Ground-Water Monitoring at Santa Barbara, California: Phase 2—Effects of Pumping on Water Levels and on Water Quality in the Santa Barbara Ground-Water Basin

United States
Geological
Survey
Water-Supply
Paper 2197

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 on Water Quality in the Santa Barbara Ground-Water Basin

By PETER MARTIN

Prepared in cooperation with the
City of Santa Barbara

U.S. GEOLOGICAL SURVEY WATER-SUPPLY PAPER 2197

DEPARTMENT OF THE INTERIOR

WILLIAM P. CLARK, Secretary

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, Director

UNITED STATES GOVERNMENT PRINTING OFFICE : 1984

For sale by the
Distribution Branch, Text Products Section
U.S. Geological Survey
604 South Pickett St.
Alexandria, VA 22304

Library of Congress Cataloging in Publication Data

Martin, Peter, 1953–
Ground-water monitoring at Santa Barbara, California.

(U.S. Geological Survey water-supply paper; 2197)
"Prepared in cooperation with the City of Santa Barbara."
Supt. of Docs. no.: I 19.13:2197
1. Santa Barbara (Calif.)—Water-supply. 2. Water quality management—California—Santa Barbara. 3. Water, Underground—California—Santa Barbara. I. Santa Barbara (Calif.) II. Title. III. Series.
TD225.S3M37 1984 363.6'1 84-600121

CONTENTS

FIGURES

TABLES

TABLES

Ground-Water Monitoring at Santa Barbara, California: Phase 2—Effects of Pumping on Water Levels and on Water Quality in the Santa Barbara Ground-Water Basin

By Peter Martin

Abstract

From July 1978 to January 1980, water levels in the southern part of the Santa Barbara ground-water basin declined more than 100 feet. These water-level declines resulted from increases in municipal pumping since July 1978. The increase in municipal pumping was part of a basin-testing program designed 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 to altitudes below sea level in the main water-bearing zones. As a result, the ground-water basin would be subject to saltwater intrusion if the study-period pumpage were maintained or increased.

Data indicate that saltwater intrusion has degraded the quality of the water yielded from six coastal wells. During the study period, the six coastal wells all yielded water with chloride concentrations in excess of 250 milligrams per liter, and 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 so that they lie against consolidated rocks on the seaward side of the fault. Results of this study indicate, however, that ocean water has intruded the deeper water-bearing deposits, and 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. Therefore, if the pumping rate maintained during the basin-testing program were continued, the degraded water 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 is estimated, using Darcy's equation, to be about 20 years.

Management alternatives for controlling 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 in order to minimize drawdown. Continued monitoring of water levels and water quality would enable assessment of the effectiveness of the control measures employed.

INTRODUCTION

Most of the water supply for the city of Santa Barbara is imported from surface reservoirs; ground water is a supplemental source. Decreasing storage capacity of surface reservoirs because of siltation and increased water demands due to population growth, however, has placed increasing stress on the resources of the Santa Barbara ground-water basin. On the basis of the recommendations of an engineering report (Owen, 1976), the city increased ground-water pumping in the basin in order 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. Water levels in this part of the basin, which were above sea level in 1978, dropped to as low as 84 ft below sea level by the end of the study period (January 1980). Because the supply wells are near the coast, the ground water of the Santa Barbara area would be threatened with saltwater intrusion if the study-period pumpage were maintained or increased.

Purpose and Scope

In 1977, the city of Santa Barbara entered into a cooperative study with the U.S. Geological Survey to develop and implement a ground-water monitoring program. The first phase of the program, completed in

1978 (Hutchinson, 1979), resulted in the construction of eight monitor wells at two sites along the coast. These wells were designed to provide an early warning of saltwater intrusion into the freshwater aquifer. At each site, wells were installed at four different depths to enable determination of the vertical distribution of water levels and water quality. The purpose of this second phase of the program is to analyze and evaluate the effect of ground-water pumping on the water levels and on water quality of the ground-water basin. The third and final phase of the program will be the development of a digital flow model for the ground-water basin; such a model will help in defining the hydrology and in managing the water resources of the basin.

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 in 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 our concern is Storage Unit I, which encompasses about 7 mi^2.

The Santa Barbara area has a Mediterranean-type climate of warm, dry summers and mild winters. The area has distinct wet and dry seasons; 95 percent

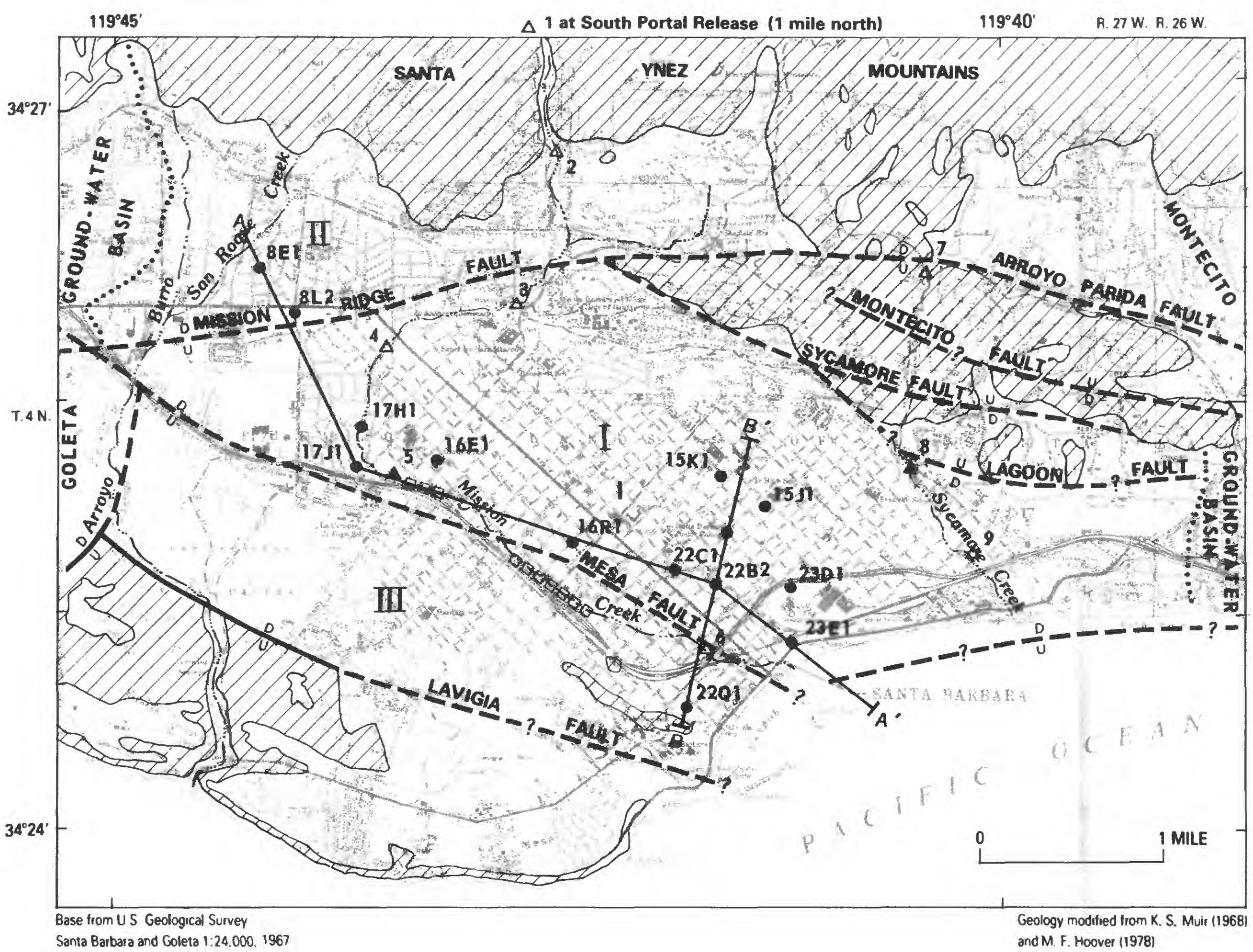


Figure 1. Geology and streamflow stations. Unnamed offshore fault as identified by K. S. Muir (1968).

of the precipitation falls between November and March. The normal precipitation at the lower altitudes of Santa Barbara is 17.41 in/yr (National Oceanic and Atmospheric Administration, 1978).

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

Previous Investigations

Several reports have been published relating to the geology and water resources of the Santa Barbara ground-water basin. The first comprehensive water-resources investigation was done 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) brought the known geohydrology of the basin up to date. They calculated transmissivity and storage characteristics of the basin and constructed an aquifer simulation model in order to estimate the ground-water levels under various basin operating conditions. The report presented the design criteria that were used to construct two city of Santa Barbara production wells.

The consulting firms of Toups Corporation (1974) and Owen (1976) furnished reports on the optimal management of the water resources in the Santa Barbara area. Toups Corporation (1974) discussed the feasibility and cost estimates for artificial recharge of ground water. Owen (1976) evaluated 11 possible ways to meet future water-supply needs. On the basis of this report the city of Santa Barbara increased the ground-water pumping in an attempt 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 which the hydrologic findings of Muir (1968) were modified to reflect 1975 conditions.

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

EXPLANATION

UNCONSOLIDATED DEPOSITS—Includes alluvium and Santa Barbara Formation } QUATERNARY AND TERTIARY

CONSOLIDATED ROCKS } TERTIARY

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

A——A' LINE OF GEOLOGIC SECTION

● 23D1 DATA POINT FOR GEOLOGIC SECTION AND WELL NUMBER

▲5 GAGING STATION AND NUMBER
- **5** Mission Street (11119750)
- **8** Alameda Padre Salinas Street (11119700)

△1 STREAMFLOW MEASUREMENT STATION
- **1** South Portal Release
- **2** Mission Canyon Road
- **3** Rocky Nook Park
- **4** Alamar Street
- **6** Gutierrez Street
- **7** Sycamore Canyon Road
- **9** Punta Gorda Street

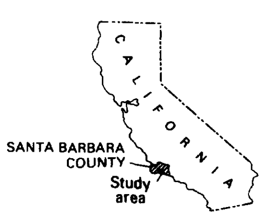


Figure 1. Continued.

Acknowledgments

The cooperation and assistance of the city of Santa Barbara Public Works Department Division of Water Resources, in supplying data (unpub. data, 1980) 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); and the letter following the section number indicates the 40-acre subdivision according to the lettered diagram below. The final digit is a serial number for wells in each 40-acre subdivision.

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

GEOHYDROLOGY

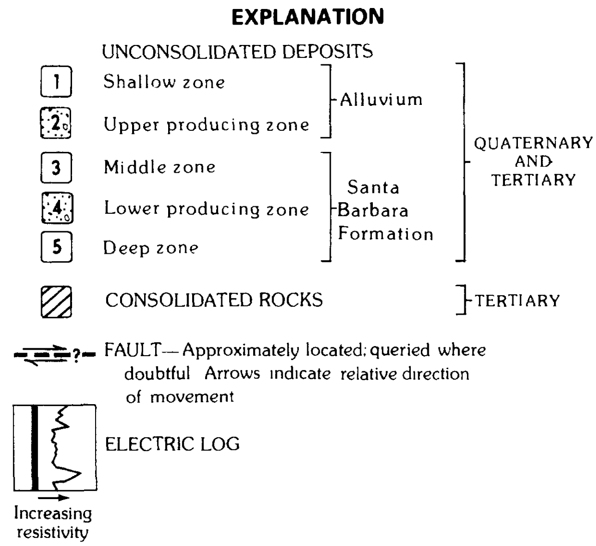
Definition of the Aquifer System

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 their stratigraphic and structural relations.

Consolidated rocks of Tertiary age underlie the ground-water basin and compose the surrounding hills. These consolidated rocks are sedimentary rocks, predominantly marine in origin, that are nearly impermeable except for slightly permeable sandstones, and in fracture zones. Neither the sandstones nor the fracture zones constitute 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, consists of fine to coarse sand, silt, and greenish-gray clay, and has 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, yellowish-brown clay, and 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



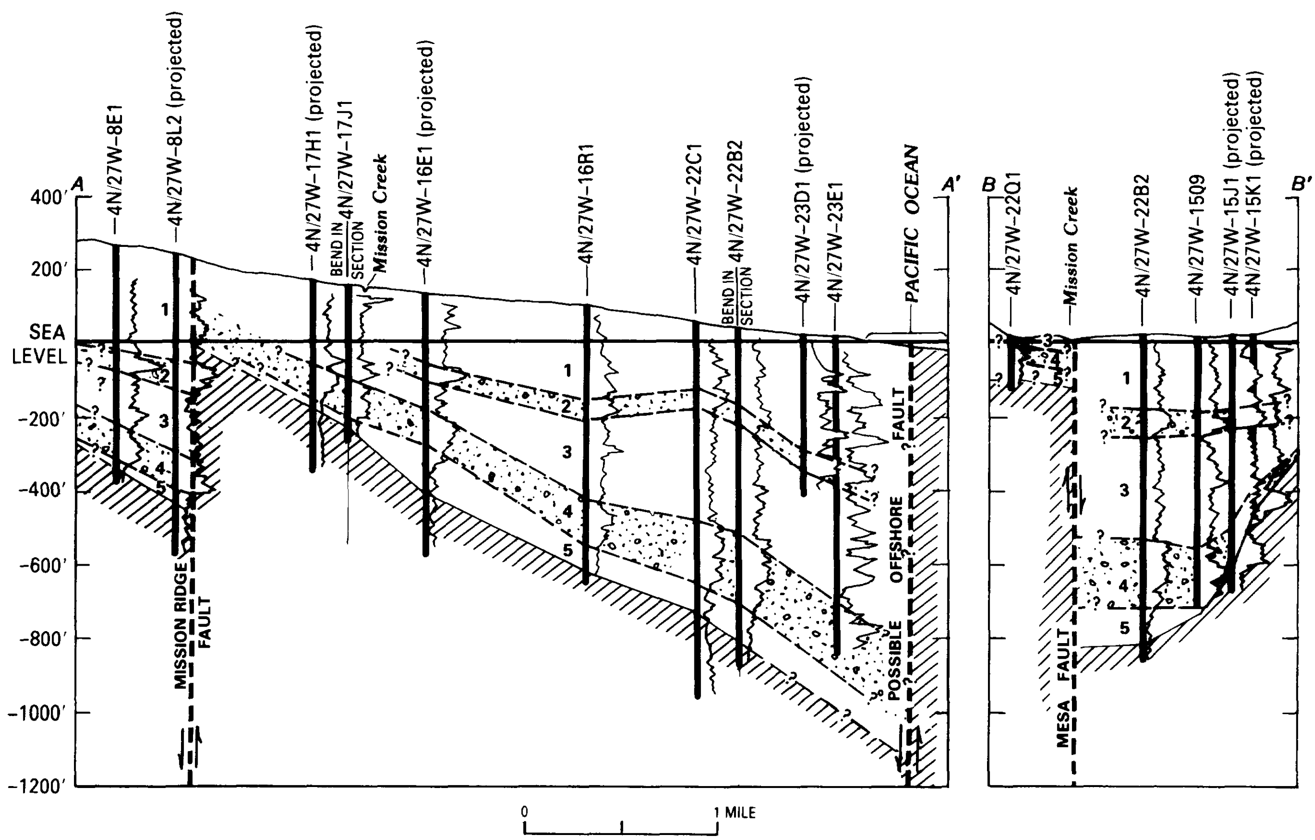


Figure 2. Geologic sections.

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. On the basis of data from the electric logs of selected wells shown in figure 2 and the lithologic logs of six observation wells presented in table 8 at the end of this report, the unconsolidated deposits have been subdivided into five main zones: (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 ground water of high salinity or fine-grained deposits that do not yield water freely to wells.

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

The upper producing zone near the base of the alluvium consists of medium to coarse 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.

Throughout most of the basin, the middle zone underlies the upper producing zone and overlies the lower producing zone. This middle 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 thickness of the middle zone ranges from less than 100 ft southeast of Mission Ridge fault to more than 300 ft 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 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; its thickness generally increases 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.

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

Recharge

The main sources of recharge to the Santa Barbara ground-water basin are infiltration of precipitation, seepage from streams, subsurface inflow from consolidated rocks, and infiltration of imported water from surface reservoirs. Muir (1968) estimated the average yearly recharge contributed by each of these sources over the period 1868-1964. The Santa Barbara County Water Agency (1977) reviewed these estimates and used them to produce an estimate for 1975 on the basis of current hydrologic conditions. The results of both studies are summarized in table 1. The results of the two studies differ primarily in the estimates of infiltration of precipitation and of imported water. Increased urbanization in recent years, according to the Santa Barbara County Water Agency (1977), has reduced the area available for the infiltration of precipitation and has thereby reduced the quantity of recharge contributed by precipitation. With urban growth, water demands also have increased, and so 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 part of the imported water used for irrigation and lawn watering to be a significant source of recharge in 1975.

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 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 the present study,

Table 1. Estimated average annual recharge in the Santa Barbara ground-water basin, in acre-feet per year

[From Todd (1978, p. 43)]

Recharge source	1868-1964 (Muir, 1968)	1975 (Santa Barbara County Water Agency, 1977)
Rainfall infiltration-------	1,100	900
Stream seepage--------------	500	500
Subsurface inflow-----------	300	300
Imported water from surface reservoirs--------	100	800
Total--------------------	2,000	2,500

Table 2. Streamflow measurements for Mission and Sycamore Creeks

Streamflow measurement station (see fig. 1)	Streamflow		Gain(+) or loss(-) of streamflow between stations (acre-ft/d)	Flow distance between stations (mi)	Rate of gain(+) or loss(-) of streamflow between stations ((acre-ft/d)/mi)
	ft^3/s	acre-ft/d			
Controlled release to Mission Creek--September 27 and 28, 1979 (average measurements)					
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

streamflow was measured between successive gaging stations on Mission and Sycamore Creeks to assess 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 of natural streamflows in both creeks and of 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 to October 1, 1979. Average streamflow measurements taken along Mission Creek on 2 consecutive days of the controlled release are shown in table 2. These measurements indicate that seepage loss was not significant until the

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	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

streamflow passed over Mission Ridge fault near the Rocky Nook Park streamflow station (fig 1). Upstream from the Mission Ridge fault, consolidated rock and relatively impermeable clay layers beneath the stream channel precluded significant seepage losses. Small gains in streamflow between the Mission Canyon Road and Rocky Nook Park streamflow stations during the controlled release were probably the result of irrigation runoff.

The greatest rates of seepage loss were measured between Rocky Nook Park and Alamar Street streamflow stations (206 (acre-ft/d)/mi) and between Alamar Street and Mission Street streamflow stations (154 (acre-ft/d)/mi). The average rate of seepage loss for this entire 1.8-mi reach of the stream is 1.78 (acre-ft/d)/mi. One possible explanation for the higher seepage loss rates downstream from Rocky Nook Park is that the clay layers beneath the stream channel on the north side of the Mission Ridge fault are less extensive or are absent 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 in order 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); as a result, seepage-loss rates are significantly reduced in this reach of the stream, where they average only 1.04 (acre-ft/d)/mi. Seepage-loss measurements of natural streamflow in Mission Creek are, in general, similar to the values recorded during the controlled release. However, unmeasured surface runoff flowing into the stream 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 over the period of record of about 73 days.

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: it does not account for (1) losses of streamflow to evapotranspiration and (2) the variations in seepage-loss rates caused by changes in the amount of streamflow. Therefore, the estimate of annual recharge shown in table 3 should be considered as only a gross estimate. To estimate 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

Table 4. Santa Barbara pumpage, 1947-79, in acre-feet

[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	Year	Pumpage	Year	Pumpage
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

September and October of 1979.

As shown in table 3 the recharge from natural streamflow seepage in Mission Creek is estimated to be 376 acre-ft/yr, and the potential recharge of controlled releases is estimated to be 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 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 on 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. Because the water table is below the channel bottom, this increase in streamflow is probably the result of unmeasured surface runoff and not of ground-water discharge. Measurements made in 1980 indicate no seepage losses upstream from the Alameda Padre Salinas Street station, where Sycamore Creek flows across predominantly consolidated rocks that would preclude significant seepage losses. A small loss (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. Because of the low seepage-loss rates measured along the stream, the potential for artificial recharge along Sycamore Creek is considered negligible.

Seepage losses along Arroyo Burro and San Roque Creek, the other major streams in the area, were not measured; 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. With the urbanization of the Santa Barbara area, the major discharge from the basin has become pumping, which has significantly lowered the water table, and natural ground-water discharges are now insignificant in comparison with pumpage from wells.

Ground-water withdrawals from wells began in the early 1800's, to supplement local surface-water sources. Ground water is still a secondary water supply. During years of low rainfall, when surface water is scarce, ground-water pumping is intensified; 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 (table 4) ranges from a low of 81 acre-ft/yr in 1958 and 1959 to a high of 4,243 acre-ft/yr in 1949 and averages 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 (table 4) has often exceeded the estimated perennial yield of the basin.

In the Santa Barbara area pumpage for domestic, agricultural, and industrial uses is small in comparison with the quantity pumped for municipal use. Nonmunicipal pumping has probably been less than 200 acre-ft/yr since 1964.

Ground-Water Levels and Movement

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

The most significant fluctuations of water levels 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 with the rates of municipal pumpage (fig. 4) shows that 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 con-

EXPLANATION

UNCONSOLIDATED DEPOSITS—Includes alluvium and Santa Barbara Formation } QUATERNARY AND TERTIARY

CONSOLIDATED ROCKS } TERTIARY

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

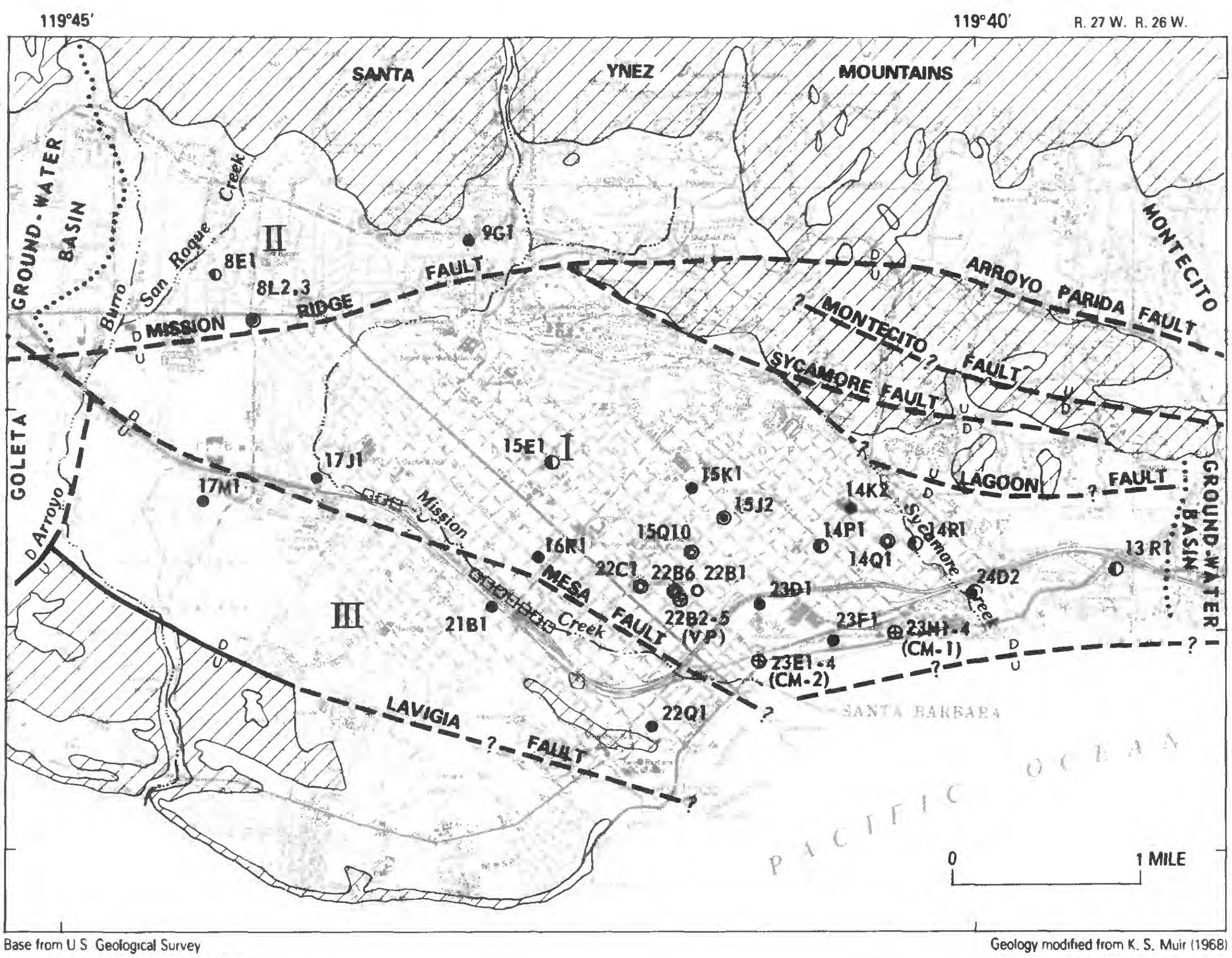
.... GROUND–WATER DIVIDE

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



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)

Figure 3. Locations of water-level and water-quality monitoring wells.

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

Well number	Altitude of land surface (ft)	Depth of well (ft)	Perforated interval[1] (ft)	Altitude of water level (ft)		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	Do.
4N/27W-15E1----	145	231	--	+47.40	+27.00	Do.
4N/27W-15J2----	12.31	579	198-579	+7.38	-45.73	Do.
4N/27W-15K1----	18.9	464	280-464	--	-39.50	Do.
4N/27W-16R1----	84.8	625	545-625	--	-42.20	Do.
4N/27W-17J1----	138.8	320	190-320	--	+91.20	Do.
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	Do.
4N/27W-9G1-----	395	221	179-221	+292.28	+298.45	Do.
			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	Do.
4N/27W-22Q1----	13	60	20-60	--	+7.18	Do.

[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.

fined throughout most of the Santa Barbara area; therefore, the water levels in these zones respond rapidly to variations in pumping.

The July 1978 water-level contours constructed from measurements in wells perforated in the lower producing zone are shown in figure 5. Because municipal pumping had been reduced significantly prior to the July 1978 water-level measurements, 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. The municipal pumping rate averaged 5.1 acre-ft/d for the period 1947-79, whereas, during the 6 months prior to July 1978 municipal pumping averaged only about 1 acre-ft/d. The reduction in municipal pumping allowed the water levels to recover almost to prepumping levels. In fact, the water level of July 6, 1978, in well 4N/27W-21B1, which has the longest record of measurements (beginning in 1931), was the third highest water level of record.

Ground-water movement in the Santa Barbara area during July 1978 was generally from the northwest, toward the Pacific Ocean (fig. 5). Throughout the area, water levels were above sea level and depressions related to pumping were not indicated by 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; figure 6 is a water-level-contour map of the lower producing zone. Comparison of the July 1978 and the January 1980 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 include 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; but during January 1980, ground water flowed northward, away from the ocean. The January 1980 ground-water-flow pattern suggests that the ground-water basin is subject to saltwater intrusion.

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

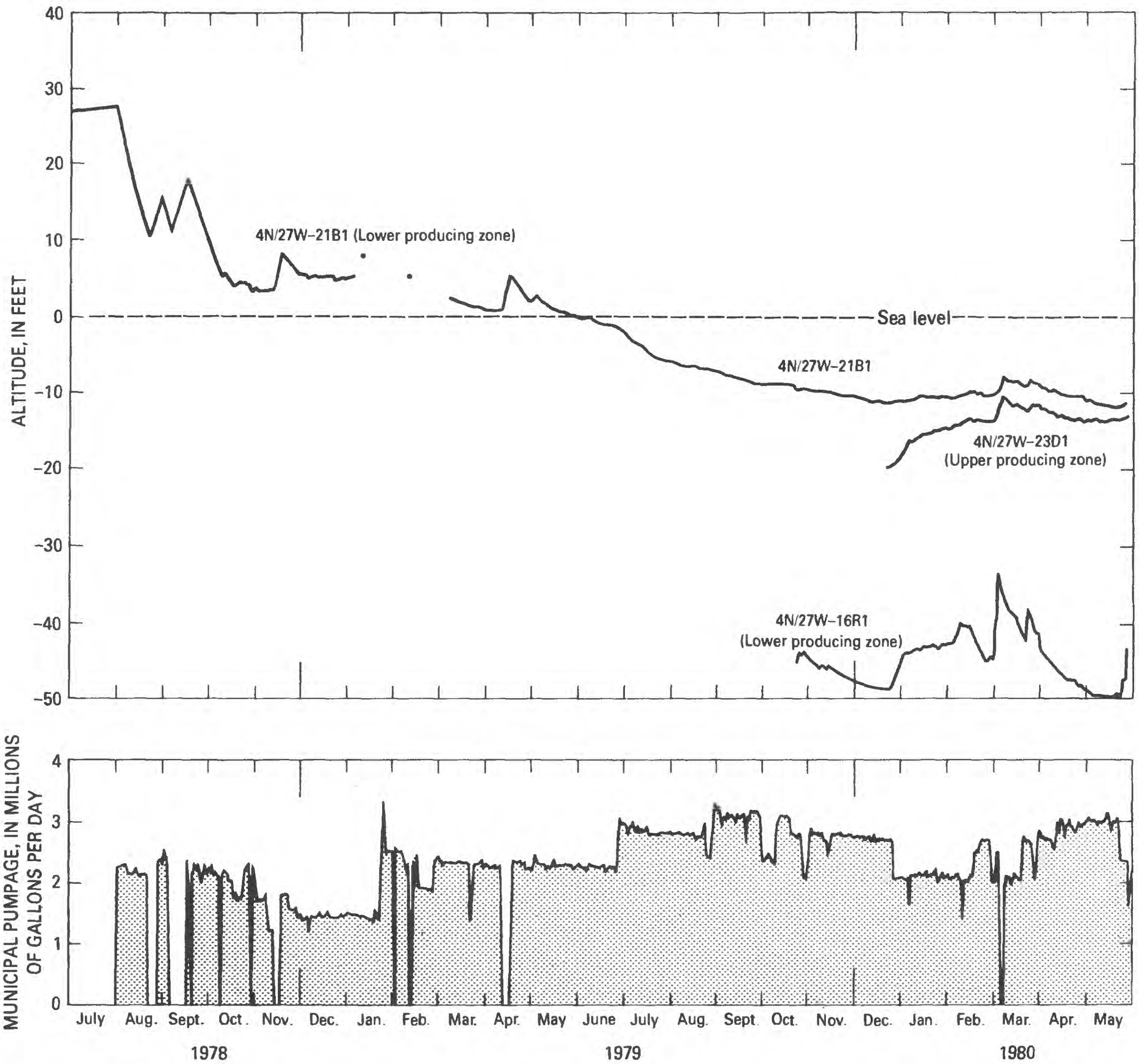


Figure 4. Water-level hydrographs of selected wells and graph of municipal pumpage, July 1978 to May 1980.

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). Water levels measured at the wells in Vera Cruz Park during July 1978 indicate that the hydraulic head increased with depth except in the deep zone, which had the lowest hydraulic head. Thus, it appears that during nonpumping conditions, water moved upward from the lower producing zone to the middle zone and downward from the lower producing zone to the deep zone. 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. So it appears that water can move upward from the underlying deep zone into the lower producing zone and downward by leakage from the middle zone into the lower producing zone.

EXPLANATION

UNCONSOLIDATED DEPOSITS—Includes alluvium and Santa Barbara Formation } QUATERNARY AND TERTIARY

CONSOLIDATED ROCKS } TERTIARY

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

GROUND-WATER DIVIDE

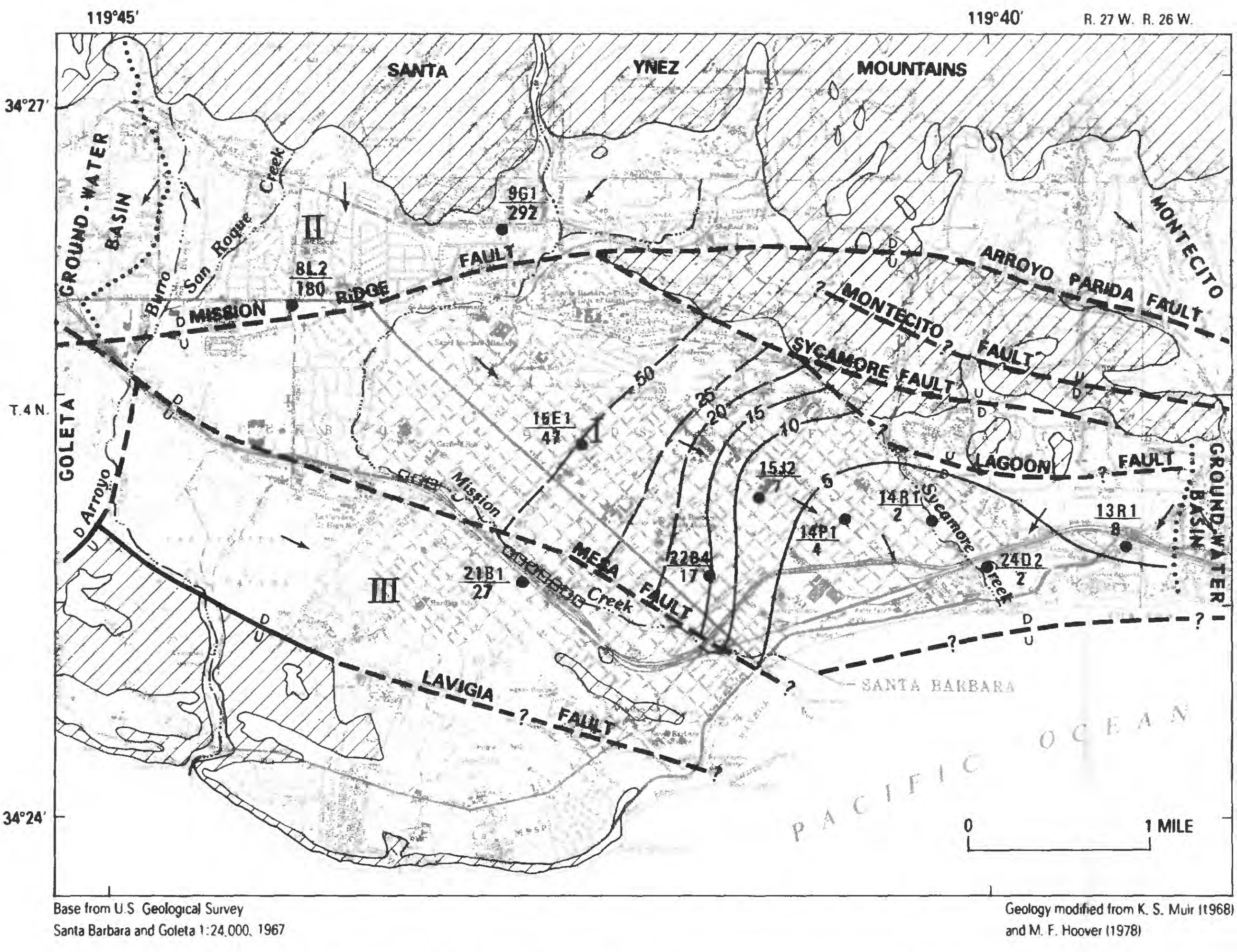
II GROUND-WATER STORAGE UNIT—Faults control storage-unit boundaries

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



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)

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

During January 1980, the water level of the shallow zone at coastal monitor site 2 was above sea level; 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 there is little hydraulic continuity between the shallow zone and the underlying, highly pumped zones. Monitor wells at the coastal sites were not constructed until August 1978, and so nonpumping conditions and pumping conditions at these sites cannot be compared.

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 were not there. 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-ft displacement between the tops 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 that appear in wells on the northeast side of the fault as a result of the municipal pumping; however, water levels in well 4N/27W-21B1 (fig. 4), also on the southwest side of the fault, do reflect those changes. Well 4N/27W-21B1 is about 1 mi northwest of well 4N/27W-22Q1; there, the vertical displacement on opposite sides of the fault is less pronounced than it is near the ocean, and so ground water might move across the fault.

GROUND-WATER QUALITY

Water-quality determinations are made annually on samples from 30 wells. Figure 3 shows the location of the sampled wells, and table 6 shows the final water-quality data for the period of this study. Most of the wells yield water suitable for domestic use; some, however, 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 table 6 shows, in 1978-80, 14 wells yielded water with a concentration of one or more chemical constituents in excess of the U.S. Environmental Protection Agency's (1976 and 1977) mandatory 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 are 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. The ground water does not necessarily have uniform quality throughout the lateral extent of any one zone.

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 has higher concentrations of dissolved solids and chloride than does ground water in the underlying zones, except for the deep zone (fig. 8). In the samples from the upper producing zone collected during 1979 (table 6), concentrations of dissolved solids range from 415 to 5,500 mg/L and chloride concentrations range from 32 to 3,100 mg/L. Five of the seven wells sampled had water with chloride concentrations exceeding 100 mg/L. The high concentrations of dissolved solids and chloride 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.

Three wells in the water-quality network yield water from the middle zone (table 6). The well that taps 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 they contain high concentrations of chloride. The source of the high chloride concentrations is discussed in the section "Potential Sources of Ground-Water Degradation."

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 (table 6) are representative of the water quality in the lower producing zone. The areal distributions of water types (in terms of abundance of ions) and the 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 figure 9, 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 and north of U.S. Highway 101 yield water containing the lowest concentration of dissolved solids (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. Because ground water in Storage Unit I is surrounded by water of poorer quality (fig. 9), underflow from the adjacent storage units is not considered a major source of water for Storage Unit I. The sources of the water with low dissolved-solids concentration are 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 for 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 ground 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 section "Potential Sources of Ground-Water Degradation."

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 that contains dissolved-solids, sodium, and chloride concentrations of 2,260, 750, and 1,200 mg/L, respectively. Only this one well taps the deep zone; however, the electric logs of the pilot holes for many wells in the ground-water basin (fig. 2) have low resistivity measurements for the deep zone that

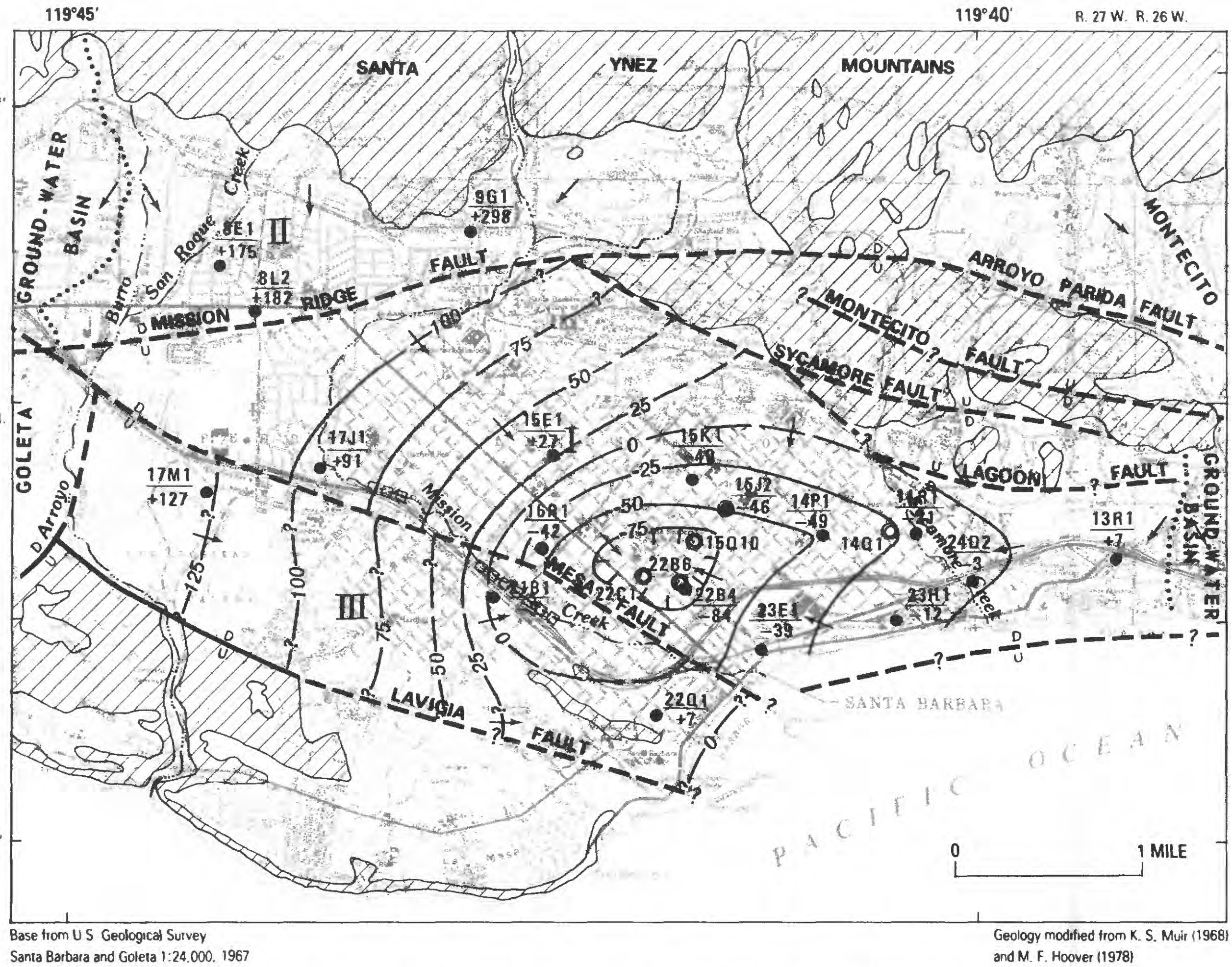


Figure 6. Water-level contours of the lower producing zone, January 1980.

suggest the presence of fine-grained deposits of low permeability or water of poor quality overlying the consolidated rocks in most of the basin.

The high sodium and chloride concentrations in the deep zone suggest saltwater intrusion; however, the sulfate concentrations of the sampled ground water are much lower than the concentration that would result from a simple mixture of native water and ocean water. The sulfate concentration of the deep zone is only 80 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 noted 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 $\mu g/L$, 7,100 $\mu g/L$, and 1.3 mg/L, respectively. The average concentrations of barium, boron, and fluoride in ocean water are 30 $\mu g/L$, 4,600 $\mu g/L$, 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 indicates that saltwater intrusion is not the source of the degraded water sampled in the deep zone. Further investigation is necessary to determine the source of the degradation.

Production wells in the Santa Barbara area are generally perforated opposite all the zones discussed except 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. Most wells have cement sanitary seals placed opposite the shallow zone to prevent contamination

EXPLANATION

UNCONSOLIDATED DEPOSITS—Includes alluvium and Santa Barbara Formation — QUATERNARY AND TERTIARY

CONSOLIDATED ROCKS — TERTIARY

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, in feet, of water level in wells. Dashed where approximately located; queried where doubtful. Contour interval 25 feet. National Geodetic Vertical Datum of 1929

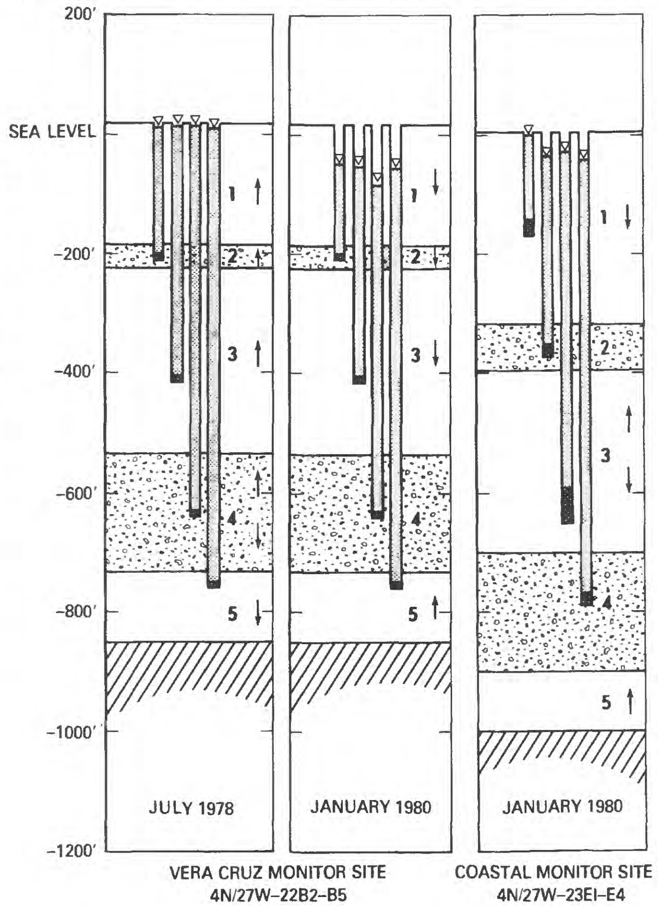
8E1 / +175 DATA POINT—Top number is well number; bottom number is altitude of water level in feet above (+) or below (–) National Geodetic Vertical Datum of 1929

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. Continued.



EXPLANATION

UNCONSOLIDATED DEPOSITS

1 Shallow zone

2 Upper producing zone

3 Middle zone

4 Lower producing zone

5 Deep zone

CONSOLIDATED ROCKS

Water level in well

Perforated interval

Potential vertical direction of ground-water movement

Figure 7. Water levels in nested wells.

Table 6. Chemical analyses of water

[Constituents and hardness are in milligrams per liter

Well location	Date of sample	Well depth (ft)	Perforated interval[1] (ft)	Specific conduct-ance (μmho/cm at 25°C)	pH	Hardness as $CaCO_3$	Calcium	Magne-sium	Sodium	Potas-sium
U.S. Environmental Protection Agency's (1976 and 1978) maximum (M) or recommended (R) limit-----------------					5-9 (R)					
Storage Unit I										
4N/27W-14K2---	07-30-79	380	260-380	1,400	8.0	520	130	47	110	4
	10-03-79			1,750	7.4	700	180	60	130	3
4N/27W-14Q1---	10-04-79	700	72-700	1,300	6.1	500	130	42	81	2
4N/27W-15J2---	10-04-79	599	198-579	820	6.1	310	82	25	44	2
4N/27W-15K1---	07-18-79	464	280-464	720	7.7	260	65	23	39	2
4N/27W-15Q10--	10-04-79	675	195-655	825	6.2	310	85	24	40	2
4N/27W-16R1---	10-03-79	625	545-625	1,010	7.9	300	85	22	96	2
4N/27W-17J1---	07-16-79	320	190-320	760	7.6	280	69	25	49	2
4N/27W-22B1---	10-04-79			1,050	6.0	370	94	33	64	2
4N/27W-22B2---	10-02-79	230	220-230	1,020	6.9	400	95	39	53	2
4N/27W-22B3---	10-03-79	435	425-435	660	7.8	250	53	29	40	2
4N/27W-22B4---	10-03-79	660	650-660	765	7.5	300	85	22	44	2
4N/27W-22B5---	10-04-79	780	770-780	4,500	7.6	330	88	27	750	9
4N/27W-22B6---	10-03-79	700	210-670	770	6.5	310	87	22	39	2
4N/27W-22C1---	10-04-79	630	180-615	725	6.2	280	77	21	36	2
4N/27W-23D1---	07-23-79	380	240-380	920	7.3	330	86	27	71	2
4N/27W-23E1---	06-14-79	805	775-800	3,300	7.5	1,100	300	90	300	5
4N/27W-23E2---	06-14-79	660	600-655	11,400	6.4	4,200	1,100	350	770	9
4N/27W-23E3---	06-14-79	385	355-380	580	7.9	250	67	21	48	2
4N/27W-23E4---	06-14-79	180	150-175	700	7.0	280	68	27	58	2
4N/27W-23F1---	10-05-79	500		985	6.8	340	85	31	74	2
4N/27W-23H1[3]--	06-21-79	781	746.5-781	1,340	8.2	200	45	21	70	220
4N/27W-23H2---	06-06-79	620	585.5-590.5	1,640	6.8	660	160	62	99	2
4N/27W-23H3---	06-06-79	310	284-299	9,200	6.3	4,400	1,100	400	310	6
4N/27W-23H4---	06-06-79	95	75.5-91	1,960	7.2	780	210	62	110	3
4N/27W-24D2---	03-15-78	473	131-473	6,700	6.9	2,600	580	290	370	4
Storage Unit II										
4N/27W-8L3[4]--	01-31-80	610	260-610	1,020	6.8	400	100	36	77	--
4N/27W-9G1---	03-16-78	221	179-221	1,170	6.5	470	95	57	77	0.8
Storage Unit III										
4N/27W-17M1---	10-15-79	375	75-375	1,180	7.4	400	110	31	110	3
4N/27W-21B1---	02-11-80	454	145-350	1,170	7.2	550	150	42	60	2
4N/27W-22Q1---	07-16-79	60	20-60	2,250	7.9	510	120	51	360	4

[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.

from surface sources. The wells are not perforated opposite the deep zone, which contains water of inferior quality. Consequently, water quality from the production wells represents a composite of that from the upper producing, middle, and lower producing zones. The chemistry of any one composite sample 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. In chemical composition the water from the Vera Cruz Park production well is very similar 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 that taps the upper producing zone. The monitor well except where noted. Constituents are dissolved]

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]
	250 (R)	250 (R)	1.4-2.4 (M)			10 (M)	1,000 (M)	750 (R)	
				Storage Unit I--Continued					
230	360	120	0.3	34	950	1.4	100	100	Upper producing
280	510	140	.5	29	1,230	2.2	--	250	--
250	280	110	.4	30	838	2.7	--	180	Lower producing
170	120	70	.4	32	490	2.7	--	40	Do.
180	140	26	.4	34	438	.00	80	90	Do.
190	110	61	.4	34	491	4.7	--	40	Do.
260	120	99	.5	30	612	.04	300	670	Do.
240	110	46	.4	39	486	.25	100	150	Do.
190	110	120	.4	36	640	15	--	40	Upper producing
180	120	120	.5	--	634	14	--	40	Do.
230	92	22	.2	--	405	.00	--	40	Middle
260	98	29	.2	--	466	.00	--	60	Lower producing
240	8.0	1,200	1.3	--	2,260	.25	3,600	7,100	Deep
240	120	35	.3	33	486	.68	--	60	Lower producing
190	110	33	.4	32	431	1.3	--	50	Do.
180	98	140	.2	38	572	.28	100	370	Upper producing
360	150	900	1.0	42	2,000	.00	0	220	Lower producing
140	100	4,000	.2	34	6,450	.01	0	190	Middle
190	98	32	.5	33	415	.00	0	60	Upper producing
240	97	50	.6	45	494	.01	0	210	Shallow
250	180	66	.5	28	617	.00	--	120	Upper producing
310	120	160	.4	5.3	830	.20	60	800	Lower producing
190	120	380	.2	33	974	.04	100	100	Middle
170	420	3,100	.4	26	5,500	2.5	100	550	Upper producing
260	190	400	.3	33	1,170	1.6	100	150	Shallow
200	270	2,000	.3	35	3,680	.79	--	140	Lower producing
				Storage Unit II--Continued					
240	210	68	0.3	--	814	3.6	--	100	Lower producing
140	340	98	.2	27	796	3.8	--	250	Do.
				Storage Unit III--Continued					
330	140	130	0.6	26	754	1.1	--	290	Lower producing
300	260	61	.3	21	785		--	150	Do.
600	260	270	.3	21	1,450	.09	400	3,000	Do.

[3]Contaminated with drilling fluid.
[4]Analysis from M. F. Hoover, Consulting Geologist (written commun., 1980).

in the middle zone yields water containing 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 has slightly lower concentrations of dissolved solids and chloride than does 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 does water from the Vera Cruz Park production well.

The nitrate-nitrogen concentration in water from the upper producing zone is also significantly higher than in water from the Vera Cruz Park production well. Nitrate-nitrogen is referred to as "Nitrite plus nitrate as N" in table 6. The nitrate-nitrogen concentrations in water from the different zones and from the Vera Cruz Park production well in October 1979 are as

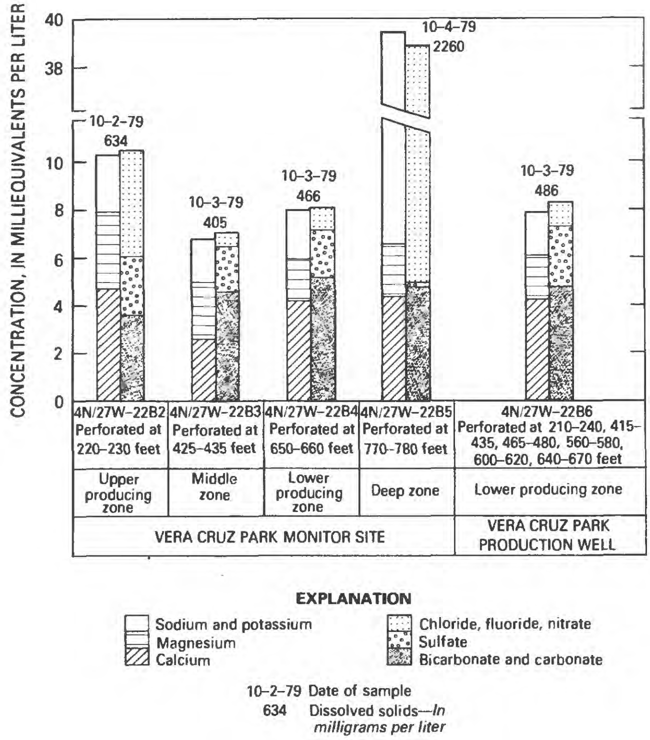


Figure 8. Chemical composition of ground-water samples from the Vera Cruz Park monitor site and production well.

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, whereas 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 amounts of water contributed by the middle and the 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 as thick as the lower producing zone. Therefore, it appears 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.

Potential Sources of Ground-water Degradation

For many years prior to and including the study period ground water of inferior quality had been produced from wells near the coast of the Santa Barbara area. The pumping was discontinued at a few of the wells because the water-quality degradation became so great that the water could no longer be used. Of the 30 wells sampled during this study, 9 wells yielded water with dissolved-solids concentrations near or in excess of 1,000 mg/L. The ground water of inferior quality usually has high chloride concentrations. Eight of these wells yielded water whose chloride concentrations exceeded the U.S. Environmental Protection Agency's (1977) recommended limit of 250 mg/L for chloride in public water supplies (table 6). The major potential sources of ground-water-quality degradation in the Santa Barbara area are ocean water and ground water from the deep zone.

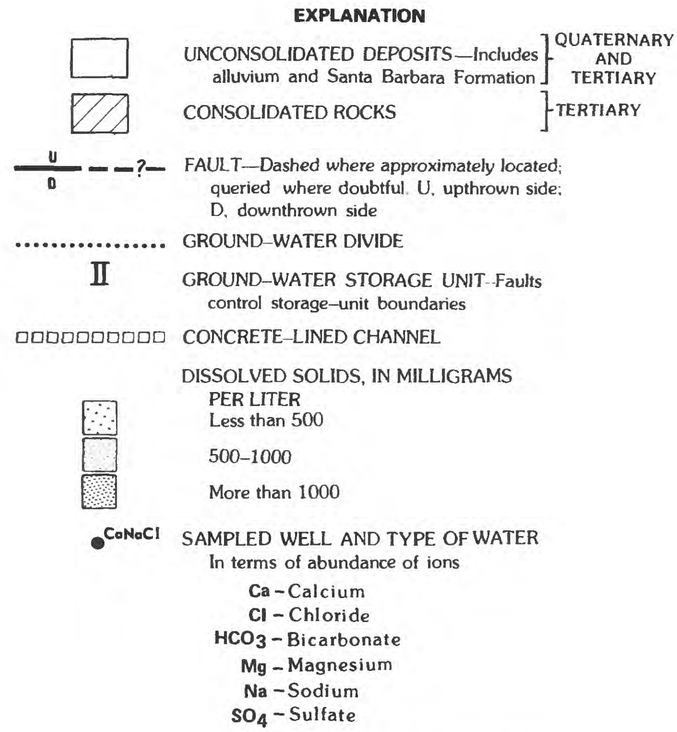
Ocean water is an obvious potential source of ground-water degradation in the Santa Barbara area because certain areas along the coast have been or are within the tidal zone and because ground-water pumping centered about 1 mi from the coast has lowered water levels near the coast to below sea level.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

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

The chemical composition of ground water from well 4N/27W-22B5 is representative of the deep zone (table 6). As described earlier in this 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 its lower concentration of sulfate and higher concentrations of barium and boron (table 7).

In general, the potential sources of the degraded water are not a simple mixture of native water and ocean water or ground water from the deep zone. This contaminated water is due to chemical modifications caused chiefly by cation exchange and sulfate reduction. This phenomenon was observed by Piper and others (1953) in a study of saltwater intrusion in the Long Beach-Santa Ana area of southern California. They noted that no single major constituent or ratio between constituents could provide a definite index for discriminating between the different sources contributing to high chloride concentration. However, in this study a basis for discriminating the sources of degradation is provided by comparing the differences between the concentrations of certain chemical constituents in ocean water and in water from the deep zone (table 7) as follows:

1. Sulfate indicates saltwater intrusion in those cases where, in the absence of reducing conditions, the concentration of sulfate in the degraded water is greater than could have been produced by the introduction of water from the deep zone (Piper and others, 1953, p. 91). The sulfate concentra-



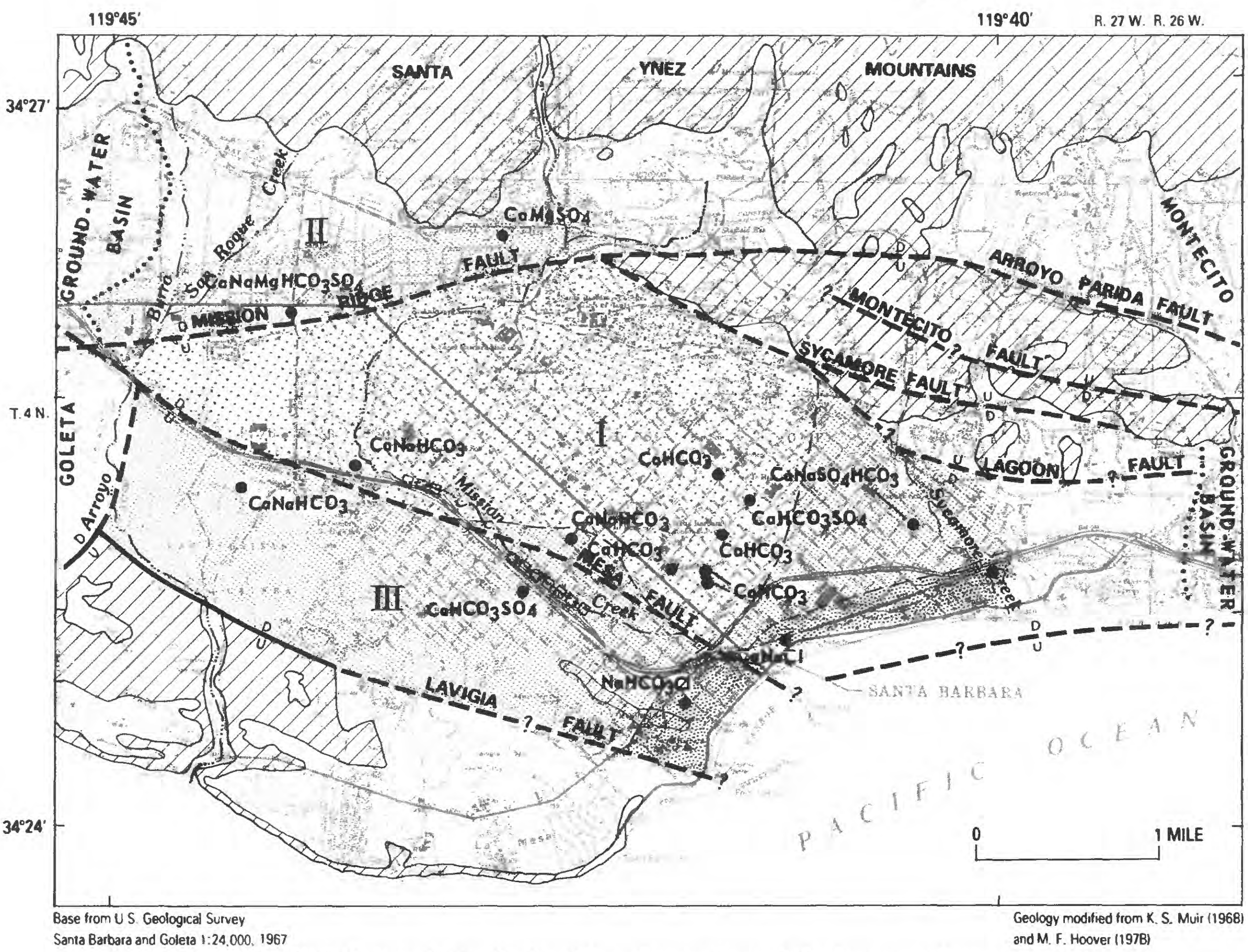


Figure 9. Distribution of dissolved solids and water type of the lower producing zone.

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

Well location or potential source of degradation	Date of sample	Sulfate (mg/L)	Chloride (mg/L)	Dissolved solids, calculated, sum of constituents (mg/L)	Barium (µg/L)	Boron (µg/L)	Chloride: sulfate (mg/L)	Chloride: 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	0.3	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	Do.
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	Do.
Native ground water (city supply wells)									
4N/27W-14Q1------	10-04-79	280	110	838	Trace[2]	180	0.4	610	Lower producing
4N/27W-15J2------	10-04-79	120	70	490	[2]100	40	.6	1,700	Do.
4N/27W-15Q1------	10-04-79	110	61	491	[2]100	40	.6	1,500	Do.
4N/27W-22B6------	10-03-79	120	35	486	[2]100	60	.3	580	Do.
4N/27W-22C1------	10-04-79	110	33	431	Trace[2]	50	.3	660	Do.

[1]Data from Hem (1970, p. 11).
[2]Barium data from the city of Santa Barbara (written commun., 1980). Sample collected June 1980.

tions 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 that is much higher than that determined for ocean water is presumptive evidence, in the absence of reducing conditions, that water from the deep zone is the source of degradation. The chloride-to-sulfate ratios in milligrams per liter for ocean water, water from the deep zone, and native ground water in the Santa Barbara area are 7.0, 150, and less than 1, respectively.
3. Barium concentrations exceeding 200 to 300 µg/L are presumptive (but not conclusive) evidence that the source of degradation is water from the deep zone and not ocean water (Piper and others, 1953, p. 91). Barium is a reactive chemical constituent, and so its concentrations are not an infallible means of determining whether ocean water or water from the deep zone is 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. A chloride-to-boron ratio in the degraded water that is substantially less than the ratio for ocean water is presumptive evidence that the source of degradation is water from the deep zone (Piper and others, 1953, p. 91). The chloride-to-boron ratios of ocean water and water from the deep zone, in 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 for ocean water, water from the deep zone, ground water of inferior quality, and native ground water. The sulfate concentration in ground water of inferior quality is substantially higher than the sulfate concentration in water from the deep zone; that difference suggests 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 of the samples are low; that, too, suggests that water from the deep zone is not a major source of ground-water degradation. The similarity of chloride-to-sulfate ratios for ocean water and for water produced from three of the wells (4N/

27W-23E1, 23H3, and 24D2) suggests strongly that ocean water is the source of degradation for these wells.

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

Except for samples from wells 4N/27W-14K2 and 22Q1, the chloride-to-boron ratios for the ground water of inferior quality are substantially higher than that ratio for native ground water and they approach or exceed the ratio determined for ocean water. These chloride-to-boron ratios suggest that ocean water is the source of ground-water degradation. Well 4N/27W-14K2 produced 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 of the southeastern part of Storage Unit I. Well 4N/27W-22Q1 yielded water with a chloride-to-boron ratio lower than that determined for water from the deep zone. This low chloride-to-boron ratio is presumptive evidence that water from the deep zone is the source of degradation for ground water produced by this well.

In summary, comparisons of the sulfate and barium concentrations, chloride-to-sulfate ratios, and chloride-to-boron ratios for the potential sources of ground-water degradation with those for ground water of inferior quality suggests that ocean water is the source of the degradation of the water yielded by six of the wells (4N/27W-23E1, 23E2, 23H2, 23H3, 23H4, and 24D2). The fact that all of these wells are adjacent to the coast adds further support to the thesis 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. Evidently, in most of the basin the clay layer above the deep zone retards significant movement of water from the deep zone to the overlying lower producing zone. The water yielded from well 4N27W14K2, the one remaining well yielding water of inferior quality, is probably representative of native ground-water conditions in the southeastern part of Storage Unit I.

EFFECTS OF PUMPING ON WATER LEVELS AND ON WATER QUALITY

From August 1978 through January 1980 municipal pumping was increased in the Santa Barbara area as part of a basin-testing program in an attempt 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. At times in the past, the municipal pumping rate had equaled or exceeded the pumping rate during the basin testing; however, comprehensive water-level data were not available then to enable assessment of the effects of the pumping on the ground-water basin.

The increase in municipal pumping caused significant water-level declines in the basin. Comparison of the July 1978 water-level map (fig. 5) with the January 1980 water-level map (fig. 6) shows 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 it has caused declines in water level 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 had dropped to as low as 84 ft below sea level in January 1980. The municipal pumping reversed the ground-water gradient between the pumping center and the Pacific Ocean. During July 1978, ground water flowed southward, toward the ocean; 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, created the potential for saltwater intrusion.

And in fact, ground-water quality data collected from six coastal wells (4N/27W-23E1, 23E2, 23H2, 23H3, 23H4, and 24D2) in the Santa Barbara area during the study period suggest that ocean water had intruded into the water-bearing deposits adjacent to the coast. Available chloride data from these wells are shown in figures 11 and 12. The six coastal wells all yielded water whose chloride concentrations exceeded the U.S. Environmental Protection Agency's (1977) recommended limit of 250 mg/L for chloride in public water supplies, and four of the wells (4N/27W-23E1, 23E2, 23H3, and 24D2) consistently yielded water with chloride concentrations in excess of 1,000 mg/L (figs. 11 and 12).

Of the six wells, only well 4N/27W-24D2 had been 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 from the surface down to 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 leakage around the cement seal 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. However, chloride data collected from the shallow, upper producing, middle, and lower producing zones at coastal monitor sites 1 and 2 (fig. 12) indicate that the shallow zone yields water with a lower

EXPLANATION

UNCONSOLIDATED DEPOSITS—Includes alluvium and Santa Barbara Formation — QUATERNARY AND TERTIARY

CONSOLIDATED ROCKS — TERTIARY

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. 6) over the July 1978 water-level map (fig. 5). Interval 20 feet

DATA POINT

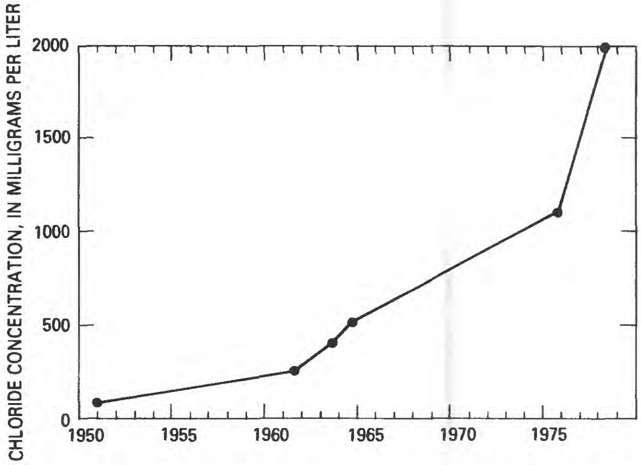
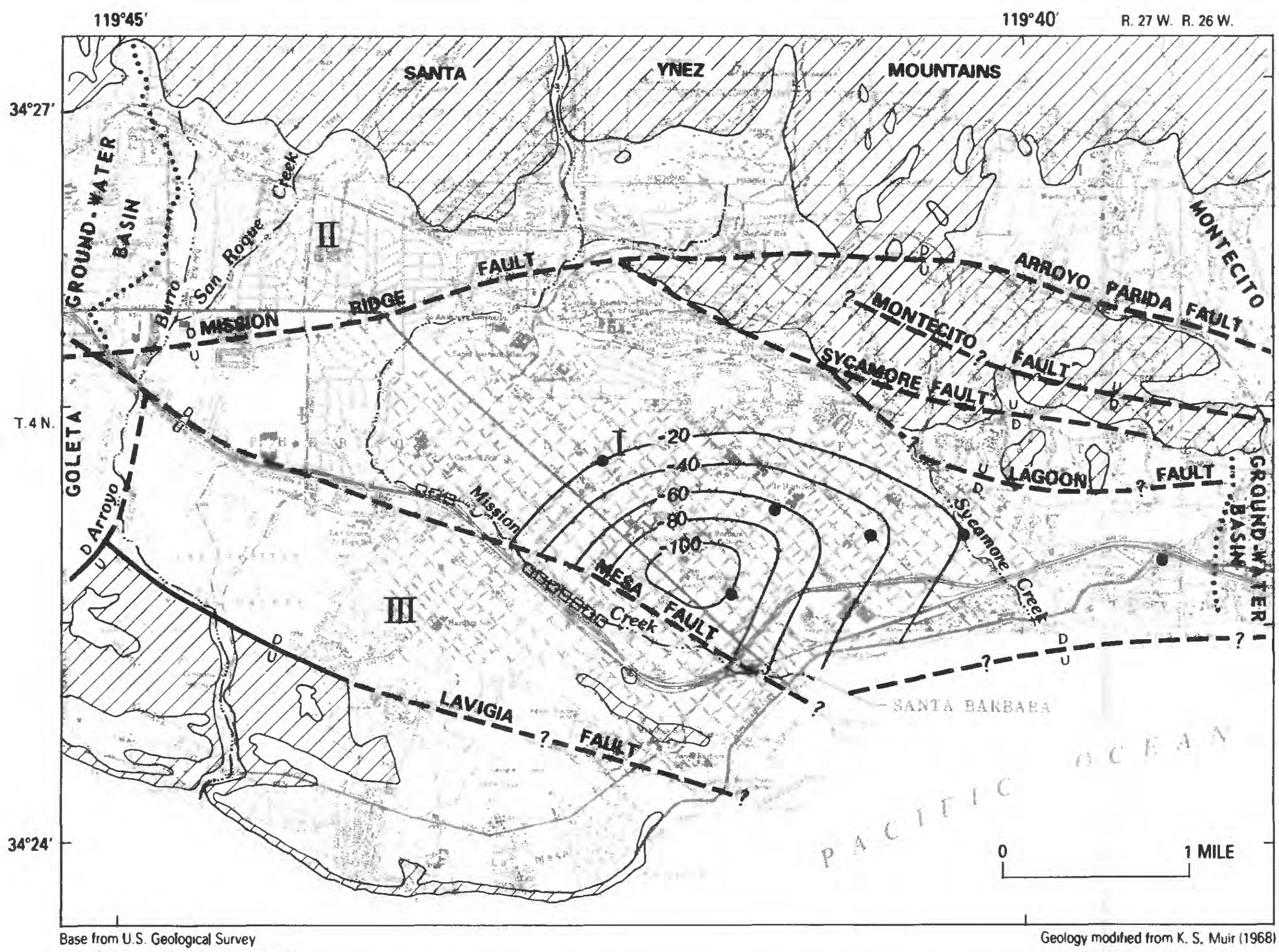


Figure 11. Chloride concentration of samples from well 4N/27W-24D2, 1950-78.



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)

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

chloride concentration than that of 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 levels of chloride. 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 intruded the deeper water-bearing deposits to a much greater extent than it intruded the shallow zone. Apparently the offshore fault (figs. 1 and 2) is not an effective barrier to saltwater intrusion. Perhaps the fault zone is permeable, so that ocean water migrated along the fault zone and then came 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 were to be continued, the degraded water already present along the coast could move inland to 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 by using the following form of Darcy's equation:

$$\overline{v} = \frac{T\, dh/dl}{b\theta}$$

where

$\overline{v}$ = average velocity of ground-water movement, in feet per day;

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

dh/dl = hydraulic gradient, in this case 0.015 ft/ft (fig. 5);

b = thickness of the lower producing zone, in this case 150 ft (fig. 2); and

θ = effective porosity of the lower producing zone, in this case 30 percent (estimated from drillers' logs, table 8 at the end of this report).

The average velocity of ground-water movement calculated by the above equation is 0.37 ft/d. At this rate

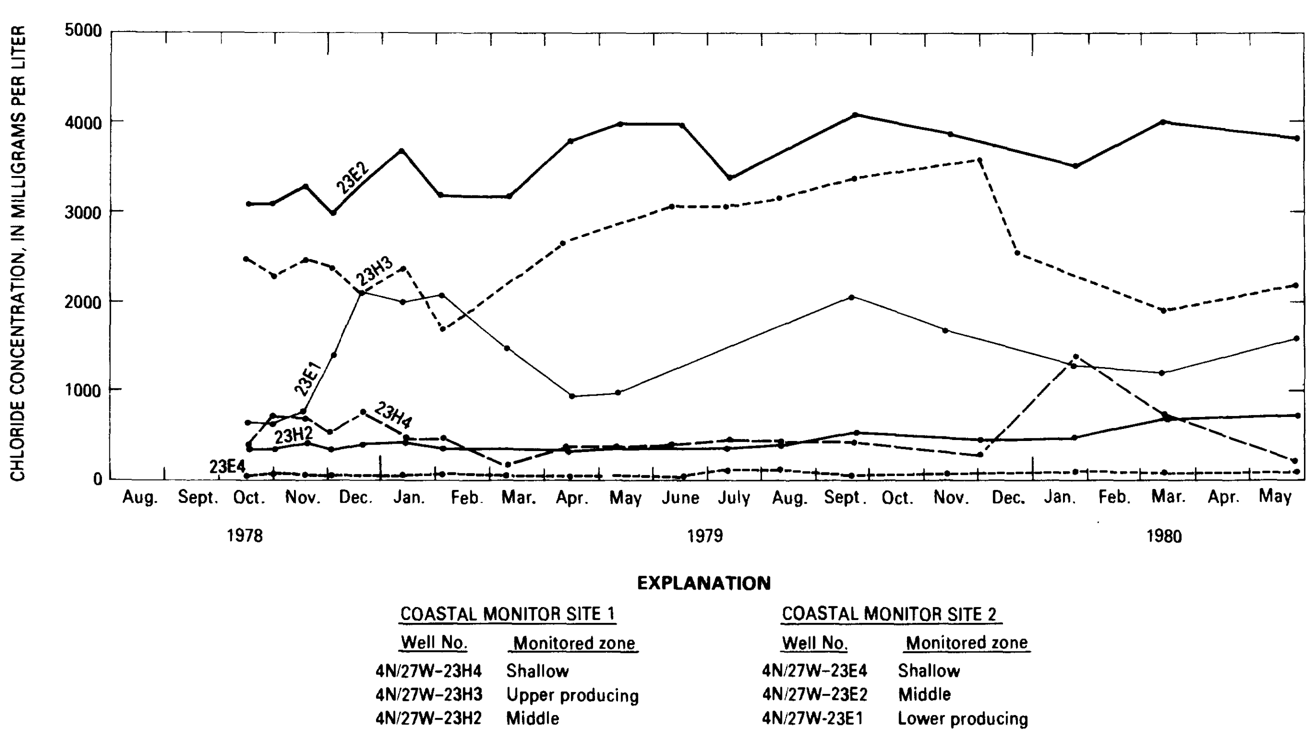


Figure 12. Chloride concentrations of samples from selected wells at coastal monitor sites 1 and 2, August 1978 to May 1980.

of ground-water movement, the degraded water would move 3,000 ft from the coast to the nearest supply well, 4N/27W-22B6, in about 22 years.

The solution to the equation above gives the average velocity; it does not purport to 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; the actual movement may take place faster or slower than calculated.

MANAGEMENT ALTERNATIVES FOR CONTROLLING SALTWATER INTRUSION

As determined from data of the study period July 1978 through January 1980, 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 this intrusion in ground-water basins is to raise water levels throughout the basin to such a height that freshwater will displace the intruded ocean water and force it seaward. Any of several alternative methods might be employed, singly or in combination, to raise water levels in the Santa Barbara ground-water basin. Continued measurements of water level and water quality at the existing monitoring wells (fig. 3) would provide the data needed in order to assess the effectiveness of the various management alternatives in most of the basin.

Decrease pumpage.—Pumpage in the Santa Barbara ground-water basin currently (1980) exceeds the estimates of annual recharge to the basin. If annual pumpage were decreased sufficiently below the estimated annual recharge, water levels in the basin would recover; past decreases in municipal pumping have in fact 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.

Increase Mission Creek recharge.—During those 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. At the same time, selective pumping along the permeable reach of Mission Creek below Mission Ridge fault would lower water levels in this part of the basin and so provide additional storage space for Mission Creek recharge. Lack of storage space in this part of the basin probably has limited the storage of seepage from Mission Creek during periods of high runoff. Additional monitoring wells along Mission Creek in the northwestern part of Storage Unit I would be useful to help determine the recharge potential of Mission Creek.

Artificial recharge by injection wells.—The ground-water basin could be recharged artificially by injecting surplus water through wells. Injection wells would place 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.

Relocating the city well field.—Five of the six 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 proximity of these wells causes a mutual interference that results in the lowering of water levels to 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 near the coast to rise. A ground-water flow model for the area could be used to determine the optimum placement of the city supply wells.

SELECTED REFERENCES

Brown and Caldwell, 1969, Water supply and distribution, a report prepared for the city of Santa Barbara: Alhambra, Calif., Brown and Caldwell Consulting Engineers, 183 p.

———1973, City of Santa Barbara ground-water supply: Alhambra, Calif., Brown and Caldwell Consulting Engineers, 92 p.

Dibblee, T. W., Jr, 1966, Geology of the central Santa Ynez Mountains, Santa Barbara County, California: California Division of Mines and Geology Bulletin 186, 99 p.

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

Hem, J. D., 1970, Study and interpretation of the chemical characteristics of natural water [2d ed.]: U.S. Geological Survey Water-Supply Paper 1473, 363 p.

Hoover, M. F., 1978, Geologic hazards evaluation of the city of Santa Barbara: Santa Barbara, Calif., Michael F. Hoover, Consulting Geologist, 35 p.

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

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

National Oceanic and Atmospheric Administration, 1978, Climatological Data—California: v. 82, nos. 1-13.

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

Piper, A. M., Garrett, A. A., and others, 1953, Chemical character of native and contaminated ground waters in the Long Beach-Santa Ana area, California: U.S. Geological Survey Water-Supply Paper 1136, 320 p.

Poland, J. F., Garrett, A. A., and Sinnott, Allen, 1959, Geology, hydrology, and chemical character of ground waters in the Torrance-Santa Monica area, California: U.S. Geological Survey Water-Supply Paper 1461, 425 p.

Rantz, S. E., 1962, Flow of springs and small streams in the Tecolote Tunnel area of Santa Barbara County, California: U.S. Geological Survey Water-Supply Paper 1619-R, 26 p.

Santa Barbara County Water Agency, 1977, Adequacy of the ground-water basin of Santa Barbara County: Santa Barbara County Water Agency, Chapter 4, p. 1-14.

Todd, D. K., 1959, Ground water hydrology: New York, John Wiley and Sons, 336 p.

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

Toups Corporation, 1974, Water resources management study, South Coast-Santa Barbara County, a report prepared for the ad hoc committee on water supply: Santa Ana, Calif., Toups Corp., 219 p.

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

U.S. Environmental Protection Agency, Office of Water Supply, 1976, National interim primary drinking water regulations: Report EPA-570/9-76-003, 163 p.

U.S. Environmental Protection Agency, 1977 [1978], Quality criteria for water: U.S. Government Printing Office, 256 p.

Conversion Factors and Abbreviations

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

Multiply	By	To obtain
acres	0.004047	km^2 (square kilometers)
acre-ft (acre-feet)	1,233	m^3 (cubic meters)
acre-ft/d (acre-feet per day)	1,233	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)	1,233	m^3/a (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)
inches	25.4	mm (millimeters)
in/yr (inches per year)	25.4	mm/a (millimeters per annum)
Mgal/d (million gallons per day)	3,785	m^3/d (cubic meters per day
mi (miles)	1.609	km (kilometers)
mi^2 (square miles)	2.590	km^2 (square kilometers)

m^3/a (cubic meters per annum)

Abbreviations used:
- mg/L, milligrams per liter
- $\mu g/L$, micrograms per liter
- $\mu mho/cm$ 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.

TABLE 8

Table 8. Drillers' logs of monitoring wells drilled during the study period

	Thickness (ft)	Depth (ft)
4N/27W-14K2. Drilled by Sierra Drilling Co., Inc. Logged by U.S. Geological Survey. Altitude 42.3 ft; 8-in. polyvinyl chloride casing; depth of hole 450 ft; depth of well 380 ft; perforated interval 260-380 ft. Drilling completed 7-26-79.		
Conductor pipe (no samples)	20	20
Sand, medium to coarse (95 percent), and 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), and 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), and clay (15 percent); moderate yellowish brown	30	270
Sand, medium to coarse (60 percent), silt (15 percent), clay (5 percent), and 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), a trace of clay, 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
4N/27W-15K1. Drilled by Sierra Drilling Co., Inc. Logged by U.S. Geological Survey. Altitude 18.9 ft; 8-in. polyvinyl chloride casing; depth of hole 500 ft; depth of well 464 ft; perforated interval 280-464 ft. Drilling completed 7-17-79.		
Conductor pipe (no samples)	20	20
Sand, medium to coarse (80 percent), and 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), clay (10 percent), and gravel (20 percent); moderate yellowish brown	15	140
Sand, medium (70 percent), silt (20 percent), and boulders (10 percent), with trace of clay; moderate yellowish brown	10	150
Sand, fine to medium (60 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), a trace of clay, and 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

Table 8. Drillers' logs of monitoring wells drilled during the study period—Continued

	Thickness (ft)	Depth (ft)
4N/27W-15K1.--Continued		
Sand, fine to medium (60 percent), silt (15 percent), a trace of clay, and 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), a trace of clay, and gravel (10 percent); moderate yellowish brown	40	460
Sand, fine to coarse (85 percent), silt (10 percent), and shell fragments (5 percent); light olive gray	15	475
Shale (100 percent); moderate olive black	25	500
4N/27W-16R1. Drilled by Sierra Drilling Co., Inc. Logged by U.S. Geological Survey. Altitude 84.8 ft; 6-in. polyvinyl chloride casing; depth of hole 720 ft; depth of well 625 ft; perforated interval 545-625 ft. Drilling completed 8-21-79.		
Sand, fine (60 percent), silt (35 percent), and clay (5 percent); moderate yellowish brown	60	60
Sand, fine to medium (55 percent), silt (25 percent), clay (10 percent), and cobbles and gravel (10 percent); moderate yellowish brown	40	100
Sand, fine (70 percent), silt (20 percent), and clay (10 percent); moderate yellowish brown	35	135
Sand, poorly sorted (70 percent), silt (10 percent), a trace of clay, and fine gravel and (or) rock fragments (20 percent); moderate yellowish brown	15	150
Sand, fine (60 percent), silt (25 percent), clay (5 percent), and gravel (10 percent); moderate yellowish brown	10	160
Sand, poorly sorted (70 percent), silt (10 percent), a trace of clay, and gravel and (or) rock fragments (20 percent); moderate yellowish brown	10	170
Sand, fine (60 percent), silt (30 percent), clay (5 percent), and gravel (5 percent); moderate yellowish brown	30	200
Sand, medium-well-sorted (85 percent), silt (10 percent), and occasional fine gravel (5 percent); moderate yellowish brown	30	230
Sand, fine to medium (75 percent), silt (15 percent), 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), and fine gravel (15 percent); moderate yellowish brown	40	320
Sand, fine to coarse (45 percent), silt (20 percent), clay (5 percent), and fine gravel (30 percent); moderate yellowish brown	30	350
Sand, fine to coarse (50 percent), silt (30 percent), clay (10 percent), and fine gravel (10 percent); dark greenish gray	25	375

Table 8. Drillers' logs of monitoring wells drilled during the study period—Continued

	Thickness (ft)	Depth (ft)
4N/27W-16R1.--Continued		
Sand, fine to medium (80 percent), silt (15 percent), and 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 percent); moderate yellowish brown---------------------	5	480
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), and a trace of clay; olive gray--	40	590
Sand, fine (60 percent), silt (30 percent), clay (10 percent), and a trace of shell fragments; light olive gray--	20	610
Sand, medium to coarse (85 percent), fine gravel (10 percent), and shell fragments (5 percent)-------------	10	620
Sand, poorly sorted (75 percent), silt (20 percent), fine gravel (5 percent), and a trace of shell fragments----	20	640
Sand, poorly sorted (55 percent), silt (30 percent), clay (5-10 percent), and shell fragments (5 percent); olive gray---	70	710
Shale (100 percent); moderate brown------------------------	10	720

4N/27W-17J1. Drilled by Sierra Drilling Co., Inc. Logged by U.S. Geological Survey. Altitude 138.8 ft; 8-in. polyvinyl chloride casing; depth of hole 385 ft; depth of well 320 ft; perforated interval 190-320 ft. Drilling completed 7-6-79.

	Thickness (ft)	Depth (ft)
Conductor pipe (no samples) -------------------------------	20	20
Sand, coarse (75 percent), and boulders (25 percent); moderate yellowish brown----------------------------------	10	30
Sand, medium to coarse (100 percent), and a trace of clay; light brown--	10	40
Sand, fine to medium (95 percent), 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 (90 percent), clay (5 percent), and cobbles (5 percent); dark greenish gray---------------	20	220
Sand, medium well-sorted (100 percent), and 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 (100 percent), and 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

Table 8. Drillers' logs of monitoring wells drilled during the study period—Continued

	Thickness (ft)	Depth (ft)
4N/27W-17J1.--Continued		
Sand, medium (50 percent), boulders (50 percent), and a trace of clay; olive gray	15	315
Sand, medium, salt and pepper (60 percent), silt (20 percent), cobbles (20 percent), and occasional shell fragments; olive gray	25	340
Sand, fine to medium (95 percent), and shell fragments (5 percent); olive gray	10	350
Sand, fine to medium (65 percent), silt (30 percent), clay (5 percent), and some shell fragments; olive gray	20	370
Shale (100 percent); grayish red	15	385
4N/27W-22Q1. Drilled by Sierra Drilling Co., Inc. Logged by U.S. Geological Survey. Altitude 13 ft; 8-in. polyvinyl chloride casing; depth of hole 120 ft; depth of well 60 ft; perforated interval 20-60 ft. Drilling completed 7-3-79.		
Sand, fine (90 percent), and clay (10 percent); olive gray	20	20
Sand, fine to medium (70 percent), gravel (20 percent), and clay (10 percent); olive gray	38	58
Shale (100 percent); grayish red	62	120
4N/27W-23D1. Drilled by Sierra Drilling Co., Inc. Logged by U.S. Geological Survey. Altitude 12 ft; 8-in. polyvinyl chloride casing; depth of hole 400 ft; depth of well 380 ft; perforated interval 240-380 ft. Drilling completed 7-20-79.		
Conductor casing (no samples)	20	20
Sand, fine to medium (95 percent), and clay (5 percent); olive gray	70	90
Sand, medium (90 percent), clay (5 percent), and organic matter (5 percent); olive gray	10	100
Sand, medium to coarse (90 percent), and fine gravel (10 percent)	10	110
Sand, medium (85 percent), silt (10 percent), and clay (5 percent)	30	140
Sand, medium to coarse (100 percent); medium olive gray	10	150
Sand, medium (85 percent), and clay (15 percent); medium light gray	30	180
Sand, fine to coarse (80 percent), and clay (20 percent); dark yellowish brown	60	240
Sand, very fine to medium (100 percent); moderate olive brown	20	260
Sand, fine to coarse (100 percent); light olive gray	20	280
Sand, fine to coarse (80 percent), and clay (20 percent); moderate olive brown	20	300
Sand, very fine (50 percent), silt (30 percent), and clay (20 percent); brownish	20	320
Sand, medium to coarse (90 percent), and gravel and clay (10 percent); light olive brown	60	380
Sand, fine (50 percent), clay (40 percent), and silt (10 percent); medium light olive gray	20	400