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U.S. Department of the Interior
U.S. Geological Survey

GEOHYDROLOGIC FRAMEWORK OF RECHARGE AND SEAWATER INTRUSION IN THE PAJARO VALLEY, SANTA CRUZ AND MONTEREY COUNTIES, CALIFORNIA

Prepared in cooperation with
PAJARO VALLEY WATER MANAGEMENT AGENCY

USGS
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Water-Resources Investigations Report 03-4096

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Geohydrologic Framework of Recharge and Seawater Intrusion in the Pajaro Valley, Santa Cruz and Monterey Counties, California

By Randall T. Hanson

U.S. GEOLOGICAL SURVEY

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Sacramento, California
2003

U.S. DEPARTMENT OF THE INTERIOR
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Denver, CO 80225-0286

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CONVERSION FACTORS

Multiply	By	To obtain
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer
square mile (mi^2)	12.590	square kilometers
acre-foot (acre-ft)	0.001233	cubic hectometer
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per year
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
acre	0.4047	hectometer
pound	0.4536	kilogram
pound per cubic foot (lb/ft^3)	0.01602	gram per cubic centimeter (g/cm^3)

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

$^{o}F = 1.8(^{o}C) + 32.$

VERTICAL DATUM

Sea Level: In this report, “sea level” refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from general adjustments of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

WATER-QUALITY INFORMATION

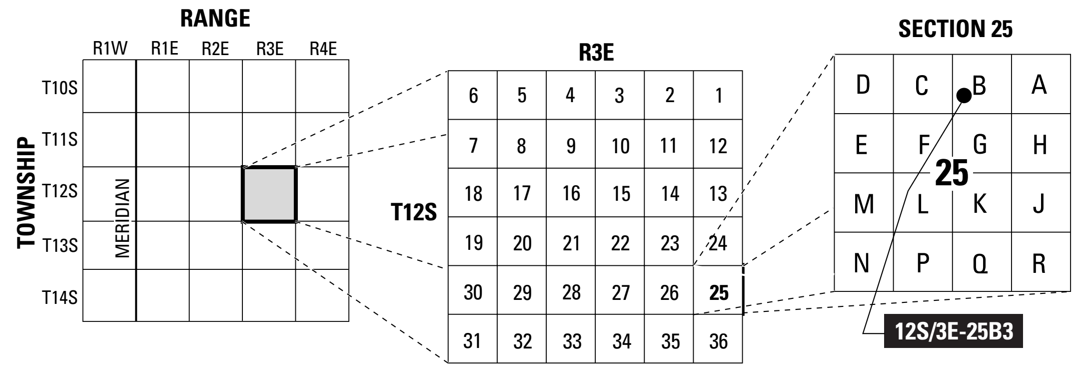
Concentrations of constituents in water samples are given in either milligrams per liter (mg/L) or micrograms per liter (µg/L). Milligrams per liter is equivalent to “parts per million” and micrograms per liter is equivalent to “parts per billion.” Selected constituents also are expressed in terms of millimoles, which is the concentration in milligrams per liter divided by the atomic weight of the element. Selected constituents also are expressed in terms of milliequivalents per liter, which is the concentration in milligrams per liter divided by the valence of the element. Specific conductance is given in microseimens per centimeter at 25 °C (µS/cm at 25 °C). Tritium activity is given in picocuries per liter (pCi/L). Carbon-14 data are expressed as percent modern carbon (pmc), and carbon-13 data are expressed in delta notation as per mil differences relative to the ratio of carbon-13 to carbon-12.

ABBREVIATIONS

PV	Pajaro Valley
EM	electromagnetic induction
ft bls	feet below land surface
km/s	kilometers per second
km-g/s-cm^3	kilometers-grams per second-centimeter cubed
MCL	(Primary) maximum contaminant level
mmho/m	milli-mhos per meter
per mil	parts per thousand
pmc	percent modern carbon
SC	Soquel Creek
SMCL	secondary maximum contaminant level (EPA)
ybp	years before present
	Organizations
EPA	U.S. Environmental Protection Agency
PVWMA	Pajaro Valley Water Management Agency
MCWRA	Monterey County Water Resources Agency
SCWD	Soquel Creek Water District
USGS	U.S. Geological Survey

WELL-NUMBERING SYSTEM

Wells are identified and numbered according to their location in the rectangular system for the subdivision of public lands. The identification consists of the township number, north or south; the range number, east or west, and the section number. Each section is further divided into sixteen 40-acre tracts lettered consecutively (except I and O), beginning with ‘A’ in the northeast corner of the section and progressing in a sinusoidal manner to ‘R’ in the southwest corner. Within the 40-acre tracts, wells are sequentially numbered in the order they are inventoried. The final letter refers to the base line and meridian. In California, there are three base lines and meridians; Humboldt (H), Mount Diablo (M), and San Bernadino (S). All wells in the study area are referenced to the Mount Diablo base line and meridian (M). Well numbers consist of 15 characters and follow the format 012S003E25B003M. In this report, well numbers (except in tables) are abbreviated and written 12S/3E-25B3. Wells in the same township and range are referred to by only their section designation, 2M1.



Well-numbering diagram (Note: maps in this report use abbreviated well numbers such as **"25B3"**)

Geohydrologic Framework of Recharge and Seawater Intrusion in the Pajaro Valley, Santa Cruz and Monterey Counties, California

By Randall T. Hanson

ABSTRACT

Pajaro Valley is a coastal watershed of 160 square miles located along Monterey Bay north of Elkhorn Slough and south of the city of Santa Cruz. The valley has been predominantly developed for agriculture since the late 1800s. In 1984 the Pajaro Valley Water Management Agency (PVWMA) was formed and was delegated with the responsibility of the management of the water resources within the Pajaro Valley by the State of California. About 84 percent of the water is used for agriculture and 16 percent is used for industrial and municipal water supply; almost all of the demand is supplied by ground water. Ground-water pumpage varies with seasonal and climatic periods.

The alluvial aquifers are composed of Quaternary- and Tertiary-aged sediments that are layered marine and terrestrial coarse-grained deposits separated by extensive fine-grained deposits that potentially restrict vertical movement of ground water and seawater intrusion in the coastal subareas. The coarse-grained deposits, which persist over large areas, control pumpage and related seawater intrusion. The Aromas Sand crops out throughout the north and central parts of the PVWMA area and offshore on the continental shelf and in Monterey submarine canyon. Because many of the wells in the coastal and inland subregions are screened at depths of 200 to 400 feet below land surface, a direct avenue is provided for seawater intrusion through the coarse-grained deposits of the shallower alluvium and Aromas Sand. Geophysical logs from monitoring wells indicate discrete zones of saline water that are related to pumpage and seawater intrusion in the aquifers of the shallower alluvium and upper Aromas Sand in the upper-aquifer system and to deeper saline waters in the lower Aromas Sand within the lower-aquifer system.

The precipitation data indicate that there were at least nine dry and nine wet periods that range from 2 to 19 years during the period of record, 1880–1997. The ground-water pumpage, runoff, streamflow and related water quality of streamflow also vary with seasonal and climatic periods.

Recharge occurs from deep percolation of precipitation and from infiltration of streamflow. Streamflow originates from local runoff and from outside the valley as inflow from the Pajaro River. Although partly regulated, streamflow in the Pajaro River at Chittenden is less than 200 cubic feet per second 88 percent of the time and is less than 12 cubic feet per second 50 percent of the time. Streamflow water-quality data suggest that there may be several sources of poor-quality water that contribute to elevated chloride, sulfate, and nitrate concentrations in streamflow. The poor water quality occurring during lower streamflows indicates that low flows may be an additional source of salinity for ground-water recharge as streamflow infiltration along the Pajaro River.

The geochemical data from this study indicate that the two main sources of recharge are deep percolation of local runoff and streamflow infiltration of Pajaro River water. The geophysical and geochemical data suggest that only the shallow alluvial aquifer and parts of the upper Aromas Sand that constitute the upper-aquifer system are being replenished by recent recharge in the coastal areas of Pajaro Valley and represent the renewable ground-water resources. These data also suggest that there is very little vertical flow through the layered aquifer systems in the coastal regions. The confining aquitards are laterally extensive but may be missing in places owing to fluvial erosion or offsetting by fault movement. Geochemical and geophysical data indicate that the ground water from some parts of the upper and lower Aromas Sand in the coastal regions was recharged thousands of years ago and may, in part, represent nonrenewable ground-water resources.

The analysis of major-ion chemistry, in combination with isotope and trace-element/chloride ratios, indicates that the coastal ground-water and surface-water samples can be described in seven groups. These groups represent recently recharged shallow aquifers (Group 1), shallower aquifers containing older water (Group 2), shallow aquifers containing recently intruded seawater (Group 3), deeper aquifers containing older seawater (Group 4), deeper aquifers containing older freshwater (Group 5), Pajaro River streamflow (Group 6), and local runoff from streams and sloughs (Group 7).

The ground-water levels have been near or below sea level at most coastal monitoring wells since their installation in the 1980s. Water-level changes include long-term decline, climate-period changes, and seasonal changes from agricultural pumping. The seasonal and long-term declines owing to dry years and increased pumpage from the lower Aromas Sand are similar to the water-level declines measured in other local deep wells since 1970. At the time of this study (1998–99), water levels in most coastal and some inland water-supply wells as far inland as Murphy Crossing in the Pajaro subarea and in the Springfield subarea were below the estimated water levels of 5 to 15 feet above sea level required to stop seawater intrusion.

The predominant source of the chloride in the coastal regions of Pajaro Valley may be recent seawater for aquifers in the older alluvium and the upper Aromas Sand and old seawater or connate water in the aquifers of the lower Aromas Sand. Geochemical and geophysical data indicate that saline water is vertically restricted for both the recent seawater intrusion in the older shallow alluvium and upper Aromas Sand and for the older seawater or connate water present in the lower Aromas Sand in Pajaro Valley.

INTRODUCTION

The Pajaro Valley Water Management Agency (PVWMA) was established in 1984 by the State of California as the agency charged with ground-water management in Pajaro Valley (figs. 1*A*, *B*). The PVWMA must deal with issues of both water supply and water quality. Managing water resources for agricultural and municipal users requires maintaining a reliable water supply to meet growing demands while preventing ground-water overdraft and the related degradation of water quality. Important regional water-quality concerns include increased nitrate concentrations and seawater intrusion. To protect the quantity and quality of the ground-water supplies, the PVWMA has implemented a plan to prevent further seawater intrusion. In order to evaluate how these activities can be conducted most effectively, it is necessary to improve the understanding of the hydrogeology and geochemistry of the water resources in the Pajaro Valley.

A Basin Management Plan (BMP) developed for the Pajaro Valley in 1993 (Montgomery Watson, 1993) is continuing to be refined to help provide reliable water resources. In order to effectively implement the BMP, it is necessary to identify the parts of the aquifer systems that are not in connection with sources of recent recharge, the parts of the aquifer system that are being actively recharged in the coastal regions and represent the renewable resource, and the sources and movement of the natural and artificial recharge and seawater intrusion.

A

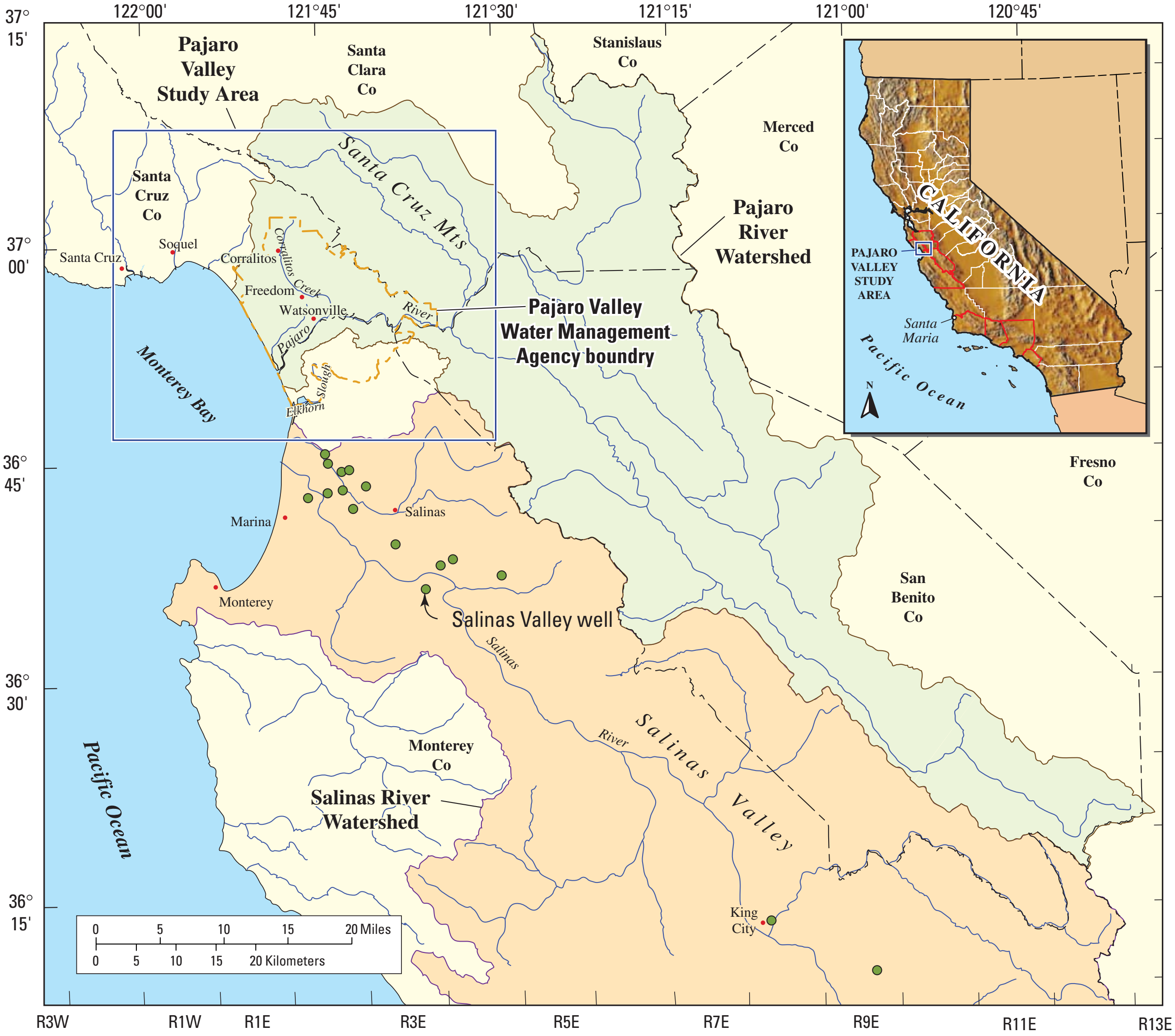


Figure 1. (*A*) Pajaro Valley study area and Salinas Valley locations for ground-water sampling sites, (*B*) outline of Pajaro Water Management Agency and selected features in the Pajaro Valley study area, California, (*C*) distribution of pumping wells, water agency boundaries, and sampling locations in the Pajaro Valley, California, and (*D*) distribution of pumping wells with depth to top of perforations in the Pajaro Valley, California.

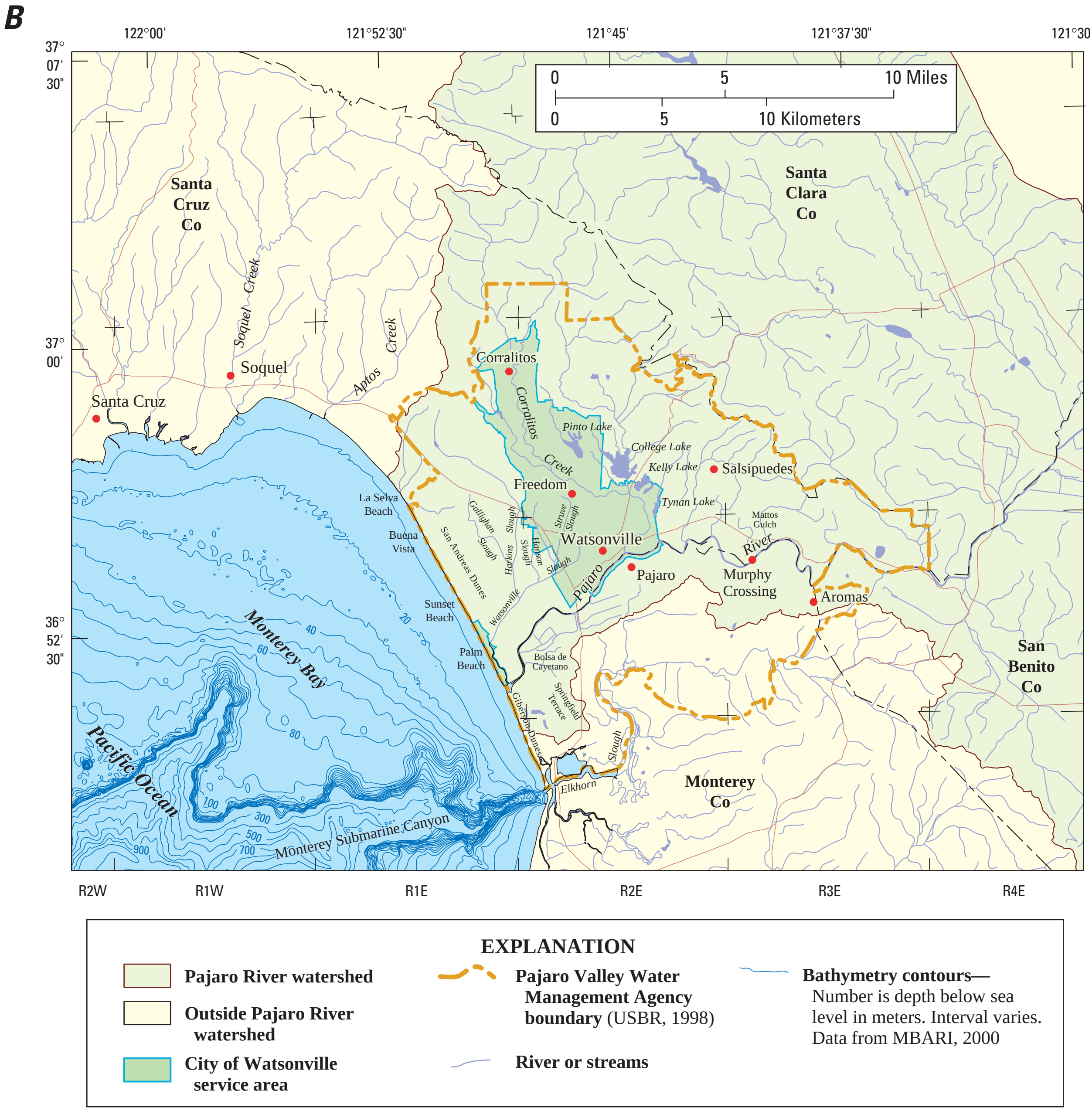


Figure 1.—*Continued.*

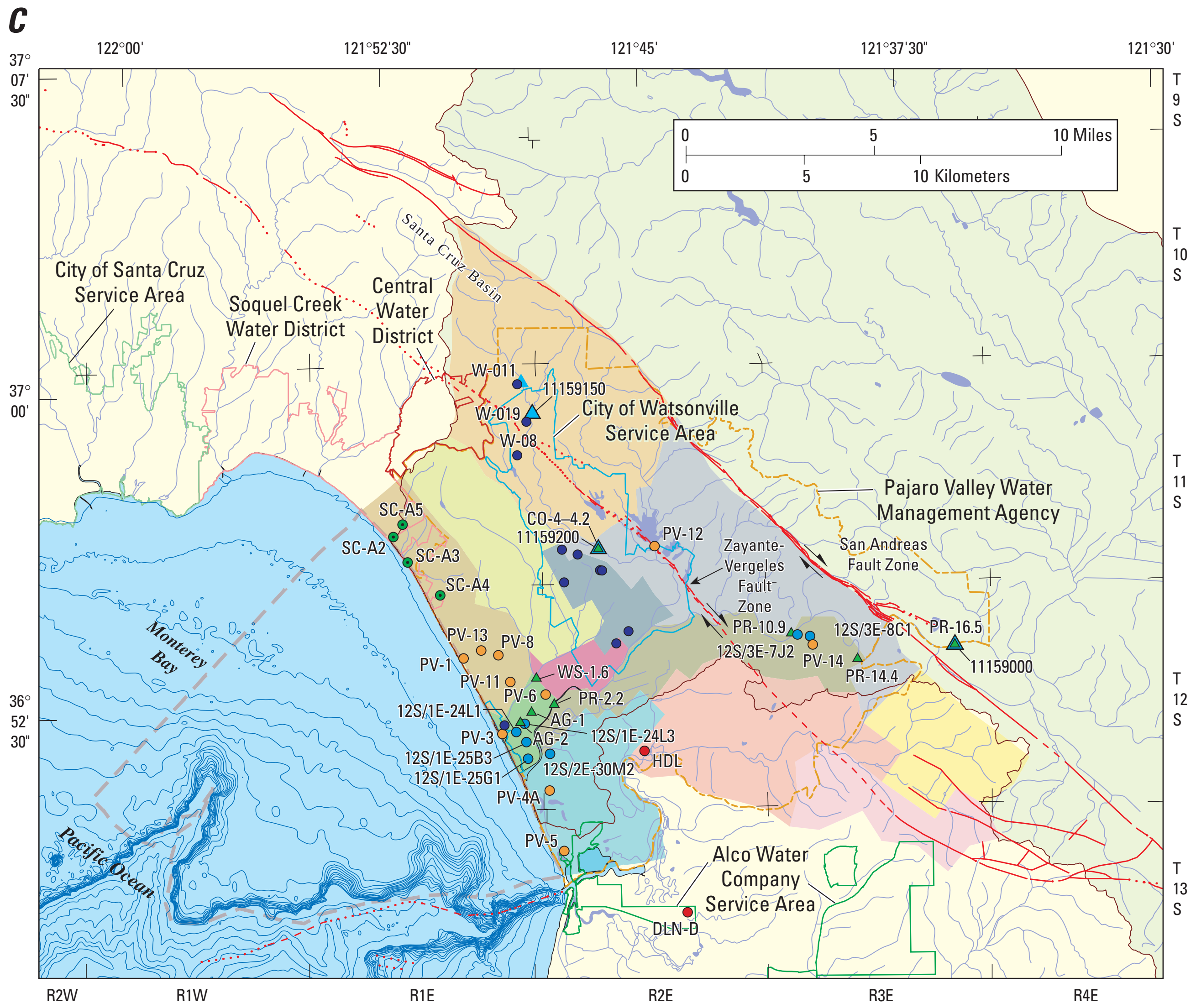


Figure 1.—*Continued.*

EXPLANATION

🟩 **Pajaro River watershed**
🟨 **Outside Pajaro River watershed**

— **River or stream**
〰 **Bathymetry contours**—Interval varies. Data from MBARI, 2000

Faults—
From USGS (Brabb and others, 1997), CDMG (Wagner and others, 2000)
— Known
- - - Concealed
····· Inferred

Multiple-well monitoring sites—
● Pajaro Valley Water Management Agency
● Soquel Creek Water District
● Monterey County Water Resources Agency

Water-supply wells—
● City of Watsonville
● Long-term monitoring wells

Surface-water sites—
▲ USGS Streamflow gage
▲ USGS streamflow/PVWMA Surface-water sampling sites

Ground-water subareas—
(Tegavhi and Smith, 1999d)
■ 1 Corralitos
■ 2 Harkins Slough
■ 3 San Andreas
■ 4 Watsonville
■ 5 Salsipuedes
■ 6 Pajaro
■ 7 Granite Ridge
■ 8 Pajaro River Mouth
■ 9 Springfield Terrace
■ 10 Beach Road
■ 11 Highlands South
■ 12 Highlands North
⬚ 13 Monterey Bay

Figure 1.—*Continued.*

The PVWMA implemented a monitoring-well network along the coast in 1989 to assess seawater intrusion (fig. 1*C*). Water-level and water-quality data have been collected from water-supply wells and five multiple-well monitoring sites. Data collected from these wells provide a basis for refining the understanding the source, movement, and distribution of recharge and seawater intrusion in the coastal region of Pajaro Valley that is related to the pumpage of ground water from hundreds of wells (fig. 1*D*).

Purpose and Scope

The purpose and scope of this study was to collect and analyze hydrologic, water-chemistry, and geologic data that will help improve the understanding of the ground-water flow systems and the relation between recharge, pumpage, seawater intrusion and other water-quality issues for the aquifers within the Pajaro Valley. Because water-resource management issues such as overdraft, conjunctive-use, and water quality are linked to the collective management of the ground-water resources, the following issues were investigated and are discussed in this report:

(1) Sources of chloride, sulfate, nitrate, and other constituents that contribute to poor ground-water quality;

(2) Vertical distribution of seawater intrusion and how it relates to the current definition of aquifers;

(3) Movement of recharge water through the ground-water system and its affect on local ground-water quality; and

(4) The relation of recharge and pumpage to seawater intrusion.

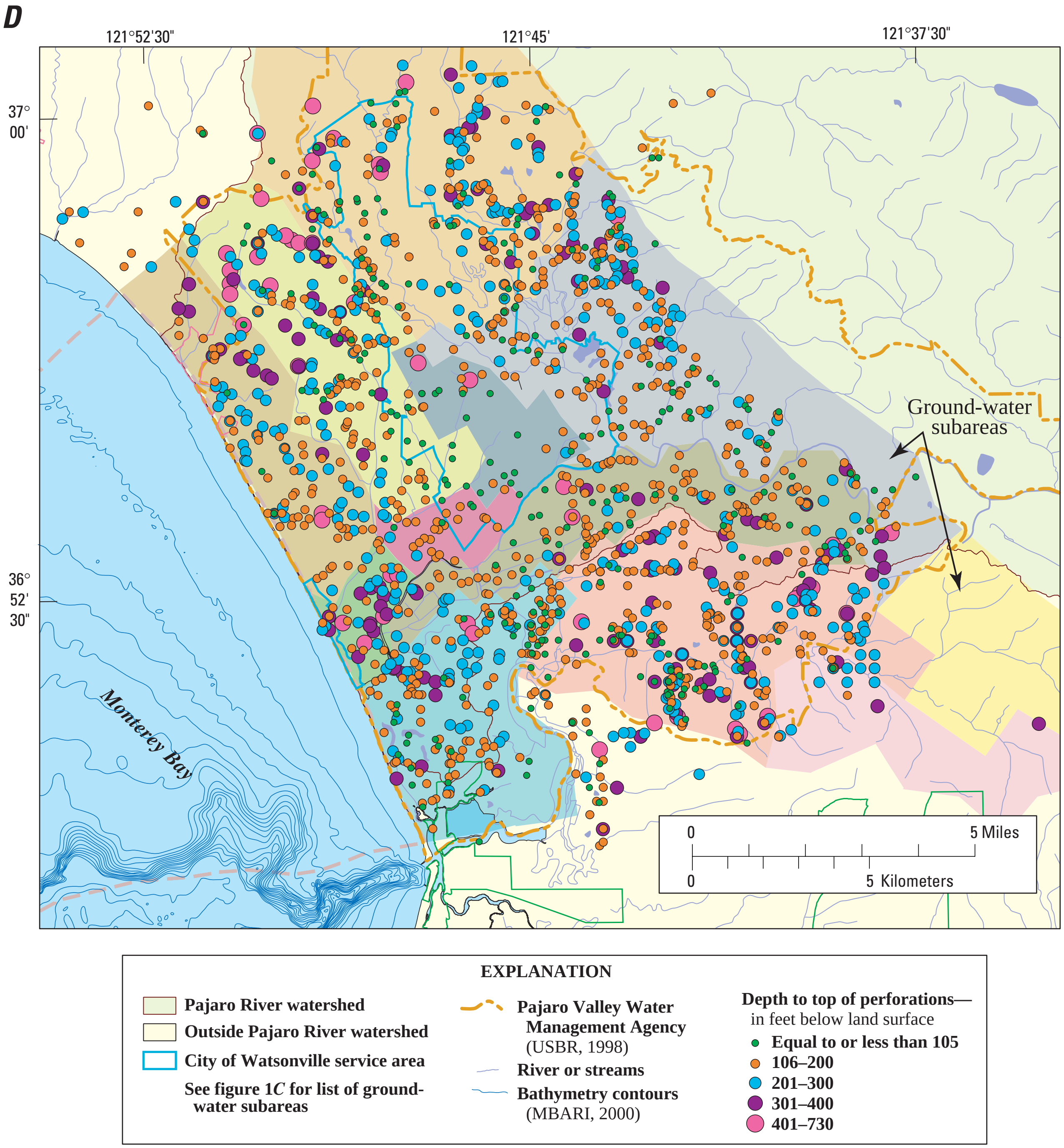


Figure 1.—*Continued.*

This report summarizes the source, age, and movement of recharge to ground water and the nature and extent of seawater intrusion in the coastal region of the Pajaro Valley.

Approach to Investigation

Existing geologic data were compiled from selected supply wells (Doug Coty, PVWMA, written commun., 1999) and integrated with other sources of geologic information. In addition, geophysical data were collected from selected monitoring wells in August 1999. The methods used and the data collected from geophysical logging and compiled from other sources are described in Appendix 1. Hydrologic data were compiled from precipitation gages, streamflow gages, and ground-water monitoring wells (Doug Coty, PVWMA, written commun., 1999). Additional water-chemistry data was provided by Soquel Creek Water District (SCWD) for selected monitoring wells and Soquel Creek (Jeff Gailey, SCWD, written commun., 1999). Water-chemistry samples of selected monitoring wells and surface waters were collected and analyzed by the U.S. Geological Survey (USGS) during the period August 1998–May 1999 (table A2.1). Water-chemistry data-collection methods and analysis are summarized in Appendix 2. These data were used to improve the geohydrologic framework of recharge and seawater intrusion and they provide a baseline for the future comparison of performance of the water-supply options that will ultimately be employed to resolve the water-supply problems of the Pajaro Valley.

Description of Study Area

Pajaro Valley is a coastal watershed of 160 mi2 in the southern part of Santa Cruz County and the northern part of Monterey County; the Pajaro River is the county boundary. The valley is the coastal part of the larger Pajaro River Basin (fig. 1*A*). The valley is drained by the Pajaro River and its tributaries, of which Corralitos Creek is the largest (figs. 1*A*, *B*). This coastal watershed is located along Monterey Bay south of the city of Santa Cruz and north of Elkhorn Slough and its offshore extension, Monterey submarine canyon (fig. 1*B*). The valley has been developed predominantly for agriculture since the late 1800s but also contains the city of Watsonville and other small towns and suburban areas (fig. 1*B*). The PVWMA service area encompasses about 70,000 acres, of which about 40 percent is used for agriculture.

Climate

The climate of the Monterey Bay region is temperate with mild summers and wet and cool winters. The mean rainfall for Pajaro Valley ranges from 16 in. near the coast to more than 40 in. in the foothills of the Santa Cruz Mountains. The average rainfall for the city of Watsonville is about 22 in. for a 109-year period of record.

Population

The total population in the valley has grown from 60,000 in 1990 to about 80,000 by 1996 (Association of Bay Area Governments, 1997). The city of Watsonville is a major urban area in the valley with a population of about 31,100 in 1990 (fig. 1*C*). There are extensive suburban areas and the additional smaller communities of Pajaro, Freedom, Corralitos, and Aromas.

Land and Water Use

Sixty-seven percent of the valley is classified as native vegetation, and agriculture remains the primary human use of land and water in Pajaro Valley. About 84 percent of the water is currently used for agriculture and about 16 percent for industrial and municipal supply (Teghavi and Smith, 1999b). Average agricultural water use was estimated to range from about 50,000 acre-ft/yr (1964–87) to 56,000 acre-ft/yr (1987–97) (Teghavi and Smith, 1999a, b). Agriculture increased from about 30,500 acres in 1966 to about 34,700 acres in 1997 (about 24 percent of land use), a 14-percent increase over 32 years (Teghavi and Smith, 1999a); this is an increase of about 0.4 percent per year. The increased acreage is accompanied by an increase in truck crops and decrease in deciduous crops. Most of the increase in truck crop is strawberries, which increased from 7 percent to 23 percent of agricultural acreage between 1966 and 1997 (Teghavi and Smith, 1999a).

Urban water use was estimated to have increased over 34 years (1964–1997) at about 2.5 percent per year (Teghavi and Smith, 1999b). More recently, urban water use increased from 9,000 acre-ft/yr (1964–87) to 10,000 acre-ft/yr (1987–97) (Teghavi and Smith, 1999b). Almost all of the water demand is supplied from wells pumping ground water (fig. 1*D*).

Acknowledgments

This study could not have been accomplished without the assistance of personnel from the Pajaro Valley Water Management Agency (PVWMA), Dr. Andy Fisher of the University of California at Santa Cruz (UCSC), Ms. Laura Brown and Mr. Jeff Gailey of the Soquel Creek Water District (SCWD), Mr. Bruce Laquerge of the county of Santa Cruz, and Mr. Galin Swain of the city of Watsonville. Other local municipalities, water mutuals, and numerous other well owners also provided well data. This study represents a cooperative effort with PVWMA and is part of an ensemble of studies and projects that were implemented to help the agency better understand the water-resources issues and apply solutions to the water-supply problems of overdraft and seawater intrusion. For this reason the author acknowledges the cooperation of the principal consultants involved in the related projects and studies: Lyndel Melton, Ali Teghavi, Chris Smith, Matt Zadar, and Martin Feeney.

The author also acknowledges the contributions of Dr. Avner Vengosh and Dr. Jim Gill of UCSC for the geochemical data collected, in part with the USGS, in the Salinas Valley. The author also thanks Tom Bullen and John Fitzpatrick of the USGS for analyses of strontium and boron isotopes and the technical input of Tom Bullen, John Izbicki, and Michael Land of the USGS.

GEOHYDROLOGY

The geology of Pajaro Valley and adjacent parts of the Monterey Bay has been compiled in various studies (California State Water Resources Board, 1953; Green, 1970; Dupre, 1975; Luhdorff and Scalmanini, 1987a, b, 1988; Brabb and others, 1997; Teghavi and Smith, 1999c; Wagner and others, 2000; Rosenberg, 2001) related to the geohydrologic framework of Pajaro Valley. The following geohydrologic description is a brief summary of these previous studies.

The alluvial aquifers in the Pajaro Valley are underlain by granitic basement rocks of Cretaceous age that generally occur at depths of 2,000 to 4,000 ft along the coast (Johnson and others, 1988). Above the relatively impermeable basement rocks are a sequence of poorly permeable consolidated rocks composed of mostly marine shales, mudstones, clay, silt, fine sand, conglomerate, and minor deposits of volcanic rock of Eocene to Miocene age (Johnson and others, 1988). The important geologic units relative to ground-water flow above the consolidated marine rocks are a sequence of westward-dipping sedimentary rocks of late Tertiary to Quaternary age. These rocks include the marine deposits of the poorly consolidated Purisima Formation of Miocene to Pliocene age and range from the land surface along the northern and eastern boundaries of the valley to depths of 800 to 900 ft below land surface at the mouth of the Pajaro River (Johnson and others, 1988). The Purisima Formation outcrops to the north within the Soquel Creek Water District (SCWD) area (fig. 2). The Purisima Formation is overlain by the unconsolidated Aromas Sand and terrace deposits of Pleistocene age. The Aromas Sand crops out throughout the north and central parts of the PVWMA area and offshore on the continental shelf and in Monterey submarine canyon (fig. 2). These rocks are overlain in places by unconsolidated alluvium, dune deposits, and younger marine sediments of Holocene age (Johnson and others, 1988) (fig. 2).

Although there is no formal designation of aquifers in the Pajaro Valley, the ground-water flow system generally can be subdivided by the major geologic units–the Purisima Formation, the Aromas Sand, the older alluvium, and the younger alluvium. In addition, the Aromas can be subdivided into an upper and lower portion on the basis of lithology and geophysical characteristics (fig. 3). The flow of ground water through the alluvial aquifers generally has been characterized as flowing from the mountains to the coast with the exception of local cones of depression in the area of the city of Watsonville and along the mouth of the Pajaro River (Johnson and others, 1988, fig. 5). The aquifers additionally can be grouped with the alluvial deposits and upper Aromas Sand representing the upper-aquifer system and the lower Aromas Sand and Purisima Formation representing the lower-aquifer system.

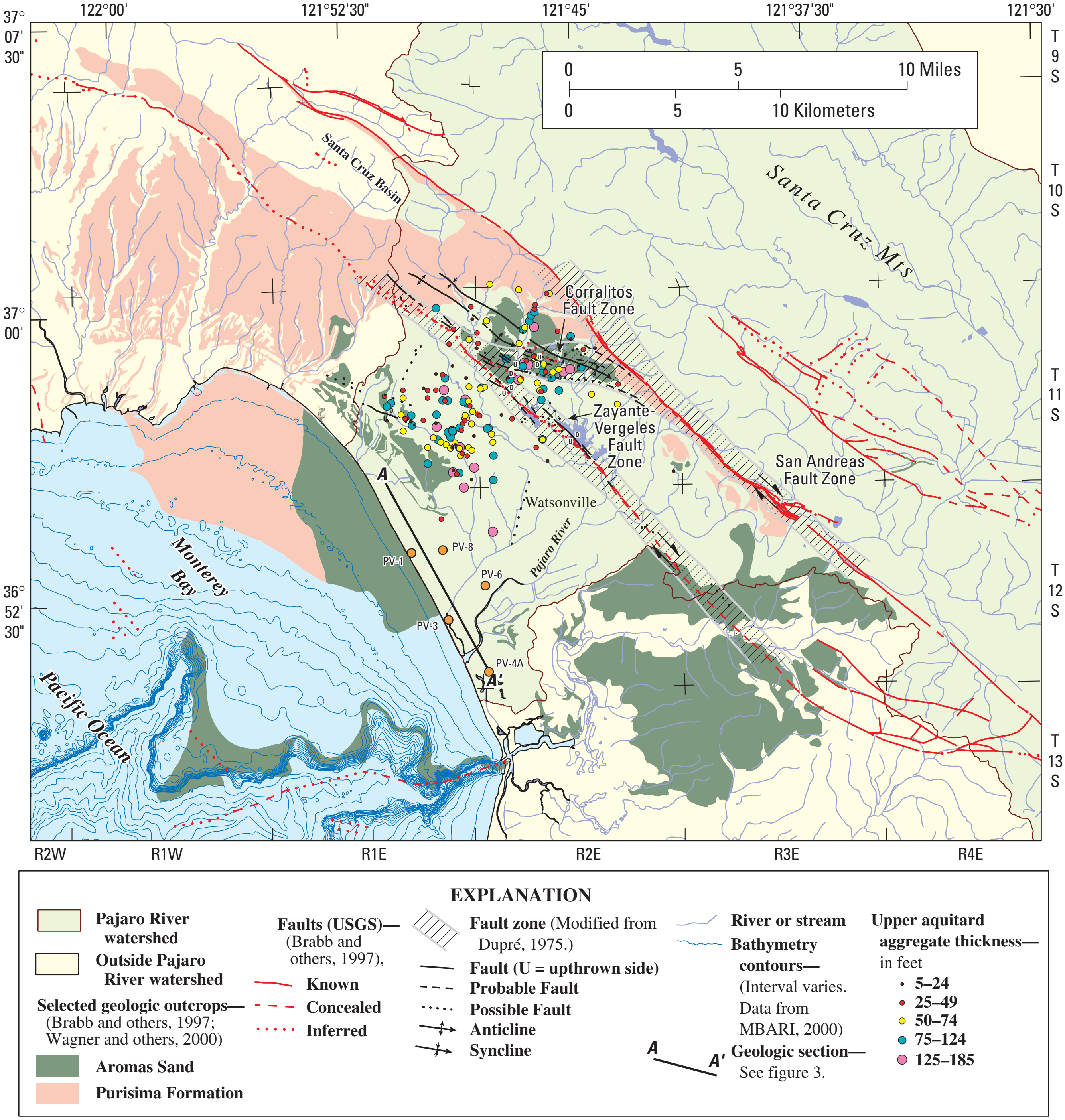


Figure 2. Geology, selected wells used to estimate aquifer thicknesses, geologic outcrops, and sites for geophysical logging in the Pajaro Valley, Santa Cruz and Monterey Counties, California.

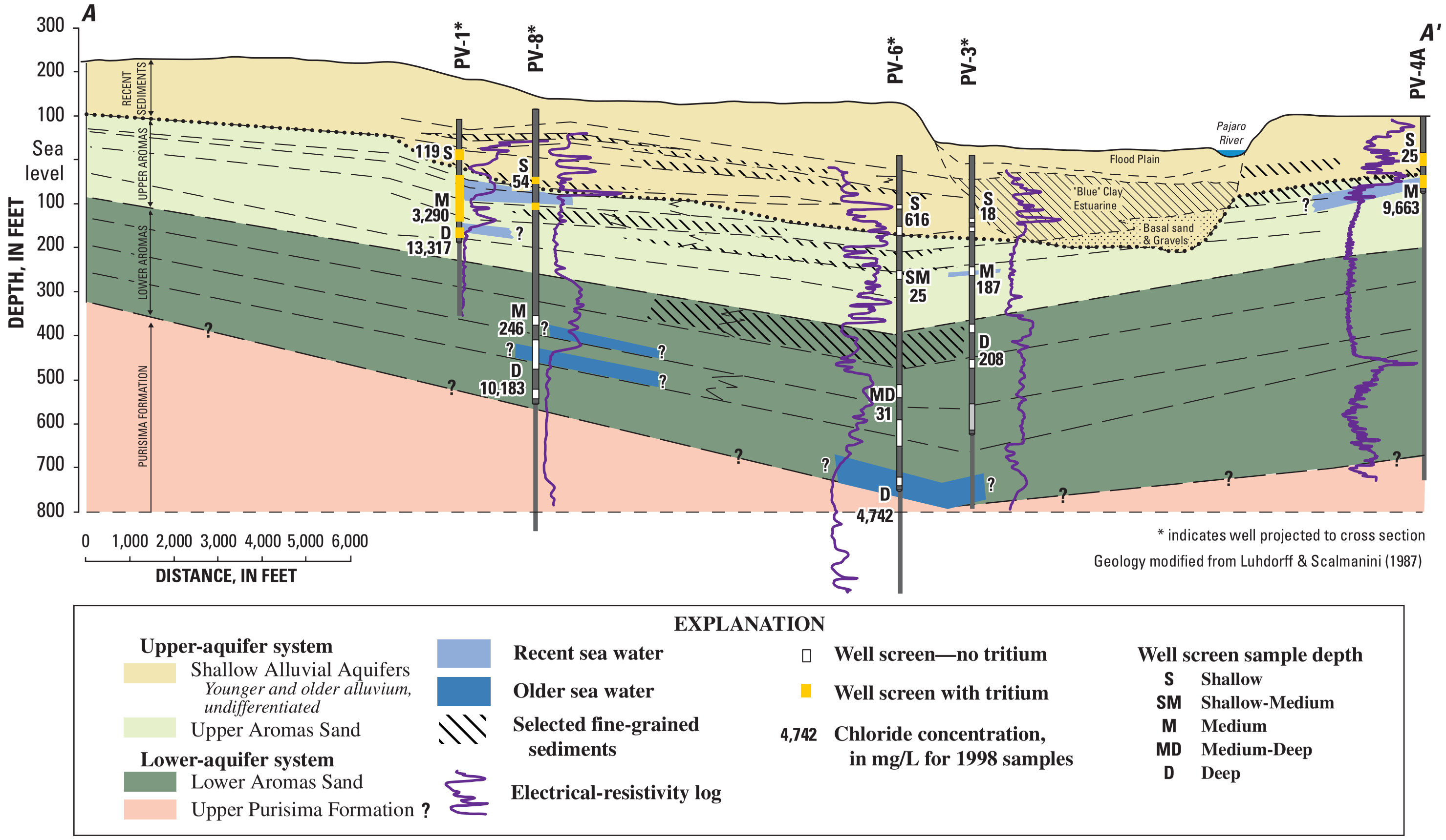


Figure 3. Relation between geology and selected water-quality attributes along the coast in the Pajaro Valley, Santa Cruz, and Monterey Counties, California.

The geologic factors that, in part, control the distribution of recharge, pumpage, and related seawater intrusion include the layering of the sediments, the potential connectivity of the coarse-grained deposits that allows deep percolation of recharge to replenish pumpage, and the potential barriers to ground-water flow or infiltration of recharge (fig. 2). The hydrogeology and its relation to seawater intrusion was summarized by Johnson (1982):

"The upper confined or semiconfined Quaternary aquifer has seawater intrusion. This aquifer consists of the main water-bearing unit of the alluvium and the upper part of the Aromas Sand which is in direct geologic and hydrologic contact with the basal gravel unit of the alluvium. The aquifer's depth near the coast is presently interpreted as corresponding to an intruded interval of 100–200 ft below sea level. The alluvial part of the aquifer extends up the valley floor east of the city of Watsonville into the upper part of the Pajaro Valley where its sediments are generally coarser grained than those between Watsonville and the coast. The upper part of the Aromas Sand outcrops north of the alluvial flood plain into a major ground-water recharge area, extends south under the Springfield coastal terrace, and outcrops to the southeast in north Monterey County....The connection between the 180-foot aquifer in the Salinas Valley and the 100 to 200 ft interval of the Quaternary aquifer in the Pajaro Valley is the upper Aromas Sand which comprises part of both principally alluvial aquifers.

"There is also a deeper aquifer layer entirely within the Aromas Sand, defined by wells pumping in the 300–600 ft interval below sea level, that shows some early indications of higher chlorides and possible intrusion along its coastal margin at the mouth of the Pajaro Valley. It might be considered as an area of potential intrusion, though not enough is known about this interval north of the Springfield coastal terrace."

The distribution of wells, well screens, and related pumpage from major aquifers in Pajaro Valley are controlled, in part, by the fine-grained deposits within the geologic units (Appendix 1; figs. 1*D*, 2, 3). The coarse-grained deposits, which persist over large areas, control pumpage, and related seawater intrusion. For example, the shallowest sediments within the upper 100 to 200 ft are a combination of eolian, terrace, and fluvial deposits (Dupre, 1975, 1998). The distribution of wells with perforations that start in these deposits is widespread and is exceptionally dense in the inland subareas, the Springfield Terrace subarea, and along the Pajaro River and Corralitos Creek and their tributaries (figs. 1*C*, *D*). The distribution of wells with screens that start at depths of 200 to 400 ft and pump from the Aromas Sand are concentrated in the coastal and inland subregions that bound the city of Watsonville (fig. 1*D*). Both the Aromas Sand and the Purisima Formation dip to the southeast from the Soquel–Aptos area (fig. 1*B*) where ground water is supplied to predominantly municipal users by SCWD. Wells with screens that start in these deeper formations are located in the northern parts of the Harkins Slough and Corralitos subareas, in the Pajaro River mouth subarea, and to the south in the Highlands subareas (figs. 1*C*, *D*). This distribution of depth to well screens and related pumpage controls the large inland pumping depression that spans the Springfield Terrace–Pajaro River Mouth subareas inland to the Watsonville, Salsipuedes, and Corralitos subareas (fig. 1*C*; Johnson and others, 1988, fig. 5).

Fine-grained deposits persist over large areas and have been mapped as a continuous layer within the flood-plain areas of the Pajaro River and Corralitos Creek (Johnson and others, 1988) and as discontinuous layers throughout most of the inland subareas. The variable aggregate thickness of shallow fine-grained deposits determined from drillers' logs, and multiple fine-grained layers indicated by the geophysical logs, suggests that these layers may not be homogeneous or laterally extensive (Appendix 1; figs. 2, 3). The thick lacusterine and marine fine-grained layers also reoccur vertically throughout the cyclic sedimentation as a result of 11 sea-level changes in recent geologic history that affected most of the Pajaro Valley (Dupre, 1975). The aggregate thickness of fine-grained layers in the Corralitos subarea is coincident with a region that has both perched and deep aquifers (Johnson and others, 1988, fig. 4) (fig. 2). These fine-grained layers range in thickness from 5 to as much as 185 ft in the Corralitos and Harkins Slough subareas (fig. 2) and represent a potentially significant barrier to the vertical flow of ground water in the inland and coastal subareas as shown in the geologic section of the layered coastal aquifers (fig. 3). The coastal section through the monitoring wells also illustrates that these layers, referred to as "aquitards," are laterally extensive parallel to the coast and separate the major aquifers and even the individual water-bearing zones within aquifers (figs. 2, 3). Because of the layering in coastal aquifer systems such as Pajaro Valley, the seawater intrusion is vertically restricted. Massive fine-grained deposits also are present to the south of the Springfield Terrace subarea (Fugro West, Inc., 1995) exemplified in the geophysical logs from test hole PV-5 and monitoring well PV-4A (Appendix 1, figs. A1.3, A1.4,). This massive clay layer may represent an ancestral submarine canyon in a manner similar to the massive clay deposits adjacent to Hueneme submarine canyon in the Ventura area (Hanson and others, 2002, fig. 8).

The San Andreas, Zayante-Vergeles, and Corralitos fault zones cross the Pajaro Valley (fig. 2) and may affect the flow of ground water. The San Andreas Fault zone trends northwest along the foothills of the Santa Cruz Mountains (fig. 2). This major fault zone may provide at least a partial barrier to ground-water flow (Teghavi and Smith, 1999c) along the northeastern side of the valley (fig. 2). The Zayante-Vergeles Fault zone is southwest of and parallel to the San Andreas Fault zone. The Zayante-Vergeles Fault zone passes through the Corralitos subarea and has been mapped or inferred throughout Santa Cruz and northern Monterey Counties (Green, 1970; Dupre, 1975; Brabb and others, 1997; Wagner and others, 2000). This potentially active fault zone is coincident with ponds on the northeast side such as College, Pinto, Kelly, and Tynan Lakes (fig. 1*B*). Like the San Andreas Fault, it is predominantly a right-lateral strike-slip fault that is also delineated by offsets in modern stream channels (fig. 2); its relatively high seismicity suggests movement throughout the Quaternary and Holocene periods (Dupre, 1975). The surface vertical displacement of about 3 ft has been mapped near Pinto Lake in the Holocene-aged deposits (Dupre, 1975), and small springs historically discharged near the town of Corralitos near the fault trace. The persistence of drainage networks and the small displacements suggest that although this fault zone could be an important barrier to ground-water flow in the Purisima Formation or lower Aromas Sand, the flow of ground water through the younger fluvial sediments may not be disrupted along stream channels where erosion and deposition have persisted. The Corralitos Fault zone (fig. 2) represents a convergent compressional wrench fault zone between the San Andreas and Zayante-Vergeles Fault zones that occurs in the Salsipuedes subarea. Although this is also a region of high seismicity, there are no known recent displacements (Dupre, 1975), and the nature of this fault zone as a barrier to ground-water flow remains uncertain. The area between the San Andreas and Zayante-Vergeles Fault zones is a deep graben (fig. 2) referred to as the "Santa Cruz basin" (Dupre, 1975).

Other minor faults (fig. 2) have been inferred from lineations onshore, and a few minor faults have been mapped offshore in the Aromas Sand (Green, 1970; Wagner and others, 2000). The northern side of the Monterey submarine canyon also is bounded by faults (fig. 2), which may affect potential seawater intrusion along these submarine outcrops (Green, 1970; Wagner and others, 2000). The role and importance of faults as hydraulic barriers or sources of poor-quality water remains uncertain.

HYDROLOGY

Hydrologic data collected as part of this study were incorporated with existing hydrologic and geologic data to further define the geohydrologic framework of recharge and seawater intrusion. The hydrologic data collected prior to this study included precipitation, streamflow, ground-water levels, and water-chemistry data from streamflow and ground-water samples (Doug Coty, written commun., Pajaro Valley Water Management Agency, 1998). Previous studies have helped identify the extent and nature of the geohydrologic framework (California State Water Resources Board, 1953; Green, 1970; Muir, 1972, 1974, 1977; Luhdorff & Scalmanini, 1987a, b, 1988; Johnson and others, 1988; Dupre, 1975, 1998) and have helped classify the potential recharge and related land use for the Pajaro Valley (Muir and Johnson, 1979; Teghavi and Smith, 1999a).

Precipitation

The deep percolation of precipitation is a significant source of recharge in the Pajaro Valley. The rainfall varies from year to year from less than 40 percent to more than 200 percent of the 109-year period-of-record mean, which as noted earlier, ranges from 16 in. near the coast to 40 in. in the foothills (California State Water Resources Board, 1953). The climatic cycles yield changes in precipitation and recharge (components of supply) that cause changes in pumpage (component of demand) and related changes in ground-water storage and seawater intrusion. In addition to multi-year cycles, precipitation is seasonal; about 90 percent of the rainfall in Pajaro Valley typically occurs between November and April. Wet and dry climate periods were delineated on the basis of the rising and falling limbs of a cumulative departure curve of precipitation at Watsonville (fig. 4). On the basis of this classification scheme, there have been nine dry-year and nine wet-year periods lasting from 2 to 19 years for the period of record, 1880–1997 (fig. 4). Droughts within dry-year periods have been as short as the severe drought of 1976–77 and as long as the sustained 7-year drought of 1986–92. These multi-year cycles also can result in seasonal changes in the use of ground water such as the 20-percent increase in pumpage from 1996 to 1997 that was caused by the relatively dry spring in 1997 (Teghavi and Smith, 1999b). Based on streamflow at Corralitos Creek and precipitation at Watsonville, the increased runoff threshold, precipitation required before increased runoff occurs, for different months range from 0 in. in summer months to more than 3 in. in January (fig. 5). Thus a series of climatic and seasonal changes in precipitation and runoff control the local ground-water recharge and tributary-runoff components of streamflow.

Streamflow

Along with deep percolation of precipitation, streamflow infiltration is the other major source of natural recharge in Pajaro Valley. Streamflow occurs from runoff that originates outside the valley that enters as streamflow in the Pajaro River. Runoff from within the valley also flows through the tributaries to the Pajaro River. Streamflow is currently measured at two gages that record the flow into Pajaro Valley of the Pajaro River at Chittenden (11159000) and Corralitos Creek at Freedom (11159200) (figs. 1*B*, *C*). A third gaging station measured the downstream flow of Corralitos Creek at Corralitos (11159150) further upstream (fig. 1*A*) for the period 1958–1973. The Pajaro River flows all year at Chittenden, with a base flow of about 7 ft^3/s (5,071 acre-ft/yr) for 1996–98 streamflow (fig. 6*A*). Flow in the Pajaro River is partly regulated upstream from the Pajaro Valley by upstream releases and diversions. There are no downstream gaging stations on the Pajaro River to assess streamflow loss, flood-control dike-failure warning, or ground-water/surface-water flow-model performance. A better understanding of the distribution of streamflow losses and gains, as well as better estimates of streambed conductivity, are needed to improve estimates of the quantity, timing, and quality of streamflow infiltration.

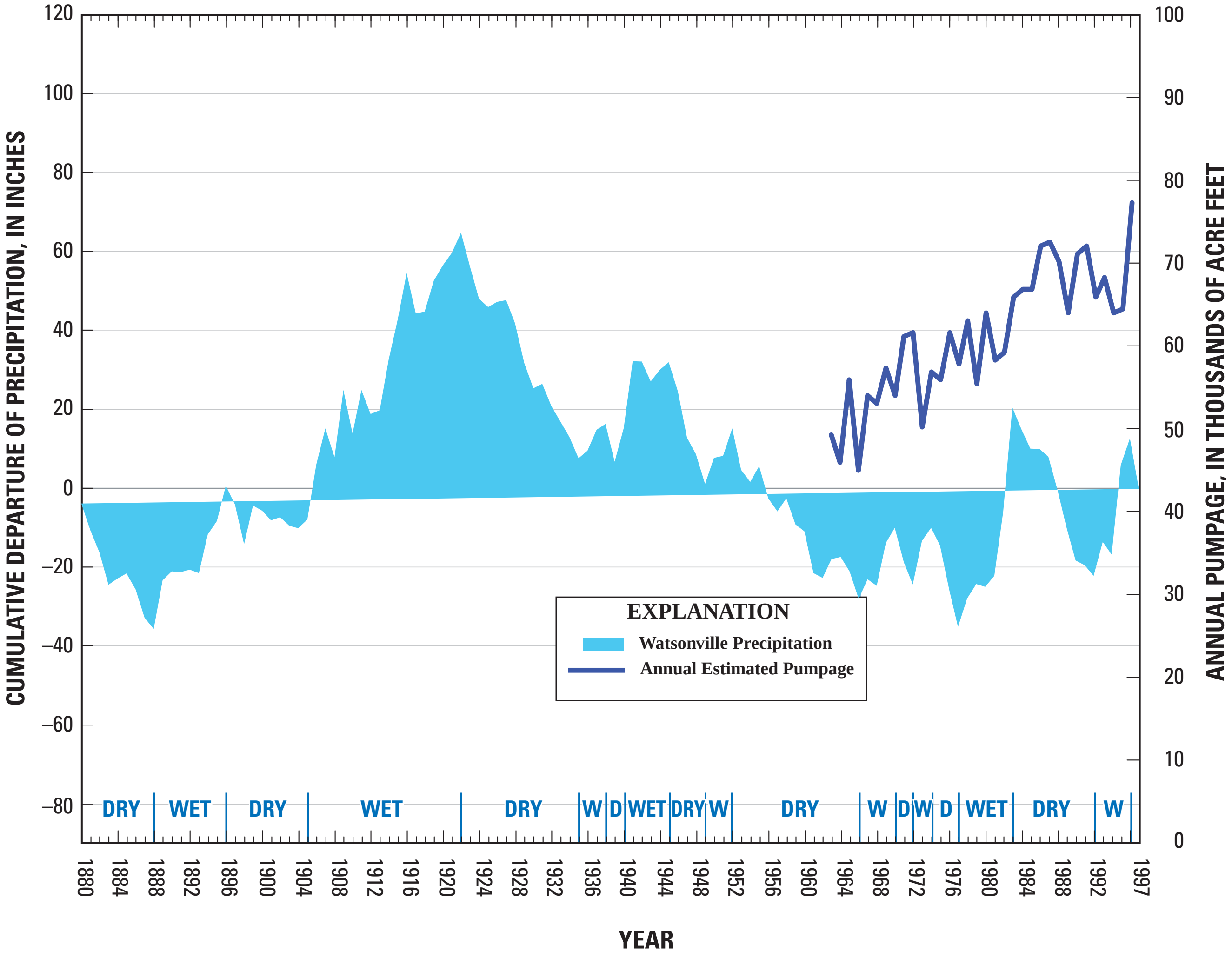


Figure 4. Cumulative departure of precipitation at Watsonville, delineation of wet and dry periods, and estimated ground-water pumpage for Pajaro Valley, Santa Cruz, and Monterey Counties, California.

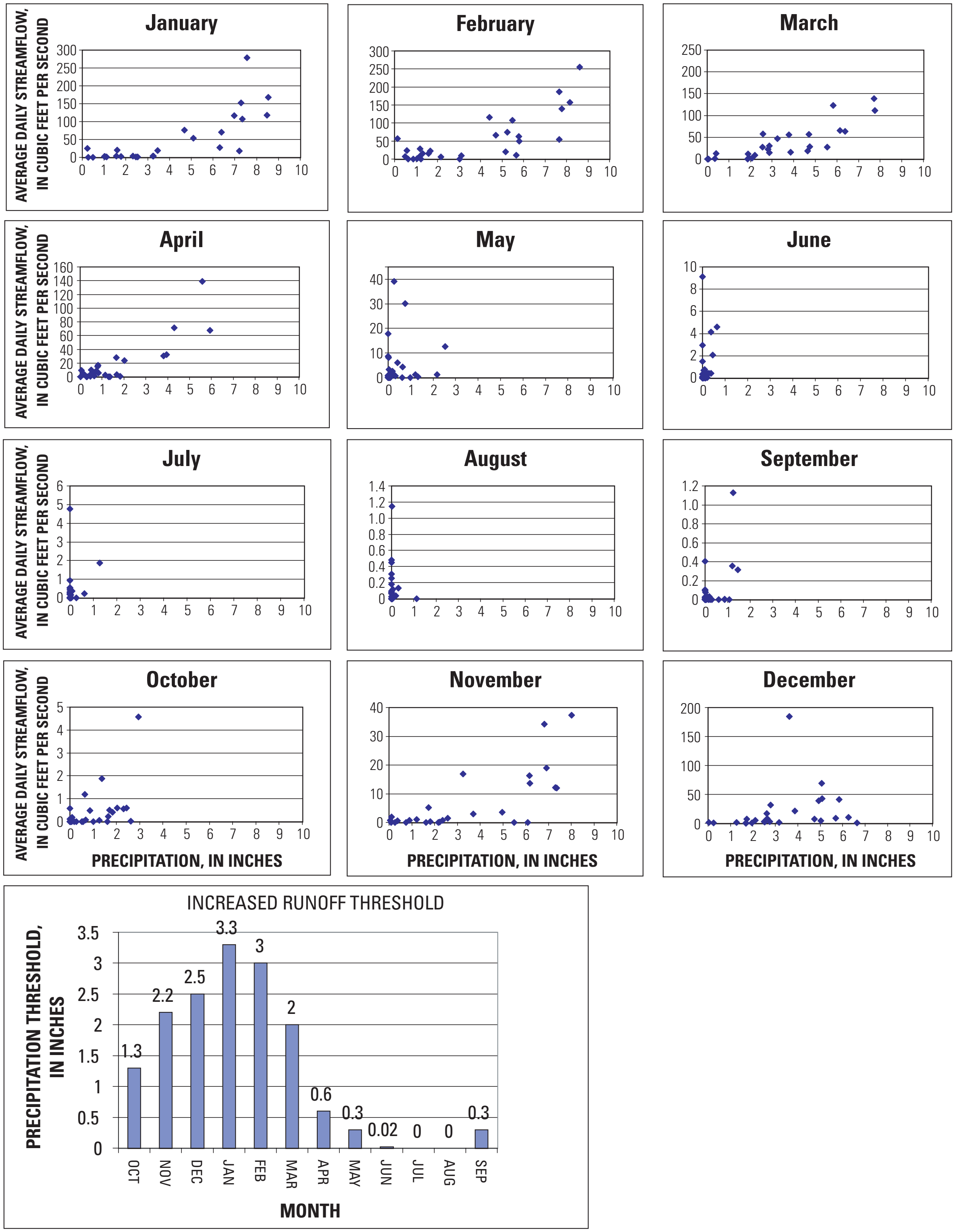


Figure 5. Relations of monthly precipitation to streamflow for Corralitos Creek near Freedom, Santa Cruz County, California, 1958–97.

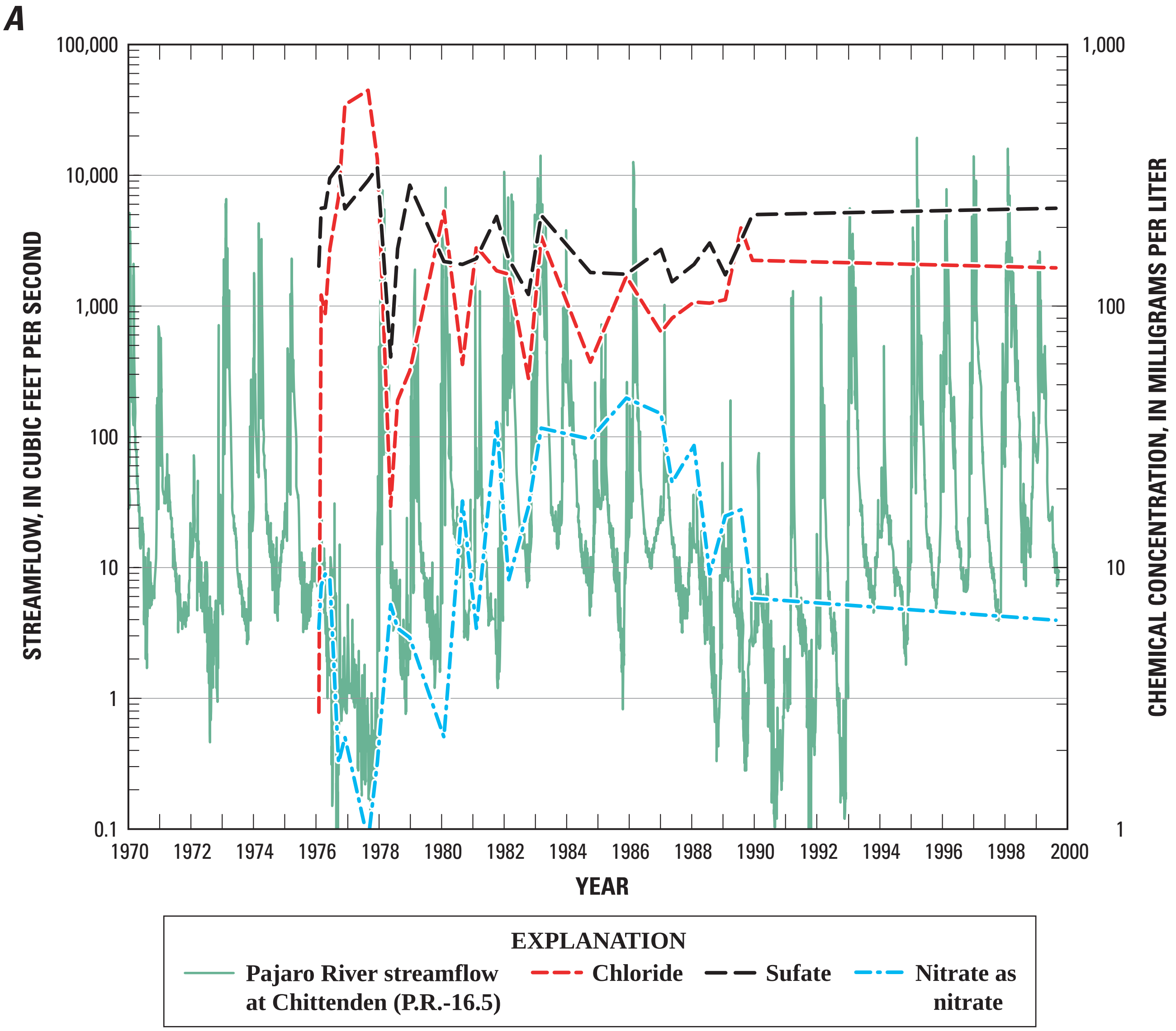


Figure 6. Relation between streamflow and water chemistry for selected sites on the Pajaro River and for Corralitos Creek at Freedom, Santa Cruz County, California.

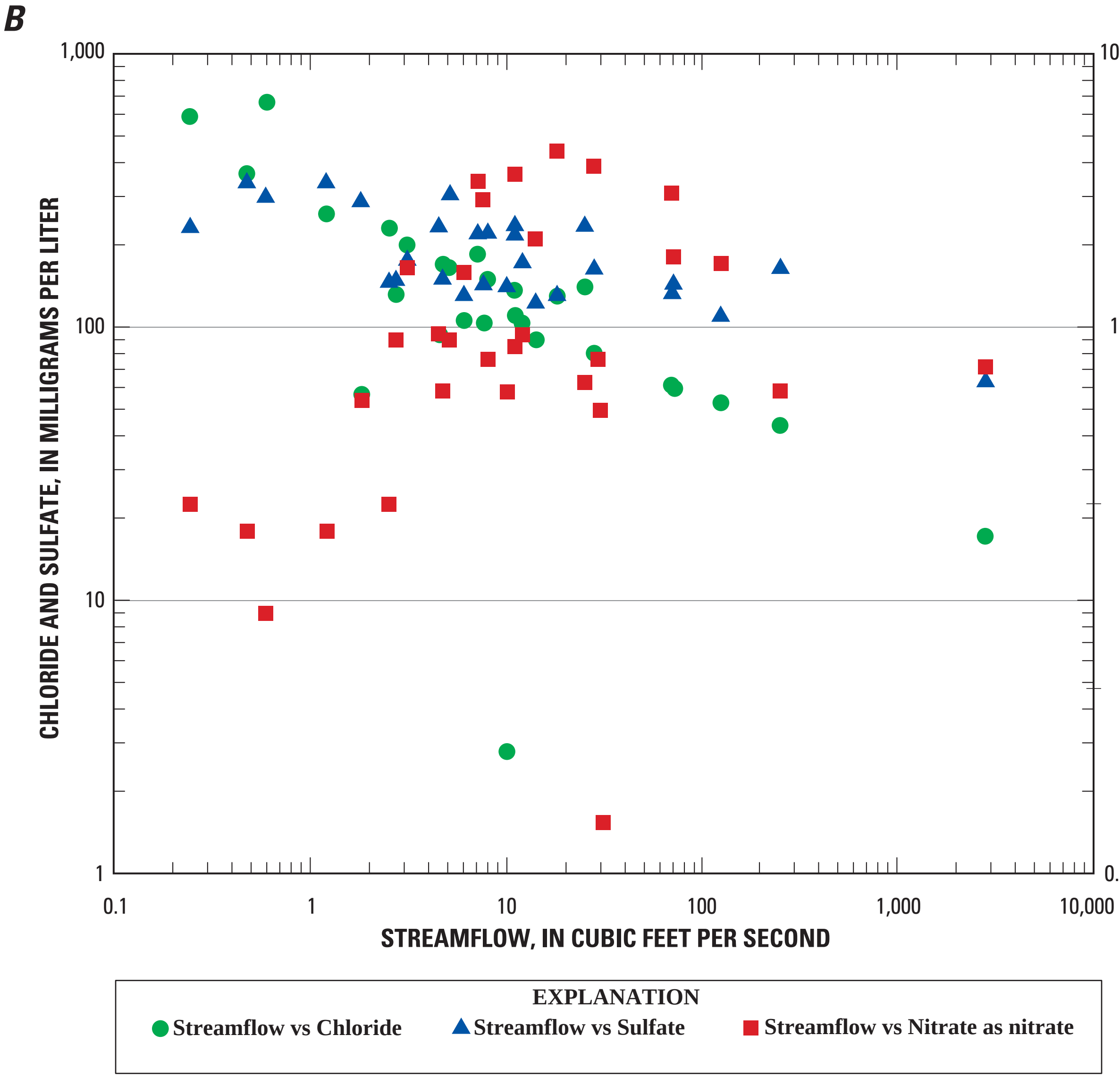
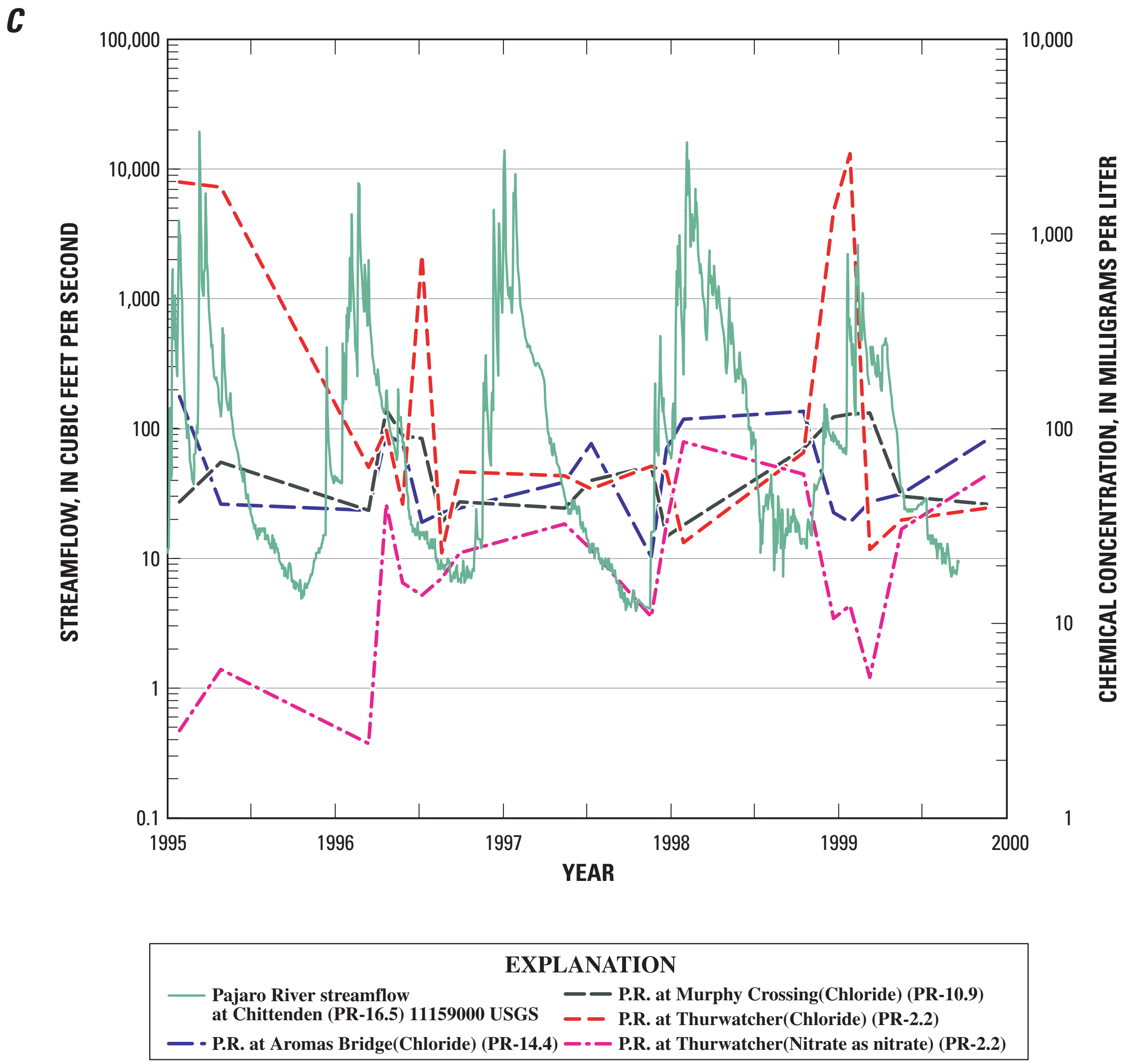


Figure 6.—*Continued.*



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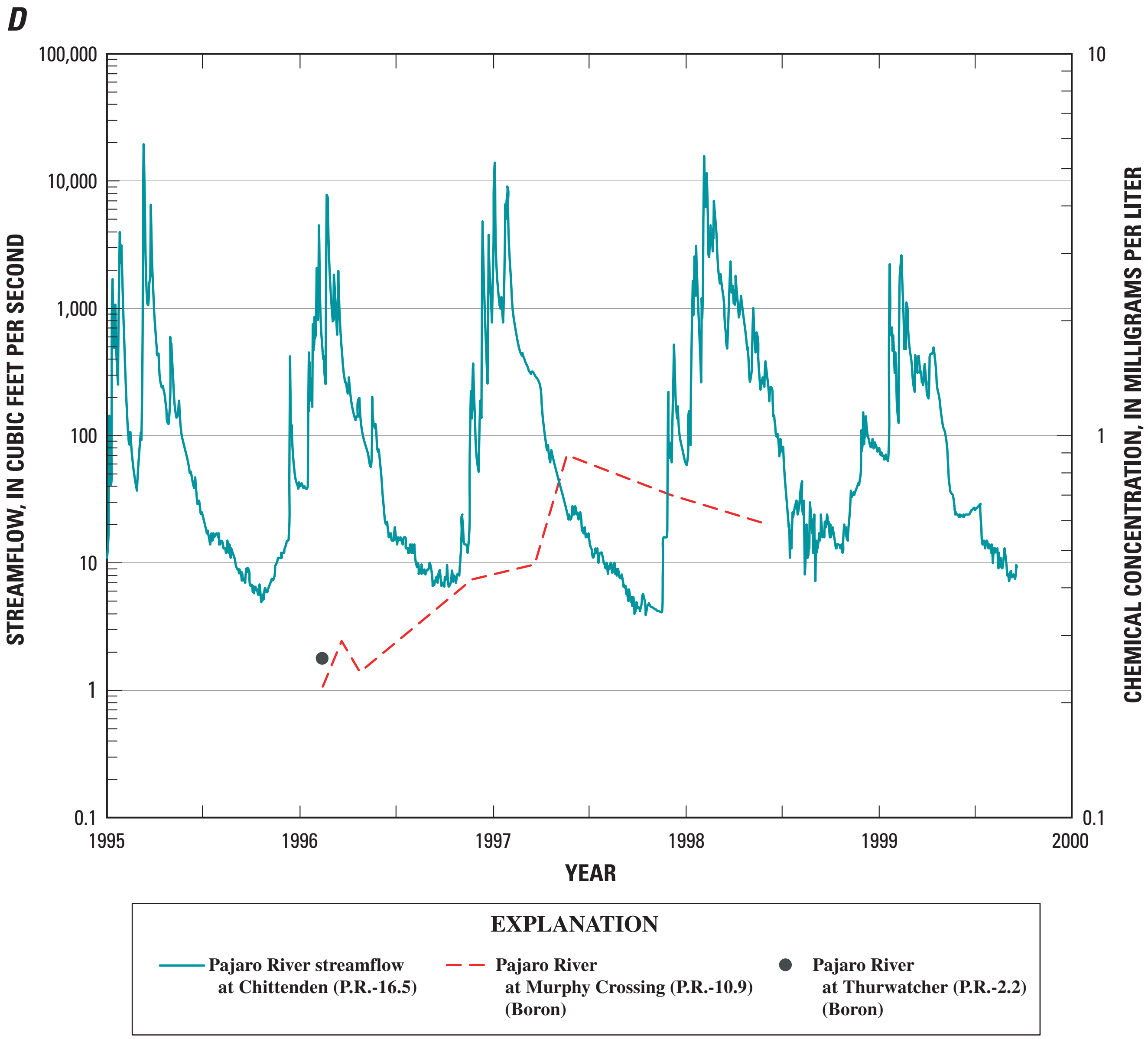

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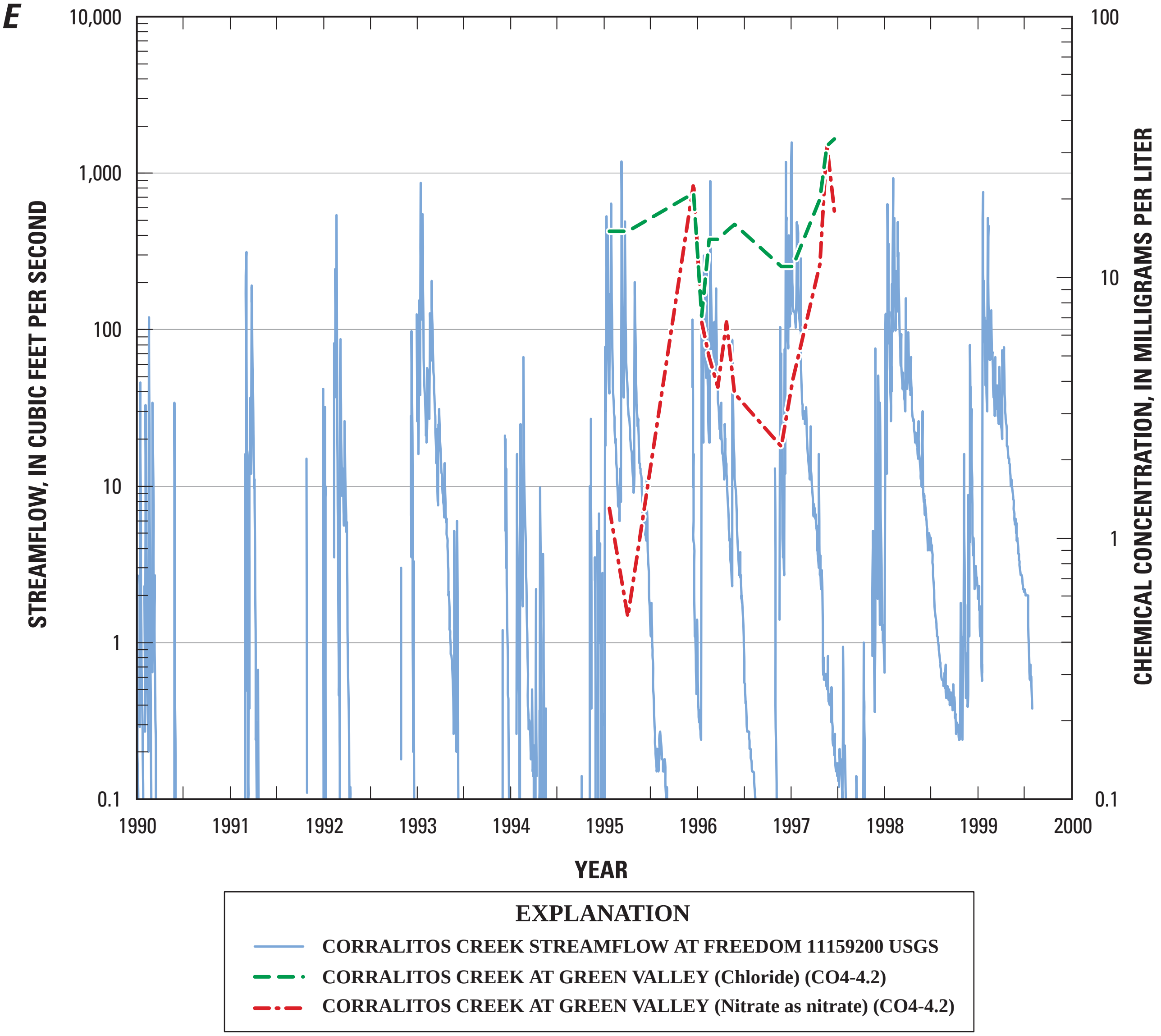

Figure 6.—*Continued.*

The streamflow record from the Pajaro River at Chittenden shows changes in streamflow and base flow, as well as relation to concentrations of selected chemical constituents, for climatic and seasonal cycles (figs. 6*A*–*E*). The annual geometric-mean streamflow for the 58-year period of record is about 10,200 acre-ft/yr (table 1). The seasonal geometric-mean streamflows range from less than 400 acre-ft/season in summer dry-year periods to almost 36,000 acre-ft/season in winter wet-year periods. Based on streamflow-duration analysis, streamflows of less than 200 $ft.^3/s$ occur about 88 percent of the time on the Pajaro River (fig. 7), with mean daily flows less than 12 ft^3/s 50 percent of the days. Streamflows that probably represent floodflows exceed or equal about 770 ft^3/s 5 percent of the time (about 18 days per year) (fig. 7). The geometric-mean annual streamflow for wet-year periods is about 4 times larger than for dry-year periods (table 1, fig. 7). Collectively, this suggests that the smaller streamflows are a substantial part of the streamflow available for ground-water recharge and that climatic cycles influence the time as well as the quantity and quality of streamflow available for additional water supply, fish habitat, or ground-water recharge.

The streamflow from Corralitos Creek at Freedom shows similar climatic and seasonal changes in streamflow (fig. 6*E*). Streamflow on Corralitos Creek also is subject to diversions as great as 8 ft^3/s (5,800 acre-ft/yr), but diversions generally are on the order of about 1,000 acre-ft/yr for water supply by the Watsonville Water Works upstream from Corralitos. The annual geometric-mean streamflow for the 42-year period of record for the gage at Freedom is about 1,400 acre-ft/yr. (table 1). The seasonal geometric-mean streamflows range from about 40 acre-ft/season in summer dry-year periods to almost 3,700 acre-ft/season in winter wet-year periods. The streamflow-duration graph indicates that mean daily flows exceed or equal 0.4 ft^3/s 50 percent of the days and equal or exceed 79 ft^3/s 5 percent of the time (about 18 days per year) (fig. 7). The geometric-mean annual streamflow for wet-year periods is about 2.4 times larger than for dry-year periods for Corralitos Creek at Freedom (table 1; fig. 6*E*).

The water quality of streamflow on the Pajaro River changes with flow (fig. 6) and affects the water quality of recharge. Increased chloride and sulfate concentrations occur during low-flow periods, which are coincident with the summer/fall agricultural pumping season (figs. 6*A*, *B*; Teghavi and Smith, 1999d). Nitrate appears to increase with increased streamflow during the 1980s (figs. 6*A*, *B*). The changes in chloride and sulfate appear to vary together for climatic periods but may not vary together for some seasons. Sulfate and the trace-constituent boron (figs. 6*A*, *D*) appear to increase with increasing flow for some periods, for example 1983, but the lack of synoptic data makes covariation with streamflow difficult to determine using existing data. These data may suggest that there are several sources of poor-quality water that contribute runoff to streamflow. These sources need to be compared with pesticides, herbicide, and wastewater loadings to help delineate the multiple sources of poor-quality water that occur during some streamflow periods. The relations between water quality and streamflow is similar to that measured on the Santa Clara River, Ventura County, which contains poorer quality water at low flow that is partly from ground-water contributions that are rejected to the surface as base flow in the bedrock constrictions at subbasin boundaries (Densmore and others, 1992). The source and concentrations of these chemical constituents may affect water-resources management and the implementation of specific water-supply options. The downstream chloride concentrations for the period 1995–97 at Aromas Bridge, Murphy Crossing, and Thurwatcher Road show similar changes in concentration that are generally opposite to changes in streamflow. The chloride concentrations in streamflow at Murphy Crossing and Thurwatcher Road (fig. 1*C*, PR-2.2) appear to change similarly with changes upstream at Aromas Bridge (fig. 6*C*). Additional sources of chloride such as irrigation or urban runoff, discharge of treated wastewater, or additional ground-water or surface-water sources could contribute to differences in chloride at downstream sites but remain uncertain owing to the lack of synoptic streamflow and water chemistry data. The streamflow and water quality relations of the data from the Chittenden streamflow gage indicate that low flows of the Pajaro River may be an additional source of salinity for ground-water recharge.

Table 1. Summary of streamflow attributes for selected streams in the Pajaro Valley, California

[AMBAG, Association of Bay Area Governments; CSWRCB, California State Water Resources Control Board; MW, Montgomery Watson; USGS, U.S. Geological Survey; —, no data]

Time period (source of summary data)	Pajaro River at Chittenden [11159000/PR-16.5][1] Average annual streamflow (acre-feet per year, except as noted)	Corralitos Creek At Freedom [11159200/CO-2.3][1] Average annual streamflow (acre-feet per year, except as noted)
[1946–49] (CSWRCB, 1953)	21,500 (1946–47) 7,300 (1947–48) 24,100 (1948–49)	—
[1984] (AMBAG, 1985)	105,000	11,350
[1964–92] (MW, 1993)	114,500	2,300
[1940–1998][2] (USGS)	(a) 124,000 (b) 10,200 (c) 19,900–4,700	(a) 11,900 (b) 1,400 (c) 2,000-800
[Winter–spring][3] (USGS)	(a)14,400–4,000 (b) 35,700–4,800 (c) 7,600–1,800	(a) 1,600–300 (b) 3,700–500 (c) 600–100
[Summer–fall][4] (USGS)	(a) 700–1,100 (b) 1,200–400 (c) 1,900–600	(a) 50–200 (b) 50–40 (c) 220–170

[1] First number is U.S. Geological Survey station number, and second number is Pajaro Valley Water Management Agency station number.

[2] (a) arithmetic mean for period of record; (b) geometric mean for period of record; (c) geometric mean of streamflow for wet- and dry-year climatic periods.

[3] (a) winter- and spring-season geometric means for period of record; (b)winter-season geometric mean for wet- and dry-year climatic periods; (c) spring geometric mean of streamflow for wet- and dry-year climatic periods of the period of record. All streamflows are reported in acre-feet per season.

[4] (a) summer- and fall-season geometric means for period of record; (b) summer-season geometric mean for wet- and dry-year climatic periods; (c) fall geometric mean of streamflow for wet- and dry-year climatic periods of the period of record. All streamflows are reported in acre-feet per season.

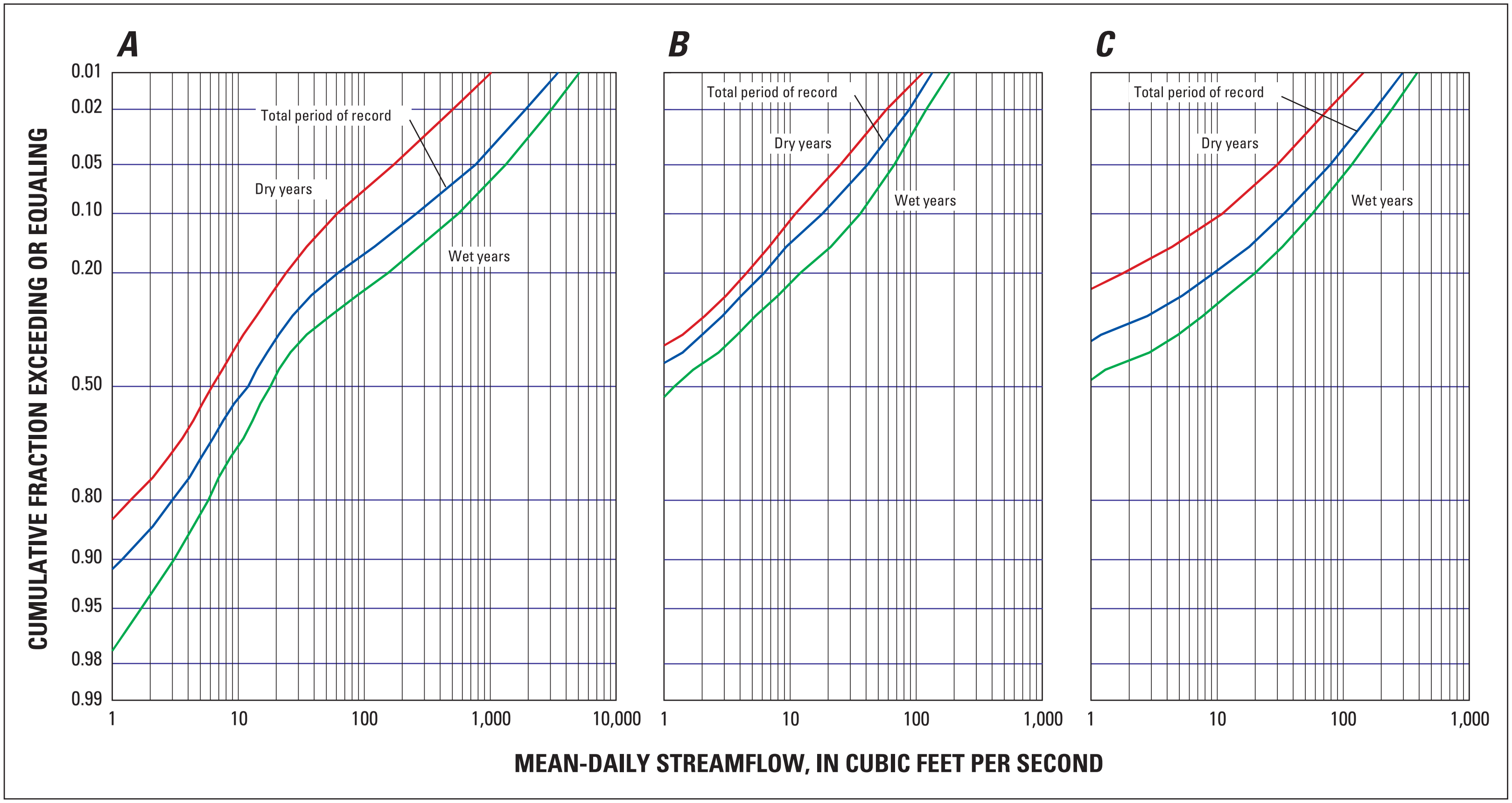

Figure 7. Flow duration for the Pajaro River at Chittenden, 1949–98, for Corralitos Creek near Corralitos, 1958–73, and for Corralitos Creek at Freedom, California 1957–98, Santa Cruz County, California.

Ground Water

The coastal monitoring wells provide information to assess water levels and seawater intrusion near the coast (fig. 1*C*). Longer term water-level records from coastal and inland water-supply wells reflect water levels and changes similar to those of the monitoring-well sites. In general, changes in ground-water levels from coastal wells show seasonal changes from agricultural pumpage in the Pajaro Valley. The lack of long-term decline in coastal wells may be due, in part, to water-level declines from pumpage with related storage depletion and subsequent water-level recoveries supplied, in part, by seawater intrusion.

The water-level declines from sustained pumpage have resulted in seawater intrusion in Pajaro Valley. Mann (1988) encapsulated the nature of seawater intrusion when he wrote to the director of the Pajaro Valley Water Management Agency:

> "It is generally agreed that there is seawater intrusion in the coastal portions of Pajaro Valley. It probably started as early as 1947....Geologic conditions favor seawater intrusion....It is generally recognized that below sea level pumping levels in wells close to the coast carry with them the danger of inland movement of sea water, especially in shallow aquifers. What is not recognized generally is that the critical fresh water level must be maintained some distance above sea level to avoid any inland movement of sea water....In the Quaternary alluvium beneath Pajaro Valley, there is a basal gravel, the bottom of which is about 200 feet below sea level. To stabilize or stop such movement, the fresh water head must be at +5 or higher. Thus, if water levels in wells tapping the alluvial aquifer are above sea level, but below elevation +5, it must be presumed that sea water is wedging in toward the shoreline from the subsea outcrop. In the deeper Aromas aquifer (assuming a depth of 600 feet) the necessary fresh water head would be +15....Under present conditions in the PVWMA, there is a pumping trough well inland from the coast, and a widespread area of below-sea-level water levels. Under these conditions, the sizes and depths of cones of depression near the coast are irrelevant to the regional problems, for sea water intrusion would continue even if there were no coastal cones of depression."

Coastal Monitoring-Well Sites

Water-level altitudes from multiple-well observation sites along the coast (figs. 1*C*, 8–17) from La Selva Beach (PV-1, fig. 8) south to Springfield Terrace (PV-4A, fig. 10) are generally below sea level with some wells showing declining winter water levels during the 7-year drought (1986–92). In the time after this drought, water levels in the monitoring wells have recovered a few feet but were still less than the height, 5 to 15 ft above sea level, required to maintain the seaward flow of ground water and prevent seawater intrusion. Most water levels in 1998 ranged from 0 to 5 ft above sea level. Summer water levels in the aquifers in the lower Aromas Sand near the mouth of the Pajaro River were still as much as 15 ft below sea level at well-site PV-3 (fig. 9) and 20 ft below sea level at well-site PV-6 (fig. 11).

The water-level hydrographs from the multiple-well sites in areas where less of the pumpage is for agriculture, such as the San Andreas (PV-1, fig. 8) and La Selva Beach (SC-3A and SC-4A, figs. 14, 15) areas, do not contain large seasonal water-level changes. The hydrographs from monitoring-well sites show that the water levels and water-level declines are similar in the shallow and medium wells but differ from the hydrographs for many of the deeper wells. These water-level differences with depth can result in downward pressure gradients that can promote the potential for vertical leakage of ground water through natural leakage or through wellbore flow in wells screened across multiple aquifers. Water-level differences between upper and lower aquifers are the largest during the irrigation season. These patterns of water-level declines and water-level changes are similar to those measured in other coastal basins with agricultural and municipal use, such as the Ventura (Hanson and others, 2002) and Santa Barbara areas (Freckleton and others, 1998).

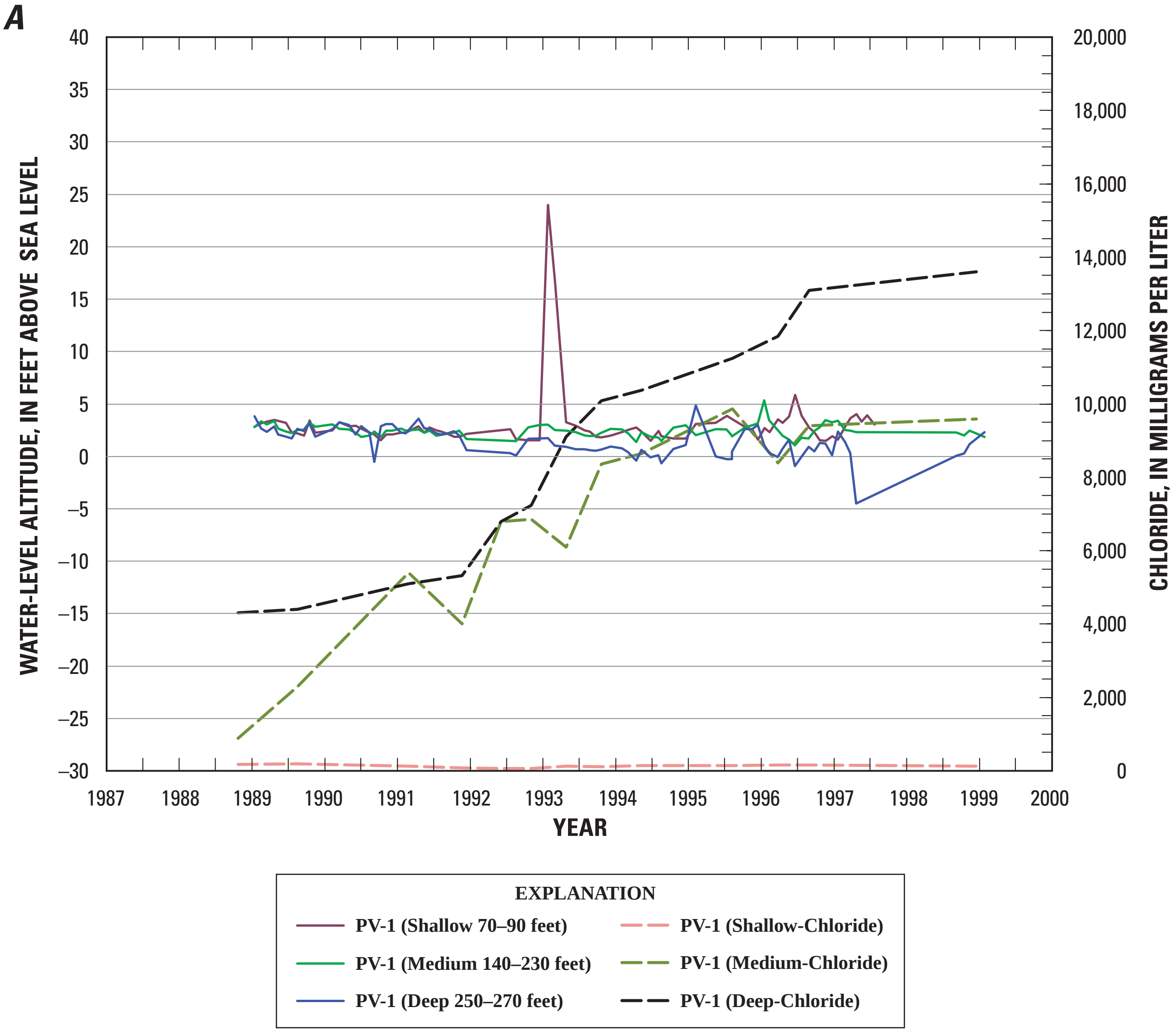

Figure 8. The PV-1 multiple-well monitoring site in the San Andreas subarea of the Pajaro Valley, Santa Cruz County, California.

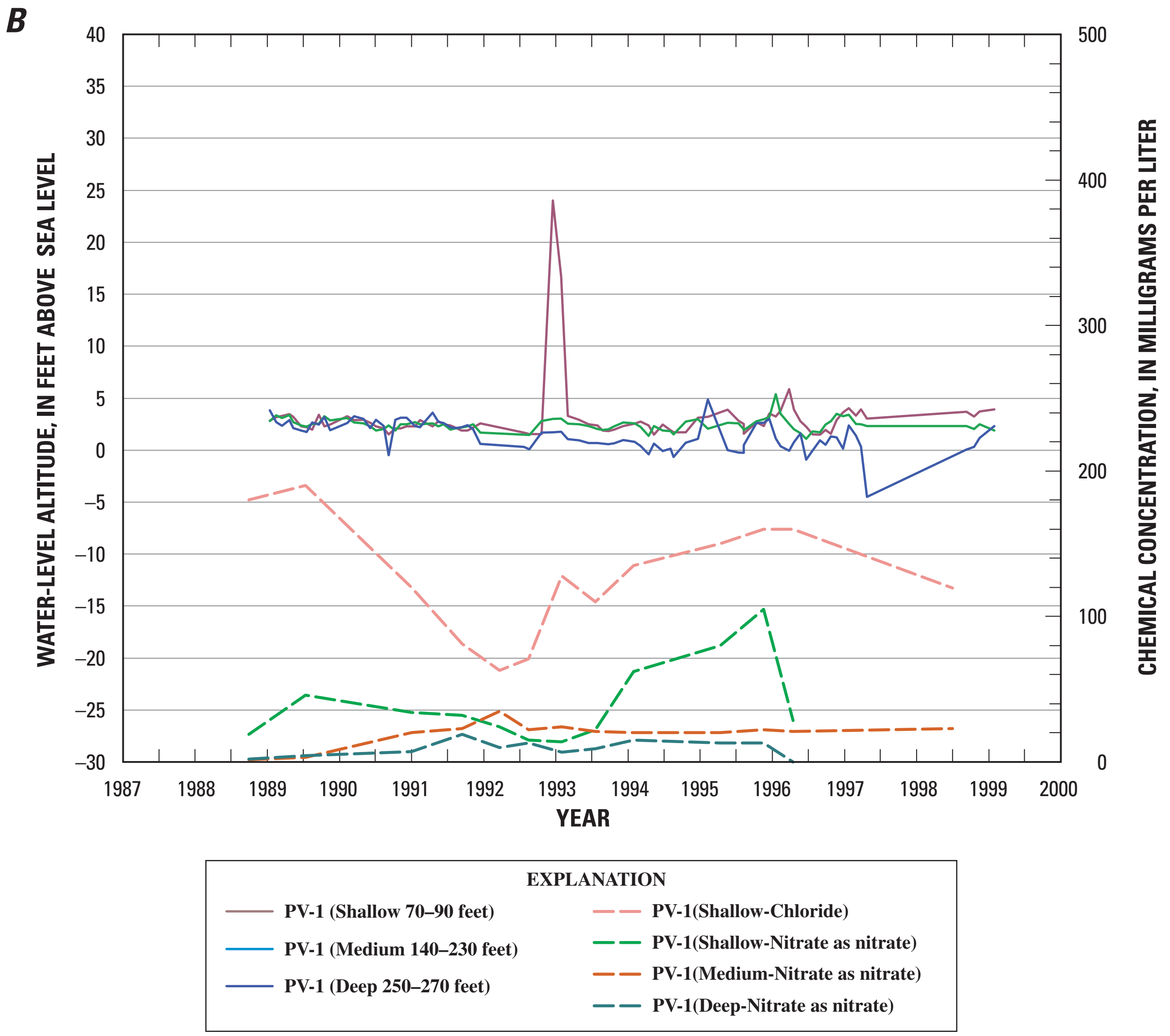

Figure 8.—*Continued.*

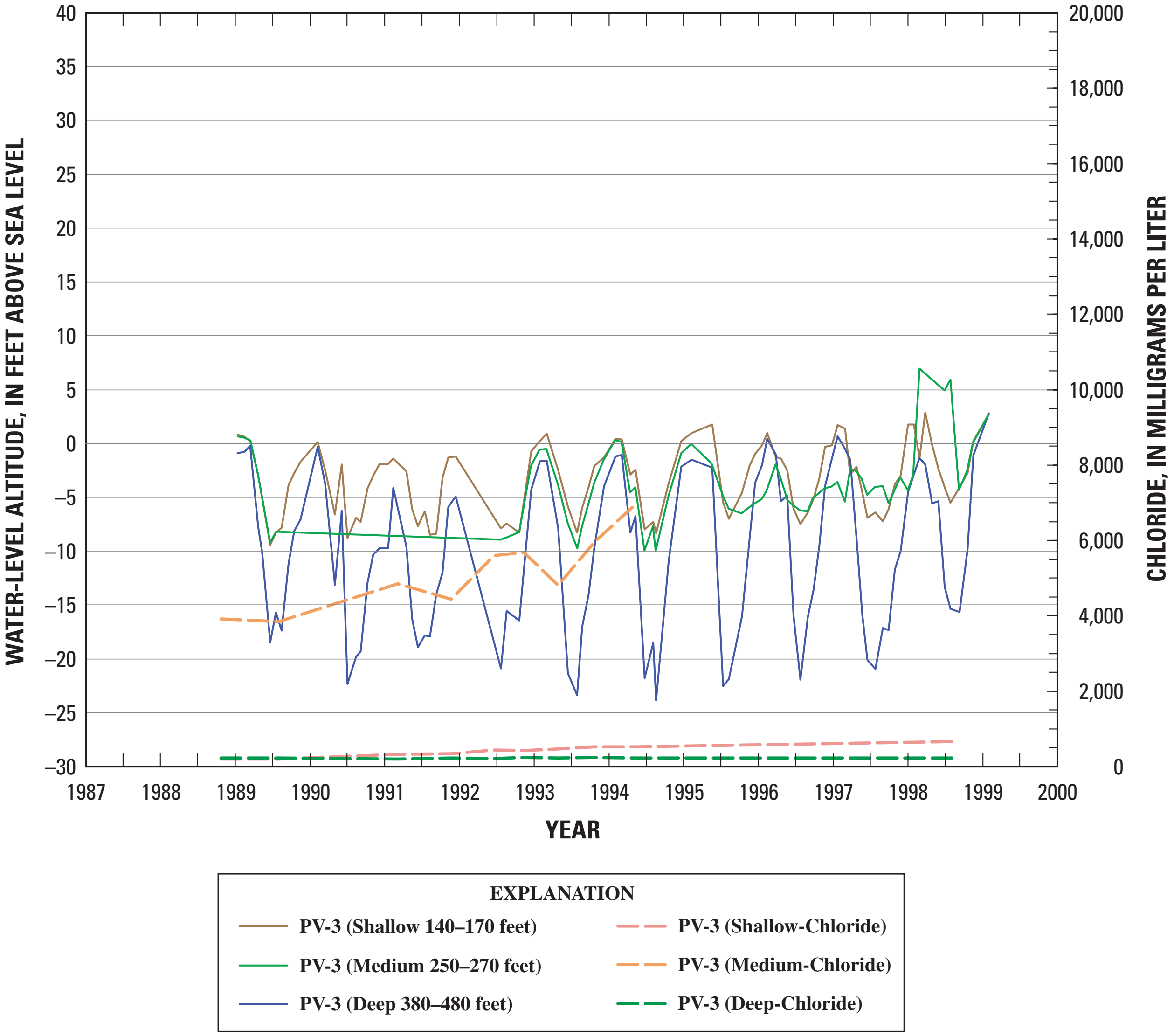

Figure 9. The PV-3 multiple-well monitoring site in the Pajaro River Mouth subarea of the Pajaro Valley, Santa Cruz County, California.

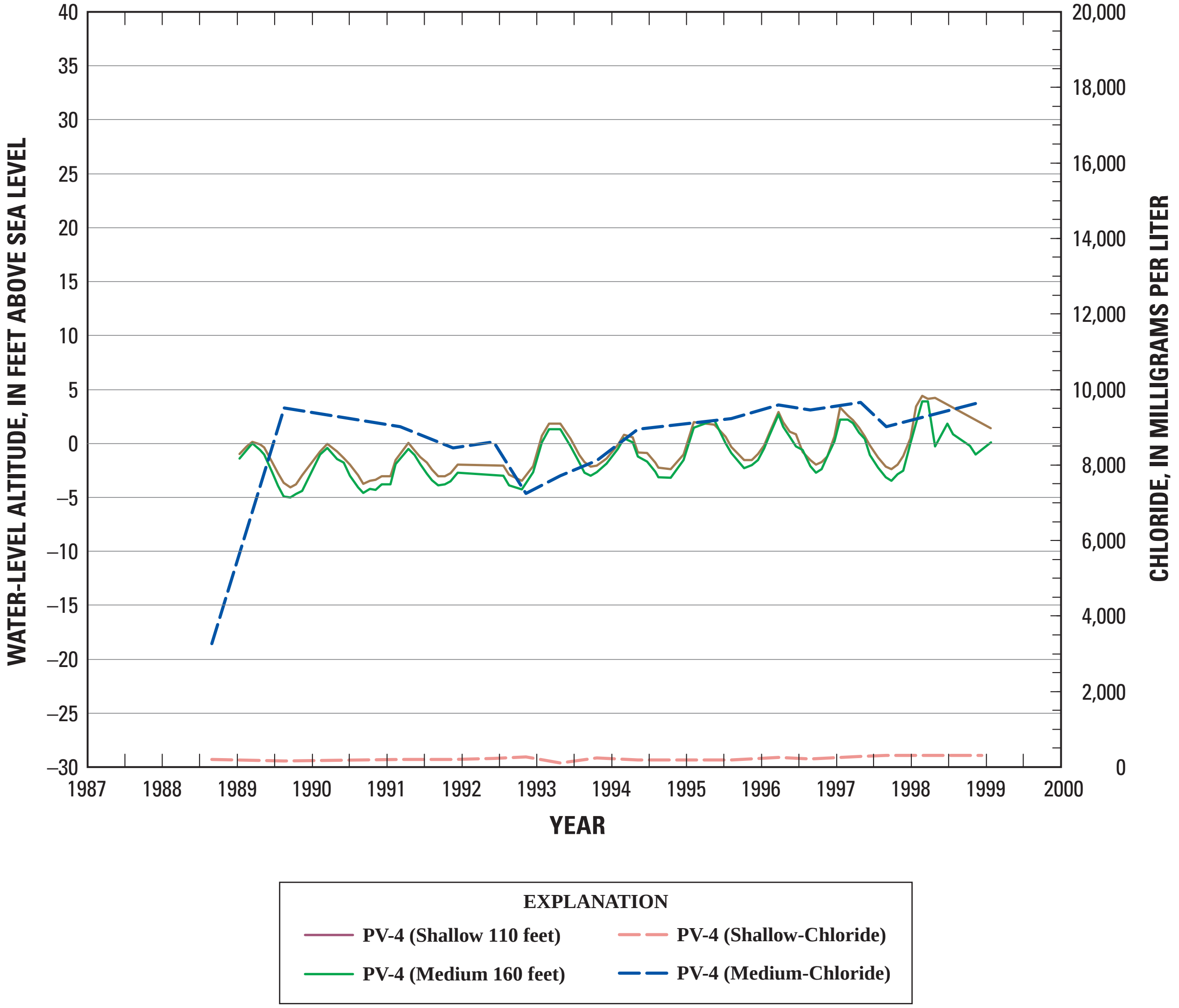

Figure 10. The PV-4 multiple-well monitoring site in the Springfield subarea of the Pajaro Valley, Monterey County, California.

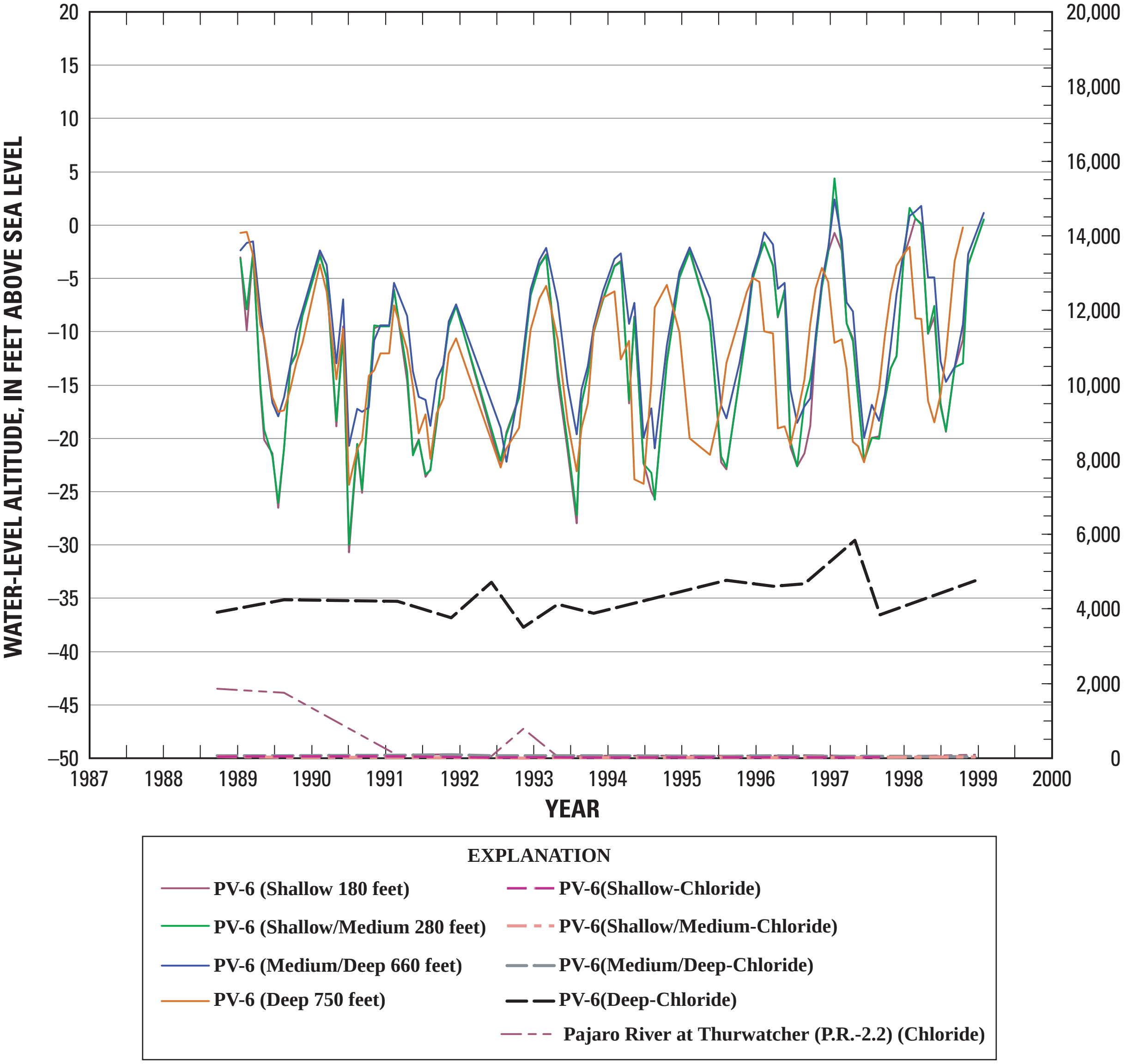

Figure 11. The PV-6 multiple-well monitoring site in the Pajaro River Mouth subarea of the Pajaro Valley, Santa Cruz County, California.

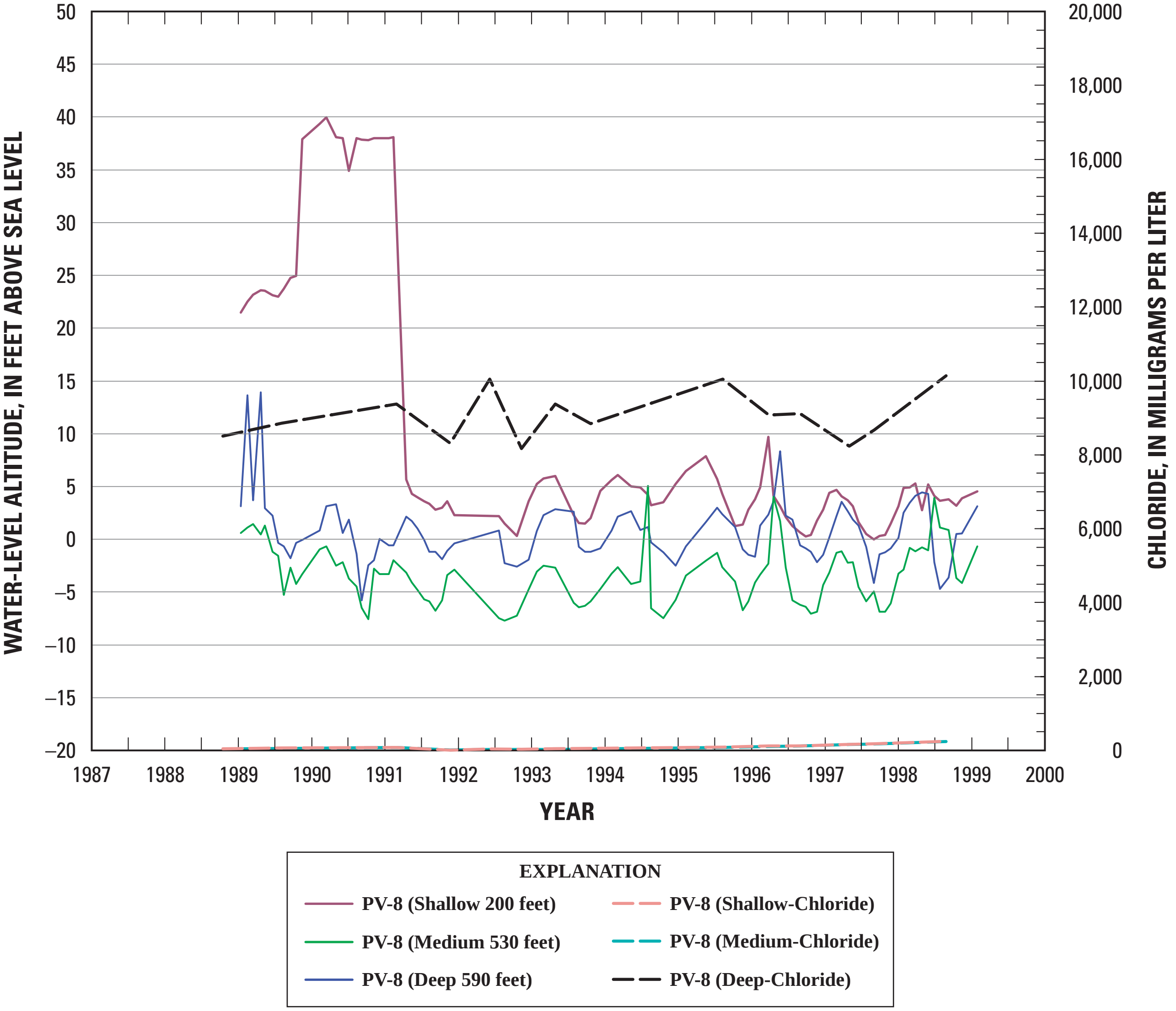

Figure 12. The PV-8 multiple-well monitoring site in the San Andreas/Harkins Slough subareas of the Pajaro Valley, Santa Cruz County, California.

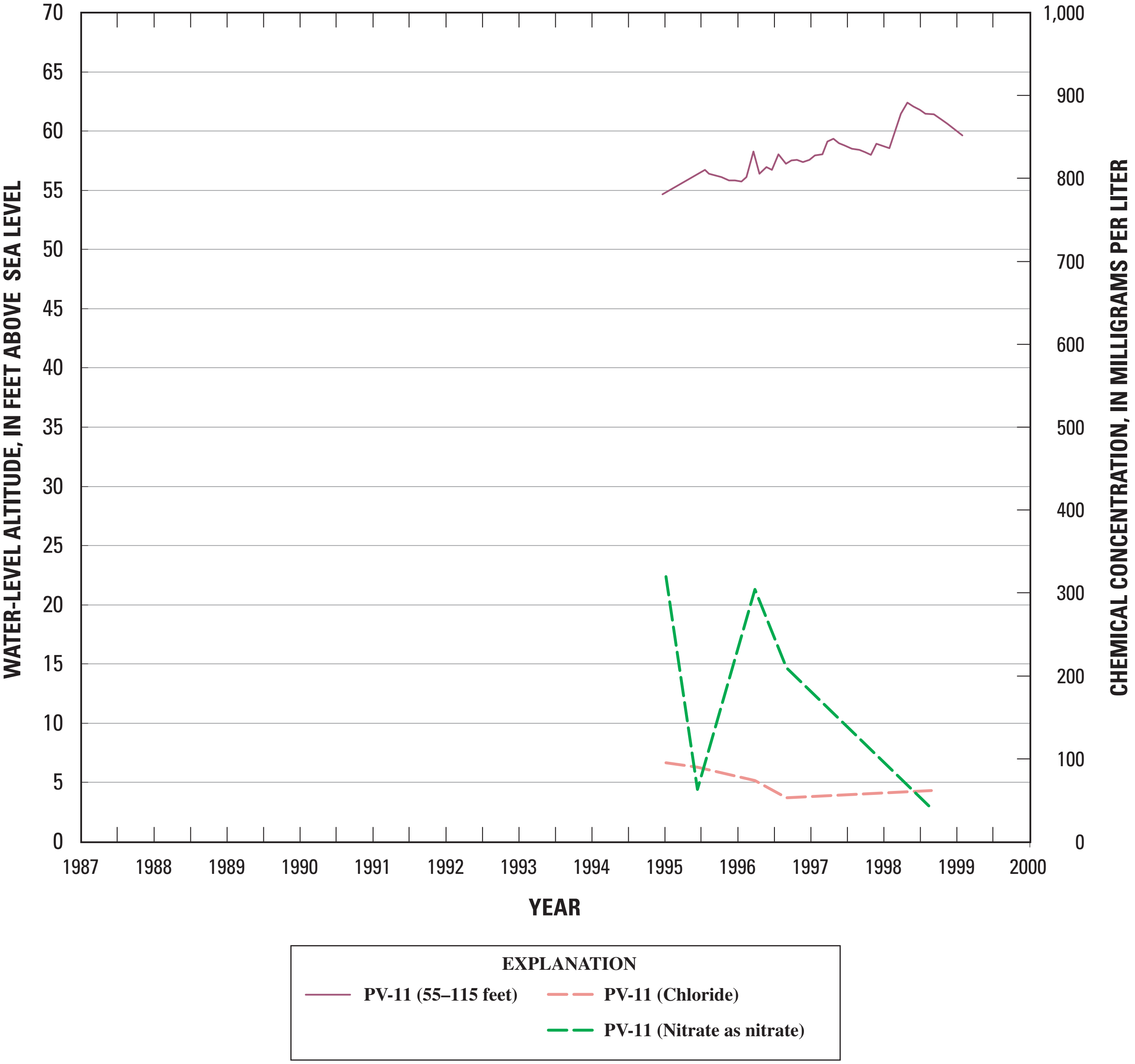

Figure 13. The PV-11 multiple-well monitoring site in the San Andreas subarea of the Pajaro Valley, Santa Cruz County, California.

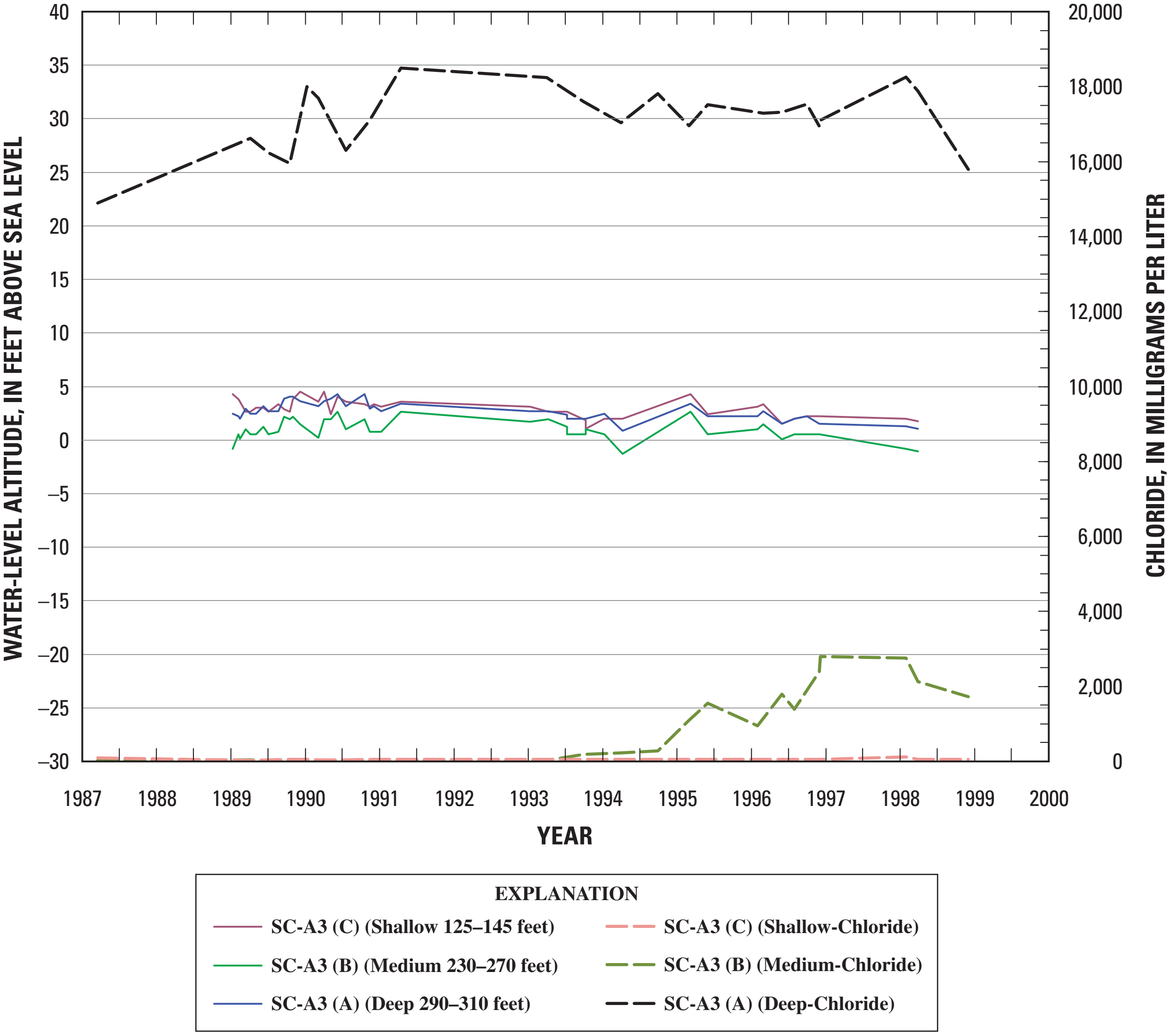

Figure 14. The SC-A3 multiple-well monitoring site in the La Selva Beach area of Soquel Creek Water District north of Pajaro Valley, Santa Cruz County, California.

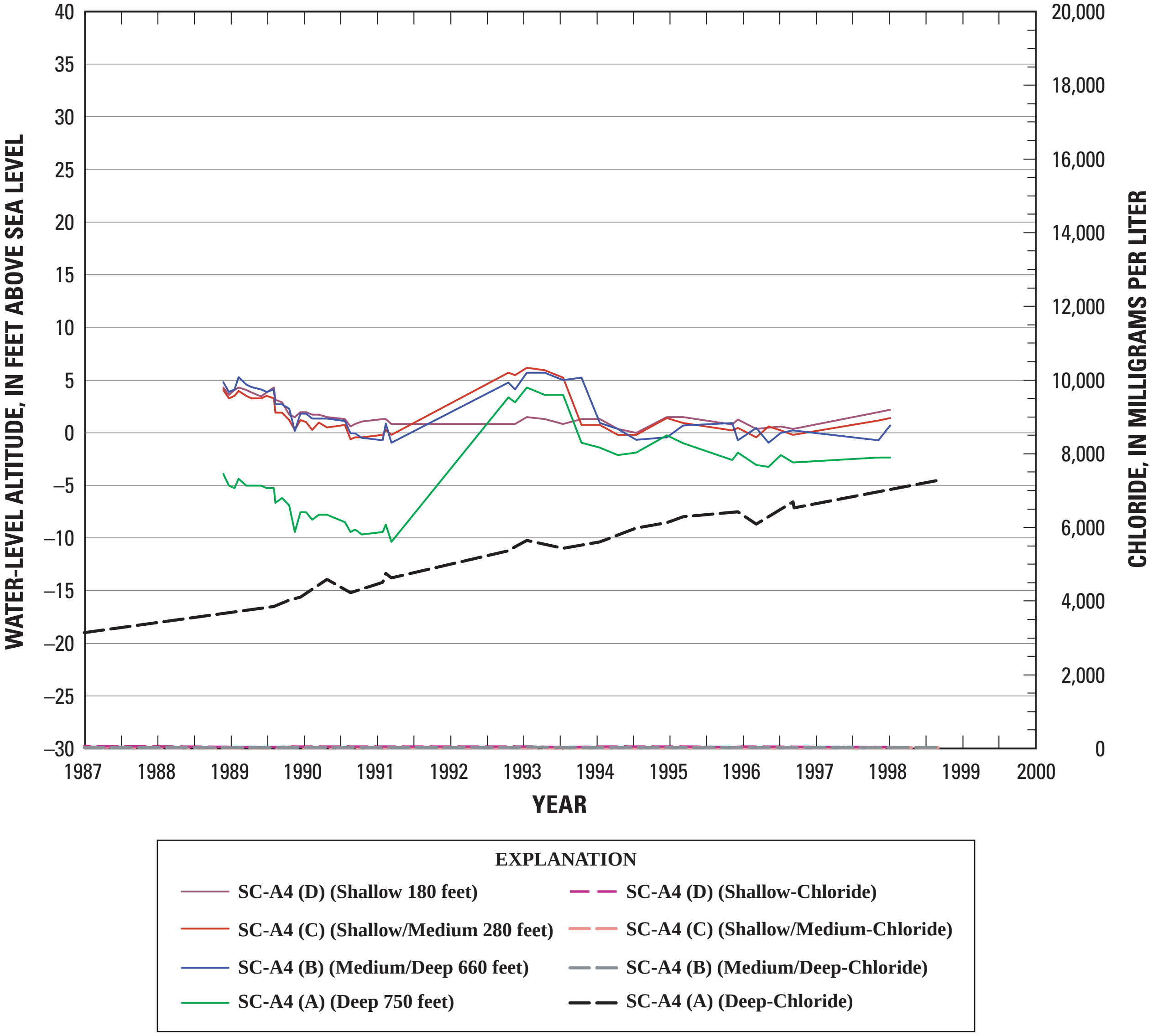

Figure 15. The SC-A4 multiple-well monitoring site in the La Selva Beach area of Soquel Creek Water District north of Pajaro Valley, Santa Cruz County, California.

Long-Term Water Levels and Seawater Intrusion

The first comprehensive study of Santa Cruz and Monterey Counties recognized seawater intrusion as early as 1943 and noted that this intrusion may be driven by seasonal pumping troughs of 15 ft below sea level (California State Water Resources Board, 1953). The seasonal pumping troughs persist throughout the coastal areas where ground-water withdrawals are predominantly agricultural pumpage (Johnson, 1983; Luhdorff & Scalmanini, 1987a, b; Johnson and others, 1988; Bond, 1986; Bond and Bredehoeft, 1987). Simpson (1946) also noted some evidence of seawater intrusion into the coastal parts of the Pajaro Valley aquifer system. In 1974, the most extensive seawater intrusion was in the aquifers from 100 to 200 ft depth below sea level; intrusion was present to a lesser extent in the lower aquifers in the Aromas Sand (300 to 600 ft below sea level) (Muir, 1974).

Comparison of long-term ground-water levels from coastal water-supply wells and monitoring wells (PV-3) indicate water levels have been below sea level since 1970 in the Pajaro River Mouth subarea (fig. 16*A*). Comparisons with the coastal monitoring wells in the Springfield subarea shows that long-term declines of more than 20 ft occurred prior to the 1990s and increasing water-level differences of more than 10 ft are occurring in the Aromas Sand (12S/2E-30M2 relative to shallower aquifers (PV-4A) (fig. 17). Long-term water levels generally have been below sea level but vary periodically with the climatic cycles in the Springfield subarea since 1965 (fig. 17). Similarly, water levels from wells in the Murphy Crossing area show shallow inland water levels that are above coastal water levels except during dry periods (figs. 16*A*, *B*). The water levels near Murphy Crossing show substantial decline during the drought of the late 1980s and are below sea level in the early 1990s. Recent assessment of the perched and regional water levels in the Corralitos subarea indicate that water levels in the aquifers of the Aromas Sand in this region also are near sea level (Koenig, 1992, 1994). The water levels from shallow and deeper water-supply wells from the Murphy Crossing region converge on water levels similar to those of coastal monitoring wells during drought periods as shown for the dry period 1983–1992 (figs. 16*A*, *B*). The resulting inland cones of depression have resulted in regional water-level declines and widespread water-level altitudes near or below sea level that have persisted for several decades and may become more widespread during droughts.

EVALUATION OF RECHARGE AND SEAWATER INTRUSION BASED ON WATER CHEMISTRY

Ground-water sampling for this study was used to assess the nature and distribution of recharge and saline ground water, as well as the source, age, and movement of ground water in the coastal areas of the Pajaro Valley aquifer systems. The sampling and analysis included physical attributes, major ions and nutrients, selected trace elements, and selected isotopes. The trace elements used for geochemical interpretations included boron, strontium, barium, bromide, and iodide. The deuterium, oxygen, and tritium isotopes were collected for all ground-water sites. In addition, isotopes of carbon, sulfur, boron, and strontium were analyzed for selected sites. The data collected in this study are summarized in Appendix 2. Additional geochemical data provided by PVWMA and SCWD also were used to help interpret the nature and distribution of recharge and seawater intrusion.

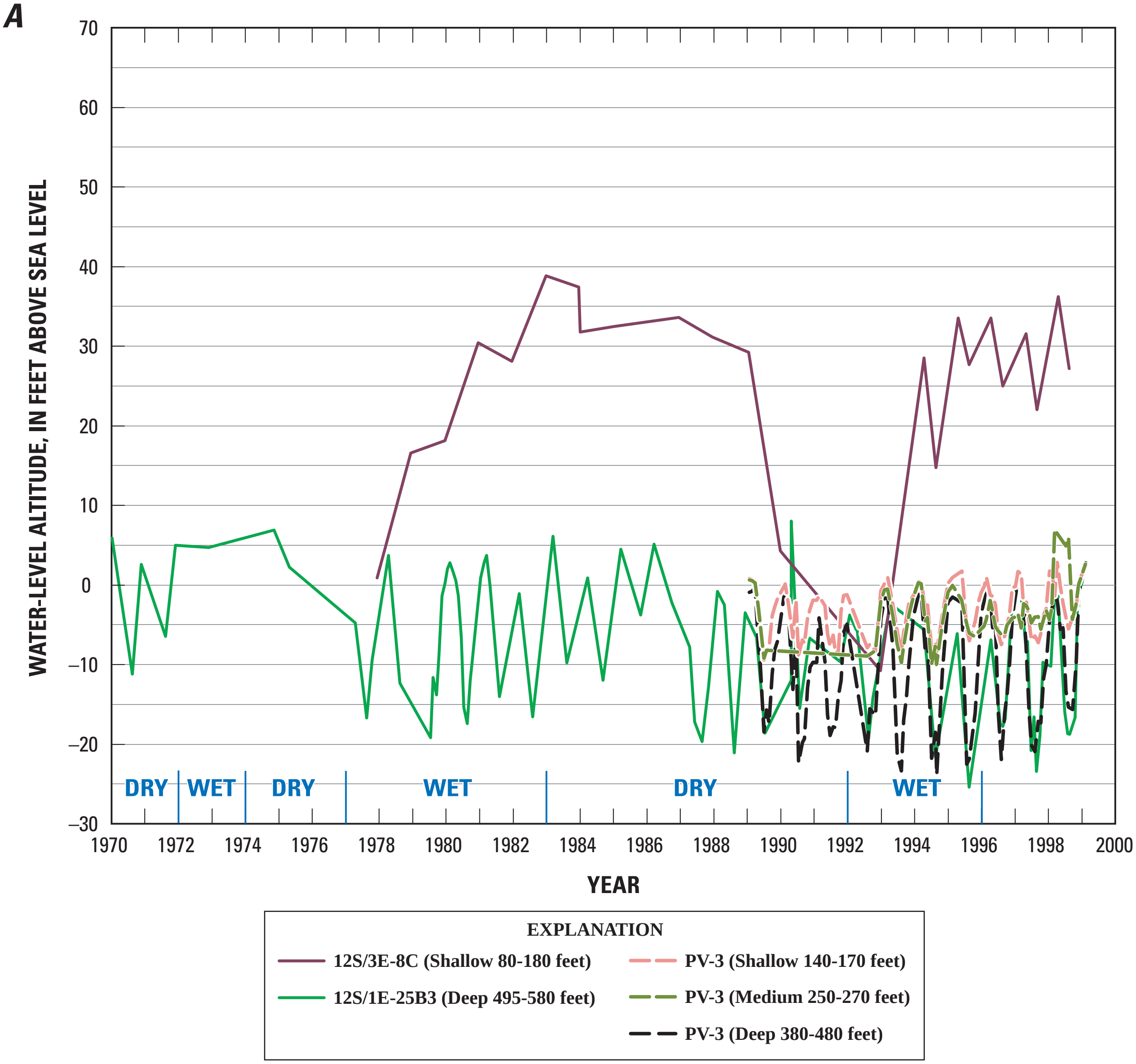

Figure 16. Multiple-well PV-3 and deep well 12S/1E-25B3 in the Pajaro River Mouth subarea and wells 12S/3E-8C and 12S/3E-7J2 in the Pajaro subarea of the Pajaro Valley, Santa Cruz County, California.

B

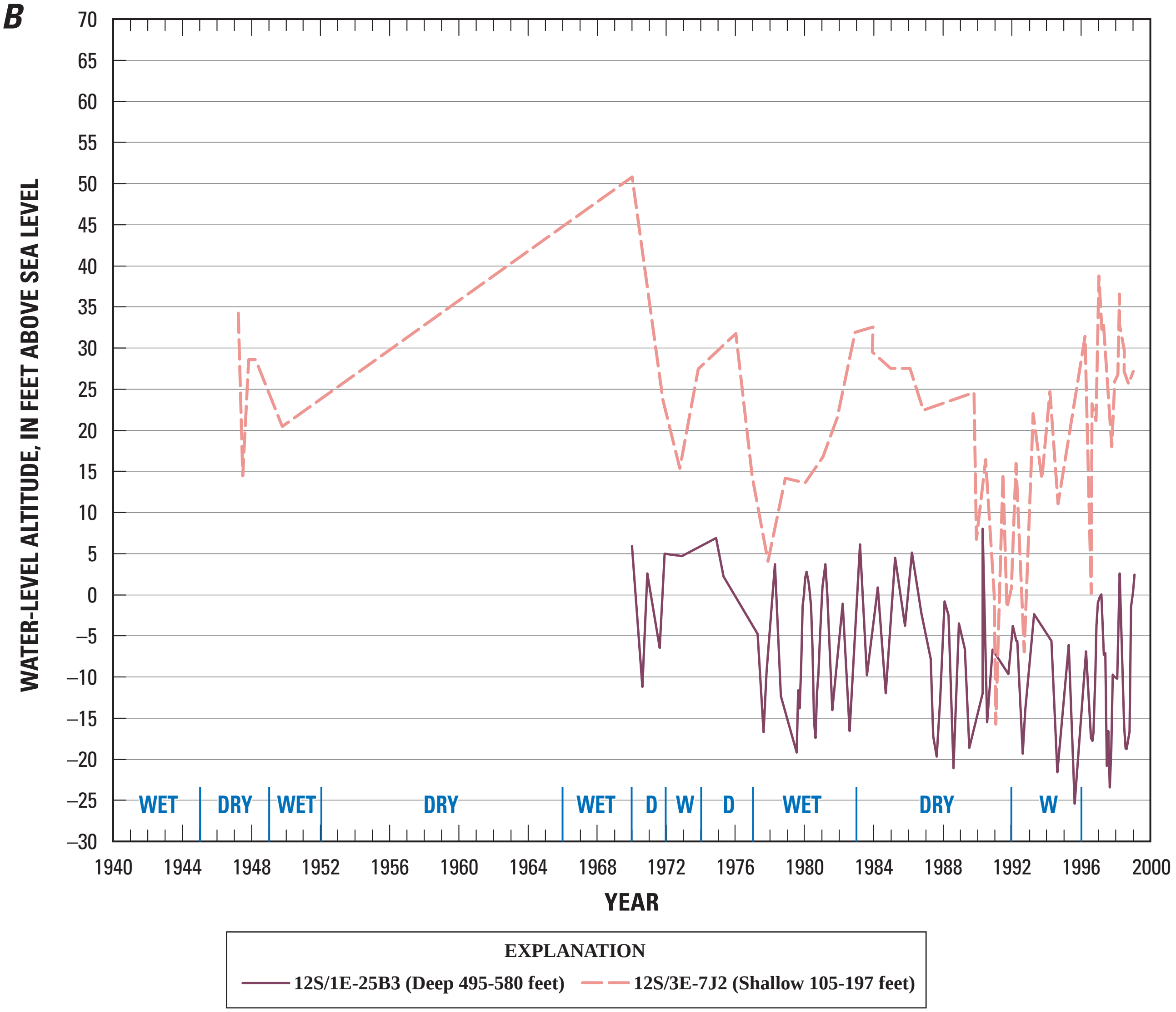

Figure 16.—*Continued.*

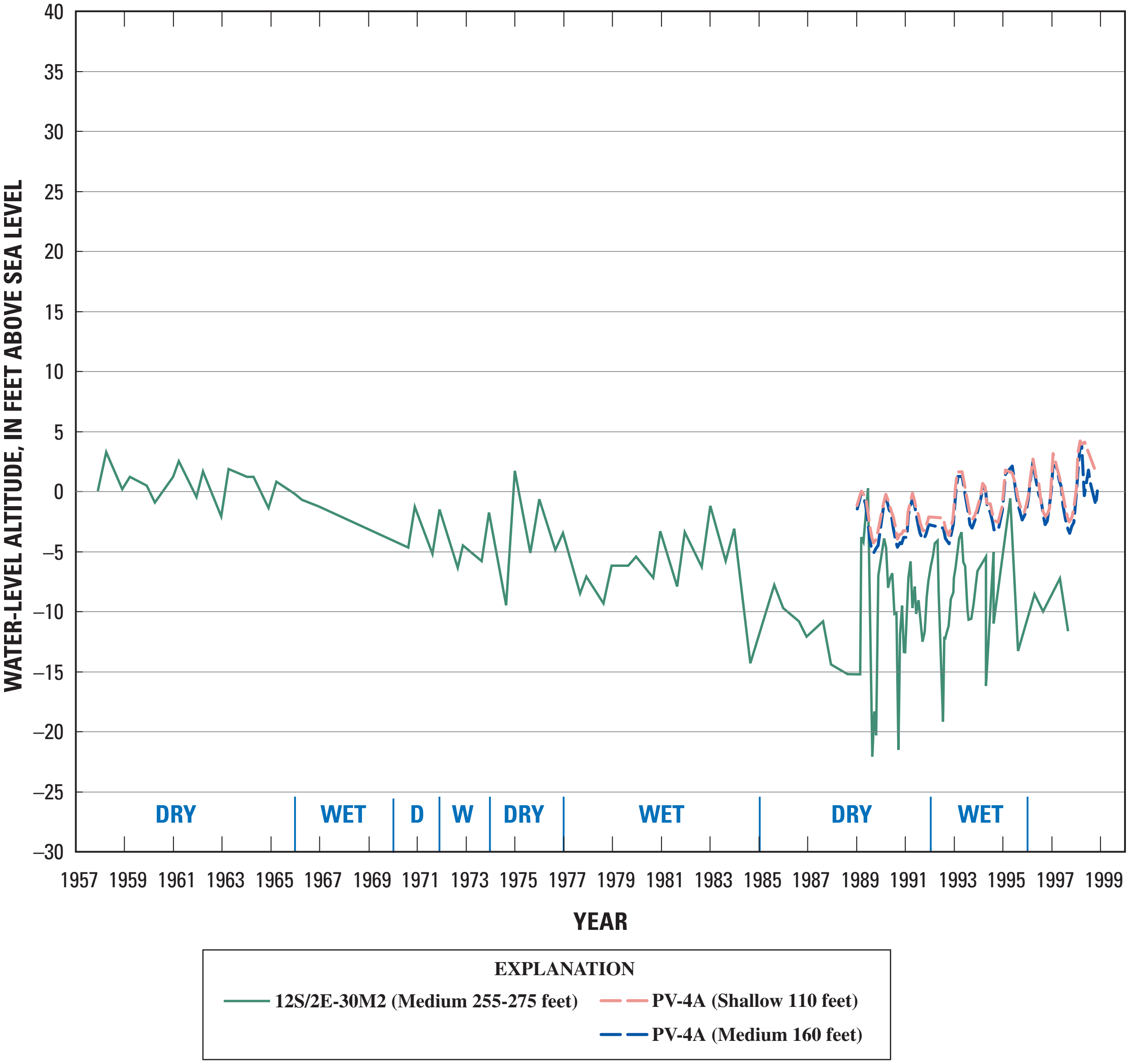

Figure 17. Multiple-well PV-4 and well 12S/2E-30M2 in the Springfield subarea of the Pajaro Valley, Monterey County, California.

Characteristics of Water from Monitoring and Supply Wells

The general distribution of poor-quality water from inorganic sources includes ground water that is high in sulfate and chloride (greater than 250 mg/L) in the coastal region and ground water that is high in sulfate (greater than 250 mg/L) near Murphy Crossing in the Salsipuedes subarea (figs. 1*B*,*C*, 18). A larger region of poor-quality water that has relatively high specific conductance (greater than 1000. µS/cm) and boron (greater than 300. µg/L) also extends northwestward away from the Pajaro River in the Santa Cruz basin portion of the Salsipuedes subarea east of the Zayante-Vergeles Fault (fig. 18). Many of the changes in water quality are coincident with changes in water levels and appear to be part of the ongoing longer term changes related to ground-water development.

Samples from the monitoring wells [PV-1 (M, D), PV-4 (M), PV-6 (D), PV-8 (D)] (figs. 1*C*, 18), and the two agricultural-drain samples, (AG-1.0 and AG-2.0) exceed the secondary drinking water standard maximum contaminant level (SMCL) concentration of 250 mg/L of chloride (U.S. Environmental Protection Agency, 1994) (App. 2, table A2.1). The samples from PV-3 (S, M) and PV-8 (M) are approaching this chloride concentration.

The samples from PV-1 (S, M), PV-6 (D), PV-8 (D), AG-1.0, and AG-2.0 exceed the SMCL concentration of 250 mg/L of sulfate (U.S. Environmental Protection Agency, 1994). The highest sulfate concentrations are in saline waters sampled from PV-1 (D) at 1,726 mg/L. Samples collected during the relatively lower summer streamflow from the Pajaro River (7.6 ft^3/s) and Watsonville Slough (0.47 ft^3/s) sites are approaching this level and are fairly similar in magnitude. These are similar to previous low-flow data from the Pajaro River (J.H. Kleinfelder & Assoc., 1983) and similar to the chemistry of base flow at subbasin boundaries in other coastal basins such as the Santa Clara River in Ventura, California (Izbicki and others, 1995). All but some of the samples from PV-6 (S, SM, MD) exceed the SMCL of 500 mg/L dissolved solids (U.S. Environmental Protection Agency, 1994). Samples from PV-6 (MD) and PV-12 exceed the SMCL concentration of 0.3 mg/L in iron (U.S. Environmental Protection Agency, 1994).

The monitoring wells were sampled for nitrate because the presence of nitrate in ground water is generally indicative of recharge from percolation of irrigation waters as well as an indicator of nonpoint pollution (H. Esmaili & Associates, Inc., 1978). The shallow ground water at monitoring wells PV-1, PV-6, PV-4, PV-8, and PV-11 have nitrate concentrations greater than 10 mg/L NO_3 as nitrogen (USEPA MCL) or 45 mg/L NO_3 as nitrate. The nitrate concentrations vary, chloride shows little change, and ground-water levels increase at well PV-11 (fig. 13) in the San Andreas Dunes area (fig. 1*B*). The relation between nitrates, chlorides, and water levels remains uncertain, on the basis of this short-term data set. The nitrate is increasing with chloride at the shallow well at PV-1 (fig. 8*B*). This well may be downgradient from percolation of irrigation water applied in the San Andreas Dunes area (fig. 1*B*). Samples from the PV-1 (S) in the San Andreas subarea contains relatively high concentrations of nitrate that vary with chloride (figs. 8*A*, *B*). Similarly, PV-4 (S), PV-6 (S), and PV-8 (S) all contain more than 10 mg/L nitrate that suggest some deep percolation of applied irrigation water. The surface-water and agricultural return-flow samples are also relatively high in nitrate (App. 2, table A2.1). On the basis of these samples, the elevated nitrate concentrations appear to be restricted to surface waters and shallow ground waters that are receiving areal recharge containing chloride and nitrate from deep percolation of irrigation waters.

The quality of ground water has been saline in aquifers in the lower Aromas Sand in the coastal regions since the monitoring wells were installed and first sampled, as shown by the water-quality data from monitoring wells PV-3 (D), PV-6 (D), and PV-8 (D) (figs. 9, 11, 12). Other chemical changes in ground water, however, are recent and may indicate additional seawater intrusion, infiltration of irrigation-return flow and runoff, and changing surface-water inflows. The complete chemistry and isotopic analyses have enabled identification of potential sources of recharge in the coastal regions, but the lack of inland monitoring wells makes it difficult to delineate the changes in chemistry of ground water as it moves through the aquifers along flow paths between the inland areas of recharge, the areas of pumpage, and the submarine outcrops.

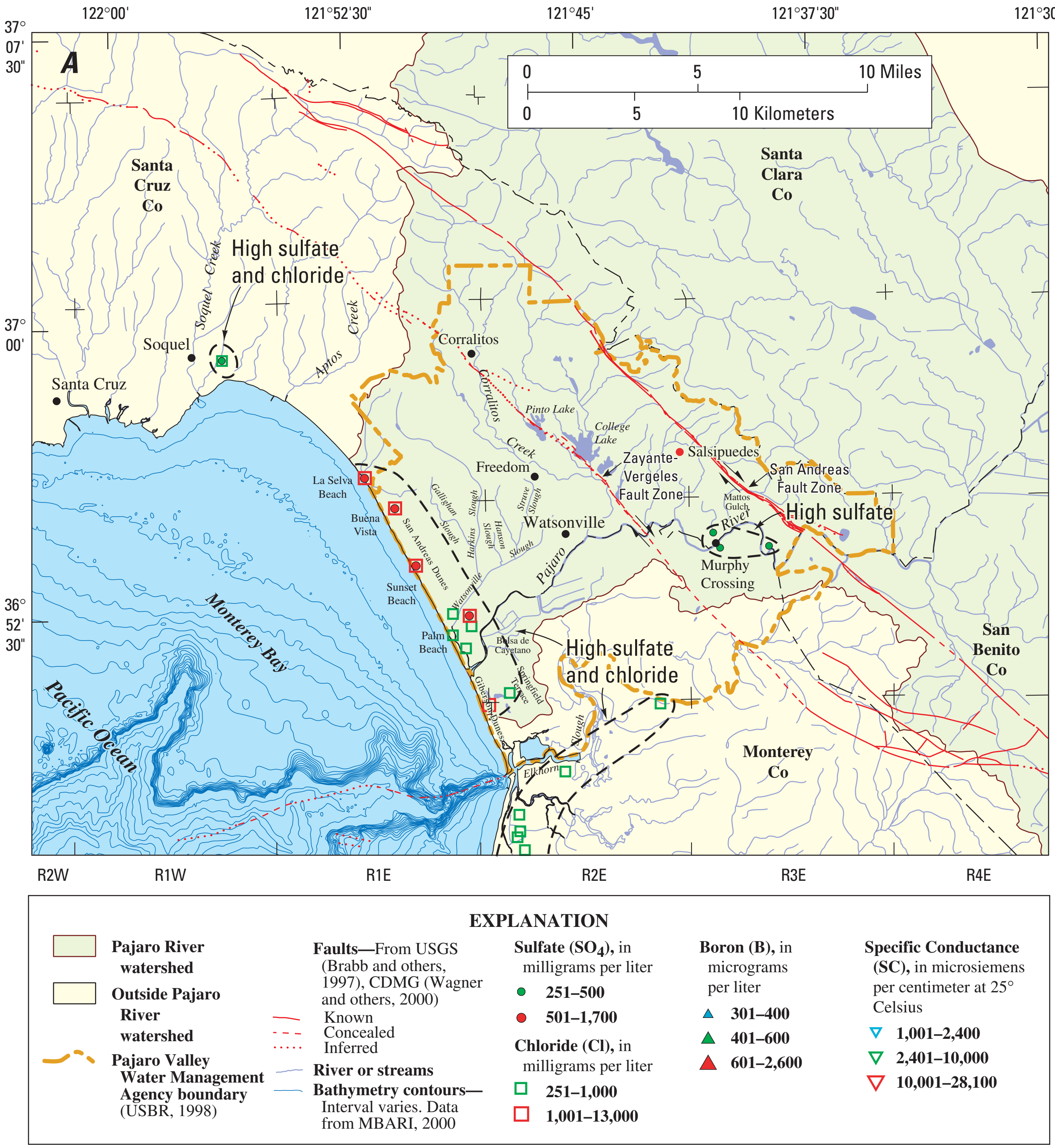

Figure 18. Distribution of boron, chloride, sulfate, and specific conductance for selected wells in the Pajaro Valley, Santa Cruz County, California.

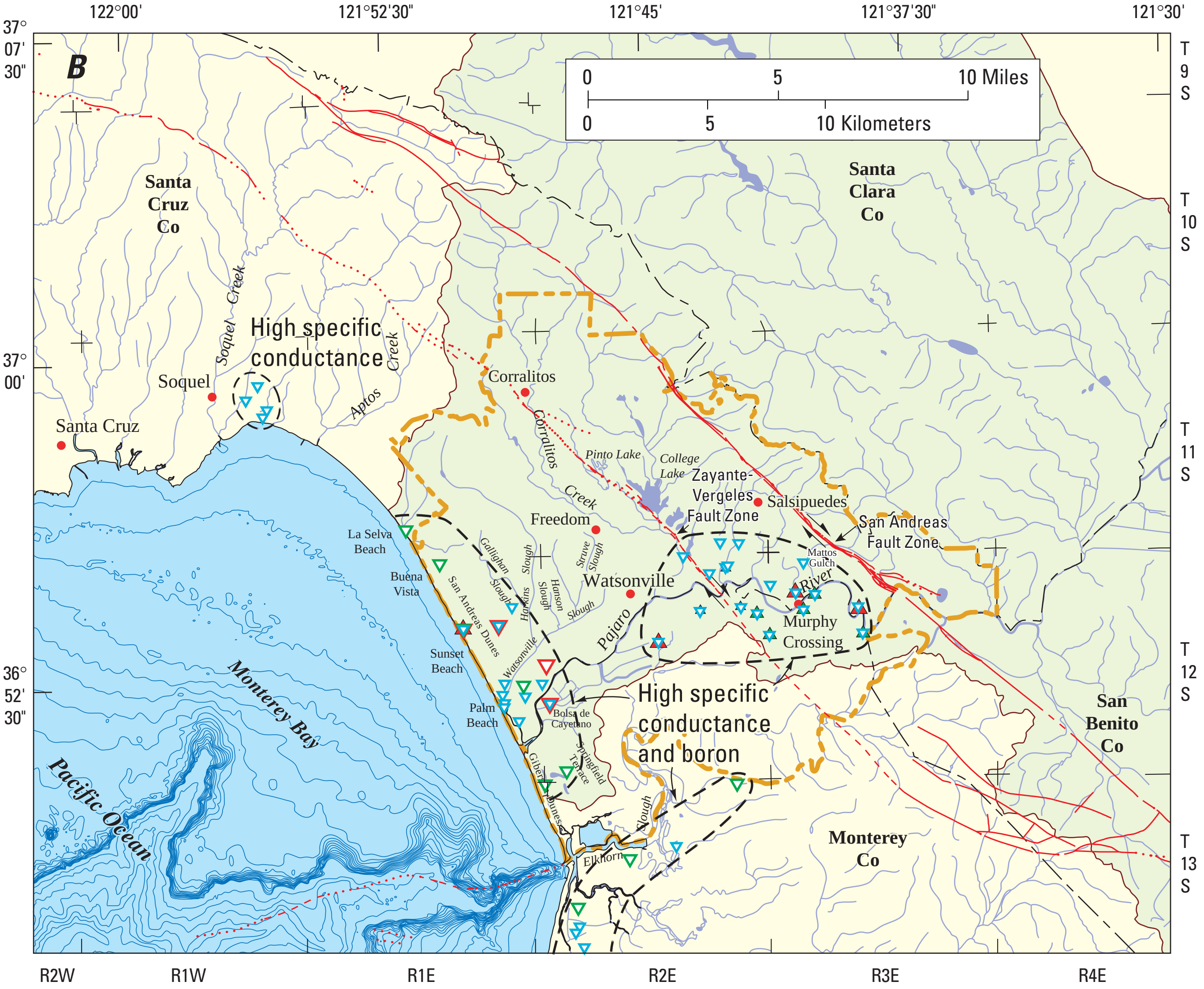

Figure 18.—*Continued.*

As ground water flows from recharge areas through the aquifers, the chemistry changes owing to chemical reactions and mixing with other water along flow paths. Changes in major-ion chemistry observed as water flows through coastal aquifers have been explained as being a result of calcite precipitation and cation exchange (fig. 19*A*) (Izbicki and others, 1993, Izbicki and Martin, 1997). Changes in major-ion chemistry observed as seawater or other high-chloride water invades freshwater aquifers have been explained as being a result of mixing and cation exchange (fig. 19*A*) (Izbicki, 1991). Sulfate reduction and chloride-bromide dissolution also are occurring along the long lateral flow paths in this coastal aquifer system (fig. 19*A*). Base exchange may also be reflected in the older seawater samples (fig. 19*A*). Cation exchange and calcite precipitation are not observed in this limited coastal data set (figs. 19*A*, *B*).

Major-ion diagrams (Piper, 1944) were used to identify groups of wells having ground water of similar major-ion chemistry and to interpret mixing and other chemical reactions that occur along flow paths through aquifers. These diagrams show the relative concentration of major cations and anions, in milliequivalents per liter, to the total ionic content of the water. Ground water from monitoring wells and surface-water samples collected in 1998 plot into seven distinct groups in the major-ion diagrams (fig. 19*B*), and show similar grouping for 1989 and 1996. The seven groups of ground-water and surface-water samples are:

(1) Recent ground water—Shallow alluvial aquifers in Holocene- and late Pleistocene-aged alluvium and upper Aromas Sand recently recharged by a combination of local runoff and Pajaro River streamflow [PV-1 (S), PV-3 (S), PV-4A (S), PV-8 (S, M), PV-11, PV-12, AG-1.0];

(2) Older ground water—Shallow alluvial aquifers in Holocene- and late Pleistocene-aged deposits and upper Aromas Sand in the Pajaro River and La Selva Beach coastal areas related to older recharge from local runoff [PV-6 (S, SM, MD), SC-A4 (B, C, D), SC-A3 (C)];

(3) Recent seawater intrusion—Shallow alluvial aquifers with a mixture of recent seawater and shallow ground water [PV-1 (M, D), PV-3 (M), PV-4A (M), SC-A3 (A)],

(4) Older seawater—Older seawater or connate water in aquifers in the lower Aromas Sand [PV-6 (D), PV-8 (D), SC-A3 (B), SC-A4 (A, B)]; and

(5) Very old ground water—Older waters in aquifers in the lower Aromas Sand from coastal areas [PV-3 (D) and AG-2.0].

(6) Pajaro River water—River inflow from San Benito and Santa Clara County watersheds [Pajaro River at Chittenden, Murphy Crossing, and Thurwatcher Road];

(7) Local runoff—Local tributary streamflow and runoff from local precipitation [Watsonville Slough, Soquel Creek];

Water from shallow wells near sources of recharge (group 1) plot near the middle and slightly to the left and above surface-water samples (groups 6 and 7) for all three years shown in the three diamond-shaped diagrams (fig. 19*B*). Water from deeper wells and wells completed at the downgradient ends of long flow paths through the shallower aquifers (group 2) plot in the middle left in the central diamond (fig. 19*B*). Water having high chloride concentrations plot toward the upper right edge of the diagram and were divided into samples from wells that are approaching the composition of seawater (group 3) and older saline water that represents older seawater or connate water (group 4) that has undergone base exchange to a calcium-magnesium chloride water. An additional group of older coastal water (group 5) that have chloride concentrations of less than 250 mg/L also occurs along the coast in Pajaro Valley in aquifers in the lower Aromas Sand. The irrigation-return-flow drain sample AG-1.0 may represent a mixture of seawater and water from the shallower aquifers (group 1) and the AG-2.0 sample is similar in chemical composition to the waters from the deeper aquifers screened at well PV-3 (D), for example.

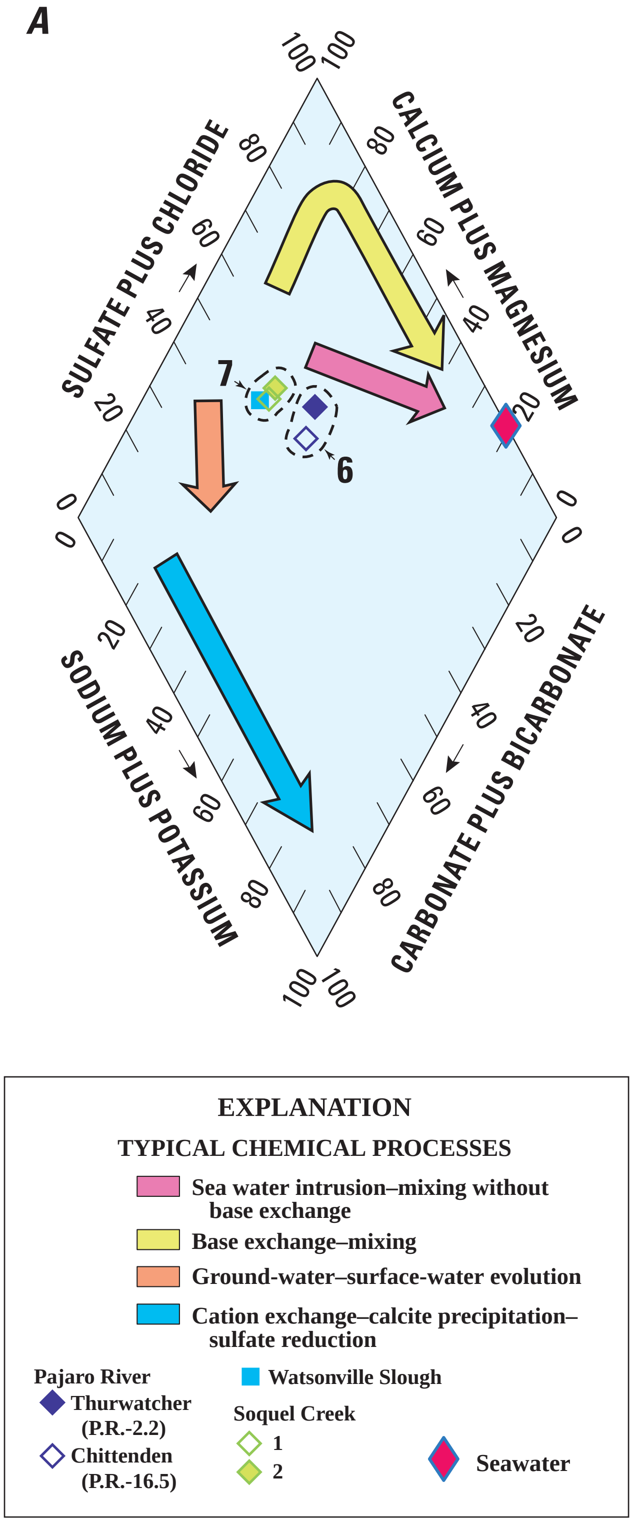

Figure 19. Major-ion chemistry for selected ground-water and surface-water samples from the Pajaro Valley 1989, 1996, and 1998.

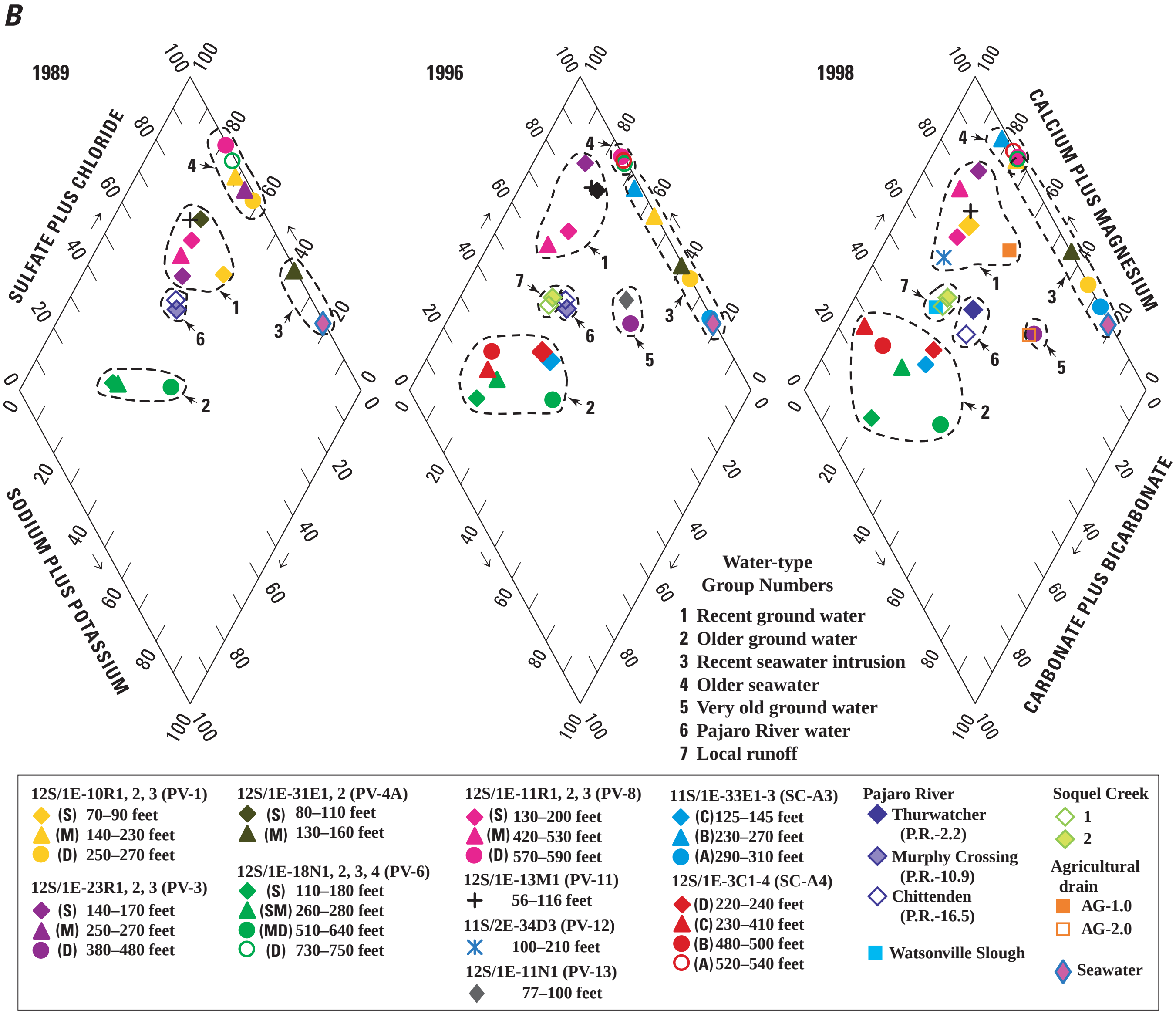

Figure 19.—*Continued.*

Selected major and minor ions and trace elements in water from monitoring wells from groups 3 and 4 were compared with the average concentrations in seawater (Hem, 1985). For wells that have more than 250 mg/L of chloride, the chloride concentration was about 28 percent of the average concentration of seawater (19,000 mg/L) (Hem, 1985) for well PV-6 (D); about 50 to 54 percent for wells PV-1 (M), PV-4A (M), and PV-8 (D); and about 70 percent for well PV-1 (D). In the wells that have more saline water, iodide was about 7 percent of the average concentration of seawater (0.06 mg/L) for PV-1 (M), PV-6 (D), and PV-8 (D); about 40 percent for well PV-1 (D); about 2 percent for well PV-4A (D). Well PV-1 (D) had a concentration of boron of about 1.6 mg/L, which is about 36 percent of the concentration in seawater (4.5 mg/L). In contrast, the Pajaro River and agricultural drains were just less than 1 mg/L of boron, which suggests this is not the source of higher boron concentrations in the coastal regions. The highest barium concentrations were sampled from PV-3 (S), PV-8 (D), and PV-12. Barium in the more saline wells ranged from about 300 percent of the concentration of seawater (20 µg/L) for well PV-1 (M) to about 1,180 percent for well PV-8 (D). Strontium concentrations greater than 1.0 mg/L and bromide concentrations greater than 10 mg/L occurred in samples from PV-1 (M, D), PV-3 (S), PV-6 (D), and PV-8 (D). Strontium ranged from about 56 percent for well PV-1 (M) to about 160 percent of the concentration of seawater (8 mg/L) for well PV-8 (D) for the more saline wells. Thus the wells that have recent seawater intrusion (group 3) are approaching the concentration found in seawater for chloride, are depleted in iodide and boron, and enriched in barium and strontium. The wells that have older seawater (group 4) also are depleted in iodide and boron but are more enriched in calcium, magnesium, barium, and strontium relative to seawater and recent seawater intrusion. This suggests that there may be additional sources for these constituents.

Source, Age, and Movement of Ground Water

The source, age, and movement of ground water in the aquifers can be delineated, in part, based on the isotopic and chemical characteristics of the monitoring-well samples from selected aquifers and from the potential “end-members” represented by waters from nearby surface-water sites and upper-aquifer-system wells from the adjacent Salinas Valley that, in part, also draw water from the Aromas Sand (Vengosh and others, 2002) south of Pajaro Valley. The range in stable isotopes, tritium, carbon-14 ages, and trace-element composition of water from wells collectively indicates multiple sources of recharge to aquifers underlying the Pajaro Valley. The stable isotopes of water (deuterium and oxygen-18) indicate that the ground-water and surface-water samples generally fall along the meteoric water line, with the more saline samples generally trending toward seawater (fig. 20). These data also generally agree with the seven groups of water identified from the major-ion diagrams (fig. 19*B*).

The most negative (lightest) deuterium and oxygen isotope values are from the deep well at PV-3 (D) (fig. 20) (group 5); these values are more similar to those of water from the Sierra Nevada that is much lighter (-74 per mil delta-deuterium and -10.2 per mil delta-oxygen-18) owing to the higher altitudes and cooler temperatures in the mountains (Muir and Coplen, 1981) than local ground-water recharged from recent local precipitation. Therefore, the ground water from PV-3 (D) may be water recharged when the climate was wetter and cooler (Izbicki, 1996b). This would tend to suggest that the ground water at the coast in aquifers in the lower Aromas Sand is older than ground waters that is present in the shallower alluvial aquifers or water-bearing zones in parts of the upper Aromas Sand. In addition to the lighter deuterium and oxygen isotopes, the water from PV-3 (D) also is similar to the Salinas Valley samples that have strontium-87/86 ratios (fig. 21) above the value for coastal California granitic rocks (Faure and Powell, 1972). This indicates that the source of the sediments for the aquifer in the lower Aromas Sand may be similar to that for the sediments of the Salinas Valley. These sediments, which are, in part, granitic may have been derived from the granitic-bedrock mountains that bound the Salinas Valley.

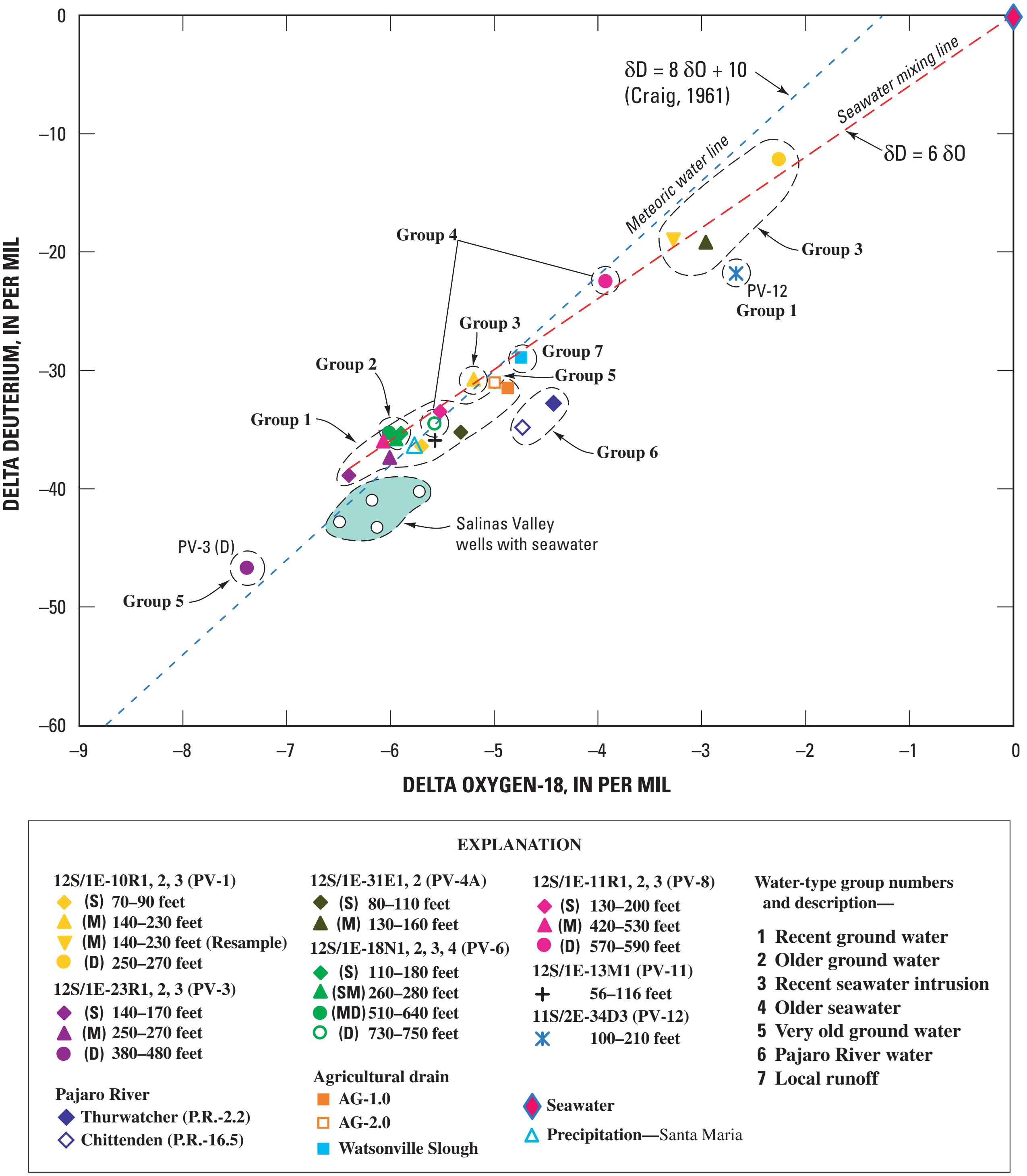

Figure 20. Deuterium and oxygen-isotope values for selected ground-water and surface-water samples from the Pajaro Valley and adjacent Salinas Valley, California, and the seawater mixing line for Pajaro Valley ground-water samples.

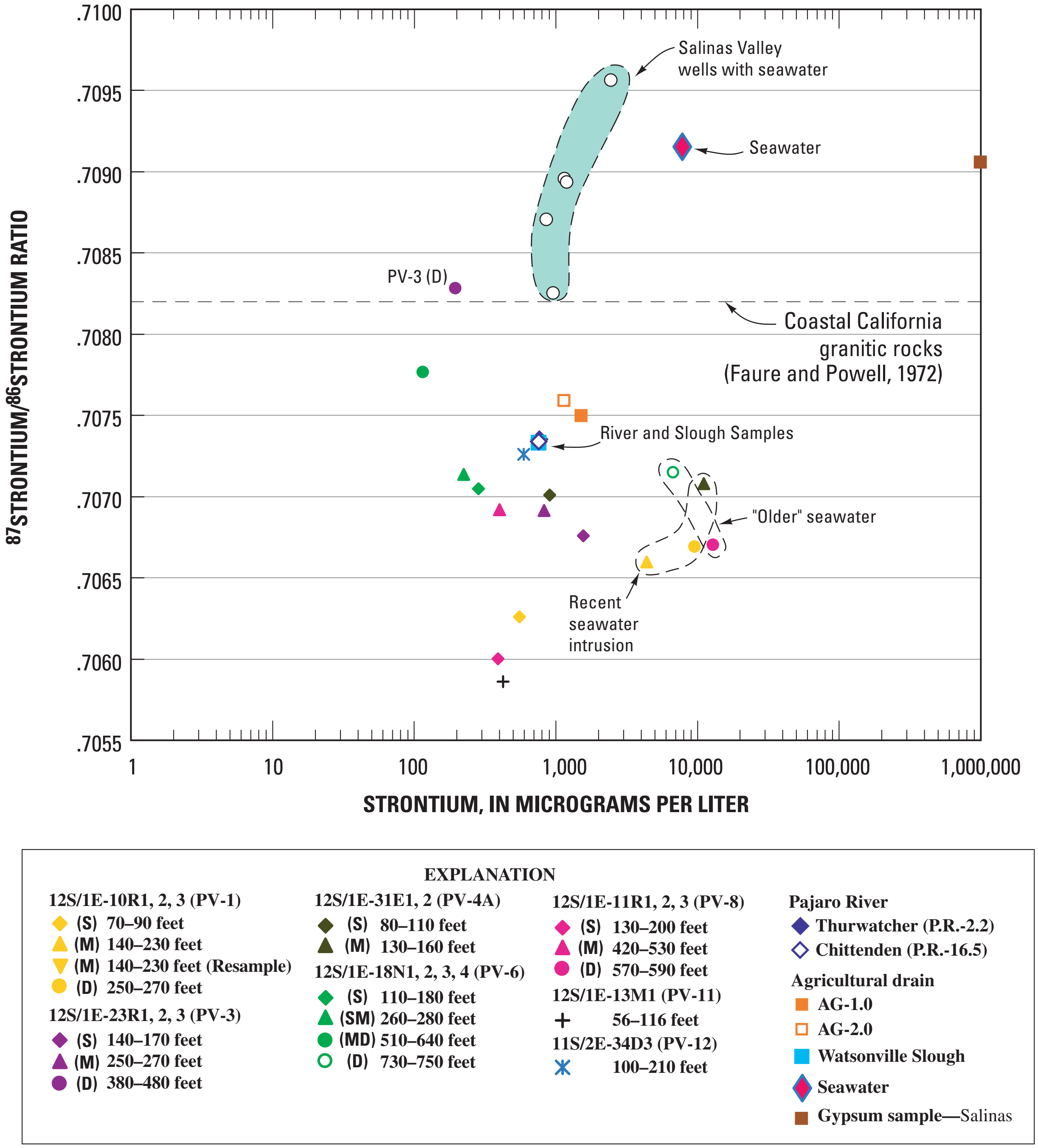

Figure 21. Strontium-isotope ratios plotted against strontium for selected ground-water and surface-water samples from the Pajaro Valley and Salinas Valley, California.

The surface-water samples are all isotopically heavier than the composition of precipitation from Santa Maria, California, about 100 mi south of Pajaro Valley (fig. 20). The samples from the Pajaro River at Chittenden and Thurwatcher (group 6) (figs. 1*C*, 19*B*, and 20) are shifted to the right of the meteoric water line and may represent some evaporation in the river samples. The agricultural drain (AG) samples also are shifted to the right of the meteoric water line but less than are the Pajaro River samples, indicating some evaporation and possibly additional concentration of salts in irrigation water. The Watsonville Slough water (group 7) plots next to the meteoric water line, along with nearby shallow ground-water samples [PV-6 (S), PV-8 (S), and PV-11], and suggest a locally derived source of water that is different from the Pajaro River. The strontium-isotope samples (fig. 21) for all the surface-water samples are below the value for coastal California granite and are similar to most of the ground-water samples.

The isotopic values from the wells completed in the shallower aquifers (groups 1 and 2), are similar to the composition of precipitation from Santa Maria, California. The lighter values reflect a combination of shallow and deep coastal monitoring wells at PV-3, PV-6, and PV-8 sites (fig. 20). The shallower monitoring wells may receive some combination of local deep infiltration and streamflow infiltration from the Pajaro River. The isotopic samples from the different depths at all of the other monitoring-well sites are different from each other, which would suggest that there is little to no vertical leakage between these water-bearing units.

The least negative (heaviest) isotope values are from seawater intrusion or from the deeper, saline waters from wells screened in the lower Aromas Sand (fig. 20). Although chloride concentrations from ground-water samples are necessary to assess the potential for seawater intrusion, they are not a complete identifier of seawater intrusion when other sources of chloride may be present (Izbicki, 1992, 1996a, b). In addition to chloride, the stable isotopes of deuterium and oxygen were used to group the samples from PV-1 (M, D), PV-4A (D), and PV-8 (D) that fall along a mixing line with seawater (fig. 20). Assuming the average oxygen-isotope composition for the coastal nonsaline water from the recently recharged shallower aquifers (group 1, -5.64 per mil), most of the recent seawater-intrusion samples indicate percentages of seawater that are within 10 percent of the chloride estimate and are consistent with recent seawater intrusion. In contrast, the percentages of seawater for the more saline well samples from the lower Aromas Sand are 30 percent for PV-8 (D) and 1 percent for PV-6 (D). These lower percentages are considerably less than the chloride-based estimates of percentage of seawater and suggest another or additional source of chloride in these saline waters. The seawater intrusion-samples from shallow wells in Salinas Valley are distinctly different from Pajaro Valley samples and may fall on a separate mixing line with seawater (fig. 20).

Samples from the shallowest ground-water sites [PV-1 (S, M, D), PV-3 (S, M), PV-8 (S), PV-11] contain detectable amounts of tritium (App. 2, table A2.1). This, along with the distribution of nitrates, would indicate that infiltration of irrigation and surface waters is actively recharging the shallow ground-water aquifers. These shallower aquifers represent renewable ground-water resources. The lack of tritium in water samples from most wells completed in the aquifers in the upper Aromas Sand beneath the Pajaro River Valley and in the lower Aromas Sand in the coastal areas indicate that these aquifers do not contain recent recharge. These deeper aquifers represent the nonrenewable ground-water resources. Although these data enable identification of processes occurring in the coastal regions, the quantification of the recharge to the deeper aquifers in the inland regions will require additional isotopic sampling of water-supply wells as well as the installation and sampling of multiple-well monitoring sites.

The carbon-14 samples indicate that the oldest waters from coastal monitoring-well samples occur in well PV-3 (D) (group 5) (App. 2). The sample from this well contained 4.89 percent modern carbon (pmc), which yields an uncorrected ground-water age estimate of about 24,900 years before present (ybp). This ground-water age is consistent with the light deuterium and oxygen isotope values (fig. 20) that represent water recharged thousands of years ago under cooler climatic conditions. Other samples from monitoring wells completed in the upper and lower Aromas Sand that do not contain tritium range from 24.1 pmc at PV-6 (D) (about 11,800 ybp) (group 4), to 37.61 pmc at PV-8 (D) (about 8,100 ybp) (group 4), and 51.21 pmc at PV-6 (S) (about 5,500 ybp) (group 2). These percentages of modern carbon were adjusted for initial waters (App. 2) and represent corrected ages of about 23,300 ybp at PV-3 (D), 10,700 ybp at PV-6 (D), 7,000 ybp at PV-8 (D), and 4,300 ybp at PV-6 (S) (App. 2, table A2.1). These estimated ages are interpretive and are subject to considerable uncertainty. Davis and Bentley (1982) estimated that errors in carbon-14 ages may be as much as 100 percent. Even considering this uncertainty, the results indicate that much of this ground water was probably recharged thousands of years before present.

The trace elements boron, iodide, and bromide also were used to help determine the origin of ground water in coastal areas where seawater, high-chloride water from partly consolidated marine deposits, and irrigation-return water from shallow unconfined aquifers may contribute to high chloride concentrations in water from wells (Piper and Garrett, and others, 1953). Graphical techniques that normalize changes in trace-element concentrations to changes in concentrations of conservative (non-reactive) tracers are useful in the interpretation of these data. Plots of the ratio of chloride to boron, iodide, and bromide as a function of chloride can be used to determine the relation of high-chloride waters from various sources (Izbicki, 1991, 1996a).

The 1998 samples from Pajaro Valley show a wide range in boron, iodide, and chloride concentrations; seawater is in the middle-right portion of the diagram and most native, low-chloride ground-water and surface-water samples are in the lower left of the diagram (figs. 22 *A*, *B*). Although shallow wells such as PV-1 (M, D) and PV-4A (M) plot near the ratio for seawater, other saline samples from deeper coastal monitoring wells have ratios higher than that of seawater (figs. 22 *A*, *B*). Most ground-water samples do not plot along a potential mixing line between native water [PV-6 (S)] and high-chloride waters [PV-6 (D)] for ratios of chloride to boron (fig. 22*A*). Some boron can be removed from ground water through adsorption (Rai and Zachara, 1984), but the higher chloride concentrations and lower boron concentrations relative to seawater from these deeper aquifers may represent older seawater or additional salinity derived from partly consolidated marine deposits (Izbicki, 1991). Unlike some deep-aquifer samples from other coastal aquifers, these samples are depleted in iodide and boron and may not represent deep marine brines.

Ratios of chloride to iodide, boron, and bromide (figs. 22*A*, *B*, *C*) indicate that some of the deeper saline waters are depleted in iodide, boron, and bromide relative to seawater. These data suggest that the waters from the lower Aromas Sand were enriched in chloride relative to these trace elements and may indicate other sources of chloride such as dissolution of *in situ* salts from these marine sediments. The potential mixing lines between Watsonville Slough, Pajaro River, or PV-12 and seawater represent the mixtures that would result if lateral mixing occurred along a flow path. In addition, the ground-water end-members that have an initial water similar to that to PV-6 (S) and a final water similar to PV-6 (D) represent the mixtures that would result if vertical mixing occurred in the coastal region. Most samples do not fall on these potential mixing lines, which suggests reduced mixing from lateral and vertical flow. However, the degree of lateral mixing in these layered aquifer systems remains uncertain on the basis of a data set that is largely restricted to the coastal regions of the aquifer systems. These potential mixing lines suggest that, where consistent with the hydraulics of the ground-water flow system, some samples are a mixture of local ground water (groups 1 and 2) with seawater, whereas very few samples appear to be a mixture of local ground water (groups 1 and 2) with water from aquifers in the lower Aromas Sand (group 5).

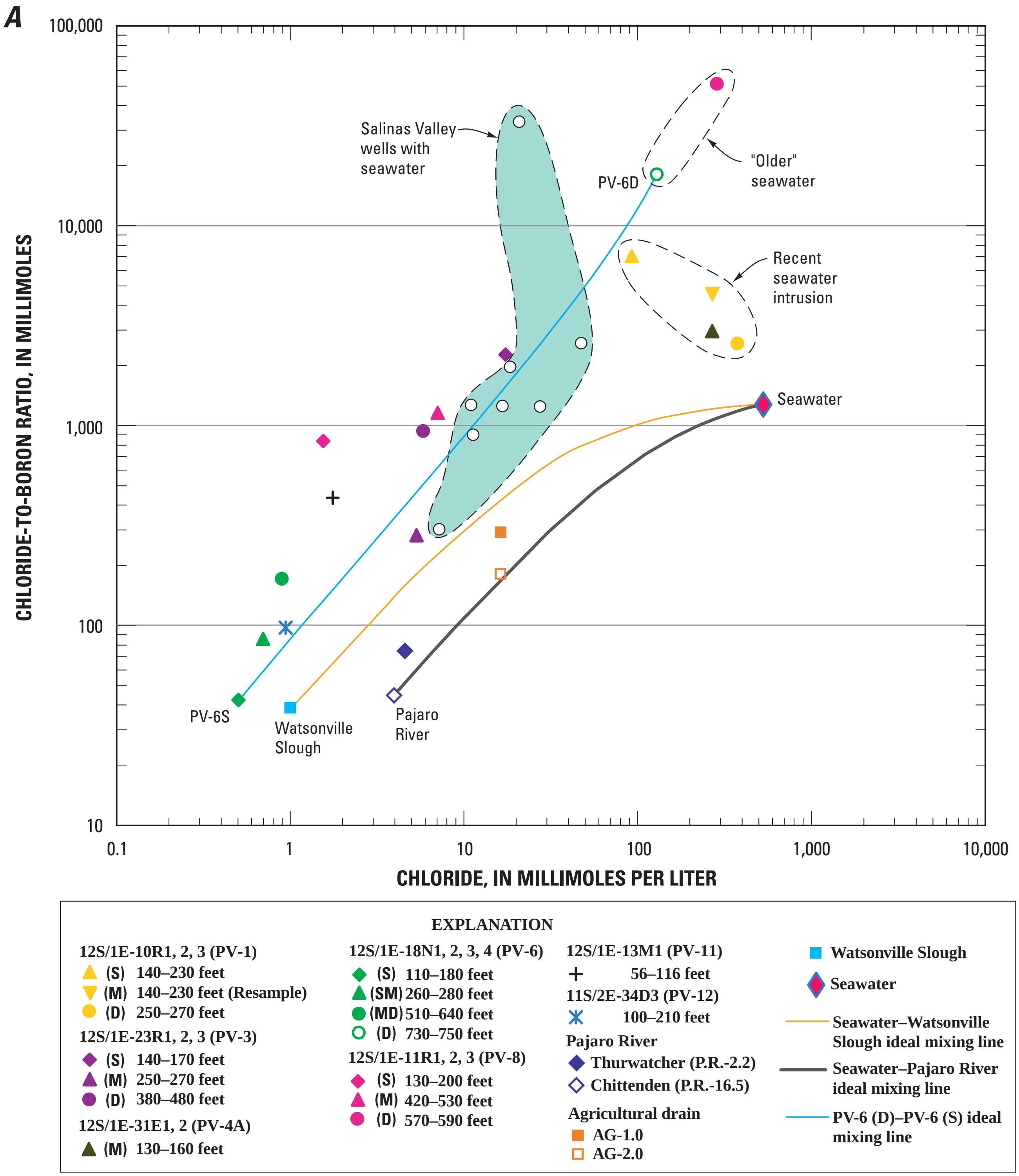

Figure 22. Chloride values plotted against the ratio of chloride to boron, chloride to iodide, and chloride to bromide for ground-water and surface-water sites in the Pajaro Valley and adjacent Salinas Valley, California.

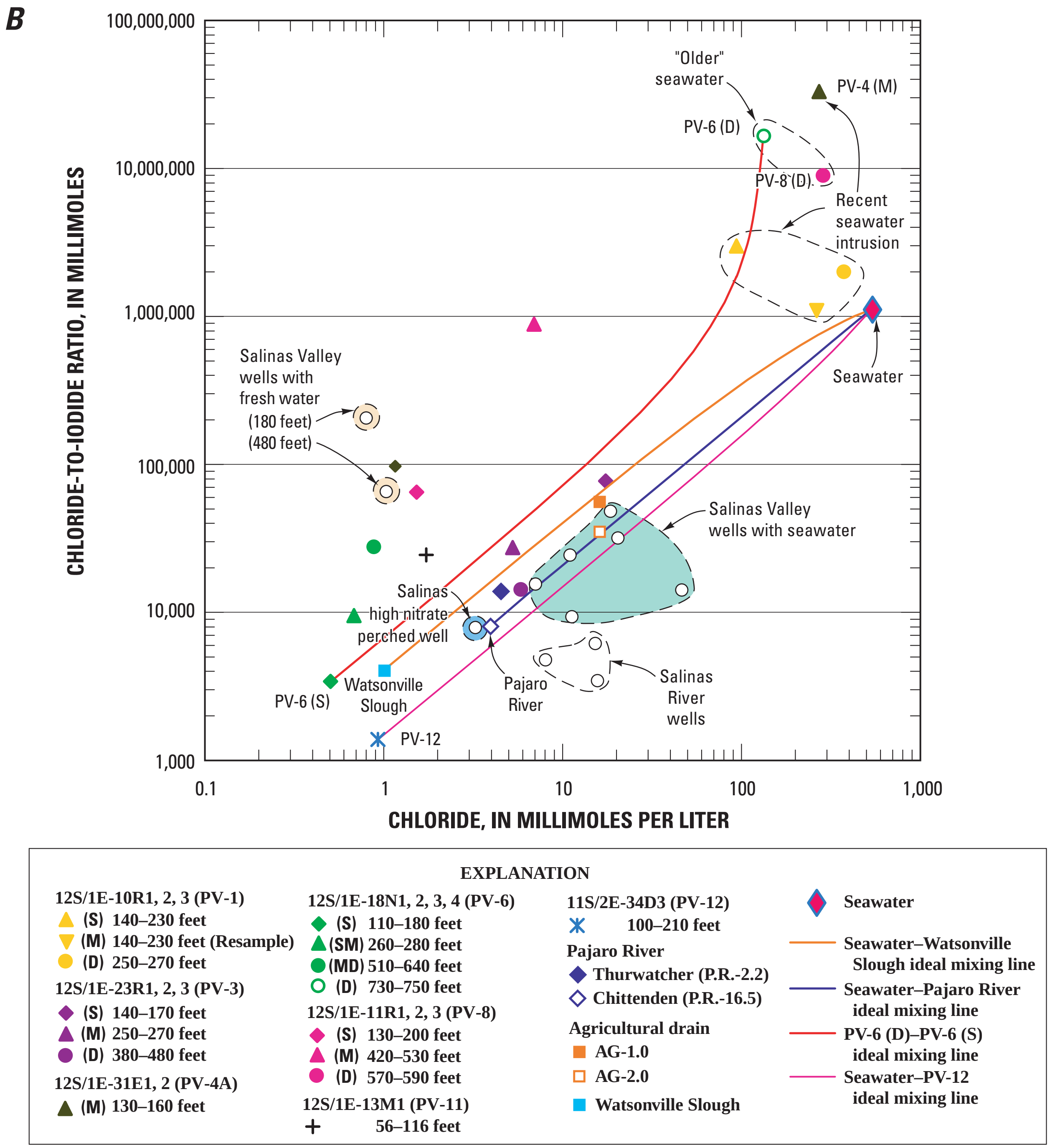

Figure 22.—*Continued.*

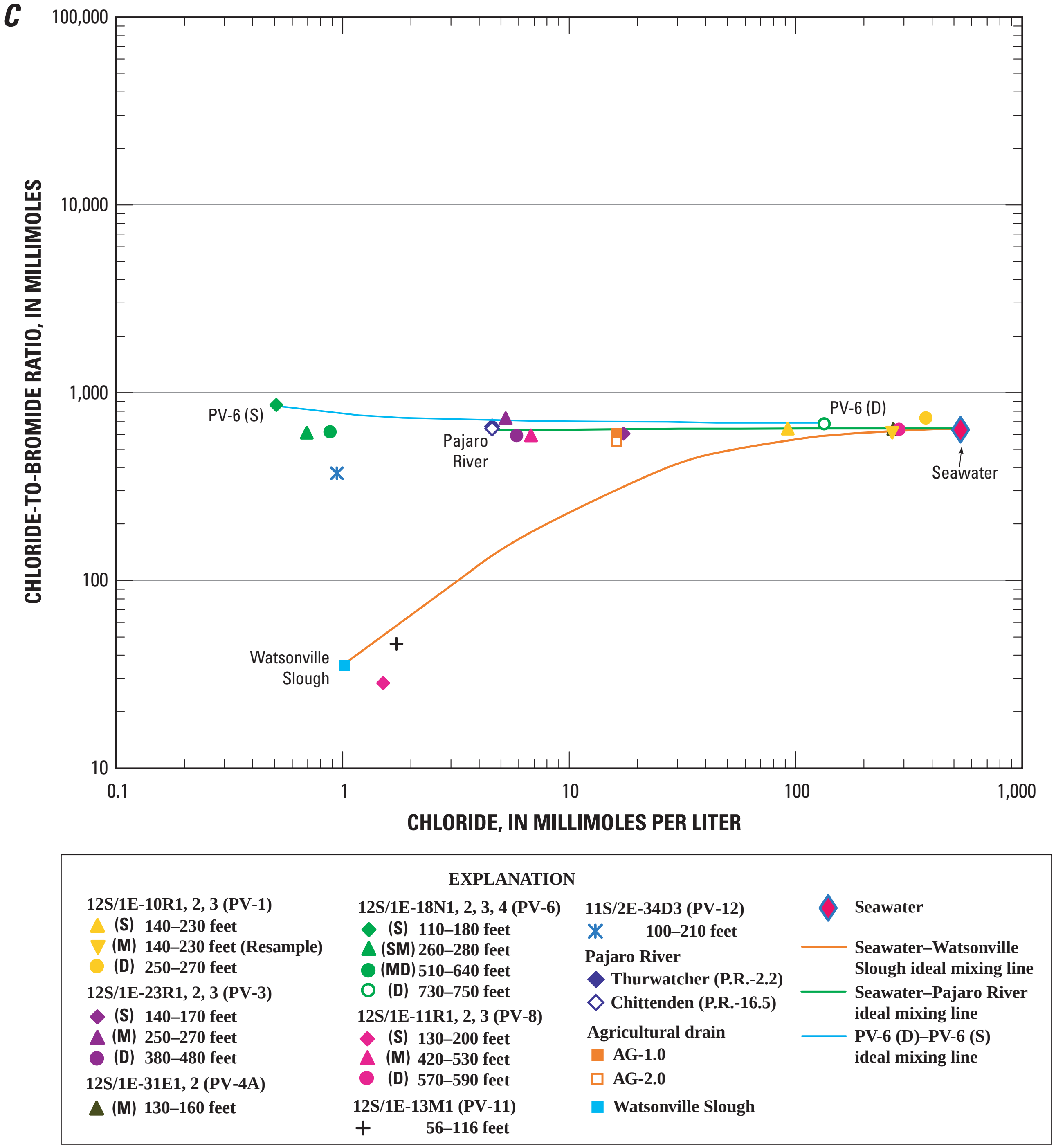

Figure 22.—*Continued.*

Some of the wells that plot near the trace-element potential mixing lines may not represent mixtures with recent seawater. The ratios of chloride to boron and chloride to iodide indicate that most ground-water samples from increasing depth do not fall on a mixing line that has seawater or deeper ground water as an end-member (figs. 22*A*, *B*). In addition, the temperature log collected at well PV-8 (M) (App. 1, fig. A1.6) indicates that there is little to no vertical flow across the massive clay layers that occurs between 200 and 380 feet bls and separates the aquifers in the upper and lower Aromas Sand. Therefore, these samples may represent different degrees of mixture of waters along different flow paths with increasing depth and not mixture from vertical flow. Conversely, the ratios of chloride to bromide (fig. 22*C*) indicate two possible types of mixing between local runoff such as Watsonville Slough water and seawater or mixing between Pajaro River water and seawater. The differences in ratios may represent a progressive dissolution of salts in the sediments that cause a relative enrichment of chloride relative to boron and iodide (figs. 22*A*, *B*) along layered flow paths that are separated by the fine-grained layers in the coastal regions.

The trace-element ratios with chloride also indicate that surface-water samples from the Pajaro River and Watsonville Slough are significantly different from water from PV-11 and PV-12, respectively. These two wells represent relatively shallow ground water that would be expected to represent some component of local recharge, which appears to be a mixture of shallow and older ground water that may result from percolation of agricultural irrigation. The relatively higher concentrations of iron and manganese in water from PV-12 are due, in part, to reduced conditions, with almost no dissolved oxygen present in this well (App. 2, table A2.1). Reduced conditions and subsequent sulfate reduction also have resulted in increased barium concentrations (App. 2, table A2.1). In addition, the deuterium and oxygen-18 samples from PV-12 suggest that this ground water may represent a mixture of meteoric water with previously heated water adjacent to the Zayante-Vergeles Fault zone (figs. 1*C*, 20). The trace-element ratios also are different than the distributions indicated for the Salinas Valley groups of samples (figs. 22*A*, *B*) that represent seawater intrusion, fresh water, or high-nitrate samples (Vengosh and others, 2002).

Seawater Intrusion and Saline Ground Water

Saline ground water occurs in parts of the aquifers of the Pajaro Valley. Some of this saline ground water is related to seawater intrusion resulting from sustained ground-water pumpage in the coastal regions. However, other saline waters may have different sources that are not related to seawater intrusion. While high chloride concentrations are commonly an indicator of seawater intrusion, additional geochemical indicators, such as trace element ratios and isotopes are needed to differentiate other sources of saline water of an origin different from seawater.

Since 1989, the chloride concentrations of water-quality samples from multiple-well observation sites along the coast from La Selva Beach to Springfield Terrace (figs. 1*B*, C) have increased for selected monitoring wells (figs. 8–12, 14, and 15). Ground-water samples from PV-1 (M), PV-1 (D), PV-3 (M), PV-4 (M), PV-6 (D), PV-8 (D), SC-A3 (A), and SC-A4 (A) have chloride concentrations, ranging from 4,000 to about 18,000 mg/L. (figs. 8–12, 14, and 15). Chloride concentrations are trending towards the average chloride concentration of seawater (19,000 mg/L) for aquifers in the upper Aromas Sand in the Sunset Beach area [PV-1 (D), fig. 8], in the Palm Beach area [PV-3 (M), fig.9], and in the Springfield Terrace area [PV-4 (M), fig. 10]. Chloride concentrations have increased in the lower Aromas Sand in the La Selva Beach area [SC-A3 (B), fig. 14]. The chloride chemographs from the coastal monitoring sites show consistently high chloride concentrations in aquifers in the lower Aromas Sand in the north-central coastal regions [PV-6 (D), PV-8 (D), SC-A3 (A), and SC-A4 (A); figs. 6, 12, 14, and 15] and in aquifers in the upper Aromas Sand in the Pajaro River mouth and Springfield Terrace areas to the south [PV-3 (M) and PV-4 (D); figs. 9, 10]. The chloride concentrations in the middle aquifers in the upper Aromas Sand aquifers have been increasing at Sunset Beach [PV-1 (M), fig. 8*A*] and began increasing in the La Selva Beach area to the north since 1993 [SC-A3 (B), figs. 1*B*, *C*, and 14]. Chloride concentrations may vary that have seasonal and other step changes in water levels at many of the wells with relatively higher chloride concentrations. The major-ion diagram in figure 19*B* indicates that ground-water samples from some of these sites completed in aquifers in the upper Aromas Sand (group 3) are trending towards the average composition of seawater (Hem, 1985).

Stable isotopes of boron and sulfur as well as tritium and carbon-14 also were used to help constrain the possible sources of older saline water (group 4) in the Pajaro Valley. The graphs of boron-isotope values from Pajaro Valley samples, combined with the anion ratios with chloride concentrations, indicate that the samples from aquifers in the lower Aromas Sand (group 4) are depleted in boron and in delta-boron-11 (fig. 23*A*). In addition, all of the saline samples from monitoring wells in the Salinas Valley are also depleted in boron 11 and have smaller chloride-to-boron ratios relative to seawater (fig. 23*A*). This also suggests a different origin of the salinity for the samples from the lower Aromas Sand relative to the recent seawater intrusion samples from the Salinas or the Pajaro Valleys. In contrast, the sulfur isotopes (fig. 23*B*) show little difference between older and recent saline waters, which may indicate that these waters are, in part, older seawater. These older calcium-magnesium-chloride saline waters lack tritium and these ages were estimated to be between 7,000 to 10,700 years before present on the basis of carbon-14 samples (App. 2, table A2.1). In addition, these wells with older waters (group 4) also are depleted in iodide as well as boron and enriched in barium and strontium relative to seawater and do not represent the intrusion of recent seawater.

Geologic and geophysical data indicate that the layering in coastal aquifer systems such as Pajaro Valley, results in seawater intrusion that is vertically restricted. This is exemplified by the geophysical logs collected at PV-1, PV-6, and PV-8 (App. 1, figs. A1.1, A1.5, and A1.6). This vertical restriction can contribute to a relatively sharp interface within the coarse-grained layers of the aquifers system. For example, the geophysical logs from PV-1 (fig. A1.1) indicate that saline water is present in discrete layers, which is typical of the geometry for the leading edge of seawater intrusion seen in other coastal alluvial basins such as the Ventura area (Hanson and others, 2002) and Los Angeles (Newhouse and Hanson, 2000). Thus, the initial seawater intrusion is not a wedge but is selectively intruding coarse-grained water-bearing units that range in thickness from 10 to 150 ft. The low resistivity in the lower part of the original resistivity log also suggests that saline waters were already present in 1988 when the monitoring well was installed, and the subsequent logs from 1999 indicate that additional shallower water-bearing zones now contain saline water (App. 1, fig. A1.1). The geophysical logs. (App. 1) indicate that these deeper saline waters in PVWMA monitoring wells occur in relatively thin intervals that are vertically adjacent to fresher ground water. This is especially evident from the multiple screens of the middle monitoring well at PV-8 (App. 1, fig. A1.6) (420–530 ft depth, App. 2, table A2.1) where the upper screen is opposite fresher water and the lower part of the deeper screen penetrates a thin zone of saline water.

The geophysical data also may indicate the presence of zones of saline water elsewhere in the lower Aromas Sand. For example, zones containing saline water were also indicated by higher electromagnetic (EM) conductivity and lower gamma activity in geophysical logs, at the bottom of monitoring well PV-8 (M) (App. 1, fig. A1.6) where composite salinity also has increased up to 245 mg/L of chloride by 1998 (fig. 12) and at the Dolan Road monitoring well, where poor-quality water appears to be present at a depth of about 365 to 395 ft (App. 1, fig. A1.11) adjacent to fine-grained layers. Because most sediments in the lower Aromas Sand were deposited during periods of rising ocean levels (Dupre, 1998), the seawater that was initially present in these sediments may not have been completely flushed from the sediments during subsequent periods of falling sea level. The deeper thin zones of high salinity seen in the geophysical logs from PV-6 and PV-8 (App. 1, figs. A1.5, A1.6) may be indicative of this older saline water. Because sea level changes are cyclic, there is also the possibility that increasing salinity that is not modern seawater may be remnant portions of paleo-intrusion as was simulated for the adjacent Soquel-Aptos watershed (Essaid, 1992). Regardless of the specific mechanism, these deeper saline waters have been saline at least since the completion of the monitoring wells in Pajaro Valley, have been resident long enough to have undergone base exchange, and represent recharge from thousands of years ago.

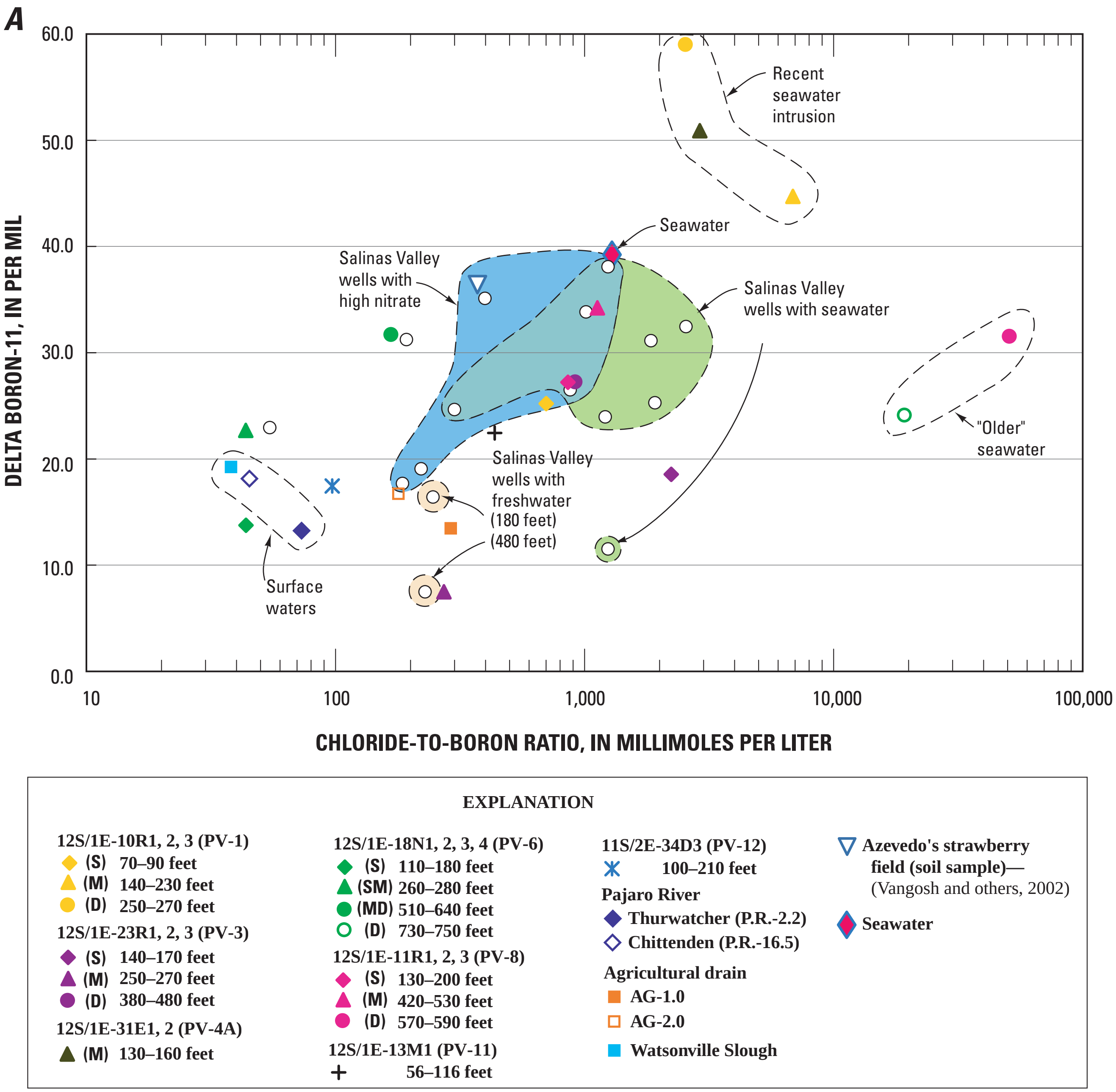

Figure 23. Boron-isotope values plotted against the ratio of chloride to boron, and sulfur-34 isotope values plotted against sulfate concentration for selected ground-water and surface-water samples from the Pajaro Valley and adjacent Salinas Valley, California.

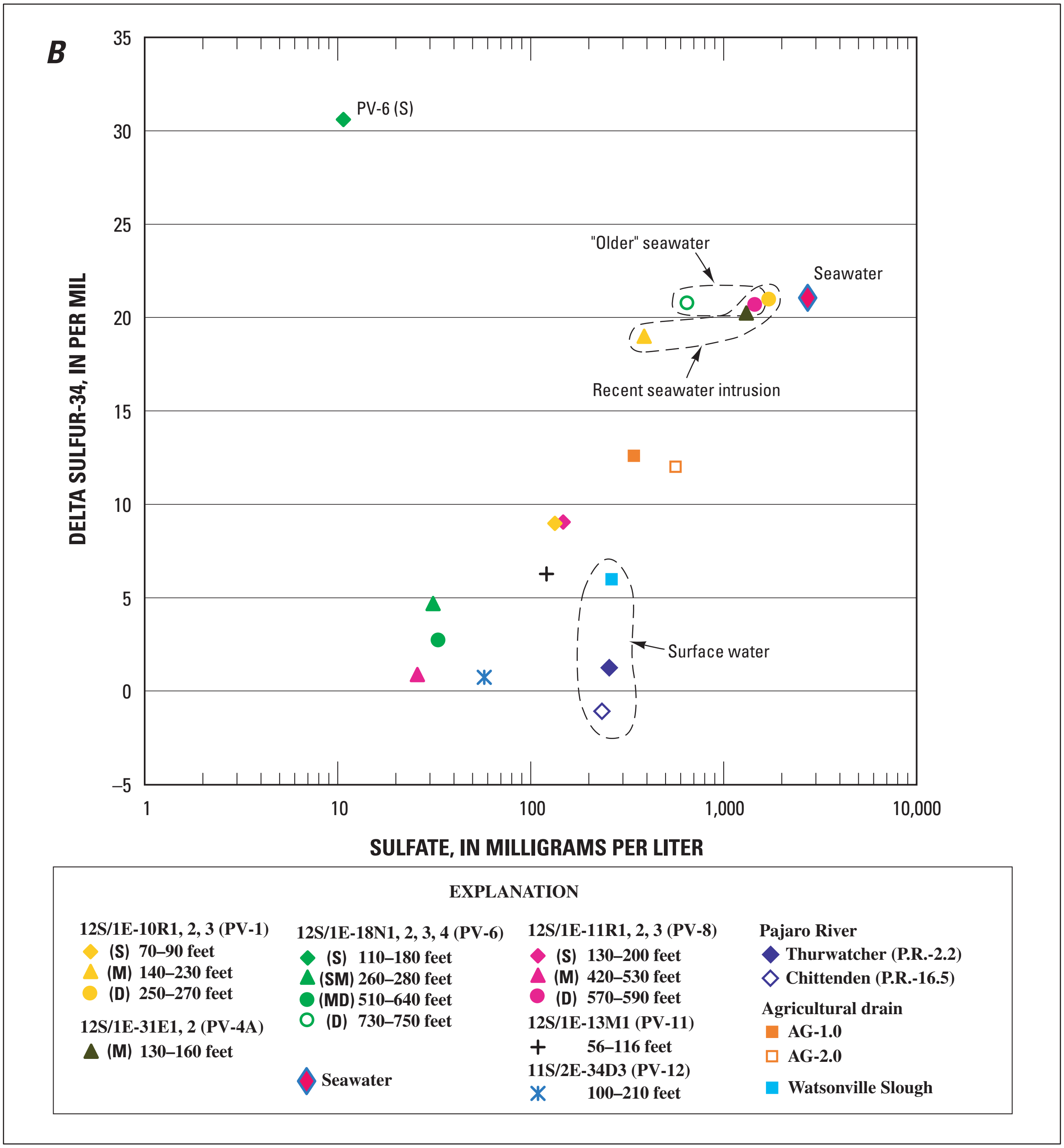

Figure 23.—*Continued.*

As noted above, not all coastal wells completed in the deeper aquifers have high chloride concentrations that are relatively constant. For example, two monitoring wells [SC-A3 (B), SC-A4 (A)] with this water type (group 4) (fig. 19*B*) have shown increasing salinity in the adjacent La Selva Beach area (figs. 14, 15) since their installation in 1987 and 1993, respectively. On the basis of major-ion chemistry, the samples from the La Selva Beach monitoring wells completed in the upper Aromas Sand [SC-A3 (B)] and the lower Aromas Sand [SC-A4 (A)] are similar to this older seawater group (group 4) while the saline sample from the upper Aromas Sand [SC-A3 (A)] is similar to recent seawater (group 3) (fig. 19*B*). However, isotope samples that would be needed to help delineate the origin of these saline waters were not collected from monitoring wells used to monitor seawater intrusion by SCWD as part of this study. Thus, the origin of the salinity in these coastal monitoring wells remains uncertain on the basis of major-ion chemistry data alone and would require additional geochemical and geophysical data to determine their origin with more certainty.

Low streamflows on the Pajaro River are another source of saline water in the Pajaro Valley. Streamflow hydrographs and chemographs for the Pajaro River indicate that chloride and sulfate concentrations increase during low flows (figs. 6*A*, *B*). The chloride and sulfate concentrations may exceed the SMCL of 250 mg/L when streamflows are less than about 10 ft^3/s (figs. 6*A*, *B*). On the basis of the streamflow duration, these low flows occur about half of the time (fig. 7) for the period of record. Concentrations as high as 600 mg/L of chloride and 300 mg/L of sulfate were present in the Pajaro River during the low base flows of severe droughts such as 1976–77. Concentrations of chloride remain less than 40 mg/L on Corralitos Creek and also increase during low flows (fig. 6*E*). Conversely, the concentration of nitrate in streamflow in the Pajaro River tends to increase with increased flow (figs. 6*A*, *B*) and to increase during lower flows on Corralitos Creek (fig. 6*E*). The concentrations of nitrate generally increase with increased base flow streamflows up to about 20 ft^3/s and do not exceeded the MCL of 45 mg/L of nitrate as nitrate when base flow streamflows are less than about 10 ft^3/s during the 1980s (fig. 6*A*). The ground-water recharge from streamflow infiltration is coincident with concentrations of boron greater than 0.3 mg/L (fig. 6*D*). The increased boron that occurs as a boron plume in the shallower alluvial aquifers adjacent to the Pajaro River was identified as a potential indicator of recharge as streamflow infiltration (J.H. Kleinfelder and Assoc., 1983).

In summary, geochemical and geophysical data indicate several sources of saline water. The saline waters in the PV-1 (M, D) and PV-4A (M) wells reflect recent seawater intrusion into the recent and older alluvium. The deeper saline waters in the PV-8 (D) and the PV-6 (D) wells may be older seawater. These older seawaters probably have undergone base exchange in which the sodium from the seawater has been exchanged (taken into sediments) with calcium and magnesium released from the fine-grained material in these sediments into the ground water. Further, they may represent seawater that was hypersaline and may also include salinity from another source. This is indicated by elevated chloride-to-iodide and chloride-to-boron ratios above the values for average seawater composition and by depleted boron-11 concentrations. This source could be dissolution of chloride salts that occur within the marine sediments of the deeper lower Aromas Sand and Purisima Formation. The chloride-to-bromide ratios, however, indicate that many of these waters are mixtures of water from either Pajaro River or Watsonville Slough and seawater. Thus, the geochemical data, in combination with the geophysical data, indicate that only the upper layers of the aquifer systems in selected areas are receiving recent recharge and that saline waters are potentially restricted to selected coarse-grained layers that contain recent seawater intrusion in the shallower alluvial aquifers and older seawater at depth in the coastal regions (fig. 3).

SUMMARY AND CONCLUSIONS

Pajaro Valley is a coastal watershed of 160 mi^2 located along Monterey Bay north of Elkhorn Slough and south of the city of Santa Cruz. The valley has been predominantly developed for agriculture since the late 1800s. In 1984 the Pajaro Valley Water Management Agency (PVWMA) was formed and was delegated with the responsibility of managing of the water resources within the Pajaro Valley by the State of California. About 84 percent of the water is used for agriculture and 16 percent is used for industrial and municipal water supply; almost all of the demand is supplied by ground water. Ground-water pumpage varies with seasonal and climatic periods.

The alluvial aquifers are composed of Quaternary- and Tertiary-aged sediments that are well-layered marine and terrestrial coarse-grained deposits separated by extensive fine-grained deposits. The fine-grained deposits potentially restrict vertical movement of ground water and constrain seawater intrusion in the coastal subareas. The coarse-grained deposits persist over large areas and control the pumpage and related seawater intrusion. The Aromas Sand crops out throughout the north and central parts of the PVWMA area and offshore on the continental shelf and in Monterey submarine canyon. Because many of the wells in the coastal and inland subregions are screened at depths of 200 to 400 ft below land surface, a direct avenue is provided for seawater intrusion through the coarse-grained deposits. Geophysical logs from monitoring wells indicate discrete zones of saline water that are related to pumpage and seawater intrusion in the aquifers of the shallower alluvium and upper Aromas Sand in the upper-aquifer system and to deeper saline waters in the lower Aromas Sand within the lower-aquifer system. Several fault zones traverse the Pajaro Valley, but the importance of faults as hydraulic barriers to ground-water flow remains uncertain.

The precipitation data indicate that there are at least nine dry and nine wet periods that range in duration from 2 to 19 years for the period of record, 1880–1997. These multiyear cycles have resulted in increases in ground-water pumpage of as much as 20 percent during dry-year periods, especially when there is a lack of precipitation in the spring. Droughts within dry-year periods have been as short as the severe drought of 1976–77 and as long as the sustained 7-year drought of 1986–92. Runoff and streamflow, and the related water quality of streamflow, also vary with seasonal and climatic periods.

Recharge occurs from deep percolation of precipitation and from infiltration of streamflow. Streamflow originates from local runoff as well as runoff that originates outside the valley and enters as streamflow in the Pajaro River. Although partly regulated, streamflow on the Pajaro River at Chittenden is less than 200 ft^3/s 88 percent of the time and is less than 12 ft^3/s 50 percent of the time. The geometric-mean streamflow on the Pajaro River at Chittenden in wet-year periods is about 4 times greater than in dry-year periods. Streamflow water-quality data suggest that there may be several sources of poor-quality water that contribute to elevated chloride, sulfate, and nitrate concentrations in streamflow. The poor water quality occurring during lower streamflows indicates that low flows may be an additional source of salinity for ground-water recharge as streamflow infiltration along the Pajaro River.

The geochemical data from this study indicate that the two main sources of natural recharge are deep percolation of local runoff and streamflow infiltration of Pajaro River water. Some of the poor-quality ground water may be from other sources that may include irrigation runoff, deep infiltration of irrigation return-flow, slough and lagoon leakage, dissolution of salts from saline sediments, old seawater, and infiltration of saline streamflow during low-flow periods. The geophysical and geochemical data suggest that only the shallow-alluvium aquifer and parts of the upper Aromas Sand are being replenished by recent recharge in the coastal areas of Pajaro Valley and represent the renewable ground-water resources. These data also suggest that there is very little vertical flow through the layered aquifer systems in the coastal regions. The confining aquitards are laterally extensive but may be missing in places owing to fluvial erosion or offsetting by fault movement. On the basis of tritium and carbon-14 ages, the ground water from some parts of the upper and lower Aromas Sand was recharged thousands of years ago and may, in part, represent nonrenewable ground-water resources.

The analysis of major-ion chemistry, in combination with isotope and trace-element/chloride ratios, indicates that the coastal ground-water and surface-water samples can be described in seven groups. These groups represent recently recharged shallow aquifers (group 1), shallower aquifers with older water (group 2), shallow aquifers with recently intruded seawater (group 3), deeper aquifers with older seawater (group 4), deeper aquifers with older freshwater (group 5), Pajaro River streamflow (group 6), and recent local runoff from streams and sloughs (group 7).

The ground-water levels have been near or below sea level at most coastal monitoring wells since their installation in the 1980s. Water-level changes include long-term decline, climate-period changes, and seasonal changes from agricultural pumping. The water-level declines in monitoring wells during seasonal and dry climatic periods are related to decreased recharge and increased pumpage. Increased pumpage from the lower Aromas Sand and resulting water-level changes in coastal monitoring wells are similar to the changes in water levels measured in other local deep water-supply wells since 1970. At the time of this study (1998–99), water levels in most coastal and some inland water-supply wells in the Springfield subarea and as far inland as Murphy Crossing in the Pajaro subarea were below the estimated water levels of 5 to 15 ft above sea level required to stop seawater intrusion. The water levels also indicate lower pressures in the deeper aquifers, especially during seasonal pumping. Thus, long-term declines of more than 20 ft owing to regional and coastal pumping, combined with seasonal water-level changes from coastal agricultural pumping, are collectively causing seawater intrusion. Water levels near sea level in the inland regions represent a regional area of long-term ground-water decline from increased ground-water development. Inland regional decline combined with low water levels in the coastal areas sustains long-term seawater intrusion.

The predominant source of the chloride in ground water in the Pajaro Valley may be recent seawater for aquifers in the older alluvium and the upper Aromas Sand and old seawater or connate water in the aquifers of the lower Aromas Sand. Ground-water samples from selected coastal monitoring wells [PV-6 (D), SC-A4 (A), PV-3 (M), PV-8 (D), PV-4 (M), PV-1 (M, D), and SC-A3 (A)] have chloride concentrations that range from 4,000 to about 18,000 mg/L. Some of these samples approach the composition of seawater, whereas other selected deeper water-bearing zones in the lower Aromas Sand contain calcium-magnesium chloride waters. Chloride chemographs, along with the geophysical logs, indicate that saline water is vertically restricted to aquifers in the older shallow alluvium and the upper and lower Aromas Sand in the northern area, to aquifers in the lower Aromas Sand farther inland from the coast in the central area, and to aquifers in the upper Aromas Sand in the central-southern coastal areas of the Pajaro Valley. On the basis of the geochemistry and geophysical logs, the seawater intrusion is similar to that occurring in other coastal alluvial aquifers. The seawater occurs in the aquifers that include eolian sands and basal layers in coarse-grained fluvial and terrace deposits. In the coastal regions, these layers are commonly bounded by thickly bedded fine-grained layers resulting in little vertical flow of ground water or local deep percolation of recharge and vertically discreet horizontal flow of intruding seawater with relatively sharp fronts.

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APPENDIXES

APPENDIX 1. SUMMARY ANALYSIS OF GEOPHYSICAL, LITHOLOGIC, AND WELL-CONSTRUCTION DATA ANALYSIS FOR SELECTED MONITORING WELLS IN THE PAJARO VALLEY

Geophysical logs that included natural gamma, electromagnetic conductivity, temperature, and fluid resistivity were completed by the USGS at selected monitoring-well sites (PV-1, 3, 6, 8, 11, 12, 13, 14). No logs were collected at PV-4 because of petroleum products in the well vault that could have entered the monitoring wells. In addition, geophysical logs were completed at the Dolan Road monitoring-well site [DLN-(D)]. Geophysical logging was also attempted at the Hudson Landing site [HD- (D, S), but the geophysical tools could penetrate only to a depth of about 80 ft below land surface. Geophysical logs that include electrical resistivity and spontaneous-potential logs from the original drilling of the monitoring wells (PV-1, 3, 4, 6, 8) and the test hole PV-5 (Luhdorff and Scalmanini, 1987a) also were digitized for purposes of comparison and analysis. The plots of all geophysical logs with lithologic and well-construction data are shown in appendix figures A1.1–A1.11, below. The SCWD and PVWMA monitoring-well numbering convention adds a letter to the local well number that designates the relative position of the well screens in the multiple-well site configuration as S (shallow), SM (shallow medium), M (medium), MD (medium deep), and D (deep). Similarly, the SCWD monitoring-well numbering convention adds a letter to the local well number from A through D that designates the relative position of the well screens in the multiple-well site configuration as D or C as the shallowest and A the deepest well.

The geophysical logging yielded additional information about the stratigraphy of the aquifers, the nature of ground-water flow and seawater intrusion, and the nature of samples taken from these monitoring wells. Electromagnetic (EM) conductivity logs are used to determine conductive sediments that contain poor-quality water or clay. Gamma logs are useful indicators of silt-and-clay layers that may be difficult to delineate based on conventional electric logs when poor-quality water is present. The combination of EM and gamma logs can be used to determine water-bearing zones with poor-quality water that may be related to saline water such as seawater intrusion. Temperature logs are useful indicators of lateral and vertical movement of ground water that may disrupt the natural linear geothermal gradient of the sediments. Electrical resistivity logs are useful for d33etermining layering and poor-quality water. Except for the EM log from well PV-1, all the other EM logs were collected in 2-inch metal casings, which dampens the induced field and causes additional alterations from collars at pipe joints.

PV-1. The original electrical resistivity logs from the deeper test hole indicate that there was poor-quality water already present when the well was drilled in November 1988 below 250 ft below land surface (bls) and may represent the initial distribution of seawater intrusion. The gamma and EM logs from 1998 indicate that additional poor-quality water occurs in well PV-1 (M) from 100 to 110 ft bls and from 145 to 180 ft bls that may indicate new seawater intrusion (fig. A1.1). The middle well [PV-1 (M)] was installed with two well screens that may straddle a stratigraphic boundary between the shallow and older alluvium. The upper screened interval for PV-1 (M) appears to represent a fresher zone that is underlain by a thin siltstone layer that is, in turn, underlain by a zone of progressively more saline water (145–180 ft bls). This relation is consistent with the results from the pumped and air-lifted water-chemistry samples taken from this monitoring well. The air-lifted sample yielded water with almost three times more specific conductivity and chloride concentration (App. 2, table A2.1) than the pumped sample that may have skimmed fresher ground water from the upper screened interval.

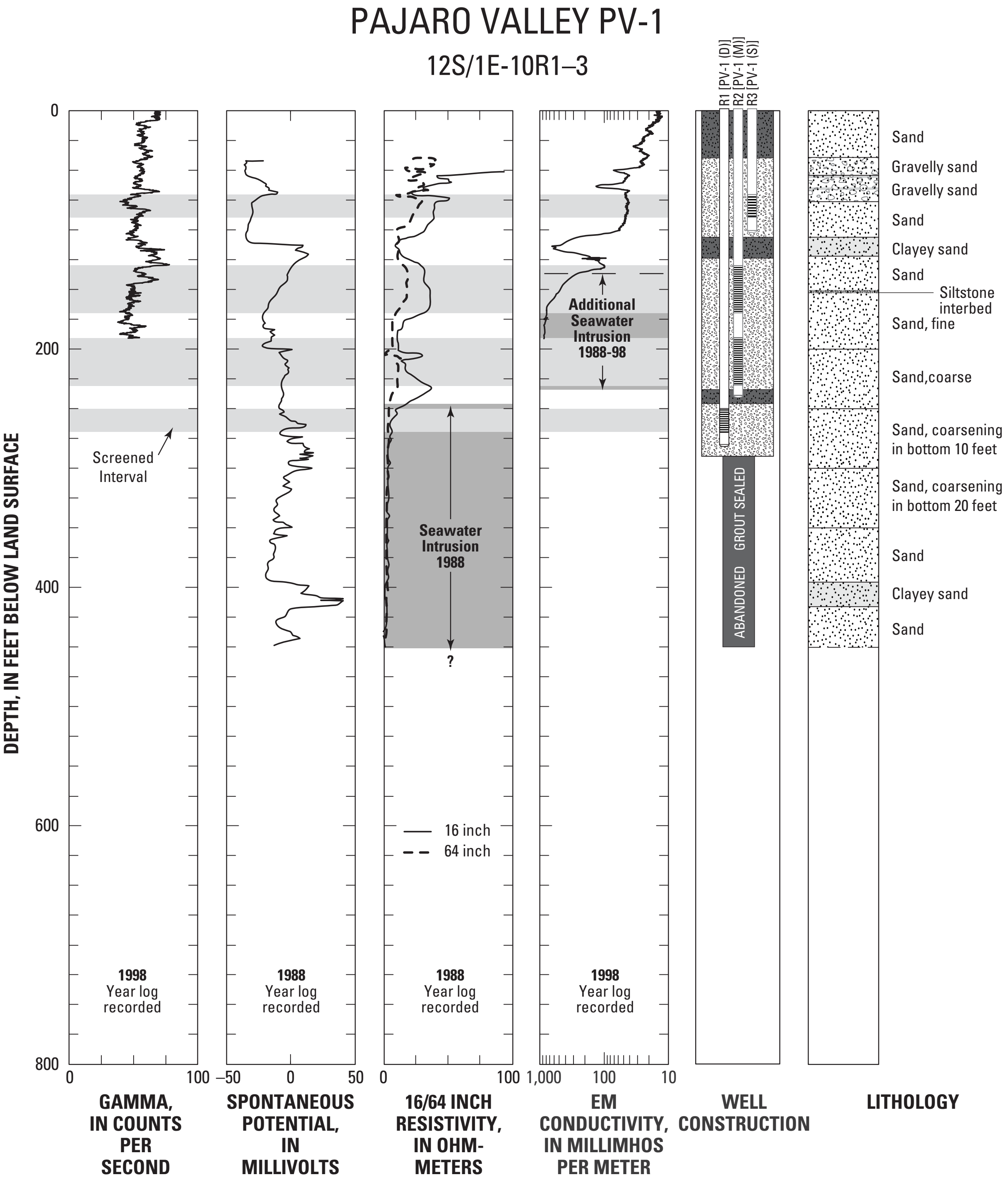


Figure A1.1. Geophysical logs and well construction for selected monitoring wells and test holes in the Pajaro Valley, Santa Cruz County, California.

PV-3. The geophysical logs indicate that poor-quality water was already present when the well was drilled in 1988, as evidenced by the low resistivity for the interval from 180 to 360 ft bls (fig. A1.2). In addition, there may be discrete zones of poor-quality water from about 100 to 175 ft bls, most of which are not screened. Note that the logs completed in the deep well [PV-3(D)] do not extend to the reported total depth as shown in the diagram (Luhdorff and Scalmanini, 1988) because the total depth is different than reported or the well has filled with sediment above the lowest screened interval since completion. The gamma and lithologic logs suggest that the thick fine-grained layer from 330 to 362 ft bls separates the water-bearing units in the Aromas Sand from the intruded-water-bearing zones in the recent and older alluvium. Shifts in the gamma log and EM log collectively show a stratigraphic break at about 362 ft bls that may be the upper boundary of the Aromas Sand. The EM log, although damped by the metal casing, appears to coincide with increased conductivity in the same zones that contained poor-quality water when the well was drilled.

PV-4A and PV-5. As at the other coastal sites, the geophysical and drillers logs from monitoring well PV-4A (fig. A1.3) and the geophysical logs from the test hole PV-5 (fig. A1.4) (Luhdorff and Scalmanini, 1988) indicate poor-quality water and very thick silt-and-clay layers from 180 to 545 ft bls. These thicker clay layers may represent deposits from an older submarine canyon that now represent a partial barrier north of the Salinas Valley between the Pajaro River and the Elkhorn Slough coastal area that was previously identified as an extension of the existing Monterey submarine canyon (Johnson, 1983).

PV-6. The geophysical logs for PV-6 also show poor-quality water below 740 ft bls (fig. A1.5) when the site was drilled in 1988. The fine-grained units occur from 385 to 410 and 465 to 480 ft bls. Based on the chemical sampling and the gamma and EM logs from 1998, the poorest quality water occurs in the zone 740 to 750 ft bls, which is below a fine-grained layer at 730 to 740 ft bls at the base of the Aromas Sand, which may also coincide with the boundary between geologic formations.

PV-8. The geophysical logs indicate that the shallow well is completed in an isothermal zone between about 120 and 200 ft bls that would indicate downward or lateral flow of ground water (fig. A1.6). Although the water-level altitudes would indicate a potential for downward flow of water to the lower aquifers, the temperature log indicates that little to no downward flow of water is occurring through the relatively fine-grained material occurring between 200 and 415 ft bls. The 415-ft depth also is the upper boundary of the Aromas Sand. The two screens completed in the middle well [PV-8 (M)] are separated by a fine-grained layer at 440–460 ft bls. Based on the fluid resistivity log, the well is probably filled with water from the upper screen, but the water from the lower screen is relatively poor quality. This log, in combination with previous purge logs of water quality, indicates that water-quality samples from PV-8 (M) may be a mixture of two different ground waters resulting in unreliable interpretations of sample data.

PV-11–PV-14. The EM and gamma logs (figs. A1.7–A1.10, below) from these monitoring wells generally indicate no saline water, and several clay layers are present. The logs from monitoring well PV-11, located in the San Andreas Dunes area west of Sunset Beach (CH2M HILL, 1994), indicate several clay layers at depths from 20 to 30, 33 to 37, and interbedded clay layers from 75 to 95 ft bls (fig. A1.7). The logs from monitoring well PV-12 also indicate (CH2M HILL, 1995) thick clay layers from 17 to 34 and 36 to 60 ft bls (fig. A1.8). The logs from monitoring well PV-13 (fig. A1.9), located in the San Andreas Dunes area west of Sunset Beach (CH2M HILL, 1994), indicate several clay layers at depths from 35 to 43, 48 to 53, and 84 to 89 ft bls. The logs from monitoring well (fig. A1.10) confirm the previous information (CH2M HILL, 1995), with a clay layer or arkosic sand from 17 to 22 ft bls.

DLN-(D). The geophysical logs (fig. A1.11) from the Monterey County Water Resource Agency monitoring well on Dolan Road indicate the possibility of poor-quality water in the red sand from 360 to 370 and 380 to 395 ft bls (Fugro West, Inc., 1995).

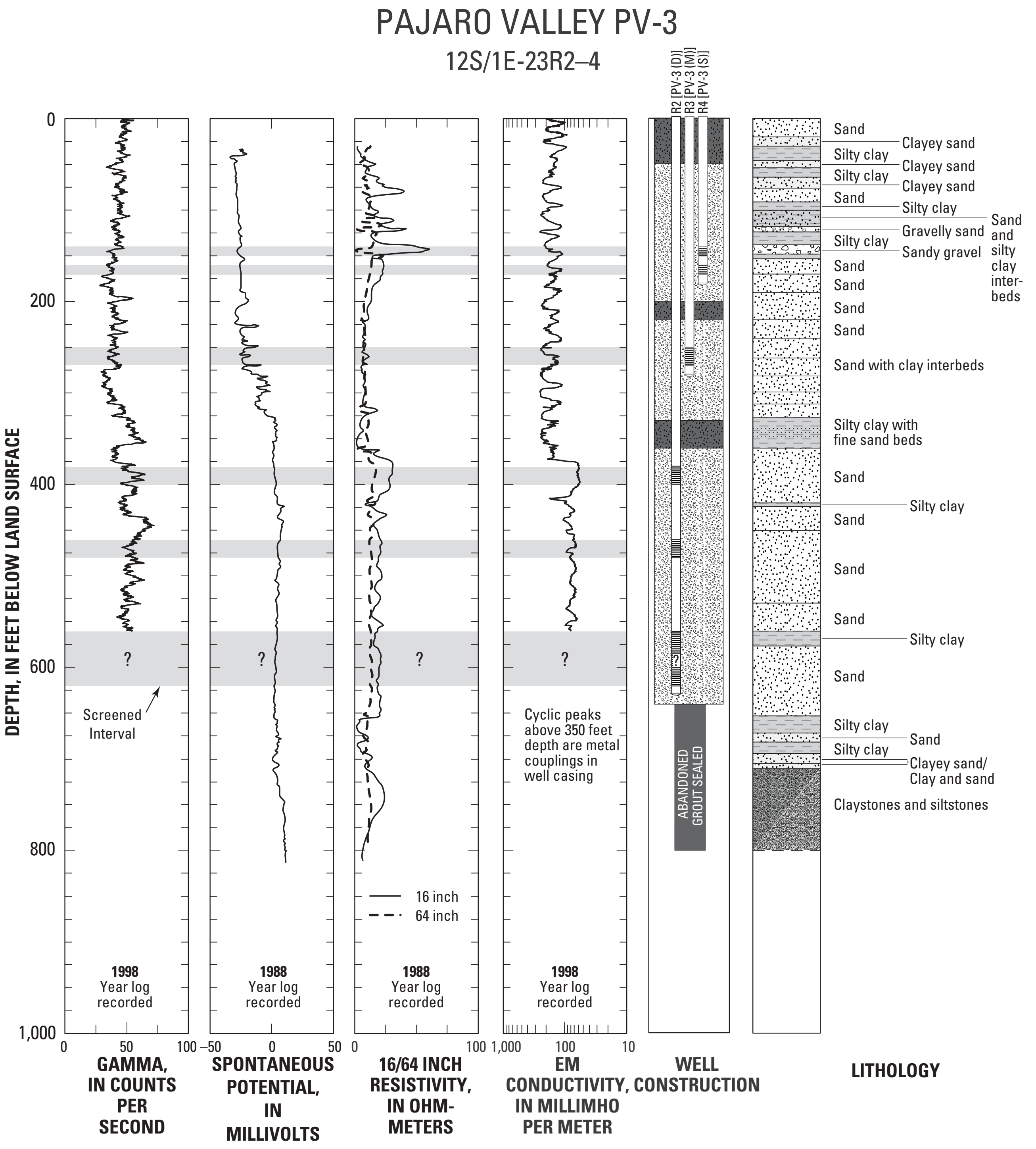
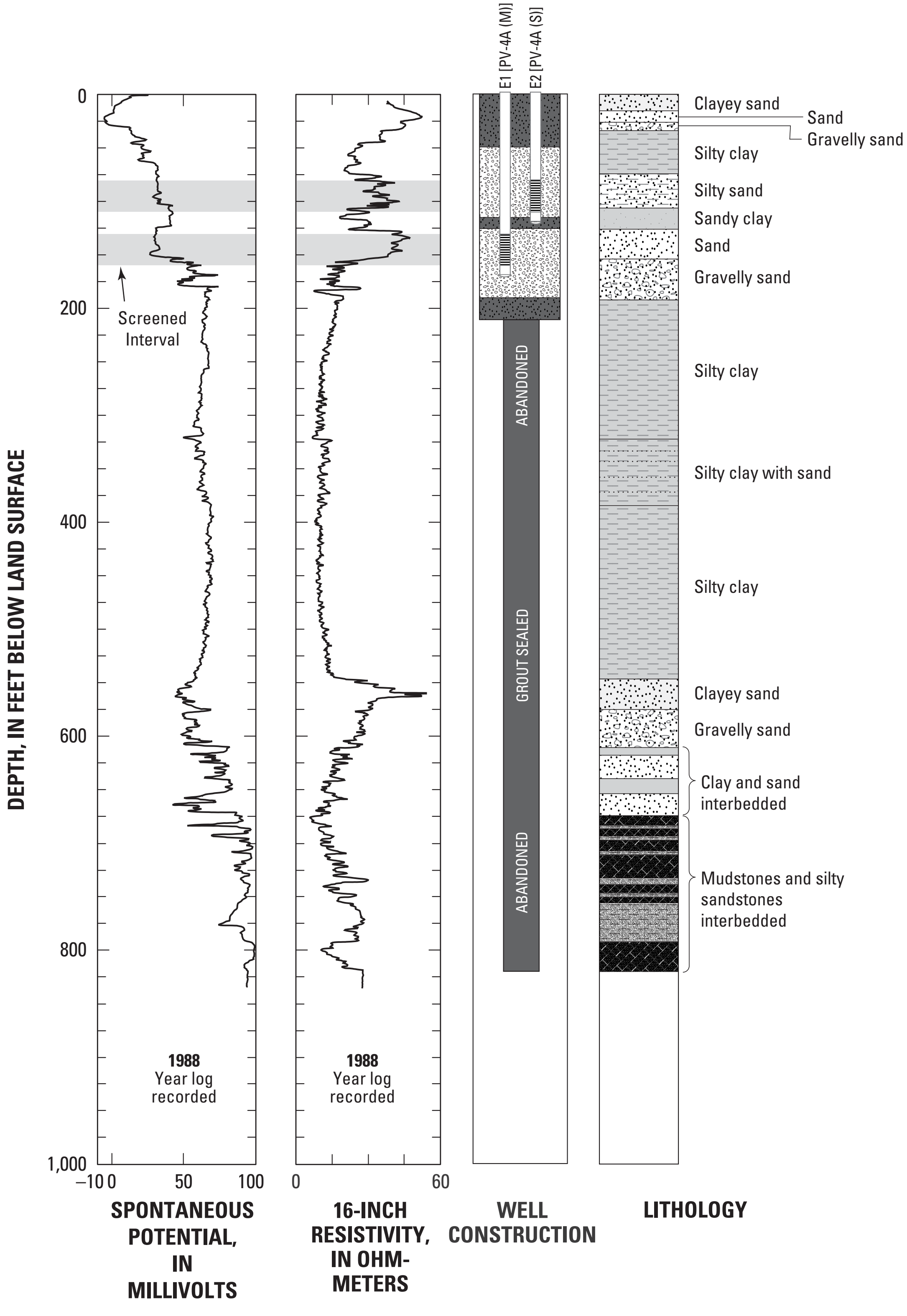


Figure A1.2. Geophysical logs and well construction for selected monitoring wells and test holes in the Pajaro Valley, Santa Cruz County, California.



PAJARO VALLEY PV-4A

12S/2E-31E1, 2

Figure A1.3. Geophysical logs and well construction for selected monitoring wells and test holes in the Pajaro Valley, Monterey County, California.

PAJARO VALLEY PV-5

13S/2E-7C1

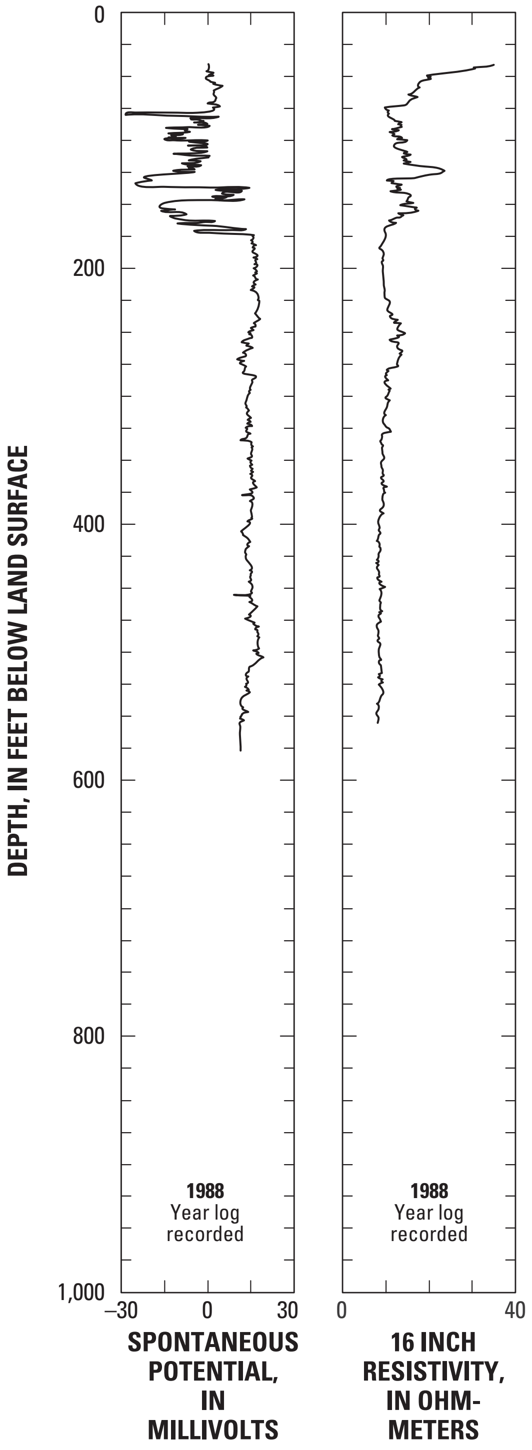


Figure A1.4. Geophysical logs for selected monitoring wells and test holes in the Pajaro Valley, Monterey County, California.

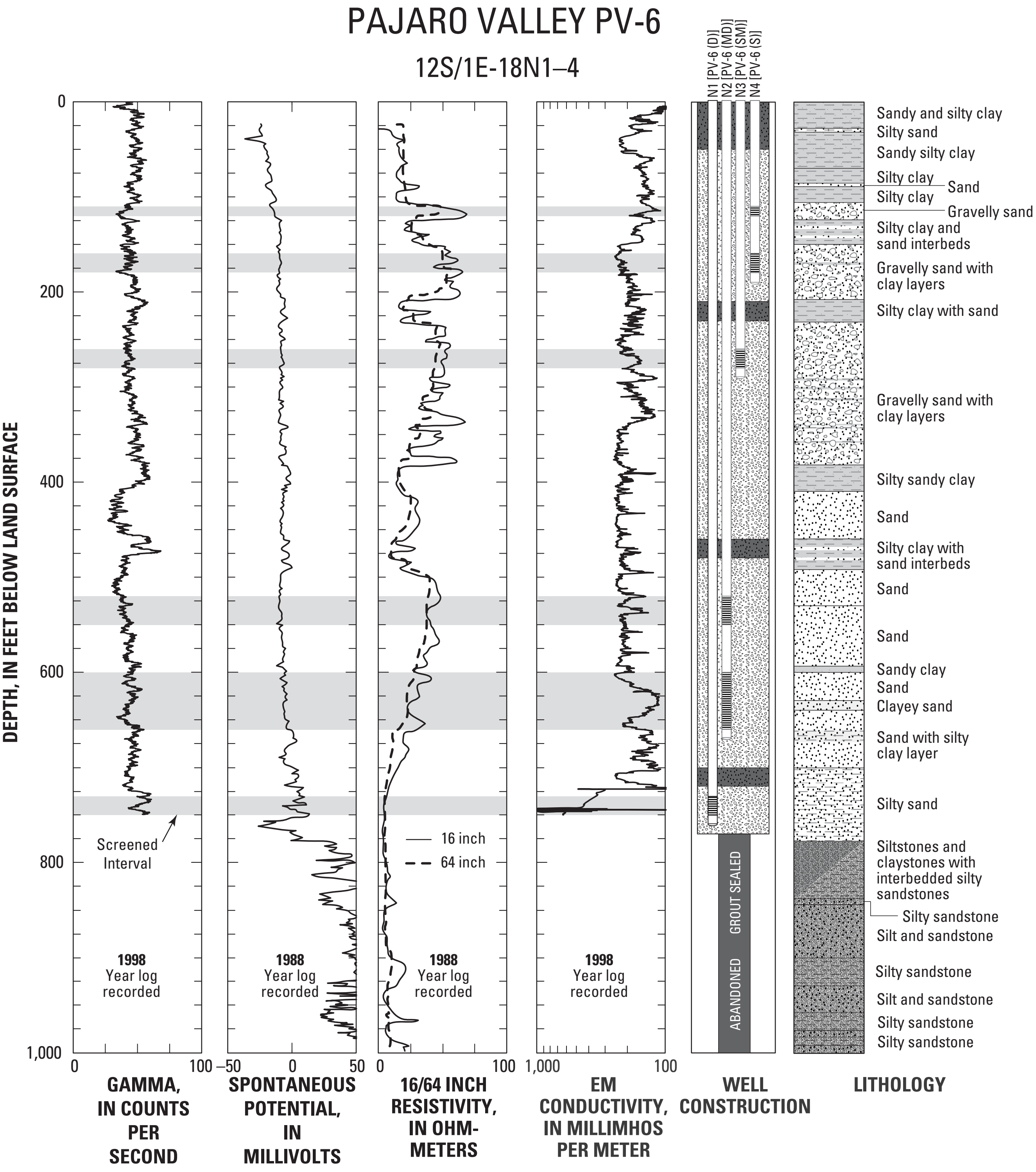


Figure A1.5. Geophysical logs and well construction for selected monitoring wells and test holes in the Pajaro Valley, Santa Cruz County, California.

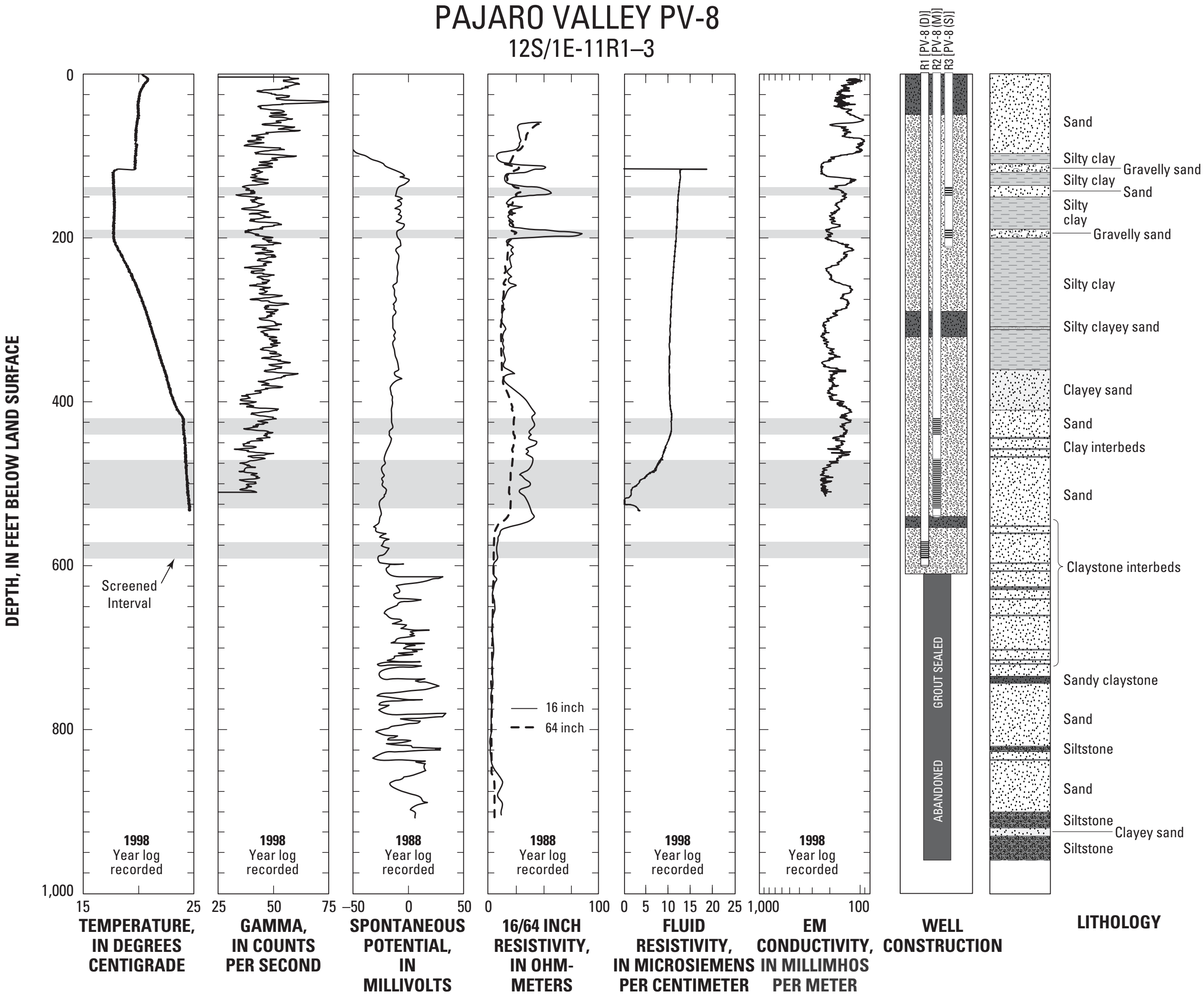


Figure A1.6. Geophysical logs and well construction for selected monitoring wells and test holes in the Pajaro Valley, Santa Cruz County, California.

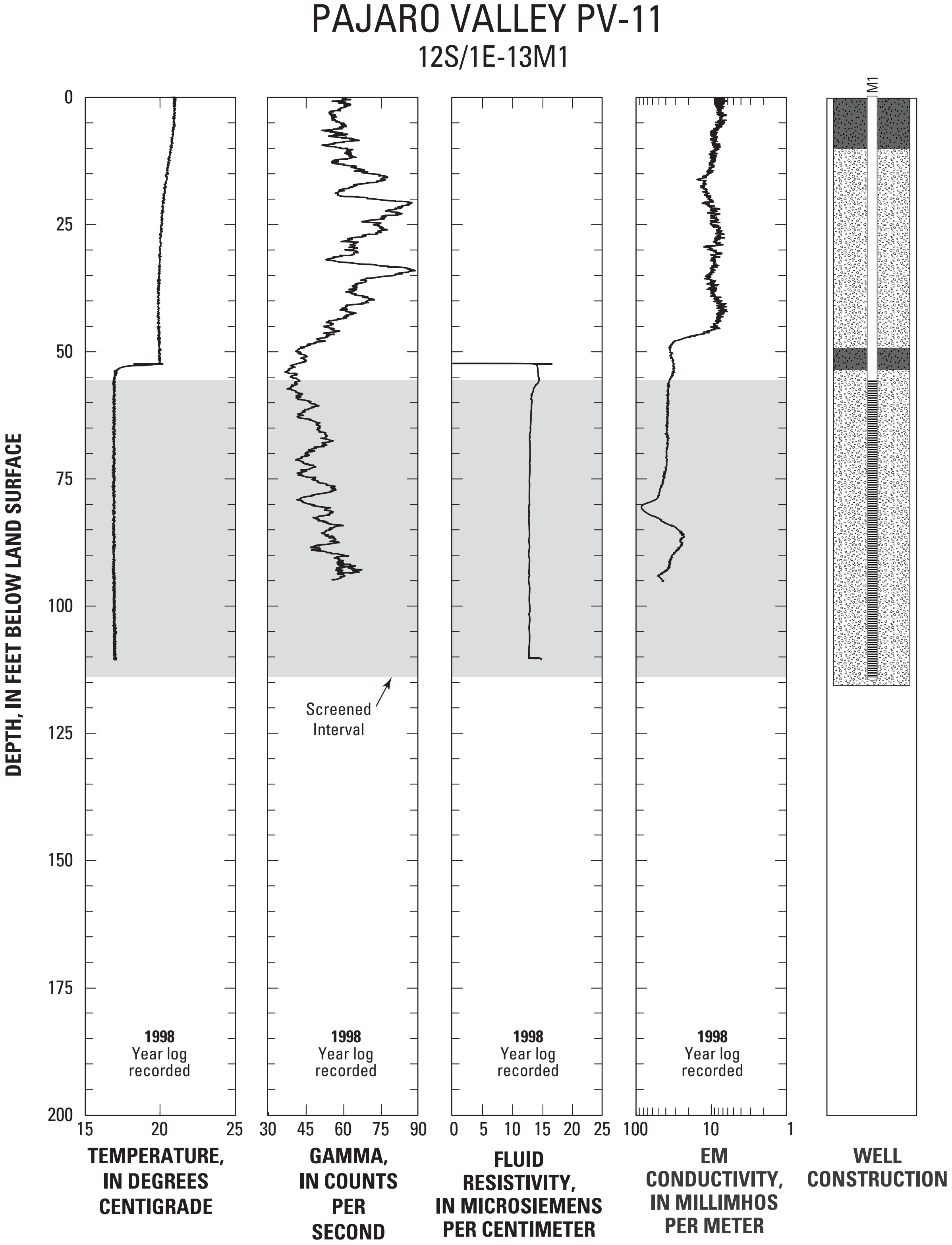


Figure A1.7. Geophysical logs and well construction for selected monitoring wells and test holes in the Pajaro Valley, Santa Cruz County, California.

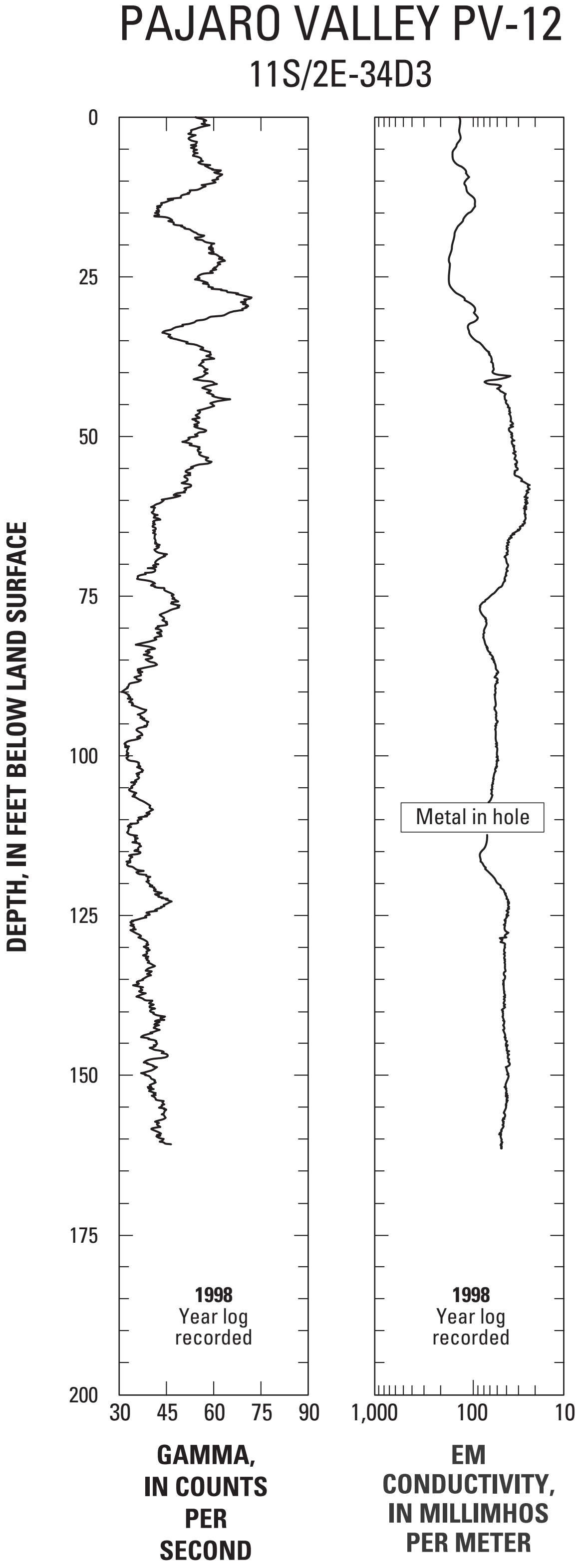


Figure A1.8. Geophysical logs and well construction for selected monitoring wells and test holes in the Pajaro Valley, Santa Cruz County, California.

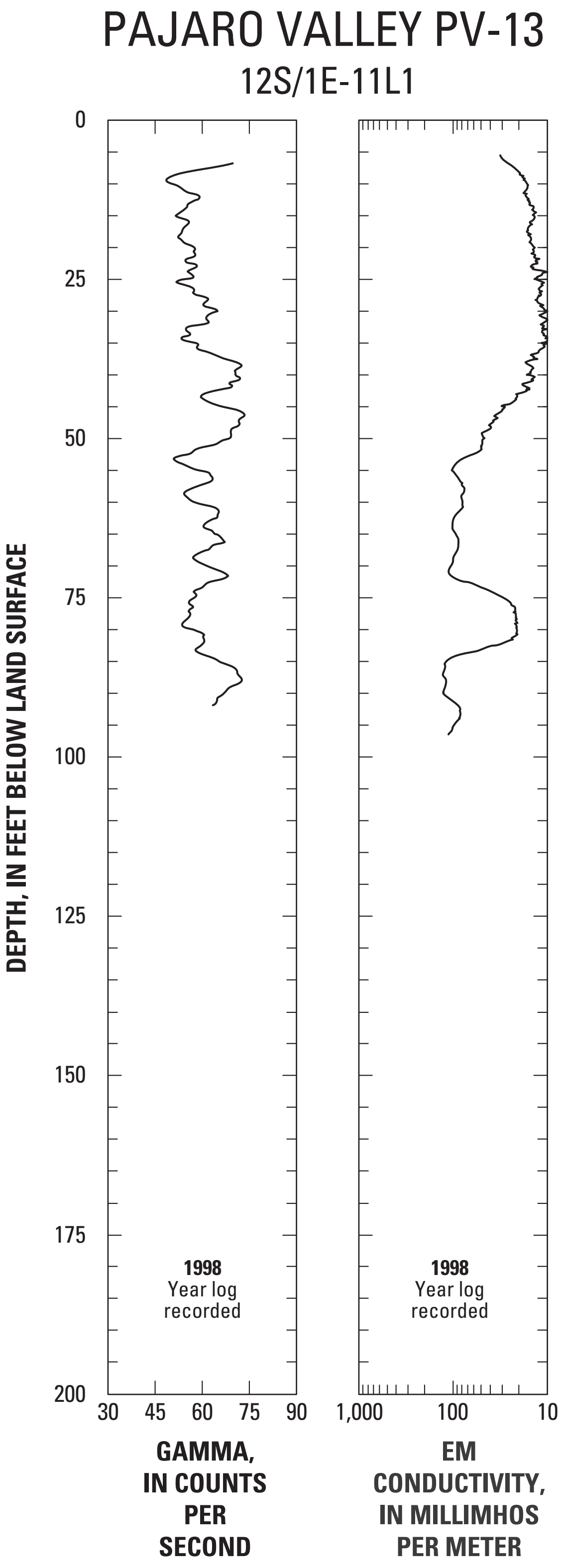


Figure A1.9. Geophysical logs and well construction for selected monitoring wells and test holes in the Pajaro Valley, Santa Cruz County, California.

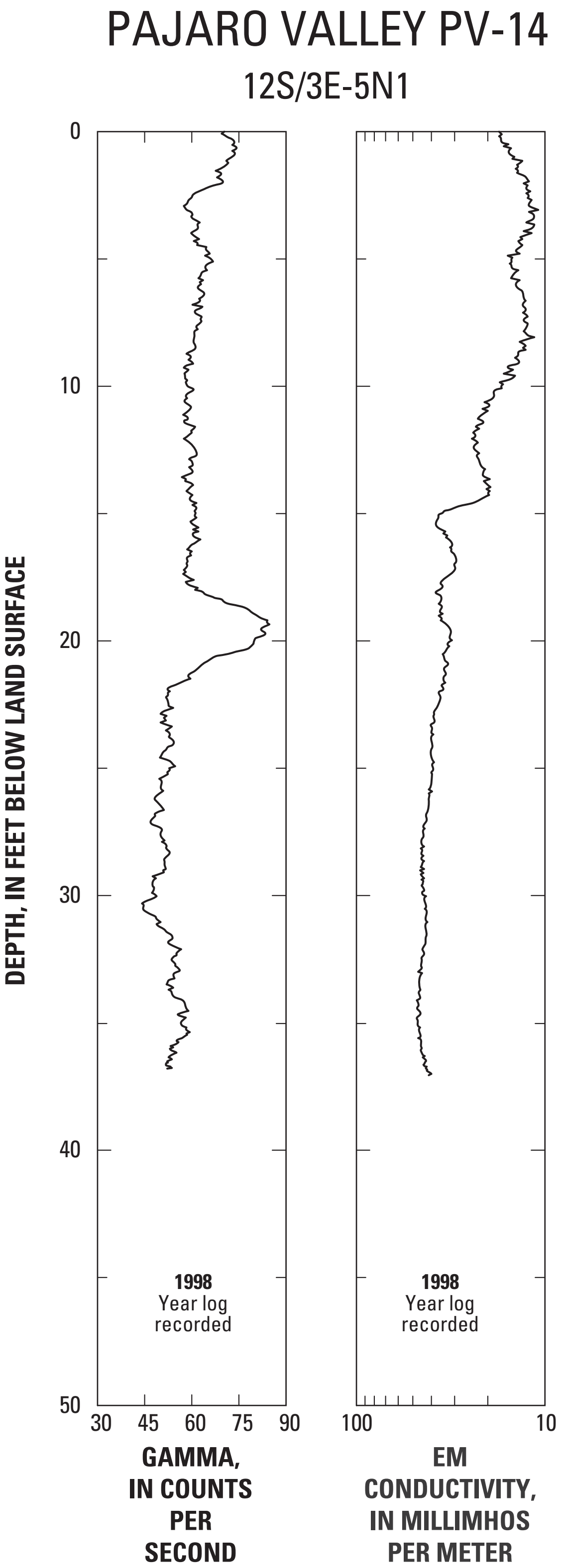


Figure A1.10. Geophysical logs and well construction for selected monitoring wells and test holes in the Pajaro Valley, Santa Cruz County, California.

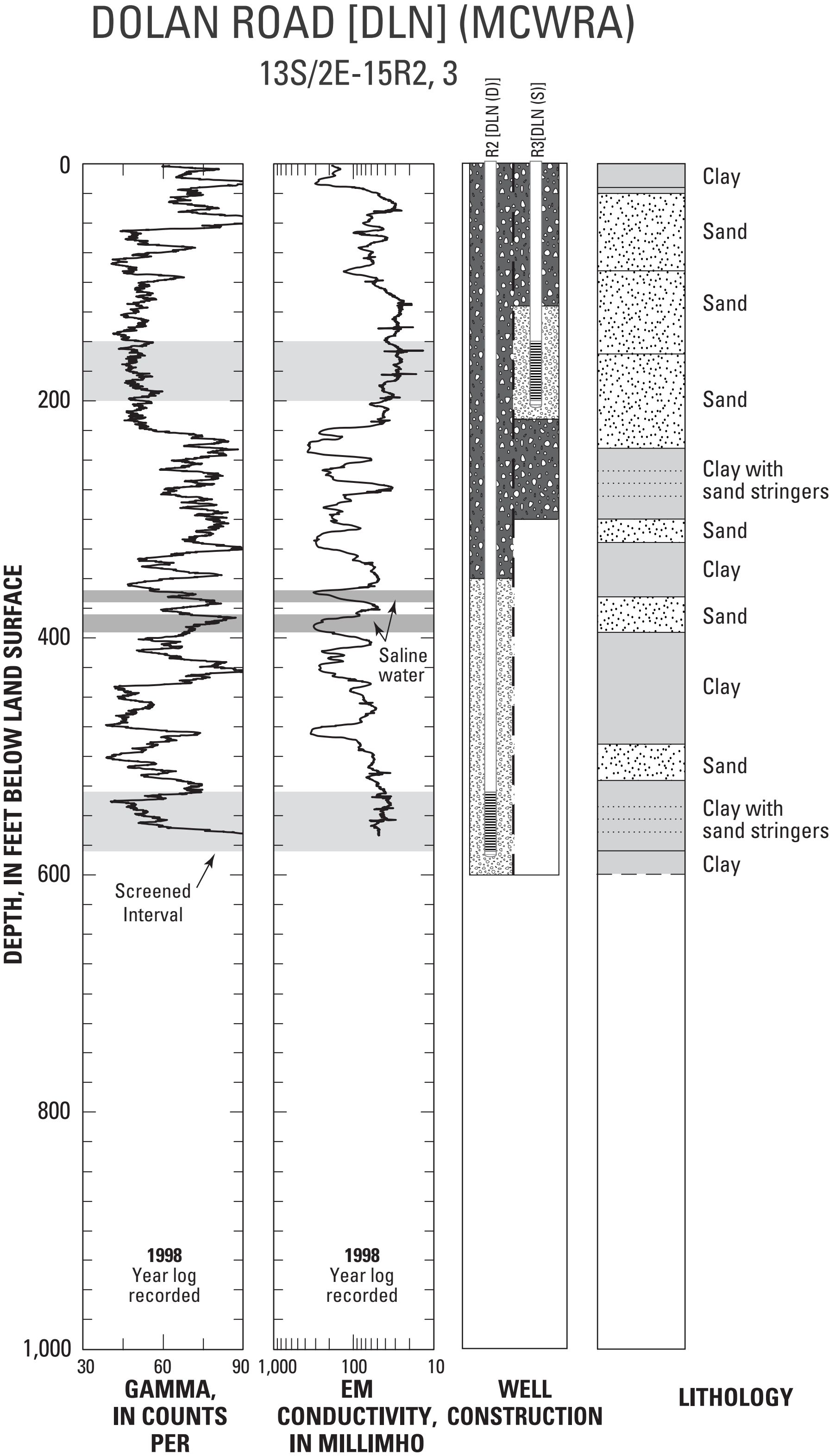


Figure A1.11. Geophysical logs and well construction for selected monitoring wells and test holes in the Pajaro Valley, Santa Cruz County, California.

APPENDIX 2. WATER-CHEMISTRY DATA FOR SELECTED MONITORING WELLS AND SURFACE WATERS IN THE PAJARO VALLEY

All coastal monitoring wells (except PV-13), inland monitoring well PV-12, and selected surface-water sources that represent the potential sources of natural recharge were sampled in August and December 1998 (fig. 1*C*; table A2.1). The surface-water samples were collected in the Pajaro River at Chittenden (PR-16.5) and at Thurwatcher Bridge (PR-2.2), at Watsonville Slough (WS-1.6), and from two agricultural sumps along the western part of Beach Rd.(AG-1.0, AG-2.0) that represent the return flow from irrigation with ground water. The surface-water samples were analyzed only for stable isotopes of deuterium, oxygen, sulfur, and boron. The boron and strontium-isotope samples were collected by the USGS along with the other water-chemistry samples for the selected monitoring wells and surface-water sites and analyzed by Tom Bullen and John Fitzpatrick of the USGS, Water Resources Discipline. The sulfur isotopes were analyzed by Tyler Coplen of the USGS, Water Resources Discipline. All of the samples presented in table A2.1 were collected and analyzed by the USGS.

Other chemistry data used in this report, other than the data for samples listed in table A2.1, were provided by PVWMA and SCWD. These data were collected by agency personnel and analyzed at five commercial laboratories: Monterey Bay Analytical Services (California State Department of Health Services Certification No. I-2385); Soil Control Labs (California State Department of Health Services Certification No. 1494); Toxscan, Inc. (California State Department of Health Services Certification No. 1515); Branchiforte Labs (California State Lab No. 1180); and Dellavalle Laboratory, Inc. (California State Department of Health Services Certification No. 1595) (Jonathan Leer, Pajaro Valley Water Management Agency, oral commun, 2002; California Department of Health Services, 2002).

The methods of data collection and analyses of other upper-aquifer system wells in the Salinas Valley are described by Vengosh and others (2002). The average composition of seawater (Hem, 1985) was used for hydrologic and water-chemistry comparisons.

The water-chemistry samples were collected under the USGS protocol established for water-chemistry sampling (U.S. Geological Survey, 1997). Water-chemistry samples were obtained from the monitoring wells with positive-displacement pumps after well development. The water-chemistry data are summarized by groups of constituents that are used for geochemical and hydrologic interpretations. These groups include major anions; dissolved-solids concentration and specific conductance; iron and manganese; other selected trace elements; pH, temperature, and dissolved oxygen; total dissolved carbon; tritium; stable isotopes of deuterium, oxygen, sulfur, boron, and strontium; and the carbon (C-14 and C-13/12) isotopes.

Some samples may not be representative of the actual water chemistry in the aquifers screened by the monitoring wells. For example, a piece of sampling hose is lodged in well PV-3 (M) and has hampered sampling since 1994. This may suggest that the sample collected in August 1998 is skimmed from the top part of the screened interval and that down-hole pumps may not yield representative samples from this well. Air-lift or down-hole “thief” sampling could be attempted to overcome this problem. The sample from PV-8 (M) may also be yielding samples that are a mixture of the saline water of the lower screen and the less saline water from the upper screened interval. Similarly, the pumped sample from PV-1 (M) was lower in salinity and had a different isotope signature than that of the subsequent air-lifted sample (table A2.1). Down-hole sampling may be required to get reliable samples from these two screened water-bearing zones.

Table A2-1. Summary of selected USGS water-chemistry data from the Pajaro Valley, Santa Cruz and Monterey Counties, California

[USGS, U.S. Geological Survey; number below the compound is the data parameter code, which is a 5-digit number used in the USGS computerized data system, National Water Information System (NWIS), to uniquely identify a specific constituent or property; PVWMA, Pajaro Valley Water Management Agency; Degrees C (°C), degrees Celsius; µS/cm, microseimen per centimeter; mg/L, milligram per liter; µg/L, microgram per liter; per mil, parts per thousand; pCi/L, picocuries per liter; — no, data; <, less than]

State well No. (USGS gaging station No.)	PVWMA (location name)	Depth of well screen, feet below land surface	Sample date	Sample time	Water temperature (°C) (00010)	Air temperature (°C) (00020)
12S/1E-10R3	PV-1 (S)	70 – 90	16-Dec-98	0940	18	—
12S/1E-10R2	PV-1 (M)	140 – 230	28-Aug-98	1145	18	17
12S/1E-10R2	PV-1 (M) (Resample)[1]	140 – 230	11-May-99	1125	18	17
12S/1E-10R1	PV-1 (D)	250 – 270	28-Aug-98	1445	19	19
12S/1E-23R4	PV-3 (S)	140 – 170	27-Aug-98	1110	18	18.8
12S/1E-23R3	PV-3 (M)	250 – 270	27-Aug-98	1500	17	20
12S/1E-23R2	PV-3 (D)	380 – 480	27-Aug-98	1140	19.5	20.5
12S/2E-31E2	PV-4A (S)	80 – 110	14-Dec-98	1600	16.1	13.5
12S/2E-31E1	PV-4A (M)	130 – 160	14-Dec-98	1530	17.6	15
12S/2E-18M4	PV-6 (S)	110 – 180	26-Aug-98	1345	19	19
12S/2E-18N3	PV-6 (SM)	260 – 280	26-Aug-98	1710	19	17
12S/2E-18N2	PV-6 (MD)	510 – 640	26-Aug-98	1430	23.5	18
12S/2E-18N1	PV-6 (D)	730 – 750	16-Dec-98	1430	22	20
12S/1E-11R3	PV-8 (S)	130 – 200	25-Aug-98	1515	18	20
12S/1E-11R2	PV-8 (M)	420 – 530	25-Aug-98	1900	23	18.5
12S/1E-11R1	PV-8 (D)	570 – 590	25-Aug-98	1945	16.5	18.5
12S/1E-13M1	PV 11	56 – 116	25-Aug-98	1300	16.5	17
11S/2E-34D3	PV 12	100 – 210	13-Dec-98	1615	17.3	13
(11159000)	PR-16.5	—	24-Aug-98	1345	21.5	23
—	PR-2.2	—	25-Aug-98	1030	18	19.5
—	WS-1.6	—	26-Aug-98	1015	16.5	18.5
—	AG-1.0	—	26-Aug-98	1015	—	19
—	AG-2.0	—	26-Aug-98	1030	—	19

See footnote at end of table.

Table A2-1. Summary of selected USGS water-chemistry data from the Pajaro Valley, Santa Cruz and Monterey Counties, California—*Continued*

PVWMA (location name)	Specific conductance, field (μS/cm at 25ºC) (00095)	Specific conductance, laboratory (μS/cm) (90095)	Oxygen, dissolved (mg/L) (00300)	pH, field (standard units) (00400)	pH, laboratory (standard units) (00403)
PV-1 (S)	1,121	1,115	7.4	7.36	7.82
PV-1 (M)	8,880	9,650	6.2	7.19	7.48
PV-1 (M) (Resample)[1]	26,800	24,400	—	—	7.54
PV-1 (D)	32,900	34,400	4.4	7.07	7.49
PV-3 (S)	2,150	2,330	.3	7.52	7.80
PV-3 (M)	1,070	1,120		7.48	7.55
PV-3 (D)	1,080	1,110	.3	8.06	8.19
PV-4A (S)	1,920	—	3.48	7.46	—
PV-4A (M)	28,100	27,200	1.2	6.83	6.99
PV-6 (S)	529	540		7.5	7.87
PV-6 (SM)	459	480	.3	7.82	8.14
PV-6 (MD)	502	520	.2	7.98	8.21
PV-6 (D)	10,100	13,200	.15	7.5	7.35
PV-8 (S)	986	996	8.2	6.99	7.84
PV-8 (M)	1,060	1,070	.4	7.52	7.80
PV-8 (D)	25,200	26,800		7.09	7.11
PV 11	880	892	7.6	6.71	7.48
PV 12	861	861	.05	6.72	7.07
PR-16.5	1,660	1,640	8.9	8.40	8.23
PR-2.2	1,690	1,700	—	8.30	8.18
WS-1.6	1,310	1,330	7.2	7.80	7.83
AG-1.0	3,140	3,340	7.2	7.91	7.68
AG-2.0	3,560	3,800	7.6	8.01	7.62

See footnote at end of table.

Table A2-1. Summary of selected USGS water-chemistry data from the Pajaro Valley, Santa Cruz and Monterey Counties, California—*Continued*

PVWMA (location name)	Calcium, dissolved (mg/L as Ca) (00915)	Magnesium, dissolved (mg/L as Mg) (00925)	Sodium, dissolved (mg/L as Na) (00930)	Potassium, dissolved (mg/L as K) (00935)
PV-1 (S)	81.1	52.5	52.9	3.13
PV-1 (M)	650	487	563	10.8
PV-1 (M) (Resample)[1]	—	—	—	—
PV-1 (D)	1,120	1,180	6,910	17.7
PV-3 (S)	168	129.1	80.6	7.59
PV-3 (M)	73.5	59.7	51.5	5.09
PV-3 (D)	29.0	35.4	132	16.2
PV-4A(S)	—	—	—	—
PV-4A(M)	1,200	1,280	4,890	20.5
PV-6 (S)	44.4	27.8	32.3	2.29
PV-6 (SM)	37.7	22.9	28.2	2.68
PV-6 (MD)	16.0	25.8	48.6	11.9
PV-6 (D)	811	994	928	83.0
PV-8 (S)	53.2	68.1	45.6	1.38
PV-8 (M)	72.5	63.0	32.1	3.21
PV-8 (D)	2,540	1,920	2,220	29.5
PV 11	49.4	55.6	40.5	.84
PV 12	91.0	38.8	41.7	1.76
PR-16.5	85.7	78.7	155	3.62
PR-2.2	81.2	89.5	149	5.04
WS-1.6	93.9	73.0	82.6	2.21
AG-1.0	18.0	199	236	.55
AG-2.0	92.2	144	507	1.89

See footnote at end of table.

Table A2-1. Summary of selected USGS water-chemistry data from the Pajaro Valley, Santa Cruz and Monterey Counties, California—*Continued*

PVWMA (location name)	Chloride, dissolved (mg/L as Cl) (00940)	Sulfate, dissolved (mg/L as SO_4) (00945)	Fluoride, dissolved (mg/L as F) (00950)	Silica, dissolved (mg/L as SiO_2) (00955)
PV-1 (S)	119	134	0.2	44.129
PV-1 (M)	3,290	387	.1	63.0
PV-1 (M) (Resample)[1]	9,500	1,300	—	—
PV-1 (D)	13,300	1,730	.1	34.6
PV-3 (S)	616	53.8	.1	31.9
PV-3 (M)	187	1.11	.12	33.2
PV-3 (D)	209	61.0	.1	29.1
PV-4A(S)	—	—	—	—
PV-4A(M)	9,660	1,310	.1	46.0
PV-6 (S)	18.1	10.8	.12	36.2
PV-6 (SM)	24.6	31.3	.1	39.2
PV-6 (MD)	31.4	33.3	.1	33.9
PV-6 (D)	4,740	648.9	.1	32.0
PV-8 (S)	54.0	148	.1	45.7
PV-8 (M)	246	24.8	.1	52.9
PV-8 (D)	10,200	1,460	.1	26.9
PV 11	61.5	122	.1	42.8
PV 12	33.1	57.6	.5	32.3
PR-16.5	140	236	.4	20.5
PR-2.2	162	260	.4	15.5
WS-1.6	35.8	264	.7	14.4
AG-1.0	569	348	.8	18.7
AG-2.0	570	429	1.2	15.1

See footnote at end of table.

Table A2-1. Summary of selected USGS water-chemistry data from the Pajaro Valley, Santa Cruz and Monterey Counties, California—*Continued*

PVWMA (location name)	Nitrogen, ammonia (mg/L as N) (00608)	Nitrogen, nitrite (mg/L as N) (00613)	Nitrogen ammonia & organic (mg/L as N) (00623)	$NO_2 + NO_3$ (mg/L as N) (00631)	Phosphorus, dissolved (mg/L as P) (00666)	Phosphorus, ortho (mg/L as P) (00671)	Carbon, organic, dissolved (mg/L as C) (00681)
PV-1 (S)	0.021	0.012	0.1	28.6	0.066	0.071	0.7
PV-1 (M)	<.020	<.010	<.100	6.83	.033	.046	.1
PV-1 (M) (Resample)[1]	—	—	—	—	—	—	—
PV-1 (D)	.106	<.010	<.100	<.050	.014	.018	.2
PV-3 (S)	.585	<.010	.529	<.050	.171	.146	.2
PV-3 (M)	3.88	<.010	4.27	<.050	1.46	1.28	3.3
PV-3 (D)	<.020	<.010	<.100	<.050	<.010	.024	.2
PV-4A(S)	.122	.01	.105	40.5	.062	.117	.5
PV-4A(M)	—	—	—	—	—	—	1.2
PV-6 (S)	<.020	.043	.495	10.1	.113	.104	1.5
PV-6 (SM)	.062	<.010	<.100	<.050	.109	.109	.3
PV-6 (MD)	.029	<.010	<.100	<.050	.054	.05	.2
PV-6 (D)	.074	.01	.1	.05	.026	.018	.1
PV-8 (S)	<.020	<.010	.112	42.6	.099	.103	.8
PV-8 (M)	<.020	<.010	<.100	<.050	.034	.039	<.100
PV-8 (D)	.041	.059	<.100	4.81	.045	.04	.4
PV 11	<.020	<.010	.158	40.0	.044	.048	1.2
PV 12	1.25	.01	1.55	.05	.842	.667	2.7
PR-16.5	1.8	<.010	2.02	.156	.875	.903	5.2
PR-2.2	.021	<.010	.798	57.7	.262	.261	4.1
WS-1.6	.053	.115	.766	11.7	.108	.094	5.6
AG-1.0	<.020	<.010	.434	81.7	.143	.144	3.9
AG-2.0	.026	.104	.466	8.81	.012	.019	7.8

See footnote at end of table.

Table A2-1. Summary of selected USGS water-chemistry data from the Pajaro Valley, Santa Cruz and Monterey Counties, California—*Continued*

PVWMA (location name)	Barium, dissolved (µg/L as Ba) (01005)	Boron, dissolved (µg/L as B) (01020)	Iron, dissolved (µg/L as Fe) (01046)	Manganese, dissolved (µg/L as Mn) (01056)	Strontium, dissolved (µg/L as Sr) (01080)	Iodide, dissolved (mg/L as I) (71865)	Bromide, dissolved (mg/L as Br) (71870)	Silica, dissolved (mg/L) (00955)
PV-1 (S)	31.8	51.8	35.3	34.3	553	0.003	0.40	44.1
PV-1(M)	60.12	146	50	157	4,480	.004	11.7	63
PV-1 (M) (Resample)[1]	—	627	—	—	12,410	.003	34.5	—
PV-1 (D)	150	1,600	200	60	9,820	.024	40.8	34.60
PV-3 (S)	218	84.6	30	513	1,590	.028	2.29	31.9
PV-3 (M)	195	208	10	997	817	.025	.587	33.2
PV-3 (D)	3.78	69	10	13.6	197	.053	.787	29.1
PV-4A (S)	—	51.7	—	—	—	—	—	—
PV-4A (M)	229	1,020	100	49.9	10,600	.001	34.62	46
PV-6 (S)	106	126	10	139.5	283	.019	.048	36.2
PV-6 (SM)	35.7	90.4	10	1.8	222	.009	.092	39.2
PV-6 (MD)	33.8	56.9	10	281	115	.004	.115	33.9
PV-6 (D)	141	75.6	2,290	388	6,750	.001	15.5	32.0
PV-8 (S)	82.9	19.6	10	3	386	.003	4.29	45.7
PV-8 (M)	34.4	66.1	10	46.3	411	.001	.953	52.9
PV-8 (D)	236	60.5	200	602	12,950	.004	35.30	26.9
PV 11	63.4	43	10	3	423	.009	3.02	42.8
PV 12	391	105	367	4,100	571	.086	.201	32.3
PR-16.5	118	947	<10.0	13.3	758	.061	.512	20.5
PR-2.2	91.7	675	<10.0	5.13	768	.042	.556	15.5
WS-1.6	110	286	16.4	37.8	756	.031	2.31	14.4
AG-1.0	87	600	<30.0	<12.0	1,520	.036	2.12	18.7
AG-2.0	56	973	<30.0	<12.0	1,140	.058	2.34	15.1

See footnote at end of table.

Table A2-1. Summary of selected USGS water-chemistry data from the Pajaro Valley, Santa Cruz and Monterey Counties, California—*Continued*

PVWMA\ (location name)	Alkalinity (mg/L as $CaCO_3$) (39036)	Alkalinity, dissolved (mg/L as $CaCO_3$) (39086)	Dissolved solids (180C) (mg/L) (70300)	Alkalinity, dissolved (mg/L as $CaCO_3$) (90410)	Delta, deuterium (per mil) (82082)	Delta, oxygen-18 (per mil) (82085)	Tritium (pCi/L) (07000)	Strontium-87/86 (ratio per mil) (75978)
PV-1 (S)	—	—	650	130	-36.4	-5.7	18.1	0.70626
PV-1 (M)	104	105	7,030	—	-30.8	-5.2	6.3	.70660
PV-1 (M) (Resample)[1]	—	—	20,300	—	-18.7	-3.27	6.3	—
PV-1 (D)	103	103	24,900	—	-12.2	-2.25	5.1	.70671
PV-3 (S)	180	180	1,490	—	-38.9	-6.4	<.3	.70676
PV-3 (M)	266	268	583	—	-37.4	-6.01	.4	.70691
PV-3 (D)	136	137	594	—	-46.7	-7.38	.3	.70828
PV-4A(S)	—	—	—	—	-35.2	-5.32	8.2	.70701
PV-4A(M)	—	—	18,200	136	-19.2	-2.96	9.34	.70707
PV-6 (S)	257	257	372	—	-35.3	-5.9	<.3	.70705
PV-6 (SM)	172	172	291	—	-35.8	-5.96	<.3	.70713
PV-6 (MD)	185	185	313	—	-35.3	-6.01	<.3	.70777
PV-6 (D)	—	—	8,360	84.5	-34.5	-5.57	<.3	.70716
PV-8 (S)	129	129	687	—	-33.5	-5.52	14.2	.70600
PV-8 (M)	133	133	575	—	-36	-6.07	<.3	.70691
PV-8 (D)	112	112	20,600	—	-22.5	-3.92	<.3	.70670
PV 11	80.4	80.4	601	—	-35.9	-5.57	10.4	.70586
PV 12	356	—	534	363	-21.8	-2.67	3.4	.70726
PR-16.5	421	423	1,030	—	-34.8	-4.71	—	.70734
PR-2.2	372	372	1,080	382	-32.8	-4.43	—	.70735
WS-1.6	372	371	908	387	-28.9	-4.74	—	.70735
AG-1.0	307	307	2,180	316	-31.5	-4.87	—	.70750
AG-2.0	525	523	2,460	542	-31	-5.0	—	.70759

See footnote at end of table.

Table A2-1. Summary of selected USGS water-chemistry data from the Pajaro Valley, Santa Cruz and Monterey Counties, California—*Continued*

PVWMA (location name)	Carbon-14 (percent modern carbon) (49933)	Carbon-13/12 (per mil) (82081)	Uncorrected age (years before present)	Corrected age (years before present)	Delta boron-11 (per mil) (—)	Delta sulfur-34 (per mil) (82086)
PV-1 (S)	108.6	-18.11	<50	—	25.2	9
PV-1 (M)	76.83	-14.55	2,200	—	44.7	18.9
PV-1 (M) (Resample)[1]	—	—	—	—	—	—
PV-1 (D)	87.8	-7.7	1,000	—	59.2	21
PV-3 (S)	42.73	-17.96	7,000	6,000	18.5	—
PV-3 (M)	48.74	-14.36	5,900	4,900	7.5	—
PV-3 (D)	4.89	-15.76	24,900	23,300	27.2	—
PV-4A (S)	87.48	-17.97	1,100	—	23.7	8.4
PV-4A (M)	75.49	-13.02	2,300	1,300	50.9	20.1
PV-6 (S)	51.21	-15.03	5,500	4,300	13.7	30.7
PV-6 (SM)	48.13	-16.24	6,100	5,000	22.7	4.6
PV-6 (MD)	35.34	-17.19	8,600	7,500	31.7	2.8
PV-6 (D)	24.1	-18.37	11,800	10,700	27.0	20.8
PV-8 (S)	114.0	-20.4	<50	—	27.2	9.1
PV-8 (M)	45.81	-16.32	6,500	5,400	34.2	.8
PV-8 (D)	37.61	-13.11	8,100	7,000	31.5	20.7
PV 11	—	—	—	—	22.5	6.3
PV 12	87.88	-17.83	1,000	—	17.5	.8
PR-16.5	—	—	—	—	18.2	-1.1
PR-2.2	—	—	—	—	13.2	1.2
WS-1.6	—	—	—	—	19.2	6
AG-1.0	—	—	—	—	13.5	12.6
AG-2.0	—	—	—	—	16.7	12

[1] The PV-1(M) was resampled by PVWMA by airlifting and analyzed by the USGS.

Major-Ion, Minor-Ion, and Trace-Element Chemistry—Major-ions, minor-ions, and trace elements are used to assess the chemical characteristics of the ground-water samples and help to determine the source and movement of the ground water.

Major Anions—Chloride concentrations from monitoring-well samples ranged from 18 mg/L at PV-6 (S) to 13,317 mg/L at PV-1 (D). The samples from the Watsonville Slough, PV-6 (S, SM, MD), PV-8 (S), PV-11, and PV-12 contain less than 65 mg/L chloride. Previous samples from PV-3 (M) indicated that chloride concentrations increased from 3,920 to 6,690 mg/L between 1989 and 1994. Sulfate concentrations from monitoring-well samples ranged from 1.1 mg/L at PV-3 (M) to 1,726 mg/L at PV-1 (D). Sulfate concentrations from surface-water samples ranged from 236 mg/L for the Pajaro River at Chittenden to 429 mg/L for drain sample AG-2.0 (table A2.1).

Dissolved-Solids Concentration and Specific Conductance—Dissolved-solids concentrations from monitoring-well samples ranged from 291 mg/L for well PV-6 (SM) to 24,900 mg/L for well PV-1 (D). The specific conductance ranged from 459 µS/cm for well PV-6 (SM) to 32,900 µS/cm for well PV-1 (D). The lowest conductance for surface-water samples was 1,310 mS/cm for Watsonville Slough but the agricultural drain samples exceeded 3,000 mS/cm.

Iron and Manganese—The iron and manganese concentrations from monitoring-well samples ranged from 10 µg/L for numerous wells to 2,288 µg/L (iron) for well PV-6 (D) and from 60 µg/L for PV-1 (D) to 4,100 µg/L for PV-12 (manganese) (table A2.1). Iron and manganese concentrations in surface-water samples ranged from less than 10 µg/L for the Pajaro River to 16 µg/L for the Watsonville Slough (table A2.1).

Other Selected Trace Elements—Ground-water samples from the monitoring-well sites contained iodide concentrations ranging from 0.001 mg/L for PV-4A (M) and PV-6 (D) to 0.086 mg/L for PV-12. Barium concentrations ranged from 3.8 µg/L for well PV-3 (D) to 391 µg/L for well PV-12. Strontium concentrations ranged from 115 µg/L for well PV-6 (MD) to 12,950 µg/L for well PV-8 (D). Bromide concentrations ranged from less than 0.05 mg/L for well PV-6 (S) to 40.8 mg/L for well PV-1 (D). Boron concentrations ranged from 19.6 µg/L for well PV-8 (S) to 1,600 µg/L for well PV-1 (D). The surface-water boron concentrations were higher than those of many of the well samples and ranged from 286 to 973 µg/L (table A2.1).

pH, Temperature, and Dissolved Oxygen—The pH values from monitoring-well samples were slightly basic, ranging from 6.7 to 8.1(table A2.1). The temperature of the water samples from the monitoring wells ranged from 17 to 23.5 ^{o}Celsius (^{o}C). The water samples from surface waters and agricultural drains ranged from 7.2 to 8.9 mg/L in dissolved-oxygen concentration. Samples from PV-1 (S, M, D), PV-4A (S, M), PV-11, PV-8 (S) ranged from 1.2 to 8.2 mg/L dissolved oxygen. The remaining ground-water samples had less than 0.4 mg/L dissolved oxygen. Samples from wells PV-3 (M), PV-6 (S), and PV-8 (D) contained no detectable dissolved oxygen. The lack of oxygen and the trace smell of hydrogen sulfide collectively indicate that the waters from these wells are under reduced conditions. The mixing of these waters with shallower oxygenated waters may result in the precipitation of minerals on well screens, within gravel packs and aquifer pore spaces, or within agricultural soils. Wells that are perforated across aquifers with different chemistry could be susceptible to encrustation.

Dissolved Organic Carbon—The concentration of dissolved organic carbon for the monitoring wells ranged from less than 0.1 mg/L for well PV-8 (M) to 3.3 mg/L for well PV-3 (M). Many of the ground-water samples ranged between 0.1 and 0.8 mg/L, with the least carbon at depth (table A2.1). Dissolved organic carbon concentration was highest in surface-water and agricultural drain samples, ranging from 3.9 to 7.8 mg/L (table A2.1).

Total Dissolved Nitrate—The concentration of nitrate in monitoring wells ranged from less than 0.05 mg/L to 42.6 mg/L (table A2.1) as nitrogen. The concentration of nitrate in surface-water samples ranged from 0.2 mg/L to 81.7 mg/L (table A2.1) as nitrogen. Samples from the Pajaro River at Thurwatcher and the drain at AG-1.0 exceeded 45 mg/L NO_3 as nitrogen.

Stable Isotopes—Stable isotopes of oxygen and hydrogen (deuterium) are used to help determine the source of water, isotopes of boron help to identify the source of dissolved ions that contribute to poor-quality water, and isotopes of strontium help to infer the source of the sediments through which the water flows.

Oxygen and Deuterium Isotopes —Oxygen-18 and deuterium are naturally occurring stable isotopes of oxygen and hydrogen. Oxygen-18 (^{18}O) and deuterium (D) abundance are expressed as ratios in delta notation as per mil (parts per thousand) differences relative to the standard known as Vienna Standard Mean Ocean Water (VSMOW) (Gonfiantini, 1978). Because the source of most of the world's precipitation is the evaporation of seawater, the delta-^{18}O and delta-D composition of precipitation throughout the world is linearly correlated. This relation is known as the meteoric water line (Craig, 1961). The delta-^{18}O and delta-D composition of ground water relative to the meteoric water line and relative to the isotopic composition of water from other sources is an indicator of the source and movement of ground water. The delta-^{18}O and delta-D composition of water from monitoring wells ranged from -7.38 to -2.25 and -46.7 to -12.2, respectively (fig. 20; table A2.1).

Boron Isotopes—Boron-10 and boron-11 are naturally occurring stable isotopes of boron. Natural and anthropogenic processes fractionate the Boron-11 content relative to Boron-10. Because boron is ubiquitous and is a soluble ion in water and because boron isotopes have fractionated through geologic time, boron isotopes provide a combined indicator of the potential for natural sources of water such as seawater intrusion as well as anthropogenic sources of boron (Bassett, 1990; Vengosh and others, 1994, 2002) (see "Stable Isotopes"). The abundance of Boron-11 (^{11}B) is expressed in delta notation as per mil (parts per thousand) differences relative to the standard reference boron isotopic ratio of Boron-11 to Boron-10 of 4.161 for National Bureau of Standards boric acid sample No. 951 (Tom Bullen, U.S. Geological Survey, written commun., 2001). Delta-boron-11 concentration in ground-water samples from the monitoring wells ranged from 7.5 to 59.2 per mil (fig. 23*A*; table A2.1). Delta-boron-11 concentration in surface water samples ranged from 13.2 to 19.2 per mil (fig. 23*A*; table A2.1).

Strontium Isotopes—Strontium-87/86 isotopes are naturally occurring stable isotopes of strontium and are expressed as a ratio (Faure and Powell, 1972). Strontium from ground-water samples undergoes cation exchange between calcium and strontium from the surrounding sediments. This exchange process is relatively rapid for most ground-water flow rates and results in a strontium isotopic composition of ground water that reflects the isotopic composition of the aquifer sediments. Therefore, strontium isotopes are a useful indicator of the source of the sediments that compose the aquifer (Izbicki and others, 1994). Strontium isotopes also can be affected by base-ion exchange during seawater intrusion, but this effect may be too localized to be discernible from sampling of ground water on a regional scale. The strontium isotope ratio for coastal California granitic rocks is 0.7082 (Faure and Powell, 1972), and the ratio for average modern seawater is 0.7092 (Vengosh and others, 2002). The strontium-87/86 ratio of ground-water samples from monitoring wells ranged from 0.70586 to 0.70828 (fig. 21; table A2.1). The strontium-87/86 ratio of surface-water samples ranged from 0.70734 to 0.70759 (fig. 21; table A2.1).

Sulfur Isotopes—Sulfur-32/34 isotopes are naturally occurring stable isotopes of sulfur and are expressed in delta notation as per mil (parts per thousand) differences relative to the standard reference sulfur isotopic ratio of troilite from the Vienna Canon Diablo meteorite (VCDT, Coplen and others, 2002). Delta-sulfur-34 concentration in ground-water samples from the monitoring wells ranged from 0.8 to 30.7 per mil (fig. 23B; table A2.1). Delta-sulfur-34 concentration in surface-water samples ranged from -1.1 to 12.6 per mil (fig. 23*B*; table A2.1).

Unstable Isotopes—Unstable isotopes of water and carbon are used to identify the potential age of ground-water samples.

Tritium—Tritium (^{3}H) is a naturally occurring radioactive isotope of hydrogen having a half-life of 12.4 years. The activity of tritium is measured in picocuries per liter (pCi/L); and one pCi/L is equivalent to about 2.2 disintegrations of tritium per minute or about one tritium atom in 3.1×10^{17} atoms of hydrogen. Prior to 1952, the tritium concentration of precipitation in coastal California was about 6.5 pCi/L (Izbicki, 1996b). Beginning in 1952, about 800 kg of tritium was released as a result of the atmospheric testing of nuclear weapons (Michel, 1976) and the tritium activity of precipitation at Santa Maria, California, increased to more than 2,200 pCi/L (International Atomic Energy Agency, 1981). This release stopped in 1962 with the signing of treaties banning the atmospheric testing of nuclear weapons. Since that time, tritium activity in precipitation has decreased to pre-1952 levels. Because tritium can be part of the water molecule and tritium activities are not significantly affected by reactions other than radioactive decay, it is an excellent tracer of the movement of water and relative age of water on time scales ranging from 0 to 50 years before present (Izbicki and others, 1993). Detectable tritium concentrations ranged from 18.08 pCi/L for well PV-1 (S) to 0.416 pCi/L for well PV-3 (M), which is just above the detection limit of 0.3 pCi/L (table A2.1). Most of the wells at PV-3, PV-8, and PV-3 did not contain detectable tritium (table A2.1). The remaining samples from monitoring wells were at the tritium-detection limit and contain waters recharged before 1952.

Carbon Isotopes—Carbon-14 (^{14}C) is a naturally occurring radioactive isotope of carbon that has a half-life of about 5,730 years. Carbon-14 data are expressed as percent modern carbon (pmc) by comparing carbon-14 activities with the specific activity of National Bureau of Standards oxalic acid: 12.88 disintegrations per minute per gram of carbon in the year 1950 equals 100-percent modern carbon. In addition to the naturally occurring carbon-14, carbon-14 also was produced during the atmospheric testing of nuclear weapons. As a result, carbon-14 activities can exceed 100 percent modern carbon. Carbon-14 is a tracer of the movement and relative age of water on time scales ranging from several hundred to more than 30,000 years before present. Because carbon-14 is not part of the water molecule, carbon-14 activities are affected by chemical reactions between dissolved constituents and aquifer material. As a result, carbon-14 data must be corrected using chemical, mineralogical, and carbon-13 data to evaluate chemical reactions that occur within an aquifer and to estimate the actual age of a water sample. Davis and Bentley (1982) estimated that errors in carbon-14 ages may be as much as 100 percent. The carbon-14 ages were adjusted in this study on the basis of the percentage of carbon-14 for initial waters that represent recent recharge. The carbon-14 content from well PV-12 (11S/3E-24D3M), with a carbon-14 content of 88 percent and tritium present, was used for adjustment to initial water. These samples represent a relatively recently recharged ground water. The percent of modern carbon-14 is increased by the resulting ratio of carbon-14 values to 88 percent for the initial water of recent aquifer recharge. For wells with no detectable tritium in water samples, the values for uncorrected percent modern carbon ranged from 4.9 pmc for PV-3 (D) to 51.2 pmc for PV-6 (S) (table A2.1). For wells containing tritium in water samples, the values for uncorrected percent modern carbon ranged from 75.5 pmc for PV-4A (M) to 114.0 pmc for PV-8 (S) (table A2.1).

Carbon-13 is a stable isotope of carbon that is commonly used in conjunction with carbon-14. Carbon-13 data are expressed as ratios in delta notation as per mil differences relative to the ratio of carbon-13 to the more common isotope carbon-12 in standard Peedee Belemnite (PDB) (Gonfiantini, 1978). The delta-carbon-13 values for the monitoring wells ranged from -7.7 per mil for well PV-1 (D) to –20.4 per mil for well PV-8 (S) (table A2.1). Along with the presence of hydrogen sulfide noted during sampling of the monitoring wells, these data may indicate that the deeper wells are in a zone where reducing conditions and methanogenesis is occurring.

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