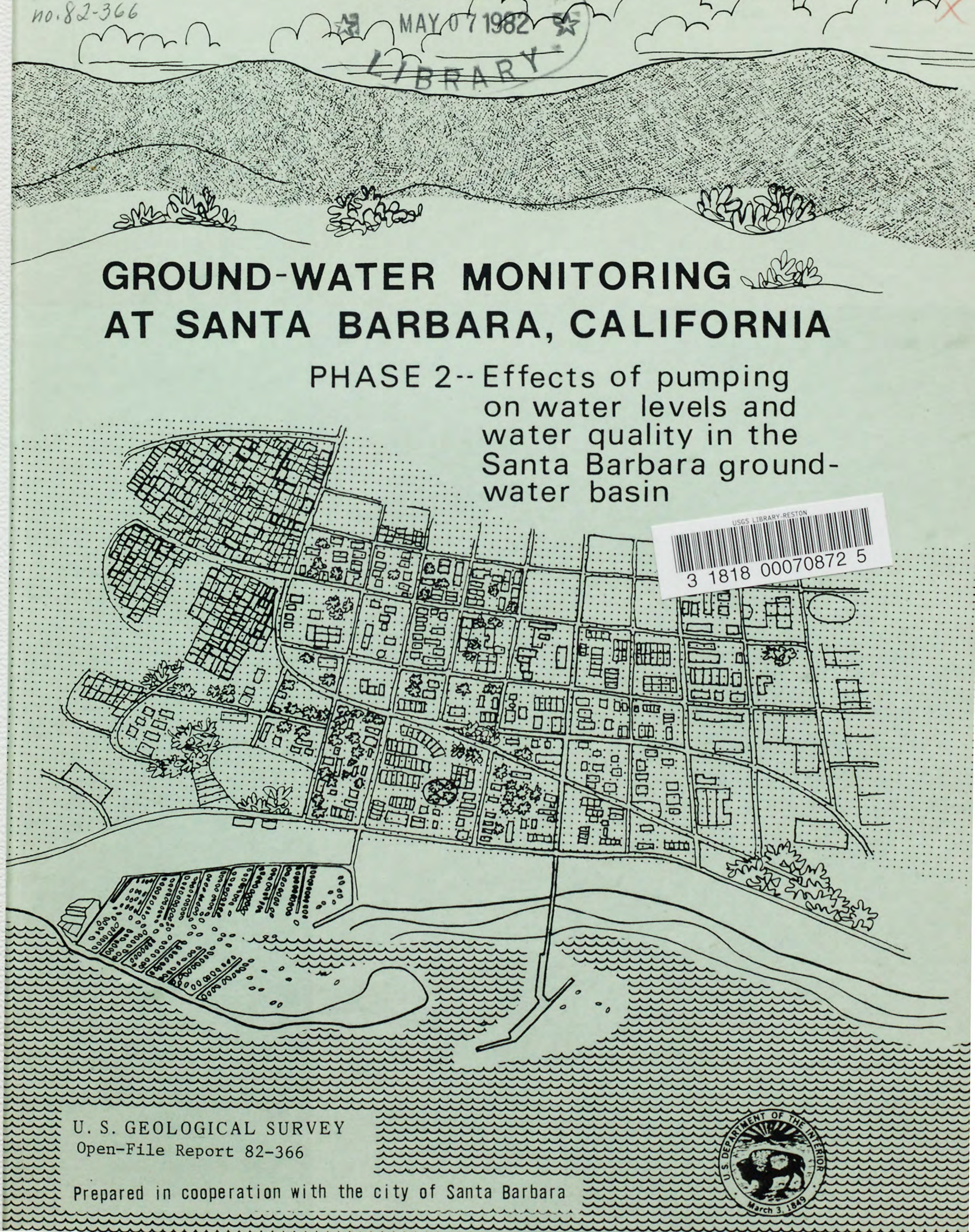

GROUND-WATER MONITORING AT SANTA BARBARA, CALIFORNIA

PHASE 2--Effects of pumping on water levels and water quality in the Santa Barbara ground-water basin

U. S. GEOLOGICAL SURVEY

Open-File Report 82-366

Prepared in cooperation with the city of Santa Barbara

GROUND-WATER MONITORING AT SANTA BARBARA, CALIFORNIA

PHASE 2--EFFECTS OF PUMPING ON WATER LEVELS AND WATER QUALITY IN THE SANTA BARBARA GROUND-WATER BASIN

By Peter Martin

U.S. GEOLOGICAL SURVEY

Open-File Report 82-366

Prepared in cooperation with the

CITY OF SANTA BARBARA

Sacramento, California
April 1982

UNITED STATES DEPARTMENT OF THE INTERIOR

JAMES G. WATT, Secretary

GEOLOGICAL SURVEY

Dallas L. Peck, Director

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Sacramento, Calif. 95825

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FIGURES

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CONVERSION FACTORS

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

Multiply	By	To obtain
acres	0.004047	km^2 (square kilometers)
acre-ft (acre-feet)	1233	m^3 (cubic meters)
acre-ft/d (acre-feet per day)	1233	m^3/d (cubic meters per day)
(acre-ft/d)/mi (acre-feet per day per mile)	766	$(m^3/d)/km$ (cubic meters per day per kilometer)
acre-ft/yr (acre-feet per year)	1233	m^3/yr (cubic meters per year)
ft (feet)	.3048	m (meters)
ft/d (feet per day)	.3048	m/d (meters per day)
ft^2/d (feet squared per day)	.0929	m^2/d (meters squared per day)
ft^3/s (cubic feet per second)	.02832	m^3/s (cubic meters per second)
Mgal/d (million gallons per day)	3785	m^3/d (cubic meters per day)
inches	25.4	mm (millimeters)
mi (miles)	1.609	km (kilometers)
mi^2 (square miles)	2.590	km^2 (square kilometers)

Abbreviations used:
- mg/L milligrams per liter
- µg/L micrograms per liter
- µmho/cm at 25°C micromhos per centimeter at 25 degrees Celsius

National Geodetic Vertical Datum of 1929 (NGVD of 1929): A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called mean sea level. NGVD of 1929 is referred to as sea level in this report.

GROUND-WATER MONITORING AT SANTA BARBARA, CALIFORNIA

PHASE 2--EFFECTS OF PUMPING ON WATER LEVELS AND WATER QUALITY

IN THE SANTA BARBARA GROUND-WATER BASIN

By Peter Martin

ABSTRACT

From July 1978 to January 1980, water levels declined more than 100 feet in the southern part of the Santa Barbara ground-water basin. The water-level declines are the result of increases in municipal pumping since July 1978. The increase in municipal pumping was part of a basin-testing program to determine the usable quantity of ground water in storage. The pumping, centered in the city less than 1 mile from the coast, has caused water-level declines in the main water-bearing zones to altitudes below sea level. Consequently, the ground-water basin is threatened with saltwater intrusion if the present pumpage is maintained or increased.

Data indicate that saltwater intrusion has degraded the quality of water yielded from six coastal wells. Chloride concentrations in the most recent samples from coastal wells ranged from about 250 to 3,800 milligrams per liter. Four of the wells yielded water with chloride concentrations in excess of 1,000 milligrams per liter.

Previous investigators believed that saltwater intrusion was limited to the shallow part of the aquifer directly adjacent to the coast. The possibility of saltwater intrusion into the deeper water-bearing deposits in the aquifer was thought to be remote because an offshore fault truncates these deeper deposits against consolidated rocks on the seaward side of the fault. Results of this study indicate, however, that ocean water has intruded into the deeper water-bearing deposits to a much greater extent than in the shallow part of the aquifer. Apparently the offshore fault is not an effective barrier to saltwater intrusion.

No physical barriers are known to exist between the coast and the municipal well field. Consequently, if the pumping rate maintained during the basin-testing program is continued, the degraded water present along the coast could move inland and contaminate the municipal supply wells. The time required for the degraded water to move from the coast to the nearest supply well was estimated using Darcy's equation to be about 20 years.

Management alternatives to control saltwater intrusion in the Santa Barbara area include (1) decreasing municipal pumping, (2) increasing the quantity of water available for recharge by releasing surplus water from surface reservoirs to Mission Creek, (3) artificially recharging the basin using injection wells, and (4) locating municipal supply wells farther from the coast and spacing them farther apart to minimize drawdown. Continued water-level and water-quality monitoring would allow assessment of the effectiveness of the management alternatives.

INTRODUCTION

Most of the water supply for the city of Santa Barbara is imported from surface reservoirs with ground water being used as a supplemental source. Decreasing efficiency of surface reservoirs because of siltation and increasing water demands due to population growth, however, have placed increasing stress on the resources of the Santa Barbara ground-water basin. On the basis of recommendations of an engineering report (Owen, 1976), the city increased ground-water pumping in the basin to determine the usable quantity of ground water in storage. The supply wells are centered in the city less than 1 mi inland from the coast. In this part of the basin, water levels which were above sea level in 1978 are now as low as 84 ft below sea level. Because the supply wells are near the coast, the ground water of the Santa Barbara area is threatened with saltwater intrusion if the present pumpage is maintained or increased.

Purpose and Scope

The city of Santa Barbara entered into a cooperative study with the U.S. Geological Survey to develop and implement a ground-water monitoring program. The first phase of the program, completed in 1978 (Hutchinson, 1979), resulted in constructing eight coastal monitor wells. The wells were constructed to provide an early warning of saltwater intrusion into the freshwater aquifer at two sites along the coast. At each site, wells were installed at four different depths to permit determination of the vertical distribution of water levels and water quality. The purpose of the current phase of the program is to analyze and evaluate the effect of ground-water pumping on the water levels and water quality of the ground-water basin. The third and final phase of the program will be to develop a digital flow model for the ground-water basin. Such a model would help in defining the hydrology and in managing the water resources of the basin. Implementation of this phase will be decided at a later date.

The current phase of the program includes:

1. Describing the geohydrology of the Santa Barbara ground-water basin, with particular reference to the water-bearing deposits, the quantity of recharge to and discharge from the basin, and ground-water levels and movement.

2. Describing the vertical variations of ground-water quality in the basin.

3. Determining the effect of pumping on water levels and water quality in the ground-water basin.

Description of the Area

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

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

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

Previous Investigations

Several reports relating to the geology and water resources of the Santa Barbara ground-water basin have been published. The first comprehensive water-resources investigation was completed by Muir (1968), who described the geology and storage capacity of the basin. Subsequent investigators have generally accepted the findings of Muir's report.

The consulting firm of Brown and Caldwell (1973) updated the geohydrology of the basin. Transmissivity and storage characteristics of the basin were calculated for this study. An aquifer simulation model was constructed to provide estimates of ground-water levels for various basin operating conditions. The design criteria developed for two city of Santa Barbara production wells were presented in the report.

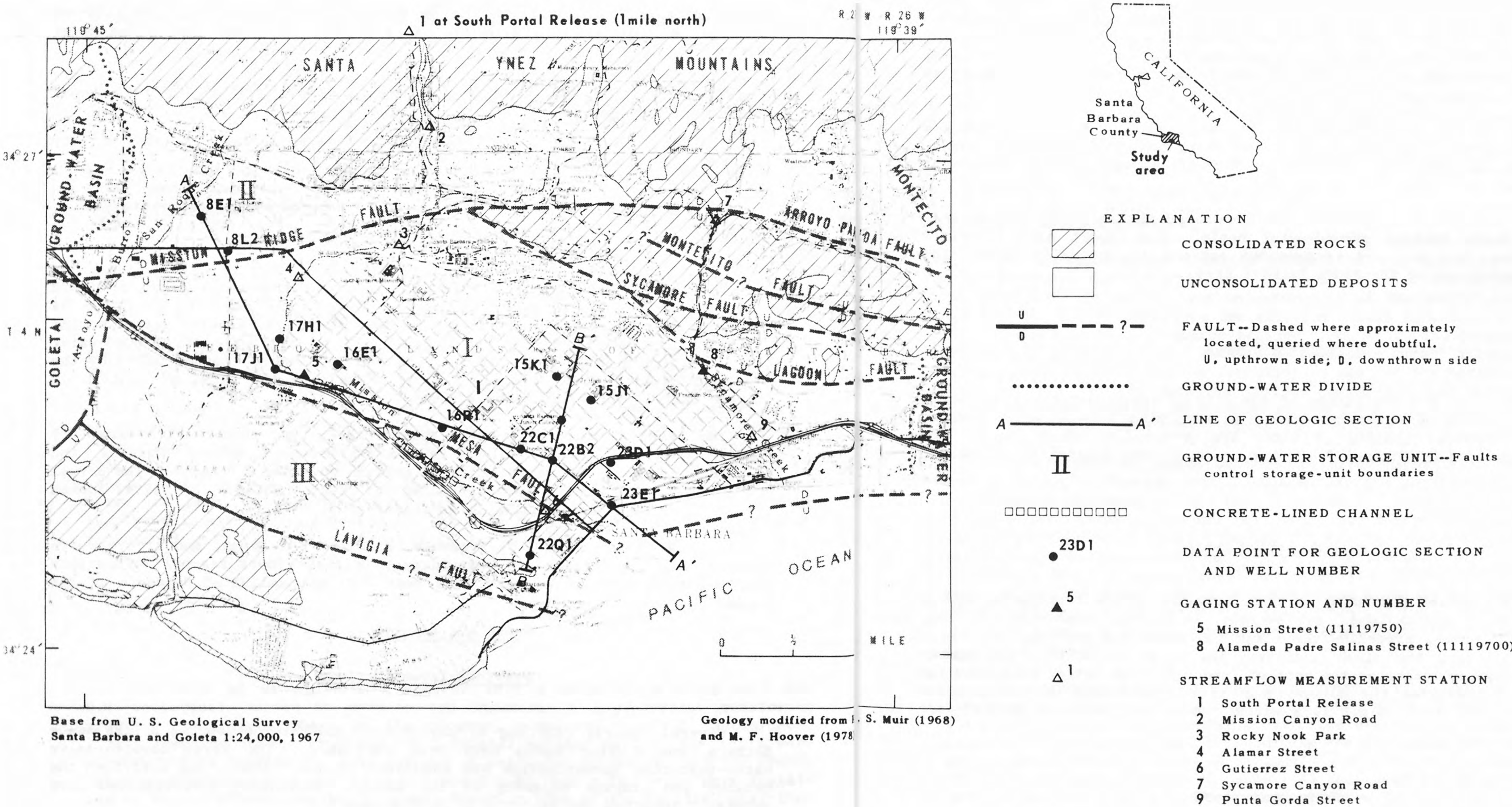


FIGURE 1.--Geology and streamflow stations of the Santa Barbara ground-water basin.

The consulting firms of Toups (1974) and Owen (1976) furnished reports on the optimal management of the water resources in the Santa Barbara area. Toups (1974) discussed the feasibility and cost estimates for artifical recharge of ground water. Owen (1976) evaluated 11 alternative concepts for meeting future water-supply needs. On the basis of this report the city of Santa Barbara increased ground-water pumping to determine the usable quantity of ground water in storage.

A report by the Santa Barbara County Water Agency (1977) included a section on the ground-water resources of the Santa Barbara ground-water basin. In this report the hydrologic findings of Muir (1968) were updated to reflect 1975 conditions.

A consulting report by Todd (1978) summarized the existing ground-water data in the Santa Barbara ground-water basin. The report also described additional data required and recommended actions to optimally manage the ground-water resources of the Santa Barbara area.

Acknowledgments

The cooperation and assistance of the city of Santa Barbara Public Works Department, Division of Water Resources, in supplying data on water levels, pumpage, and chemical quality of water are gratefully acknowledged. The information provided by Michael F. Hoover, a consulting geologist, is greatly appreciated.

Well-Numbering System

Wells are numbered according to their location in the rectangular system for subdivision of public land. For example, in the well number 4N/27W-14Q1, the part of the number preceding the slash indicates the township (T. 4 N.); the number following the slash indicates the range (R. 27 W.); the number following the hyphen indicates the section (sec. 14); the letter following the section number indicates the 40-acre subdivision according to the lettered diagram below. The final digit is a serial number for wells in each 40-acre subdivision.

D	C	B	A
E	F	G	H
M	L	K	J
N	P	Q	R

Definition of the Aquifer System

For this report the lithologic units mapped by Dibblee (1966) and Muir (1968) were generalized in the Santa Barbara area into consolidated rocks and unconsolidated deposits. Figure 1 shows the outcrop pattern of the formations and figure 2 shows the stratigraphic and structural relations.

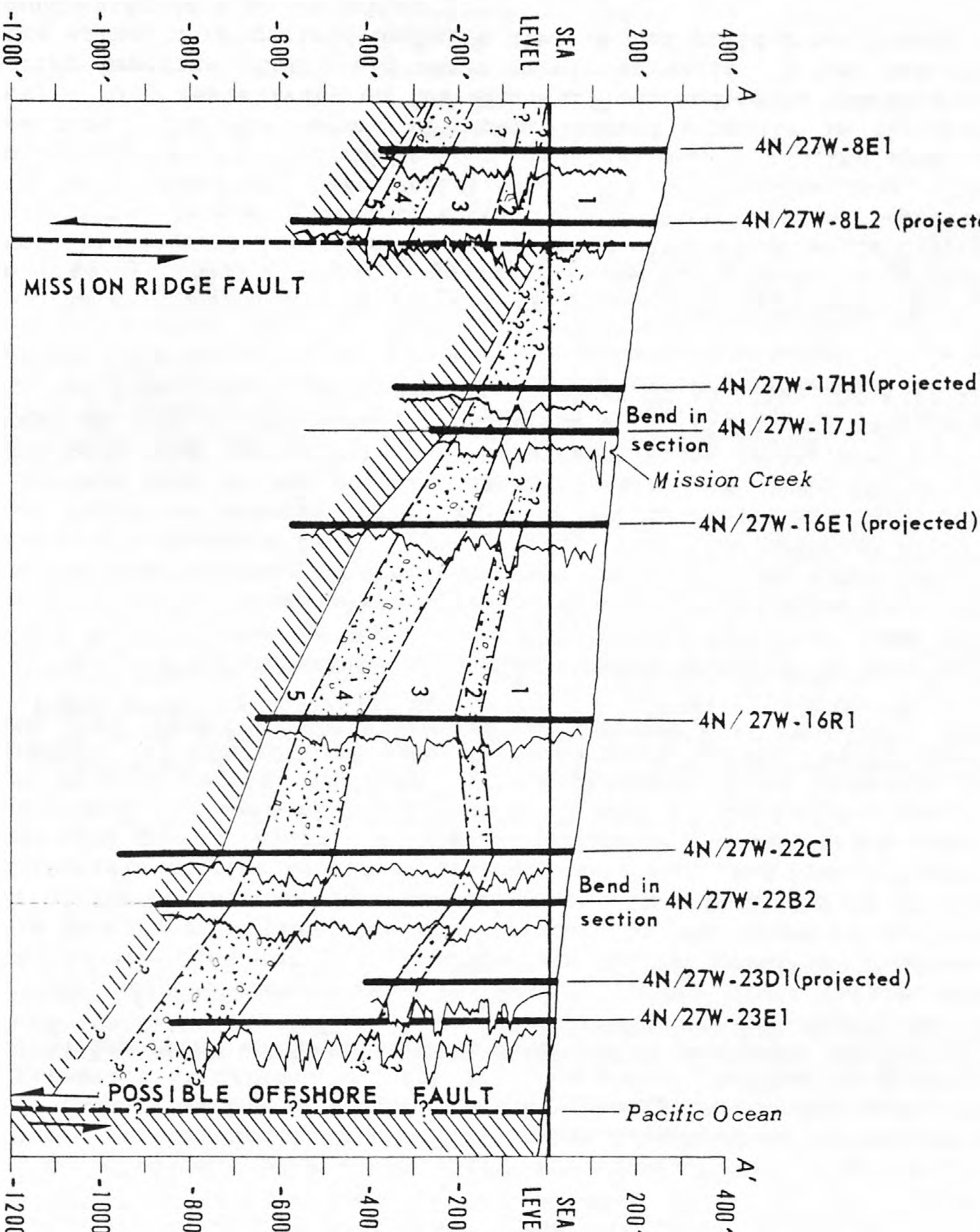
Consolidated rocks of Tertiary age underlie the ground-water basin and compose the surrounding hills. The consolidated rocks are sedimentary rocks, predominantly marine in origin, that are nearly impermeable except for slightly permeable sandstones and for fracture zones. Neither is generally considered an important source of ground water.

The unconsolidated deposits consist of the Santa Barbara Formation of late Pliocene and early Pleistocene age and alluvium of Holocene age. The Santa Barbara Formation lies unconformably on the consolidated rocks and, in most of the basin, underlies the alluvium. This formation is of marine origin and consists of fine to coarse-grained sand, silt, and greenish-gray clay with occasional gravel layers. A layer of permeable, fossiliferous sand and gravel occurs near the base of the formation in most of the basin. The alluvium, as used in this report, includes terrace deposits, older alluvium, and younger alluvium. It consists of poorly sorted sand, gravel, silt, and yellowish-brown clay, with occasional cobbles and boulders.

The greatest thickness of unconsolidated deposits is more than 1,000 ft and is found in Storage Unit I adjacent to the northeast side of Mesa fault near the Pacific Ocean. From here the unconsolidated deposits in Storage Unit I become progressively thinner northwest toward Mission Ridge fault and northeast toward Sycamore fault. On the south side (the upthrown side) of Mission Ridge fault the unconsolidated deposits are probably less than 300 ft thick. In Storage Unit II the unconsolidated deposits are about 700 ft thick on the north side (the downthrown side) of Mission Ridge fault, then become progressively thinner to the north. In Storage Unit III the unconsolidated deposits are less than 100 ft thick near the Pacific Ocean, then increase in thickness to the northwest.

The unconsolidated deposits vary greatly in lithology, both vertically and areally. The electric logs of selected wells shown in figure 2 and the lithologic logs of six recently constructed observation wells presented in the supplemental data were used to subdivide the unconsolidated deposits into five main zones based on these variations: (1) The shallow zone, (2) the upper producing zone, (3) the middle zone, (4) the lower producing zone, and (5) the deep zone. For the saturated unconsolidated deposits in the Santa Barbara area, a high resistivity on the electric logs indicates coarse-grained water-bearing deposits that yield water freely to wells. A low resistivity indicates either fine-grained deposits that do not yield water freely to wells or ground water of high salinity.

The shallow zone includes the alluvium from land surface to the top of the upper producing zone. Water-bearing deposits are present in the shallow zone but are continuous only for short distances. Fine-grained deposits present in the shallow zone confine or partly confine the underlying upper producing zone throughout most of the basin.


A
A'
400'
200'
SEA LEVEL
-200'
-400'
-600'
-800'
-1000'
-1200'
4N/27W-8E1
4N/27W-8L2 (projected)
MISSION RIDGE FAULT
4N/27W-17H1(projected)
Bend in section
4N/27W-17J1
Mission Creek
4N/27W-16E1 (projected)
4N/ 27W-16R1
4N/27W-22C1
Bend in section
4N/27W-22B2
4N/27W-23D1(projected)
4N/27W-23E1
POSSIBLE OFFSHORE FAULT
Pacific Ocean
1
2
3
4
5

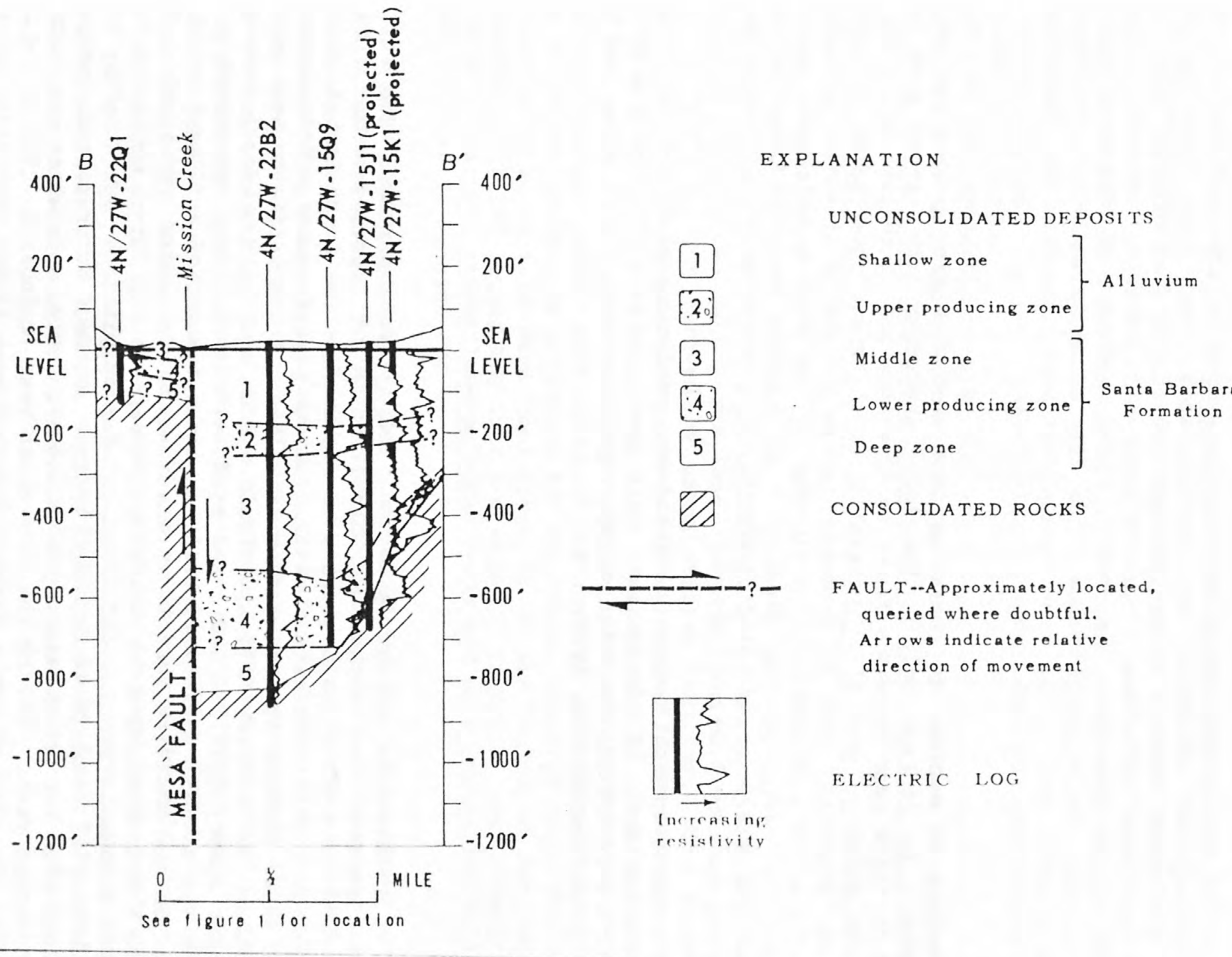


FIGURE 2.--Geologic sections of the Santa Barbara ground-water basin.

The upper producing zone near the base of the alluvium consists of medium- to coarse-grained sand with some fine gravel. This zone is about 50 ft thick and is distinct and continuous throughout most of Storage Unit I. The upper producing zone and the lower producing zone are the two main water-bearing units in the Santa Barbara area.

The middle zone underlies the upper producing zone and overlies the lower producing zone throughout most of the basin. This zone forms the upper part of the Santa Barbara Formation and consists of fine-grained deposits interspersed with occasional coarse-grained water-bearing deposits. The middle zone ranges from less than 100 ft thick southeast of Mission Ridge fault to more than 300 ft thick beneath the city of Santa Barbara. The fine-grained deposits of the middle zone confine or partly confine the underlying lower producing zone throughout most of the basin.

The lower producing zone, near the base of the Santa Barbara Formation, consists of medium- to coarse-grained sand with fine gravel and shell fragments. In Storage Unit I, the lower producing zone ranges from less than 50 ft thick near Sycamore fault to more than 200 ft thick beneath the city of Santa Barbara, generally increasing in thickness from north to south. The lower producing zone is probably the major source of water to wells in the Santa Barbara ground-water basin due to its greater thickness compared with the other water-bearing deposits. An aquifer test conducted by Brown and Caldwell (1973, p. 65) indicated that the transmissivity of the lower producing zone is 1,090 ft^2/d.

The deep zone separates the lower producing zone from the consolidated rocks in most of the basin. This zone consists of fine-grained deposits reportedly containing water of poor quality (Muir, 1968; Brown and Caldwell, 1973; and Hutchinson, 1979).

Recharge

Infiltration of precipitation, seepage from streams, subsurface inflow from consolidated rocks, and infiltration of imported water from surface reservoirs are the main sources of recharge to the Santa Barbara ground-water basin. Muir (1968) estimated the average yearly recharge contributed by each of these sources for the period 1868-1964. These estimates were reviewed and updated to reflect 1975 hydrologic conditions by the Santa Barbara County Water Agency (1977). The results of both studies are summarized in table 1. The two studies differ primarily in the estimates of infiltration of precipitation and infiltration of imported water. Increased urbanization in recent years was considered by the Santa Barbara County Water Agency to reduce the area available for the infiltration of precipitation, and thereby reduce the quantity of recharge contributed by this source. Water demands have increased along with the urbanization growth; consequently, more water has been imported in recent years. During the 1976 water year (October 1, 1975 to September 30, 1976) the city of Santa Barbara imported over 15,000 acre-ft/yr of water from surface reservoirs (Santa Barbara County Water Agency, 1977). Although most of the imported water is a piped supply which, after use, is discharged to the ocean as sewage, the Santa Barbara County Water Agency (1977) considered the imported water used for irrigation and lawn watering to be a significant source of recharge in 1975.

TABLE 1. - Average annual recharge in the Santa Barbara ground-water basin

[From Todd (1978, p. 43)]

Recharge source	Estimated recharge amounts, acre-feet per year	
	Muir for the period 1868-1964	Santa Barbara County Water Agency for 1975 conditions
Rainfall infiltration	1,100	900
Stream seepage	500	500
Subsurface inflow	300	300
Imported water from surface reservoirs	100	800
	2,000	2,500

Seepage loss from streams is usually estimated from the decrease in streamflow between two gaging stations; however, the seepage loss estimates shown in table 1 were derived by using indirect methods. Muir's estimate (1968, p. A19) of seepage loss assumed that seepage from streams averaged about 14 percent of the basin runoff. For the purposes of this study, streamflow was measured between successive gaging stations on Mission Creek and Sycamore Creek to assess more directly the seepage loss from streams in the basin and to determine the potential for artificial recharge along the streams. All losses in streamflow were considered to be the result of seepage loss. The locations of the gaging stations are shown in figure 1. Measurements were made both on natural streamflows in both creeks and on a controlled release of reservoir water to Mission Creek.

The data collected during the controlled release of imported water to Mission Creek are probably the most reliable because the streamflow was held at a nearly constant rate and little, if any, surface runoff was added to the streamflow. The controlled release lasted for 8 days, from September 24, 1979, to October 1, 1979. Average streamflow measurements made along Mission Creek on two consecutive days of the controlled release are shown in table 2. The measurements indicate that seepage loss was not significant until the streamflow passed over Mission Ridge fault near the Rocky Nook Park streamflow station (fig. 1). Consolidated rock and relatively impermeable clay layers beneath the stream channel precluded significant seepage losses upstream from the Mission Ridge fault. During the controlled release, small gains in streamflow between the Mission Canyon Road and Rocky Nook Park streamflow stations were probably the result of irrigation runoff.

TABLE 2. - Streamflow measurements for Mission and Sycamore Creeks

Streamflow measurement station (see fig. 1)	Streamflow ft^3/s	Streamflow acre-ft/d	Gain (+) or loss (-) of streamflow between stations (acre-ft/d)	Flow distance between stations (mile)	Rate of gain (+) or loss (-) of streamflow between stations [(acre-ft/d)/mi]
Controlled Release to Mission Creek Average Measurements--September 27 and 28, 1979					
South Portal Release	3.46	6.86	--	--	--
Mission Canyon Road	3.24	6.43	-0.43	1.61	-0.27
Rocky Nook Park	3.72	7.38	+.95	.85	+1.12
Alamar Street	2.84	5.63	-1.75	.85	-2.06
Mission Street	2.10	4.17	-1.46	.95	-1.54
Gutierrez Street	1.13	2.24	-1.93	1.85	-1.04
Natural Streamflow in Sycamore Creek--February 15, 1979					
Alameda Padre Salinas Street	1.20	2.38	--	--	--
Punta Gorda Street	1.53	3.03	+0.65	0.76	+0.86
Natural Streamflow in Sycamore Creek--January 21, 1980					
Sycamore Canyon Road	0.45	0.89	--	--	--
Alameda Padre Salinas Street	.45	.89	0	1.04	0
Punta Gorda Street	.28	.56	-.33	.76	-.43

The greatest rates of seepage loss were measured between Rocky Nook Park and Alamar Street streamflow stations (2.06 [acre-ft/d]/mi) and between Alamar Street and Mission Street streamflow stations (1.54 [acre-ft/d]/mi). The average rate of seepage loss for this entire 1.8-mile reach of the stream is 1.78 (acre-ft/d)/mi. One possible explanation for the higher seepage loss rates downstream of Rocky Nook Park is that the clay layers that exist beneath the stream channel on the north side of the Mission Ridge fault are absent or less extensive south of the fault. The clay layers may have eroded because of the upward displacement of the deposits on the south side of the fault. Observation wells are needed between Rocky Nook Park and Alamar Street to determine the geohydrology in this part of the basin. Downstream from the Mission Street station much of the stream channel is lined with concrete (fig. 1); consequently, seepage loss rates are significantly reduced in this reach of the stream, averaging only 1.04 (acre-ft/d)/mi. Seepage loss measurements made for natural streamflow in Mission Creek are, in general, similar to the values recorded during the controlled release. Unmeasured surface runoff flowing into the stream, however, causes variability in the data.

Estimates of the annual recharge contributed by seepage losses of natural streamflow along Mission Creek, and estimates of potential recharge from controlled releases to the stream are shown in table 3. The amount of recharge contributed by natural streamflow in Mission Creek was difficult to estimate because the amount of streamflow and the number of days of streamflow vary significantly. For the 8-year period of record, October 1970 to September 1978, flow measured at the Mission Street gage ranged from 2,580 ft^3/s to the more common condition of no flow. The number of days per year with measurable flow at the gage ranged from a low of 20 days to a high of 189 days, with an average of about 73 days over the period of record.

TABLE 3. - Estimates of annual recharge from natural streamflow and potential recharge from controlled releases along Mission Creek

Streamflow station (see fig. 1)	Average daily loss in streamflow between stations (acre-ft/d)	Estimated number of days with flow per year (d/yr)	Estimated annual recharge between stations (acre-ft/yr)
	Natural Streamflow		
Rocky Nook Park	--	73	--
Alamar Street	1.75	73	128
Mission Street	1.46	73	107
Gutierrez Street	1.93	73	141
TOTAL			376
	Controlled Release		
Rocky Nook Park	--	365	--
Alamar Street	1.75	365	639
Mission Street	1.46	365	533
Gutierrez Street	1.93	365	704
TOTAL			1,876

The annual recharge rates shown in table 3 were estimated by multiplying the seepage loss rates measured along Mission Creek during the controlled release by the average number of days of streamflow per year. This method of estimating the annual recharge rates has two main deficiencies: (1) Losses of streamflow to evapotranspiration are neglected, and (2) the variations in seepage loss rates caused by changes in the amount of streamflow are neglected. Consequently, the estimate of annual recharge shown in table 3 should only be considered as a gross estimate. For the estimation of potential recharge from controlled releases to Mission Creek, the releases were assumed to continue throughout the year at a constant rate equal to the release rate during September and October of 1979.

As shown in table 3 the recharge from natural streamflow seepage in Mission Creek is estimated at 376 acre-ft/yr, and the potential recharge of controlled releases is estimated at 1,876 acre-ft/yr. Both estimates assume that the water table remains below the elevation of the channel bottom. Thus, the release of surplus surface water to Mission Creek can be considered as a large potential source of recharge to the Santa Barbara ground-water basin. Any further lining of the channel with concrete would decrease recharge to the basin.

Seepage-loss measurements were made for natural streamflow in Sycamore Creek February 15, 1979, and January 21, 1980 (table 2). The measurements made in 1979 indicate increases in streamflow between the Alameda Padre Salinas Street station and the Punta Gorda Street station. The increase in streamflow is probably the result of unmeasured surface runoff and not ground-water discharge, because the water table is below the channel bottom. Measurements made in 1980 indicate no seepage losses upstream from the Alameda Padre Salinas Street station, where the stream flows across predominantly consolidated rocks that would preclude significant seepage losses. A small loss of about 0.33 acre-ft/d between the Alameda Padre Salinas Street station and the Punta Gorda Street station indicates that Sycamore Creek adds little recharge to the ground-water basin. Clay layers present in the upper stratigraphic profile of much of the Santa Barbara ground-water basin probably reduce the rate of seepage losses downstream from the Alameda Padre Salinas Street station. The potential for artificial recharge along Sycamore Creek is considered negligible, due to the low seepage loss rates measured along the stream.

Arroyo Burro and San Roque Creek, the other major streams in the area, were not measured for seepage losses; however, seepage losses along these streams are considered small. North of the Mission Ridge fault these streams probably overlie clay of low permeability which would preclude significant seepage losses. South of the fault most of the Arroyo Burro stream channel lies outside of the Santa Barbara ground-water basin.

Discharge

In the 1700's, prior to ground-water withdrawals from wells, discharge from the ground-water basin included streamflow, evapotranspiration, springs, and subsurface outflow. Currently, the major discharge from the basin is by pumping. The pumping has significantly lowered the water table in the Santa Barbara area. As a result, natural ground-water discharges are insignificant compared to pumpage from wells.

Ground-water withdrawals from wells began in the early 1800's to supplement local surface-water sources. Ground water is still used as a secondary water supply. During years of low rainfall, when surface water is scarce, ground-water pumping is intensified and during years of high rainfall, when surface water is abundant, ground-water pumping is reduced (Todd, 1978, p. 48). Pumpage by the city of Santa Barbara from 1947 to 1979 is shown in table 4. Pumping is variable ranging from a low of 81 acre-ft/yr in 1958 and 1959, to a high of 4,243 acre-ft/yr in 1949, with an average of 1,866 acre-ft/ yr for the 33-year period of record. Muir (1968, p. A23) estimated the perennial yield of the basin to be between 1,700 and 2,000 acre-ft/yr. Municipal pumpage has often exceeded the estimated perennial yield of the basin, as shown in table 4.

TABLE 4. - Santa Barbara pumpage, 1947-79

[Source of data: 1947-64, Muir (1968, p. A22); 1965-71, Toups Corporation (1974, p. 106); 1972-79, City of Santa Barbara (written commun., 1980)]

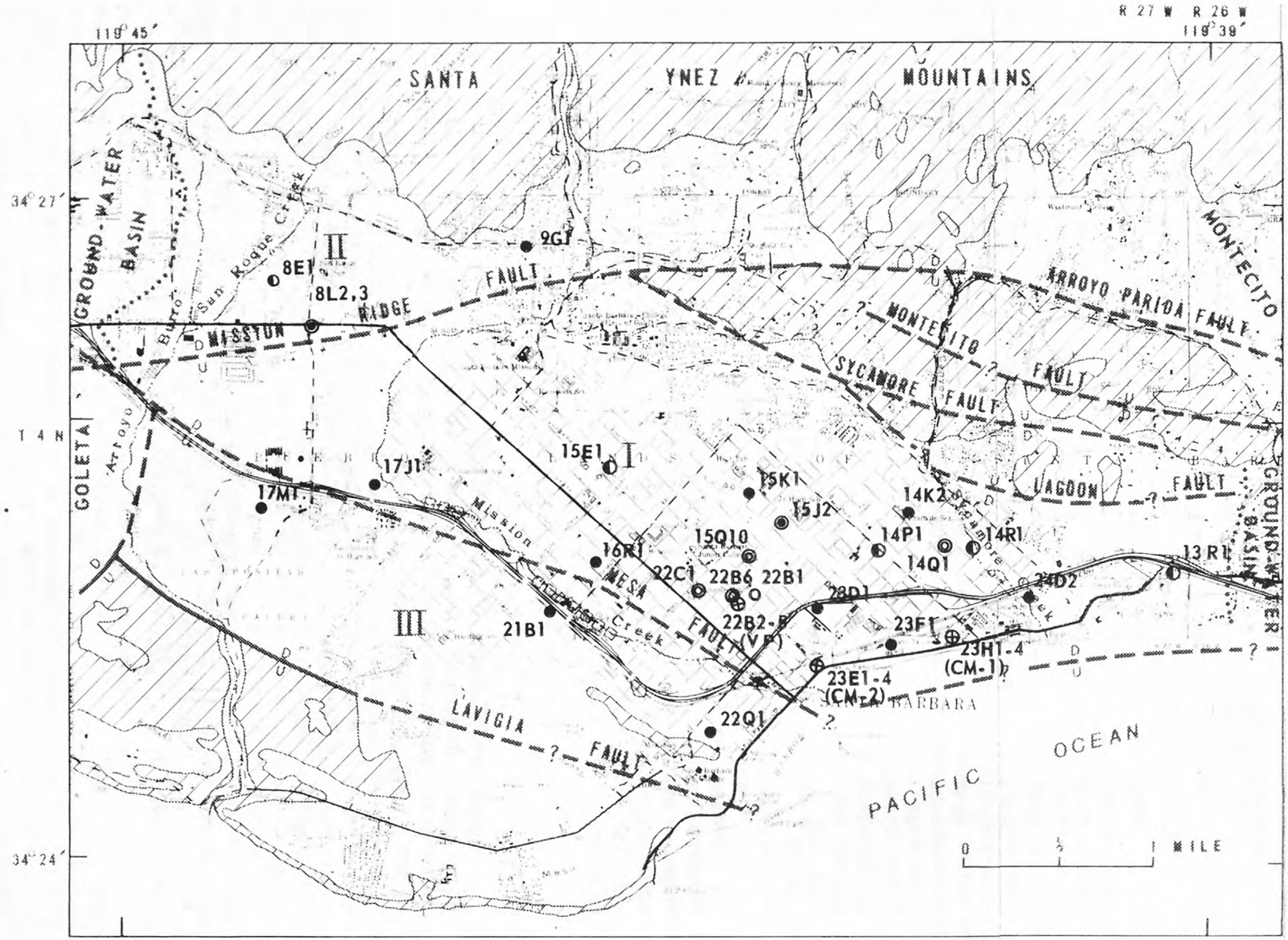
Year	Pumpage (acre-feet)	Year	Pumpage (acre-feet)	Year	Pumpage (acre-feet)
1947	336	1958	81	1969	2,890
1948	3,471	1959	81	1970	1,895
1949	4,243	1960	2,961	1971	1,138
1950	3,987	1961	2,961	1972	544
1951	2,745	1962	2,535	1973	1,031
1952	1,002	1963	2,941	1974	727
1953	1,497	1964	2,888	1975	372
1954	891	1965	3,180	1976	1,171
1955	413	1966	3,080	1977	1,919
1956	220	1967	2,310	1978	1,034
1957	1,480	1968	2,780	1979	2,760

Pumpage for domestic, agricultural, and industrial uses in the Santa Barbara area is small compared with the quantity pumped for municipal use. Nonmunicipal pumping has probably been less than 200 acre-ft/yr since 1964 (Muir, 1968).

Ground-Water Levels and Movement

Water-level measurements are made monthly at 30 wells in the Santa Barbara area. Figure 3 shows the location of the monitored wells and table 5 summarizes the construction specifications of the wells and the July 1978 and January 1980 water-level measurements.

The most significant fluctuations in water levels in the Santa Barbara area were in response to pumping from wells. Figure 4 shows water-level fluctuations in several wells that tap the upper and lower producing zones. Comparison of the water-level hydrographs to the municipal pumpage in the Santa Barbara area (fig. 4) shows how the water levels of wells in the upper and lower producing zones respond directly to changes in municipal pumpage. The upper and lower producing zones are confined or partly confined throughout most of the Santa Barbara area. Hence, the water levels in these zones respond rapidly to variations in pumping.



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

Geology modified from K. S. Muir (1968)
and M. F. Hoover (1978)

EXPLANATION

CONSOLIDATED ROCKS

UNCONSOLIDATED DEPOSITS

U / D — FAULT--Dashed where approximately located, queried where doubtful. U, upthrown side; D, downthrown side

GROUND-WATER DIVIDE

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

CONCRETE-LINED CHANNEL

MONITORING WELL AND NUMBER

15J2 — Municipal; water level and water quality

Municipal; water quality only

Water level and water quality

Water level only

Water quality only

Nested water level and water quality

(CM-1) Coastal monitor site 1

(CM-2) Coastal monitor site 2

(VP) Vera Cruz Park monitor site

FIGURE 3.--Location of water-level and water-quality monitoring wells in the Santa Barbara ground-water basin.

TABLE 5. - Water levels in monitored wells, July 1978 and January 1980

Well number	Altitude of land surface (feet)	Depth of well (feet)	Perforated interval[1] (feet)	Altitude of water level (feet)		Monitored zone[2]
				July 1978	January 1980	
			Storage Unit I			
4N/27W-13R1	38.63	540	255-540	+8.44	+6.63	Lower producing
4N/27W-14K2	42.3	380	260-380	--	-15.39	Upper producing
4N/27W-14P1	18	783	181-783	+3.94	-49.03	Lower producing
4N/27W-14R1	27.84	700	107-635	+1.96	-20.93	Lower producing
4N/27W-15E1	145	231	--	+47.40	+27.00	Lower producing
4N/27W-15J2	12.31	579	198-579	+7.38	-45.73	Lower producing
4N/27W-15K1	18.9	464	280-464	--	-39.50	Lower producing
4N/27W-16R1	84.8	625	545-625	--	-42.20	Lower producing
4N/27W-17J1	138.8	320	190-320	--	+91.20	Lower producing
4N/27W-22B2	20	230	220-230	+15.25	-47.49	Upper producing
4N/27W-22B3	20	435	425-435	+15.84	-50.44	Middle
4N/27W-22B4	20	660	650-660	+16.59	-84.15	Lower producing
4N/27W-22B5	20	780	770-780	+13.07	-55.50	Deep
4N/27W-23D1	12	380	240-380	--	-15.50	Upper producing
4N/27W-23E1	7.5	805	775-800	--	-38.73	Lower producing
4N/27W-23E2	7.5	660	600-655	--	-25.50	Middle
4N/27W-23E3	7.5	385	355-380	--	-32.95	Upper producing
4N/27W-23E4	7.5	180	150-175	--	+2.36	Shallow
4N/27W-23F1	4	500	--	+2.71	+0.37	Upper producing
4N/27W-23H1	7	781	746.5-781	--	-11.60	Lower producing
4N/27W-23H2	7	620	585.5-590.5	[3]+5.81	-1.80	Middle
4N/27W-23H3	7	310	284-299	[3]+2.12	-2.12	Upper producing
4N/27W-23H4	7	85	75.5-91	[3]+5.77	+6.25	Shallow
4N/27W-24D2	12	473	131-473	[4]+2.00	-2.65	Lower producing
			Storage Unit II			
4N/27W-8E1	251	580	52-580	--	+175.02	Lower producing
4N/27W-8L2	230	642	90-640	+179.54	+182.38	Lower producing
4N/27W-9G1	395	221	179-221	+292.28	+298.45	Lower producing
			Storage Unit III			
4N/27W-17M1	152	375	75-375	--	+126.80	Lower producing
4N/27W-21B1	68	454	145-350	+26.87	-9.40	Lower producing
4N/27W-22Q1	13	60	20-60	--	+7.18	Lower producing

[1]Depth of first and last perforation; not necessarily perforated throughout the interval.
[2]Determination of monitored zone based on well perforations and water quality.
[3]Measurement made August 16, 1978.
[4]Interpolated between April 8, 1978, and November 8, 1978, measurements.

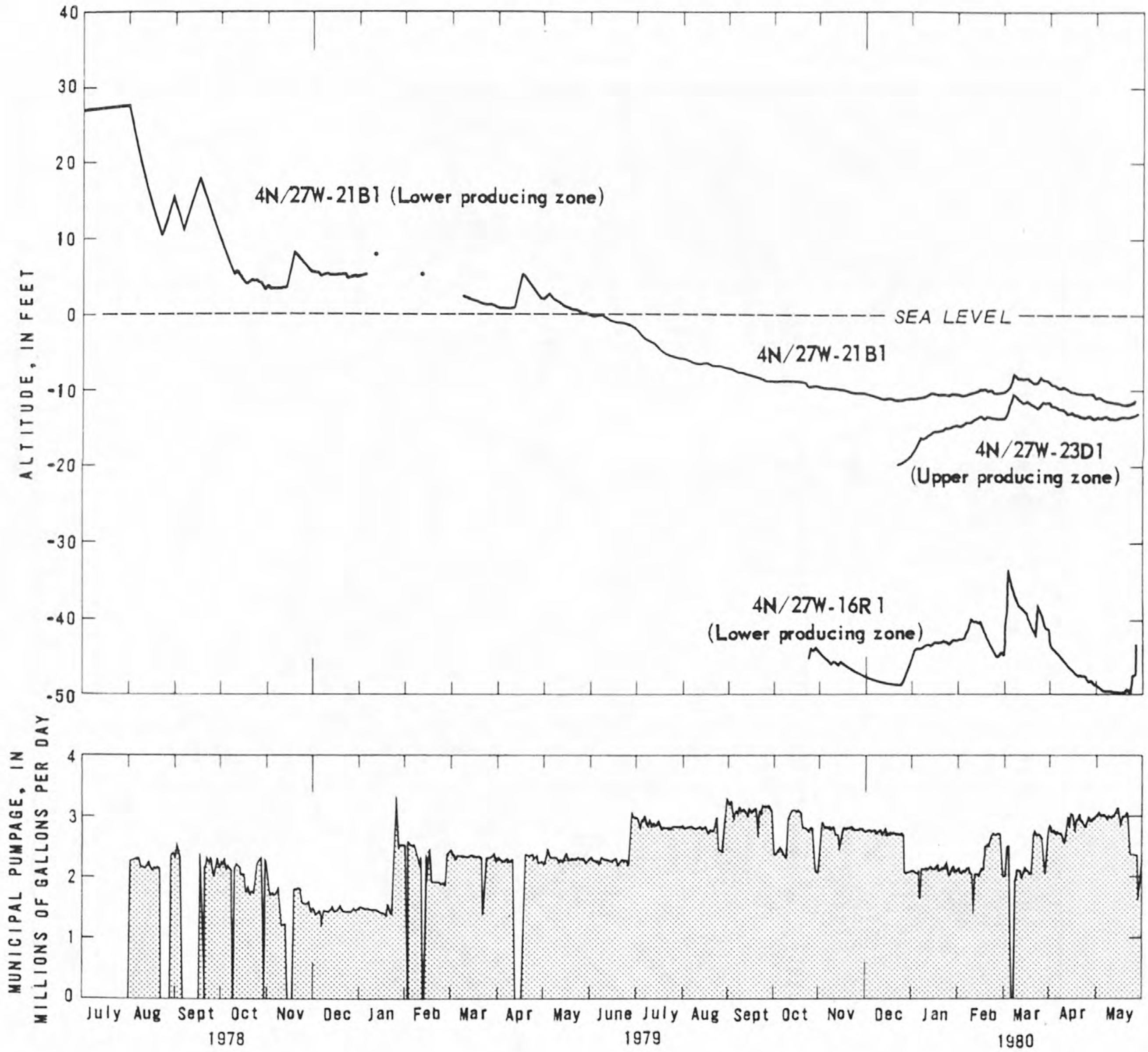
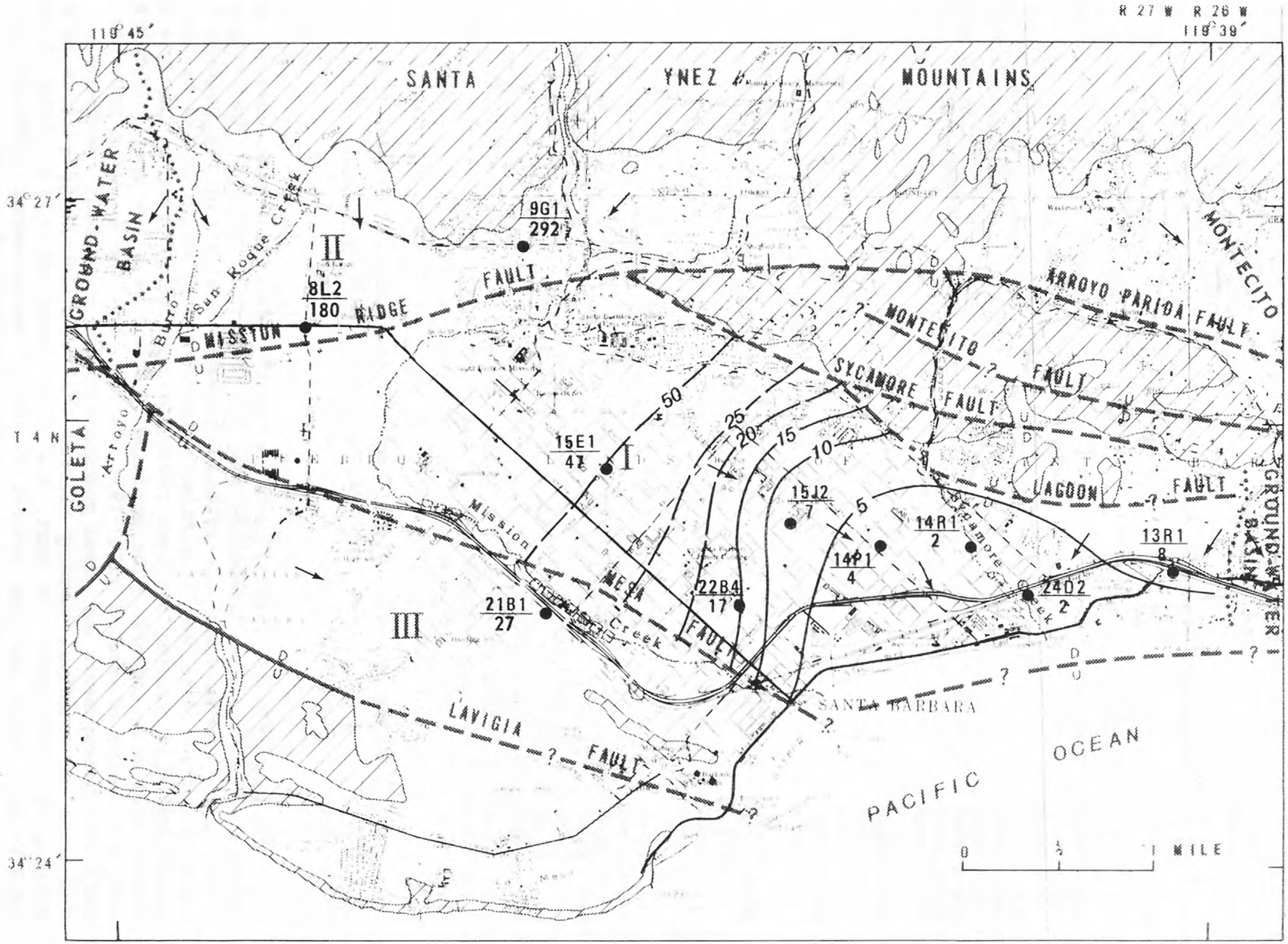


FIGURE 4.--Water-level hydrographs of selected wells and graph of municipal pumpage.

The July 1978 water-level contours constructed from measurements in wells perforated in the lower producing zone are shown in figure 5. The pattern of water-level contours in July 1978 is probably similar to the pattern that existed before there was significant ground-water pumping in the basin, because municipal pumping had been reduced significantly prior to the July 1978 water-level measurements. The municipal pumping rate averaged 5.1 acre-ft/d for the period of record (1947-79); whereas, for the 6 months prior to the July 1978 measurements municipal pumping averaged only about 1 acre-ft/d. The reduction in municipal pumping allowed the water levels to recover to near prepumping conditions. In fact, the water level of July 6, 1978, in well 4N/27W-21B1, which has the longest record of measurements (1931-80) in the Santa Barbara area, was the third highest water level of record.



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

Geology modified from K. S. Muir (1968)
and M. F. Hoover (1978)

EXPLANATION

CONSOLIDATED ROCKS

UNCONSOLIDATED DEPOSITS

U / D — FAULT--Dashed where approximately located, queried where doubtful. U, upthrown side; D, downthrown side

GROUND-WATER DIVIDE

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

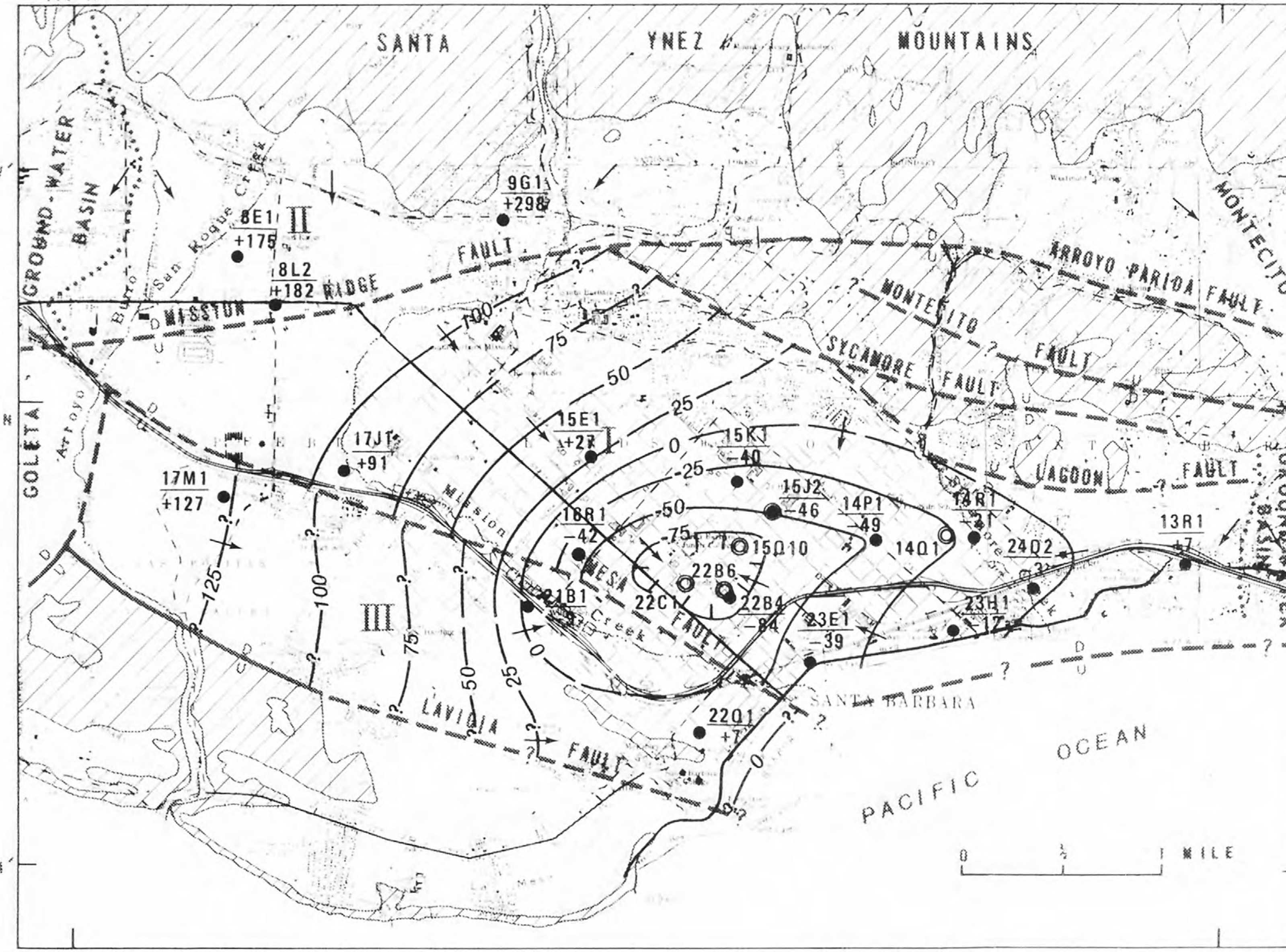
CONCRETE-LINED CHANNEL

5 — WATER-LEVEL CONTOUR--Shows altitude, in feet, of water level in wells. Dashed where approximately located. Contour interval variable. National Geodetic Vertical Datum of 1929

21B1 / 27 — DATA POINT--Top number is well number; bottom number is altitude of water level, in feet

DIRECTION OF GROUND-WATER MOVEMENT

FIGURE 5.--Water-level contours of the lower producing zone, July 1978.



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

Geology modified from K. S. Muir (1968)
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EXPLANATION

CONSOLIDATED ROCKS

UNCONSOLIDATED DEPOSITS

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

GROUND-WATER DIVIDE

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

CONCRETE-LINED CHANNEL

——25——?— WATER-LEVEL CONTOUR--Shows altitude of water level. Dashed where approximately located, queried where doubtful. Contour interval 25 feet. National Geodetic Vertical Datum of 1929

8E1 / +175 DATA POINT--Top number is well number; bottom number is altitude of water level in feet above (+) or below (−) National Geodetic Vertical Datum of 1929

15J2 / −46 DATA POINT (MUNICIPAL SUPPLY WELL) --Top number is well number; bottom number is altitude of water level in feet above (+) or below (−) National Geodetic Vertical Datum of 1929

22C1 MUNICIPAL SUPPLY WELL AND NUMBER

DIRECTION OF GROUND-WATER MOVEMENT

FIGURE 6.--Water-level contours of the lower producing zone, January 1980.

Ground-water movement in the Santa Barbara area during July 1978 was generally from the northwest toward the Pacific Ocean (fig. 5). Water levels were above sea level throughout the area and depressions related to pumping were not indicated by the ground-water-level contours.

From August 1978 through January 1980, the rate of municipal pumping increased significantly, averaging about 7 acre-ft/d. Table 5 shows the January 1980 water levels for the network wells and figure 6 is a water-level-contour map of the lower producing zone. Comparison of the January and the July 1978 maps shows significant changes in the pattern of ground-water movement. In a large part of the Santa Barbara area, water levels were below sea level during January 1980. The January 1980 contours show a distinct cone of depression related to municipal pumping near the southern part of Storage Unit I. Five municipal wells (4N/27W-14Q1, 15J2, 15Q10, 22B6, and 22C1) are in this area. The municipal pumping has reversed the water-level gradient between the pumping center and the Pacific Ocean. During July 1978, ground water generally flowed southward towards the ocean; whereas, during January 1980 ground water flowed northward away from the ocean. The January 1980 ground-water-flow pattern suggests that conditions are favorable for saltwater intrusion in the Santa Barbara area.

Water-level data from nested wells at the Vera Cruz Park monitor site and coastal monitor site 2 indicate that the hydraulic head (or water level) varies with depth (fig. 7). The Vera Cruz Park monitor site is near the center of municipal pumping, and coastal monitor site 2 is about a half mile from the closest municipal supply well (fig. 3). During July 1978, water levels measured at the wells in Vera Cruz Park indicate that the hydraulic head increased with depth except for the deep zone, which had the lowest hydraulic head. Thus, during nonpumping conditions, water moves upward from the lower producing zone to the overlying aquifer and downward from the lower producing zone to the deep zone. As recently as 1963, wells flowed in this area which were perforated opposite the upper producing zone, middle zone, and lower producing zone (Muir, 1968, p. A10). January 1980 water-level data from these same wells (fig. 7) show a reversal in the hydraulic gradient due to municipal pumping. During January 1980 the hydraulic head was lowest in the highly pumped lower producing zone, was somewhat higher in the underlying deep zone, and was highest in the upper producing zone. Consequently, water potentially can move upward from the underlying deep zone into the lower producing zone, and downward by leakage from the overlying aquifer into the lower producing zone.

At coastal monitor site 2 the water level of the shallow zone was above sea level during January 1980; however, the water levels measured in the other zones were all at least 25 ft below sea level. The high hydraulic head in the shallow zone and the significantly lower hydraulic heads in the underlying zones suggest that little hydraulic continuity exists between the shallow zone and the underlying highly pumped zones. Monitor wells at the coastal sites were not constructed until August 1978; therefore, a comparison of nonpumping conditions and pumping conditions cannot be made at these sites.

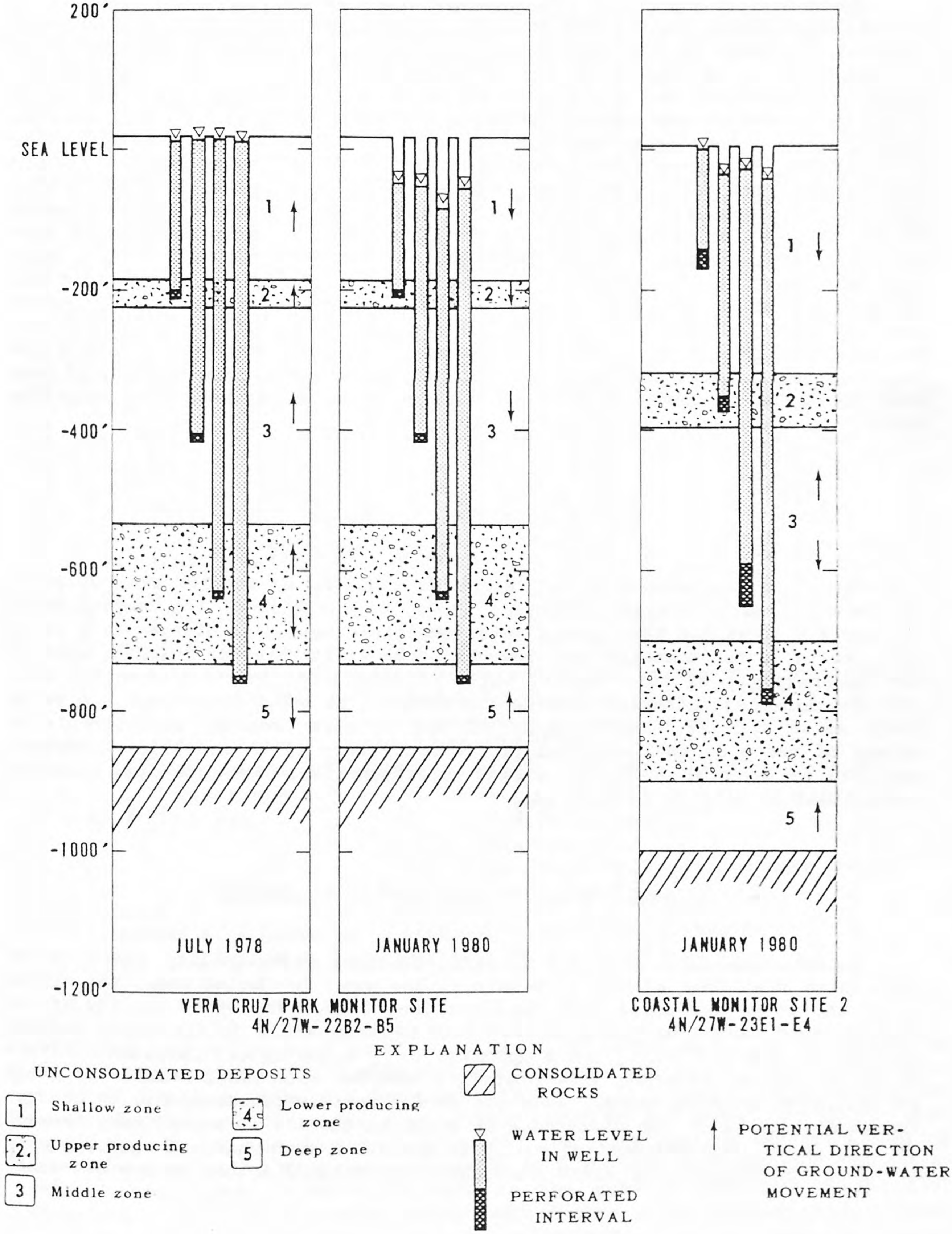


FIGURE 7.--Water levels in nested wells in the Santa Barbara area.

Sparse water-level data from Storage Units II and III (fig. 6) indicate that Mission Ridge fault and Mesa fault are partial barriers to ground-water movement at least in the lower producing zone. Water levels during January 1980 were higher on the north side of Mission Ridge fault than would be expected if the fault did not exist. Figure 2 shows that the upper and lower producing zones are not continuous across the fault. Because of the vertical displacement, ground water is probably, in effect, dammed up on the north side of the fault. The Mesa fault is probably an effective barrier to ground-water movement near the ocean where consolidated rocks are uplifted to near the land surface. Geologic section B-B' (fig. 2) shows about a 700-foot displacement between the top of the consolidated rocks on the east and west sides of Mesa fault. Water levels in well 4N/27W-22Q1, on the southwest side of the fault near the ocean, do not reflect the changes in water levels of wells on the northeast side of the fault caused by the municipal pumping; however, water levels in well 4N/27W-21B1 (fig. 4), also on the southwest side of the fault, do. Well 4N/27W-21B1 is about 1 mi northwest of well 4N/27W-22Q1, where the vertical displacement on opposite sides of the fault is less pronounced than near the ocean, a condition that might allow ground-water movement across the fault.

GROUND-WATER QUALITY

Water-quality determinations are made annually on samples from 30 wells in the Santa Barbara area. Figure 3 shows the location of the sampled wells and table 6 shows the most recent water-quality data. Most of the wells yield water suitable for domestic use; however, some yield water of inferior quality. For the purposes of this report, water is considered inferior when its dissolved-solids concentration exceeds 1,000 mg/L. As shown in table 6, 14 wells yield water with the concentration of one or more chemical constituents in excess of the U.S. Environmental Protection Agency (1976 and 1978) mandatory and (or) recommended limit for public water supplies. The principal chemical constituent of concern is chloride.

Vertical Variation in Ground-Water Quality

Beneath the city of Santa Barbara, distinct water-quality types can be associated with four of the five zones: the upper producing zone, the middle zone, the lower producing zone, and the deep zone. The water quality of the shallow zone cannot be characterized because most wells in the Santa Barbara basin have cement sanitary seals opposite the shallow zone. Chemical analyses of water samples from the Vera Cruz Park monitor site (4N/27W-22B2-B5), near the municipal pumping center, show the differences in chemical quality between the zones (fig. 8). The difference in chemical quality is significant between certain zones, and between others it is minor. Ground water of uniform quality does not necessarily exist throughout the lateral extent of any one zone.

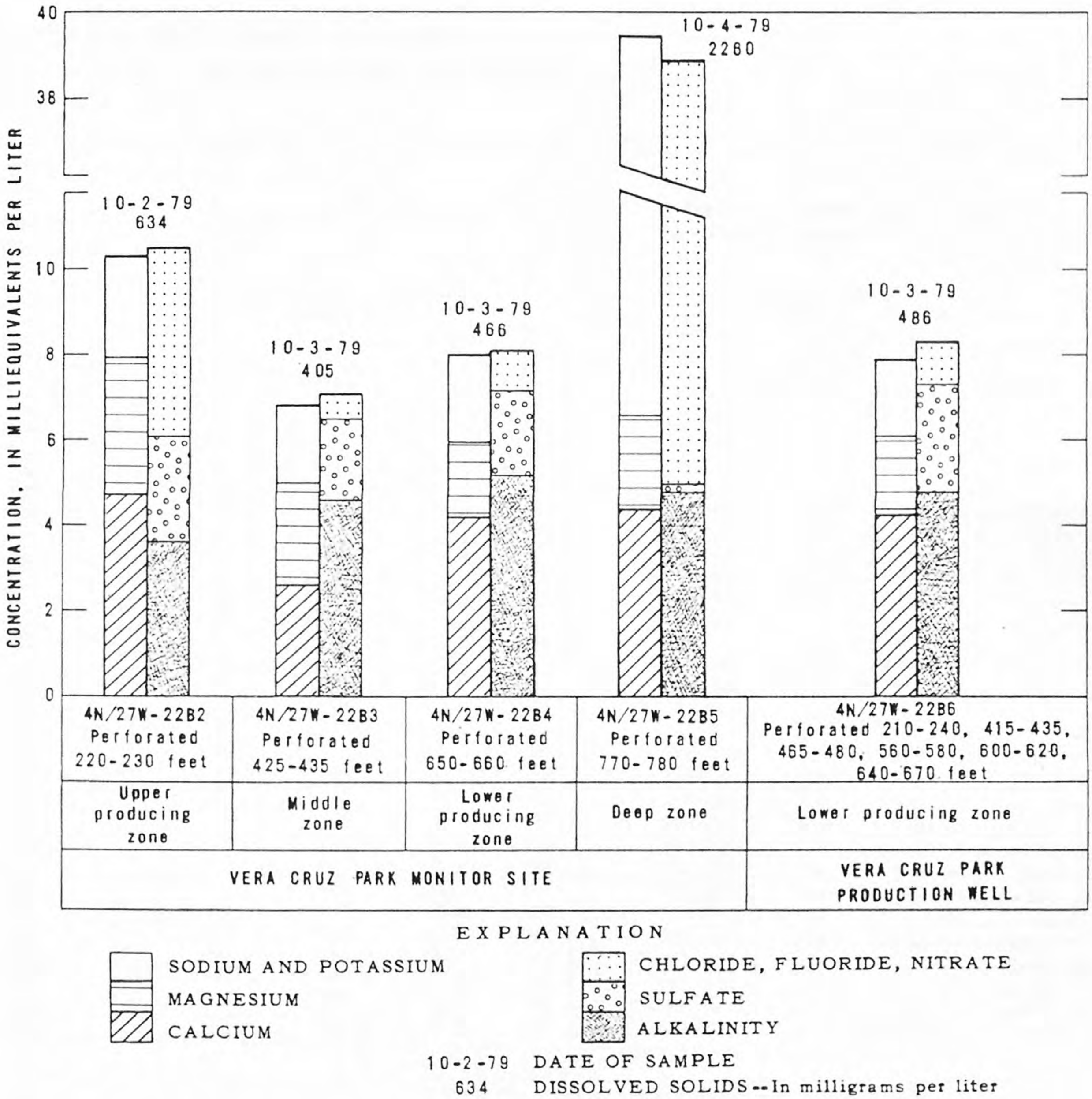


FIGURE 8.--Chemical composition of ground-water samples from the Vera Cruz Park monitor site and production well.

Chemical analyses of samples collected at seven wells are representative of the water quality in the upper producing zone (table 6). The data suggest that ground water from the upper producing zone is higher in dissolved-solids and chloride concentrations than ground water in the underlying zones, with the exception of the deep zone (fig. 8). Dissolved-solids concentrations in the upper producing zone range from 415 to 5,500 mg/L and chloride concentrations range from 32 to 3,100 mg/L in the samples collected during 1979 (table 6). Five of the seven wells sampled have water with chloride concentrations exceeding 100 mg/L. The high dissolved-solids and chloride concentrations are probably due to the upper producing zone's proximity to surface sources of contamination such as urban runoff, irrigation return flows, and leaking sewer pipes.

TABLE 6. - Chemical analyses of water in the Santa Barbara ground-water basin

[Constituents and hardness are in milligrams per liter except where noted. Constituents are dissolved]

Well location	Date of sample	Well depth (ft)	Perforated interval[1] (ft)	Specific conductance (μmho/cm at 25°C)	pH	Hardness as $CaCO_3$	Calcium	Magnesium	Sodium	Potassium	Alkalinity as $CaCO_3$	Sulfate	Chloride	Fluoride	Silica	Dissolved solids, calculated sum of constituents	Nitrite plus nitrate as N	Barium (μg/L)	Boron (μg/L)	Monitored zone[2]
U.S. Environmental Protection Agency (1976 and 1978)			Maximum limit											1.4-2.4			10	1,000		
			Recommended limit		5-9							250	250						750	
Storage Unit I																				
4N/27W-14K2	07-30-79	380	260-380	1,400	8.0	520	130	47	110	4	230	360	120	0.3	34	950	1.4	100	100	Upper producing
	10-03-79			1,750	7.4	700	180	60	130	3	280	510	140	.5	29	1,230	2.2		250	
4N/27W-14Q1	10-04-79	700	72-700	1,300	6.1	500	130	42	81	2	250	280	110	.4	30	838	2.7		180	Lower producing
4N/27W-15J2	10-04-79	599	198-579	820	6.1	310	82	25	44	2	170	120	70	.4	32	490	2.7		40	Lower producing
4N/27W-15K1	07-18-79	464	280-464	720	7.7	260	65	23	39	2	180	140	26	.4	34	438	.00	80	90	Lower producing
4N/27W-15Q10	10-04-79	675	195-655	825	6.2	310	85	24	40	2	190	110	61	.4	34	491	4.7		40	Lower producing
4N/27W-16R1	10-03-79	625	545-625	1,010	7.9	300	85	22	96	2	260	120	99	.5	30	612	.04	300	670	Lower producing
4N/27W-17J1	07-16-79	320	190-320	760	7.6	280	69	25	49	2	240	110	46	.4	39	486	.25	100	150	Lower producing
4N/27W-22B1	10-04-79			1,050	6.0	370	94	33	64	2	190	110	120	.4	36	640	15		40	Upper producing
4N/27W-22B2	10-02-79	230	220-230	1,020	6.9	400	95	39	53	2	180	120	120	.5		634	14		40	Upper producing
4N/27W-22B3	10-03-79	435	425-435	660	7.8	250	53	29	40	2	230	92	22	.2		405	.00		40	Middle
4N/27W-22B4	10-03-79	660	650-660	765	7.5	300	85	22	44	2	260	98	29	.2		466	.00		60	Lower producing
4N/27W-22B5	10-04-79	780	770-780	4,500	7.6	330	88	27	750	9	240	8.0	1,200	1.3		2,260	.25	3,600	7,100	Deep
4N/27W-22B6	10-03-79	700	210-670	770	6.5	310	87	22	39	2	240	120	35	.3	33	486	.68		60	Lower producing
4N/27W-22C1	10-04-79	630	180-615	725	6.2	280	77	21	36	2	190	110	33	.4	32	431	1.3		50	Lower producing
4N/27W-23D1	07-23-79	380	240-380	920	7.3	330	86	27	71	2	180	98	140	.2	38	572	.28	100	370	Upper producing
4N/27W-23E1	06-14-79	805	775-800	3,300	7.5	1,100	300	90	300	5	360	150	900	1.0	42	2,000	.00	0	220	Lower producing
4N/27W-23E2	06-14-79	660	600-655	11,400	6.4	4,200	1,100	350	770	9	140	100	4,000	.2	34	6,450	.01	0	190	Middle
4N/27W-23E3	06-14-79	385	355-380	580	7.9	250	67	21	48	2	190	98	32	.5	33	415	.00	0	60	Upper producing
4N/27W-23E4	06-14-79	180	150-175	700	7.0	280	68	27	58	2	240	97	50	.6	45	494	.01	0	210	Shallow
4N/27W-23F1	10-05-79	500		985	6.8	340	85	31	74	2	250	180	66	.5	28	617	.00		120	Upper producing
4N/27W-23H1[3]	06-21-79	781	746.5-781	1,340	8.2	200	45	21	70	220	310	120	160	.4	5.3	830	.20	60	800	Lower producing
4N/27W-23H2	06-06-79	620	585.5-590.5	1,640	6.8	660	160	62	99	2	190	120	380	.2	33	974	.04	100	100	Middle
4N/27W-23H3	06-06-79	310	284-299	9,200	6.3	4,400	1,100	400	310	6	170	420	3,100	.4	26	5,500	2.5	100	550	Upper producing
4N/27W-23H4	06-06-79	95	75.5-91	1,960	7.2	780	210	62	110	3	260	190	400	.3	33	1,170	1.6	100	150	Shallow
4N/27W-24D2	03-15-78	473	131-473	6,700	6.9	2,600	580	290	370	4	200	270	2,000	.3	35	3,680	.79		140	Lower producing
Storage Unit II																				
4N/27W-8L3[4]	01-31-80	610	260-610	1,020	6.8	400	100	36	77		240	210	68	.3		814	3.6		100	Lower producing
4N/27W-9G1	03-16-78	221	179-221	1,170	6.5	470	95	57	77	0.8	140	340	98	.2	27	796	3.8		250	Lower producing
Storage Unit III																				
4N/27W-17M1	10-15-79	375	75-375	1,180	7.4	400	110	31	110	3	330	140	130	.6	26	754	1.1		290	Lower producing
4N/27W-21B1	02-11-80	454	145-350	1,170	7.2	550	150	42	60	2	300	260	61	.3	21	785			150	Lower producing
4N/27W-22Q1	07-16-79	60	20-60	2,250	7.9	510	120	51	360	4	600	260	270	.3	21	1,450	.09	400	3,000	Lower producing

[1]Depth of first and last perforation; not necessarily perforated throughout the interval.
[2]Determination of monitored zone based on well perforations and water quality.
[3]Contaminated with drilling fluid.
[4]Analysis from M. F. Hoover, Consulting Geologist (written commun., 1980).

Three wells in the water-quality network yield water from the middle zone (table 6). The well tapping the middle zone at the Vera Cruz Park monitor site (4N/27W-22B3) yields water with the lowest dissolved-solids and chloride concentrations of the wells at the monitor site (fig. 8). Calcium, magnesium, and bicarbonate are the predominant ions in water yielded from this well, with dissolved-solids and chloride concentrations of 405 and 22 mg/L, respectively (table 6). The other two wells that yield water from the middle zone are near the coast and contain high concentrations of chloride. The source of the high chloride concentrations is discussed later in the report.

The lower producing zone is the most extensively sampled water-bearing zone in the Santa Barbara ground-water basin. Chemical analyses of samples collected at 17 wells are representative of the water quality in the lower producing zone (table 6). The areal distributions of water types (in terms of abundance of ions) and dissolved-solids concentrations of ground water in the lower producing zone are shown in figure 9. Chemical data from well 4N/27W-23H1 are not included in the figure because the water from this well is contaminated with drilling fluid (Hutchinson, 1979, p. 21).

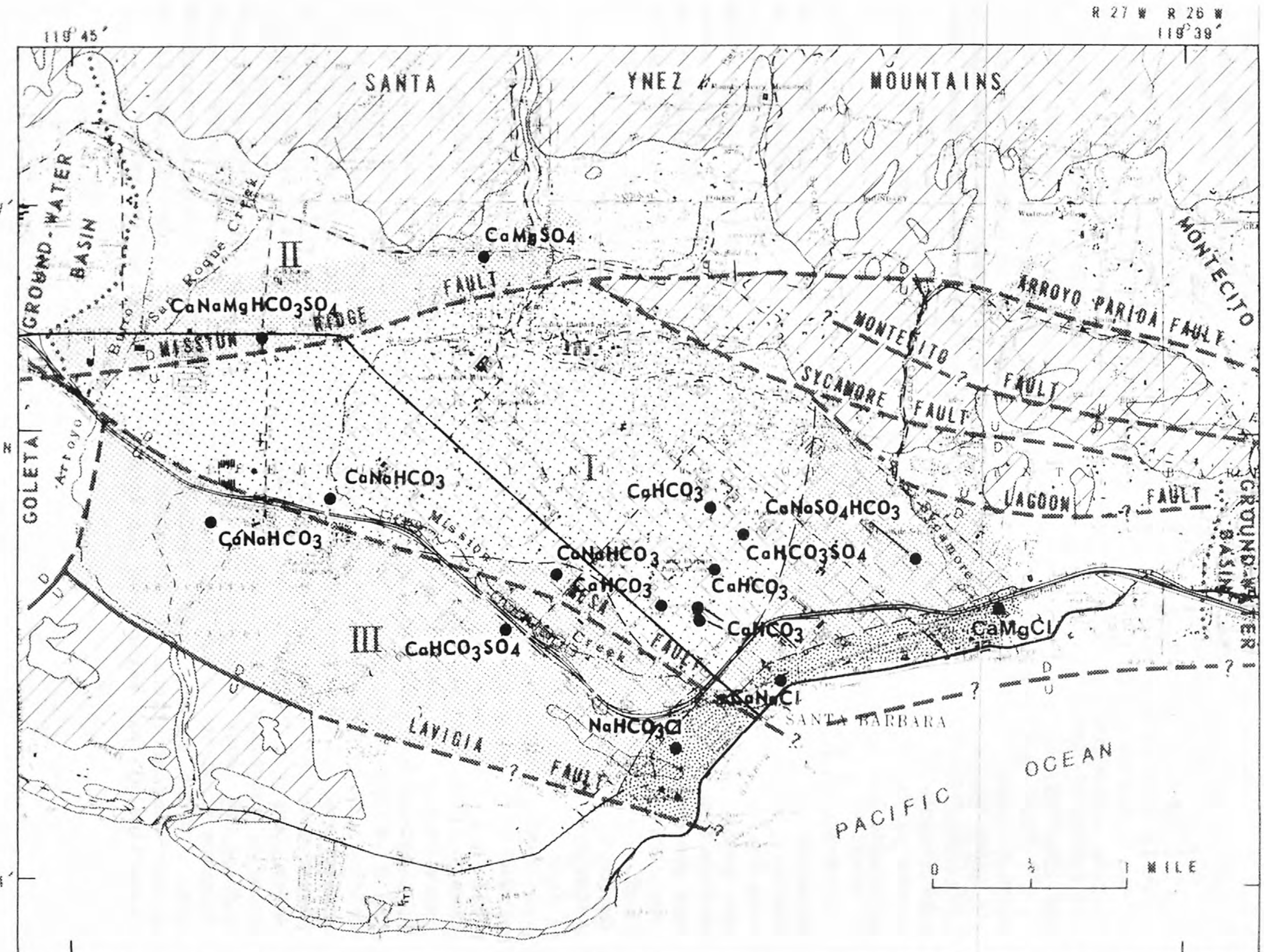
Wells in Storage Unit I, south of Mission Ridge fault to State Highway 101, yield water containing the lowest dissolved-solids concentration (less than 500 mg/L) found in the lower producing zone. The chemical analysis of water sampled from the Vera Cruz Park monitor well 4N/27W-22B4 is representative of ground water in this part of the basin. Ground water in Storage Unit I is surrounded by water of poorer quality (fig. 9). Therefore, underflow from the adjacent storage units is not considered a major source of water to Storage Unit I. The source of the water with low dissolved-solids concentration is probably infiltration of precipitation and Mission Creek streamflow in the upper part of Storage Unit I. Geologic section A-A' (fig. 2) shows that the lower producing zone is near the land surface in this part of the basin. Additional geologic data are needed in the upper part of Storage Unit I along Mission Creek to determine whether silt and clay beds that could interfere with the infiltration of precipitation and Mission Creek streamflow are present above the lower producing zone. A band of water of inferior quality is present along the coast of Santa Barbara (fig. 9). The source of this water is discussed in detail later in the report.

Only one well (4N/27W-22B5) is perforated solely in the deep zone in the Santa Barbara ground-water basin (table 6). This well yields a sodium-chloride water of inferior quality, with dissolved-solids, sodium, and chloride concentrations of 2,260, 750, and 1,200 mg/L, respectively. Although only this one well taps the deep zone, the electric logs of many wells in the ground-water basin (fig. 2) have low resistivity measurements opposite the deep zone, suggesting the presence of fine-grained deposits of low permeability or poor water quality overlying the consolidated rocks in most of the basin.

The high sodium and chloride concentrations in the deep zone are suggestive of saltwater intrusion; however, the sulfate concentrations of the sampled ground water are much lower than what would result from a simple mixture of native water and ocean water. The sulfate concentration of the deep zone is only 8.0 mg/L; whereas the sulfate concentrations of the overlying water-bearing deposits generally exceed 100 mg/L. The low sulfate concentration is probably due to the biochemical reduction of sulfate to sulfide. A very strong hydrogen sulfide odor was detected during pumping of this well. The sulfide concentration in a sample from this well in 1973 was 2.7 mg/L (Brown and Caldwell, 1973, p. 48). The ground water sampled from the deep zone also had high concentrations of barium, boron, and fluoride, amounting to 3,600 μg/L, 7,100 μg/L, and 1.3 mg/L, respectively. The average concentrations of barium, boron, and fluoride in ocean water are 30 μg/L, 4,600 μg/L, and 1.3 mg/L, respectively (Hem, 1970, p. 11). The presence of barium and boron in concentrations significantly in excess of the concentration of the two constituents in ocean water suggests that saltwater intrusion is not the source of the water to the deep zone. Further investigation is necessary to determine the source of this water.

Production wells in the Santa Barbara area are generally perforated opposite all the zones discussed above, except for the deep zone. For example, the city's Vera Cruz Park production well 4N/27W-22B6 has perforations opposite the upper producing zone, two water-bearing units in the middle zone, and the lower producing zone. Sanitary cement seals are usually placed opposite the shallow zone to prevent contamination from surface sources. The wells are not perforated opposite the deep zone, which contains water of inferior quality. Consequently, water from the production wells has a quality of water that represents a composite of the upper producing, middle, and lower producing zones. The chemistry of the composite is controlled by the relative production rate from each zone.

Representative water samples from the upper producing, middle, and lower producing zones were collected at the Vera Cruz Park monitor site (4N/27W-22B2-B4), less than 200 ft from the Vera Cruz Park production well. The chemical character of the water from the Vera Cruz Park production well compares closely to water from the lower producing zone (fig. 8). The Vera Cruz Park production well and the monitor well in the lower producing zone both yield water with calcium and bicarbonate as the predominant ions; whereas, calcium, magnesium, bicarbonate, and chloride are the predominant ions in the monitor well in the upper producing zone. The monitor well in the middle zone yields water with calcium, magnesium, and bicarbonate as the predominant ions. Water from the Vera Cruz Park production well contains dissolved-solids and chloride concentrations of 486 and 35 mg/L, respectively. Water from both the middle and lower producing zones is slightly lower in dissolved-solids and chloride concentrations than the water from the Vera Cruz Park production well. Water in the upper producing zone, however, contains significantly higher concentrations of dissolved solids and chloride (634 and 120 mg/L, respectively) than water from the Vera Cruz Park production well.



Base from U. S. Geological Survey
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GROUND-WATER DIVIDE

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

CONCRETE-LINED CHANNEL

DISSOLVED SOLIDS, IN MILLIGRAMS PER LITER--

- Less than 500
- 500-1000
- More than 1000

CaNaCl — SAMPLED WELL AND TYPE OF WATER In terms of abundance of ions

- Ca — Calcium
- Cl — Chloride
- HCO_3 — Bicarbonate
- Mg — Magnesium
- Na — Sodium
- SO_4 — Sulfate

FIGURE 9.--Distribution of dissolved solids and water type of the lower producing zone.

The nitrate-nitrogen concentration of water from the upper producing zone is also significantly higher than in water from the Vera Cruz Park production well (table 6). (Nitrate-nitrogen is referred to as nitrite plus nitrate as N in the table.) The nitrate-nitrogen concentrations of water from the different zones and from the Vera Cruz Park production well in October 1979 are as follows: Upper producing zone (4N/27W-22B2), 14 mg/L; middle zone (4N/27W-22B3), 0.00 mg/L; lower producing zone (4N/27W-22B4), 0.00 mg/L; and Vera Cruz Park production well (4N/27W-22B6), 0.68 mg/L. A mass balance calculation indicates that the upper producing zone contributes approximately 5 percent of the water and 100 percent of the nitrate-nitrogen, while the middle and lower producing zones contribute 95 percent of the water and 0 percent of the nitrate-nitrogen in the Vera Cruz Park production well. The amount of water contributed individually by the middle and lower producing zones cannot be determined by the mass balance calculation. The electric log of well 4N/27W-22B2 (fig. 2) indicates, however, that the water-bearing deposits of the middle zone are less than one-third the thickness of the lower producing zone. Therefore, it is assumed that the lower producing zone contributes most of the water to the Vera Cruz Park production well and other production wells of similar design in the Santa Barbara ground-water basin.

Occurrence and Chemical Character of Potential Sources of Ground-Water Degradation

Ground water of inferior quality has been produced from wells near the coast of the Santa Barbara area for many years. Use of a few wells was discontinued because the water-quality degradation became so intense that the water could no longer be used. Of the 30 wells sampled during this study, nine wells yielded water with dissolved-solids concentrations near or in excess of 1,000 mg/L. The ground water of inferior quality is usually high in chloride concentrations. As shown in table 6, eight of these wells yielded water with chloride concentrations in excess of the U.S. Environmental Protection Agency (1976) recommended limit of 250 mg/L for chloride in public water supplies. The major potential sources of chloride degradation in the Santa Barbara area are ocean water and ground water from the deep zone.

Ocean water is an obvious potential source of ground-water degradation in the Santa Barbara area because certain areas along the coast have been or are within the tidal zone and because ground-water pumping, centered about 1 mi from the coast, has lowered water levels below sea level near the coast. Previous investigators (Muir, 1968; Brown and Caldwell, 1969; and Todd, 1978) believed that saltwater intrusion was limited to the shallow zone directly adjacent to the coast. Along the coast, ocean water that moves inland by the tides may percolate downward into the shallow zone wherever the overlying materials are permeable. Electric logs of wells near the coast indicate that saline water is present in the upper part of the shallow zone. The possibility of horizontal migration of ocean water through the deeper water-bearing deposits was thought to be remote because an unnamed offshore fault (figs. 1 and 2) truncates the lower water-bearing deposits against consolidated rocks on the seaward side of the fault. Selected chemical constituents of ocean water are shown in table 7.

TABLE 7.--Comparison of selected chemical constituents from potential sources of ground-water degradation, in ground water of inferior quality, and in samples of native ground water

Potential source of degradation or well location	Date of sample	Sulfate (mg/L)	Chloride (mg/L)	Dissolved solids, calculated, sum of constituents (mg/L)	Barium (μg/L)	Boron (μg/L)	Chloride (mg/L) / Sulfate (mg/L)	Chloride (mg/L) / Boron (mg/L)	Monitored zone
POTENTIAL SOURCES OF GROUND-WATER DEGRADATION									
Ocean water[1]	--	2,700	19,000	34,500	Trace	4,600	7.0	4,100	
Deep zone (4N/27W-22B5)	10-04-79	8.0	1,200	2,260	3,600	7,100	150	170	Deep
GROUND WATER OF INFERIOR QUALITY									
Storage Unit I									
4N/27W-14K2	10-03-79	510	140	1,230	--	250	.3	560	Upper producing
4N/27W-23E1	06-14-79	150	900	2,000	0	220	6.0	4,100	Lower producing
4N/27W-23E2	06-14-79	100	4,000	6,450	0	190	40	21,000	Middle
4N/27W-23H2	06-06-79	120	380	974	100	100	3.2	3,800	Middle
4N/27W-23H3	06-06-79	420	3,100	5,500	100	550	7.4	5,600	Upper producing
4N/27W-23H4	06-06-79	190	400	1,170	100	150	2.1	2,700	Shallow
4N/27W-24D2	03-15-78	270	2,000	3,680	--	140	7.4	14,000	Lower producing
Storage Unit III									
4N/27W-22Q1	07-16-79	260	270	1,450	400	3,000	1.0	90	Lower producing
NATIVE GROUND WATER (city supply wells)									
4N/27W-14Q1	10-04-79	280	110	838	Trace[2]	180	.4	610	Lower producing
4N/27W-15J2	10-04-79	120	70	490	[2]100	40	.6	1,700	Lower producing
4N/27W-15Q1	10-04-79	110	61	491	[2]100	40	.6	1,500	Lower producing
4N/27W-22B6	10-03-79	120	35	486	[2]100	60	.3	580	Lower producing
4N/27W-22C1	10-04-79	110	33	431	Trace[2]	50	.3	660	Lower producing

[1]Data from Hem (1970, p. 11).

[2]Barium data from the city of Santa Barbara (written commun., 1980). Sample collected June 1980.

In the deep zone, ground water of inferior quality underlies the fresh water in most of the Santa Barbara area. This water of inferior quality is a potential source of degradation because municipal pumping has lowered the hydraulic head of the lower producing zone below that of the underlying deep zone. Consequently, conditions are favorable for upward migration of the water of inferior quality into the lower producing zone. Clay layers present between the lower producing and deep zones, however, undoubtedly retard the movement of water between the two zones.

The chemical character of ground water from well 4N/27W-22B5 is representative of the deep zone (table 6). As described earlier in the report, this well produces sodium chloride water with a chloride concentration of 1,200 mg/L. The water from the deep zone is distinguished from a simple mixture of native ground water and ocean water by a lower sulfate concentration and higher barium and boron concentrations (table 7).

Of the major dissolved constituents in the ground water of the Santa Barbara area, probably only chloride is chemically conservative. Therefore, the chloride concentration of ground water degraded by ocean water or water from the deep zone indicates the proportion to which native ground water and the degraded water have mixed, provided the source of the degraded water and its chemical composition are known. In a study of saltwater intrusion in the Long Beach-Santa Ana area of southern California, Piper and Garrett (1953, p. 90) determined that due largely to cation exchange and reduction of sulfate, the concentrations of all other major constituents in the degraded water were so much greater or so much less than a simple mixture of the proportions indicated by the concentration of chloride, that no single major constituent or ratio between such constituents provided a definite means of discriminating between the different sources of high chloride concentrations. The differences between the concentration of certain chemical constituents in ocean water and water from the deep zone (table 7), however, provide some basis for discriminating the source of degradation, as follows:

1. Sulfate may identify saltwater intrusion provided its concentration in the degraded water is greater than could have been introduced by water from the deep zone in the absence of reducing conditions (Piper and Garrett, 1953, p. 91). The sulfate concentrations of ocean water and of water from the deep zone are 2,700 and 8.0 mg/L, respectively.

2. A chloride to sulfate ratio in the degraded water much higher than that determined for ocean water, in the absence of reducing conditions, is presumptive evidence that water from the deep zone is the source of degradation. The chloride to sulfate ratios for ocean water, water from the deep zone, and native ground water in the Santa Barbara area, in terms of milligrams per liter, are 7.0, 150, and less than 1, respectively.

3. Barium concentrations exceeding a few hundred micrograms per liter are presumptive evidence that the source of degradation is water from the deep zone and not ocean water (Piper and Garrett, 1953, p. 91). Barium, however, is not a conservative chemical constituent. Consequently, barium concentrations are not an infallible means of discrimination between ocean water and water from the deep zone as the source of ground-water degradation. The concentration of barium in ocean water is less than 100 μg/L; whereas, its concentration in water from the deep zone is 3,600 μg/L.

4. Boron concentrations in the contaminated water, such that the chloride to boron ratio is substantially less than that present in ocean water, are presumptive evidence that the source of degradation is water from the deep zone (Piper and Garrett, 1953, p. 91). The chloride to boron ratios of ocean water and water from the deep zone, in terms of milligrams per liter, are 4,100 and 170, respectively.

Table 7 shows the sulfate and barium concentrations and the chloride to sulfate and chloride to boron ratios determined for ocean water, water from the deep zone, ground water of inferior quality, and native ground water. The sulfate concentrations determined for the ground water of inferior quality are substantially higher than the sulfate concentration of water from the deep zone, suggesting that the water from the deep zone is probably not a significant source of ground-water degradation in the Santa Barbara area.

The chloride to sulfate ratios in the samples are low, which would also suggest that water from the deep zone is not a major source of ground-water degradation. The similarity of chloride to sulfate ratios between ocean water and water produced from three of the wells (4N/27W-23E1, 23H3, and 24D2) is highly suggestive that ocean water is the source of degradation to these wells.

Barium concentrations in the water of inferior quality are all less than or equal to 100 μg/L--except for the sample from well 4N/27W-22Q1--which also suggests that water from the deep zone is not the source of ground-water degradation. The relatively high barium concentration produced by well 4N/27W-22Q1 (400 μg/L) is presumptive evidence that water from the deep zone is the source of degradation to this well.

The chloride to boron ratios determined for the ground water of inferior quality are substantially higher than the ratio of the two ions in native ground water and approach or exceed the ratio determined for ocean water, except for samples from wells 4N/27W-14K2 and 22Q1. The chloride to boron ratios suggest that ocean water is the source of ground-water degradation. Well 4N/27W-14K2 produces water with a chloride to boron ratio similar to that of native ground water. The water of inferior quality produced by this well is probably the result of slow ground-water movement in the fine-grained deposits in the southeastern part of Storage Unit I. Well 4N/27W-22Q1 yields water with a chloride to boron ratio less than that determined for water from the deep zone. The low chloride to boron ratio is presumptive evidence that water from the deep zone is the source of degradation to ground water produced by this well.

In summary, comparison of sulfate and barium concentrations, chloride to sulfate ratios, and chloride to boron ratios determined for the potential sources of ground-water degradation to those determined for ground water of inferior quality suggests that ocean water is the source of the degraded water yielded by six of the wells (4N/27W-23E1, 23E2, 23H2, 23H3, 23H4, and 24D2). These wells are adjacent to the coast, further suggesting that ocean water is the source of the ground-water degradation. Probably only well 4N/27W-22Q1 is significantly degraded by water from the deep zone. The clay layer above the deep zone evidently retards significant movement of water from the deep zone to the overlying lower producing zone in most of the basin. The water yielded from well 4N/27W-14K2, the remaining well yielding water of inferior quality, is probably representative of native-ground water conditions in the southeastern part of Storage Unit I.

From August 1978 through January 1980 municipal pumping was increased in the Santa Barbara area as part of a basin-testing program to determine the usable quantity of ground water in storage. The rate of municipal pumping increased from an average of about 1 acre-ft/d in July 1978, prior to the basin testing, to an average of about 7 acre-ft/d during the basin testing. Historically, the municipal pumping rate has equaled or exceeded the pumping rate during the basin testing; however, comprehensive water-level data were not available to assess the effects of the pumping on the ground-water basin.

The increase in municipal pumping has caused significant water-level declines in the basin. Comparison of the July 1978 water-level map (fig. 5) and the January 1980 water-level map (fig. 6) show that water levels declined more than 100 ft in the southern part of Storage Unit I, near the pumping center (fig. 10). The pumping is centered less than 1 mi north of the coast and has caused water-level declines to depths below sea level in the coastal area of Storage Unit I (fig. 6). Near the pumping center, water levels that were as high as 17 ft above sea level in July 1978 were as low as 84 ft below sea level in January 1980. The municipal pumping has reversed the ground-water gradient between the pumping center and the Pacific Ocean. During July 1978, ground water in general flowed southward toward the ocean; whereas, during January 1980, after 18 months of the basin testing, ground water flowed northward from the ocean toward the pumping center. The increased pumping rate, therefore, has created conditions favorable for saltwater intrusion.

Ground-water quality data from six coastal wells (4N/27W-23E1, 23E2, 23H2, 23H3, 23H4, and 24D2) in the Santa Barbara area suggest that ocean water has already intruded into the water-bearing deposits adjacent to the coast. Available chloride data from these wells are shown in figures 11 and 12. Chloride concentrations in the most recent samples from the wells ranged from about 250 mg/L to 3,800 mg/L (figs. 11 and 12). Four of the coastal wells (4N/27W-23E1, 23E2, 23H3, and 24D2) yielded water with chloride concentrations in excess of 1,000 mg/L.

Of the six wells, only well 4N/27W-24D2 was constructed prior to the start of the basin-testing program. From 1950 to 1978 chloride concentrations in samples from this well increased from 78 to 2,000 mg/L (fig. 11). This well has a cement seal between the surface and a depth of 116 ft which should prevent degradation from saline water in the shallow zone (Muir, 1968, p. A26). Todd (1978, p. 77) suspected that the cement seal may leak and suggested that the degradation in the quality of water yielded from well 4N/27W-24D2 resulted from the migration of saline water in the shallow zone past the seal to the lower zones. Chloride data collected from the shallow, upper producing, middle, and lower producing zones at coastal monitor sites 1 and 2 (fig. 12) indicate, however, that the shallow zone yields water with a lower chloride concentration than the deeper zones. In fact, the average chloride concentration of samples from the middle zone at coastal monitor site 2 (4N/27W-23E2) is about 40 times as high as the average chloride concentration of samples from the shallow zone (4N/27W-23E4). Therefore, the high chloride concentrations of ground water in the upper producing, middle, and lower producing zones cannot be the result of downward migration of saline water from the shallow zone.

Clay layers present in the shallow zone must prevent significant ground-water movement between the upper water-bearing deposits of the shallow zone which reportedly contain saline ground water and the lower water-bearing deposits of the shallow zone which contain relatively low-chloride ground water. The high chloride concentrations in samples from the upper producing, middle, and lower producing zones and the relatively low chloride concentrations in samples from the shallow zone suggest that ocean water has intruded into the deeper water-bearing deposits to a much greater extent than the shallow zone. Apparently the offshore fault (figs. 1 and 2) is not an effective barrier to saltwater intrusion. The fault zone may be permeable, allowing ocean water to migrate along the fault zone and come into direct contact with the water-bearing deposits at depth.

No physical barriers are known to exist between the coast and the municipal well field. Consequently, if the pumping rate maintained during the basin-testing program is continued, the degraded water present along the coast could move inland and contaminate the municipal supply wells. The time required for the degraded water to move from the coast to the supply wells can be estimated on the basis of January 1980 conditions using the following form of Darcy's equation:

$$\bar{v}=\frac{T}{b}\cdot\frac{dh/dl}{\theta}$$

where

$\bar{v}$=Average velocity of ground-water movement in feet per day,

T=Transmissivity of the lower producing zone, 1,090 ft^2/d (Brown and Caldwell, 1973, p. 65),

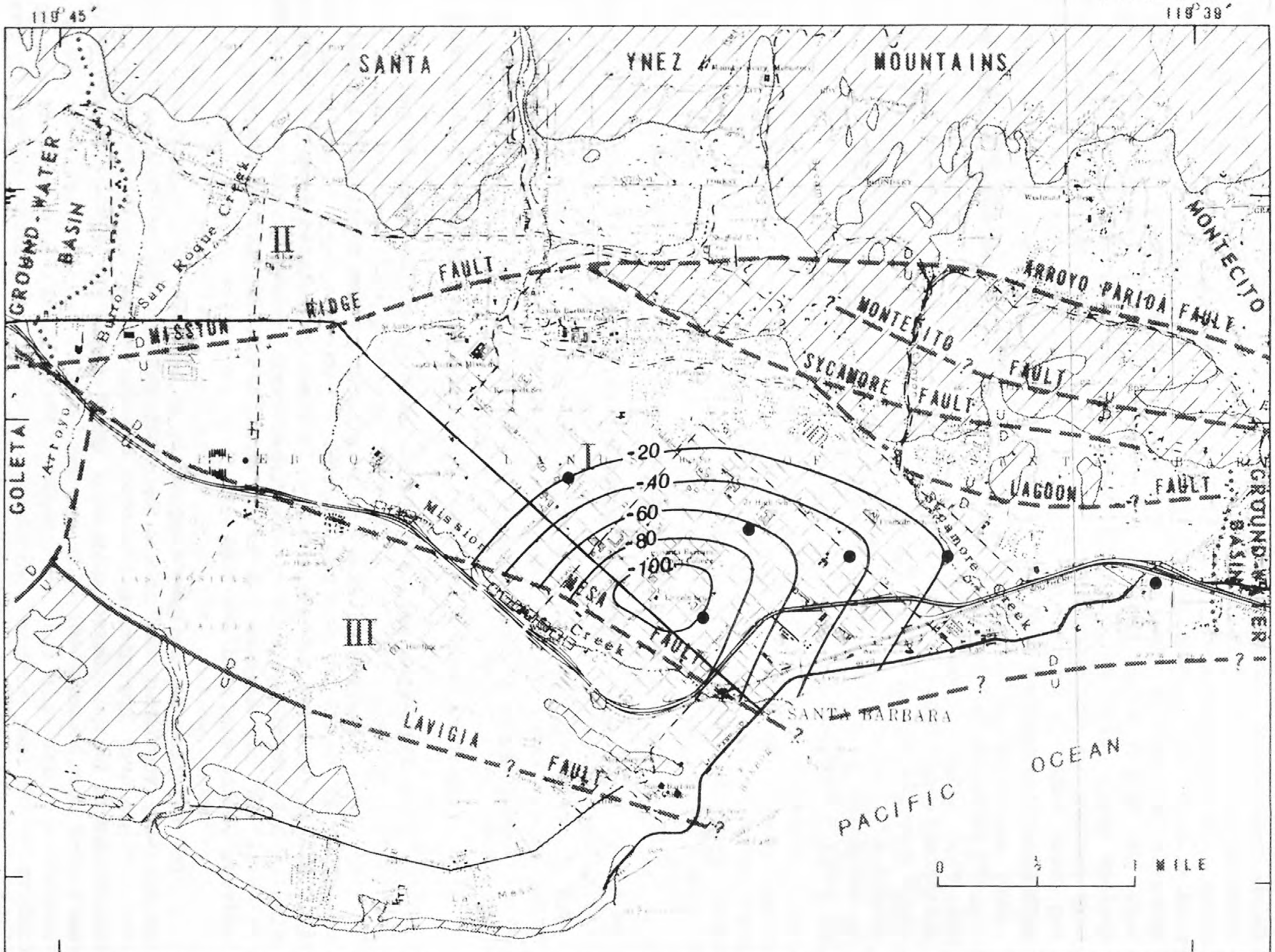
dh/dl=Hydraulic gradient, 0.015 ft/ft (fig. 5),

b=Thickness of the lower producing zone, 150 ft (fig. 2), and

θ=Effective porosity of the lower producing zone, 30 percent (estimated from drillers' logs in the Supplemental Data).

The average velocity of ground-water movement calculated from the above equation is 0.37 ft/d. At this rate of ground-water movement, it would take about 22 years for the degraded water to move the 3,000 ft from the coast to the nearest supply well, 4N/27W-22B6.

The solution to the above equation is the average velocity and does not necessarily represent the actual velocity between any two points in the aquifer. Therefore, the time calculated for the degraded water to reach the well field should be considered only as a gross estimate, and actual movement may be faster than calculated.



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

Geology modified from K. S. Muir (1968)
and M. F. Hoover (1978)

EXPLANATION

CONSOLIDATED ROCKS

UNCONSOLIDATED DEPOSITS

U
D
?

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

GROUND-WATER DIVIDE

II

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

CONCRETE-LINED CHANNEL

-20

LINE OF EQUAL WATER-LEVEL DECLINE--Constructed by superposition of the January 1980 water-level map (fig. 5) over the July 1978 water-level map (fig. 6). Interval 20 feet

DATA POINT

FIGURE 10.--Water-level declines in the lower producing zone, July 1978-January 1980.

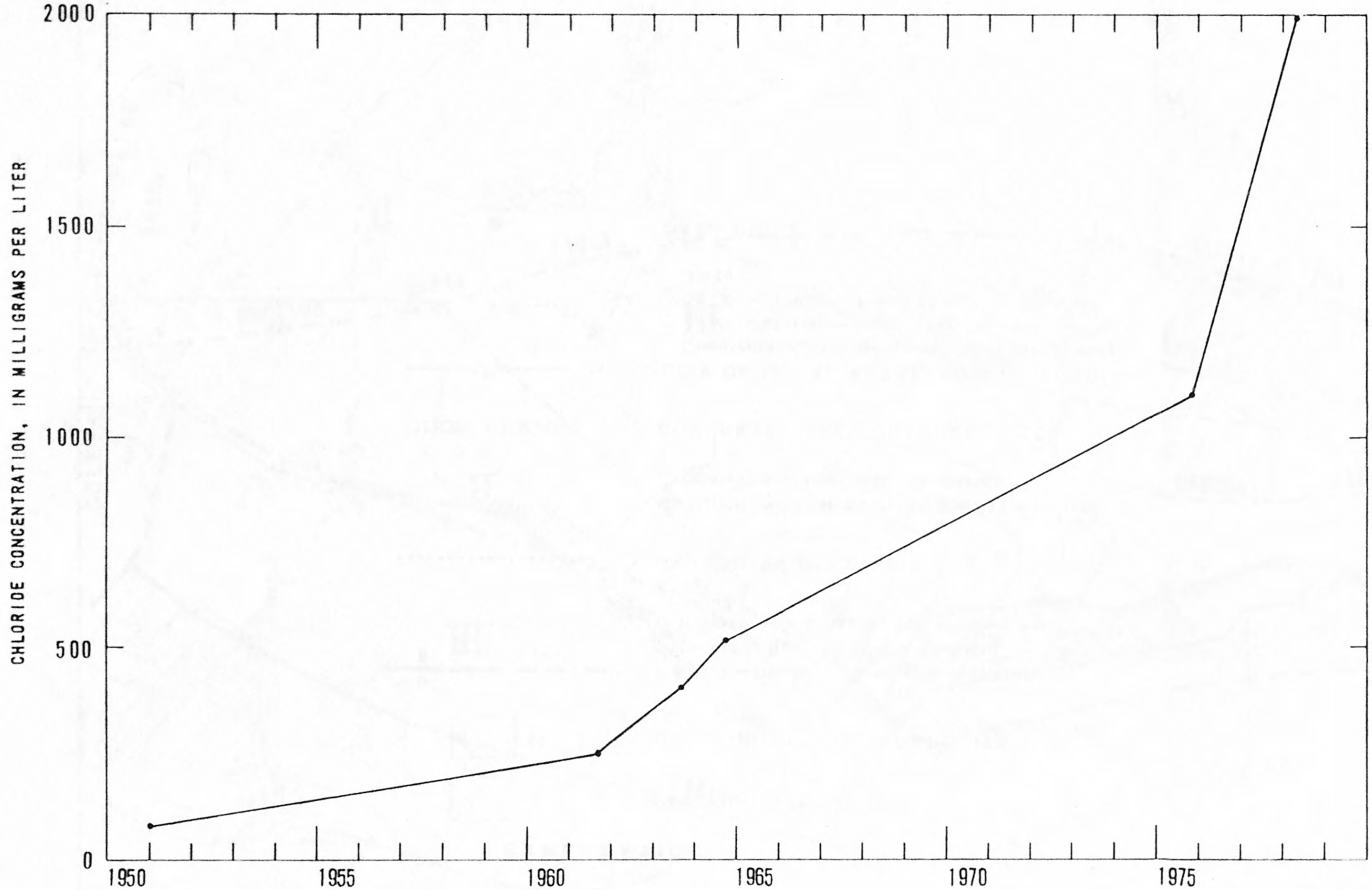
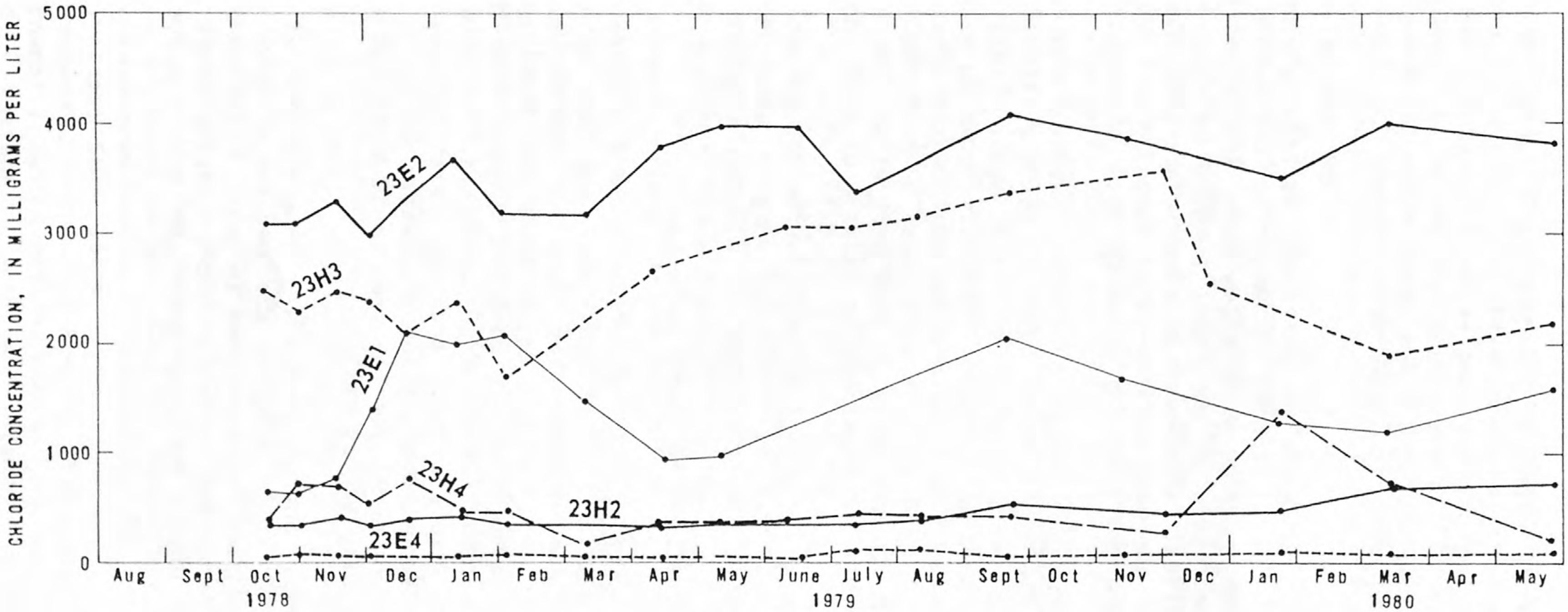


FIGURE 11.--Chloride concentration of samples from well 4N/27W-24D2, 1950-78.



EXPLANATION

Coastal Monitor Site 1

Well No.	Monitored Zone
4N/27W-23H4	Shallow
4N/27W-23H3	Upper producing
4N/27W-23H2	Middle

Coastal Monitor Site 2

Well No.	Monitored Zone
4N/27W-23E4	Shallow
4N/27W-23E2	Middle
4N/27W-23E1	Lower producing

FIGURE 12.--Chloride concentrations of samples from selected wells at coastal monitor sites 1 and 2.

Saltwater intrusion is probably the principal source of water-quality degradation in the Santa Barbara ground-water basin. One of the most effective methods for restraining or reversing saltwater intrusion in ground-water basins is to raise water levels throughout the basin to a height such that freshwater will displace the intruded ocean water seaward. Several management alternatives might be employed to raise water levels in the Santa Barbara ground-water basin.

1. Decrease pumpage.--Pumpage in the Santa Barbara ground-water basin currently exceeds estimates of annual recharge to the basin. Decreasing pumpage sufficiently below recharge would allow water levels to recover in the basin. Historically, decreases in municipal pumping have been followed by rapid water-level recoveries. Decreases in pumpage are possible at the present time (1980) because adequate surface-water supplies are available, but, in the future, short-term overdrafting probably will be required at times.

2. Increase Mission Creek recharge.--During periods when surface-water supplies exceed demand, the ground-water basin could be artificially recharged by releasing surplus water to Mission Creek, which under normal conditions is dry in its lower reaches most of the year. Selective pumping along the permeable reach of Mission Creek below Mission Ridge fault would lower water levels in this part of the basin and provide additional storage space for Mission Creek recharge. Lack of storage space in this part of the basin has probably limited the seepage from Mission Creek during periods of high runoff.

3. Artificial recharge by injection wells.--The ground-water basin could also be artificially recharged by injecting surplus water through wells. Injection wells would have the advantage of placing water in areas where recharge is most needed. In the Santa Barbara area, injection wells would be most effective if they were located along the coast.

4. Relocating the city well field.--Five of the six currently operating city supply wells are within 1 mi of the coast and four of the wells are clustered within a half mile of each other (fig. 3). The mutual interference of these wells results in water levels being below sea level in the southern part of Storage Unit I, even when the combined pumpage from these wells is less than the estimated annual recharge to the basin. Locating city supply wells throughout Storage Unit I farther from the coast and spacing them farther apart to minimize drawdown would allow freshwater levels to rise near the coast. A ground-water flow model for the area could be utilized to determine optimum placement of the city supply wells.

Continued water-level and water-quality measurements at the existing monitoring wells (fig. 3) would provide the necessary data to assess the effectiveness of the management alternatives in most of the basin. Additional monitoring wells would be useful, however, along Mission Creek in the northwestern part of Storage Unit I to help determine the recharge potential of Mission Creek.

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SUPPLEMENTAL DATA

4N/27W-14K2. Drilled by Sierra Drilling Co., Inc. Logged by U.S. Geological Survey. Altitude 42.3 feet; 8-inch polyvinyl chloride casing; depth of hole 450 feet; depth of well 380 feet; perforated interval 260-380 feet. Date finished 7-26-79.

	Thickness (feet)	Depth (feet)
Conductor pipe (no samples)	20	20
Sand, medium to coarse, occasional gravel and clay (5 percent), moderate brown	20	40
Sand, medium (75 percent), silt (20 percent), and clay (5 percent), with occasional cobbles, moderate yellowish-brown	35	75
Sand, medium to coarse (70 percent), silt (20 percent), clay (5 percent), and fine gravel (5 percent), moderate yellowish-brown	25	100
Sand, fine to medium (50 percent), silt (30 percent), clay (10 percent), with occasional cobbles and (or) gravel (5-10 percent), moderate yellowish-brown	100	200
Same as above, except clay is moderate brown	40	240
Sand, fine to medium (50 percent), silt (35 percent), clay (15 percent), moderate yellowish-brown	30	270
Sand, medium to coarse (60 percent), silt (15 percent), and clay (5 percent), with fine gravel (20 percent), moderate yellowish-brown	40	310
Sand, fine to medium (50 percent), silt (35 percent), and clay (15 percent), light olive-gray	35	345
Sand, medium (70 percent), silt (15 percent), trace of clay, with fine gravel (5 percent), and occasional cobbles and (or) boulders (10 percent), moderate yellowish-brown	20	365
Sand, fine (60 percent), silt (25 percent), and clay (15 percent), moderate yellowish-brown	85	450

	Thickness (feet)	Depth (feet)

4N/27W-15K1. Drilled by Sierra Drilling Co., Inc. Logged by U.S. Geological Survey. Altitude 18.9 feet; 8-inch polyvinyl chloride casing; depth of hole 500 feet; depth of well 464 feet; perforated 280-464 feet. Date finished 7-17-79.

	Thickness (feet)	Depth (feet)
Conductor pipe (no samples)	20	20
Sand, medium to coarse (80 percent), with gravel (20 percent), moderate yellowish-brown	40	60
Sand, medium (55 percent), silt (30 percent), and clay (15 percent) with occasional gravel, moderate yellowish-brown	65	125
Sand, medium (40 percent), silt (30 percent), and clay (10 percent), with gravel (20 percent), moderate yellowish-brown	15	140
Sand, medium (70 percent), silt (20 percent), trace of clay with boulders (10 percent), moderate yellowish-brown	10	150
Sand, fine to medium (40 percent), silt (30 percent), and clay (10 percent), olive-black	30	180
Sand, fine to medium (80 percent), silt (20 percent), and a trace of clay, with occasional cobbles, dark greenish-gray	20	200
Sand, fine to medium (60 percent), silt (20 percent), and a trace of clay, with gravel (20 percent), light olive-brown	15	215
Sand, fine to medium (70 percent), silt (20 percent), and clay (10 percent), moderate yellowish-brown	90	305
Sand, fine to medium (60 percent), silt (15 percent), and trace of clay, with gravel (25 percent), moderate yellowish-brown	15	320
Sand, fine to medium (80 percent), silt (15 percent), and clay (5 percent), moderate yellowish-brown	40	360
Sand, fine to medium (65 percent), silt (30 percent), and clay (5 percent), moderate yellowish-brown	50	410
Same as above, except grayish-olive	10	420
Sand, fine to coarse (80 percent), silt (10 percent), trace of clay, with some gravel (10 percent), moderate yellowish-brown	40	460
Sand, fine to coarse (85 percent), silt (10 percent), with some shell fragments (5 percent), light olive-gray	15	475
Shale, moderate olive-black	25	500

	Thickness (feet)	Depth (feet)
4N/27W-16R1. Drilled by Sierra Drilling Co., Inc. Logged by U.S. Geological Survey. Altitude 84.8 feet; 6-inch polyvinyl chloride casing; depth of hole 720 feet; depth of well 625 feet; perforated 545-625 feet. Date finished 8-21-79.		
Sand, fine (60 percent), silt, and clay (5 percent), moderate yellowish-brown	60	60
Sand, fine to medium, silt, and clay (10 percent), with cobbles and gravel, moderate yellowish-brown	40	100
Sand, fine (70 percent), silt (20 percent), and clay (10 percent), moderate yellowish-brown	35	135
Sand, poorly sorted, silt, trace of clay, with fine gravel and (or) rock fragments (20 percent), moderate yellowish-brown	15	150
Sand, fine (60 percent), silt, clay (5 percent), with gravel (10 percent), moderate yellowish-brown	10	160
Sand, poorly sorted, silt, trace of clay with gravel and (or) rock fragments (20 percent), moderate yellowish-brown	10	170
Sand, fine (60 percent), silt (30 percent), clay (5 percent), with occasional gravel (5 percent), moderate yellowish-brown	30	200
Sand, medium well sorted, silt (F10 percent), with occasional fine gravel (F5 percent), moderate yellowish-brown	30	230
Sand, fine to medium, silt, and clay (10 percent), moderate yellowish-brown	10	240
Sand, fine to coarse (80 percent), silt (15 percent), and clay (5 percent), moderate yellowish-brown	40	280
Sand, fine (50 percent), silt (25 percent), clay (10 percent), with fine gravel (15 percent), moderate yellowish-brown	40	320
Sand, fine to coarse (45 percent), silt (20 percent), clay (5 percent) with fine gravel (30 percent), moderate yellowish-brown	30	350
Sand, fine to coarse (50 percent), silt (30 percent), clay (10 percent), with fine gravel (10 percent), dark greenish-gray	25	375
Sand, fine to medium (80 percent), silt (15 percent), with occasional gravel (5 percent), moderate yellowish-brown	25	400
Sand, fine to medium (70 percent), silt (25 percent), and clay (5 percent), moderate yellowish-brown	75	475
Sand, fine (60 percent), silt (35 percent), and clay	5	480

	Thickness (feet)	Depth (feet)
4N/27W-16R1--Continued		
Sand, fine to medium (80 percent), silt (15 percent), and clay (5 percent), medium bluish-gray----------------------	20	500
Sand, fine (65 percent), silt (30 percent), and clay (5 percent), dark greenish-gray--------------------------	50	550
Sand, medium (90 percent), silt (10 percent), with trace of clay, olive-gray---	40	590
Sand, fine (60 percent), silt (30 percent), and clay (10 percent), with trace of shell fragments, light olive-gray--	20	610
Sand, medium to coarse, fine gravel, and shell fragments----	10	620
Sand, poorly sorted (30 percent coarse), silt (20 percent), fine gravel (5 percent), with trace of shell fragments----	20	640
Sand, poorly sorted, silt (30 percent), and clay (5-10 percent), with some shell fragments (5 percent), olive-gray--	70	710
Shale, moderate-brown-------------------------------------	10	720

	Thickness (feet)	Depth (feet)
4N/27W-17J1. Drilled by Sierra Drilling Co., Inc. Logged by U.S. Geological Survey. Altitude 138.8 feet; 8-inch polyvinyl chloride casing; depth of hole 385 feet; depth of well 320 feet; perforated 190-320 feet. Finished 7-6-79.		
Conductor pipe (no samples)	20	20
Sand, coarse, and boulders, moderate yellowish-brown	10	30
Sand, medium to coarse, with trace of clay, light-brown	10	40
Sand, fine to medium, and clay (5 percent), light-brown	20	60
Sand, fine to medium (55 percent), silt (30 percent), and clay (15 percent), moderate yellowish-brown	80	140
Sand, medium (60 percent), silt (30 percent), and clay (10 percent), grayish-olive	40	180
Sand, fine to medium (60 percent), silt (25 percent), and clay (15 percent), dark greenish-gray	20	200
Sand, fine to coarse, clay (5 percent), and cobbles, dark greenish-gray	20	220
Sand, medium, well-sorted, with a trace of clay, grayish-olive	30	250
Sand, fine to medium (70 percent), silt (20 percent), and clay (10 percent), grayish-olive	10	260
Sand, fine to coarse, with a trace of clay, light grayish-olive	20	280
Sand, fine to medium (75 percent), silt (20 percent), and clay (5 percent), light olive-gray	20	300
Sand, medium (50 percent), boulders (50 percent), with a trace of clay, olive-gray	15	315
Sand, medium, salt and pepper (60 percent), silt (20 percent), and cobbles (20 percent) with occasional shell fragments, olive-gray	25	340
Sand, fine to medium, with some shell fragments, olive-gray	10	350
Sand, fine to medium (65 percent), silt (30 percent), and clay (5 percent), with some shell fragments, olive gray	20	370
Shale, grayish-red	15	385

	Thickness (feet)	Depth (feet)

4N/27W-22Q1. Drilled by Sierra Drilling Co., Inc. Logged by U.S. Geological Survey. Altitude 13 feet; 8-inch polyvinyl chloride casing; depth of hole 120 feet; depth of well 60 feet; perforated 20-60 feet. Date finished 7-3-79.

	Thickness (feet)	Depth (feet)
Sand, fine, and clay, olive-gray	20	20
Sand, fine to medium (70 percent), gravel (20 percent), and clay (10 percent), olive-gray	38	58
Shale, grayish-red	62	120

4N/27W-23D1. Drilled by Sierra Drilling Co., Inc. Logged by U.S. Geological Survey. Altitude 12 feet. 8-inch polyvinyl chloride casing; depth of hole 400 feet; depth of well 380 feet; perforated 240-380 feet. Date finished 7-20-79.

	Thickness (feet)	Depth (feet)
Conductor casing (no samples)	0	20
Sand, fine to medium, with some clay, olive-gray	70	90
Sand, medium, clay, olive-gray, some organic matter	10	100
Sand, medium to coarse, fine gravel (10 percent)	10	110
Sand, medium, with silt, and clay	30	140
Sand, medium to coarse, medium, olive-gray	10	150
Sand, medium, with clay (15 percent), medium light-gray	30	180
Sand, fine to coarse, with some clay, dark yellowish-brown	60	240
Sand, very fine to medium, moderate olive-brown	20	260
Sand, fine to coarse (10 percent), light olive-gray	20	280
Sand, fine to coarse, with clay (20 percent), moderate olive-brown	20	300
Sand, very fine, silt and clay, brownish	20	320
Sand, medium to coarse (40 percent), with some gravel and clay, light olive-brown	60	380
Sand, fine, clay (40 percent), and silt, medium light olive-gray	20	400