models. These estimates indicated that net recharge during 1988–89 was about 470 and 540 acre-ft in the Santa Rosa and the San Simeon Basins, respectively.

Areal recharge was estimated using a soil-moisture budget algorithm that balanced daily rainfall, irrigation, runoff, evaporation, transpiration, deep percolation, and storage change in the soil zone. The algorithm was applied to 119 zones of uniform vegetation overlying the ground-water basins. Local reference evapotranspiration was estimated by comparing short-term field measurements with longer term records from other coastal stations. Both Penman and eddy-correlation methods were used. Annual reference evapotranspiration in Cambria averages about 38 in. and was several inches above average in 1988. Local temperature data confirmed that coastal fog results in lower evapotranspiration rates at the coast than at locations a few miles inland. Root depths and monthly crop coefficients were estimated for each crop and vegetation type. Areal recharge to the ground-water basins was assumed to occur whenever the cumulative amount of soil moisture exceeded the field capacity of the root zone. Areal recharge from rainfall and irrigation-return flow for April 1988 through

March 1989 totaled 460 acre-ft in the Santa Rosa Basin and 220 acre-ft in the San Simeon Basin.

Transpiration by phreatophytes is strongly affected by ground-water levels, and estimates of transpiration rates were obtained from the ground-water models. Transpiration by phreatophytes during 1988–89 was about 160 and 30 acre-ft in the Santa Rosa and the San Simeon Basins, respectively.

Agricultural pumpage and irrigation efficiency were estimated by comparing crop water demand estimated by the soil-moisture budget algorithm with measured electricity consumption by irrigation wells. Electricity consumption was converted to pumpage estimates by means of well efficiency tests. Calculated irrigation efficiencies ranged from 53 to 80 percent, with a median value of 66 percent. Agricultural pumpage from April 1988 through March 1989 was 890 acre-ft in the Santa Rosa Basin and 450 acre-ft in the San Simeon Basin.

Municipal pumpage has increased dramatically in recent decades, from 130 acre-ft in 1956 to 820 acre-ft in 1988. Curve separation of monthly municipal water use indicates that about 83 percent of the annual total is used indoors. Net unaccounted-for losses from water and sewer pipes during 1988 were less than 10 percent.

The quantity of subsurface inflow entering the ground-water basins from adjacent bedrock areas was initially estimated using soil-moisture budgets. These estimates were highly uncertain, however, and were later revised during calibration of the ground-water models. The revised estimates were 370 and 150 acre-ft/yr for the Santa Rosa and the San Simeon Basins, respectively. These rates probably do not fluctuate much seasonally or annually.

Subsurface outflow from the ground-water basins to the ocean was difficult to estimate because ground water also can reach the ocean by seeping into the lower reaches of the creeks. Calibration of the ground-water models indicated that the proportion of total outflow that occurs as subsurface outflow is larger in the San Simeon Basin than in the Santa Rosa Basin. Subsurface outflow during 1988–89 was about 60 and 320 acre-ft/yr in the Santa Rosa and the San Simeon Basins, respectively.

Net ground-water storage changes from year to year are negligible in all but extremely dry years because the creeks usually replenish the water withdrawn during the dry season.

The accuracy of the calibrated models is good, although the data used for calibration were limited to relatively dry climatic conditions and to locations near the center of the valleys. The principal limitations of the model are its inability to simulate flow in the vertical direction, its omission of effects related to the saltwater wedge near the coast, and its inability to simulate pumping water levels in wells.

The models were used to simulate the effects of pumpage, drought, and several water-resources management alternatives. The effects of pumpage were investigated in a series of simulations in which all pumpage or either agricultural or municipal pumpage were eliminated. Agricultural pumpage increases dry-season water-level declines everywhere except in the Van Gordon Creek area. In the San Simeon Basin, the effect decreases uniformly downstream from a maximum of about 10 ft. The effect is more variable (from less than 2 to 25 ft) in the Santa Rosa Basin because agricultural pumpage interacts with baseflow in the creek.

Municipal pumpage affects water levels throughout the San Simeon Basin, with effects ranging from 1 ft at the upper end of the valley to 7 ft at the CCSD well field. Municipal pumpage does not affect water levels in the upper one-half of the Santa Rosa Basin but contributes up to 33 ft of dry-season water-level decline near well 27S/8E-26D1. Even with no pumpage at all, large dry-season water-level declines occur at the upper ends of the valleys because ground water naturally drains from those areas to downvalley areas. In years with long dry seasons (such as 1988), these natural dry-season water-level declines are about 75 percent as large as declines that occur with pumping.

Three types of drought were investigated: a long dry season, a winter with incomplete basin recharge, and two successive winters with incomplete recharge. Statistical analysis of streamflow records indicated that the average duration of the dry season is about 146 days in the Santa Rosa Basin and 164 days in the San Simeon Basin. However, the streamflow record is short and spans a relatively wet period. Longer estimates of dry-season duration result if streamflow data are adjusted according to long-term rainfall patterns. Simulations of progressively longer dry seasons (up to 266 days for Santa Rosa Creek and 296 days for San Simeon Creek) indicated that with present (1988) agricultural and municipal pumping rates, dry-season water-level declines increase as much as 5 ft and dry-season storage deficits increase as much as 96 acre-ft for every additional month of dry season. These rates decrease slightly as the duration of the dry season increases. The effects on water levels are greatest near the upper ends of the basins and can cause some wells to go dry, as happened in 1988. Incremental water-level declines are not large near the coast, and seawater intrusion did not occur in any of the simulations. However, water levels decline almost to the threshold at which some subsidence could occur in the Santa Rosa Basin even during dry seasons with a recurrence interval of only 5 years.

If insufficient streamflow occurs during winter, ground-water basins will not be fully recharged. The minimum amount of stream discharge required to completely recharge the basins equals the storage deficit accumulated during the preceding dry season. In 1988, this deficit was about 660 and 500 acre-ft in the Santa Rosa and the San Simeon Basins, respectively. The likelihood that stream discharge would be less than these amounts was estimated from the probability distribution of annual rainfall and the regression equations relating annual stream discharge to annual rainfall. This procedure indicated that the recurrence interval of a year with incomplete recharge is about 18 years in the Santa Rosa Basin and 25 years in the San Simeon Basin. The recurrence interval of a winter with no streamflow at all is about 32 years for both basins. There is considerable uncertainty in these estimates, but the recurrence intervals are short enough to warrant consideration during water-supply planning.

The ground-water models were used to investigate the effects of a winter without streamflow or rainfall recharge. In the simulations, numerous wells in both basins went dry by the end of the subsequent dry season; subsidence occurred in the Santa Rosa Basin, and seawater intrusion occurred in the San Simeon Basin. These simulations probably overestimate the water-level declines because pumping was maintained at 1988 rates and was not decreased as wells went dry.

The probability of the third type of drought—two successive winters of incomplete recharge—was estimated from rainfall and tree-ring data. Records of rainfall (120 years) and tree growth rings (about 400 years) showed little or no serial correlation from year to year. Two successive years of incomplete recharge are therefore likely to occur only once in 360 years or more. Even allowing for a small amount of serial correlation, the recurrence interval probably is greater than 100 years.

The first water-resources management alternative explored with the ground-water models was the possibility of increased agricultural pumpage. Cropping patterns representing reasonable but fully irrigated conditions were devised. The corresponding increases in agricultural pumpage was 310 and 120 acre-ft (35 and 26 percent) in the Santa Rosa and the San Simeon Basins, respectively. The effect of the increase on pumpage was to increase simulated dry-season water-level declines by less than 3 ft in the San Simeon Basin and by as much as 10 ft in the Santa Rosa Basin. In the simulation, no wells went dry, but a small amount of subsidence could have occurred in the Santa Rosa Basin. The larger dry-season storage deficits in this simulation would increase the likelihood of incomplete recharge in winter.

The second alternative considered was the addition of a new municipal well near well 27S/8E-27G1. A well pumping 100 acre-ft/yr was added to the calibration simulation for this location. Pumpage from an additional well pumping 100 acre-ft/yr would increase the municipal water supply by 12 percent. The resulting minimum dry-season water level in that area was lower by about 13 ft. This level is very close to the level at which subsidence could resume. Simulated water levels between the new well and the coast remained above sea level, and there was no seawater intrusion.

The third simulated alternative was a redistribution of treated municipal wastewater in the San Simeon Basin. In this simulation, 270 acre-ft of ground water was pumped during the dry season from wells in the CCSD wastewater sprayfield. After treatment, the water was recharged to the ground-water basin by means of two percolation ponds located upstream of the CCSD well field. Results indicated that dry-season water-level declines upstream of the well field were smaller by as much as 12 ft. A small amount of seawater intrusion occurred when the extraction wells were assumed to be located toward the western end of the sprayfield, but none occurred when their locations were farther inland. There was no evidence of water-table mounding or emerging streamflow near the percolation ponds.

The final alternative was a hypothetical water-marketing agreement that would decrease agricultural water use in order to maintain municipal water use in the event of a winter with no recharge from streamflow or rainfall. The effects of omitting agricultural pumpage upstream and downstream of the CCSD well field were evaluated separately. Seawater intrusion decreased by only 29 percent when pumpage was omitted upstream of the well field. In contrast, seawater intrusion was completely eliminated when pumpage also was omitted downstream of the well field, even though the incremental pumpage change was smaller.

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