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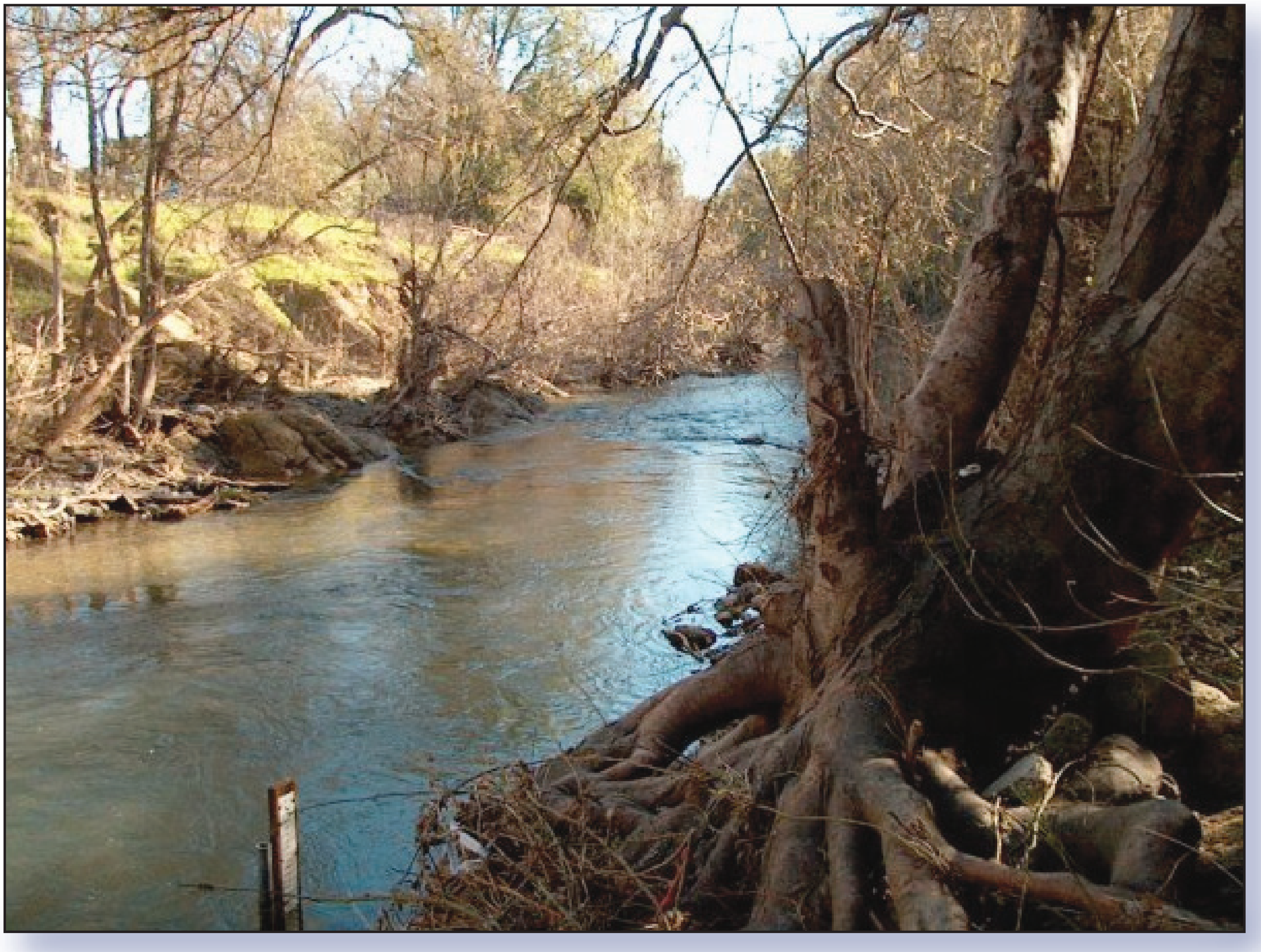
Geohydrological Characterization, Water-Chemistry, and Ground-Water Flow Simulation Model of the Sonoma Valley Area, Sonoma County, California



Scientific Investigations Report 2006-5092

U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Cover. Photograph of Sonoma Creek at Agua Caliente, Sonoma County, California, by Marisa Cox, U.S. Geological Survey

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With a section on Basement Rock Configuration Interpreted from Gravity Data

By Victoria E. Langenheim

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

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Conversion Factors, Datum, Abbreviations, and Acronyms

SI to Inch/Pound

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square kilometer (km^2)	0.3861	square mile (mi^2)
	Density	
kilogram per cubic meter (kg/m^3)	0.06242	pound per cubic foot (lb/ft^3)

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	0.004047	square kilometer (km^2)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
acre-foot (acre-ft)	1,233	cubic meter (m^3)
	Velocity	
foot per day (ft/d)	0.3048	meter per day (m/d)
foot per year (ft/yr)	0.3048	meter per year (m/yr)
	Flow rate	
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year (m^3/yr)
cubic feet per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
	Specific capacity	
gallon per minute per foot [(gal/min)/ft)]	0.2070	liter per second per meter [(L/s)/m]
	Transmissivity*	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C=(°F-32)/1.8

Vertical coordinate information is referenced to North American Vertical Datum of 1988 (NAVD 88), except where noted.

Horizontal coordinate information is referenced to North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

*Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [(ft^3/d)/ft^2]ft. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

NOTE TO USGS USERS: Use of hectare (ha) as an alternative name for square hectometer (hm^2) is restricted to the measurement of small land or water areas. Use of liter (L) as a special name for cubic decimeter (dm^3) is restricted to the measurement of liquids and gases. No prefix other than milli should be used with liter. Metric ton (t) as a name for megagram (Mg) should be restricted to commercial usage, and no prefixes should be used with it.

Abbreviations and Acronyms:

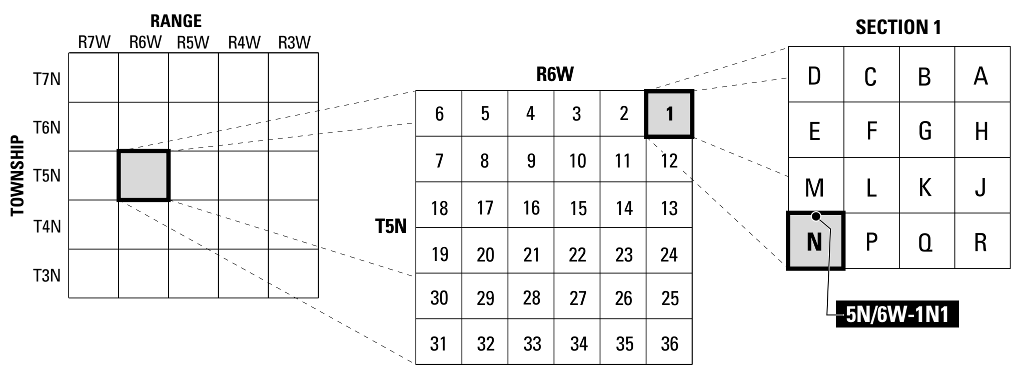
~	approximate
bls	below land surface
δ	delta notation
^2H	deuterium
CIMIS	California Irrigation Management Information System
ET	evapotranspiration
ET_0	total potential evapotranspiration rate
GMWL	global meteoric water line
GIS	geographic information system
HFB	Horizontal Flow Barrier
K	hydraulic conductivity
K/Ar	potassium/argon
^1H	hydrogen
ma	millions of years ago
MCL	maximum contaminant level
meq/L	milliequivalents per liter
mGal	milligal
mL	milliliter
MF2K	MODFLOW-2000
NGVD 29	National Geodetic Vertical Datum of 1929
NO_3	dissolved nitrogen in the form of nitrate
^{16}O	oxygen-16
^{18}O	oxygen-18
‰	per mil
%	percent
R^2	correlation coefficient
ROE	residue on evaporation
RMSE	root mean squared error
S	storage coefficient
SC	specific conductance
S_s	specific storage
SVTP	Sonoma Valley Wastewater Treatment Plant
S_y	specific yield
TDS	total dissolved solids
VSMOW	Vienna Standard Mean Ocean Water
WY	water year
WWTP	waste water treatment plant

Organizations

CADWR	California Department of Water Resources
COS	City of Sonoma Water Department
SCWA	Sonoma County Water Agency
VOM	Valley of the Moon 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. Identification consists of the township number, north or south; the range number, east or west; and the section number. Each section is divided into sixteen 40-acre tracts lettered consecutively (except I and O), beginning with "A" in the northeast corner of the section and progressing in a sinusoidal manner to "R" in the southeast corner. Within the 40-acre tract, wells are sequentially numbered in the order they are inventoried. The 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 Bernardino (S). All wells in the study area are referenced to the Humboldt base line and meridian (H). Well numbers consist of 15 characters and follow the format 005N006W-001N001. In this report, well numbers are abbreviated and written 5N/6W-1N1. Wells in the same township and range are referred to only by their section designation, -1N1. The following diagram shows how the number for well 05N/6W-1N1 is derived.



Well-numbering diagram

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With a section on Basement Rock Configuration Interpreted from Gravity Data By Victoria E. Langenheim

Abstract

The Sonoma Valley, located about 30 miles north of San Francisco, is one of several basins in Sonoma County that use a combination of ground water and water delivered from the Russian River for supply. Over the past 30 years, Sonoma Valley has experienced rapid population growth and land-use changes. In particular, there has been a significant increase in irrigated agriculture, predominantly vineyards. To provide a better understanding of the ground-water/surface-water system in Sonoma Valley, the U.S. Geological Survey compiled and evaluated existing data, collected and analyzed new data, and developed a ground-water flow model to better understand and manage the ground-water system. The new data collected include subsurface lithology, gravity measurements, ground-water levels, streamflow gains and losses, temperature, water chemistry, and stable isotopes.

Sonoma Valley is drained by Sonoma Creek, which discharges into San Pablo Bay. The long-term average annual volume of precipitation in the watershed is estimated to be 269,000 acre-feet. Recharge to the ground-water system is primarily from direct precipitation and Sonoma Creek. Discharge from the ground-water system is predominantly outflow to Sonoma Creek, pumpage, and outflow to marshlands and to San Pablo Bay. Geologic units of most importance for ground-water supply are the Quaternary alluvial deposits, the Glen Ellen Formation, the Huichica Formation, and the Sonoma Volcanics. In this report, the ground-water system is divided into three depth-based geohydrologic units: upper (less than 200 feet below land surface), middle (between 200 and 500 feet), and lower (greater than 500 feet).

Synoptic streamflow measurements were made along Sonoma Creek and indicate those reaches with statistically significant gains or losses. Changes in ground-water levels in wells were analyzed by comparing historical contour maps with the contour map for 2003. In addition, individual hydrographs were evaluated to assess temporal changes by region. In recent years, pumping depressions have developed southeast of Sonoma and southwest of El Verano.

Water-chemistry data for samples collected from 75 wells during 2002–04 indicate that the ground-water quality in the study area generally is acceptable for potable use. The water from some wells, however, contains one or more constituents in excess of the recommended standards for drinking water. The chemical composition of water from creeks, springs, and wells sampled for major ions plot within three groups on a trilinear diagram: mixed-bicarbonate, sodium-mixed anion, and sodium-bicarbonate. An area of saline ground water in the southern part of the Sonoma Valley appears to have shifted since the late 1940s and early 1950s, expanding in one area, but receding in another. Sparse temperature data from wells southwest of the known occurrence of thermal water suggest that thermal water may be present beneath a larger part of the valley than previously thought. Thermal water contains higher concentrations of dissolved minerals than nonthermal waters because mineral solubilities generally increase with temperature.

Oxygen-18 ($\delta^{18}O$) and deuterium (δD) values for water from most wells plot along the global meteoric water line, indicating that recharge primarily is derived from the direct infiltration of precipitation or the infiltration of seepage from creeks. Samples from shallow- and intermediate-depth wells located near Sonoma Creek and (or) in the vicinity of Shellville plot to the right of the global meteoric water line, indicating that these waters are partly evaporated. The $\delta^{18}O$ and δD composition of water from sampled wells indicates that water from wells deeper than 200 feet is isotopically lighter (more negative) than water from wells less than 200 feet deep, possibly indicating that older ground water was recharged under cooler and (or) wetter climatic conditions. Alternatively, isotopically lighter water could represent recharge originating from higher elevations of the Sonoma Creek watershed.

A simulation model of ground-water flow in the Sonoma Valley was developed using MODFLOW-2000. The eight-layer model was parameterized to represent the three geohydrologic units. Model development required estimating model fluxes (pumpage and recharge) and hydraulic parameters (hydraulic conductivity and storage) for the area. The hydraulic barrier created by the Eastside Fault was incorporated into the model. In general, the calibrated model simulated water-level declines that matched measured values. The cumulative volume of water pumped from the ground-water basin between 1975 and 2000 was about 1.97×10^5 acre-ft; of this total pumpage, the model simulated that about 9 percent (1.73×10^4 acre-ft) was removed from storage. This fairly small decrease in storage explains the localized nature of the water-level declines. A sensitivity analysis indicated that the model would most benefit from additional data collection in the northern part of the basin.

Introduction

Sonoma County is in the northern part of the greater San Francisco Bay region, an area of Northern California that has experienced rapid population growth and accelerated urbanization in response to economic expansion over the past few decades. The large increase in population and concomitant changes in land use within Sonoma County require reassessment of the water resources and how best to manage them for optimal utilization over the next few decades. Most basins in the county currently rely on a combination of Russian River water and native ground water to meet demand. Recycled water is used on a limited basis. In addition, water conservation programs have been implemented and are being expanded.

The Sonoma Valley is a well-defined hydrologic basin in southeastern Sonoma County. The basin has some areas of declining ground-water levels, potential water-quality problems from seawater intrusion and upwelling of geothermal waters, and ground-water/surface-water interaction.

Location of the Study Area

The study area is located approximately 30 miles (mi) northeast of San Francisco and includes the entire Sonoma Creek watershed in southeastern Sonoma County, California (*fig. 1*). The study focused on the area of the valley floor and the adjacent hills where most of the urban development and irrigated agriculture have been occurring. The watershed includes approximately 166 square miles (mi^2) of land that drains by way of Sonoma Creek and its tributaries to San Pablo Bay (*fig. 2*), which is the northern arm of the San Francisco Bay. The Sonoma Mountains form the southwestern side of the watershed and the Mayacmas Mountains form the northeastern side. Between these two mountain ranges lies the northwest trending elongate depression of Sonoma Valley, which extends roughly 20 mi from the shore of San Pablo Bay to near Kenwood (*fig. 2*).

Purpose and Scope

The U.S. Geological Survey (USGS), in cooperation with the Sonoma County Water Agency (SCWA), undertook this study to evaluate the ground-water resources of Sonoma Valley and to develop a tool to better understand and manage the ground-water system. The goals of the study were to update the geohydrologic characterization of the study area; to provide a current assessment of hydrologic conditions, including a description of historical ground-water level and water-quality changes; and to provide water-supply agencies with a ground-water flow model that can be used as a planning tool for water-resources assessment and management.

To meet the objectives of this study, four principal tasks were identified: (1) evaluation of existing geohydrologic, geophysical, and geochemical data; (2) collection and analysis of new geohydrologic data, including subsurface lithologic data, gravity measurements, ground-water levels, and streamflow gains and losses; (3) collection and analysis of new water chemistry, temperature, and isotopic data; and (4) development a ground-water flow model.

This report provides a geologic and hydrologic description of the area, presents selected hydrologic data collected from the 1970s to 2004, quantifies historical changes in the ground-water system, documents a ground-water flow simulation model, and presents an interpretation of surface geophysical data that help define the geometry of the ground-water reservoir.

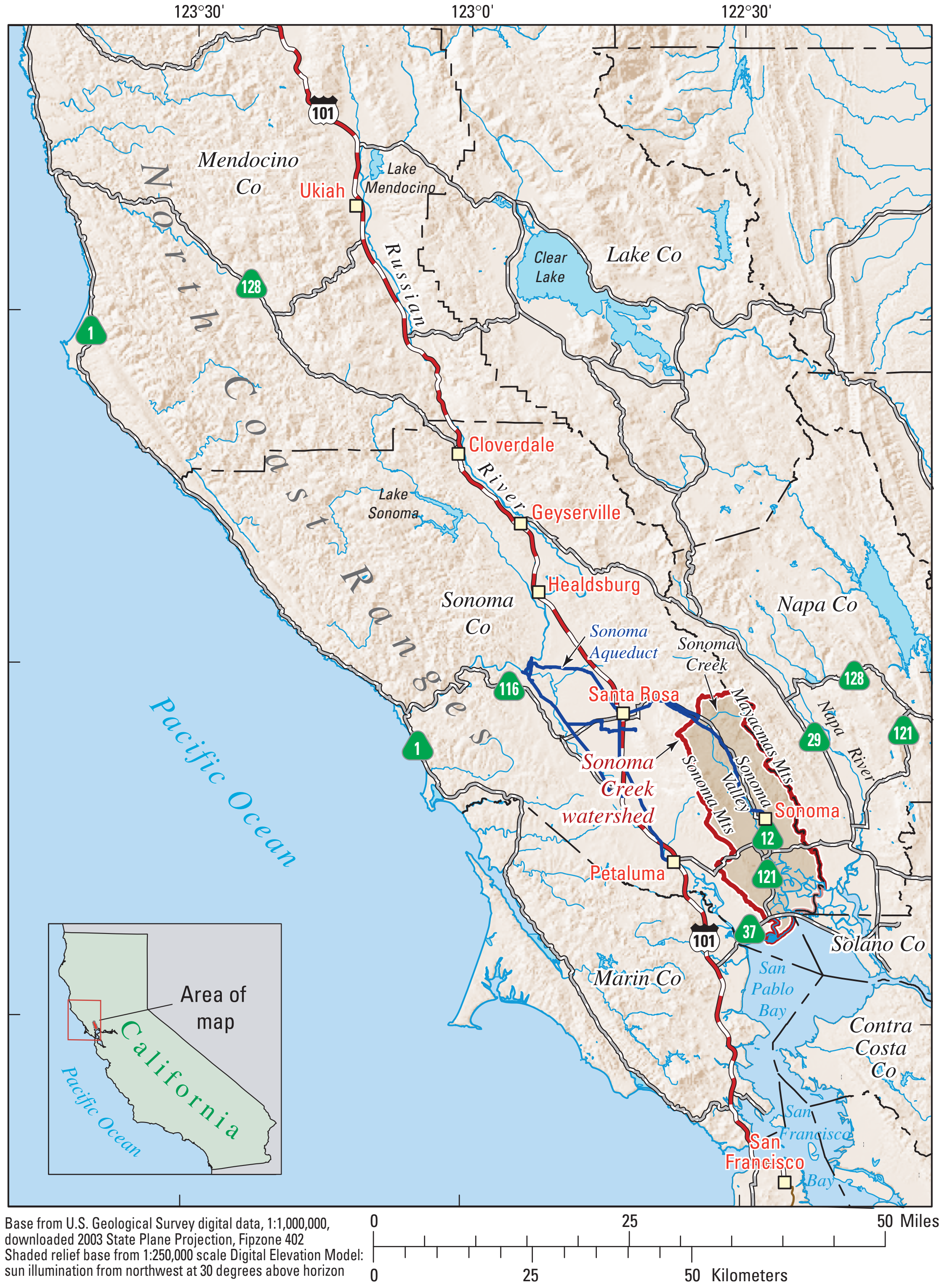


Figure 1. Location of Sonoma Valley, Sonoma County, California.

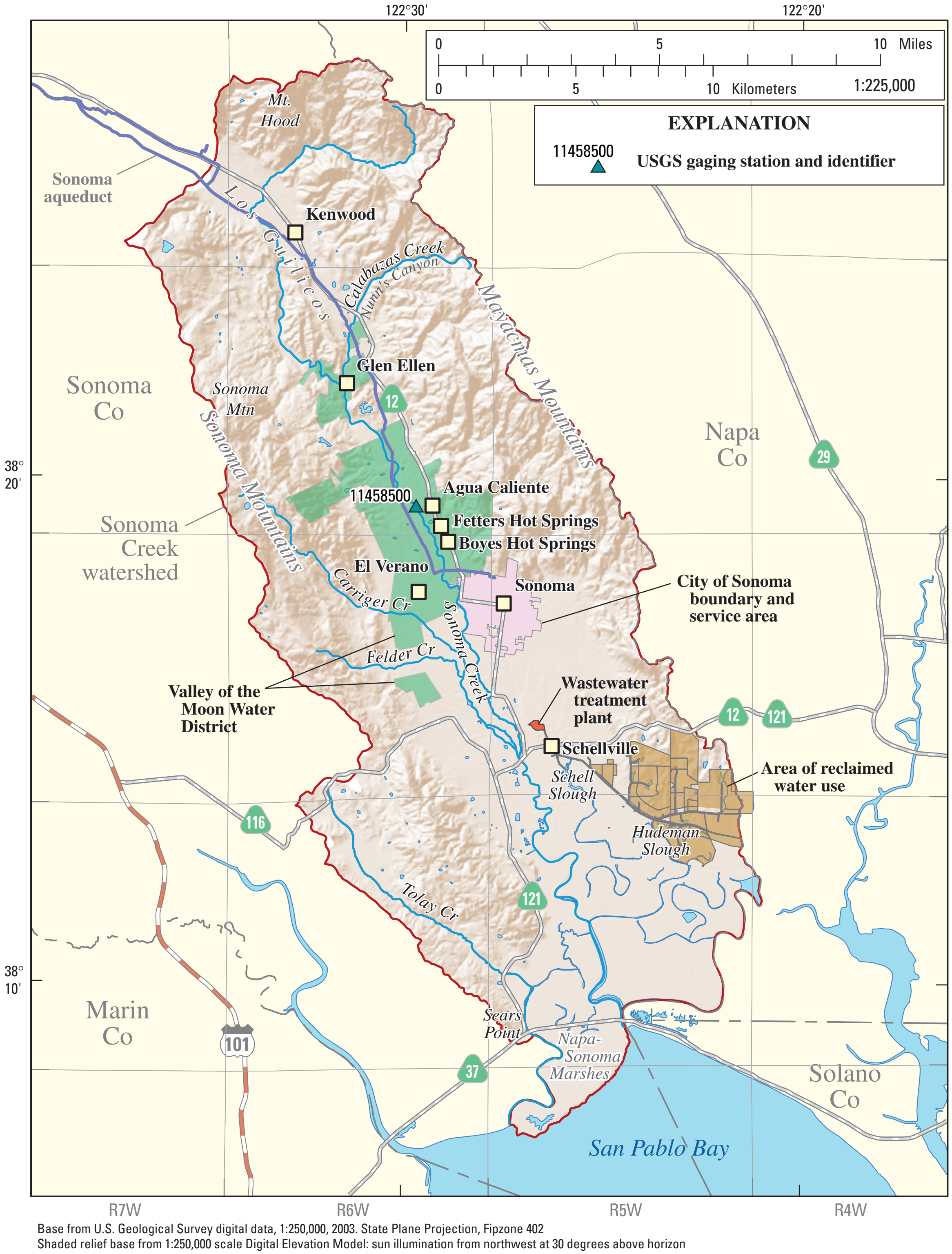


Figure 2. Location of Sonoma Creek watershed, and topographic and hydrologic features, cities and towns, and other cultural development in the study area, Sonoma Valley, Sonoma County, California.

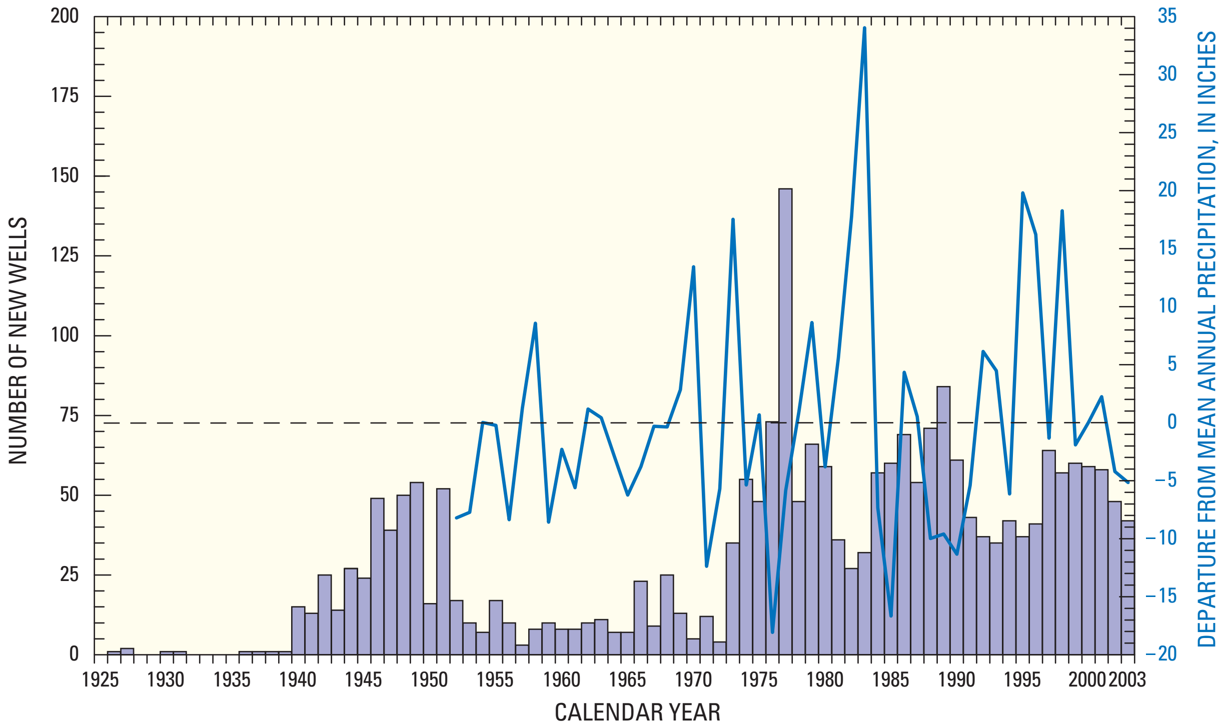


Figure 3. Well development versus departure from mean annual precipitation, Sonoma Valley, Sonoma County, California.

New hydrologic data presented in this report were collected between April 2003 and November 2004. These data include ground-water levels; surface-water discharge measurements; water chemistry, including isotopic composition, temperature logs of wells; and geophysical measurements.

Land and Water Use

In the early part of the twentieth century, surface water and springs provided almost all of the water used in the valley (Renick, 1924). Early historical records describe Sonoma Valley as having abundant water in perennial streams, vernal pools, and wetlands (Dawson and others, 2002). Ground water discharged from the many springs throughout the lower parts of the mountains and around the valley margin. After the 1920s, wells became more common; the number and the depth of wells generally have increased over time (*figs. 3* and *4*, respectively).

One of the earliest and most significant changes in land use was the draining of the salt marshes adjacent to San Pablo Bay. This was accomplished by adding artificial fill and increasing drainage by dredging the natural sloughs that meander through the low lands along the bay. During the period 1880–1930, an estimated 10,000 acres of marshland were drained and converted to farmland (Dawson and others, 2002). During the early 1900s, unregulated gravel mining was common in Sonoma Creek and on some of the tributaries.

Today the study area comprises large tracks of native vegetation, as well as lands used for agriculture (*fig. 5, A–D*; *table 1*) (California Department of Water Resources, 1974, 1979, 1986, and 1999, unpublished crop surveys of Sonoma County, Division of Planning and Local Assistance, Sacramento). Lands designated for urban, residential, commercial, and industrial purposes constitute a small percent of the study area. Development is located primarily in the valley. Throughout the study period, the primary crop has been vineyards (*table G-1*) (California Department of Water Resources, 1974, 1979, 1986, and 1999, unpublished crop surveys of Sonoma County, Division of Planning and Local Assistance, Sacramento). The major urban and residential areas include the cities of Sonoma, Kenwood, and Glen Ellen, several unincorporated communities, and areas of rural and semi-rural residential development. According to the 2000 population census, 42,355 people live in the study area (Association of Bay Area Governments, 2002).

Land-use surveys for 1974 through 1999 show that native vegetation and agriculture constitute about 59 and 17 to 25 percent percent of the study area, respectively. Development and mixed uses made up the remainder (*fig. 5A–D*; *table 1*) (California Department of Water Resources, 1974, 1979, 1986, and 1999, unpublished crop surveys of Sonoma County, Division of Planning and Local Assistance, Sacramento). For the period 1974–86, urban and residential uses constituted about 4 percent of the study area. After 1986, urban and residential uses increased to about 7 percent of the study area. From 1974 to 1999, about 10 to 15 percent of the study area was converted from native vegetation to agriculture or mixed land uses. In the study area, lands used for agriculture increased from 17 percent in 1974 (of which 3 percent was irrigated) to about 23 percent in 1999 (of which 13 percent was irrigated). Between 1986 and 1999, mixed use lands were converted to agriculture. In 1999, mixed use lands amounted to only about 3 percent of the study area. Native vegetation increased from 59 percent in 1986 to 65 percent in 1999, mostly owing to abandonment of agriculture fields in the salt marsh.

Residential water supply in the study area comes from private domestic wells, imported water, and public-supply wells. Since 1963, water has been imported by aqueduct from the Russian River (Beach, 2002). Currently about 5,400 acre-feet per year (acre-ft/yr) of imported water is delivered for domestic use to purveyor areas by the city of Sonoma Water Department (COS) and by the Valley of the Moon Water District (VOM; *fig. 2*). Both the COS and the VOM supplement Russian River deliveries with water from public-supply wells drilled within their purveyor areas. In 2000, VOM supplied water to about 21,000 people (*fig. 2*) (Association of Bay Area Governments, 2002). A small number of households within the VOM purveyor area rely on private domestic wells. The COS supplies water to about 4,300 people within the city of Sonoma (*fig. 2*) (Association of Bay Area Governments, 2002). The remaining residents living outside the purveyor areas rely on private domestic wells.

The largest use of water in the study area is for irrigation of agriculture, followed by domestic water use. Most of the water demand for irrigation is met from ground water. A detailed discussion of the estimation of pumpage within the part of the study included in the ground-water simulation model is provided in the section "Ground-Water Flow Model" and its associated appendix.

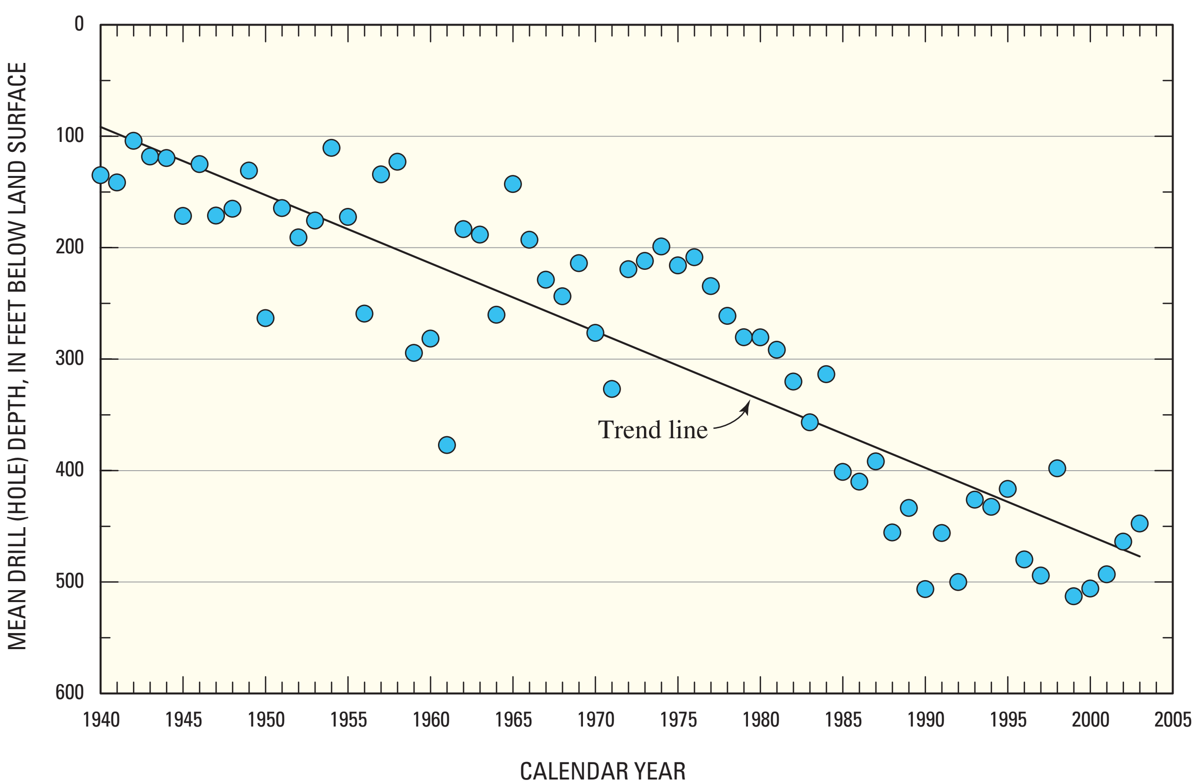


Figure 4. Mean annual drill (hole) depths for wells in the Sonoma Valley area, 1940–2003, Sonoma Valley, Sonoma County, California.

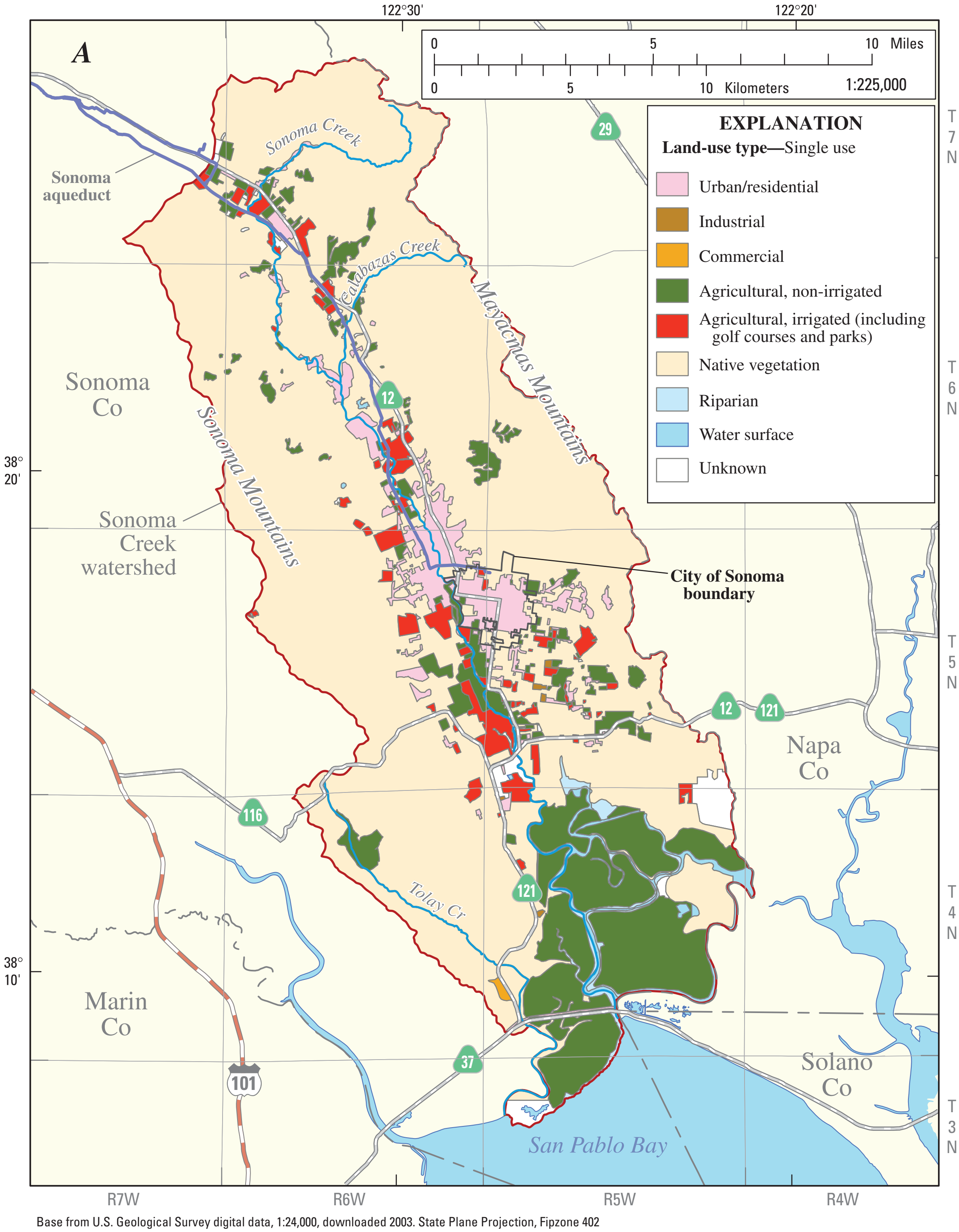


Figure 5. Land use in the Sonoma Valley study area, Sonoma County, California. *A*. 1974. *B*. 1979. *C*. 1986. and *D*. 1999. (Modified from California Department of Water Resources unpublished crop surveys of Sonoma County, Division of Planning and Local Assistance, Sacramento.)

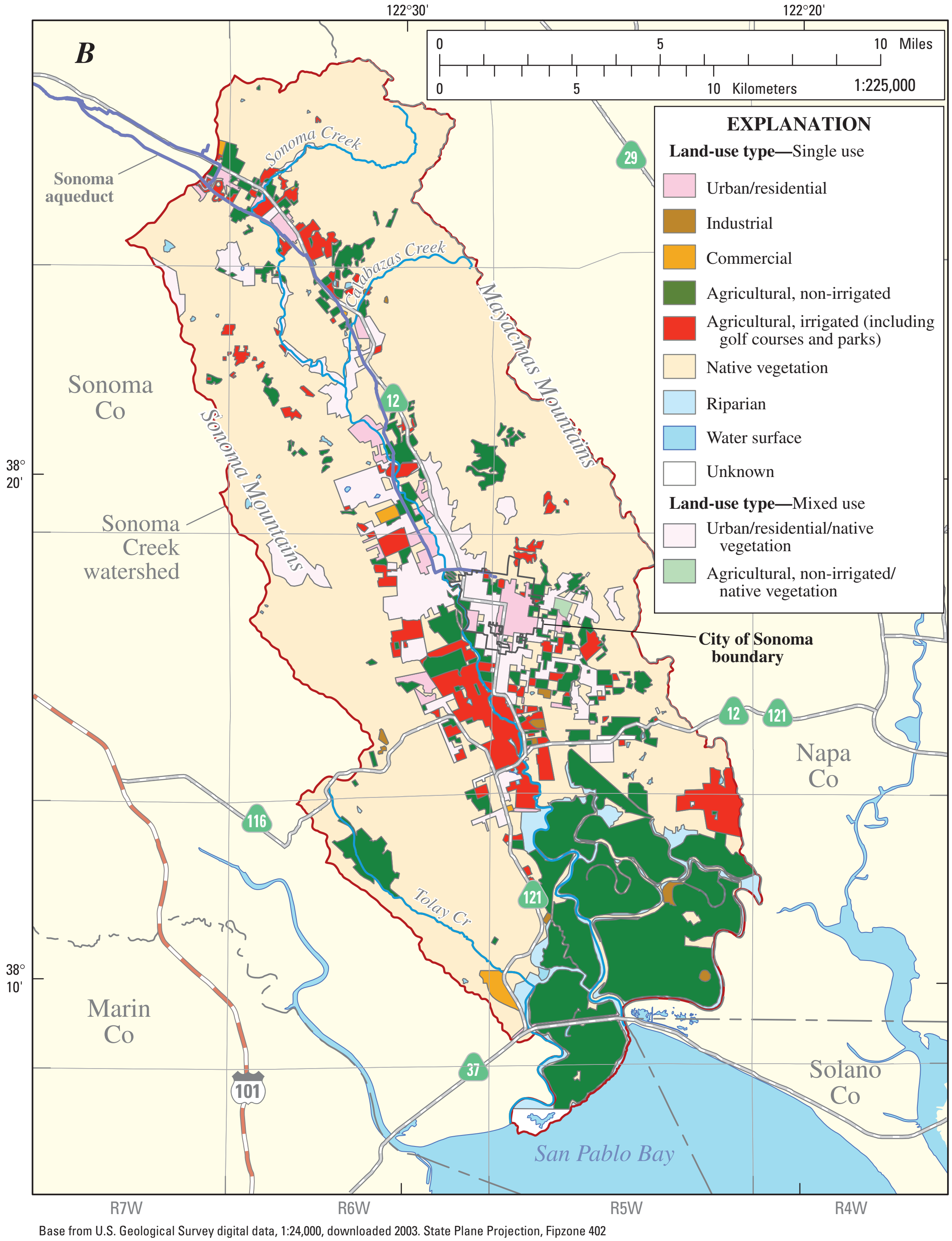
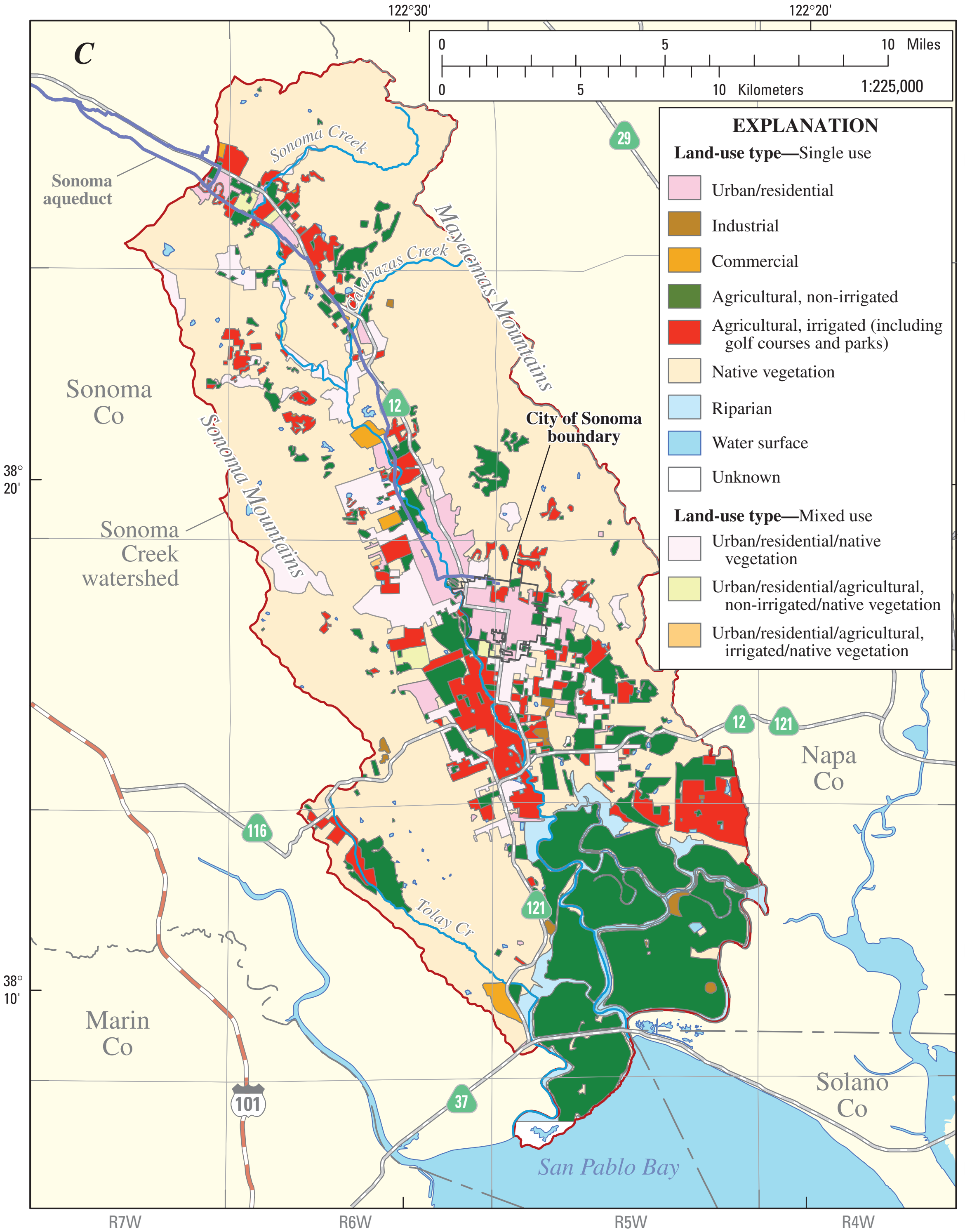


Figure 5.—Continued.



Base from U.S. Geological Survey digital data, 1:24,000, downloaded 2003. State Plane Projection, Fipzone 402

Figure 5.—Continued.

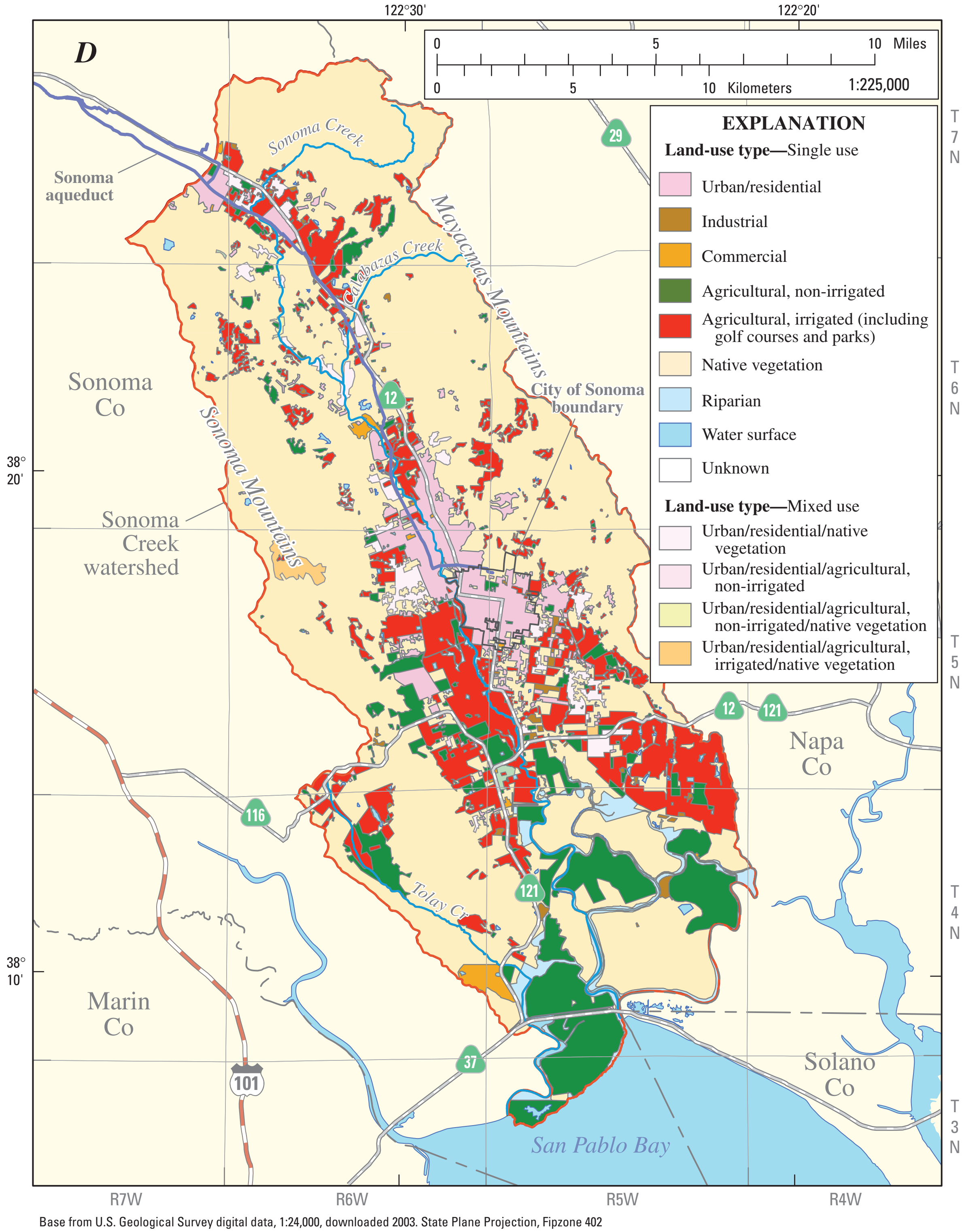


Figure 5.—Continued.

Table 1. Land use in Sonoma Valley, California, 1974, 1979, 1986, and 1999.

[Bracketed, italized numbers are a subset of total agriculture and are not included in total area and total percent; mi^2, square miles]

	Land-use surveys[1]							
	1974		1979		1986		1999	
Land use type	**Acres**	**mi^2**	**Acres**	**mi^2**	**Acres**	**mi^2**	**Acres**	**mi^2**
Single use								
Urban and residential	4,944	8	2,199	3	3,896	6	6,026	9
Commerical and industrial	120	0	674	1	927	1	1,148	2
Total agriculture (irrigated and non-irrigated)	18,118	28	23,193	36	26,402	41	24,148	38
[Irrigated agriculture only (including golf courses and parks)]	*[3,201]*	*[5]*	*[5,342]*	*[8]*	*[7,671]*	*[12]*	*[14,270]*	*[22]*
Native vegetation	79,905	125	69,633	109	64,369	100	68,923	107
Riparian	749	1	2,205	3	2,415	4	2,540	4
Water surface	1,378	2	290	0	877	1	885	1
Unknown designation	1,461	2	457	1	364	1	11	0
Mixed use								
Urban/residential/native vegetation	0	0	7,950	12	6,934	11	2,326	4
Urban/residential/irrigated agriculture/native vegetation	0	0	0	0	42	0	470	1
Urban/residential/non-irrigated agriculture/native vetetation	0	0	0	0	461	1	147	0
Urban/residential/non-irrigated agriculture	0	0	0	0	0	0	33	0
Non-irrigated agriculture/native vegetation	0	0	76	0	0	0	30	0
Total area	106,675	166	106,676	166	106,687	166	106,687	166
Percent of land use type in study area								
Urban, residential, commerical and industrial		5		3		4		7
Total agriculture (irrigated and non-irrigated)		17		22		25		23
[Irrigated agriculture only]		*[3]*		*[5]*		*[7]*		*[13]*
Native vegetation		75		64		59		64
Riparian and water surface		2		4		5		3
Unknown designation		1		0		0		0
Mixed use		0		7		7		3
Total percent		100		100		100		100

[1]Modified from California Department of Water Resources, 1974, 1979, 1986, and 1999, unpublished crop surveys of Sonoma County, Division of Planning and Local Assistance, Sacramento.

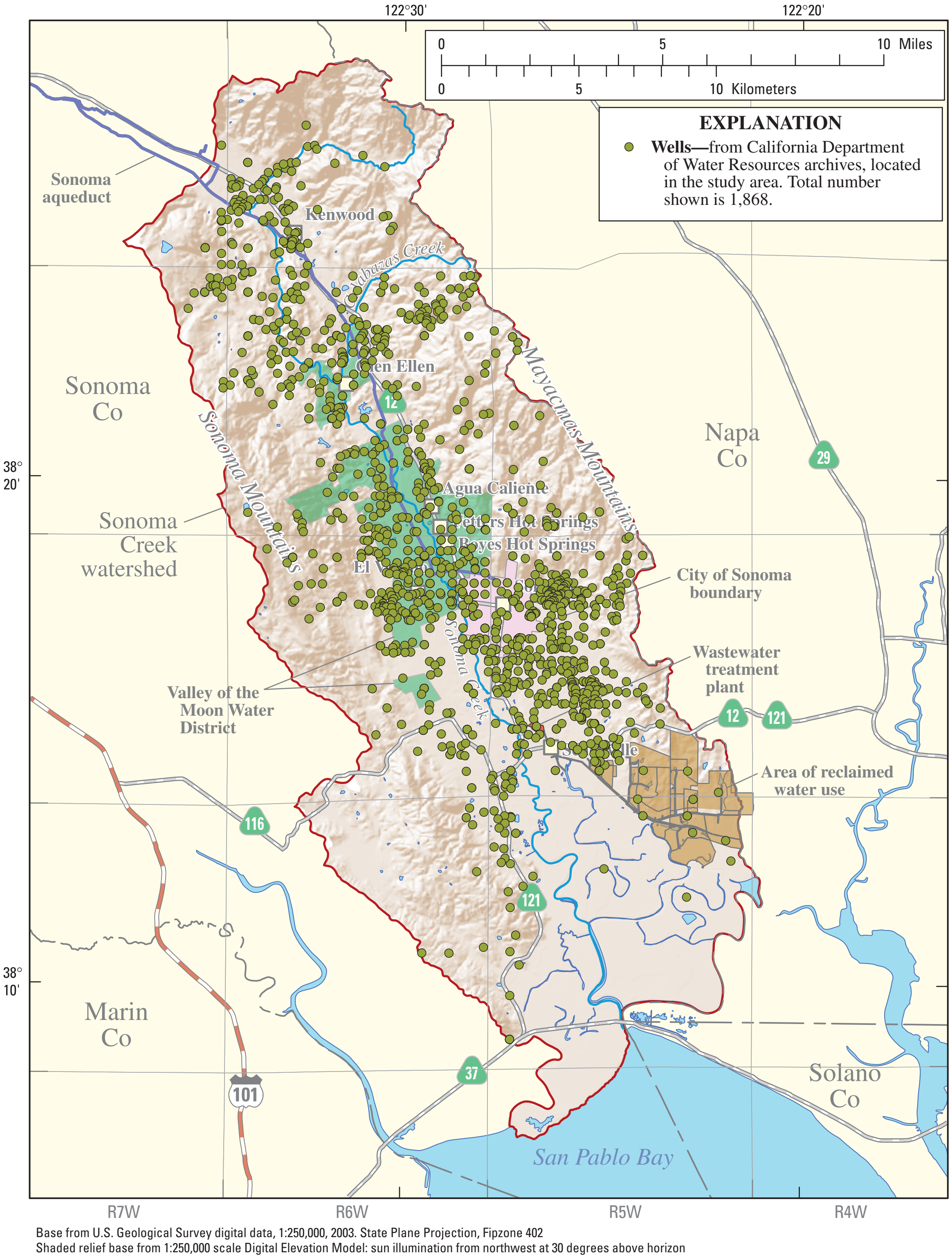


Figure 6. Locations of wells identified in drillers' reports for the Sonoma Valley, Sonoma County, California.

For this study, the number of wells drilled per year was estimated from information included in about 2,200 drillers' reports obtained from the California Department of Water Resources (CADWR) (the 1,868 wells for which a location or estimated location could be obtained are shown on *fig. 6*). The number of wells in this database shows a roughly inverse correlation with the amount of precipitation received in the study area from year to year (*fig. 3*).

Since 1992, the Sonoma County Water Agency has implemented and managed a program to deliver reclaimed water from the wastewater treatment plant in the south of the valley for wetlands management at San Pablo Bay and to irrigate agricultural fields in the southeast adjacent to the wetlands (*fig. 2*). Effluent is delivered for irrigation and wetlands management from May 1 to October 31. On November 1, any stored effluent is released by way of Shell Slough (*fig. 2*). Between November 1 and April 31, effluent amounting to about 300 to 350 acre-ft is released to the wetlands by way of Schell and Hudeman Sloughs. A small amount of effluent, about 92 acre-ft/yr, is released to management units and upland ponds near the wastewater treatment plant (*fig. 2*) (Jim Zambenini, Sonoma Valley County Sanitation District, unpub. data, 2005). From 1996 to 2000, reclaimed water deliveries for irrigation were estimated to replace about 860 acre-ft of annual ground-water pumpage.

Climate

The climate of the study area is Mediterranean, with moderate temperatures and distinct wet and dry seasons. Mean annual air temperature at the city of Sonoma is about 59.9°F (15.5°C), freezing temperatures on the valley floor are rare but do occur on the higher slopes of the bordering mountains. About 90 percent of the annual precipitation occurs as rain during the months of November through April. Mean annual precipitation at Sonoma averaged about 29.8 inches (75.7 cm) from water year 1953 through 2002 (*table 2*) (National Oceanic and Atmospheric Administration, 2003). *Figure 7* shows, annual precipitation can deviate significantly from the 50-year average.

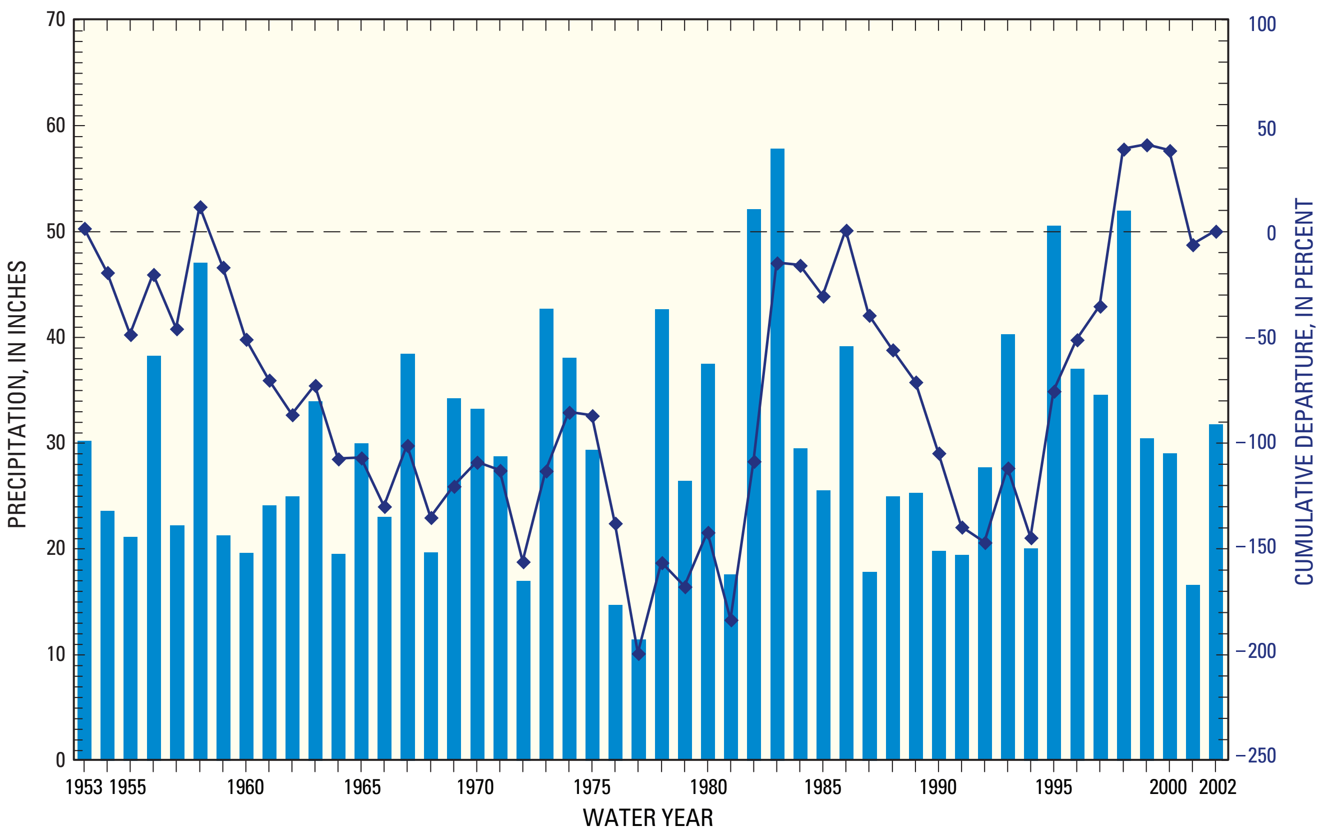


Figure 7. Annual precipitation and cumulative departure of precipitation for water years 1953–2002, at city of Sonoma, Sonoma County, California.

Table 2. Monthly precipitation at Sonoma, Sonoma County, California,1952–2002.

[Station: CIMIS Station SONOMA.C (NCDC #8351, Sonoma); location: approximately 0.5 mile northwest of Sonoma Post Office; latitude: 38º 17’ 55” N, longitude: 122º 27’ 43” W (NGVD 29), elevation: 97 ft; location information and data from California Irrigation Management Information System web site, except for latitude and longitude, which are from California Department of Water Resources Bulletin 230-81; precipitation in inches; ND, no data; INC, incomplete data]

Water year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Total
1951–52					1.34	4.79	0.85	0.04	0.97	0.00	0.00	0.07	INC
1952–53	0.05	2.63	11.80	6.33	0.08	3.11	4.15	1.04	0.89	0.00	0.10	0.00	30.18
1953–54	0.56	4.20	1.22	5.70	3.03	4.93	2.35	0.10	0.65	0.15	0.72	0.00	23.61
1954–55	0.39	4.75	6.66	3.55	1.35	0.59	3.29	0.00	0.00	0.00	0.00	0.57	21.15
1955–56	0.15	2.81	16.87	10.33	5.31	0.42	1.72	0.55	0.04	0.00	0.00	0.07	38.27
1956–57	2.14	0.08	0.39	4.09	6.35	3.04	1.51	2.61	0.05	0.00	0.00	1.95	22.21
1957–58	5.84	1.21	4.02	7.75	12.87	6.65	6.87	0.70	1.14	0.00	0.00	0.00	47.05
1958–59	0.10	0.38	1.53	6.50	8.50	1.06	0.41	0.12	0.00	0.00	0.00	2.70	21.30
1959–60	0.00	0.00	1.54	4.77	6.46	4.02	1.41	1.43	0.00	0.00	0.00	0.00	19.63
1960–61	0.05	5.36	3.61	5.22	2.42	4.39	1.62	0.84	0.04	0.00	0.14	0.40	24.09
1961–62	0.43	3.64	4.68	2.40	8.61	4.26	0.47	0.00	0.00	0.00	0.00	0.46	24.95
1962–63	9.12	0.69	4.57	5.77	2.94	4.86	5.28	0.71	0.00	0.00	0.00	0.03	33.97
1963–64	2.30	6.99	0.96	5.62	0.20	2.18	0.21	0.25	0.75	0.04	0.03	0.00	19.53
1964–65	2.36	5.88	8.96	5.33	1.23	2.08	3.44	0.00	0.00	0.00	0.66	0.00	29.94
1965–66	0.20	6.74	3.49	7.50	3.31	0.54	0.63	0.15	0.23	0.05	0.07	0.10	23.01
1966–67	0.00	7.50	5.54	12.64	0.34	4.23	5.69	0.20	2.28	0.00	0.00	0.02	38.44
1967–68	0.53	1.21	1.97	7.34	3.69	3.92	0.27	0.47	0.00	0.00	0.27	0.00	19.67
1968–69	1.98	3.15	7.95	8.01	9.09	1.66	2.27	0.00	0.10	0.00	0.00	0.00	34.21
1969–70	1.80	1.08	8.23	16.31	2.93	2.16	0.24	0.00	0.48	0.00	0.00	0.00	33.23
1970–71	1.54	10.71	8.47	2.43	0.44	3.99	0.74	0.28	0.00	0.00	0.00	0.12	28.72
1971–72	0.23	2.64	6.17	3.16	2.06	0.26	1.27	0.10	0.22	0.00	0.00	0.85	16.96
1972–73	4.58	6.92	4.29	13.79	8.60	3.76	0.03	0.05	0.00	0.00	0.00	0.63	42.65
1973–74	1.73	12.95	5.40	5.34	2.41	6.04	3.05	0.00	0.00	1.11	0.01	0.00	38.04
1974–75	1.39	0.56	4.14	3.12	10.93	7.34	1.56	0.05	0.05	0.18	0.05	0.00	29.37
1975–76	4.73	1.19	0.89	0.36	2.78	1.23	1.83	0.02	0.03	0.00	0.98	0.67	14.71
1976–77	0.50	1.92	1.02	1.74	1.43	2.42	0.22	1.47	0.01	0.00	0.00	0.71	11.44
1977–78	0.62	8.04	6.91	11.02	6.01	6.19	3.39	0.06	0.00	0.00	0.00	0.40	42.64
1978–79	0.00	2.51	0.77	12.12	6.81	2.12	1.55	0.56	0.00	0.00	0.00	0.00	26.44

Table 2. Monthly precipitation at Sonoma, Sonoma County, California,1952–2002—Continued.

[Station: CIMIS Station SONOMA.C (NCDC #8351, Sonoma); location: approximately 0.5 mile northwest of Sonoma Post Office; latitude: 38º 17' 55" N, longitude: 122º 27' 43" W (NGVD 29), elevation: 97 ft; location information and data from California Irrigation Management Information System web site, except for latitude and longitude, which are from California Department of Water Resources Bulletin 230-81; precipitation in inches; ND, no data; INC, incomplete data]

Water year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Total
1979–80	3.45	5.04	6.39	7.99	10.62	1.55	1.89	0.25	0.14	0.18	0.00	0.00	37.50
1980–81	0.26	0.33	2.39	5.90	2.15	5.82	0.30	0.21	0.00	0.00	0.00	0.20	17.56
1981–82	2.51	7.49	10.40	11.97	6.10	8.72	3.69	0.00	0.05	0.00	0.00	1.20	52.13
1982–83	3.15	8.78	3.53	9.28	13.61	13.77	3.82	0.40	0.00	0.00	0.83	0.66	57.83
1983–84	0.73	9.07	11.28	0.49	2.48	2.05	1.92	ND	0.45	0.01	0.35	0.00	INC
1984–85	2.48	10.04	1.80	1.42	3.04	ND	ND	ND	ND	ND	ND	ND	INC
1985–86	1.36	3.62	2.78	6.47	14.80	7.62	0.42	0.30	0.00	0.00	0.00	1.28	INC
1986–87	0.31	0.21	2.35	5.52	5.22	3.90	0.12	0.21	0.00	0.00	0.00	0.00	17.84
1987–88	1.59	5.08	8.29	6.54	0.54	0.12	1.67	0.88	0.24	0.00	0.00	0.00	24.95
1988–89	0.19	5.36	3.88	1.50	1.61	10.08	0.79	0.06	0.06	0.00	0.00	1.77	25.30
1989–90	2.23	1.71	0.01	6.92	3.40	1.43	0.35	3.68	0.00	0.00	0.02	0.05	19.80
1990–91	0.45	0.51	1.26	0.69	4.19	10.51	0.74	0.16	0.53	0.03	0.36	0.00	19.43
1991–92	3.02	1.23	2.54	2.21	9.82	7.01	0.90	0.00	0.92	0.00	0.00	0.03	27.68
1992–93	4.47	0.40	9.79	10.79	7.71	2.67	1.52	2.05	0.88	0.00	0.00	0.00	40.28
1993–94	1.82	3.32	3.13	3.35	5.46	0.23	1.32	1.37	0.05	0.00	0.00	0.00	20.05
1994–95	0.59	7.00	3.91	20.64	0.82	13.29	1.33	1.89	1.04	0.00	0.00	0.00	50.51
1995–96	0.00	0.25	9.95	8.95	8.27	2.61	3.49	3.37	0.00	0.00	0.00	0.17	37.06
1996–97	2.17	3.49	13.11	11.45	0.65	1.02	0.78	0.39	0.27	0.00	1.02	0.21	34.56
1997–98	1.25	7.48	3.55	12.05	18.89	2.31	2.35	3.90	0.16	0.00	0.00	0.05	51.99
1998–99	0.85	5.67	1.44	4.21	11.33	4.13	2.62	0.05	0.03	0.00	0.00	0.12	30.45
1999–2000	0.94	3.19	0.88	5.71	10.80	2.73	2.58	1.72	0.29	0.00	0.02	0.14	29.00
2000–01	2.64	1.21	1.59	3.37	4.74	1.73	0.89	0.00	0.05	0.00	0.00	0.35	16.57
2001–02	0.75	8.76	11.00	4.37	2.53	2.66	0.48	1.23	0.00	0.00	0.00	0.00	31.78
2002–03	0.00	3.95	9.98	2.99	2.29								INC
Average	1.58	4.10	5.04	6.53	5.24	3.96	1.81	0.69	0.26	0.04	0.11	0.32	29.74
Minimum													11.44
Maximum													57.83
Years													47

The distribution of mean annual precipitation for the period 1906–56 in the study area is shown in *figure 8* (Rantz, 1971). According to Rantz, the average annual precipitation for 1906–56 was about 28 inches. Precipitation generally increases with increasing altitude from a low of 18 inches in the southwest to a high of 40 inches in the Mayacamas Mountains in the northeast of the study area.

Previous Investigations and Databases

Part of the current study area was included in a comprehensive hydrogeologic investigation of Napa and Sonoma Counties conducted in the 1950s by the U.S. Geological Survey (Kunkel and Upson, 1960). Their data and interpretation provided the foundation for later hydrologic studies. In the early 1980s, CADWR carried out a more detailed study focused solely on Sonoma Valley (California Department of Water Resources, 1982). The study estimated transmissivities and storage capacities for the area of the valley underlain by alluvial units and described the quality of water. Luhdorff and Scalmanini (1999) synthesized previous investigations to describe ground-water development in the Valley of the Moon Water District service area (*fig. 2*)

The Sonoma Ecology Center under contract with SCWA has developed a geographic information system (GIS) for Sonoma Valley. The USGS has added to the GIS. The current working database includes geology; soils; surface hydrology; digital elevation information describing slope and aspect and altitudes; climate data; water-well location and construction data; surface-water gaging station information; public water-supply service areas; septic, wastewater treatment, and reclaimed water delivery systems; landfills; historical land use; roads; pipelines; census population map; public land survey system delineations; and land ownership parcel information. The GIS was used to manage spatial data to compute supporting data for the ground-water model and to characterize the study and model area in terms of land-use water-demand categories, ground- and surface-water quality, ground-water levels, topography, altitudes, geology, and the distribution of precipitation and runoff.

Acknowledgments

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Physiography and Geologic Setting

The Sonoma Creek watershed is located in the North Coast Ranges geomorphic province of California. This province is characterized by a predominantly northwest trending physiography (Page, 1966). The mountain ranges are underlain by thick, highly deformed Mesozoic sedimentary strata that in places are covered by younger volcanic and sedimentary rocks. The mountains commonly exhibit a knobby, irregular topography that was produced by landslides of large and small scales. The core of the North Coast Ranges consists of three major pre-Tertiary rock groups: the Franciscan Complex, the Coast Range ophiolite, and the Great Valley Sequence (Blake and others, 2000). Within the Sonoma Creek watershed, exposed basement rocks are predominantly Franciscan Complex but include a few minor outcrops of ophiolite. The Great Valley Sequence is not exposed within the study area, but may underlie younger formations beneath parts of Sonoma Valley (Wagner and others, 2004). All three pre-Tertiary rock groups, which overlap in age, were tectonically transported from a marine basin in the Pacific Ocean and accreted to the continental margin of California during Cretaceous to early Tertiary time (Blake and others, 2000). During and after accretion the rocks have been folded and faulted into mountain ranges and intervening valleys. Most of the valleys and ridges have formed in response to regional tectonic stresses which produced northwest-trending, right-lateral, strike-slip faults; west-dipping, high-angle, reverse faults; and normal faults (McLaughlin and others, 2005). These faults are related regionally to the San Andreas Fault system that occupies a 50-mi wide strip of coastal California north of the San Francisco Bay.

Within the Sonoma Creek watershed (*fig. 2*), the Sonoma Mountains are of moderate relief sloping gently from a few hundred feet in the southern part to greater than 2,000 ft southwest of Glen Ellen and reaching a maximum altitude of about 2,295 ft on Sonoma Mountain. The Mayacmas Mountains are mostly less than 1,500 ft in altitude. Altitudes increase from south to north and attain a maximum of 2,730 ft at Mt. Hood in the northeastern part of the study area.

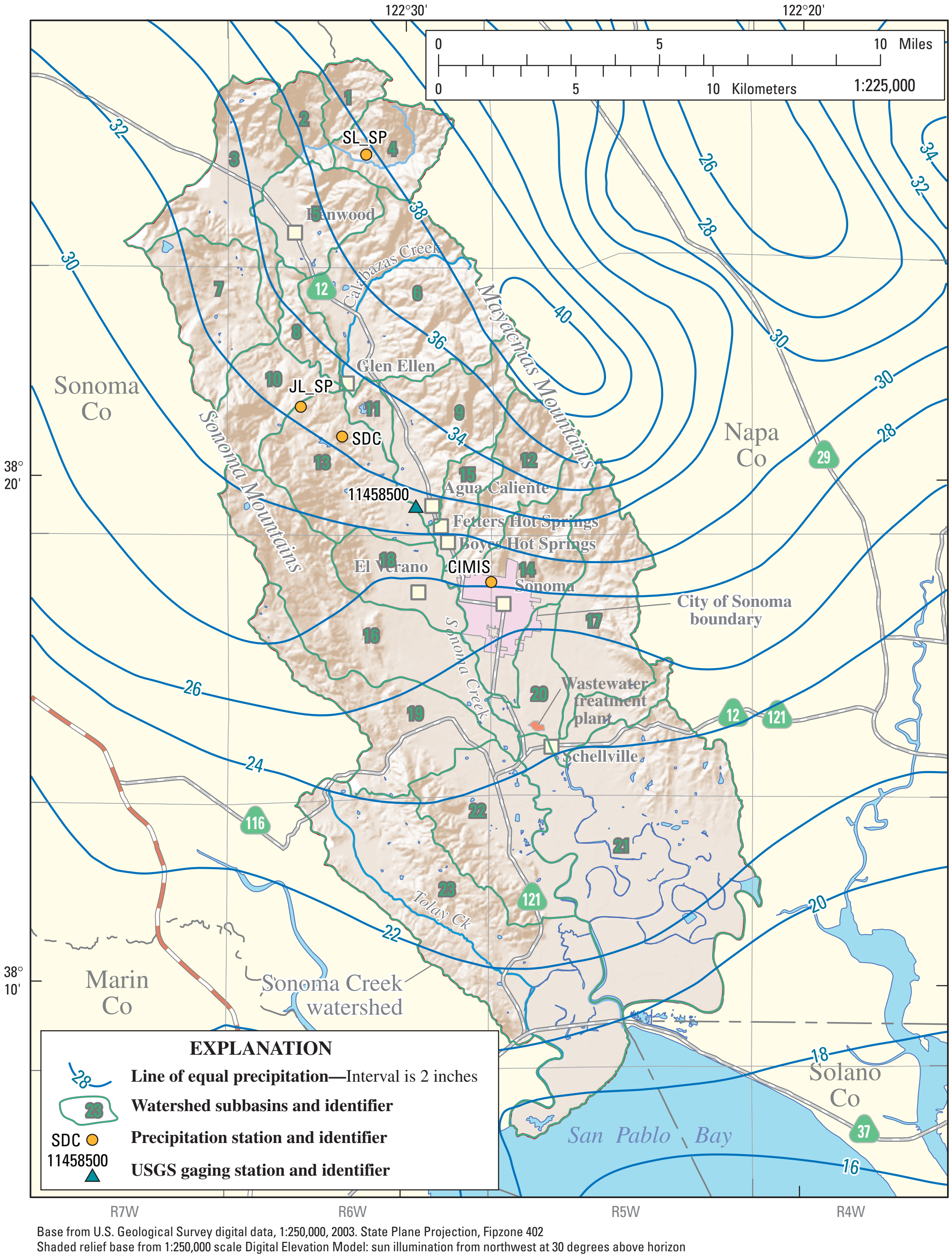


Figure 8. Mean annual precipitation in the Sonoma Creek watershed, Sonoma County, California, 1906–56. (Modified from Rantz, 1971)

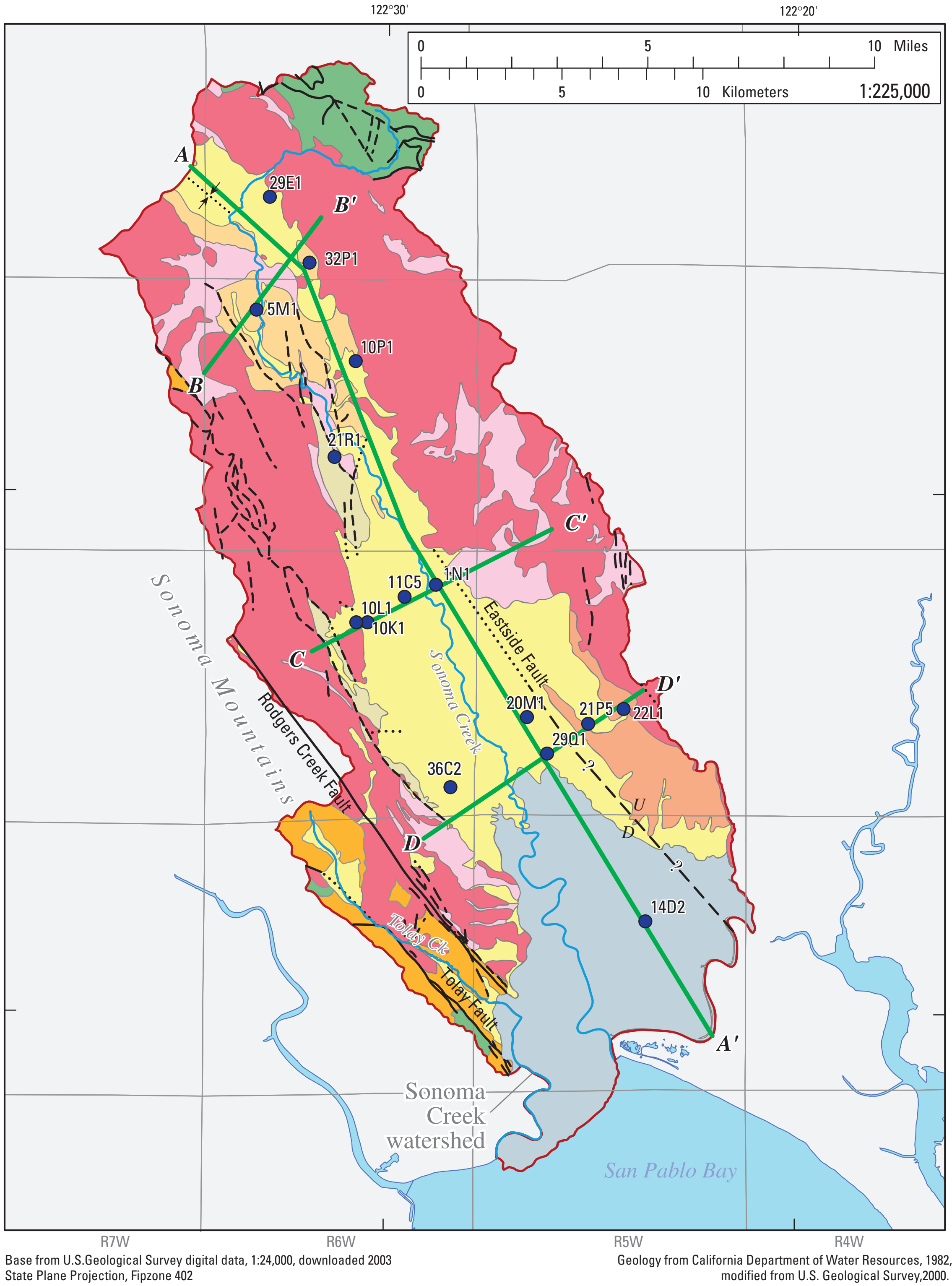


Figure 9. Geology of the Sonoma Creek watershed, Sonoma County, California.

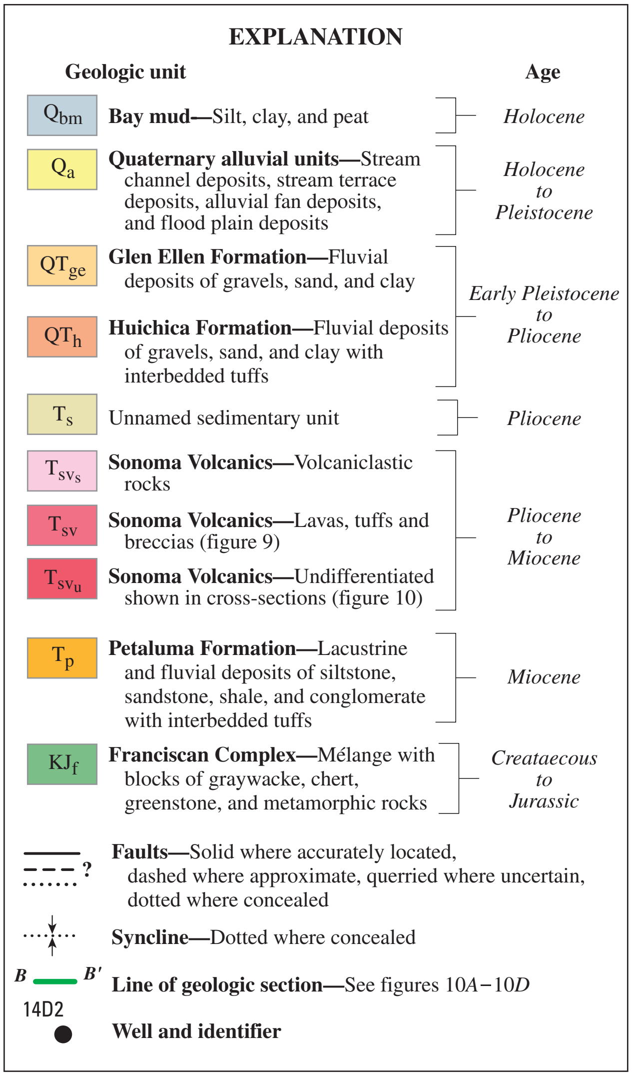


Figure 9.—Continued.

The valley between the two ranges is not uniform in width or slope. The valley can be subdivided into three parts on the basis of topography. The uppermost part of the valley, which includes Kenwood, extends about 3.5 mi southeastward from the northwestern drainage divide to near Nunns Canyon and is sometimes referred to as Los Guilicos. Here the valley floor is relatively flat at an altitude of about 400 ft and is about 1 mi wide. The middle part of the valley is much narrower than the upper part and has a hilly topography. This part of the valley is sometimes referred to as the Valley of the Moon; it extends southward to near Boyes Hot Springs and includes the Glen Ellen area. In this part of the valley, altitudes drop from about 400 ft to about 100 ft over an approximately 5-mi distance. The remainder of the valley southward to San Pablo Bay is Sonoma Valley. This part of the valley has a flat topography and ranges as much as 5 mi in width. The altitude of the valley floor changes from about 100 ft to sea level over a distance of about 12 mi. In this report, the entire valley from Kenwood to San Pablo Bay is referred to as Sonoma Valley because Sonoma Creek drains the entire area.

Geology

The stratigraphy described here is based on exposures of rocks in the mountains bordering Sonoma Valley (*fig. 9*) and on lithologic logs from a few deep exploration wells and from several water wells that have been drilled on the valley floor. The entire watershed is underlain by basement rocks consisting of Franciscan Complex, Coast Range ophiolite, and Great Valley Sequence which are overlain by younger volcanic and sedimentary rocks and unconsolidated sediments.

Several previous investigators have addressed various aspects of the geology of the Sonoma Valley. Osmont (1905) described the St. Helena Rhyolite, now included in the Sonoma Volcanics. Morse and Bailey (1935) provided one of the earliest descriptions of the Petaluma Formation near Sears Point. Weaver (1949) carried out one of the earliest comprehensive geologic investigations which included the area of the current study. His work defined the basic geology of the area in terms of stratigraphy and structure. Studies by Fox and others (1973) provided more detailed geologic maps of the study area, and later Fox and others (1985) provided radiometric age dates for several of the formations in the study area. Currently, the California Geological Survey, in cooperation with the USGS, is carrying out new geologic mapping of several 7.5-minute quadrangles covering parts of the Sonoma Creek watershed and adjacent areas. Mapping has been completed in only part of the area as of 2005.

Basement Rocks

At least part of the basement rocks are Franciscan Complex. The Franciscan Complex includes rocks of several different lithologies; these commonly include sandstone, graywacke, shale, conglomerate, chert, greenstone, and serpentinite. These rocks, originally deposited in marine basins during Jurassic to Cretaceous time, have become highly indurated through the processes of compaction and secondary mineralization. The rocks are all weakly to strongly metamorphosed, having been deeply buried and subjected to elevated temperatures during the intervening millions of years.

Rocks of the Franciscan Complex probably underlie much of the watershed (Wright and Smith, 1992) but are exposed over only a small part of the area in the Mayacmas Mountains, in the northeastern part of the study area, and at the southern end of the Sonoma Mountains (*fig. 9*). The thickness is unknown, but probably is a few tens of thousands of feet (Blake and others, 2000). Primary porosity and permeability are very low in Franciscan rocks because most of the original pore spaces are filled by minerals that cement the individual grains together. Most of the modern permeability is secondary, due to fracturing after lithification. Because of the low permeability and storage capacity, Franciscan rocks are commonly considered to be non-water bearing and to form the boundaries of ground-water basins throughout the Coast Ranges.

Exposures of Coast Range ophiolite have been mapped as small outcrops within larger masses of Franciscan Complex in the Mayacmas Mountains and the southern part of the Sonoma Mountains (Fox and others, 1973; Wagner and others, 2003). The ophiolite consists of serpentinized peridotite, gabbro, and basalt that has been faulted and tectonically interleaved with the Franciscan Complex (McLaughlin and others, 2005).

The Great Valley Sequence is not exposed in the study area but has been identified in deep petroleum exploration wells at the southern end of Sonoma Valley and beneath San Pablo Bay (Wright and Smith, 1992). Great Valley Sequence rocks are exposed on the east side of Mayacmas Mountains, east of the Sonoma Creek drainage divide. The presence of these rocks, at least in places, beneath Sonoma Valley is supported by the consistently low ratios of dissolved boron to chloride in water samples from thermal wells along the east side of the valley (Donnelly–Nolan and others, 1993). In exposures to the east of the study area, Great Valley Sequence rocks are mostly sandstones, shales, and minor conglomerates. These rocks are typically well cemented and indurated. Wells drilled in these rocks generally yield little or no water (Kunkel and Upson, 1960; Page, 1986).

Appendix A describes how gravity data were compiled and analyzed to characterize the configuration of the basement rocks in the Sonoma Valley.

Basin Fill

The basin is filled by younger rocks and sediments deposited unconformably upon basement rocks. The basin fill includes the Petaluma Formation, an unnamed Tertiary sedimentary unit, the Sonoma Volcanics, the Huichica Formation, the Glen Ellen Formation, and several Quaternary alluvial units (*fig. 10A–D*). Where well exposed, the Franciscan Complex is overlain by Tertiary sedimentary rocks in the southwestern part of the study area and overlain by the Sonoma Volcanics in the northeastern part. Several of the formations that constitute the basin fill have interbedded stratigraphic relations and may represent different facies of the same geologic period.

Only one small exposure of Neroly Sandstone (part of the San Pablo Group) has been mapped high in the Mayacmas Mountains in the northeastern part of the study area. Because of the very small outcrop area and its location far from the main ground-water resource, the Neroly is not shown in figure 9. The presence or absence of San Pablo Group beneath Sonoma Valley is uncertain. However, if present, rocks of the San Pablo Group would lie at depths much greater than the depth of any water wells in the study area, as of 2005 (Wright and Smith, 1992). For this reason, the San Pablo Group is not discussed any further in this report.

Tertiary Sedimentary Rocks

Sedimentary rocks exposed in outcrops around the southwestern margin of Sonoma Valley (*fig. 9*) were mapped as Petaluma Formation by Fox and others (1973) and in preliminary geologic mapping by Wagner and others (2002). More recently, Wagner and others (2003) mapped the outcrops east of the Rodgers Creek Fault informally as unnamed sedimentary deposits on the basis of a 4.8 ma interbedded tuff, precluding them from inclusion in the Petaluma Formation. The stratigraphic nomenclature is still a subject of debate. In this report, the nomenclature of Wagner and others (2003) is followed.

The Petaluma Formation is exposed in a small area at the southern end of the Sonoma Mountains (*fig. 9*). In its type locality, the Petaluma Formation is composed of sandstone, shale, siltstone, clay, minor beds of nodular limestone and conglomerate, and interbeds of tuff. The formation is described in detail by Allen (2003). Much of the formation was deposited under brackish-water conditions but includes both a continental and a marine facies. The transition to the marine facies occurs west of the Sonoma Mountains. On the basis of outcrops and cuttings from deep petroleum exploration wells, the total thickness of the formation probably is at least 3,000 ft beneath the Santa Rosa Plain, west of the study area. The Petaluma Formation is generally considered to be Miocene to Early Pliocene in age. Roblar tuff is interbedded with the Petaluma Formation and was dated at 6.26 ma (Wagner and others, 2002). West of the study area the Petaluma Formation is unconformably overlain by the Sonoma Volcanics, but the upper part of the formation is coeval with the older rocks of the Sonoma Volcanics. Within the study area, the thickness and extent of the Petaluma Formation are not known.

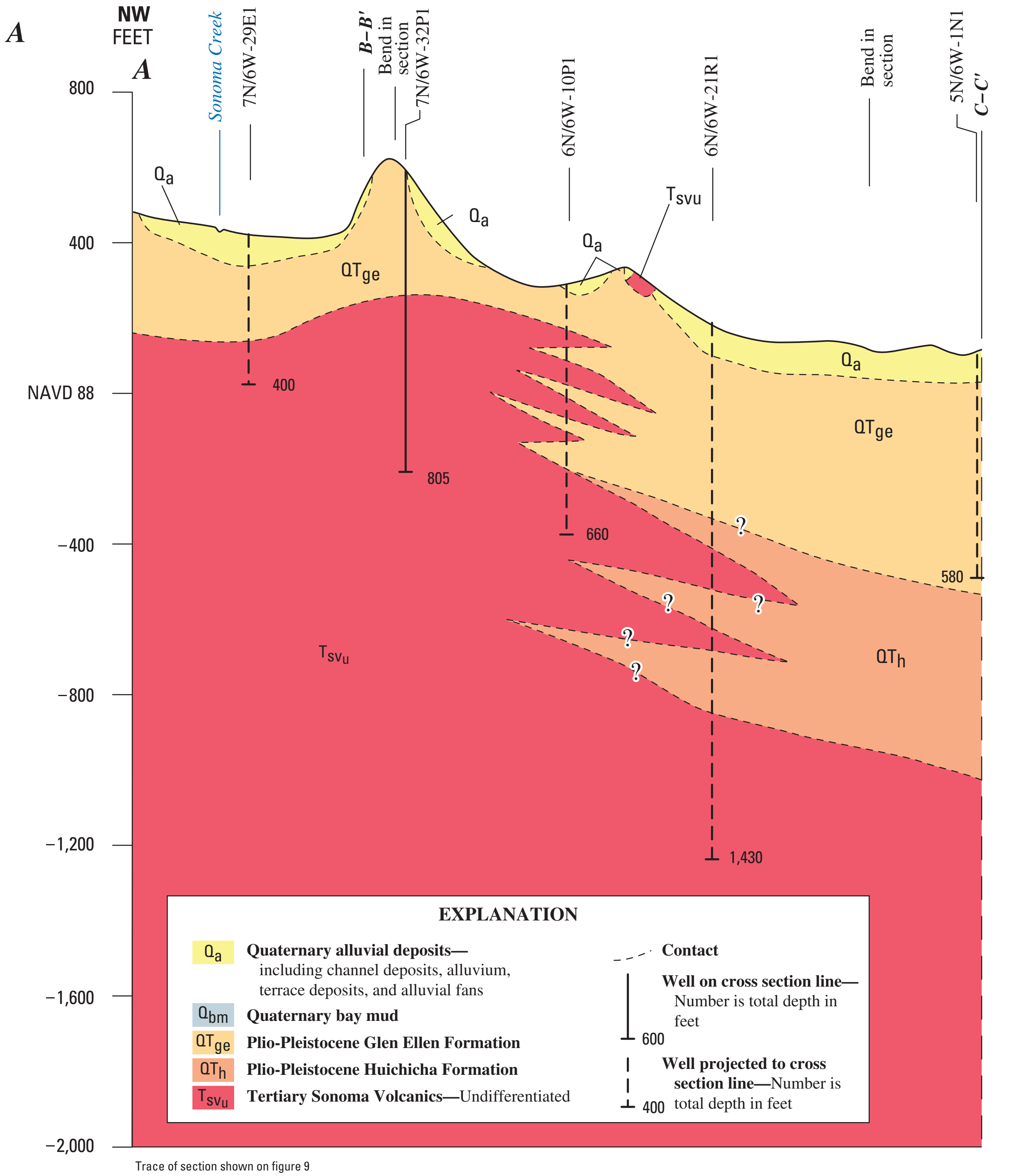
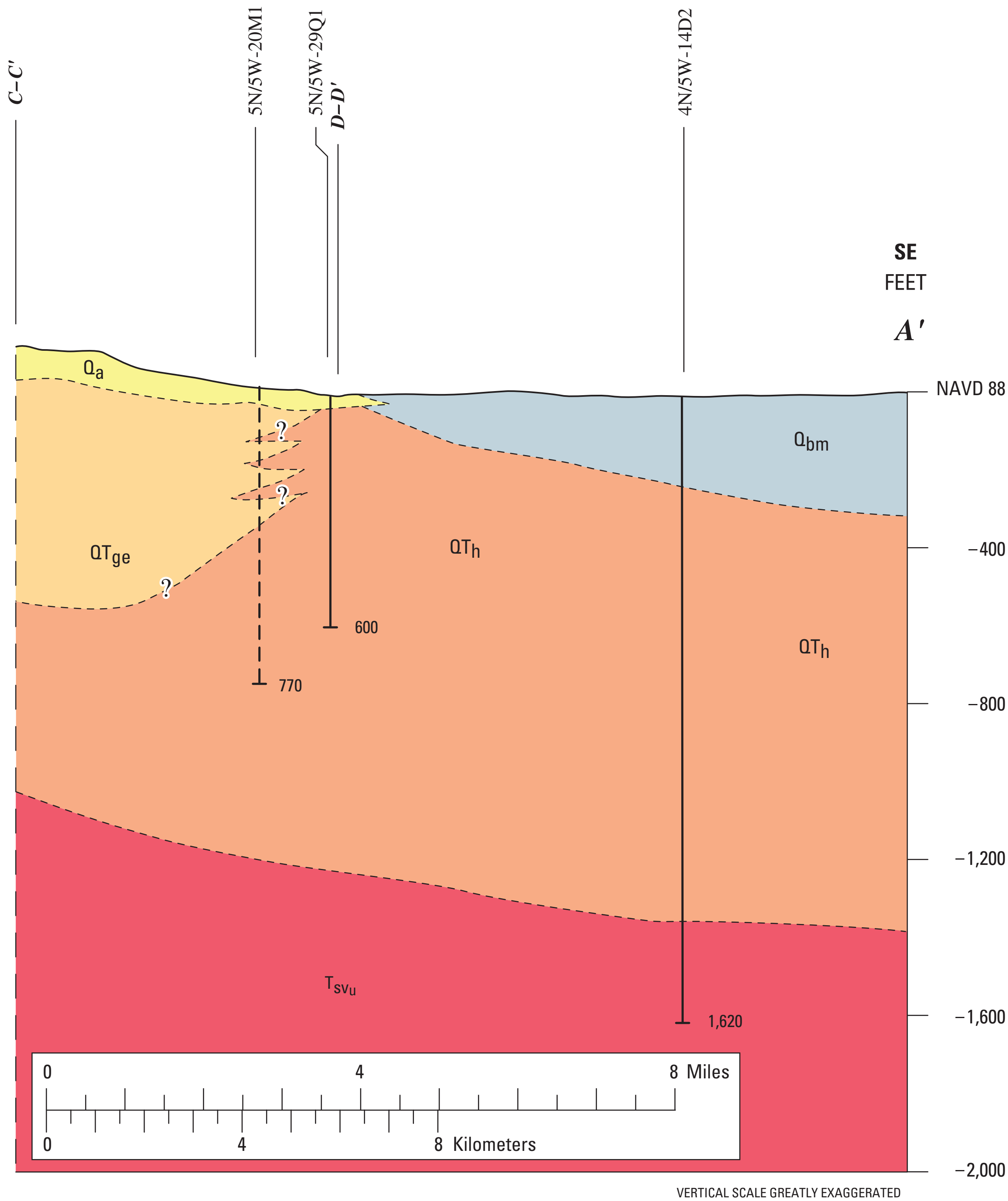


Figure 10. Geologic cross sections of the Sonoma Creek watershed, Sonoma County, California. *A*, *A–A′*. *B*, *B–B′*. *C*, *C–C′*. *D*, *D–D′*.



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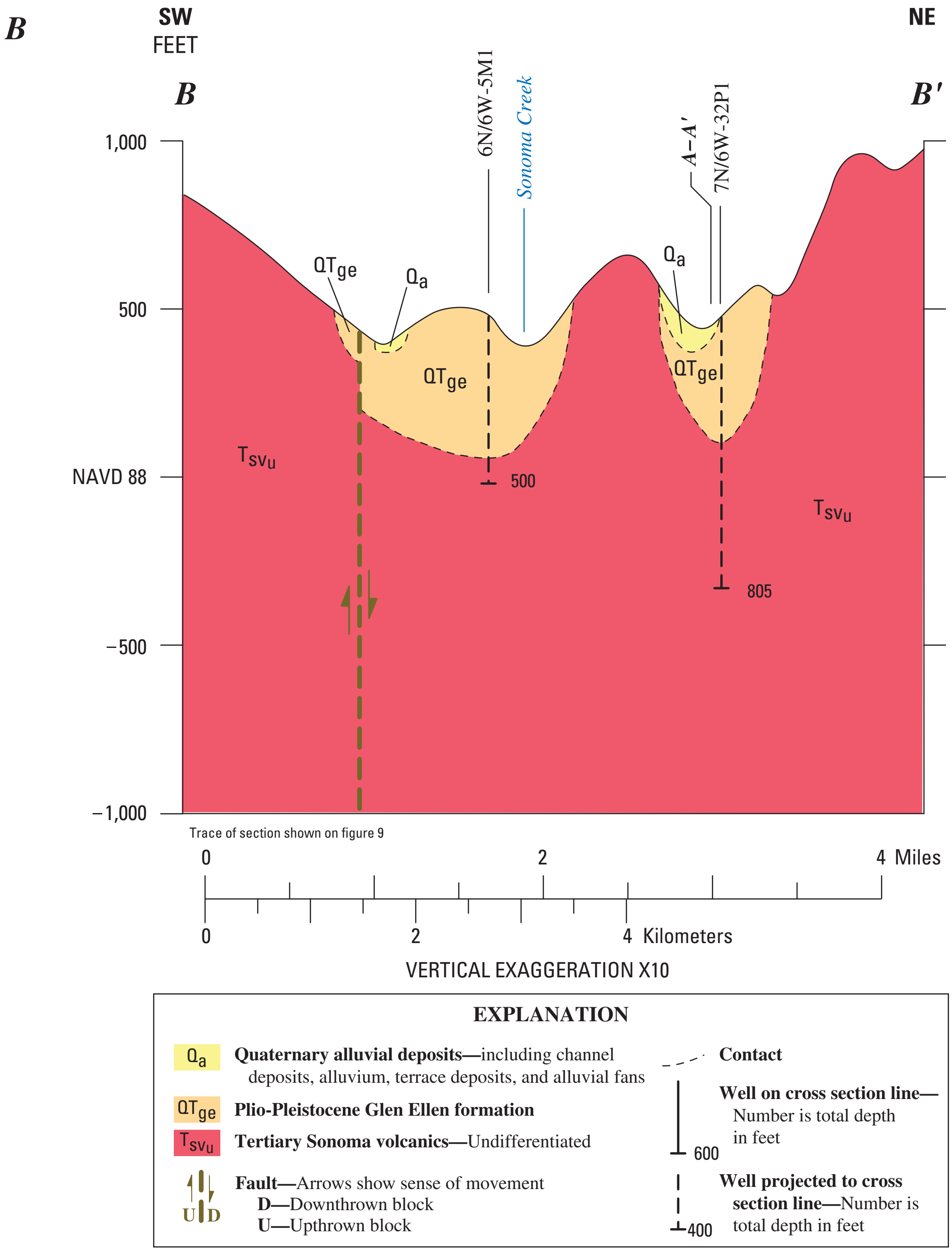

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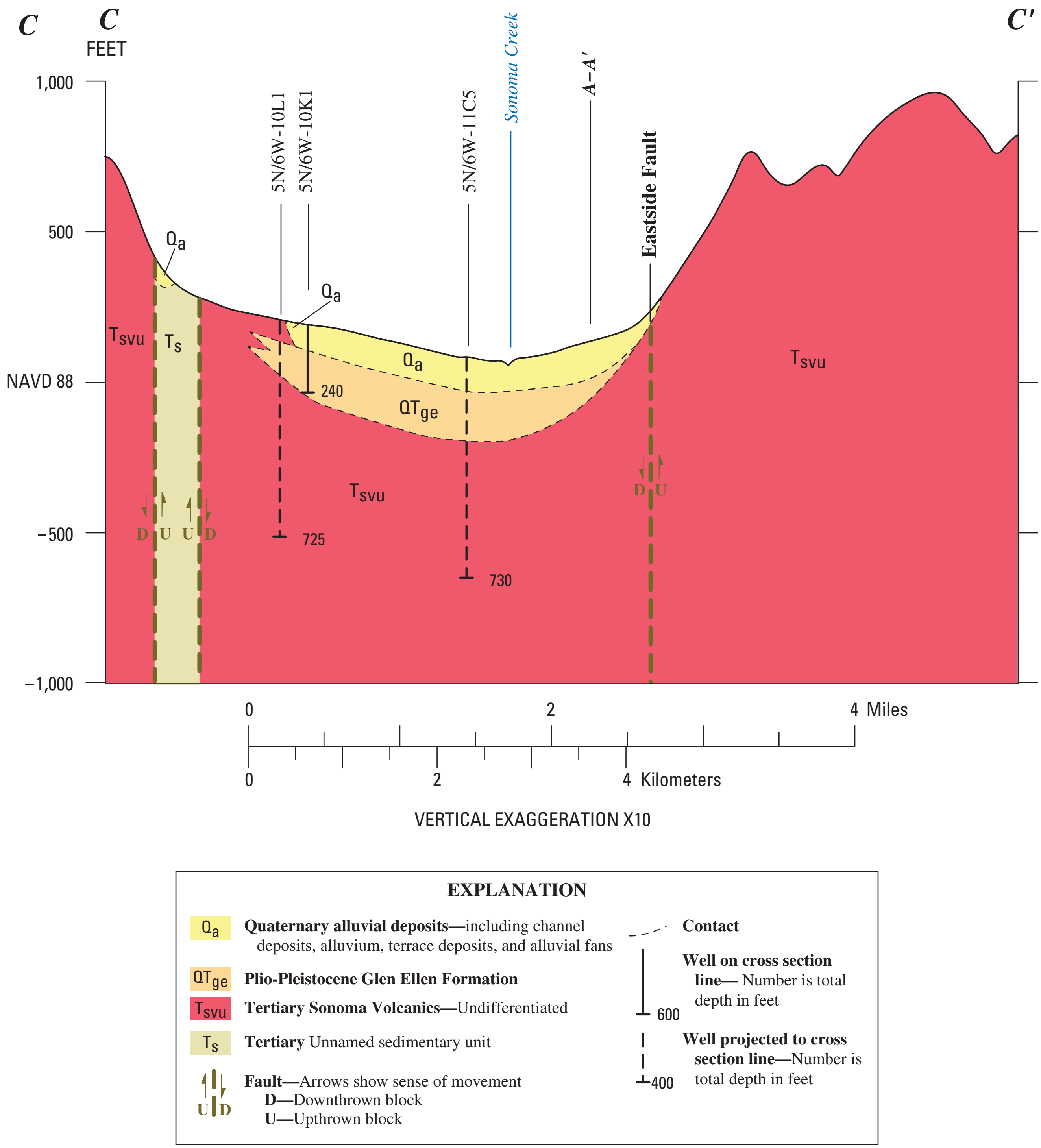

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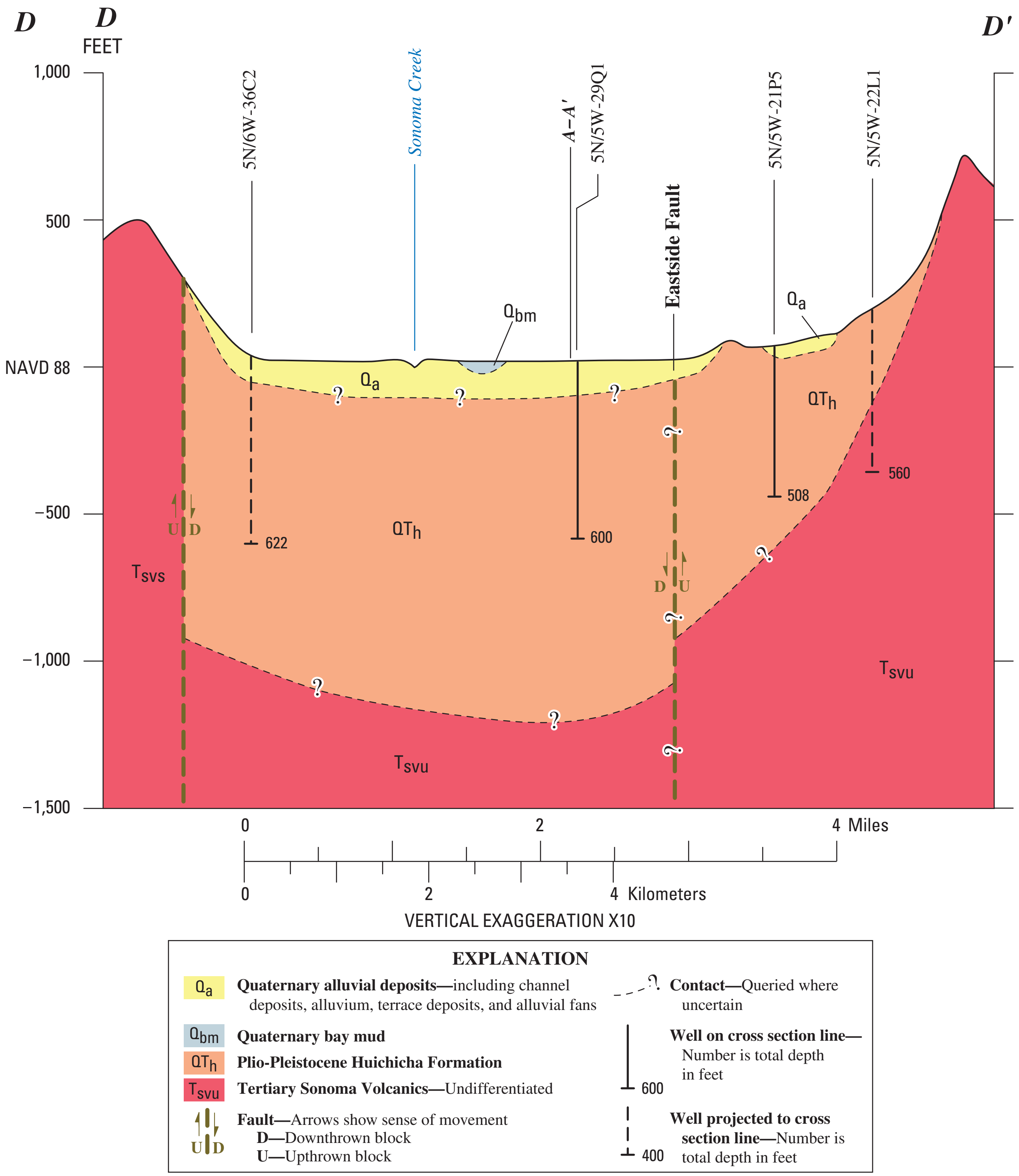


Figure 10.—Continued.

The unnamed sedimentary deposits mapped by Wagner and others (2003) are exposed in outcrops around the southwestern margin of Sonoma Valley. Here slivers of the formation have been uplifted along high-angle reverse faults (*fig. 10C*). These unnamed sedimentary deposits are Pliocene in age and consist of weakly consolidated fluvial, lacustrine, and brackish water sediments. These deposits are mostly fine-grained and consist of clay, silt with thin interbeds of sandstone, conglomerate, and tuff. Conglomerate cobbles consist of banded silicic volcanic rocks, red chert, black chert, and quartz. Within the study area, the thickness and extent of the unnamed sedimentary deposits of Pliocene age are not known.

Sonoma Volcanics

The Sonoma Volcanics are of Miocene to Pliocene age; they are widely distributed throughout parts of Napa and Sonoma Counties. In the study area, the Sonoma Volcanics lie unconformably on rocks of the Franciscan Complex or on the Tertiary sedimentary rocks. On the basis of stratigraphic relations and several radiometric K/Ar and $^{39}Ar/^{40}Ar$ ages obtained from samples collected in the Sonoma Creek watershed, the Sonoma Volcanics were extruded and deposited within the study area over an interval from approximately 8 to 2.5 ma (Sarna–Wojcicki, 1976; Fox and others, 1985; McLaughlin and others, 2005). The Sonoma Volcanics are a thick, highly variable sequence of continental volcanic and volcaniclastic rocks including basalt, andesite, and rhyolite lavas interbedded with tuffs, lahar deposits, debris avalanche deposits, mudflow units, hyaloclastites, reworked tuffs, sedimentary deposits derived from volcanic rocks, and lacustrine deposits. These rocks were first described by Osmont (1905) and named for Sonoma Mountain, east of Santa Rosa. A large part of the Sonoma Mountains is underlain by volcanic rocks but exposures are generally widely separated by oak and grass covered slopes veneered with thin soils, colluvium, and landslide deposits. The Sonoma Volcanics crop out extensively in the Mayacamas Mountains (*fig. 9*) and also underlie parts of the valley floor (*fig. 10A*) where it is frequently penetrated by water wells. The total thickness of Sonoma Volcanics near Glen Ellen was estimated by Sickles (1974) to be about 600 ft. Cardwell (1958) estimated the thickness to be 1,000 to 1,200 ft northeast of Kenwood. The total thickness of the Sonoma Volcanics in the mountains near Sonoma probably is at least 3,000 ft based on recent mapping by the California Geological Survey (David Wagner, California Geological Survey, oral commun., 2005).

The Sonoma Volcanics were produced by a complex eruptive history from many vents that produced lava flows, dikes, plugs, breccias, pumice beds, welded tuff layers, and debris flows. Many of the units are lenticular. Most lava flows are from a few feet to a few tens of feet thick. In places, these rocks are strongly folded or broken by faults. Kunkel and Upson (1960) divided the formation into three members: a basal member of mostly basalt and andesite lavas interbedded with tuff units; a diatomite member; and an upper member consisting mostly of rhyolite lavas and tuffs, often welded. Recent mapping (David Wagner, California Geological Survey, and R.J. McLaughlin, U.S. Geological Survey, unpub. data, 2003–2004) shows that the Sonoma Volcanics can be separated into older, middle, and younger members on the basis of the structural attitude and age of individual units, with the older member dipping more steeply than the overlying volcanics. Each of the members includes several rock units that represent long periods of volcanic activity from multiple vents. The members are separated by angular unconformities that represent unknown lengths of time. The Sonoma Volcanics are overlain by the Glen Ellen and Huichica Formations; however, the upper part of the Sonoma Volcanics interfingers with these two formations in places. In locations around the valley margin, where the Glen Ellen and Huichica Formations have eroded away, the Sonoma Volcanics are overlain unconformably by Quaternary alluvial units.

Huichica Formation

The Huichica Formation of early Pleistocene to Pliocene in age was named by Weaver (1949) for the continental beds cropping out east of the study area. Within the study area, the Huichica Formation crops out primarily in the hills along the southeastern part of Sonoma Valley and underlies the valley floor beneath the Bay Mud and alluvial sediments near the mouth of the valley. The westward and northward extent of the Huichica beneath the valley floor is unknown. This formation consists of massive yellow silt and yellow and blue clay with interbedded lenses of sands, gravels, and tuff beds. Much of this material was derived from erosion of the Sonoma Volcanics. The sediments making up the Huichica Formation were deposited as alluvial fans by small streams with low hydraulic gradients and in small lakes or lagoons (Kunkel and Upson, 1960). The total thickness of the Huichica is probably greater than 1,000 ft beneath parts of the valley floor (*fig. 10A*). The basal 200 ft contain higher fractions of coarse materials including cobbles and boulders of volcanic rocks. Interbeds of tuff are prevalent in the lower part of the formation, and one has a K/Ar age of 4.09±0.19 ma (Wagner and others, 2002). The Huichica Formation unconformably overlies the Sonoma Volcanics but in places probably interfingers with the upper part of the Sonoma Volcanics. The stratigraphic relation with the Glen Ellen Formation is uncertain; although the Glen Ellen is mostly younger than the Huichica, it may interfinger with the upper part of the Huichica (*fig. 10A*). The two formations were formed by similar geologic processes acting within different parts of the sedimentary basin. The composition varies between them because they were derived, at least in part, from different source areas in the basin (R.J. McLaughlin, U.S. Geological Survey, unpub. data, 2004).

Glen Ellen Formation

The Glen Ellen Formation, of Pliocene to Pleistocene age, was first described by Weaver (1949) for continental deposits that crop out near Glen Ellen in Sonoma Valley (*figs. 2* and *9*). The formation is largely of fluvial origin and consists of clay-rich stratified deposits of poorly sorted sand, silt, and gravel interbedded with minor beds of matrix-supported conglomerate and silicic tuffs. Beds grade from coarse- to fine-grained laterally and vertically, across distances of a few tens to a few hundreds of feet. Bedding is thick to massive and often is lenticular in form. Most of the clasts and probably much of the matrix were derived from the Sonoma Volcanics. Cobbles in the conglomerates are mostly subangular to rounded and range mostly between 3 and 6 inches (in.) in diameter. The cobbles are mostly of andesitic or basaltic composition. Obsidian clasts are one of the hallmark characteristics of this formation and serve to distinguish the Glen Ellen Formation from the Huichica Formation. The sedimentary rocks probably were originally deposited as alluvial fans and piedmont. The Glen Ellen Formation is estimated to be about 600 ft thick in outcrops near Glen Ellen (Youngs and others, 1983), but the thickness may be greater beneath parts of the valley floor. The thickness of Glen Ellen Formation in a well located approximately 2 mi west of Kenwood is about 900 ft (Cardwell, 1958).

The stratification of the Glen Ellen Formation indicates that it is of late Pliocene to early Pleistocene age. An intercalated tuff was correlated with the Putah Tuff, which was radiometrically dated at 3.3 ma. Within parts of the study area the Glen Ellen Formation rests unconformably upon rocks of the Franciscan Complex; but in most of the outcrop area, the formation laps onto the Sonoma Volcanics, and in places the lower part of the Glen Ellen Formation interfingers with the upper part of the Sonoma Volcanics. Beneath Sonoma Valley, the lower part of the Glen Ellen Formation may interfinger with the upper part of the Huichica Formation. Along the valley margins the Glen Ellen Formation is overlain by alluvial units of Quaternary age. The formation is gently folded in many outcrops, typically with dips of 15 to 30 degrees toward the valley axis.

Quaternary Alluvial Units

The alluvial sediments of Quaternary age were mapped by various investigators (Kunkel and Upson; 1960, Fox and others, 1973; Knudsen and others, 2000; and Wagner and others, 2004) as distinct deposits on the basis of the degree of consolidation, cementation, clast size and sorting, and geomorphic expression. The alluvial units cover about 38 mi^2 of the watershed forming a broad apron in the central part of the valley from Schellville northward beneath Sonoma and El Verano and then in a narrower band to Glen Ellen (*figs. 2* and *9*). Discontinuous patches of alluvial units crop out north of Glen Ellen and form a wider blanket covering the valley floor around Kenwood. The alluvial units consist of poorly consolidated to unconsolidated clastic materials ranging from clay size to boulders. The deposits, depending on mode of origin, are wedge-shaped, lense-shaped, or channel-shaped. Sorting within a particular unit depends on the distance from source materials, the type of source materials, and the hydraulic energy of the transporting medium. In general, the alluvial material nearest the valley margins contain the greatest proportions of course clasts and are generally less well sorted than deposits farther from the mountain flanks. The greatest thicknesses of fine-grained materials are found beneath the central axis of the valley. Channel deposits near the present-day course of Sonoma Creek and some of the larger tributary streams consist of boulders, cobbles, gravel, and sand that form thin sinuous bodies within more poorly sorted, finer-grained sediments deposited on flood plains. The channel deposits tend to be thin and discontinuous owing to shifting channel locations over time. Overall the alluvial deposits range in thickness from near zero at the valley margins and upper parts of tributary channels to as much as 300 ft near the center of the valley.

Bay Mud Deposits

Bay Mud deposits crop out over about 26 mi^2 covering a continuous area between Schellville and San Pablo Bay (*fig. 9*) and extend southward beneath the bay. The mud consists of clay, silt, small amounts of sand, and organic materials that were deposited in a shallow bay or marsh environment. The Bay Mud was deposited during higher stands of sea level that existed during Quaternary inter-glacial periods, probably in the last 120,000 years, and is still being deposited on the floor of San Pablo Bay. The thickness of this unit ranges from near zero at the contact with other formations on the valley floor to an estimated 200 ft along the shore of San Pablo Bay (Goldman, 1969). The Bay Mud interfingers with the alluvial units along the northern and eastern contacts and unconformably overlies the Sonoma Volcanics and older formations along the southwestern edge of the valley. Beneath the valley floor, the Bay Mud rests unconformably upon the Huichica Formation (*fig. 10A*), and in the western part of the outcrop area the Bay Mud also may rest unconformably upon the Glen Ellen Formation. The Bay Mud deposits have been heavily excavated to construct drainage channes in some of the marshlands. In other areas the deposits have been covered with artificial fill for various construction activities.

Geologic Structure

Sonoma Valley is a distinctive topographic feature and is one of several narrow northwest trending valleys in the mountainous terrain north of San Francisco Bay. Volcanic and sedimentary rocks on either side of the valley mostly dip toward the valley axis but in places this simple geometry is disrupted by minor folds and faults (Campion and others, 1984). Correlations of rocks on either side of the valley can not be made with confidence because of the discontinuous nature of individual beds or units within the Sonoma Volcanics and the Glen Ellen and Huichica Formations. However, the predominance of stratification dipping toward the valley axis clearly indicates that the valley is a synform structure rather than a purely erosional feature. The folding took place in at least three episodes over a few million years, between the time of deposition of the oldest units in the Sonoma Volcanics to the deposition of the youngest part of the Glen Ellen Formation (D. Wagner, California Geological Society, unpub. data, 2005). The folding is not uniform, and the synform probably is asymmetric, being steeper on the east side of the valley.

The rocks around the margin of the valley west of Kenwood have been folded into a syncline that strikes northwest. The folding has affected the Glen Ellen Formation which has dips of 25 to 40 degrees toward the valley axis (California Division of Mines and Geology, 1984).

Several faults can be recognized in the Sonoma Mountains along the southwest side of Sonoma Valley (*figs. 9* and *10C*). Some of the faults are branches or splays of the Tolay Fault or the Rodgers Creek Fault, both of which are northwest-striking large-scale faults. Movement on the Rodgers Creek Fault has been predominantly right-lateral strike-slip, but it also has components of dip-slip. Movement on the Tolay Fault has been predominantly reverse slip. High-angle normal and reverse faults also have been mapped in the Sonoma Mountains (Fox and others, 1973). Some of these faults have a more northerly strike and project into the valley near Glen Ellen. Youngs and others (1983) describe northwest striking high-angle faults on both sides of the northern part of Sonoma Valley. Most of these faults show a vertical component of displacement. In this area the Glen Ellen Formation does not appear to have been affected by faulting. A thrust fault on the northeast side of the valley has displaced a block of Sonoma Volcanics onto rocks of the Franciscan Complex.

In the Mayacmas Mountains, several faults have been mapped (Wagner and others, 2004). Most of the faults strike northwest or north to east of north, but the sense of displacement is not known. Some of these faults probably are right-lateral strike-slip related to the regional pattern of faulting north of San Francisco Bay. No faults have clear surface expression on the valley floor; however, there is a concealed northwest-striking high-angle normal fault (*fig. 9*) This fault was mapped on the basis of the outcrop pattern of Huichica sediments gravity and magnetic geophysical surveys and on speculation that a fault must exist along the eastside of the valley to account for the distribution of thermal waters in Sonoma, Agua Caliente, and Boyes Hot Springs (Youngs and others, 1983; Campion and others, 1984). In this report, this fault is referred to as the "Eastside Fault."

Hydrology

Surface-Water Hydrology

Sonoma Creek begins in the Mayacmas Mountains in the northeastern part of the study area at an altitude of about 1,600 ft. The creek flows generally westward through a narrow canyon with a steep gradient from the headwaters to the edge of the valley floor near Kenwood. In this 3-mi reach, the creek drops about 1,100 ft to an altitude of about 500 ft. The course of the creek turns to the south near Kenwood and then turns to the southeast near Glen Ellen. The gradient is much less steep in the 6.5-mi reach between the mountain front and Glen Ellen, dropping in altitude by about 280 ft. The gradient flattens further between Glen Ellen and San Pablo Bay. South of State Route 121 where Sonoma Creek flows through tidal marshland to San Pablo Bay, the stream drops only about 10 ft in 9 mi.

Discharge in Sonoma Creek is gaged (USGS station number 11458500) near the middle part of the valley at the Agua Caliente Avenue bridge near Agua Caliente (*fig. 2*). At this point the contributing drainage area is 58.4 mi^2. The gage was operated from 1955 through 1981 and was then temporarily discontinued until 2001 when it was restarted. Discharge varies considerably seasonally and interannually (*fig. 11A*). The mean annual discharge is 50,621 acre-ft, on the basis of records for water years 1956–81 and 2002–04. A maximum annual discharge of 113,821 acre-ft was measured in 1956, and a minimum discharge of 1,002 acre-ft was measured in 1977. In most water years, discharge does not increase markedly until November or December, after which it begins to rapidly decrease in April or May in response to the normal annual cycle of precipitation. A flow duration curve (*fig. 11B*) shows that instantaneous discharge is greater than 10 cubic feet per second (ft^3/s) about 40 percent of the time, and greater than 100 ft^3/s only about 11 percent of the time. The mean annual runoff for the Sonoma Creek watershed was estimated to be 101,000 acre-ft on the basis of gaged streamflow values and estimated runoff from Rantz (1968) for northern coastal California.

The Sonoma Creek watershed can be subdivided into 23 subbasins of the main tributaries (*fig. 8*). The subbasins range in area from 1.1 mi^2 for subbasin 11 to 24.4 mi^2 for subbasin 21.

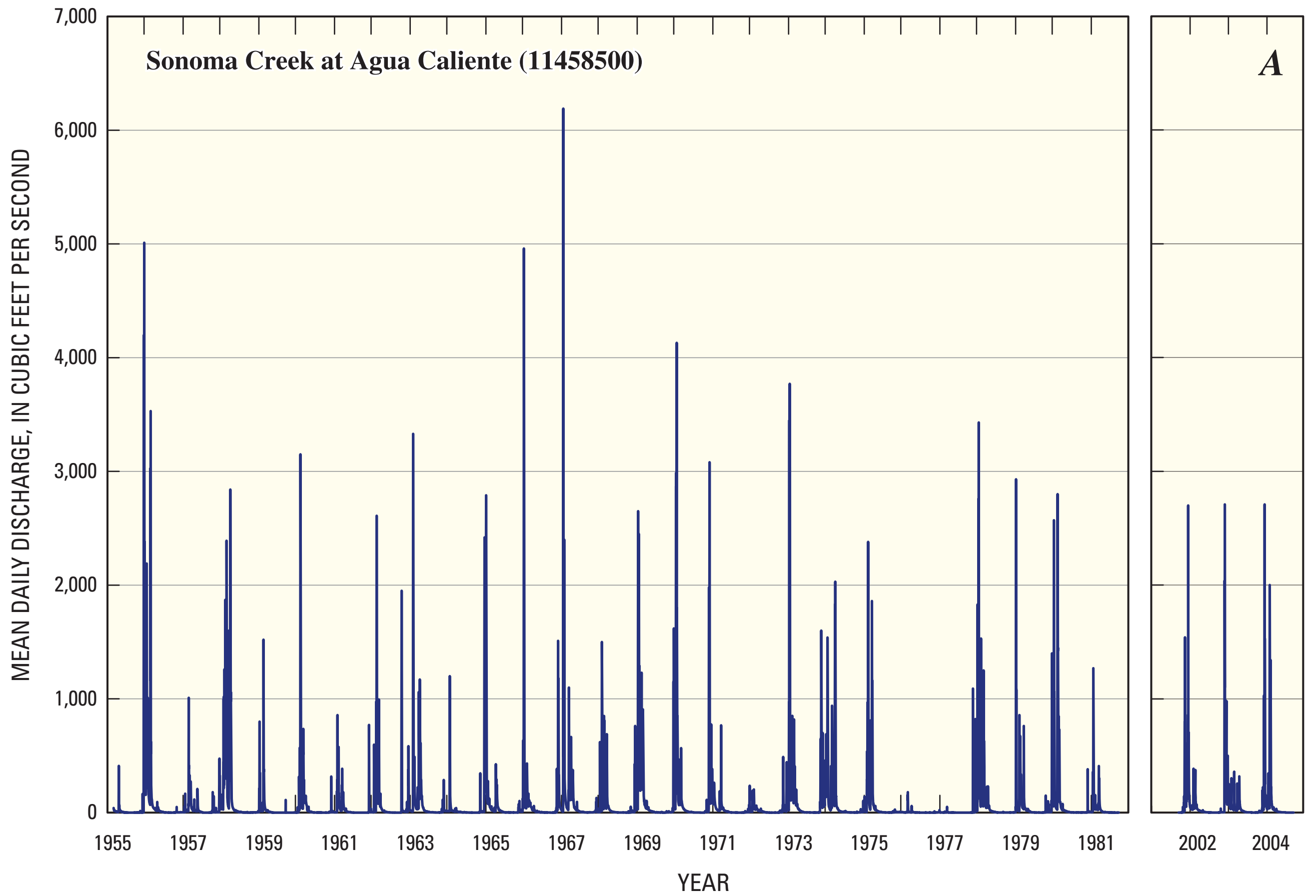


Figure 11. Discharge of Sonoma Creek at U.S. Geological Survey (USGS) stream gage 11458500 in Agua Caliente, Sonoma County, California. *A*. Mean daily discharge for water years 1955–81 and 2002–04. *B*. Flow duration of discharge. Note: Gage was not in operation from 1982 through 2000.

Precipitation has been measured at four stations within the watershed. The areal distribution of average annual precipitation for northern coastal California (Rantz, 1968) was modified for this current study area using an adjustment based on the precipitation–altitude relationship derived from the four stations. Using the modified distribution of precipitation, the estimated mean annual precipitation in the Sonoma Creek watershed is 269,000 acre-ft.

Ground-Water Hydrology

All the geologic formations and alluvial deposits in the Sonoma Creek watershed contain ground water (*fig. 9*); however, the water-bearing properties of the geologic units vary considerably and largely determine how much water can be obtained from a well in different parts of the watershed. The predominant source of ground water recharge in the study area is local precipitation that falls on the mountains and valley floor. Other comparatively minor sources of water include imported water, connate water contained in the Bay Mud and adjacent sediments, and possibly saline water from San Pablo Bay. To date (2005), ground water has been obtained from the rocks and sediments that lie within a maximum of about 1,600 ft of land surface; in most parts of the study area water is obtained from wells that are less than 700 ft deep. The discussion of water-bearing properties that follows is restricted to the depth interval penetrated by water wells.

The most important sources of ground water in the study area are the Quaternary alluvial deposits, the Glen Ellen Formation, the Huichica Formation, and the Sonoma Volcanics. All these geologic units are widely distributed and contain zones of high porosity and permeability.

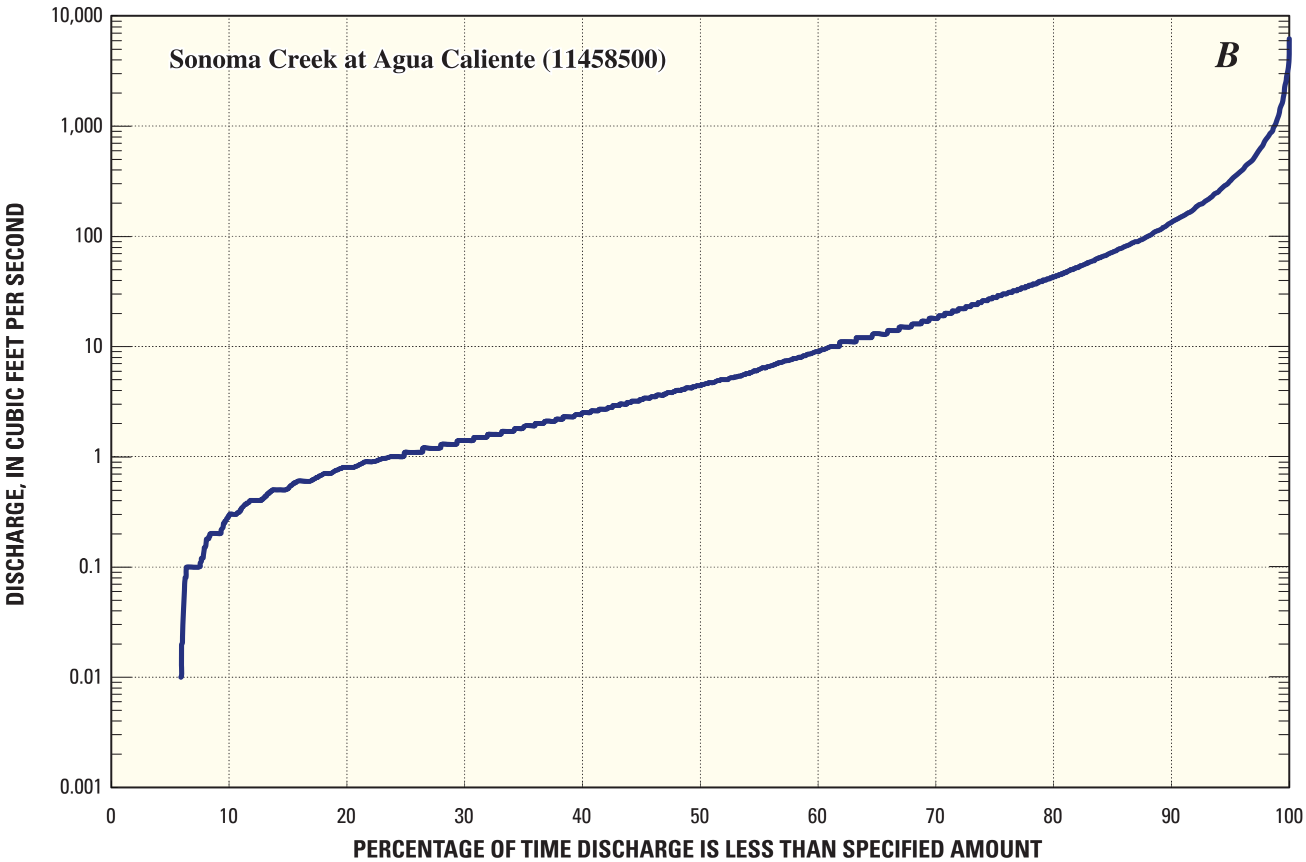


Figure 11.—Continued.

Water-Bearing Properties

Quaternary alluvial units in this report include alluvial fans, stream terraces, flood-plain deposits, and channel alluvium. All these deposits contain varying amounts of poorly consolidated, uncemented to weakly cemented, sands, gravels, cobbles, and boulders in a matrix of silt- and clay-sized material. The alluvial units have high porosity and, where they consist mostly of coarse-grained material, high permeability. Where the units contain large fractions of silt and clay, permeability is greatly reduced. The alluvial units were estimated to have a range in specific yield of between 3 and 15 percent (California Department of Water Resources, 1982). The alluvial units, where sufficiently thick and saturated, are the highest yielding aquifers in the study area. Near the axis of the valley, close to Sonoma Creek, most of the thickness of the alluvial units is saturated, but some elevated stream terrace deposits on the valley floor and in the higher parts of alluvial fans remain unsaturated at least through the dry season of most years. Well yields range from less than 1 gallon per minute (gal/min) to more than 100 gal/min. The actual yield depends largely on the saturated thickness, median grain size, and sorting of the alluvial units at any particular site. Most wells, except those close to the valley axis, that were drilled in the past few decades were drilled deep enough to obtain at least part of their water from formations beneath the alluvial units.

The Bay Mud consists almost entirely of clay and silt; sand beds are rare and generally occur only as very thin lenses (Goldman, 1969). The Bay Mud has very high porosity, probably 50 percent or greater. But the fine-grained composition of the mud results in very low permeability. A specific yield of less than 3 percent was estimated by California Department of Water Resources (1982). Because of the low permeability and specific yield, and the occurrence of saline water in this unit, the Bay Mud is not considered an aquifer for water supply.

The Huichica and Glen Ellen Formations have very similar lithologies and possibly interfinger beneath the central part of Sonoma Valley. Both units mostly consist of consolidated, weakly to moderately cemented silt and clay with minor sand beds. The large amount of clay-sized material, although high in porosity, greatly limits permeability. The specific yield of these formations was estimated to be 3 to 7 percent (California Department of Water Resources, 1982). Well yields from the Glen Ellen Formation generally are lower in the study area than in the Santa Rosa Plain (10 mi west of the study area). Well yields in the Glen Ellen and the Kenwood areas are mostly less than 20 gal/min and often only 1 to 2 gal/min with drawdowns of tens of feet. Well yields from the Huichica Formation are similar to those from the Glen Ellen Formation. A few wells drilled to depths greater than 1,000 ft in the southern part of the study area provide records that show that the basal 200 ft of the Huichica contains a higher percentage of coarse-grained materials and provides greater amounts of ground water to wells than the upper part of the formation (Kunkel and Upson, 1960).

The Sonoma Volcanics have the greatest variability in lithology and water-bearing properties. Within the Sonoma Volcanics fractured lavas, interflow zones, scoria, and unwelded tuffs provide the best aquifers. The lavas have insignificant primary permeability. Secondary permeability in lavas can be created by fracturing related to folding or faulting, and this can result in rocks with high permeability. Separations between cooling units are commonly seen in outcrops and, although thin (less than 1 ft thick), they can be laterally extensive significantly enhance permeability. The interflow zones between lavas often consist of rubblely material and scoria that can have very high porosity and permeability. Unwelded tuffs contain of ash, lapilli, and larger sized pumice fragments and other lithic clasts. Such units have hydraulic characteristics similar to alluvial materials with high porosity and high permeability. The debris-flow deposits and lahars are poorly sorted and contain large fractions of fine-grained materials which, although high in porosity, are low in permeability.

The distribution of lithologies within the Sonoma Volcanics at depth throughout the study area is not accurately known. For this reason the productivity of a well drilled into the Sonoma Volcanics at any particular location cannot be accurately predicted. Although water generally can be obtained from the Sonoma Volcanics, some dry holes have been reported (Kunkel and Upson, 1960). Most dry holes are encountered at sites in the mountains where ground-water levels can be greater than 200 ft below land surface. Successful wells in the Sonoma Volcanics generally yield between 10 and 50 gal/min and occasionally as much as a few hundred gal/min (Kunkel and Upson, 1960; California Department of Water Resources, 1975). Because of the heterogeneities in this formation, wells close to one another can have markedly different yields and drawdowns.

The Petaluma Formation and the unnamed Tertiary sedimentary unit, which crop out in small areas along parts of the lower slopes of the Sonoma Mountains, have similar water-bearing properties. These units contain mostly siltstone and claystone with minor fine- to medium-grained sandstones. These units are consolidated and cemented which limits porosity and permeability. The specific yield of these rocks was estimated to be between 3 and 7 percent (California Department of Water Resources, 1982). On the Santa Rosa Plain (10 mi west of the study area) well yields from the Petaluma Formation typically are low, ranging from less than 5 gal/min to greater than 100 gal/min (California Department of Water Resources, 1975). Because of the very limited extent of the Petaluma and unnamed Tertiary sedimentary deposits, these two units are not important sources of water in the study area.

The oldest and most indurated rocks in the watershed are the Franciscan Complex (Fox and others, 1973). These rocks are exposed in the mountains on the northeast side and southwest side of the study area. Although the rocks of the Franciscan Complex are commonly described as non-water bearing (Kunkel and Upson, 1960), small amounts of water can be obtained from these rocks where they are sufficiently fractured to provide secondary permeability (Cardwell, 1965; California Department of Water Resources, 1975). The best locations for obtaining ground water from Franciscan rocks are near fault zones and in canyon bottoms. Wells in these settings can produce sufficient supplies for a single residence but generally not enough water for irrigation or multiple residences (California Department of Water Resources, 1975). Few wells in the study area are drilled solely into the Franciscan Complex because outcrops are almost exclusively in the higher altitudes of the mountains where residential and agricultural development is very sparse or the formation is deeply buried by younger formations.

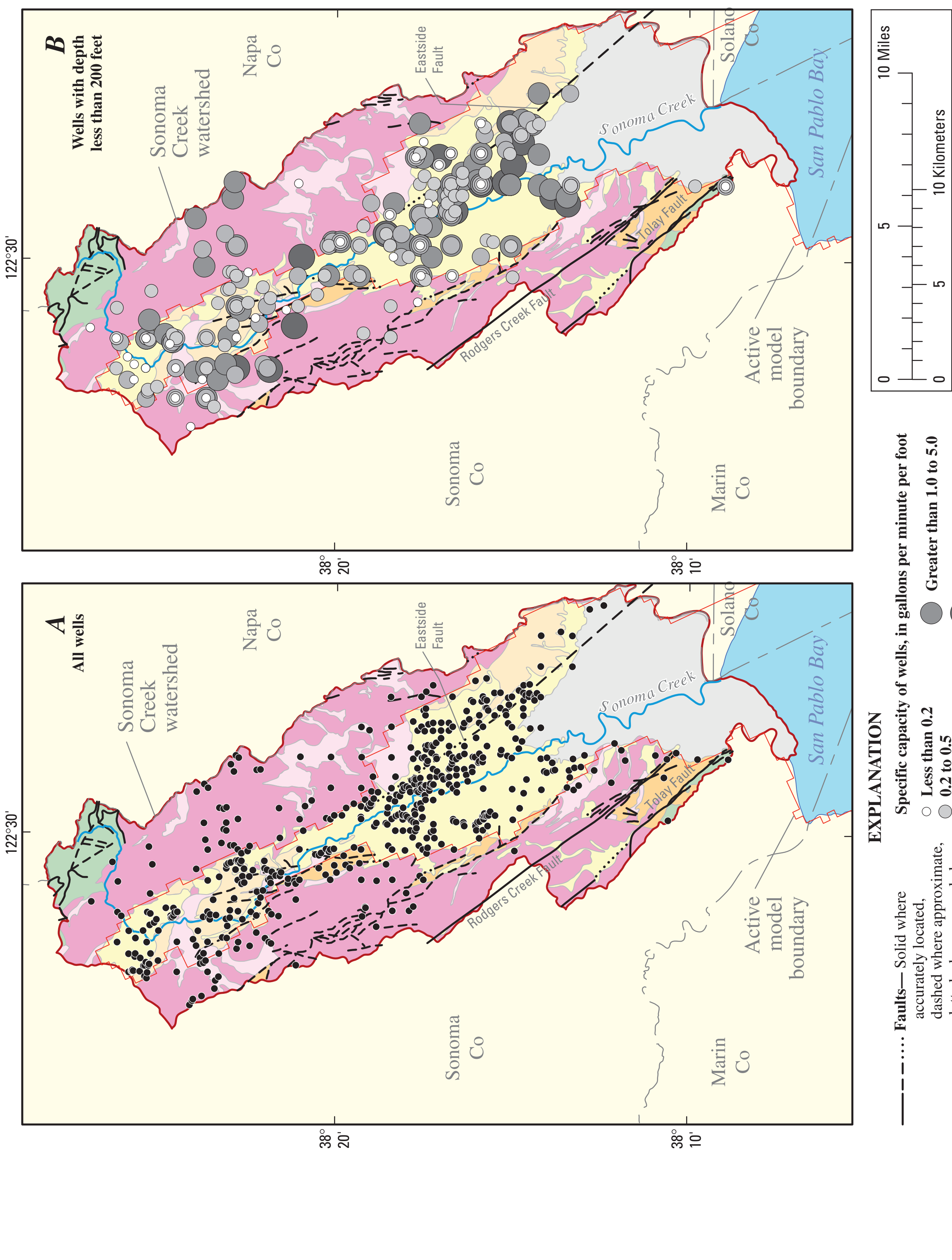


Figure 12. Specific capacity of wells in Sonoma Valley area, Sonoma County, California. *A*. Location of all wells with specific capacity data. *B*. Specific capacity of wells with depth less than 200 ft. *C*. Specific capacity of wells with depth between 200 and 500 ft. *D*. Specific capacity of wells with depth greater than 500 ft.

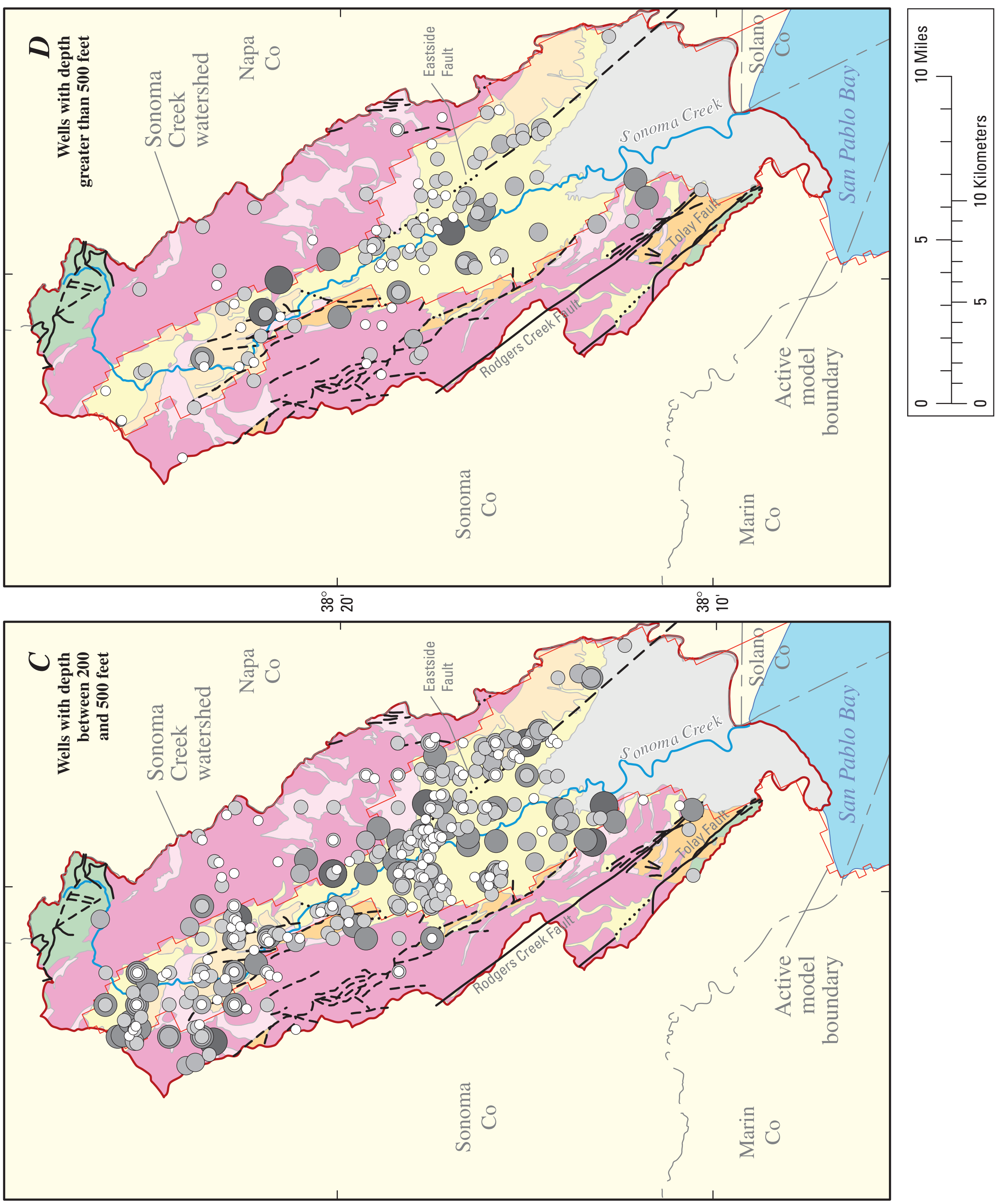


Figure 12.—Continued.

For this study, more than 2,000 drillers' reports for water wells drilled in the study area were examined to determine the range and distribution of well productivity. The drillers' reports provide information on well tests, including discharge rate, water-level drawdown, and the length of test. About 1,000 of the reports contained enough information to determine the well location, depth, and specific capacity of the well at the time of well completion (*fig. 12*). Specific capacity is a measure of well productivity and is given in terms of gallons per minute per foot (gal/min/ft) of drawdown. Most wells in the study area are constructed with multiple screen intervals or long screen intervals, and many are gravel-packed in the annulus between the casing and the borehole wall. This construction practice is done to maximize well yield, but it limits using the well for determination of depth-dependent changes in water-yielding properties, water-level fluctuations, and water quality. Nevertheless, 970 wells were classified into three depth categories: less than 200 ft, 200 to 500 ft, and greater than 500 ft (*figs. 12B-D*). The choice of these three depth categories was somewhat arbitrary; a scatter plot showing specific capacity in relation to well depth for all the wells showed no clear breaks or clusters that defined natural groupings. However, the use of depth ranges for this analysis resulted in a fairly even distribution of wells among the groups and clearly showed the general relation of diminishing specific capacity with depth. Well yields and specific capacities are shown by depth category in *figures 13A* and *B*. From these graphs it is clear that the deeper wells generally provide greater amounts of water, but only about 20 percent of the wells yield more than 100 gal/min (*fig. 13A*). *Figure 13B* shows that the shallow deposits generally have higher specific capacities than the deeper deposits. This is consistent with greater compaction and cementation in deeper geologic formations. The most permeable geologic materials are the alluvial units which are mostly less than 200 ft thick. The differences in specific capacity between the depth ranges are not very large owing to the large amount of fine-grained material in most of the alluvial units, as well as in the Glen Ellen Formation, the Huichica Formation, and some of the volcaniclastic rocks included in the Sonoma Volcanics.

Maps showing specific capacity for the three depth ranges are shown in *figure 12B, C, and D*. The specific capacity for wells less than 200 ft deep generally is low in the Kenwood and the Glen Ellen areas; highly variable in the main part of the valley from El Verano and Sonoma to the Bay Mud outcrop area; and possibly lower west of Sonoma Creek than to the east. For wells with medium depths (200 to 500 ft), the specific capacity is greater than that for wells with shallow depths in the Kenwood area, but elsewhere in the study area the specific capacity of medium depth wells is lower than that of shallow wells. The specific capacity of the deep wells (greater than 500 ft) is lower than that for shallow or medium depth wells throughout the study area. Moderately high specific capacity in deep wells is almost exclusively in areas underlain by alluvial deposits or close to Sonoma Creek owing to the well-construction practices that result in measuring composite effects of both the shallow and the deep zones.

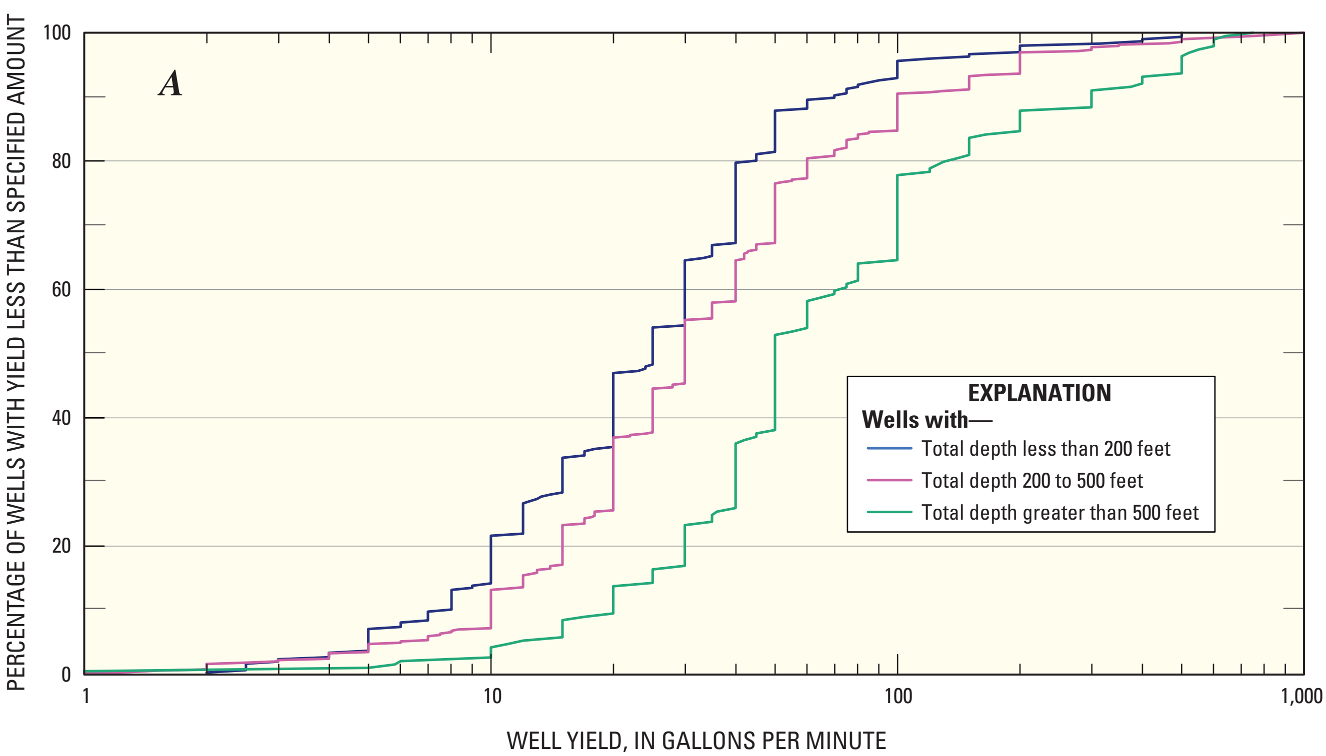


Figure 13. Percentage of wells in Sonoma Valley area, Sonoma County, California, with: *A*. Well yields less than specified amounts. *B*. Specific capacity less than specified amounts.

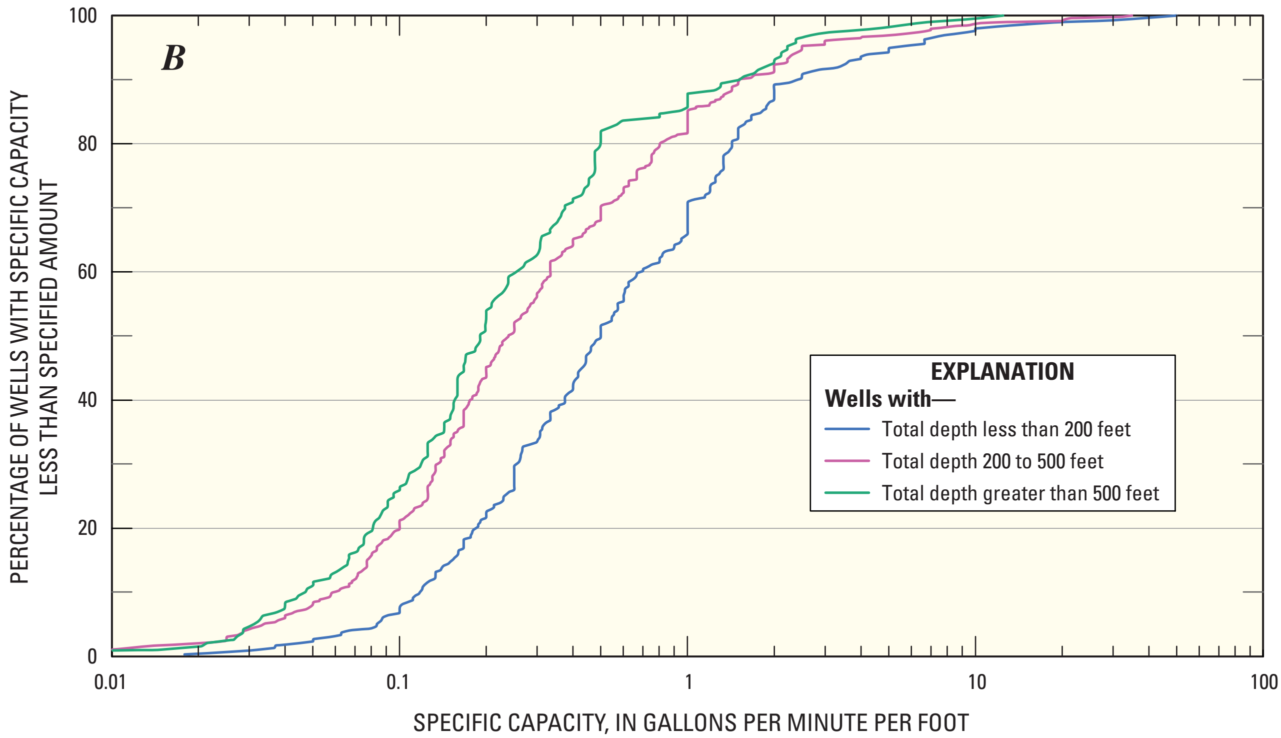


Figure 13.—Continued.

The relation of decreasing specific capacity with depth and the stratigraphic sequence was used to define three geohydrologic units. Because the assemblage of rocks in any particular depth interval varies from place to place within the study area, each geohydrologic unit comprises more than one geologic unit. The upper geohydrologic unit (upper 200 ft) comprises Quaternary alluvial deposits and the upper parts of the Glen Ellen Formation, the Huichica Formation, and the Sonoma Volcanics, as well as the Bay Mud. The middle unit (depths from 200–500 ft) comprises the deeper parts of the Glen Ellen Formation, the Huichica Formation, and the middle part of the Sonoma Volcanics. The lower unit (greater than 500 ft in depth) comprises the lower parts of the Huichica Formation and the Sonoma Volcanics and the San Pablo Group. The hydraulic properties of each of the geohydrologic units vary areally, but less so vertically. The variability depends on lithologic differences between and within geologic formations. Within formations, lithologic differences between locations are mostly related to differences in distance from source areas, changes in topography, and hydraulic gradients of streams at the time of deposition, and for volcanic rocks, changes in the types of volcanic activity. Diagenetic processes can affect the geologic formations after original deposition through compaction, chemical weathering, cementation, and biological activity (for example, bioturbation, burrowing). The three depth-based geohydrologic units were used as the basis for the vertical layering in the ground-water model discussed later in this report.

Within the study area, ground water occurs under both confined and unconfined conditions. Generally unconfined conditions prevail at shallow depths (less than 200 ft); however, where wells are drilled through thick sections of impermeable rocks (in other words, in clay or unfractured lavas), confined or semi-confined conditions can exist (Kunkel and Upson, 1960). Ground water is more commonly confined in deeper aquifers found in the Sonoma Volcanics, the Huichica Formation, and the Glen Ellen Formation than in shallow aquifers in alluvial units. In the Bay Mud, confined conditions can occur at very shallow depths because this unit is predominantly clay. In the early part of the twentieth century, when ground-water development was beginning, shallow artesian wells produced flows of water at land surface without pumping (Kunkel and Upson, 1960).

The quantity of ground water in storage was not estimated during this study because the complexity of subsurface stratigraphy and lithologic characteristics that would lead to very large uncertainties in any estimation. Also, the amount of ground water in storage generally is not the determining factor for estimating a balance in ground-water extraction and ground-water recharge (Bredehoeft and others, 1982). In the study area, ground-water extraction is concentrated in specific parts of the area where agricultural and urban development are most extensive. The total amount of ground water in storage in the watershed has little value in determining the amount of ground water that might be available or the rates at which it can be withdrawn from such areas of extensive development.

Estimates of ground-water storage have been made in previous studies. Kunkel and Upson (1960) estimated that 180,000 acre-ft of ground water was stored in the sediments within the upper 200 ft of a 21-mi^2 area of Sonoma Valley in 1950. California Department of Water Resources (1982) estimated that 559,000 acre-ft of ground water was stored in the formations, excluding the Sonoma Volcanics, beneath the valley floor between Kenwood and San Pablo Bay (approximately 85 mi^2) in 1980. This estimate excluded saline water beneath the salt marshes around the bay.

Effects of Geologic Structures on Ground-Water Movement

Geologic structures can affect ground-water flow (Meinzer, 1923). In the study area the rocks have been folded and faulted. Sonoma Valley is described as a synform, with the rocks on either side of the valley dipping toward the valley axis. The Sonoma Volcanics and the Glen Ellen Formation have been gently folded into a northwest-striking syncline west of Kenwood (*fig. 9*). Smaller folds have been mapped within the valley and in the mountains on either flank of the valley. Folds within heterogeneous formations can affect the direction of ground-water movement because most of the ground water moves through relatively thin permeable beds or zones within less permeable materials. Where a fold axis is oblique to the general ground-water flow direction, the fold can inhibit the movement of ground water if less permeable material is displaced into a horizon of significant ground-water flow. At a broad scale in the study area, ground water in the mountains flows to lower altitudes, generally following the structural dip of permeable beds and zones that dip toward the valley axis. The general dip of formations toward the valley axis in the study area can provide a structural setting that produces artesian conditions where the formation is deeply buried beneath the valley floor.

Several faults are well-exposed in the mountains on either side of the valley and along the mountain front on the southwest side of the valley. Faults can affect ground-water movement by several processes, some that enhance permeability and some that decrease it. Faults can juxtapose rocks of significantly different hydraulic properties; this can disrupt the continuity of an aquifer. Faults can cause fracturing in well-indurated rocks which can produce secondary permeability. This process can be particularly important in the lavas or welded tuffs of the Sonoma Volcanics and in the rocks of the Franciscan Complex. Some faults are marked by the presence of fault gouge, a fine-grained product produced by the grinding of rocks as they move past one another during faulting. Fault gouge can impede ground-water flow. Some faults or fault zones begin as planes of relatively high permeability but later become sealed because of mineral deposition from ground water that is oversaturated in calcium carbonate, iron oxides, silica, or other dissolved constitutents. The Eastside Fault may restrict ground-water movement either because of the presence of fault gouge or secondary mineralization (Campion and others, 1984).

Recharge

The principal source of recharge to the ground-water system in the study area is precipitation within the Sonoma Creek watershed. No streams enter the study area from outside the watershed. It is unlikely that a substantial quantity of ground water enters the study area from outside the watershed because most of the rocks underlying the boundaries in the mountains on the northeast and southwest sides of Sonoma Valley have low permeability. A ground-water divide forms the northwestern boundary of the study area, and the direction of ground-water flow along the southern boundary is away from the study area. In the future, ground water could enter the study area if ground-water extraction lowers hydraulic head sufficiently near the northern divide. Seawater from San Pablo Bay also is a potential source of water.

Recharge to the ground-water system primarily occurs as seepage from creeks, lakes, reservoirs, and direct infiltration of precipitation on soils. Results from a seepage run to characterize gaining and losing reaches of Sonoma Creek are described later in this report. Minor recharge can come from infiltration from septic tanks, leaking water-supply pipes, irrigation water in excess of crop requirements, and crop frost-protection applications. Although recharge from excess irrigation sometimes can be a significant part of total recharge within some basins, within this study area it is considered minor because the predominant crop is wine grapes and because local growers use highly efficient drip irrigation systems.

Discharge

Ground-water discharge from the study area occurs through several mechanisms. A small amount of ground water discharges from springs. Evapotranspiration (ET) is a large component of discharge from the watershed; however, a large part of ET is from soil moisture above the zone of saturation and is not ground-water discharge. Ground-water discharge to streams probably occurs in the lower reaches of some of the tributaries to Sonoma Creek, but insufficient data are available to quantify this amount. Characterization of ground-water discharge to Sonoma Creek is discussed in the next section. Ground-water pumpage is an important component of ground-water discharge. A detailed description of the methodology used to develop spatially distributed estimates of pumpage for the area of the simulation model is provided in the section "Ground-water Flow Model" and its associated appendix.

Ground-water discharges to the marshlands near San Pablo Bay by direct evaporation and transpiration from plants and some water discharges to a series of sloughs that drain the marsh area. Ground water can also discharge into sediments and rocks beneath the floor of the bay.

Streamflow Gains and Losses

To better understand the locations of gaining and losing reaches along Sonoma Creek and its tributaries, a seepage run was conducted during May 2003. The seepage run was scheduled to avoid peak-flow conditions and periods of significant changes in stage, such as receding stormflows. A seepage run consists of a series of streamflow measurements made at several sites along a stream to quantify streamflow gains and losses (Riggs, 1972). A gaining reach is defined as one in which streamflow increases in the downstream direction owing to ground-water inflow, tributary inflow, or precipitation (Blodgett and others, 1992). If ground-water inflow is the only source of streamflow gain, it may be referred to as a seepage gain. In contrast, a losing reach is defined as one in which streamflow decreases by infiltration to the subsurface or by evapotranspiration. A seepage loss is a decrease in streamflow attributable to infiltration only.

Methods of Data Collection and Analysis

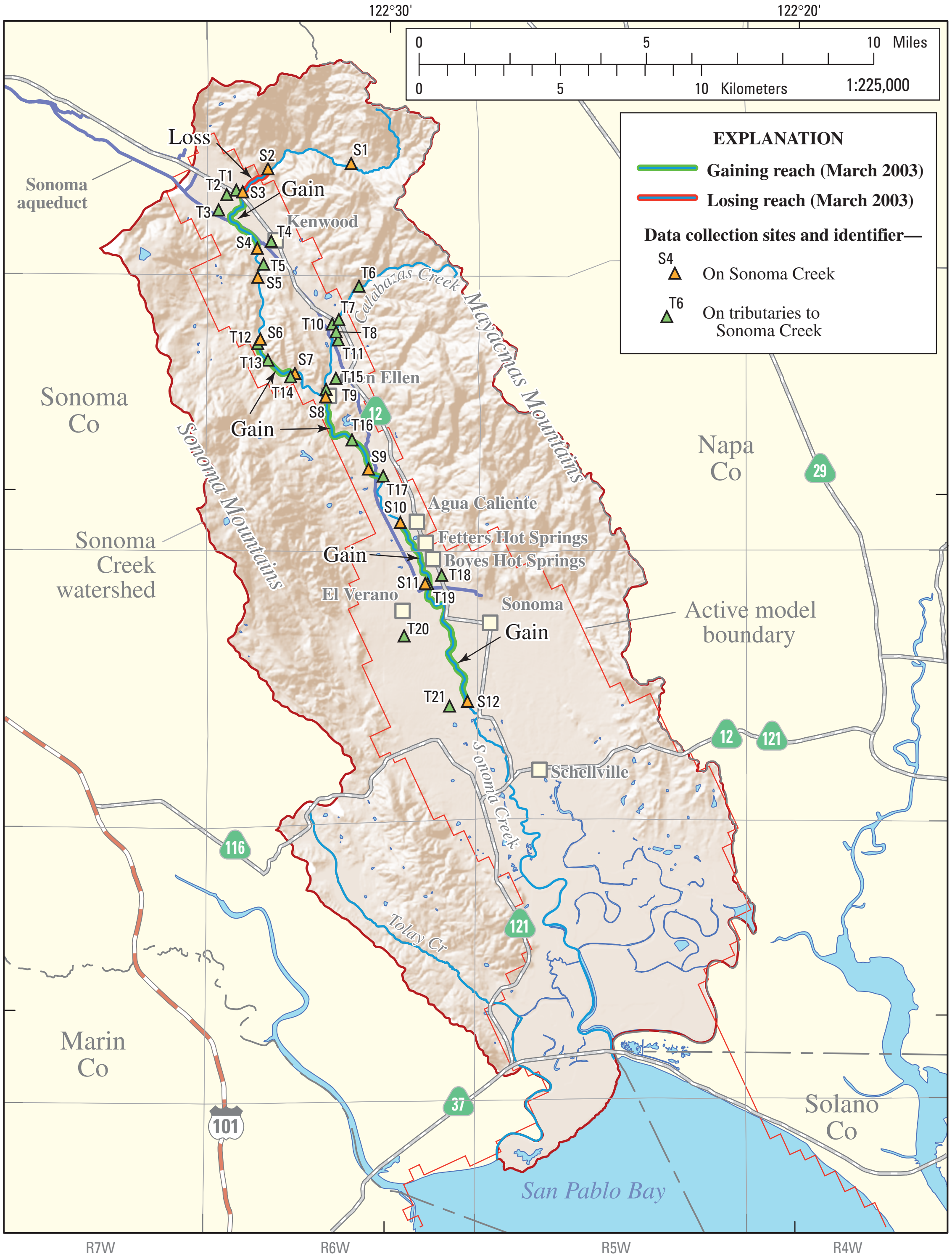
Streamflow, water temperature, and specific conductance were measured at 33 sites in the watershed (*fig. 14*). The sites were assigned identifiers beginning with "S" for those on Sonoma Creek and beginning with "T" for the sites on tributaries; a sequential number, generally increasing in downstream order, is used to complete the identifier. Streamflow was measured at 12 sites along Sonoma Creek from near the headwaters in the Mayacmas Mountains to Watmaugh Road, southwest of Sonoma. Downstream of Watmaugh Road, Sonoma Creek becomes strongly influenced by tides from San Pablo Bay and therefore cannot be accurately measured.

Most of the measurements were made using velocity-area methods, but a modified Parshall flume was used at one site and flows were estimated for two sites [for a description of these methods see Rantz and others (1982)]. The accuracy of streamflow measurements is largely dependent on flow conditions and measurement technique (Rantz and others, 1982). For this study, the accuracy of the streamflow measurements was estimated with consideration of channel characteristics, water depths, velocities, and condition of equipment. All the measurements were estimated to have errors of 10 percent or less, but most had errors of 5 to 8 percent.

Streamflow Measurements and Estimated Gains and Losses

Streamflow gains and losses in Sonoma Creek were calculated for each reach using streamflow measurements from successive stations. Seepage gains or losses were calculated by subtracting tributary inflows between sites on Sonoma Creek. For this study, only those reaches of Sonoma Creek where the seepage gain or loss was 10 percent or greater than the streamflow were classified as gaining or losing. Measured gains and losses smaller than 10 percent may be real; however, the precision of the measurements did not justify classifying these reaches as gaining or losing, so they instead were classified as neutral. Streamflow measurements, water temperature, specific conductance, gains or losses between sites, seepage gains or losses, reach classification, and surface geologic unit are shown in *table 3*.

The seepage run data collected for this study indicate that Sonoma Creek, under conditions similar to May 2003, has a seepage loss in the reach between sites S2 and S3 where it flows across the alluvial fan between the mountain front and Highway 12 (*fig. 14*). Downstream from site S3, Sonoma Creek is mostly gaining flow from ground-water seepage to the stream. Seepage gains were measured between sites S3–S4, S6–S7, S8–S9, and S10–S12. Small differences in streamflow were measured in several reaches between S4 and S10 (USGS gaging station 11458500), but the differences were too small to classify as gaining or losing.



Base from U.S. Geological Survey digital data, 1:250,000, 2003. State Plane Projection, Fipzone 402
Shaded relief base from 1:250,000 scale Digital Elevation Model: sun illumination from northwest at 30 degrees above horizon

Figure 14. Locations of streamflow-measurement sites in the Sonoma Creek watershed, and gains and losses along Sonoma Creek, Sonoma County, California.

Table 3. Instantaneous streamflow, specific conductance, and water temperature measured during a seepage run along Sonoma Creek and its tributaries, Sonoma County, California, May 2003.

[Delta Q, difference in streamflow between stations, exclusive of tributary contributions, in ft^3/s; reach, gain or loss is ascribed only if delta Q is greater than 10 percent of the average streamflow between two stations; losses smaller than 10 percent designated as neutral; reach length, distance between stations, in miles; EC, electrical conductivity at 25°C; °C, degrees Celsius; ft, foot; ft^3/s, cubic feet per second; mi, miles; mm/dd/yyyy, month/day/year; *, denotes measurement made in laboratory, others are field measurements; —, no data]

Streamflow station	Sample date (mm/dd/yyyy)	Instaneous streamflow (ft^3/s)	Field EC (25°C)	Water temperature (°C)	Delta Q (ft^3/s)	Reach	Reach length (mi)	Altitude (ft)	Geologic unit
Sonoma Creek									
Sonoma Creek in Sugar Loaf Park (S1)	05/28/2003	1.45	363	13.5	—	—	—	1,190	Franciscan
Sonoma Creek at Foster Crossing (S2)	05/28/2003	4.17	410	14.5	2.72	—	—	475	Sonoma Volcanics
Sonoma Creek in Sugar Loaf Park (S1)	05/28/2003	1.45	363	13.5	—	—	—	1,190	Franciscan
Sonoma Creek at Foster Crossing (S2)	05/28/2003	4.17	410	14.5	2.72	—	2.31	475	Sonoma Volcanics
Sonoma Creek at Hwy 12 - bridge (S3)	05/28/2003	3.76	391	17.0	–0.41	Loss	0.83	430	Alluvial deposits
Sonoma Creek at Mound Avenue (S4)	05/28/2003	9.90	379	17.0	6.14	Gain	1.75	390	Alluvial deposits
Sonoma Creek at Lawndale Road and Warm Springs (S5)	05/28/2003	10.7	365	17.5	0.80	Neutral	0.80	350	Sonoma Volcanics
Sonoma Creek at Bennett Valley Road (S6)	05/29/2003	11.6	368	16.5	0.90	Neutral	1.50	310	Alluvial deposits
Sonoma Creek at Warm Springs Road (S7)	05/29/2003	14.1	350*	17.2	2.50	Gain	1.38	240	Glen Ellen
Sonoma at Calabazas inflow near Glen Ellen (S8)	05/29/2003	12.9	348*	17.6	–1.20	Neutral	1.16	210	Glen Ellen
Sonoma Creek at downstream side Madrone Street bridge (S9)	05/29/2003	16.5	322	18.0	3.60	Gain	2.18	150	Alluvial deposits
Sonoma Creek at Agua Caliente (S10)	05/30/2003	16.2	313*	17.0	–0.30	Neutral	1.71	105	Alluvial deposits
Sonoma Creek at Verano Road (S11)	05/30/2003	18.8	323	17.5	2.60	Gain	1.60	80	Alluvial deposits
Sonoma Creek at Watmaugh Road (S12)	05/30/2003	21.1	535*	19.0	2.3	Gain	3.28	20	Alluvial deposits
Sonoma Creek at San Pablo Bay	—	—	—	—	—	—	12.23	0	Bay mud

Table 3. Instantaneous streamflow, specific conductance, and water temperature measured during a seepage run along Sonoma Creek and its tributaries, Sonoma County, California, May 2003—Continued.

[Delta Q, difference in streamflow between stations, exclusive of tributary contributions, in ft^3/s; reach, gain or loss is ascribed only if delta Q is greater than 10 percent of the average streamflow between two stations; losses smaller than 10 percent designated as neutral; reach length, distance between stations, in miles; EC, electrical conductivity at 25°C; °C, degrees Celsius; ft, foot; ft^3/s, cubic feet per second; mi, miles; mm/dd/yyyy, month/day/year; *, denotes measurement made in laboratory, others are field measurements; —, no data]

Streamflow station	Sample date (mm/dd/yyyy)	Instaneous streamflow (ft^3/s)	Field EC (25°C)	Water temperature (°C)	Delta Q (ft^3/s)	Reach	Reach length (mi)	Altitude (ft)	Geologic unit
Sonoma Creek Tributaries									
Unnamed tributary at Highway 12, Kenwood (T1)	05/28/2003	0.01	72*	17.3	—	—	—	—	—
Unnamed tributary on Lawndale Road (T2)	05/28/2003	0.84	145*	15.6	—	—	—	—	—
Unnamed tributary on Lawndale Road (T3)	05/28/2003	1.48	—	17.0	—	—	—	—	—
Unnamed tributary in Plaza Park, Kenwood (T4)	05/28/2003	1.48	173*	16.8	—	—	—	—	—
Unnamed tributary at 986 Warm Springs Road (T5)	05/28/2003	0.86	239*	19.5	—	—	—	—	—
Calabazas Creek upstream site below confluence (T6)	05/29/2003	0.76	192	16.0	—	—	—	—	—
Calabazas at Highway 12 (T7)	05/27/2003	1.06	183	17.0	—	—	—	—	—
Calabazas at Dunbar Road (T8)	05/27/2003	—	—	—	—	—	—	—	—
Calabazas near Warm Springs Rd (T9)	05/27/2003	2.42	205	17.5	—	—	—	—	—
Unnamed tributary at Dunbar Road (NF tributary Calabazas) (T10)	05/27/2003	0.36	196	19.6	—	—	—	—	—
Unnamed tributary at Dunbar Road (T11)	05/27/2003	0.22	—	19.0	—	—	—	—	—
Yulupa Creek at Warm Springs Road (T12)	05/29/2003	0.50	215	16.0	—	—	—	—	—
Unnamed tributary near Bennett Valley Road (T13)	05/29/2003	0.25	295	16.5	—	—	—	—	—
Graham Creek at Warm Springs Road (T14)	05/28/2003	0.80	254*	17.3	—	—	—	—	—
Stuart Creek at Arnold Road (T15)	05/27/2003	0.79	209	18.5	—	—	—	—	—
Mill Creek (T16)	05/29/2003	0.20	187*	16.8	—	—	—	—	—
Wilson Creek (T17)	05/29/2003	0.71	135*	16.5	—	—	—	—	—
Agua Caliente Creek at Highway 12 (T18)	05/30/2003	Dry	—	14.0	—	—	—	—	—
Agua Caliente Creek at Sonoma Creek (T19)	05/30/2003	0.25	121	14.0	—	—	—	—	—
Carriger Creek at Arnold Drive (T20)	05/30/2003	0.10	—	15.6	—	—	—	—	—
Fowler Creek at Watmaugh Road (T21)	05/30/2003	0.62	—	18.5	—	—	—	—	—

The set of measurements were made when discharge at the Agua Caliente gage was 16.2 ft^3/s. It is not known if the reaches for the May 2003 seepage run indentified as gaining or losing reaches would have continued to be gaining or losing reaches when flow in the creek was higher or lower. However, on the basis of the May 2003 seepage run, Sonoma Creek generally is a gaining stream downstream of the Kenwood area.

Watershed Hydrologic Budget

A watershed hydrologic budget accounts for inflows and outflows of water to and from the basin and for changes in storage within the basin. The sources of inflow and outflow were discussed in the “Recharge” and “Discharge” sections of this report. Inflows to the Sonoma Creek watershed include precipitation; imported water; and, potentially, ground-water inflow; no surface water or ground water enters the watershed from outside its boundaries. The sources of outflows from the watershed include surface-water runoff, evaporation, transpiration, ground-water outflow, and consumptive use by residents of the area. Evaporation is the net loss of water from surfaces owing to a change in state from liquid to vapor. Transpiration is the net loss of water by evaporation from plant leaves through leaf stomata. Evaporation and transpiration are closely tied in natural ecological systems and thus are often combined in water budgets as one variable, evapotranspiration (ET). The various components of the water budget for the Sonoma Creek watershed can be represented by the equation

INFLOW – OUTFLOW =
CHANGE IN STORAGE

The equation can be expanded to show the individual components of the budget.

$$(P + I + GW_I) - (SW_O + ET + GW_O + C) = \Delta S ,$$

where

P = precipitation,
I = imported water,
GW_I = ground-water inflow,
SW_o = surface-water outflow,
ET = evapotranspiration,
GW_o = ground-water outflow,
C = consumptive residential use, and
ΔS = change in storage,

Under natural conditions (no human intervention), I, GW_I, and C are zero. If a long enough period (in other words, several decades to centuries) is considered, the change in storage is nearly zero because variable inflows and outflows owing to climatic variability tend to balance out over the long term. Under the assumption of no change in storage, the long-term averages of the inflow and outflow components of the budget represent the steady-state values. If these assumptions are applied to the Sonoma Creek watershed, the water-budget equation reduces to

$$P \cong SW_O + ET + GW_O$$

As described in the “Surface-Water Hydrology” section, the estimated mean annual precipitation in the watershed is 269,000 acre-ft, and the estimated mean annual surface-water outflow, or runoff, is 101,000 acre-ft.

Evapotranspiration (ET) is an exceedingly difficult value to quantify accurately for most watersheds. This is because evaporation and transpiration vary widely within a watershed and over time owing to variations in temperature, humidity, wind speed, solar radiation, soil type, slope aspect, plant species, vegetation density, and other factors (Brooks and others, 2003). ET is sometimes estimated from pan evaporation or from methods based on climatic variables (Wilson and others, 2001; Vose and others, 2003). The CADWR maintains stations for measuring and recording climatic variables to allow calculation of the total potential evapotranspiration rate (ET_0) at specific locations (California Department of Water Resources, California Irrigation Information System, 2005). ET_0 is the amount of water lost from a heavily irrigated plot of turf (Penman, 1948), and generally is much larger than the actual ET from native vegetation. The CADWR uses a modified Penman equation (Pruitt and Doorenbos, 1977) to calculate hourly ET_0 Data from the Valley of the Moon and the Carneros CADWR stations, which are within or close to the watershed boundary, show that annual ET_0 is equivalent to about 46.5 inches of water per year. For deciduous orchards in north coast interior valleys, the California Department of Water Resources (1974) estimated an annual ET of 32.5 inches. Native vegetation is believed to use far less water than irrigated crops in many environments. This is because native vegetation has adapted to survive and grow with water available in the local environment.

The Sonoma Creek watershed receives an average of about 30 in. of precipitation annually, about 11.5 in. of this runs off to streams, leaving a remainder of 18.5 in. that represents a maximum mean annual ET. It is unlikely that the mean ET in the Sonoma Creek watershed is as much as 18.5 in. annually because some of the ground water probably discharges naturally to the San Pablo Bay or to the marshlands near the bay. During this study, it was determined that in 9 of the 23 subbasins in the Sonoma Creek watershed, the residual amount of water (equivalent to maximum ET), when runoff was subtracted from precipitation, was between 14 and 17 in. ET for the other 14 subbasins was assumed to be 18 inches. The estimated weighted mean ET for the entire watershed is about 15.8 in., which is equivalent to a total annual ET of about 140,000 acre-ft. This estimate of ET is similar to that estimated by Farrar and Metzger (2003) (15.2 in.) for a part of southeastern Napa County, some 10 mi east of the study area.

Another method of estimating ET is based on the soil-moisture deficit in autumn. Because the watershed has a Mediterranean climate, receiving almost no precipitation about half of the year, plants survive by extracting water from soil moisture. By the end of the dry season, a soil-moisture deficit develops equivalent to the difference between soil moisture at field capacity and the actual soil moisture present. When seasonal precipitation begins in autumn, initially a large part is taken up by the dry soils, and thus streamflow does not increase significantly. A linear regression on the annual runoff versus annual precipitation for the entire watershed shows that about 120,000 acre-ft of precipitation is required before streamflow begins to increase in the autumn, which is equivalent to about 11 inches of precipitation at Sonoma. This suggests that about 120,000 acre-ft/yr of precipitation is needed to replenish soil moisture within the watershed. The 120,000 acre-ft soil-moisture deficit is a minimum estimate of ET; additional ET occurs through the rainy season when soil moisture is intermittently replenished. Much less ET occurs during autumn and winter because temperatures, solar radiation, and leaf area all decrease during that time. In summary, ET estimates for the watershed range from 120,000 to 140,000 acre-ft/yr.

Ground-water outflow from the watershed cannot be measured directly. Under natural conditions, before ground-water extraction through wells began, ground water discharged to the marshlands and probably some amount discharged into the San Pablo Bay. The amount of ground-water outflow can be estimated as the residual of subtracting total runoff and ET from total precipitation giving a range of 28,000 to 48,000 acre-ft/yr. This range provided the initial estimate for steady-state areal ground-water recharge used in the ground-water flow model.

Ground-Water Levels and Movement

Previous investigators developed water-level contour maps of Sonoma Valley (Kunkel and Upson, 1960; California Department of Water Resources, 1982). In addition, ground-water levels have been measured in three networks of wells in Sonoma Valley. In this report the three networks are identified as CADWR, VOM, and COS, in reference to the agencies making the measurements (*fig. 15A–C*, respectively). The CADWR network consists of about 20 wells distributed mainly along the axis of the valley between Sonoma and Kenwood (*fig. 15A*) (California Department of Water Resources, accessed March 1, 2005). Most of this network was developed beginning in 1974, but a small number of wells in the network were constructed prior to 1974. Measurements at some of the wells in the network were discontinued because of difficult access, well-bore obstructions, or other reasons. Other wells were added to replace wells removed from the network or to improve areal coverage of the initial network. Measurements generally were made in April and October at the beginning and ending of the dry season, respectively. The VOM started a ground-water level monitoring program in 1996. Water levels in this primary network are measured a few times per month in five wells (*fig. 15B*). Personnel from the VOM and volunteers have also made measurements in several other wells within and near the boundaries of the VOM service area. By 2004, this secondary well network included 24 wells in which measurements are made in spring and autumn. The primary COS network includes seven wells, which have been monitored since 1998. Beginning in 1999, COS added a secondary network of additional wells within the COS service area (*fig. 15C*).

Data from the three ground-water level networks and additional water levels measured by the USGS during this study were used to prepare a hydraulic-head contour map of the study area for 2003 and a series of graphs showing water-level changes in individual wells. Measurements suspected of having been affected by pumping were excluded from the analysis of water-level conditions in this report. The contour map and the water-level graphs show water-level altitude. Ground-water level data reported by the CADWR are given in altitude and depth below land surface. Data from the VOM and the COS are given in depth below a measuring point. The VOM and COS data were converted to ground-water level altitudes using topographic maps to determine land-surface altitudes at the wells and using notes on the measuring point height. The topographic maps have contour intervals ranging between 10 and 40 ft, and the land-surface altitudes have a corresponding accuracy of plus or minus 2.5 and 20 ft, respectively.

Ground-water-level measurements do not necessarily represent the water table because hydraulic head can vary with depth in an aquifer. Therefore, the water levels in wells open to large depth intervals represent composite heads for the respective depth intervals. The correct interpretation of ground-water level data is, in part, dependent on complete well-construction information, including total depth, perforation intervals, seals, and gravel-pack depth. Complete construction information, however, was not available for several of the wells in the water-level monitoring networks which limited analysis and interpretation of the data.

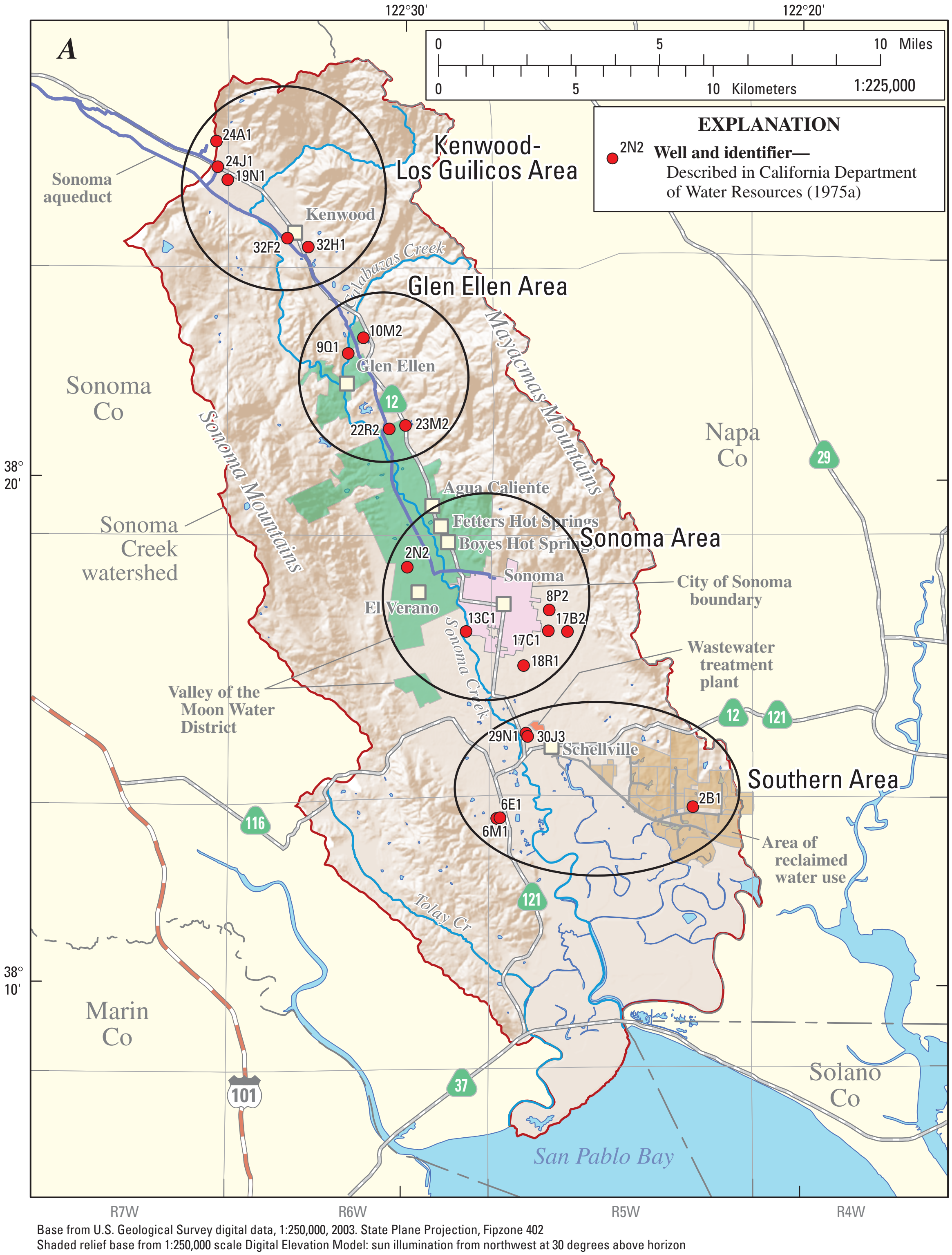
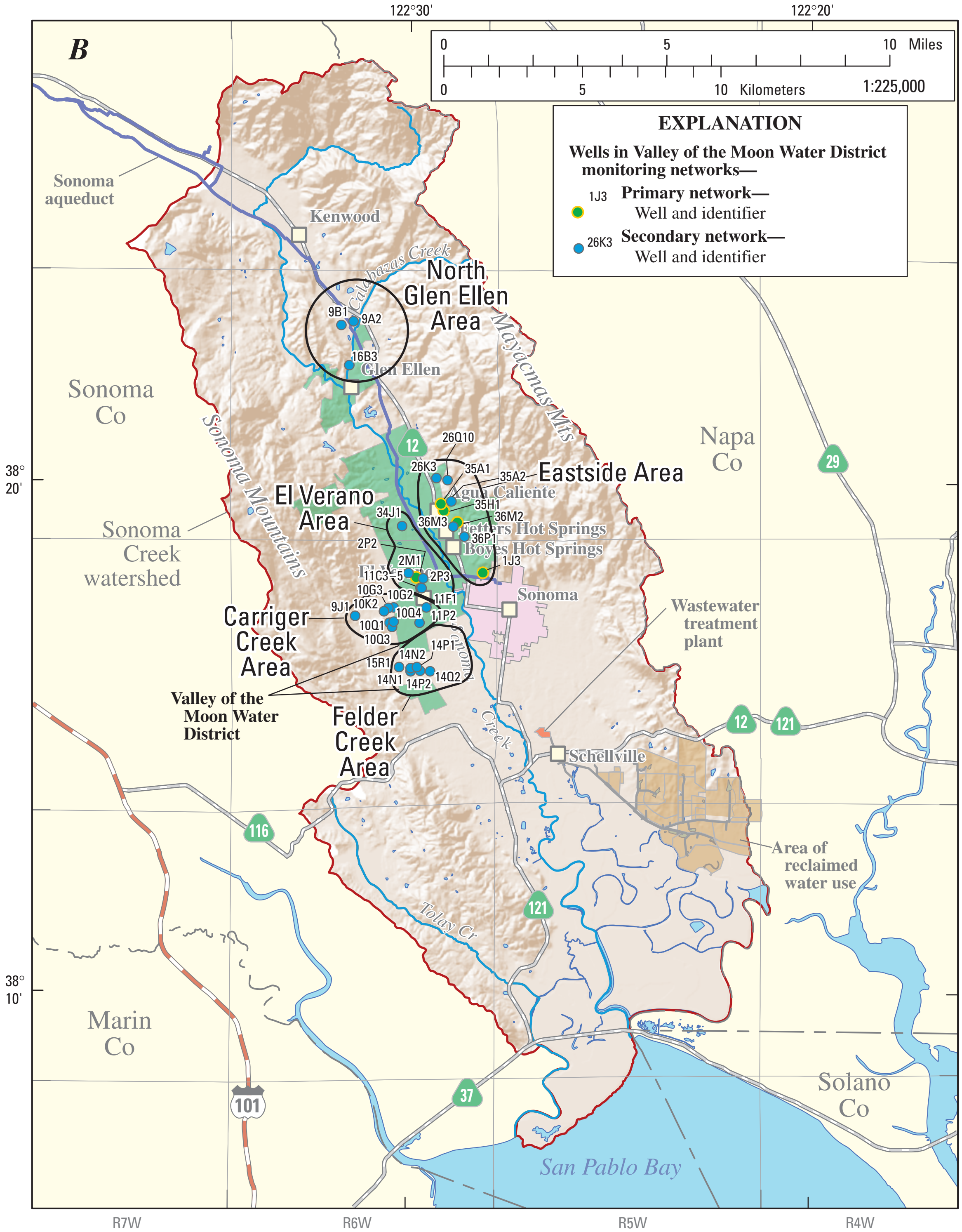
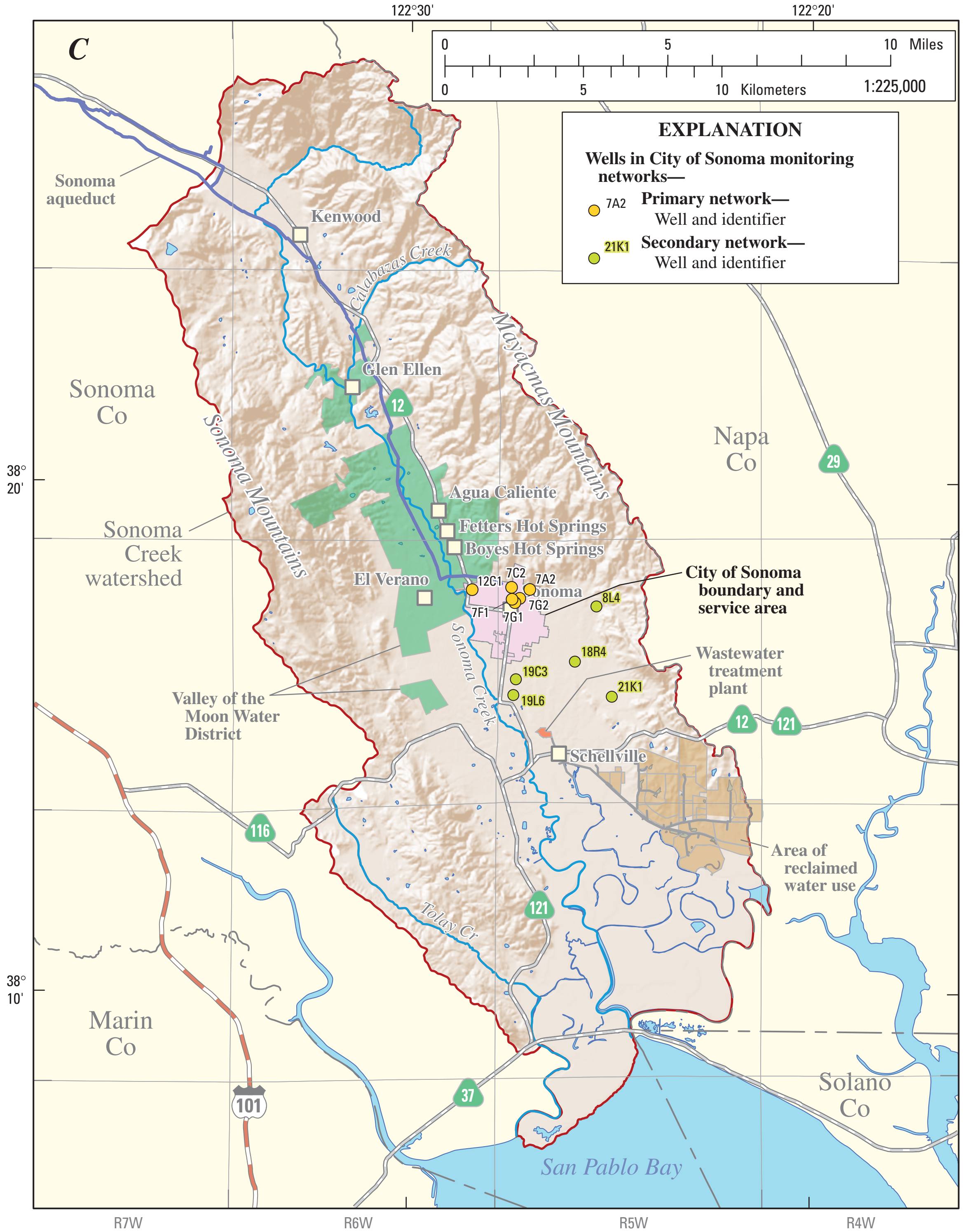


Figure 15. Locations of wells in the water-level monitoring networks in Sonoma Valley, Sonoma County, California. *A*. California Department of Water Resources (CADWR) network. *B*. Valley of the Moon Water District (VOM) networks. *C*. city of Sonoma (COS) networks.



Base from U.S. Geological Survey digital data, 1:250,000, 2003. State Plane Projection, Fipzone 402
Shaded relief base from 1:250,000 scale Digital Elevation Model: sun illumination from northwest at 30 degrees above horizon

Figure 15.—Continued.



Base from U.S. Geological Survey digital data, 1:250,000, 2003. State Plane Projection, Fipzone 402
Shaded relief base from 1:250,000 scale Digital Elevation Model: sun illumination from northwest at 30 degrees above horizon

Figure 15.—Continued.

Comparison of Water-Level Contour Maps: 1950, 1980, and 2003

The water-level maps published by Kunkel and Upson (1960) and California Department of Water Resources (1982) are reproduced in this report (*figs. 16* and *17*) to compare with a new map showing water levels in spring 2003 (*fig. 18*). It is important to note that all the water-level contour maps in *figure 18* are based on a composite of data from wells with different depths.

The earliest map, by Kunkel and Upson (1960), shows water-level contours for spring 1950 for the area of the valley between Glen Ellen and San Pablo Bay (*fig. 16*). This map is the best representation of water levels before significant ground-water withdrawals from the valley began. The general direction of ground-water movement was from recharge areas in the mountains around the perimeter of the study area toward the valley axis and from the northwest end of the valley southeastward toward San Pablo Bay. Water levels are approximately at sea level over a broad area of marshland south of Schellville.

The CADWR map (*fig. 17*) shows water-level contours for autumn 1980 for the entire valley. The water levels are a maximum of 480 ft above NGVD 1929 in the extreme northwest part of the valley and drop at a fairly uniform gradient to 60 ft near Sonoma. The gradient flattens from Sonoma to the marshlands south of Schellville where water levels are approximately at sea level. For the part of the area in *figure 17* with contours on the 1950 map (*fig. 16*), water levels are very similar; but, in general, the water levels in autumn 1980 are 10 to 20 ft lower than the water levels in spring 1950. This probably was mostly due to the seasonal fluctuations in water levels, which generally reach a maximum in spring and drop through the summer and early autumn. In summary, the water levels in the area between Glen Ellen and the marshlands south of Schellville changed little between 1950 and 1980.

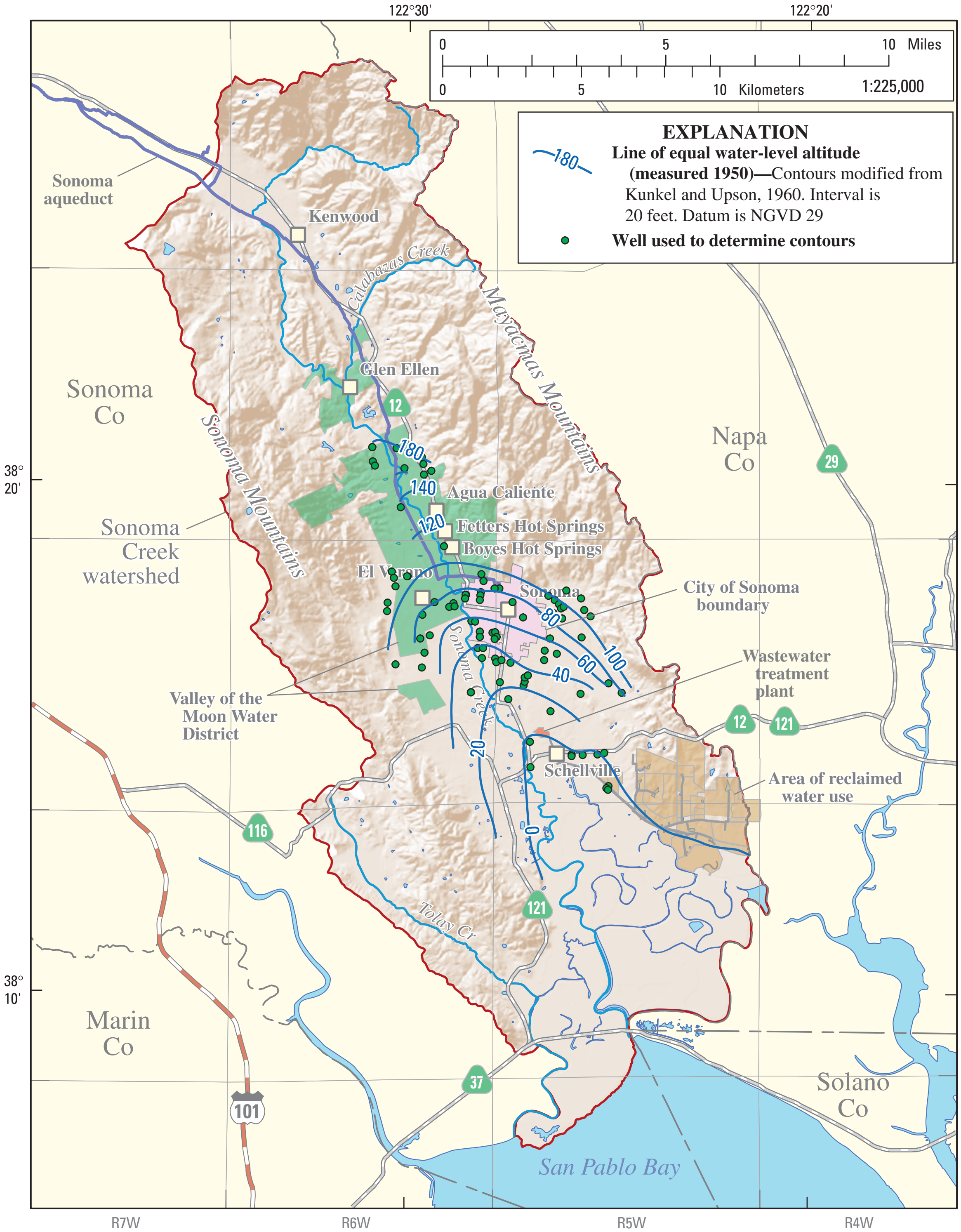
Water levels changed significantly between 1980 and 2003 (*figs. 17* and *18*). In the northwest part of the area, near Kenwood, heads generally were 10 to 20 ft higher in spring 2003 than in autumn 1980. This primarily was due to the general seasonal pattern of higher water levels in spring than in autumn. Water levels in the Glen Ellen area were very similar in 1980 and 2003 (*figs. 17* and *18*); because the 1980 data are for autumn and the 2003 data are for spring, this similarity may indicate that water levels generally declined in this area. From Boyes Hot Springs southward, water-level contours for 2003 show a more complicated pattern than those for 1980. Some of this complexity may result from a greater number of data points used in 2003 than in 1980, but some of the complexity could be due to changes in water levels caused by greater extraction of ground water. In areas of heavy ground-water pumping, water levels are lower, which can cause pumping depressions to develop. *Figure 18* shows that in spring 2003, pumping depressions had developed in at least two areas: southeast of Sonoma and southwest of El Verano. The lowest water level southeast of Sonoma is about 40 ft below sea level. Southwest of El Verano, water levels have declined to about 20 ft above sea level.

Long-Term Changes in Ground-Water Levels in Different Parts of the Sonoma Valley

Graphs showing long-term water-level changes were made using data from the three networks in Sonoma Valley (*Appendix B*, *fig. B-1*). Because the period of record is different for each network, data for each network are shown separately. This allowed the time scale to be maximized. The graphs show data for groups of wells; the groupings were based primarily on geographic location to allow comparison of water-level changes in various parts of the study area.

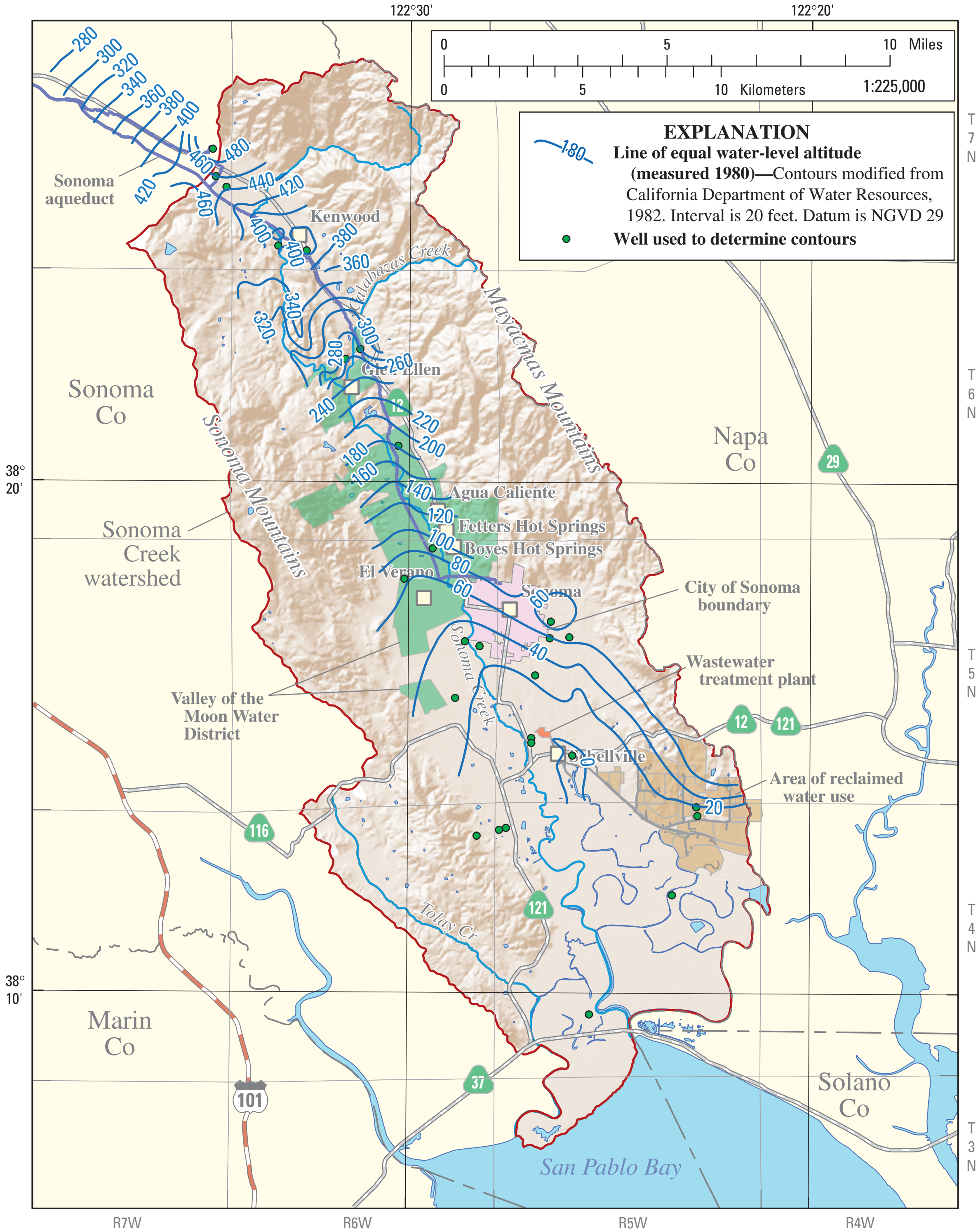
When a large area of the salt marshes was drained in the 1880s to 1930s, ground-water levels in parts of the southern end of the valley undoubtedly declined. In the northern part of the study area, ground-water levels probably declined following the draining of 5,000 acres of marshland near Kenwood in the 1880s. In the early 1900s, water flowed to land surface from many of the wells drilled in Sonoma Valley; by the 1950s, most of the wells had ceased flowing (Kunkel and Upson, 1960). As ground-water pumpage increased through the 1960s, reports of ground-water level declines were common and some shallow wells went dry. But after deliveries of surface water from the Russian River began in 1965, ground-water levels recovered (California Department of Water Resources, 1982) to some extent and changed little through 1980. Although water-level records for the first half of the 1900s are insufficient for creating hydrographs, records for five wells in the study area have at least 20 years of data that begin in the 1960s or earlier (*fig. B-1A*).

Four of these five wells are located between the southern part of Sonoma to Schellville, and one is near Kenwood (*fig. 15A*). The water-level data show no distinct trend for the period 1950 to 2004. Water levels do fluctuate seasonally, generally between 10 and 20 ft. Throughout Sonoma Valley, the annual maximum water level generally occurs in the spring (March or April) and the annual minimum water level generally occurs in autumn (September or October). The change in level between autumn and spring is a measure of ground-water-level recovery in the aquifer near the well. The amount of recovery depends on recharge derived from precipitation during the previous season and the amount of reduction in ground-water pumping during October to February.



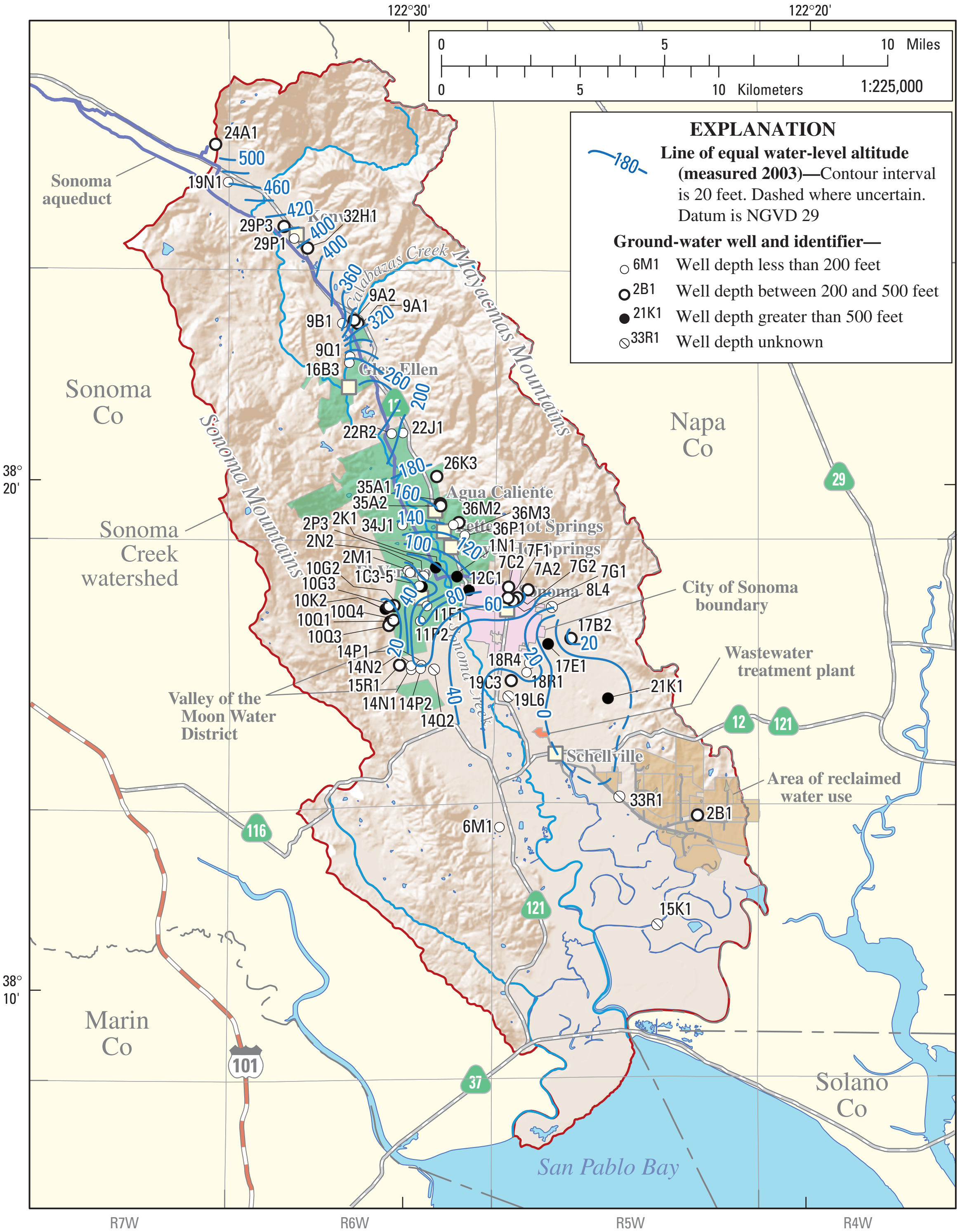
Base from U.S. Geological Survey digital data, 1:250,000, 2003. State Plane Projection, Fipzone 402
Shaded relief base from 1:250,000 scale Digital Elevation Model: sun illumination from northwest at 30 degrees above horizon

Figure 16. Spring 1950 water levels in Sonoma Valley, Sonoma County, California.



Base from U.S. Geological Survey digital data, 1:250,000, 2003. State Plane Projection, Fipzone 402
Shaded relief base from 1:250,000 scale Digital Elevation Model: sun illumination from northwest at 30 degrees above horizon

Figure 17. Autumn 1980 water levels in Sonoma Valley, Sonoma County, California.



Base from U.S. Geological Survey digital data, 1:250,000, 2003. State Plane Projection, Fipzone 402
Shaded relief base from 1:250,000 scale Digital Elevation Model: sun illumination from northwest at 30 degrees above horizon

Figure 18. Spring 2003 water levels in Sonoma Valley, Sonoma County, California.

Several new wells were added to the CADWR network after 1974; the data for these wells are shown grouped into four areas based on geographic location (*fig.15A*). The network included five wells in the southern area, which range in depth from 80 to 375 ft below land surface (bls) (*fig. B-1B*). Measurements in well 5N/5W-29N1 were discontinued in 1981, the available data show no significant trend in water level. Three of the monitor wells that are still active show no significant long-term trend in water levels. The fourth active monitor well (4N/5W-2B1), which is the deepest, shows a steep decline in water levels between 1989 and 1998 and large seasonal fluctuations through 2000; by 2002, the water levels returned to altitudes similar to the mid 1980s. The large water-level change could be caused by increased pumping of nearby wells between 1989 and 2000.

The Sonoma area of the CADWR network consists of six wells, ranging in depth between 64 and 600 ft (*fig. 15A*, *B-1C*). Data for two of the wells (5N/5W-17C1 and -18R1) show no significant water-level trend for the period of record; both wells are 150 ft bls or less deep. Data for three wells (5N/5W-8P2, 5N/6W-2N2, and 5N/6W-13C1) show distinct trends of declining water levels for the period of record. Increases in seasonal water-level fluctuations in well 8P2 (245 ft bls) were large during the 1990s compared with fluctuations in earlier years; possibly caused by increased ground-water extraction near this well. Data for well 5N/5W-17B2 (493 ft bls) show a variable long-term change; water levels declined during the late 1980s, remained low through the 1990s, and then rose to levels about 20 ft lower than in the early 1980s.

The Glen Ellen area of the CADWR network includes four wells ranging in depth between 96 and 224 ft bls (*fig. 15A*, *B-1D*). Data for three of the wells show no significant trend in ground-water levels over the period of record. Data for well 6N/6W-10M2 (the deepest of the four wells) show ground-water levels declined about 30 ft between 1974 and 2000. The seasonal fluctuations increased to as much as 40 ft between the late 1970s and 1994 after which water-level recoveries between autumn and spring decreased to 10 ft or less. The data for well 10M2 suggest that ground-water extraction near the well has increased since the late 1970s and that by the mid 1990s ground-water pumping was done at a more constant rate throughout the year. Ground-water levels periodically are above land surface at well 6N/6W-22R, which is 159 ft bls deep.

The Kenwood area of the CADWR network includes five wells, ranging in depth between 76 and 406 ft bls (*fig. 15A*, *B-1E*). Data for four of these wells show no significant water-level trends over the period of record. Data for well 7N/7W-24A1 (385 ft deep) show a trend of declining water levels and increasing annual fluctuation, indicative of increased ground-water extraction near this well. Perforation data are not available for this well.

Static water-level data for the five wells in VOM's primary network (*fig. B-1F*) were collected non-uniformly over time. The discontinuous nature of the data from these wells makes definition of long-term trends more difficult. However, at least three of the wells (6N/6W-35A1, -35H1, and -36M2) show trends of declining water levels since the late 1990s.

Twenty-four wells in the VOM's secondary network (*figs. B-1G–K*) are grouped into five geographic areas (*fig. 15B*). Most of the wells have 5 or fewer years of record. A comparison of the earliest spring water-level measurements for these wells with the latest (mostly 2004) spring measurements shows insignificant changes for most wells. Water-level data for a few of the wells, however, do show significant changes in spring water levels as noted in the following. Data for well 6N/6W-16B3 (124 ft bls deep), in the North Glen Ellen area, show a water-level decline of about 10 ft over a 4-year period (*fig. B-1G*). In the El Verano area (*fig. 15B*), three piezometers are located together (5N/6W-11C3, 4, and 5). Data for the shallow piezometer (92 ft bls deep) show no significant change in water level, but data for the two deeper piezometers (562 and 674 ft bls deep) show about 6 ft of water-level decline in 3 years. In the Carriger Creek area, six wells were monitored; they range in depth between 90 and 595 ft bls (*fig. B-1I*; *Appendix C*). Data for wells 5N/6W-10Q1 (595 ft deep) and -10R2 (240 ft deep) show water-level declines of 8 and 16 ft, respectively, over a 3-year period (*fig. B-1I*). However, data for three other wells, ranging in depth between 90 and 485 ft, in that same area show essentially no change, and the water level in well 5N/6W-10G3 (312 ft deep) rose by 6 ft. The perforated intervals of only two of the six wells are known. In the Felder Creek area, VOM monitors water levels in six wells that range in depth between 84 and 355 ft (the depth of one well is unknown). Water-level data were available for all six wells for spring 2000 and spring 2004 (*fig. B-1J*). Water-level changes range between +6 ft and –2 ft over the 4-year period. In the Eastside area (*fig. 15B*), VOM monitors three wells that range in depth between 80 and 260 ft. One well (well 6N/6W-26K3) had only four water-level measurements over a 2-year period (*fig. B-1K*), and it was not possible to discern a trend. Water-level changes in the other two wells were +6 ft and –6 ft over a 4-year period and also show no clear general trend in this area.

Data for the six wells in the COS primary network (*fig. 15C*), which range in depth between 75 and 730 ft bls, show that water levels (*fig. B-1L*) in four wells declined by 12 to 21 ft in 5 years. The water level in well 5N/5W-7A2 (210 ft deep) declined 24 ft in 4 years, but the water level in well 5N/5W-7F1 (165 ft deep) showed little change in 4 years. Water levels in four wells in the COS secondary well network (*fig. B-1M*) declined by 5 to 24 ft in 4 years; well 5N/5W-19L6 had no change. Well depth and perforated intervals are not known for three of these wells.

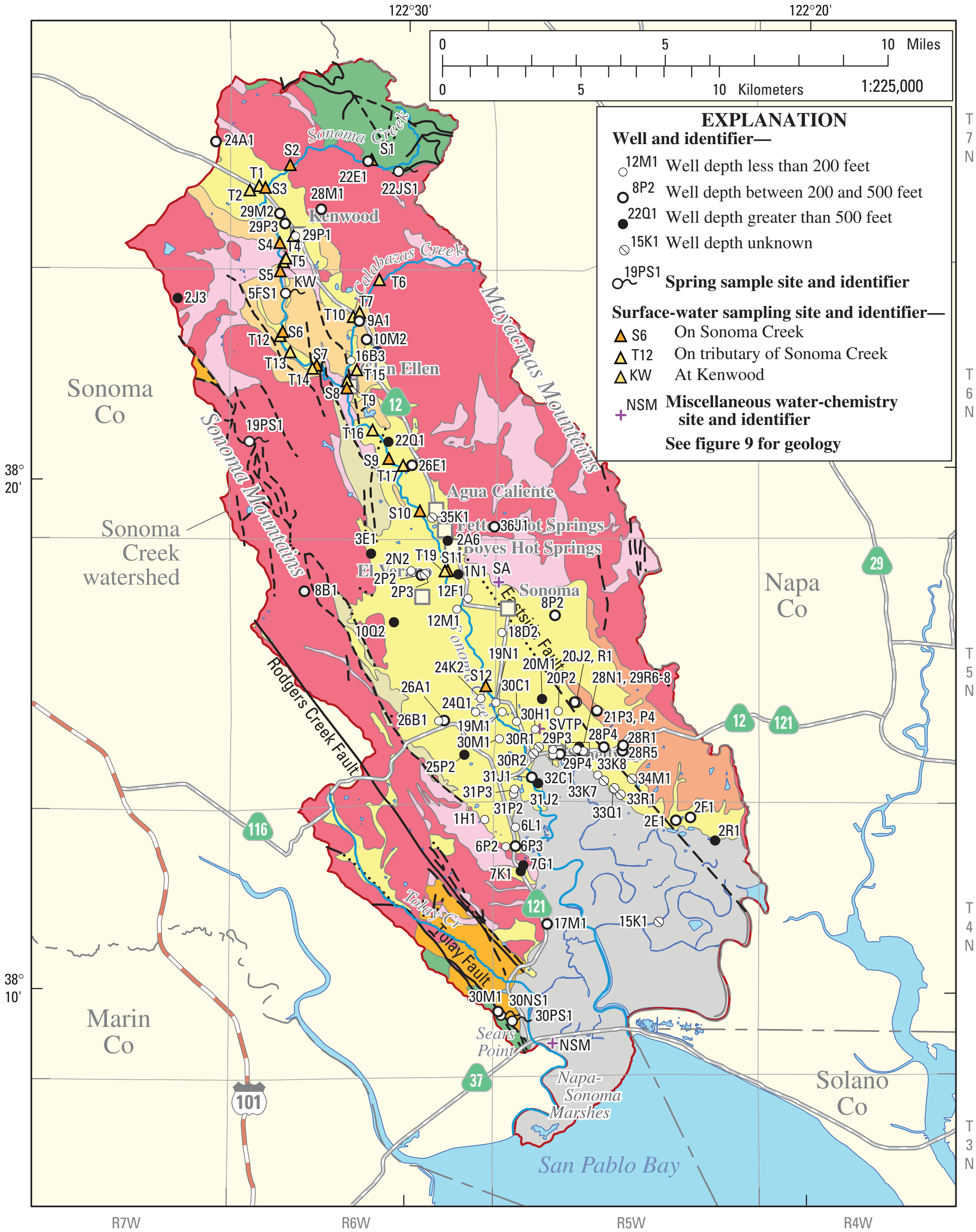
In summary, ground-water levels have declined in some parts of the study area, especially in the central part near Sonoma, El Verano, and the Carriger Creek area. Most of the wells with water-level declines have 5 or fewer years of measurements, so it is inconclusive as to whether these declines are long-term trends or an indication that ground-water levels are declining at an accelerated rate since 1999 or 2000. These water-level declines could be related in part to variations in precipitation over the years. In water year 2000 (WY2000), the area received less than 60 percent of the long-term mean annual precipitation. With the exception of WY2000, however, precipitation was near or above the long-term mean since WY1995. Most of the water-level declines probably have been caused by increased ground-water withdrawals in localized areas.

The water-level contour maps (*figs. 16–18*) provide the best means of identifying broad areas where water levels have changed significantly. Comparison of these maps reveals two areas, near Sonoma and southwest of El Verano, where significant water-level changes have occurred and pumping depressions have formed. The parts of the study area up-valley from Sonoma do not show any clear trend of declining water levels over broad areas. However, because different seasons are represented in the hydraulic-head maps for 1980 and 2003, data for the two periods are not directly comparable, and areas with less than 20 ft of change may be difficult to discern. Note that many of the water-level changes described above have occurred since 1999–2000. The ground-water simulation model extends only through 2000.

Surface-Water and Ground-Water Chemistry

Water-chemistry data compiled by the USGS and the CADWR were used to help characterize the spatial variations in surface- and ground-water quality and to help identify the source and movement of ground water in the Sonoma Valley. Surface-, spring-, and ground-water data from sites located throughout the Sonoma Valley were used for this study (*fig. 19*). *Appendix C* provides construction data for wells sampled as part of this study. Major ion, trace element, silica, and nutrient data from 3 sites along Sonoma Creek, 2 springs, and 30 wells sampled during 2002–04 are summarized in *Appendix D*. Water use for some of the 30 wells is unknown, but at least half of these wells are believed to be used for drinking water and the remaining wells are used primarily for irrigation and (or) non-potable uses. Specific conductance and water temperature measurements are summarized in *table 3* for 33 streamflow measurement sites along and tributary to Sonoma Creek sampled in 2003, and are summarized in *Appendix E* for 74 wells sampled from 1969 through 2004, and 2 miscellaneous sources sampled in 2003. Data for stable isotopes of oxygen (oxygen-18) and hydrogen (deuterium) are summarized in *Appendix F* for samples collected during 2002–04 from 8 streamflow measurement sites along and tributary to Sonoma Creek, 4 springs, 33 wells, and 3 miscellaneous sources. USGS water-chemistry data presented in this report include data for 13 wells sampled in 2004 for the Ground-Water Ambient Monitoring and Assessment Program, a comprehensive statewide effort designed to understand and identify risks to ground-water resources (Kulongoski and Belitz, 2004).

Ground-water-quality in the Sonoma Valley has been monitored since 1949. Most analyses represent one-time samples for short-term studies or individual well-specific assessments. Water-chemistry data for 75 wells (including wells sampled for this study and data compiled from other sources) are included in this report (*fig. 19*, *Appendixes C*, *D*, and *E*), but only 28 of these wells have complete cation and anion data needed for determining the most recent (2002–04) ionic composition of ground water. A few groups of wells have repeatedly been sampled every 2 to 3 years for more than 10 years. Wells identified as public-supply wells are required by State law (Title 22, California Code of Regulations) to be sampled for inorganic, organic, radiological, and microbiological constituents on a routine basis. The longest sustained water-quality monitoring effort in the Sonoma Valley has been done by the CADWR. Since the late 1950s the CADWR has sampled and analyzed ground water for major ions (calcium, magnesium, potassium, sodium, chloride and sulfate), boron, nitrate, total dissolved solids, total alkalinity, specific conductance (referred to as either specific conductance [USGS] or electrical conductance (CADWR]), pH, and water temperature. Water-chemistry data covering a minimum of 10 and maximum of 46 years are available for 18 wells monitored by the CADWR, including 12 wells that were being monitored as of 2004. Samples from these wells are collected on average every 2 to 3 years between July and September.



Base from U.S. Geological Survey digital data, 1:24,000, downloaded 2003. State Plane Projection, Fipzone 402

Figure 19. Locations of ground-water, spring-water, surface-water, and miscellaneous water-chemistry sampling sites in the Sonoma Valley, Sonoma County, California, 2002–04.

In general, water chemistry and (or) isotopic composition may vary geographically and with depth in ground-water systems. Ground-water wells in the study area have a wide range of completed depths and perforated or screened intervals. Most of the wells included in this study were completed (cased with perforated or screened intervals) to the same or nearly same depth as the well boring was drilled (hole depth). Some wells, especially the older ones, may have been constructed as uncased open holes, but this information is unavailable. Among the 75 wells with major ion, specific conductance, water temperature, and stable isotope data used in this study, 26 wells (35 percent) were completed at a depth of less than 200 ft bls, 26 (35 percent) wells are were completed at depths between 200 ft and 500 ft bls, 14 wells (19 percent) were completed at a depths greater than 500 ft bls, and the remaining 9 have questionable or no depth information (*Appendix C*). Perforation information is available for 42 of the 75 water-chemistry wells. The average (middle) perforation depth for each depth category is 100 ft bls (completed well depth less than 200 ft), 247 ft bls (completed well depth 200 to 500 ft) and 528 ft bls (completed well depth greater than 500 ft). To make a statistically meaningful comparison of water chemistry or isotopic values, the wells have been divided into the three depth categories indicated. These depth categories coincide with the geohydrologic units described in the “Ground-Water Hydrology” section.

Methods of Water Sampling and Analysis

Surface-water samples analyzed for major ions, selected trace elements, and nutrients were collected using a DH-81 sampler according to methods given in Wilde and others (1999). Spring water samples were collected in a churn splitter placed directly under the open end of a discharge pipe leading from a sealed collector box located directly over the spring. Ground-water samples from wells sampled by the USGS were collected from faucets either at or near the well head to minimize potential chemical alteration of the water between the well and the sampling point. Prior to the collection of the ground-water samples, a minimum of three casing volumes of water were purged from the wells. Sequential measurements of specific conductance, pH, and temperature were made at 5-minute intervals until readings stabilized to ensure that they were representative of the ground water. All USGS samples collected for the analysis of major ions, trace elements, silica, and nutrients were collected, treated, and preserved following procedures outlined by the U.S. Geological Survey (1997 to present). These samples were analyzed at the USGS National Water Quality Laboratory at Arvada, Colorado, using standard analytical methods described by Fishman and Friedman (1989), Fishman (1993), and Struzeski and others (1996). All CADWR samples were analyzed at the California Department of Water Resources Bryte Analytical Laboratory in West Sacramento, California (Bruce Agee, California Department of Water Resources, unpub. data, 2005). Laboratory analyses and field measurements were done according to the referenced methods of the American Public Health Association (1999), and the U.S. Environmental Protection Agency (1993, 1994).

Specific conductance and water temperature measurements were made at 44 wells and 2 springs in the southern part of the Sonoma Valley in September 2003 to assess salinity in that part of the study area. Most measurements were made at a faucet at or near the well head or spring collector box. At several of the wells, the pumps could not be turned on during the site visit so measurements were made from well pressure tanks. These measurements may be unrepresentative of ambient subsurface conditions (see *Appendix E* footnotes). Final measurements were taken after readings stabilized or after observing the full range of readings for cycling wells. Temperatures were measured to 0.1°C, but are reported to the nearest 0.5°C.

Water samples for analysis of stable isotopes of oxygen-18 and deuterium were collected in unrinsed 60-milliliter (mL) glass bottles. Surface-water samples were collected directly from creeks by immersing the bottle until filled. Spring-water samples were collected by placing the sample bottle directly at the open end of a collector-box discharge pipe and allowing it to overflow with several volumes of water prior to being capped. Ground-water samples were bottom filled using tygon tubing connected to the sampling point and allowed to overflow with several sample volumes of water prior to being capped. Bottles were capped with conical-seal caps. Stable isotopes of oxygen and hydrogen were analyzed by the USGS Isotope Fractionation Project at Reston, Virginia, using a hydrogen-water-equilibration technique (Coplen and others, 1991; Revesz and Coplen, U.S. Geological Survey, unpub. data, 2004) and an automated version of the carbon dioxide equilibration technique of Epstein and Mayeda (1953) (Revesz and Coplen, U.S. Geological Survey, unpub. data, 2004).

General Chemical Composition of Surface, Spring, and Ground Water

Dissolved-oxygen concentrations in all waters ranged from less than 0.1 to 11.1 milligrams per liter (mg/L); the highest concentrations were measured in the samples from Sonoma Creek with dissolved-oxygen concentrations in the four samples ranging from 8.7 to 11.1 mg/L (*Appendix D*). The dissolved-oxygen concentrations of 16 water samples from 15 wells (4N/5W-2F1, 5N/5W-20M1, -30H1, 5N/6W-1N1, -2P2, -2P3, -3E1, -10Q2, 6N/6W-9A1, -16B3, -22Q1, -36J1, 7N/6W-22E1, -29P3, and 7N/7W-24A1) ranged from 0.1 to 6.3 mg/L with a median value of 1.2 mg/L; these concentrations show no correlation with well depth.

The pH of all samples collected by both the USGS and the CADWR during 2002–04 ranged between 6.1 and 8.8 (*Appendix D*); a total of four well samples did not meet the secondary drinking-water standard range of 6.5 to 8.5 established for the protection of taste, odor, or appearance of drinking water (U.S. Environmental Protection Agency, 2002).

Specific electrical conductance (SC), a measurement of the ability of water to conduct an electrical current and an indicator of ionic concentration, varied widely depending on the type of sample, the location, and the time of year. The conductivity of water from Sonoma Creek and several tributaries during the May 2003 seepage run ranged from 72 to 535 microsiemens per centimeter (μS/cm) (*table 3*). The lowest conductivity values were measured in samples from Sonoma Creek tributaries; all tributary samples had conductivity values less than 300 μS/cm. The highest conductivity values were measured in samples collected from Sonoma Creek where the conductivity of all the samples exceeded 300 μS/cm. The highest conductivity value of 535 μS/cm was measured in a sample from Sonoma Creek at Watmaugh Road (S12) (*fig. 19*). Site S12 was the most downstream location sampled on Sonoma Creek and it may represent the inland extent of mixing of fresh and brackish water from the sloughs of San Pablo Bay during high tide. Specific conductance of creek water varied depending on the time of year and flow conditions. For example, at the site on Sonoma Creek at Agua Caliente (S10) conductivity was lower in May 2003 than in November 2002 corresponding with higher streamflow (*table 3*, *Appendix D*). The conductivity of samples from springs ranged from 154 to 2,140 μS/cm, and the conductivity of water from wells ranged from 124 to 2,020 μS/cm (*Appendix E*). The conductivity of the water from 2 springs and from 19 of the 75 wells sampled by both the USGS and the CADWR during 2002–04 exceeded the secondary drinking-water standard recommended level of 900 μS/cm (California Department of Health Services, 2003). The high conductivity of the samples from these particular wells is discussed in greater detail in a later subsection of this report (“High Salinity Waters”).

Major-ion concentrations in surface- and ground-water samples are plotted in a trilinear diagram (*fig. 20*). A trilinear diagram shows the proportions of common cations and anions for comparison and classification of water samples independent of total analyte concentrations (Hem, 1985). Trilinear diagrams can be used to identify groups of samples that have similar relative ionic concentrations (Freeze and Cherry, 1979). In general, *figure 20* shows that most samples are bicarbonate type water and fall along a mixing line from sodium-potassium type water to calcium-magnesium type water. On the basis of the trilinear diagram, water samples in the Sonoma Valley can be divided into three groups (*fig. 20*). Ground-water wells sampled more than once during 2002–04 for major ions (5N/5W-18D2, -28R1, 5N/6W-3E1, -12F1, 6N/6W-9A1, and -10M2) are represented in *figure 20* by the earliest analyses listed in *Appendix D*; the major ion composition in ground-water wells sampled more than once was generally consistent.

Group 1 includes samples from 14 wells, 2 springs, and 3 surface-water sites on Sonoma Creek, including 2 samples collected at Agua Caliente (S10) in November 2002 and June 2003. Most group 1 samples can be characterized as a mixed-bicarbonate type water. Magnesium was the predominant cation in samples from six wells in group 1 (5N/5W-18D2, -30H1, 5N/6W-2P3, -12M1; 7N/6W-22E1, -29P1), one spring (6N/6W-19PS1), and both surface-water samples from Sonoma Creek at Agua Caliente (S10). Sodium was the predominant cation in samples from six other wells in group 1 (5N/6W-1N1, -2N2, -12F1; 6N/6W-9A1; 7N/6W-29P3; and 7N/7W-24A1), and one spring (7N/6W-22JS1). In terms of a chemical equivalence basis (milliequivalents per liter, meq/L), both magnesium and sodium constituted less than 50 percent of all cations in their respective samples. Similarly, calcium was the predominant cation in the remaining two well samples with mixed cation-bicarbonate type water (wells 5N/6W-2P2 and -10Q2). Two surface-water samples in group 1, Sonoma Creek at Kenwood (KW) and Sonoma Creek at Lawndale Rd (S5), can be characterized as magnesium-bicarbonate type waters where magnesium constitutes more than 50 percent of total cations.

Group 2 includes samples collected from four wells, including one well (6N/6W-35K1) that yields geothermal water. The chemical composition of group 2 samples can be characterized as a sodium-mixed anion (4N/5W-2F1), mixed cation-chloride (5N/5W-28N1), mixed cation-mixed anion (6N/6W-10M2), and sodium-chloride (6N/6W-35K1) type water. The predominant cation and anion of mixed samples was sodium and chloride, respectively.

Group 3 includes samples collected from 10 wells (5N/5W-8P2, -20M1, -20R1, -28R1, 5N/6W-3E1, -25P2, 6N/6W-16B3, -22Q1, -26E1, and -36J1). The composition of all samples in group 3 can be characterized as sodium-bicarbonate type water.

Water samples that plot within the same group may be indicative of waters that are of similar origin or may have undergone changes in composition as a result of similar chemical processes. For example, samples in Group 3 may represent waters that may have acquired their sodium bicarbonate composition through cation exchange along ground-water flow paths (sodium cations on the clay minerals being replaced by calcium and magnesium cations, releasing the sodium cations to water) (Drever, 1982).

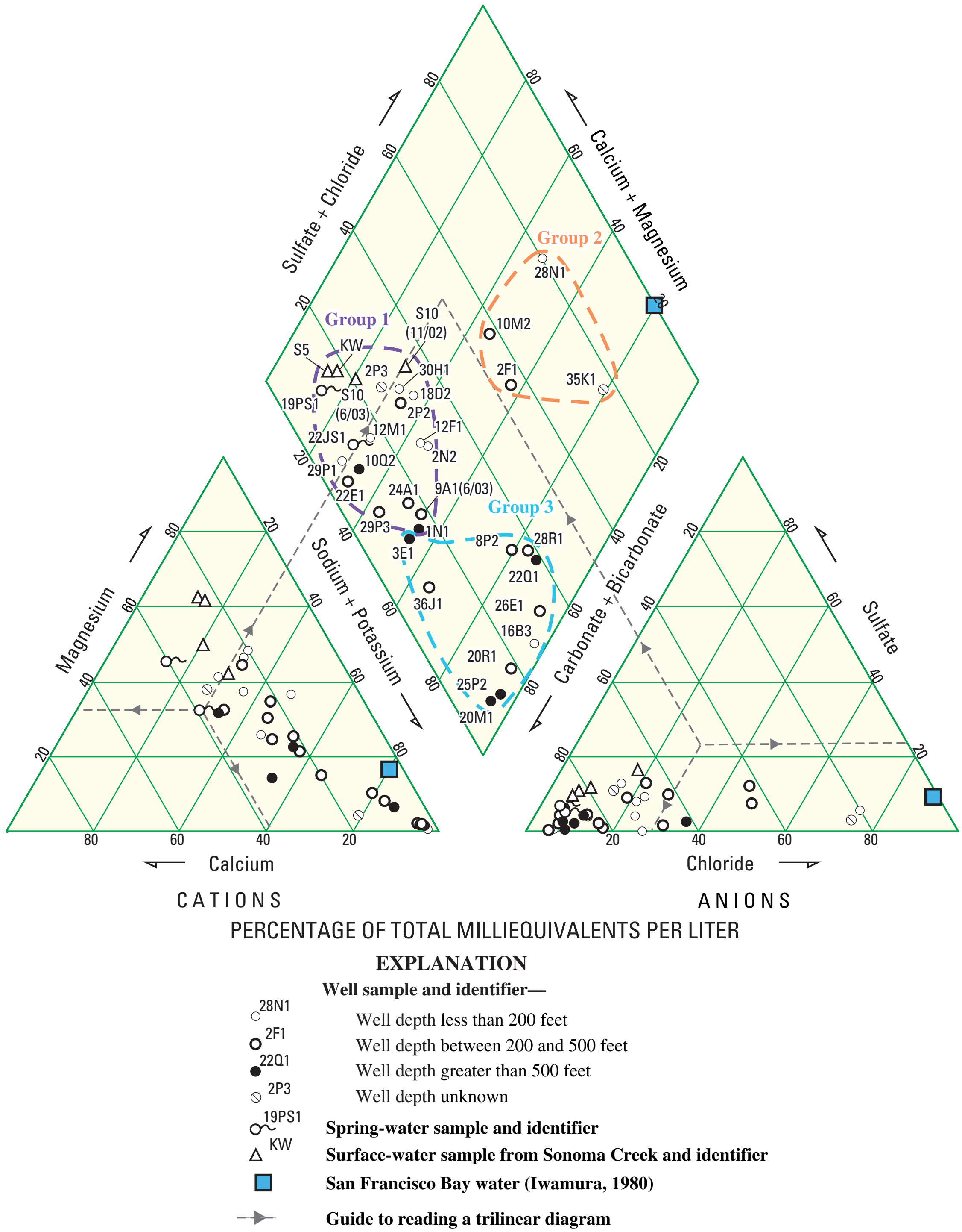


Figure 20. Chemical composition of water from selected ground-water, spring-water, and surface-water sampling sites in the Sonoma Valley, Sonoma County, California, 2002–04.

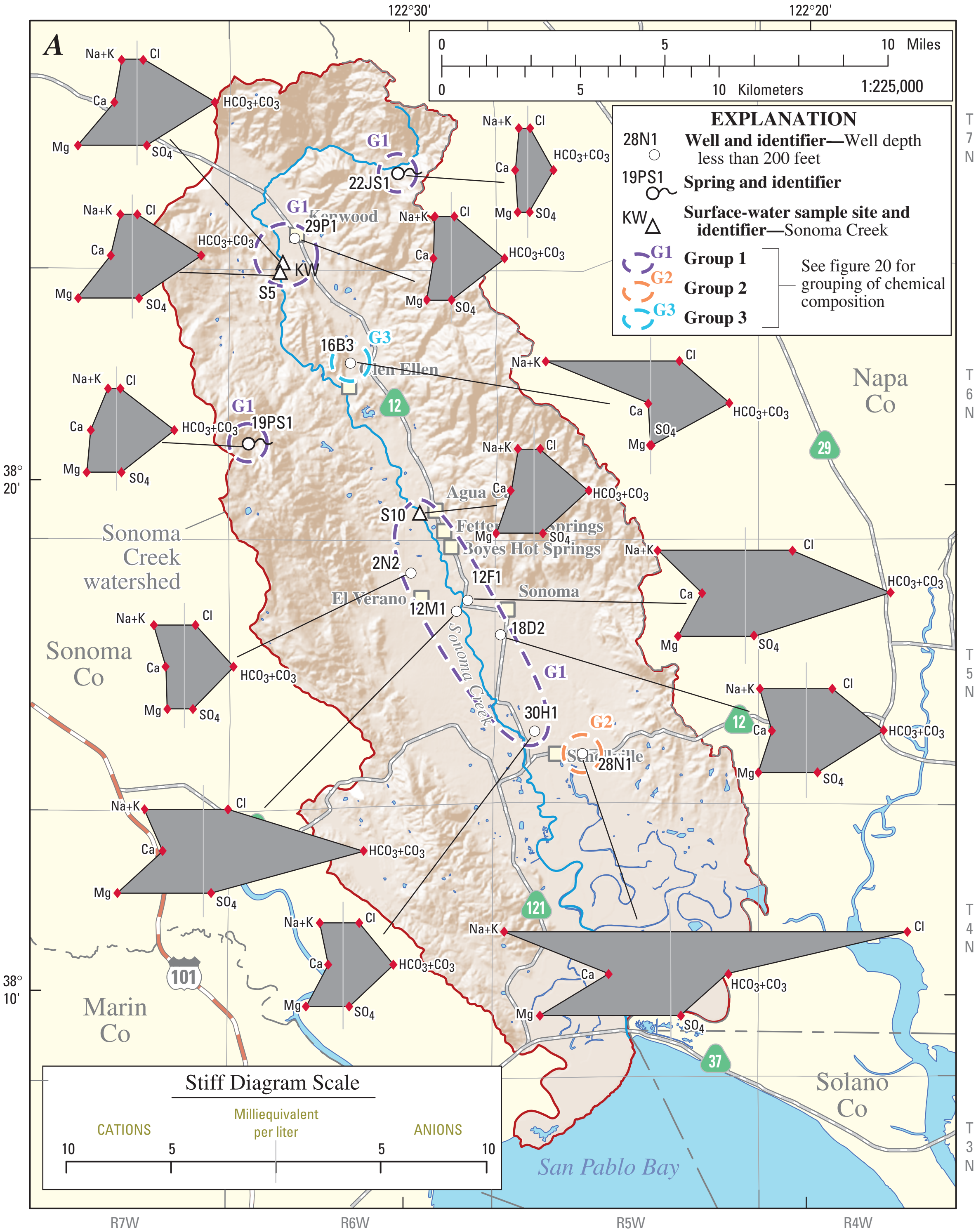
The spatial distribution of the different water types in the Sonoma Valley is illustrated using Stiff diagrams. Stiff diagrams plot in an identical sequence the concentration (in meq/L) of major cations to the left of zero and major anions to the right of zero (Stiff, 1951) (as depicted in *fig. 21*). The width of the diagram is an approximate indication of the total ionic content (Hem, 1985). Wells sampled more than once during 2002–04 for major ions (5N/5W-18D2, -28R1, 5N/6W-3E1, -9A1, -10M2, and 12F1) are represented by the earliest analyses listed in *Appendix D*. Sonoma Creek at Agua Caliente (S10) is represented by the latest of two analyses listed in *Appendix D* because that sample was collected in the middle of the 2002–04 period. *Figure 21*, shows the ionic composition of samples based on site type and, for well samples, on depth. The group designation of each site, which was based on the trilinear diagram (*fig. 20*), is shown on *figure 21*.

The Stiff diagrams for the surface- and spring-water samples, for the samples from five wells less than 200 ft deep (5N/6W-2N2, -12F1, -12M1, 5N/5W-18D2,-30H1) to the south and west of the city of Sonoma along Sonoma Creek and from one well less than 200 ft deep in the Kenwood area (7N/6W-29P1) are similar (trilinear group 1) (*fig. 21A*). Dissolved-solids concentrations (residue on evaporation) ranged from 135 mg/L (7N/6W-22JS1) to 269 mg/L (Sonoma Creek at Kenwood [KW]) in the surface- and spring-water samples and from 164 mg/L (7N/6W-29P1) to 539 mg/L (5N/6W-12F1) in ground-water samples from wells less than 200 ft deep. The similar ionic composition and relatively low dissolved solids of these water samples are consistent with water derived either directly from precipitation or indirectly from precipitation by means of ground-water losses to streams (seepage gains) or streamflow losses to ground water (seepage losses). Location and seasonal variations in hydrologic conditions determine which process prevails. In areas where static water levels are within 10 or 20 ft of land surface, such as along Sonoma Creek south of Kenwood and in the vicinity of the Bay Mud deposits near Schellville, streamflow may principally comprise ground-water inflow except during periods of the highest streamflows. In areas where water levels are drawn down by ground-water pumping, particularly between late spring and autumn, and where static water levels may be greater than 10 or 20 ft below land surface, such as along Sonoma Creek upstream of Highway 12 at Kenwood (seepage site S3), stream seepage may be the principal source for shallow ground water. Given that both seepage gains and losses may occur at the same locations at different times of the year, the source of surface water, spring water, and water from some wells less than 200 ft deep cannot be positively identified based on ionic composition.

The composition of the samples from wells 5N/6W-12F1 and -12M1 are represented by diagrams that are similar in shape, but wider than the diagrams from wells having water with a similar composition (5N/5W-18D2 and -30H1). Wider diagrams are indicative of higher total ionic content. The total dissolved-solids concentrations of samples from wells 5N/6W-12F1 and -12M1 were 539 and 485 mg/L, respectively, compared with the median value of 247 mg/L for all samples in group 1. The higher ionic content of shallow ground water in the area of wells 5N/6W-12F1 and -12M1 may be attributed to land use; both wells are located in established residential areas served almost exclusively by municipal sewer and water lines. Leaking sewer lines or infiltration from septic tank leach fields that pre-date public sewer lines, leaking water lines, and irrigation return flow from domestic residential water use may be contributing sources of ground water in some areas.

Samples from well 5N/5W-28N1 near Schellville and well 6N/6W-16B3 near Glen Ellen (*fig. 21A*) have a distinctly different chemical composition than water from the other wells with depths less than 200 ft. The relatively high ionic content (1,060 mg/L) of ground water from well 5N/5W-28N1 (trilinear group 2) may be attributed to its location. Well 5N/5W-28N1 is completed in alluvium, but it is situated at the boundary between alluvial fan deposits and bay-mud deposits. As is discussed in the section "High-Salinity Waters," this boundary marks the northern edge of an area identified by Kunkel and Upson (1960) as an area of saline ground water, possibly a result of the landward movement of brackish water from the tidal marshlands north of San Pablo Bay. The sodium-bicarbonate composition of ground water from well 6N/6W-16B3 (trilinear group 3) may be attributed to the geology of the area. Located near Calabasas Creek, this well is at least partly completed in alluvium, possibly extending into the Glen Ellen Formation at depth. Unlike other wells less than 200 ft deep that were sampled as part of this study, well 6N/6W-16B3 is located adjacent to one of several north–south trending faults in northern part of the Sonoma Valley (*fig. 19*). This fault may act as a partial barrier to ground-water flow and result in the upward circulation of relatively mineralized ground water from greater depths.

Stiff diagrams depicting the ionic composition of ground-water samples from wells with depths between 200 ft and 500 ft are shown on *figure 21B*. The ionic compositions of ground water from four wells (6N/6W-9A1, 7N/6W-22E1, -29P3, and 7N/7W-24A1) located north of Glen Ellen and from one well (5N/6W-2P2) located on the west side of Sonoma Creek near the city of Sonoma (trilinear group 1) are similar to the ionic composition of most of the ground-water samples from wells less than 200 ft deep (*fig. 21A*). Dissolved-solids concentrations ranged from 142 mg/L (7N/7W-24A1) to 262 mg/L (7N/6W-29P3). The similar ionic composition of dissolved solids in the samples from group 1 wells with depths between 200 and 500 ft compared with those in the samples from the shallower group 1 wells is consistent with water derived from direct infiltration of precipitation and (or) from surface-water seepage losses.



Base from U.S. Geological Survey digital data, 1:250,000, 2003. State Plane Projection, Fipzone 402
Shaded relief base from 1:250,000 scale Digital Elevation Model: sun illumination from northwest at 30 degrees above horizon

Figure 21. Stiff diagrams showing chemical composition of samples from selected wells, springs, and Sonoma Creek in the Sonoma Valley, Sonoma County, California, 2002–04. *A*. Springs, Sonoma Creek, and wells less than 200 feet deep. *B*. Wells 200 to 500 feet deep. *C*. Wells greater than 500 feet deep or of unknown depths.

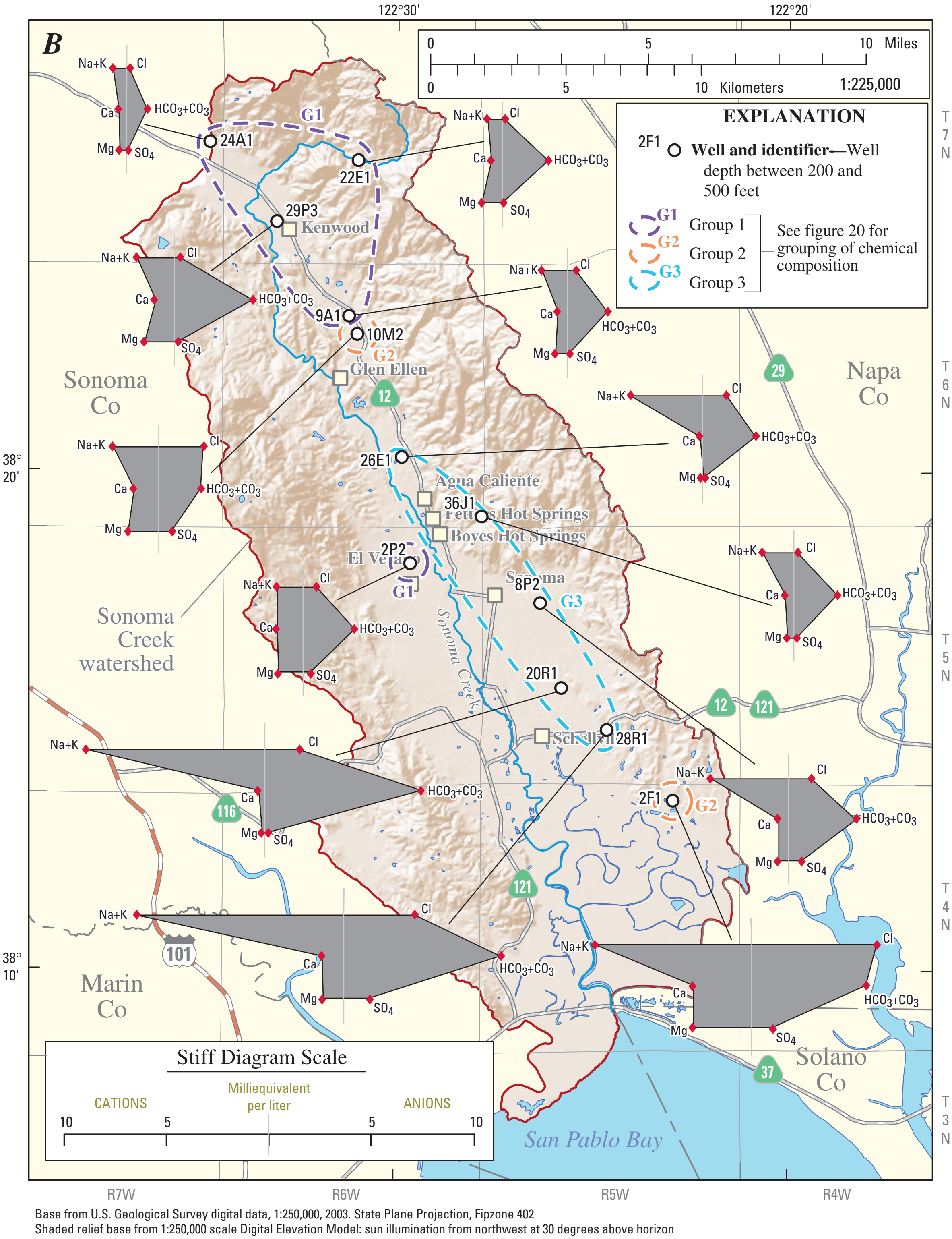
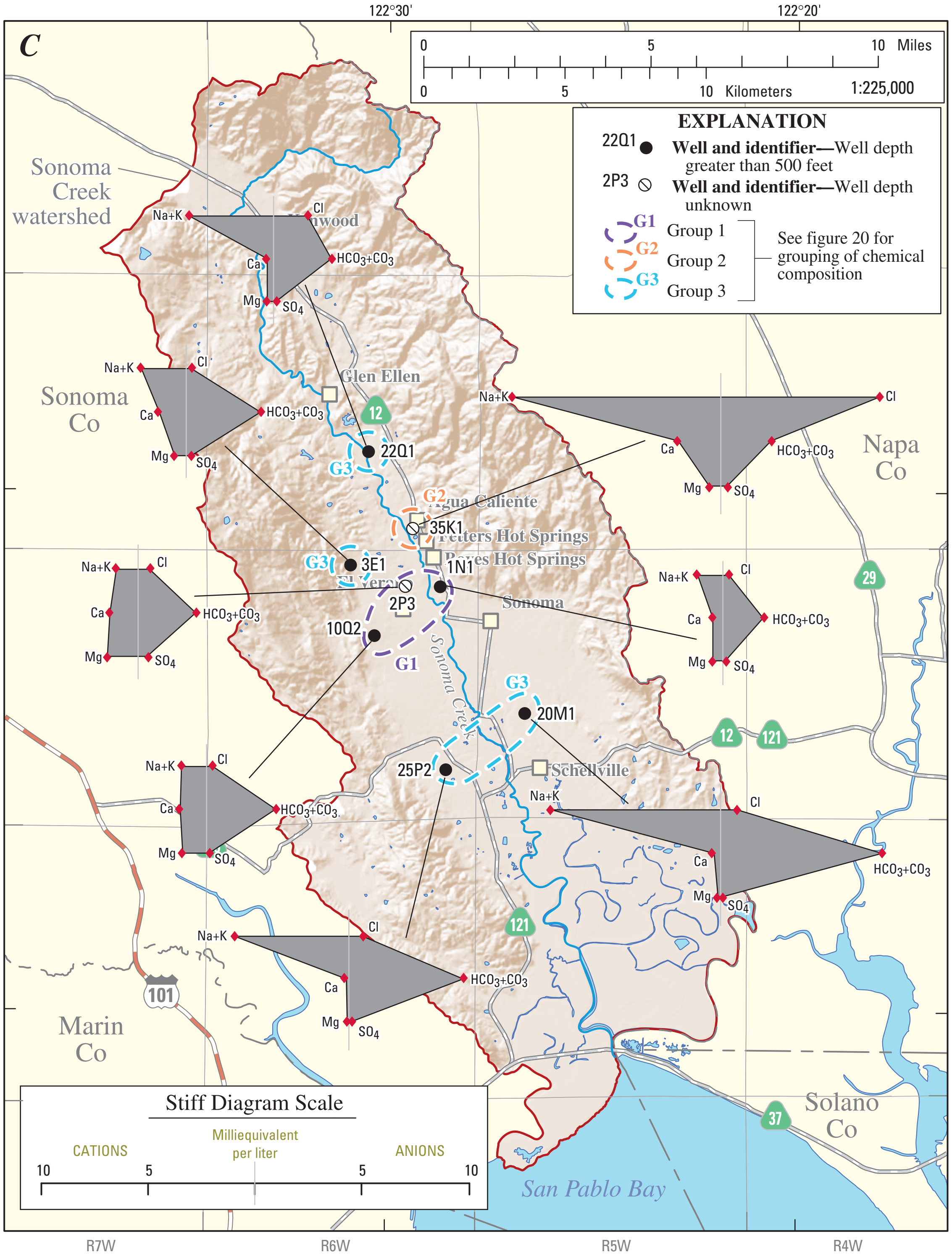


Figure 21.—Continued.



Base from U.S. Geological Survey digital data, 1:250,000, 2003. State Plane Projection, Fipzone 402
Shaded relief base from 1:250,000 scale Digital Elevation Model: sun illumination from northwest at 30 degrees above horizon

Figure 21.—Continued.

East of Sonoma Creek and extending from the Schellville area (4N/5W-2F1) to just north of Glen Ellen (6N/6W-10M2), the composition of ground water from wells 200 to 500 ft deep is characterized by greater ionic content, in particular greater proportions of sodium and chloride and greater concentrations of total dissolved solids (trilinear group 2) than most ground water from wells less than 200 ft deep. The composition of ground water from five wells (5N/5W-8P2, -20R1, -28R1, 6N/6W-26E1, and -36J1) is a sodium-bicarbonate type water (trilinear group 3). Water from wells 4N/5W-2F1, 5N/5W-20R1, and -28R1 have relatively high salinity which may be caused by mixing of meteoric waters with connate water trapped during deposition of sediments in a marine or brackish environment or by seawater intruding through the Bay-Mud deposits north of San Pablo Bay.

Wells 5N/6W-1N1, -2P3, and -10Q2, which have depths greater than 500 ft, have a mixed-bicarbonate type composition (trilinear group 1; *fig. 20*); these wells are located on either side of Sonoma Creek and just west of the city of Sonoma (*fig. 21C*). To the northeast, in the Agua Caliente area, water from well 6N/6W-35K1 has a relatively high concentration of dissolved solids (673 mg/L) and relatively high concentrations of potassium, sodium, and chloride (trilinear group 2) (*fig. 21C*; *Appendix D*). The chloride concentration (255 mg/L) in ground water from this well is comparable with that (273 mg/L) for a sample collected by Kunkel and Upson (1960) from a 450-ft-deep well (5N/6W-2A3) at Boyes Hot Springs, an area identified as having thermal waters (see sections “Chemical Composition of Thermal Waters” and “Ground-Water Temperature” for further discussion). Wells 5N/5W-20M1, -25P2, and 6N/6W-22Q1, which also have depths greater than 500 feet, have a sodium-bicarbonate type composition (trilinear group 3; *fig. 20*). Well 6N/6W-22Q1 is located in the Glen Ellen area, close to where Sonoma Creek crosses an inferred fault (*fig. 9*). The ionic content of the ground water from well 5N/5W-20M1 is very similar to the ionic content of samples from wells 5N/5W-20R1 and -28R1, which have depths between 200 and 500 ft, indicating that the intermediate and deep wells in the southern part of the Sonoma Valley may be affected by similar processes.

Constituents of Potential Concern

Dissolved nitrogen in the form of nitrate (NO_3) is one of the most commonly identified contaminants found in ground water (Freeze and Cherry, 1979). Nitrate is attributable to both natural and anthropogenic sources. Natural sources of nitrates include igneous rocks, the atmosphere, and decomposition of organic material. Anthropogenic sources include agricultural activities, fertilizers used for landscaping, leakage from underground sewers, septic-tank leach fields, and the atmosphere as a result of human activities. Nitrate concentrations in drinking water in excess of 45 mg/L are considered hazardous and may result in methemoglobinemia (blue-baby syndrome) in small children (Hem, 1985).

Concentrations of nitrate in samples collected during 2002–04 ranged from less than 0.1 mg/L (below the detection level) to 35 mg/L (*fig. 22*). The highest concentrations of nitrate (equal or greater than 10 mg/L) were from six wells (4N/5W-2F1 [10.8 mg/L], 5N/5W-18D2 [35 mg/L], -28N1 [32.7 mg/L], 5N/6W-2N2 [10 mg/L], -2P2 [14.5 mg/L], and -2P3 [12.5 mg/L]) located to the west and south of the city of Sonoma and all less than 500 ft deep. In some areas, concentrations of nitrate in ground water may have decreased through time. For example, well 5N/5W-18D2, which has been periodically sampled since 1958, has exceeded the primary maximum contaminant level (MCL, 45 mg/L) for drinking water several times (U.S. Environmental Protection Agency, 2002; California Department of Health Services, 2005), including a peak concentration of 66 mg/L in a sample collected in 1959 (California Department of Water Resources, 1982). The concentration of nitrate in samples from this well have remained below the MCL since 1967.

Boron is a widely occurring trace element in the Sonoma Valley. Boron commonly is associated with igneous rocks (Hem, 1985). In the Sonoma Valley, likely sources of boron include thermal waters, the Sonoma Volcanics, connate waters associated with fault zones or evaporite deposits, and brackish water from the tidal marshlands north of San Pablo Bay. Anthropogenic sources such as wastewater and fertilizers may contribute relatively low concentrations of boron to wells in developed areas (Phillips and others, 1993). Boron is not regulated by a MCL for drinking water, but the California Department of Health Services has established an advisory level (“notification level”) of 1,000 micrograms per liter (µg/L) as higher concentrations may pose a health risk to people ingesting that water on a daily basis (California Department of Health Services, 2005). Plants require small amounts of boron for growth, but in excess boron can be toxic. Boron in irrigation water at concentrations as low as 0.7 mg/L can be toxic to sensitive plants such as grapes (Ayers and Westcot, 1985).

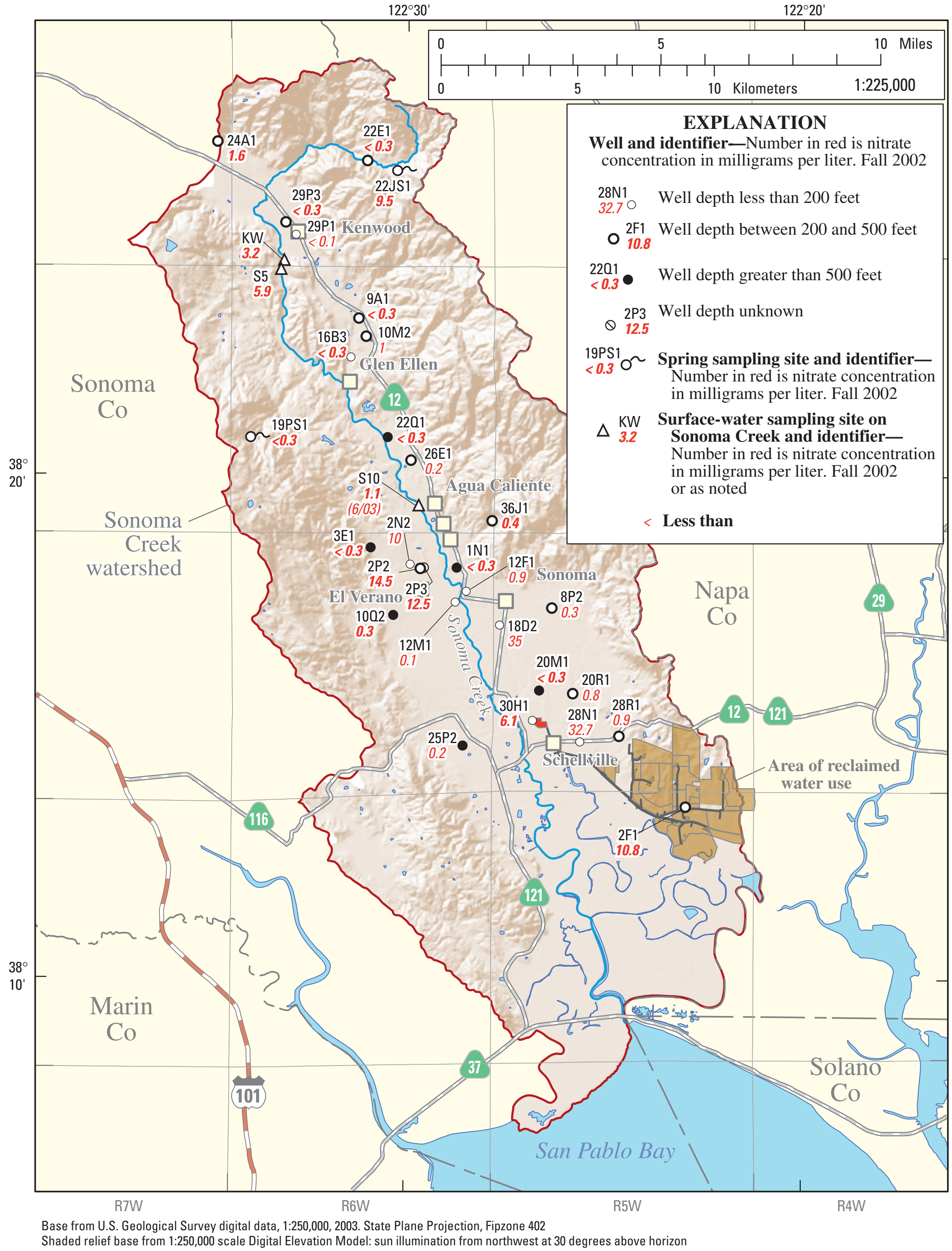


Figure 22. Locations of ground-water, spring-water, and surface-water sites with recent nitrate analyses in the Sonoma Valley, Sonoma County, California, 2002–04.

Concentrations of boron in samples collected during 2002–04 ranged from 0.01 mg/L (10 µg/L) in water from spring 7N/6W-22JS1 to 15.7 mg/L (15,700 µg/L) in water from well 6N/6W-2A6 (*fig. 23*). Samples from eight wells (5N/5W-20M1, -20R1, 5N/6W-2A6, -25P2, 6N/6W-16B3, -22Q1, -26E1, and -35K1), had concentrations in excess of the 1 mg/L [1,000 µg/L] California Department of Health Services notification level. All these wells, with the exception of wells 6N/6W-16B3 and -35K1, are deeper than 200 ft and are located between Glen Ellen and Hwy 12/121 in the Schellville area (*fig. 23*). The relatively high concentrations of boron in ground water in this section of the Sonoma Valley may be attributed to the following sources for the corresponding wells shown in parentheses: (1) the movement of boron-rich water from the Sonoma Volcanics (6N/6W-22Q1 and -26E1) (California Department of Water Resources, 1982), (2) thermal waters in the Fetters Hot Springs and Boyes Hot Springs areas (6N/6W-35K1 and 5N/6W-2A6) (California Division of Mines and Geology, 1984), and (3) either connate water, incorporated in sediments during deposition, or modern saltwater intrusion from the Bay-Mud deposits and tidal sloughs near San Pablo Bay (5N/5W-20M1, -20R1, and 5N/6W-25P2) (Kunkel and Upson, 1960). The relatively high boron concentration in the sample from well 6N/6W-16B3 (5.8 mg/L [5,780 µg/L]) may be attributed to upward-flow of deep ground water along a nearby fault (*fig. 9*). Samples taken in the late 1940s and 1950s from three nearby wells had comparable concentrations of boron ranging from 6.2 to 7.7 mg/L (6,200 to 7,700 µg/L) (California Department of Water Resources, 1982).

Additional elements of concern because of their potentially adverse effect on health or taste, odor, and appearance of water used for domestic consumption include arsenic, iron, and manganese, fluoride, and chloride. The concentration of arsenic in all the samples collected from Sonoma Creek, springs, and wells during 2002–04 ranged from 1 µg/L (estimated) to 17 µg/L (*Appendix D*). Samples from wells 5N/5W-20M1 (17 µg/L), 5N/6W-1N1 (11 µg/L), and 6N/6W-35K1 (12 µg/L) exceeded the primary MCL of 10 µg/L (U.S. Environmental Protection Agency, 2002). The concentration of dissolved iron in samples collected during 2002–04 from Sonoma Creek, springs, and wells ranged from 4 µg/L (estimated) to 1,480 µg/L (*Appendix D*). Samples from four wells (6N/6W-9A1, -22Q1, -35K1, and 7N/6W-22E1) contained dissolved iron that exceeded the secondary Federal and State MCL of 300 µg/L (U.S. Environmental Protection Agency, 2002; California Department of Health Services, 2005). The concentration of manganese in all samples collected from Sonoma Creek, springs, and wells during 2002–04 ranged from 0.3 to 540 µg/L (*Appendix D*). Samples from nine wells (4N/5W-2E1, 5N/6W-1N1, -3E1, -10Q2, 6N/6W-9A1, -22Q1, -35K1, 7N/6W-22E1, and -29P3) contained dissolved manganese in concentrations exceeding the secondary Federal and State MCL of 50 µg/L (U.S. Environmental Protection Agency, 2002; California Department of Health Services, 2005). Fluoride concentrations in samples from two thermal wells (5N/6W-2A6 and 6N/6W-35K1), neither of which is used for drinking water, equaled or exceeded the recommended secondary drinking-water standard of 2 mg/L; one sample had a concentration of 8.5 mg/L (5N/6W-2A6). Chloride concentrations in samples from all wells ranged from 5 to 578 mg/L; concentrations from three wells (5N/5W-28N1, 5N/6W-2A6, and 6N/6W-35K1) exceeded the secondary drinking-water standard of 250 mg/L.

Thirty-six samples from the 30 wells were analyzed for physical constituents (pH and specific conductance) and chemical constituents (sum of constituents [dissolved solids], chloride, fluoride, arsenic, boron, iron, and manganese). Results showed that 45 of the analytes had concentrations equaling or exceeding Federal and (or) State drinking-water standards and advisory levels (*Appendix D*).Wells with water having values equal to or in excess of standards and advisory levels were disproportionately from wells in the northern half of the Sonoma Valley; wells located in townships 6N and 7N were the source of 36 percent of all samples collected for major constituents, but were the source of 53 percent of all analyses having values equal to or in excess of standards and advisory levels. Ground-water depth intervals were more proportionately represented; wells less than 200 ft deep, 200 to 500 ft deep, greater than 500 ft deep and of questionable or unknown depth were the source of 28, 44, 22, and 6 percent, respectively, of all samples collected for major constituents. These depth categories constituted 22 percent (less than 200 ft), 36 percent (200 to 500 ft), 19 percent (greater than 500 ft) and 6 percent (questionable or unknown) of all the analyses having values equal to or in excess of standards and advisory levels for physical and chemical constituents.

High-Salinity Waters

High-salinity waters are commonly associated with modern saltwater intrusion, connate ground water in areas with evaporites or marine sedimentary deposits, and (or) thermal waters. The criterion frequently used to define salinity-affected waters includes chloride greater than (100 mg/L [Tolman and Poland, 1940; Iwamura, 1980]) and total dissolved solids (TDS) or residue on evaporation (ROE) greater than 1,000 mg/L (brackish: approximately 1,000–20,000 mg/L; saline: 20,000–35,000 mg/L; brine: greater than 35,000 mg/L [Drever, 1982]). For the purposes of this report, high-salinity waters are defined as waters having conductivity greater than 1,000 µS/cm (ROE = 614 mg/L).

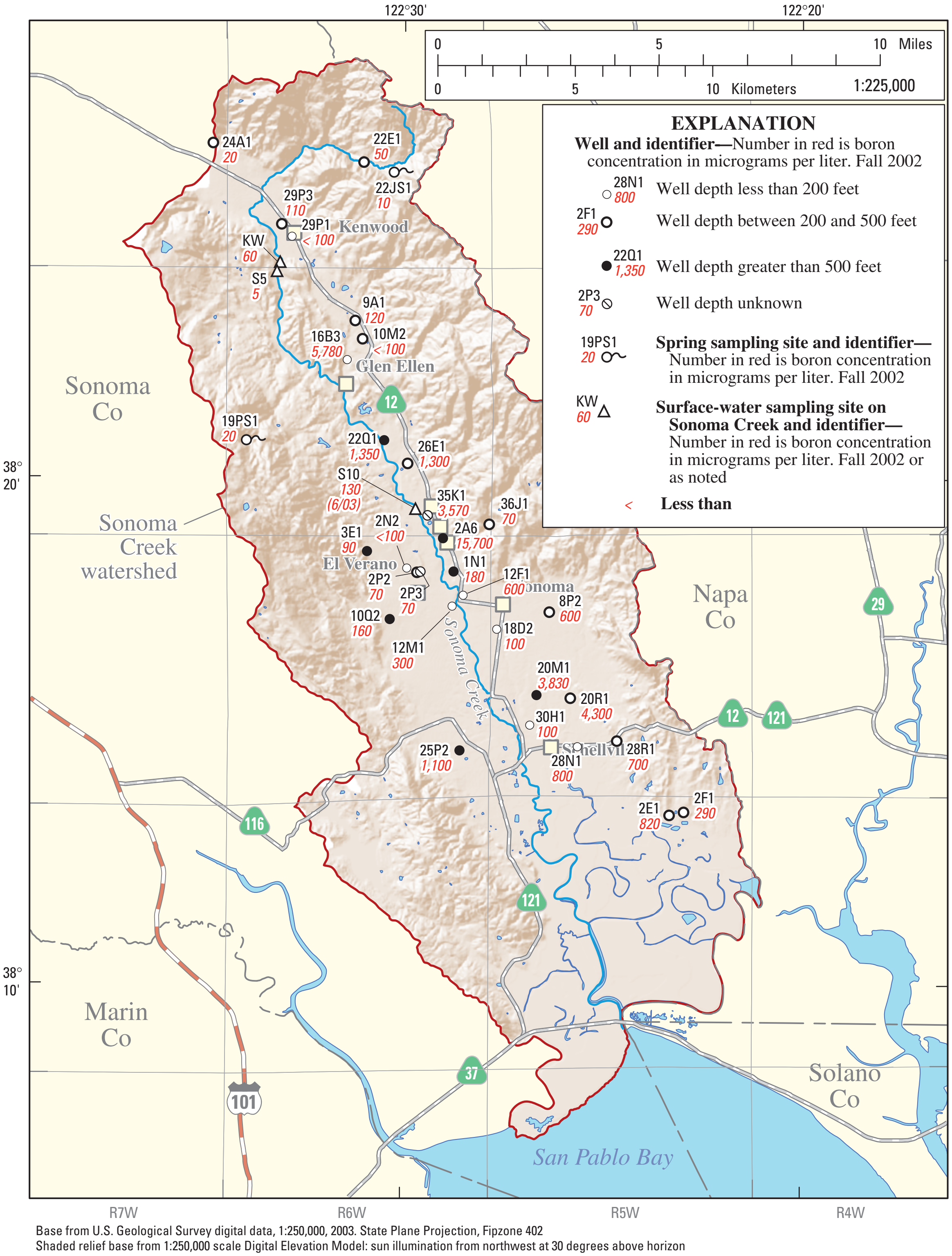


Figure 23. Locations of ground-water, spring-water, and surface-water sites with recent boron analyses in the Sonoma Valley, Sonoma County, California, 2002–04.

Major-ion and trace-element data, including chloride and TDS and (or) ROE, for a limited number of historical and recent analyses indicate that saline ground water exists in parts of the Sonoma Valley. Because these limited data are insufficient for characterizing the magnitude and extent of salinity in the study area, measurements of conductivity for an expanded group of sampling sites were used as a surrogate. Linear regression of water-chemistry data for wells sampled during 2002–04 indicates that dissolved solids (ROE) in ground water and the specific conductance (SC) of ground water are strongly correlated (ROE [mg/L]=0.563 SC [µS/cm] + 50.717; R^2=0.98).

The temporal variation of conductivity in water from 12 wells used as long-term monitoring sites by CADWR is shown on *figure 24*. Time-series plots of conductivity suggest that the most significant changes in water chemistry during 1969–2004 occurred in the southern part of the Sonoma Valley. The conductivity at well 5N/5W-28N1 increased significantly during the mid-1970s, coinciding with a period of below normal rainfall. Following a peak conductivity of 1,420 µS/cm in 1978, conductivity decreased to pre-1976 levels. However, the most recent conductivity measurement of 1,780 µS/cm in September 2002 (*Appendix E*) suggests that salinity has increased sharply since 1998 (1,110 µS/cm). Conductivity gradually and steadily increased at well 5N/5W-28R1 between 1969 and 2004, with the most recent conductivity measurement, 1,290 µS/cm, measured in September 2004, being the peak measurement for the period. The conductivity at well 5N/5W-18D2 slowly increased over time reaching a peak of 643 µS/cm in 2004. Conductivity measurements at wells 5N/6W-12F1 (888 µS/cm in 2004) and 5N/6W-12M1 (806 µS/cm in 2003) increased significantly from the late 1960s to the early 1990s and then decreased through 2004. Although recent conductivity measurements at these wells are not peak measurements, they are almost two times higher than the conductivity measurements in 1969. Large periodic fluctuations in conductivity at these wells may be attributed to the amount of streamflow in Sonoma Creek. For example, the peak conductivity measurement of 1,440 µS/cm at well 5N/6W-12F1 in 1991 coincides with the end of a 5-year period (1987–91) of deficient rainfall and, presumably, in the absence of streamgage records, of low streamflow. However, the conductivity of water from well 5N/6W-12F1 in 1977 was relatively low (462 µS/cm) despite record low annual discharge in Sonoma Creek (USGS stream gage 11458500). This seemingly poor correlation between conductivity, rainfall, and streamflow suggests that leaking sewer lines, septic-tank leach fields, and water lines may represent additional sources of recharge to wells 5N/6W-12F1 and -12M1. Alternatively, variations in conductivity may be related to a combination of variations in pumping stress and recharge.

Plots of ground-water conductivity in the southern part of the Sonoma Valley, as represented by recent measurements at wells 5N/5W-28N1 and 5N/5W-28R1, suggest that ground-water salinity is increasing in this area. Kunkel and Upson (1960) used water-chemistry data from well samples collected during 1949–52 to identify an area of saline ground water (conductivity greater than 1,000 µS/cm) located primarily south of Highway 12/121 (*fig. 24*). They defined the 0-ft hydraulic-head contour for spring 1950 (*fig. 16*) as a boundary between generally satisfactory unconfined ground water in alluvium to the north and saline unconfined ground water in alluvium and bay-mud deposits to the south. Several wells drilled in the Huichica Formation and alluvium reportedly yielded water of satisfactory quality at the time they were drilled but became brackish as a result of summer pumping (Kunkel and Upson, 1960). A report by the California Department of Water Resources (1982) concluded that there had been no appreciable change in the area impacted by saline ground water since 1960.

The current (2002–04) extent of saline water in the southern part of the Sonoma Valley was assessed using conductivity measurements for 44 wells made by the USGS in September 2003 (*Appendix E*). These 44 wells sampled included 20 wells less than 200 ft deep, 11 wells 200 to 500 ft deep, 7 wells greater than 500 ft deep, and 6 wells of unknown depth (*Appendix C*). The September 2003 measurements were used to create generalized contours representing areas of equal conductivity and, in particular, to identify the location of the 1,000-µS/cm contour used to delineate the extent of saline ground water during 1949–52. Because of the wide range of well depths (approximately 60 to 821 ft; *Appendix C*), these contours (*fig. 25*) should be considered composite conductivity values representing all three depth zones (less than 200 ft, 200 to 500 ft, and greater than 500 ft) described in this report.

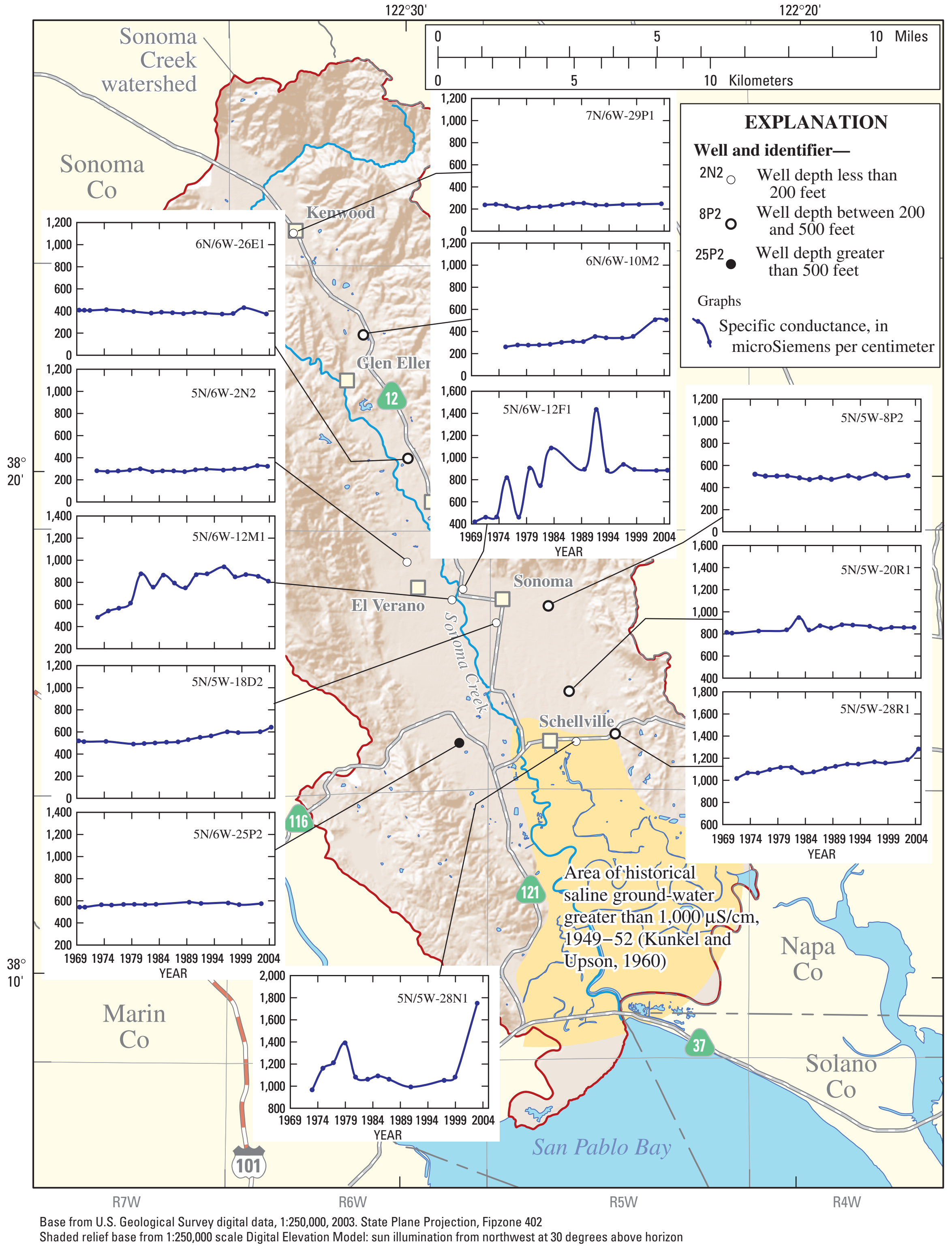
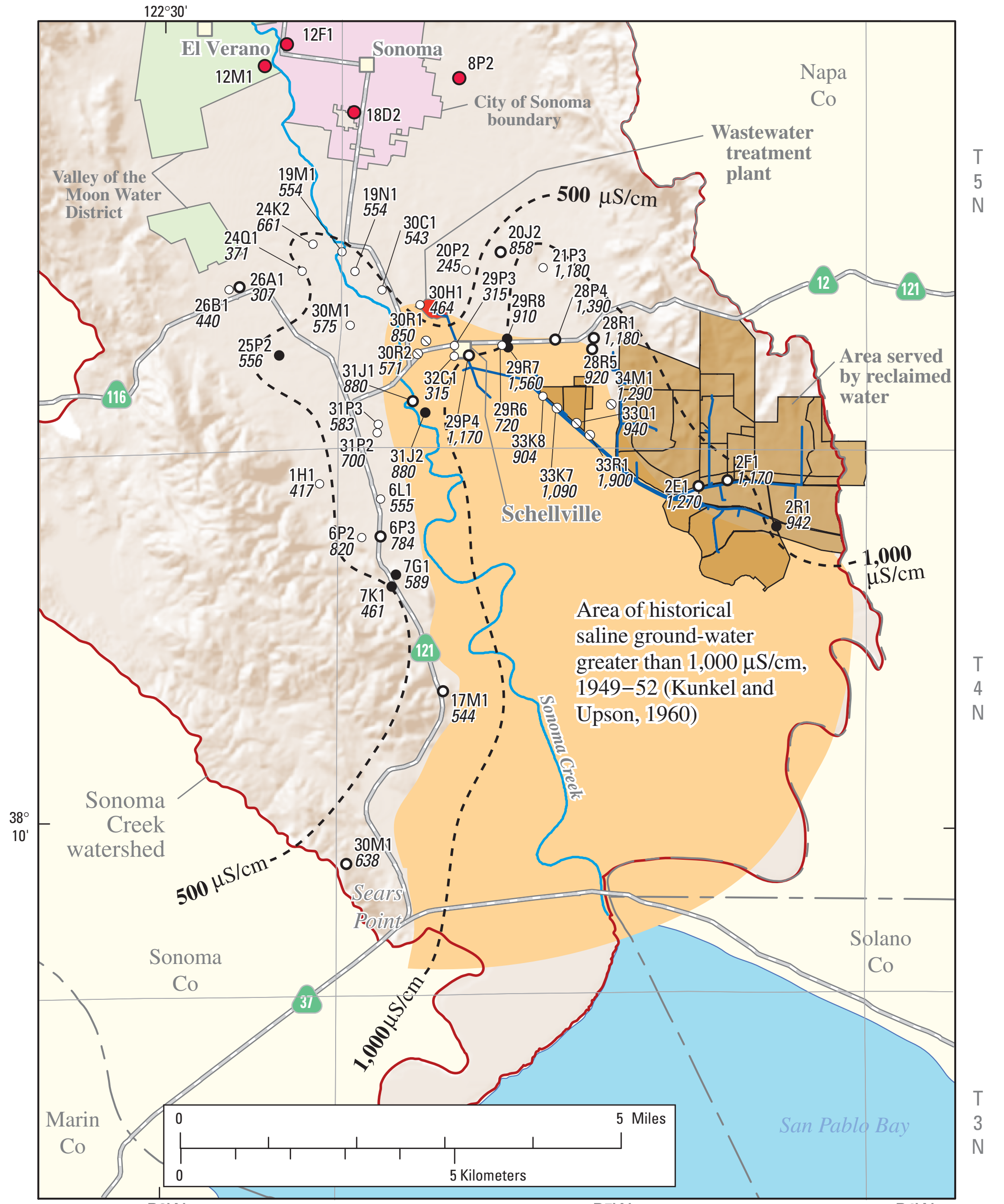


Figure 24. Time-series plots of specific conductance for selected ground-water wells in the Sonoma Valley, Sonoma County, California, 1969–2004.



Base from U.S. Geological Survey digital data, 1:250,000, 2003. State Plane Projection, Fipzone 402. Shaded relief base from 1:250,000 scale Digital Elevation Model: sun illumination from northwest at 30 degrees above horizon

EXPLANATION

Reclaimed water distribution system

Line of equal specific conductance (field) for September 2003, in microsiemens per centimeter

18D2 **Well and identifier—**Near City of Sonoma with specific conductance greater than 500 microsiemens per centimeter, as measured by CADWR 2002–04

Well and identifier—Number in italics is specific conductance in microsiemens per centimeter, measured by USGS 2003

30H1 *464* Well depth less than 200 feet

17M1 *544* Well depth between 200 and 500 feet

31J2 *880* Well depth greater than 500 feet

33K7 *1,090* Well depth unknown

Figure 25. Locations of ground-water wells sampled for specific conductance in the southern part of the Sonoma Valley, Sonoma County, California, September 2003.

Generalized contour lines depicting areas of equal conductivity (1,000 µS/cm and 500 µS/cm) in September 2003 suggest that the area affected by saline ground water in the southern part of the Sonoma Valley has shifted since 1949–52 (*fig. 25*). The northern edge of the saline area may have advanced as much as 1 mi north of Highway 12/121. This apparent movement of saline ground water may be in response to ground-water pumping and the resulting depression of hydraulic heads southeast of the city of Sonoma (fig. 18). In contrast, the northwestern part of the 1949–52 area of saline ground water, near the intersections of Highways 12 and 121 and Sonoma Creek, may have diminished. The current (2003) northwestern extent of the 1,000-µS/cm contour is located approximately 0.5 mi southeast of the Sonoma Valley Wastewater Treatment Plant at Schellville (*fig. 25*). The 500-µS/cm conductivity contour may be farther south of the wastewater treatment plant then depicted on *figure 25*; the conductivity of water from two shallow wells (5N/5W-29P3 and -32C1) was 315 µS/cm for both wells. These wells are located near a transmission line that conveys reclaimed water for agricultural use in areas south and east of the wastewater treatment plant. The conductivity data from September 2003 are insufficient for determining whether the increasing usage of reclaimed water for irrigation of agricultural lands located toward the eastern boundary of the Sonoma Creek watershed might be reducing the areal extent of saline ground water in that area (*fig. 25*). The available data are also insufficient for determining whether current (2002-04) conductivity values in excess of 500 µS/cm measured by CADWR in several wells near the city of Sonoma (5N/5W-8P2, -18D2, 5N/6W-12F1, and -12M1) might be attributed to the main area of saline ground water (*fig. 25*). Additional measurements in the area between the city of Sonoma and the wastewater treatment plant could show that saline ground water associated with the Bay-Mud deposits extends further north than depicted by *figure 25*.

Conductivity measurements from September 2003 indicate that significant spatial variability in water quality exists among the three depth zones. The vertical variability in conductivity may be illustrated by comparing the values from samples of two adjacent wells of different depths. For example, the conductivities of water from wells 5N/5W-29R6 (less than 200 ft deep) and -29R7 (greater than 500 ft deep), were 720 and 1,560 µS/cm, respectively (*fig. 25*, *Appendix E*). The variation of conductivity with depth may be indicative of different sources of salinity in the southern part of the Sonoma Valley. The primary source of salinity to shallow wells may be modern saltwater that has intruded the bay-mud deposits along the tidal sloughs that extend northward from San Pablo Bay. High evaporation rates in the marshlands also could increase salinity in the shallow ground water in or near the marshes. The source of salinity to intermediate and deep wells may be connate water incorporated into the sediments during deposition or modern saltwater in areas where abandoned or improperly constructed wells may act as conduits for the downward movement of surface water or shallow ground water. Information on the number and location of abandoned wells is unavailable, but the chemical composition of water from wells anywhere in the study area may be affected wherever such wells are in proximity to abandoned or improperly constructed wells.

The trace elements barium, boron, bromide, and iodide have been used successfully to evaluate the source and movement of saline water in coastal aquifers in other parts of California (Piper and others, 1953; Izbicki, 1991; Izbicki and others, 2003; Land and others, 2004). A limited number of samples were analyzed for these constituents during 2002–04, including samples from four wells in the southern part of the Sonoma Valley. Among the trace elements analyzed, iodide may be the most useful indicator for distinguishing between modern salt-water intrusion and connate water (Izbicki, 1991). Concentrations of iodide in samples from wells 4N/5W-2E1, -2F1, 5N/5W-20M1, and -30H1, were 1.1, 0.225, 0.138, and 0.007 mg/L, respectively (*Appendix D*); in comparison, the concentration of iodide in seawater is 0.06 mg/L (Hem, 1985). Water from shallow well 5N/5W-30H1 is not affected by salinity from any source, based on the low concentrations of iodide and other constituents analyzed (*Appendix D*). The relatively high concentrations of iodide and other constituents, including sodium, chloride, and boron, in water from wells 4N/5W-2E1, 2F1, and 5N/5W-20M1 suggests that connate water is the source of salinity to these particular wells (*Appendix D*). Iodide is a minor constituent of seawater which, when entrapped in estuarine mud or sedimentary deposits of marine origin, becomes concentrated over time (Lloyd and others, 1982). Additional sampling and trace element analyses could help determine whether saline waters elsewhere in the study area can be attributed to recent seawater intrusion or to ground waters that have had a long residence time.

Ground-Water Temperature

The occurrence of warm ground water in some areas of Sonoma County has been known since the late 1800s. In Sonoma Valley, ground-water temperatures in the Sonoma Volcanics range between 18 and 48°C (California Division of Mines and Geology, 1984). Six thermal areas, first recognized by the presence of thermal springs (Waring, 1915), are known in Sonoma Valley between Los Guilicos in the northwest to Boyes Hot Springs in the southeast. An area that extends northwest from Sonoma and includes Fetter's Hot Springs, Boyes Hot Springs, and Agua Caliente is described as a "warm water belt" in a study by the California Division of Mines and Geology (1984). That study also identified a fault, informally named the Eastside fault, which is believed to be the western boundary of the main geothermal reservoir. Forty six wells and springs in Sonoma Valley with temperatures greater than or equal to 20°C were identified by California Division of Mines and Geology (1984).

There is no universally accepted definition of thermal water. Shallow ground water typically has a temperature close to the mean annual air temperature. The mean annual air temperature at Sonoma is about 15.4°C. According to Waring (1965), any water with a temperature greater than 8°C above the mean annual air temperature is considered thermal. By this definition any well or spring with a water temperature greater than 23.4°C would be considered thermal. For the geothermal resources study of Napa and Sonoma Counties, any water greater than 20°C was considered thermal (California Division of Mines and Geology, 1984). Ground-water temperatures increase with depth owing to the prevailing geothermal gradient. Todd (1980) cites an average geothermal gradient of 1°C per 100 ft.

Ground-water temperatures were measured by the USGS at the land surface in water samples pumped from 40 wells in September 2003 (excluding wells in which samples may represent water from well pressure tank, as listed in *Appendix E*); temperature-depth logs were made for 8 other wells (*fig. 26*). The sample temperature measurements were made after several minutes of pumping, when temperatures were stable and measurements were within 0.5°C. The temperature logs (*fig. 27*) were made between August 3 and August 5, 2004, under nonpumping conditions. The temperatures were measured using a calibrated precision thermistor suspended on a four-conductor cable. Temperature measurements were made at discrete points from near the water surface to the maximum accessable depth in the well. The number and spacing of measurements were chosen on the basis of the total depth of the water-filled section of the well and the rate of temperature change with depth. Resistance at discrete depths was recorded after the thermistor output stabilized. The recorded resistance was converted to temperature using a polynomial calibration curve. This system provides temperature measurements accurate to 0.1°C .

The temperatures, rounded to the nearest 0.5°C, ranged from 17.5 to 36.0°C in the samples pumped from wells that ranged from 60 to 845 ft in depth. The water temperatures of pumped samples show a positive correlation with depth. The linear correlation has an R^2 of 0.48 and gives an average temperature gradient of 1.4°C/100 ft. It is important to recognize that the temperature of samples pumped from wells generally differ from in situ temperatures. Submersible pumps generate heat during pumping and the temperature of water samples can be affected by ambient surface conditions. These effects may partially explain the scatter in the temperature in relation to well depth.

The maximum temperatures in the eight wells that were logged ranged from 16.5 to 27.0°C; the depths of these wells range between 53 and 674 ft. In all cases, the recorded maximum temperature was at the well bottom. Temperature logs for the eight wells are shown in *figure 27*.

Maximum temperature gradients were calculated for the eight wells logged. Well 4N/5W-6P3 had the highest maximum temperature gradient, 6.6°C/100 ft (*fig. 27*). This well was drilled to 420 ft; however, the temperature sensor could not be lowered deeper than 100 ft owing to inadequate clearance between the pump and the casing. Well 5N/5W-18R1 is reported to be 134 ft deep, but when sounded on August 3, 2004, it was measured as 53 ft deep. The maximum temperature in this well was 16.5°C at 53 ft deep. This well had the coolest temperatures of the eight wells logged.

The three wells (5N/6W-11C3, -11C4, and -11C5) located at the same site in El Verano have depths of 92, 526, and 674 ft, respectively (*Appendix C*). The shallowest well of the three (5N/6W-11C3) was temperature logged between 40 and 94 ft with a static water level of 35.97 ft below land surface and a maximum temperature gradient of 1.5°C/100 ft. The two deeper wells (5N/6W-11C4 and -11C5) had static water levels of 143.69 and 146.31 ft below land surface, respectively; temperatures were measured at depths between 150 ft and the bottom of the well. The temperature profiles for wells 5N/6W-11C4 and -11C5 are nearly identical over the common depth interval. Both wells have a nearly isothermal zone at depths between 225 and 525 ft and have high temperature gradients near the bottom of the well casings. Well 5N/6W-11C4 apparently is just deep enough to be affected by the zone of high gradient which begins at about 550 ft below land surface. Well 5N/6W-11C5 is in the zone of high gradient between 550 ft and the well bottom at 674 ft; the temperature gradient in this zone is 5.9°C/100 ft. The temperature and water-level data for wells 5N/6W-11C3, -11C4, and -11C5 show that at this site a zone of high temperature gradient exists below about 550 ft. The temperature at 674 ft below land surface is 26.5°C. The isothermal zone between 225 and 525 ft probably is a zone of relatively high ground-water flux or a zone of large vertical flow.

Well 5N/5W-17E1 has a bottom-hole temperature of 26.7°C and an accessible depth (measured by the USGS in August 2004) of 657 ft, which are similar to those for well 5N/6W-11C5. The temperature profile for well 5N/5W-17E1, however, does not show a thick isothermal zone as do the profiles for wells 5N/6W-11C4 and -11C5; instead the temperature gradients at depths between 200 and 650 ft are fairly uniform at about 2.2°C/100 ft. At the bottom of well 5N/5W-17E1 at depths between 650 and 657 ft, the gradient increases to 6.5°C/100 ft, similar to that for well 5N/6W-11C5. The linear gradient section between 200 and 650 ft could be caused by relatively low permeability rocks that inhibit ground-water flow.

The total depth of well 5N/6W-1N1 is reported to be 555 ft; however, an obstruction prevented logging deeper than 440 ft. This well had the hottest temperatures recorded of the eight wells with logged temperature data, reaching a maximum of 27.0°C at 440 ft below land surface. This well had a modest temperature change of only 2.2°C over the depth interval 40 to 440 ft, which equates to a composite temperature gradient of about 0.6°C/100 ft. The nearly isothermal profile suggests this well may be sited close to an upflow zone of thermal water.

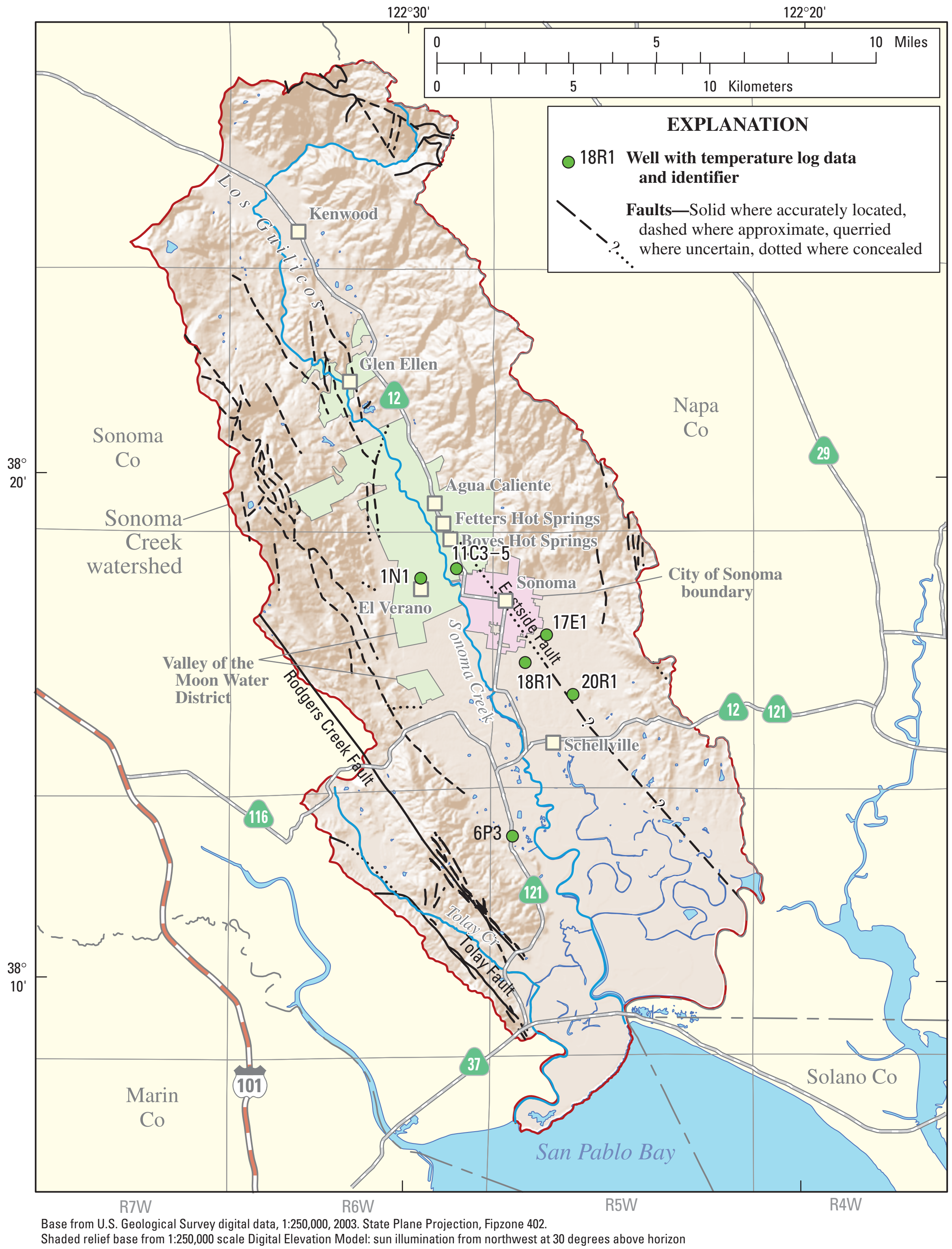


Figure 26. Locations of wells with water-temperature logs in the Sonoma Valley, Sonoma County, California.

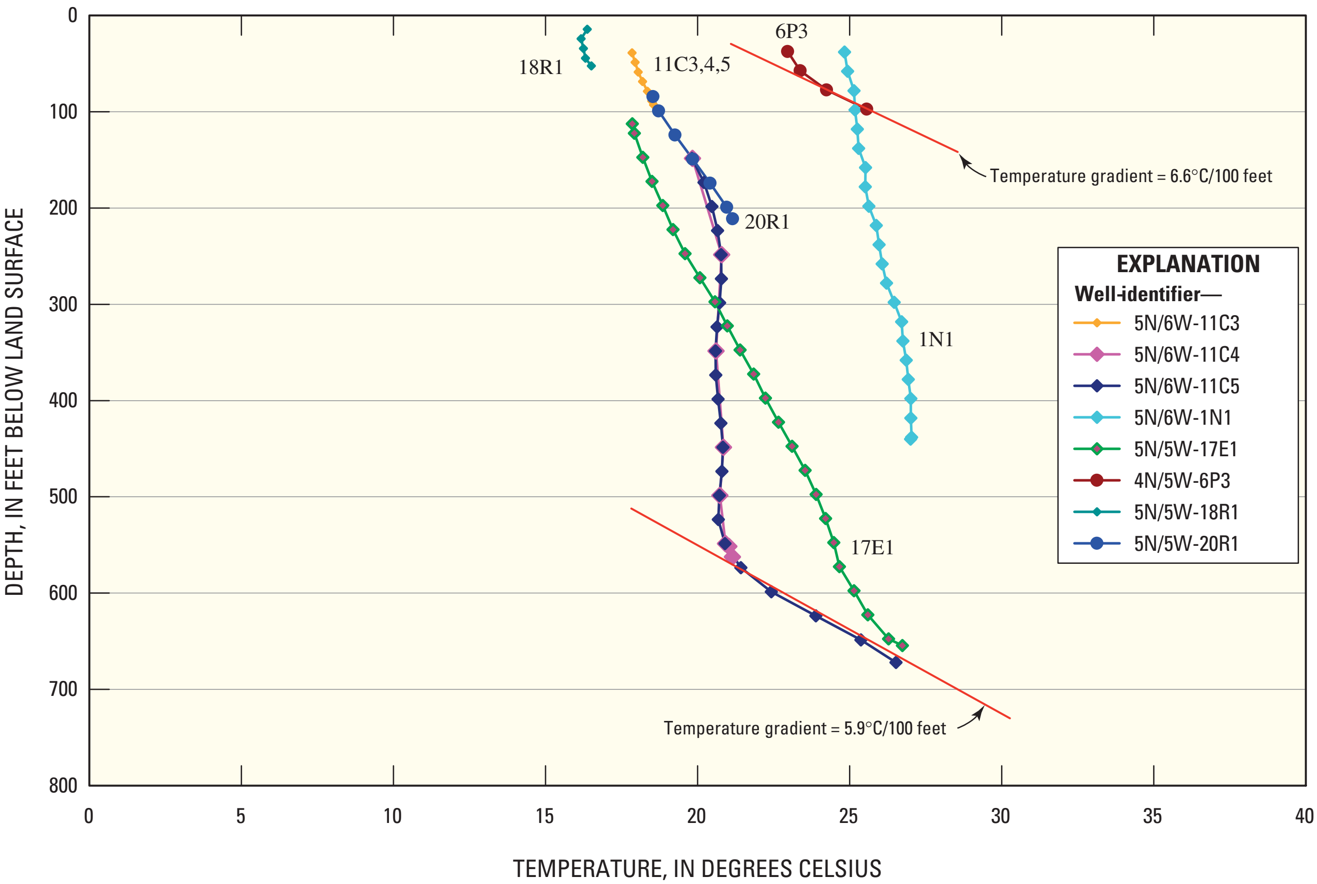


Figure 27. Temperature logs for selected wells in the Sonoma Valley, Sonoma County, California.

Well 5N/5W-20R1 is reported to be 449 ft deep; obstructions prevented logging deeper than 212 ft at which the temperature was 21.2°C. The temperature gradient between depths of 125 and 200 ft was relatively uniform at about 2.3°C/100 ft, which is similar to the gradient for well 5N/5W-17E1 over the same depth interval.

The temperature data from wells 5N/5W-17E1, -20R1, 5N/6W-1N1, -11C4, and -11C5 suggest that thermal water exists in a broad area beneath Sonoma and El Verano (*figs. 2*, *26*). In places, the thermal water is confined at depths below about 550 ft, but in some places the thermal water rises to less than 50 ft below land surface. The high temperature gradient in well 4N/5W-6P3 suggests that the thermal-water zone may extend over much of the southern half of Sonoma Valley. Alternatively, the thermal water in well 6P3 could be separate from that under the Sonoma–El Verano area and could be related to upflow along fractures in the Rodgers Creek Fault Zone (*fig. 26*).

Chemical Composition of Thermal Waters

In many areas, ground water with elevated temperatures correlates with poor water quality. This is because the solubility of most common minerals increases with temperature. Thermal waters generally are sodium-chloride type waters and often contain high concentrations of trace elements such as arsenic, boron, fluoride, and lithium in concentrations that exceed drinking-water standards and that can damage crops irrigated using this type of water (Hem, 1985). Major-ion analyses of samples collected from wells during 2002–04 show a poor correlation between temperature and ROE owing to the predominance of nonthermal sources of dissolved minerals to sampled wells, including modern saline or brackish water from bay-mud deposits, connate water from marine sedimentary deposits, and anthropogenic sources such as leaking sewer lines and septic tank leach fields. Similarly, historical analyses by the California Division of Mines and Geology (1984) for 1949–83 indicate a poor correlation between temperature and total dissolved solids even after eliminating analyses of about a dozen wells known for, or suspected of (based on location), being recharged by either modern saline or connate water.

A comparison of water temperatures and analyses from the current 2002–04 study with that from the study by the California Division of Mines and Geology (1984) indicates that thermal water is a contributing source of water to some wells in the Sonoma Valley, particularly in the area between Fetters Hot Springs and the city of Sonoma. Samples collected in 2004 from two wells, 5N/6W-2A6 near Boyes Hot Springs and 6N/6W-35K1 near Fetters Hot Springs, appear to be sodium-chloride type water based on the high concentrations of these constituents, relative to other major ions (*fig. 2*; *fig. 20*; *Appendix D*). Because well 5N/6W-2A6 was missing bicarbonate data, it could not be included in the trilinear diagram on *figure 20*. The chemical composition of samples from these wells are comparable to the results of analyses by Murray (1996) for the upper Napa Valley where thermal waters are distinguished by elevated concentrations of sodium (greater than 170 mg/L), chloride (greater than 180 mg/L), boron (greater than 8 mg/L), and fluoride (greater than 7 mg/L). The source and mechanism of the movement of thermal water in the Sonoma Valley may be similar to that for the upper Napa Valley where evidence suggests that the most mineralized and the hottest thermal waters may upwell along faults or fractures extending from depth to near land surface (Murray, 1996). As in the upper Napa Valley, the most mineralized thermal waters in the Sonoma Valley, represented by the composition of samples from wells 5N/6W-2A6 and 6N/6W-35K1, may coincide with the topographic axis of the valley. Temperature and limited water chemistry data from wells and springs suggest that thermal waters also are present along the western margin of the Bay-Mud deposits between Schellville and Sears Point and in the vicinity of Glen Ellen (*fig. 2*).

Oxygen-18 and Deuterium

Water samples were collected from selected sites in the study area for analysis of oxygen-18 (^{18}O) and deuterium (^{2}H). Oxygen-18 and deuterium data can provide information on source and movement of ground water.

Background

Oxygen-18 and deuterium are naturally occurring stable isotopes of oxygen and hydrogen, respectively. The abundance of oxygen-18 relative to lighter oxygen-16 (^{16}O) and deuterium relative to hydrogen (^{1}H) atoms can be used to help infer the source and the evaporative history of water. Oxygen-18 and deuterium abundances are expressed in delta notation (δ) as per mil (parts per thousand) differences in the ratios of $^{18}O/^{16}O$ and $^{2}H/^{1}H$ in samples relative to a standard known as Vienna Standard Mean Ocean Water (VSMOW) (Craig, 1961; Gat and Gonfiantini, 1981):

$$\delta^{18}O = \left[\frac{\left({}^{18}O/{}^{16}O\right)_{sample}}{\left({}^{18}O/{}^{16}O\right)_{VSMOW}} - 1\right] \times 1,000$$

and

$$\delta D = \left[\frac{\left({}^{2}H/{}^{1}H\right)_{sample}}{\left({}^{2}H/{}^{1}H\right)_{VSMOW}} - 1\right] \times 1,000$$

By convention, the value of VSMOW is 0 per mil. Delta oxygen-18 ($\delta^{18}O$) and delta deuterium (δD) ratios relative to VSMOW can be measured more precisely than absolute abundances; these ratios are useful for a wide variety of hydrologic studies (Gat and Gonfiantini, 1981). When run in duplicate, the analytical precision of $\delta^{18}O$ and δD generally is within 0.2 and 2 per mil, respectively (Coplen, 1994).

Because the source of much of the world's precipitation is derived from the evaporation of seawater, the $\delta^{18}O$ and δD composition of precipitation throughout the world clusters along a line known as the global meteoric water line (GMWL) (Craig, 1961)

$$\delta D = 8\delta^{18}O + 10 .$$

The isotopic compositions of precipitation plot in various places along the GMWL for a variety of reasons. Differences in the isotopic composition of precipitation result if water vapor in clouds originated from evaporation of cooler or warmer seawater (Gat and Gonfiantini, 1981). Storms that originate over cold waters in the Gulf of Alaska have a lighter isotopic composition than storms that originate over warm tropical waters in the vicinity of Hawaii. Differences in locations and precipitation on the GMWL also occur as the result of fractionation as moist air masses move over land; as storms move inland from coastal areas, the concentration of heavier isotopes relative to lighter isotopes decreases because heavier isotopes are preferentially fractionated as water molecules repeatedly undergo evaporation and condensation. In addition, precipitation that condenses at high altitudes and at cool temperatures tends to be isotopically lighter than precipitation that forms at low altitudes and warm temperatures (Muir and Coplen, 1981). Water that has not been subject to evaporation will plot near the GMWL.

Stable Isotope Results

The $\delta^{18}O$ and δD values for the entire suite of water samples ranged from –3.08 to –7.75 per mil and –21.9 to –52.0 per mil, respectively (*Appendix F*). These values plot on either side of, and along, the GMWL (*fig. 28A*). Waters affected by evaporation plot to the right of the GMWL. The sample from the Napa–Sonoma Marshes at Tolay Creek and Highway 37 (NSM) (*fig. 19*) was overall the isotopically heaviest (least negative) water sampled ($\delta^{18}O$ and δD values, –3.08 and –21.9 per mil, respectively). The relatively heavy isotopic composition of this sample may be attributed primarily to mixing of freshwater and seawater rather than to evaporation. This water had a specific conductance of about 22,000 µS/cm (*Appendix E*). Seawater has an isotopic composition, by definition of the VSMOW scale, of 0 per mil for both $\delta^{18}O$ and δD (Gat and Gonfiantini, 1981) and a specific conductance of about 50,000 µS/cm (Hem, 1985). The isotopically heaviest freshwater sample (–5.36 and –38.8 per mil of $\delta^{18}O$ and δD, respectively) was the sample from spring 4N/5W-30PS1, located near Sears Point. The sample from well 5N/6W-2A6, located near Boyes Hot Springs, was overall the isotopically lightest (most negative) water sampled ($\delta^{18}O$ and δD values, –7.64 and –52.0 per mil, respectively; *Appendix F*).

The $\delta^{18}O$ and δD composition of the surface-water samples collected from Sonoma and Calabazas Creeks ranged from –5.09 to –6.68 per mil for $\delta^{18}O$ and from –33.0 to –41.1 per mil for δD (*fig. 28A*, *Appendix F*). The heaviest (least negative) value was from Sonoma Creek at Agua Caliente (S10) ($\delta^{18}O$ and δD values, –5.09 and –33.0 per mil, respectively) in mid-November 2002. The lightest (most negative) value was from Sonoma Creek at Lawndale Road (S5) ($\delta^{18}O$ and δD values, –6.45 and –41.1 per mil, respectively) in late May 2003. These values should not be considered representative of the annual range of $\delta^{18}O$ and δD as the isotopic composition of surface water usually varies because of temporal changes in hydrologic conditions and contributions of water from surface and subsurface sources (Gat and Gonfiantini, 1981).

Because neither set (mid-November 2002 and late May to early June 2003) of surface-water samples was collected during the wettest part of the water year (between November and April), these samples may primarily represent recently discharged ground, spring, and (or) soil water. The heavier isotopic composition of two samples collected in mid-November 2002, particularly the partly evaporated sample from Sonoma Creek at Agua Caliente (site S10), suggests that water in Sonoma Creek and its tributaries may at times also include large fractions of infiltrated water from uncovered retention ponds or perhaps shallow soil-water flushed out by irrigation return flow.

The $\delta^{18}O$ and δD composition of the samples from the springs ranged from –5.36 to –7.05 per mil for $\delta^{18}O$ and –38.8 to –45.3 per mil for δD (*Appendix F*). Three of four spring samples collected between early June and early September 2003 were from the northern part of the Sonoma Valley and have an isotopic composition that plots on the GMWL. The isotopic composition of the fourth sample, 4N/5W-30PS1 (–5.36 and –38.8 per mil of $\delta^{18}O$ and δD, respectively), collected from a spring near Sears Point, plots to the right of the GMWL (*fig. 28B*). Because this partly evaporated sample from September 2003 was collected from an above-ground collector box located several hundred yards downhill from the actual spring, it probably is not representative of spring water in the southern part of the Sonoma Valley.

The $\delta^{18}O$ and δD composition of the ground-water samples collected from the wells in the study area ranged from –5.52 to –7.75 per mil and –37.6 to –52.0 per mil, with a median composition of –6.68 and –42.5 per mil, respectively (*Appendix F*). These ranges are somewhat lighter (more negative) then the $\delta^{18}O$ and δD composition for surface-water samples collected in mid-November 2002 and late May-early June 2003, but similar to the expected overall range of surface-water values based on isotopic data from a similar study in the lower Milliken-Sarco-Tulucay Creeks area of southeastern Napa County (Farrar and Metzger, 2003), located approximately 12 mi east of the city of Sonoma. The median values for the isotopic composition of ground water are slightly lighter than the median volume-weighted $\delta^{18}O$ and δD composition of precipitation of –5.88 and –37.3 per mil, respectively, measured approximately 250 miles southeast of the Sonoma Valley at Santa Maria, California, between 1962 and 1976 by the International Atomic Energy Agency (2005). The difference is slightly less than the 2 per mil per degree of latitude decrease in δD expected with increasing latitude for sea-level precipitation in western North America (Williams and Rodini, 1997). Adjusted by about 3.3 degrees latitude to match the latitude of the city of Sonoma, the median volume weighted δD composition of sea-level precipitation would be about –43.9 per mil.

Water from most of the wells plot along the GMWL (*fig. 28A*), indicating that recharge primarily is derived from the direct infiltration of precipitation or from the infiltration of seepage from creeks. The scatter of these samples along the GMWL suggests that the samples may represent different ground-waters ages and (or) mixing of infiltrated surface water and precipitation with other contributing sources. The $\delta^{18}O$ and δD composition of water from the sampled wells indicates that water from wells deeper than 200 ft is isotopically lighter than water from wells less than 200 ft deep. Ground water from wells deeper than 200 ft may represent water that precipitated at higher elevations or cooler temperatures. The median $\delta^{18}O$ and δD composition of samples from seven wells with depths less than 200 ft was –6.04 and –38.9 per mil, respectively. The median $\delta^{18}O$ and δD composition of samples from 15 wells with depths 200 to 500 ft was –6.82 and –42.9 per mil, respectively. The median $\delta^{18}O$ and δD composition of samples from eight wells with depths greater than 500 ft was –6.89 and –44.6 per mil,
respectively.

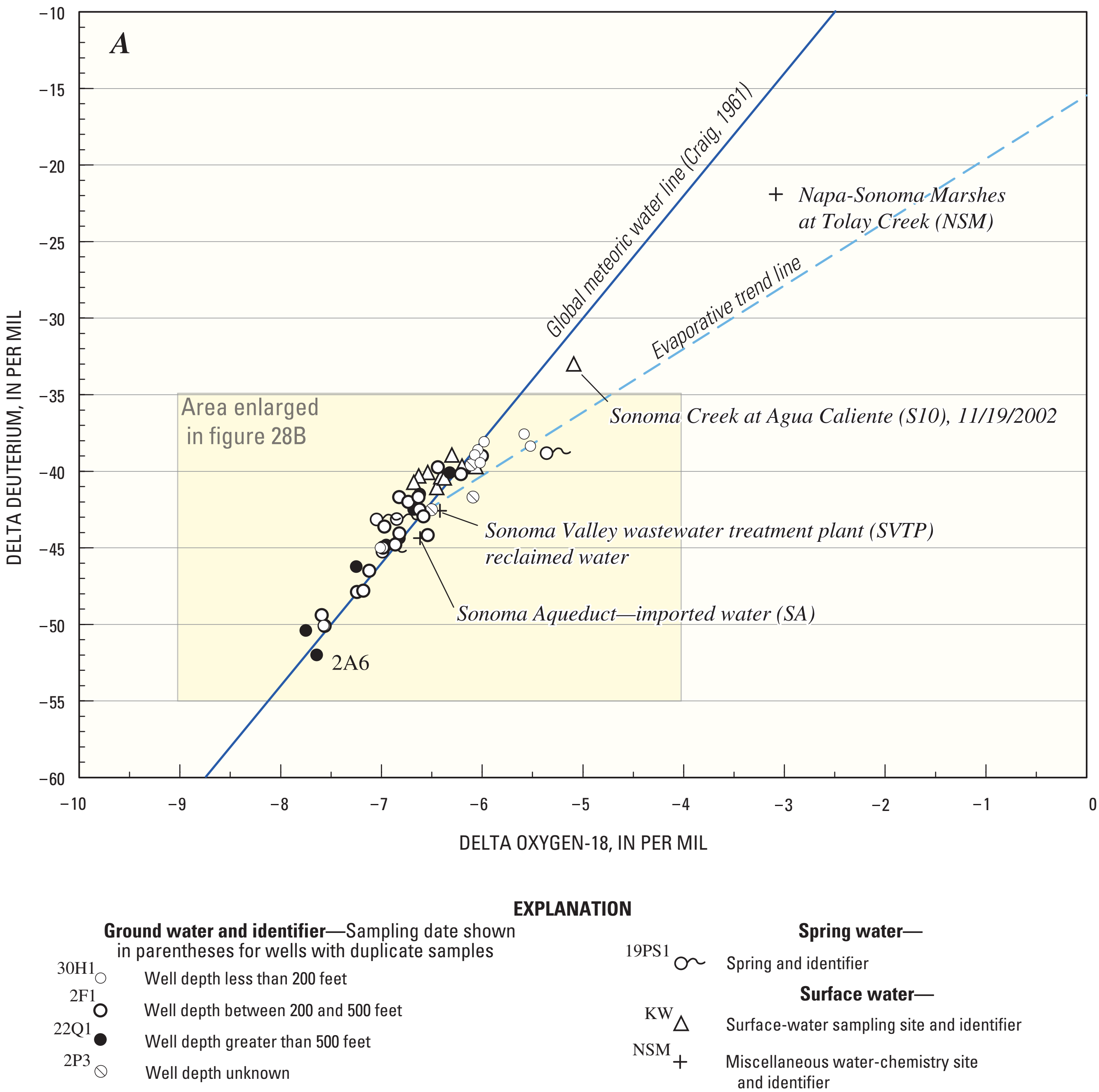


Figure 28. Relation between delta deuterium and delta oxygen-18 for (*A*) all water samples and (*B*) ground-water samples, spring-water samples, and selected surface-water samples, Sonoma Valley, Sonoma Valley, California, 2002–04.

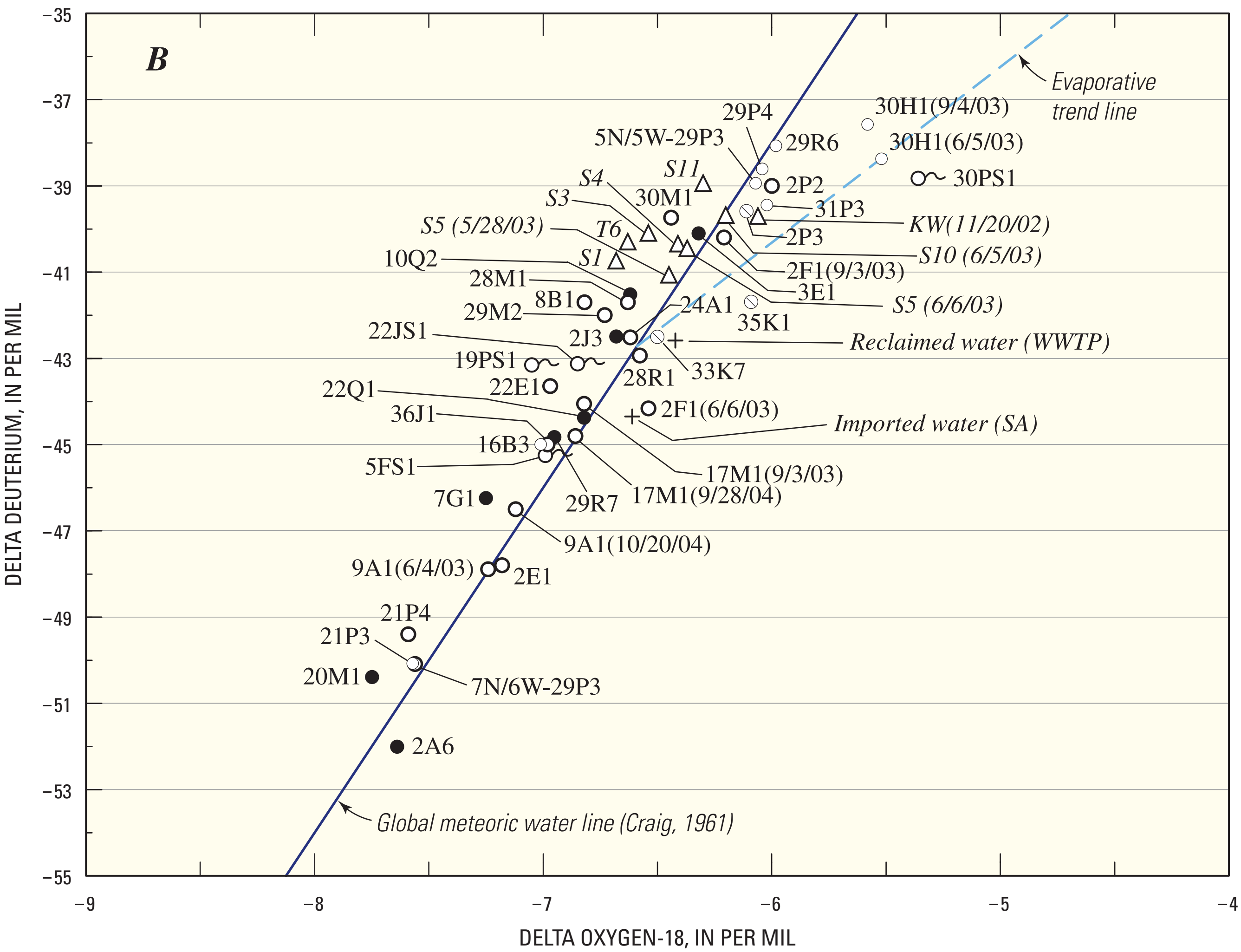


Figure 28.—Continued.

Waters affected by evaporation or modified by isotopic exchange after infiltration are represented by samples that plot to the right of the GMWL (*fig. 28B*). Samples from shallow and intermediate wells located near Sonoma Creek and (or) near the northern margin of the Bay-Mud deposits (4N/5W-2E1, -2F1, 5N/5W-28R1, -29P3, -29P4, -29R6, -30H1, -31P3, -33K7, 5N/6W-2P2, and -2P3) appear to have been subject to evaporation. Recharge to these wells is meteoric, derived directly from local precipitation or storm runoff, but modified by evaporation prior to infiltration or mixed with evaporated waters from contributing sources. Contributing sources of evaporated waters in these areas may include seepage from Sonoma Creek, irrigation return flow (primarily domestic irrigation in developed areas), delayed infiltration of shallow soil water in areas with heavy soils, infiltration or downstream release of surface water from uncovered retention ponds, and saline waters either from the infiltration and inland movement of brackish water from the tidal sloughs and marshlands north of San Pablo Bay or connate water associated with marine sedimentary deposits.

The most evaporated well samples were collected from a shallow well (5N/5W-30H1) located at the Sonoma Valley Wastewater Treatment Plant at Schellville (*fig. 19*). The isotopic composition of two samples (mean $\delta^{18}O$ and δD composition of –5.55 and –38.0 per mil, respectively) from this well plot along an evaporative trend line (*fig. 28A*). Wastewater treatment operations that are open to the atmosphere (secondary clarifier tanks and stormwater retention ponds) provide the opportunity for evaporation and isotopic enrichment of reclaimed water. Release of plant effluent to the marshlands of San Pablo Bay by way of Schell Slough is permitted from October 31 to May 1, but this occurs downstream of the wastewater treatment plant (Jim Zambenini, Sonoma Valley County Sanitation District, written commun., 2005). Alternatively, this water may have been isotopically enriched prior to treatment. Much of the influent received by the wastewater treatment plant originates as Russian River water imported into the study area by way of the Sonoma Aqueduct for public supply. The isotopic composition of samples representing imported and reclaimed water are partly evaporated and plot slightly to the right of the GMWL (*fig. 28B*).

Samples from wells 5N/6W-2A6 and 6N/6W-35K1 also plot to the right of the GMWL. These wells, given their proximity to each other, presumably, tap the same hydrothermal reservoir. However, the isotopic composition of water from well 5N/6W-2A6 is significantly lighter (more negative) and less evaporated, plotting only slightly off the GMWL. The isotopic variability of the thermal waters from these wells may be attributed to meteoric waters of different origins, mixing of different fractions of similar source waters, or modification by isotopic exchange after infiltration. Well 5N/6W-2A6, which was reportedly drilled to a depth of 1,000 ft, may produce thermal water that originated from precipitation that fell during a time when the climate was cooler and wetter than the present (Gat and Gonfiantini, 1981). The depth of well 6N/6W-35K1 is unknown, but based on construction information for nearby wells it may be less than 200 ft deep and water to this well may include a large fraction of isotopically enriched soil water. Alternatively, water to this well may have been modified by isotopic exchange. The isotopic composition of waters that are exposed to high temperatures (80°C or more) experience a shift toward heavier $\delta^{18}O$, but δD values remain largely unchanged (Gat and Gonfiantini, 1981) (*fig. 28B*). In a high temperature environment, an exchange reaction can occur between water and rock whereby some of the relatively light ^{16}O is transferred from the water to the rock and some of the relatively heavy ^{18}O is transferred from the rock to the water. Because rock contains an abundance of oxygen, but very little hydrogen, there is insufficient deuterium in the rock to balance any significant change in deuterium in the water. As a result, the rock becomes isotopically lighter and the water becomes isotopically heavier with respect to oxygen only (Gat and Gonfiantini, 1981).

Waters not affected by evaporation are represented by samples that plot on or to the left of the GMWL (*fig. 28B*). Recharge waters not affected by evaporation may occur in areas where precipitation and runoff infiltrate rapidly through coarse-grained alluvium or fractured rock and where there is negligible mixing with evaporated waters. These waters include samples from wells located near Sonoma Creek or its tributaries in the northern part of the Sonoma Valley (6N/6W-9A1, 7N/6W-29M2, and -29P3), in or along the margins of the Mayacmas or Sonoma Mountains (4N/5W-7G1, -17M1, -30M1, 5N/6W-3E1, -8C1, -10Q2, 6N/6W-36J1, 6N/7W-2J3, 7N/6W-22E1, and 7N/7W-24A1), near mapped or inferred faults (6N/6W-16B3 and -22Q1), and in the area of high-salinity ground water south of the city of Sonoma (5N/5W-20M1, -21P3, -21P4, and -29R7) (*fig. 19*).

Stream channels in the northern part of the Sonoma Valley generally have steeper gradients and coarser grained channel deposits than those in the southern Sonoma Valley. These factors may allow for faster downstream movement and infiltration of runoff, thereby minimizing evaporation. Similarly, in the Mayacmas and Sonoma Mountains (*fig. 19*), along the mountain front at the valley margins, and along fault zones, rapid infiltration of precipitation and runoff minimizes evaporation. The isotopic compositions of spring and well samples from the northern part of the study area and in the vicinity of the mountains suggest that these waters are of similar origin.

Four of the samples that plot to the left of the GMWL were collected from wells (5N/5W-20M1, -21P3, -21P4, and -29R7) located in the area of high-salinity ground water discussed in the section "High-Salinity Waters." Samples from three of these wells (5N/5W-20M1, -21P3, -21P4) were among the isotopically lightest (most negative) compositions of any sample analyzed ($\delta^{18}O$ and δD less than –7.5 and –49 per mil, respectively) (*fig. 28B*). The relatively light isotopic composition of these waters is not characteristic of water associated with modern saltwater intrusion, brackish shallow ground water from the marshlands north of San Pablo Bay, irrigation return flow, or soil water from fine-grained sediments. Concentration of dissolved solids from these potential sources would have to occur through evaporation which would result in heavier (less negative) $\delta^{18}O$ and δD values that would plot to the right of the GMWL. The lighter isotopic composition of the water in these four wells is consistent with older meteoric (connate) waters that originated during a cooler and wetter climatic period. Salinity in the water from these wells may also be attributed to simple leaching of salts by percolating water which would not change the isotopic composition (Gat and Gonfiantini, 1981).

Samples were collected from four wells more than once during 2003–04. The variation in the $\delta^{18}O$ and δD composition of water from one well (4N/5W-2F1) exceeded the analytical precision (0.5 and 2 per mil, respectively), suggesting that seasonal variation occurs in parts of the study area. The $\delta^{18}O$ and δD values increased from –6.54 and –44.2 per mil, respectively, in well 2F1 in early June 2003 to 6.21 and –40.2 per mil, respectively, in early September 2003 (*fig. 28B*, *Appendix F*). The seasonal variation may be attributed to different proportions of contributing sources as a result of seasonal pumping and irrigation of a nearby vineyard with reclaimed water. Other wells sampled more than once, 4N/5W-17M1, 5N/5W-30H1, and 6N/6W-9A1, showed much smaller seasonal changes in isotopic values (*fig. 28B*).

Ground-Water Flow Model

To better understand the ground-water flow in the Sonoma Valley ground-water basin, a numerical flow model of the basin was developed for the period 1974–2000. The ground-water flow model was developed using MODFLOW-2000 (MF2K) (Harbaugh and others, 2000). MF2K is a finite-difference model that simulates ground-water flow in a three-dimensional heterogeneous and anisotropic medium provided the fluid has constant density (Harbaugh and others, 2000).

Model Discretization

Spatial Discretization

The horizontal spacing of the MF2K model grid is 1,320 by 1,320 ft (*fig. 29*). The areal model domain generally corresponds to the areal extent of the alluvium and the topographic delineation of the valley floor. Estimates of average aquifer properties were assigned to the representative cell volume, and average hydraulic head was calculated at the center, or node, of each cell.

Vertical layering in the model along with the relative thicknesses and the altitudes of the modeled hydrogeologic units is shown in *figure 30*. The mean thicknesses of each model layer are presented in *table 4*. The aquifer system was vertically discretized into eight model layers. Model layers 1 and 2 represent the upper hydrogeologic unit discussed in the "Ground-Water Hydrology" section (generally the upper 200 ft). Model layers 3 through 6 represent the middle hydrogeologic unit (generally ranging from 200 to 500 ft in depth below land surface). Model layers 7 and 8 represent the lower geohydrologic unit (greater than 500 ft below land surface). All model layers have the same areal extent except where the elevation of the bedrock is greater than the top elevation of a model layer, which affects a small number of cells in model layers 5 through 8.

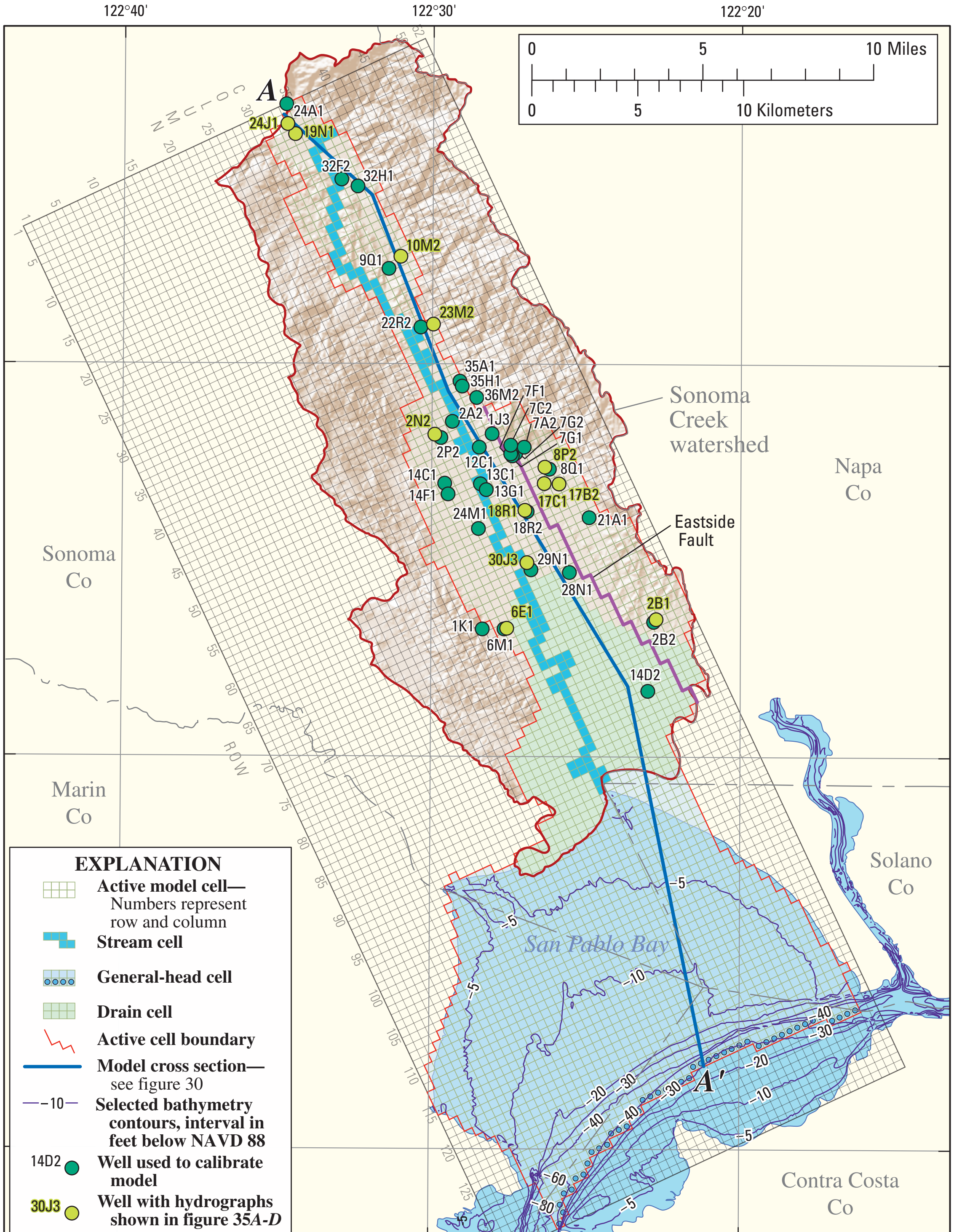
Temporal Discretization

MF2K allows a modeler to simulate the first stress period as steady state and the following stress periods as transient state. In this study, it was assumed that pre-1975 conditions reflected quasi-steady-state conditions (*fig. B-1A*) and were simulated as steady state in the model. After about 1975, ground-water development increased (*fig. 3*). The transient-state simulation period, 1975–2000, was simulated using annual stress periods, with six time steps per stress period. The total number of steady- and transient-state stress periods was 27. The end of the model simulation period was chosen to correspond with the most recent land-use data (1999) used to estimate agricultural pumpage (*Appendix G*).

To determine the adequacy of the transient temporal discretization, the time-varying mass-balance errors (the difference between total inflow and outflow for each stress period) were considered. In general, time-varying mass-balance errors should not fluctuate in an unstable manner and the final mass-balance error should be relatively small. A plot of percent mass-balance error for each stress period for the ground-water flow model is shown in *figure 31*. The mass-balance error fluctuates with time; however, the absolute error generally was less than 0.01 percent; the greatest absolute error is 0.02 percent for stress periods 8, 11, 13, 15, and 27 (*fig. 31*). The time-varying and final mass-balance errors indicate that the temporal discretization was adequate.

Model Boundaries

Three types of boundary conditions are used in the ground-water flow model: no-flow, general head, and drain. A no-flow boundary indicates that there is no exchange of water between the model cell and the domain outside the model. All lateral boundaries, with exception of the southern boundary with San Pablo Bay, were simulated as no-flow boundaries (*fig. 29*). For the most part, these no-flow boundaries correspond to the lateral extent of the mapped quaternary alluvial units, Bay Mud deposits, Huichica Formation, Glen Ellen Formation, and volcanolastic Sonoma Volcanics. The bottom of the model corresponds with the top of the basement complex as defined by the gravity data presented in *Appendix A*. The depth to basement complex, as described in *Appendix A*, can be as great as 10,000 ft. The lowest model layer extends to the estimated top of the basement complex for completeness; however, the depth of the basement complex is well below the active flow system and includes older geologic units that do not produce or transmit significant amounts of water.



Base from U.S. Geological Survey digital data, 1:250,000, 2003. State Plane Projection, Fipzone 402. Shaded relief base from 1:250,000 scale Digital Elevation Model: sun illumination from northwest at 30 degrees above horizon

Figure 29. Model grid showing boundary conditions; locations of stream cells, observation wells, and faults; and bathymetry contours, used in the ground-water flow model of the Sonoma Valley, Sonoma County, California.

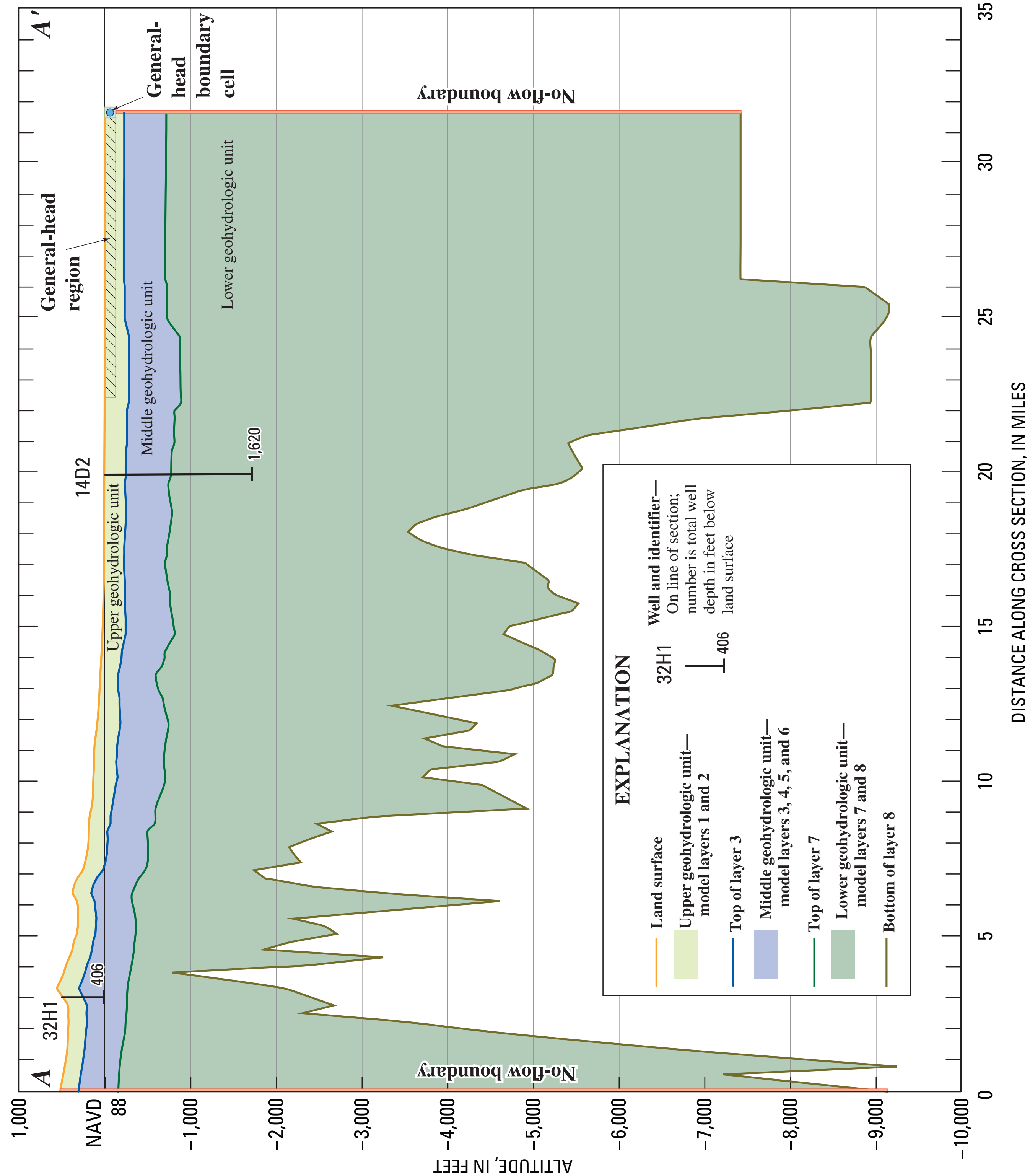


Figure 30. Cross section showing geology and vertical representation of geohydrologic units in the ground-water flow model of the Sonoma Valley, Sonoma County, California.

Table 4. Mean thickness of layers of the ground-water flow model of Sonoma County, California.

[ft, feet]

Model layer	Mean thickness (ft)
1	125
2	127
3	127
4	127
5	127
6	127
7	126
8	3,898

A general-head boundary simulates a source of water outside the model area that either supplies, or receives water from, adjacent cells at a rate proportional to the hydraulic-head differences between the source and the model cells (Harbaugh and others, 2000). The constant of proportionality is the hydraulic conductance (L^2/t) whose value is determined during the calibration process. The general-head boundaries were located on the vertical faces of cells along the edge of model layer 1 at the approximate location where the modeled strata outcrop into San Pablo Bay and on the horizontal face of other cells of model layer 1 underlying San Pablo Bay (*fig. 29*).

A drain boundary simulates features that remove water from the aquifer at a rate proportional to the difference between the head in the aquifer and some fixed head as so long as the head in the aquifer is above that fixed head, but has no effect if head falls below that level (McDonald and Harbaugh, 1988). The constant of proportionality is the drain conductance (L^2/t) whose value is determined during the calibration process. Drain boundaries were located at the approximate location of the Bay Mud deposits to simulate the marsh-like conditions (*fig. 29*).

Subsurface Properties

Model layer properties [horizontal and vertical hydraulic conductivity, storage coefficient, specific yield, hydraulic conductance (used to simulate faults), and boundary conditions] affect the rate at which simulated water moves through an aquifer, the volume of water in storage, and the rate and areal extent of changes in ground-water levels caused by ground-water pumping and (or) recharge. For this study, some of the aquifer-system properties (hydraulic conductivity, storage coefficient, and specific yield) were estimated initially from well logs, specific-capacity tests, and published literature. Final estimates of these properties were made using a trial-and-error approach under steady-state and transient-state conditions (*table 5*).

Most aquifer-system properties (such as hydraulic conductivity and storage properties) are continuous functions of the spatial variables and, therefore, the number of property values could be infinite. For estimation purposes, the infinite number of property values may be reduced through parameterization (Yeh, 1986). For this study, the hydraulic-conductivity distribution for each model layer, except model layers 7 and 8, were assumed to be heterogeneous and anisotropic; model layers 7 and 8 were assumed to be homogeneous and anisotropic. Storage-property distributions for each model layer were assumed to be homogeneous.

Hydraulic Conductivity

According to Lohman (1979), an aquifer has “a hydraulic conductivity (*K*) of unit length per unit time if it will transmit in unit time a unit volume of ground water at the prevailing viscosity through a cross section of unit area, measured at right angles to the direction of flow, under a hydraulic gradient of unit change in head through unit length of flow.” MF2K requires specification of horizontal and vertical hydraulic-conductivity values for each active cell in the model domain.

Initially, the hydraulic-conductivity values were estimated using point-lithology data from drillers’ logs and published values associated with the lithologic description (Freeze and Cherry, 1979; Linda R. Woolfenden, U.S. Geological Survey, unpub. data, 2004). The point-hydraulic-conductivity values were then kriged, yielding a hydraulic-conductivity value for each active model cell. The number of model parameters using the kriged estimates was too large; therefore, the hydraulic-conductivity values were parameterized into homogeneous zones (*fig. 32*). The zonation was based on the general values of the kriged estimates and the initial value assigned to each zone was based on values reported by Freeze and Cherry (1979). Model layers 1 and 2 have seven zones, model layers 3 through 6 have six zones, and model layers 7 and 8 are simulated as a single homogenous zone. In model layers 1 and 2, zone 1 represents the Bay Mud deposits and offshore in San Pablo Bay, zones 2 and 4 represent the west and east areas of the central part of the valley, zone 3 represents the middle area of the central part of the valley, zone 5 represents areas where the Sonoma Volcanics are exposed, zone 6 represents the upper valley, and zone 7 (present in model layers 1 and 2) represents the relatively permeable streambed. In general, the same zonation applies to model layers 3 through 6, except zone 1 represents similar material as zones 2 and 4.

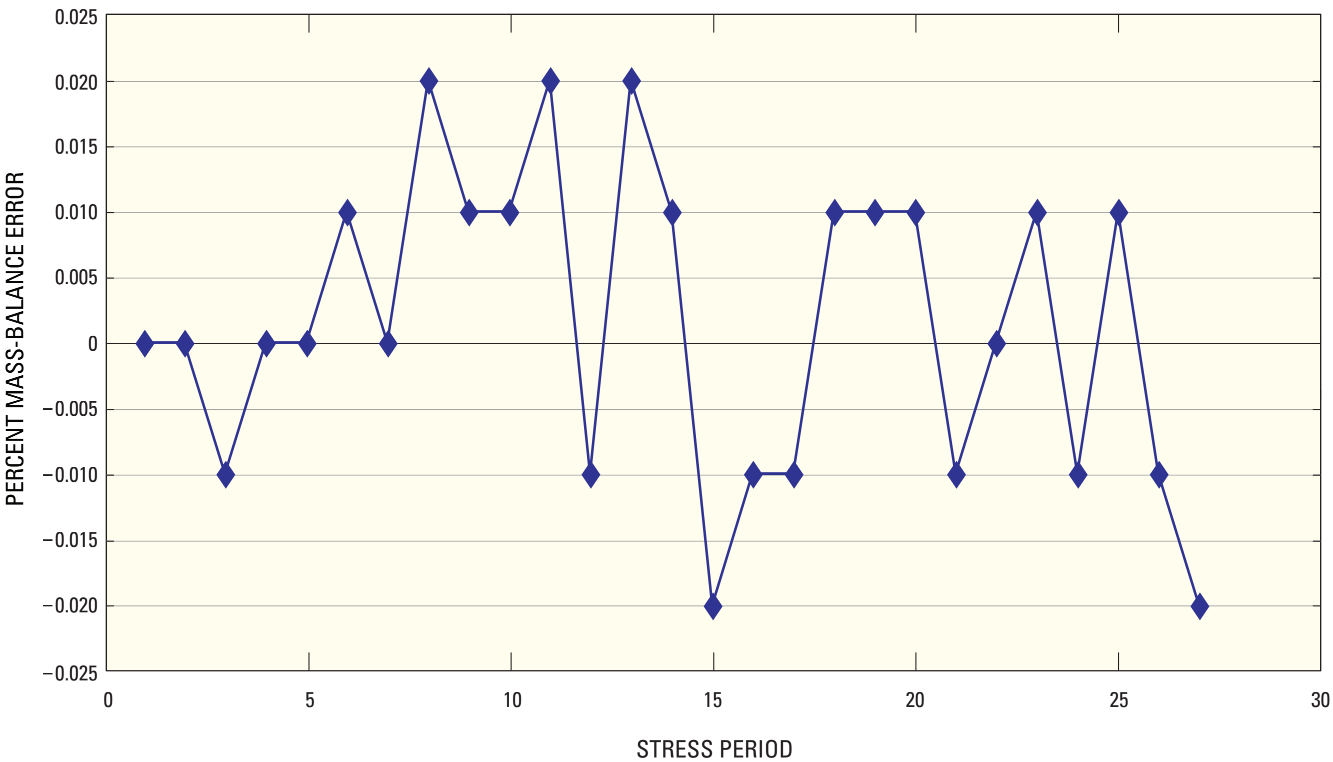


Figure 31. Time-varying mass-balance error in the simulation of the ground-water flow model of the Sonoma Valley, Sonoma County, California.

Storage Coefficient and Specific Yield

The storage coefficient (also known as storativity, S) of a saturated confined aquifer of thickness b is the volume of water that an aquifer releases from storage per unit of surface area of aquifer per unit decline in the component of hydraulic head normal to that surface (Freeze and Cherry, 1979). For confined aquifers, water is released from storage when pumping causes a decrease in pore-fluid pressure (hydraulic head or head is equal to the pore-fluid pressure divided by the specific weight of water) that increases the intergranular stress transmitted by the solid skeleton of the aquifer and results in a small reduction in porosity. The decrease in pore-fluid pressure also produces a slight expansion of water. The combination of the small reduction in porosity and the slight expansion of the water results in a certain volume of water being released from storage (Bear, 1979).

The specific yield (S_y) for an unconfined aquifer is the volume of water released from storage per unit surface area of aquifer per unit decline in the water table (Freeze and Cherry, 1979). For unconfined aquifers, water is released from storage when a decline in ground-water level results in the desaturation of the porous medium. S_y and S [specifically, specific storage ($S_s = S/b$)] were specified for model layer 1 because it was simulated as a convertible model layer and S_s was specified for model layers 2 through 8. S_y and S_s were assumed homogeneous in model layer 1 and layers 2 through 8, respectively. Initial estimates of these parameters were based on values reported by Freeze and Cherry (1979).

Faults

Faults can be barriers to ground-water flow. The Eastside Fault (*fig. 29*), which may affect ground-water flow in the Sonoma Valley ground-water basin, was modeled using the Horizontal Flow Barrier (HFB) Package (Hsieh and Freckleton, 1993). The HFB package simulates faults as thin, vertical, low-permeability geologic features that impede the horizontal flow of ground water. Faults are approximated as a series of horizontal-flow barriers between pairs of adjacent cells in the finite-difference grid (Hsieh and Freckleton, 1993). Flow across a simulated fault is proportional to the hydraulic-head difference between adjacent cells. The constant of proportionality is the hydraulic characteristic (t^{-1}) that is equal to the hydraulic conductivity divided by the thickness of the fault (here, assumed to equal 1 ft) adjusted for the angle that the fault crosses the model cell (Richard B. Winston, U.S. Geological Survey, unpub. data, 2005). The hydraulic characteristic was modified using a multiplier; the value of the multiplier was estimated during the calibration process.

Table 5. Initial and final model parameter estimates used to calibrate the ground-water flow model of Sonoma County, California.

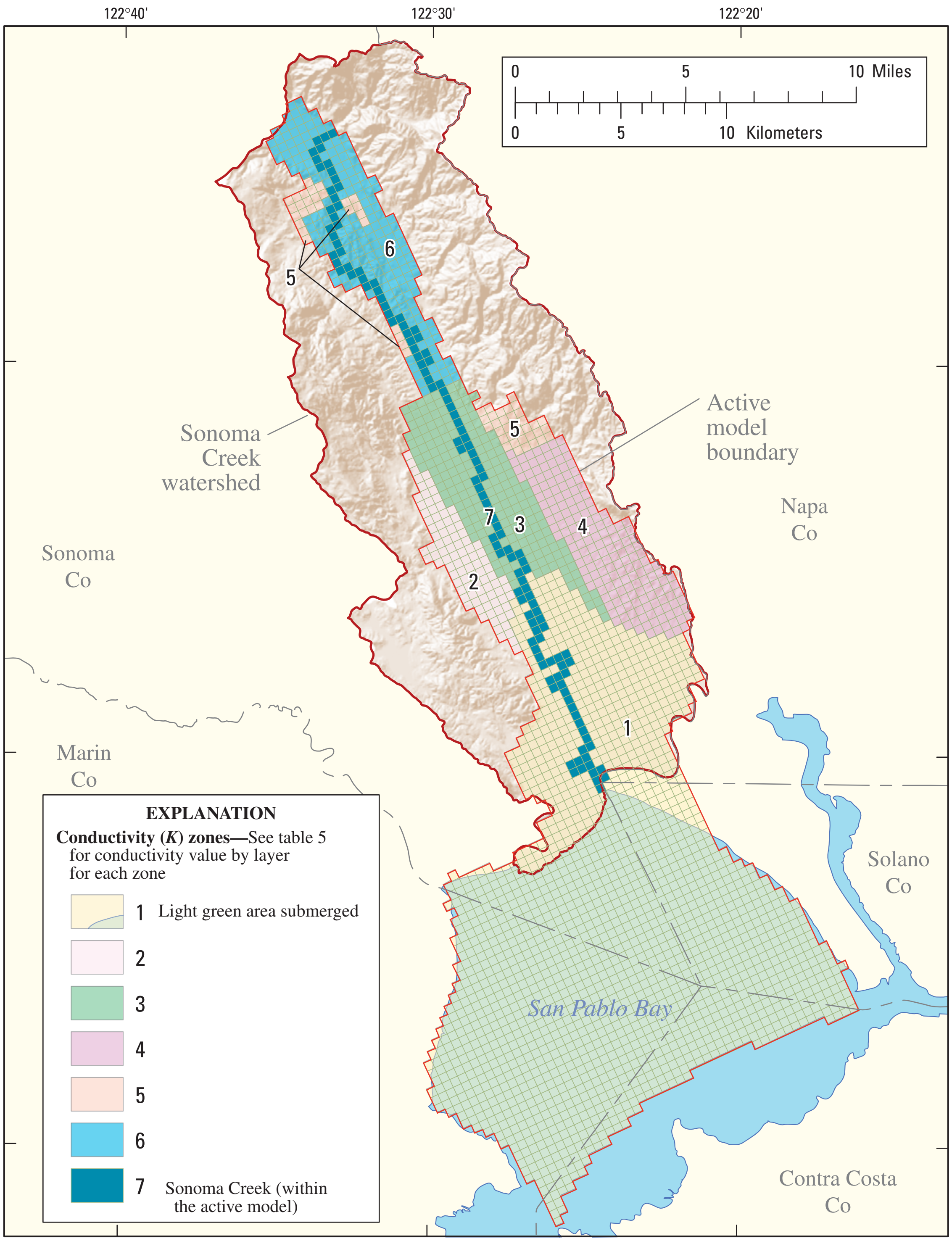
[ft/d, foot per day; acre-ft/yr, acre-feet per year; /ft, per foot; NA, not applicable; S_s, specific storage; S_y, specific yield]

Model layers	Horizontal hydraulic conductivity (ft/d)						
	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7
	(Initial) Final	(Initial) Final	(Initial) Final	(Initial) Final	(Initial) Final	(Initial) Final	(Initial) Final
1	(3.0) 1.0	(5.0) 5.0	(7.0) 25.0	(5.0) 5.0	(3.0) 3.0	(10.0) 25.0	(25.0) 50.0
2	(3.0) 3.0	(5.0) 5.0	(7.0) 25.0	(5.0) 5.0	(3.0) 3.0	(10.0) 25.0	(25.0) 50.0
3	(3.0) 3.0	(5.0) 5.0	(7.0) 7.0	(5.0) 5.0	(3.0) 3.0	(10.0) 25.0	NA
4	(3.0) 3.0	(5.0) 5.0	(7.0) 7.0	(5.0) 5.0	(3.0) 3.0	(10.0) 10.0	NA
5	(3.0) 3.0	(5.0) 5.0	(7.0) 7.0	(5.0) 5.0	(3.0) 3.0	(10.0) 10.0	NA
6	(3.0) 3.0	(5.0) 5.0	(7.0) 7.0	(5.0) 5.0	(3.0) 3.0	(10.0) 10.0	NA
7	(3.0) 0.8	(3.0) 0.8	(3.0) 0.8	(3.0) 0.8	(3.0) 0.8	(3.0) 0.8	NA
8	(1.0) 0.8	(1.0) 0.8	(1.0) 0.8	(1.0) 0.8	(1.0) 0.8	(1.0) 0.8	NA

Model layers	Vertical hydraulic conductivity (ft/d)						
	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7
	(Initial) Final	(Initial) Final	(Initial) Final	(Initial) Final	(Initial) Final	(Initial) Final	(Initial) Final
1	(0.03) 0.01	(0.05) 0.05	(0.07) 0.1	(0.05) 0.05	(0.03) 0.03	(0.1) 0.1	(2.50) 5.0
2	(0.03) 0.03	(0.05) 0.05	(0.07) 0.1	(0.05) 0.05	(0.03) 0.03	(0.1) 0.1	(2.50) 5.0
3	(0.03) 0.03	(0.05) 0.02	(0.07) 0.07	(0.05) 0.01	(0.03) 0.01	(0.1) 0.03	(2.50) 5.0
4	(0.03) 0.03	(0.05) 0.02	(0.07) 0.07	(0.05) 0.01	(0.03) 0.01	(0.1) 0.03	NA
5	(0.03) 0.03	(0.05) 0.02	(0.07) 0.07	(0.05) 0.01	(0.03) 0.01	(0.1) 0.03	NA
6	(0.03) 0.03	(0.05) 0.02	(0.07) 0.07	(0.05) 0.01	(0.03) 0.01	(0.1) 0.03	NA
7	(0.03) 0.08	(0.03) 0.08	(0.03) 0.08	(0.03) 0.08	(0.03) 0.08	(0.03) 0.08	NA
8	(0.01) 0.08	(0.01) 0.08	(0.01) 0.08	(0.01) 0.08	(0.01) 0.08	(0.01) 0.08	NA

Model layers	Storage coefficient	
	Sy (1)	Ss (/ft)
	(Initial) Final	(Initial) Final
1	(0.25) 0.1	(1 × 10-6) 1.5 × 10-4
2	NA	(1 × 10-6) 1.5 × 10-4
3	NA	(1 × 10-6) 1.5 × 10-4
4	NA	(1 × 10-6) 1.5 × 10-4
5	NA	(1 × 10-6) 1.5 × 10-6
6	NA	(1 × 10-6) 1.5 × 10-6
7	NA	(1 × 10-6) 1.5 × 10-6
8	NA	(1 × 10-6) 1.5 × 10-6

Recharge (acre-ft/yr)	
Area	
Northern	3.43 × 104
Middle	2.98 × 103
Southern	0.00 × 100
Total	3.73 × 104



Base from U.S. Geological Survey digital data, 1:250,000, 2003. State Plane Projection, Fipzone 402..
Shaded relief base from 1:250,000 scale Digital Elevation Model: sun illumination from northwest at 30 degrees above horizon

Figure 32. Hydraulic conductivity zones used in model parameterization, Sonoma County, California.

The trace of the simulated Eastside Fault is shown in *figure 29*. It is simulated in model layers 2 through 8.

Initially, the hydraulic-characteristic-multiplier value for the fault was set to a large value allowing ground water to flow freely across the fault. Through the calibration process, the hydraulic-characteristic-multiplier value was lowered to simulate measured water levels.

Stream-Aquifer Interactions

The Streamflow-Routing Package (Prudic, 1989) was used to simulate stream-aquifer interactions along Sonoma Creek and, to a lesser extent, streamflow in Sonoma Creek. The streamflow routing package is not a true surface-water flow model; however, it does simulate the interaction between the creek and the ground-water system, and tracks the amount of flow in the creek. If the hydraulic head in the aquifer is greater than or equal to the elevation of the bottom of the streambed, then leakage between the stream and aquifer is proportional to the difference between the hydraulic head in the stream and the hydraulic head in the aquifer beneath the streambed. If the hydraulic head in the aquifer is less than the elevation of the bottom of the streambed, then leakage is proportional to the difference between hydraulic head in the stream and the elevation of the bottom of the streambed. The constant of proportionality is the streambed conductance (L^2/t); this value was estimated during the calibration process.

Streams superimposed on the aquifer system are divided into segments and reaches. A segment is a stream or diversion in which streamflow from surface sources are added at the beginning of the segment or subtracted (in the case of a diversion) at the end of the segment (Prudic, 1989). A reach is the part of a segment that corresponds to an individual model cell in the finite-difference grid used to simulate ground-water flow in the aquifer system. For this work, it was assumed that there were no surface sources or losses along Sonoma Creek; therefore, the creek was simulated using one segment. The segment was subdivided into 128 reaches (*fig. 29*).

Model Inflow

Potential sources of model inflow are natural recharge from precipitation, stream leakage, and inflow from San Pablo Bay. Direct recharge from precipitation was simulated using areal recharge with annual average fluxes applied to different recharge zones (*fig. 33*). The flux rate applied to each recharge zone was based on the average annual rates presented earlier in this report. Long-term average ground-water recharge to the valley was estimated to range from 2.90 to 4.90×10^4 acre-ft/yr. Initially, areal recharge for the steady-state simulation was distributed among five recharge zones (*fig. 33*) based on the 23 contributing subbasins described in the "Surface-Water Hydrology" section and shown on *figure 8*. These steady-state recharge estimates were modified during calibration. Variable recharge was estimated in the transient simulation by multiplying the annual average flux rate by the fraction of average annual precipitation (normalized to 1974 conditions). For example, the total precipitation in 1975 was 125 percent of the average annual precipitation; therefore, the average annual flux rate was multiplied by 1.25. As described in the "Model Calibration" section, an upper bound on maximum annual recharge was applied. The fraction of average annual precipitation for 1974–2000 is presented in *table 6*.

Water from streams can either flow into or flow out of the ground-water system. The magnitude and direction of flow are functions of stream stage, simulated hydraulic head in the aquifer side of the streambed, and streambed conductance.

Model Outflow

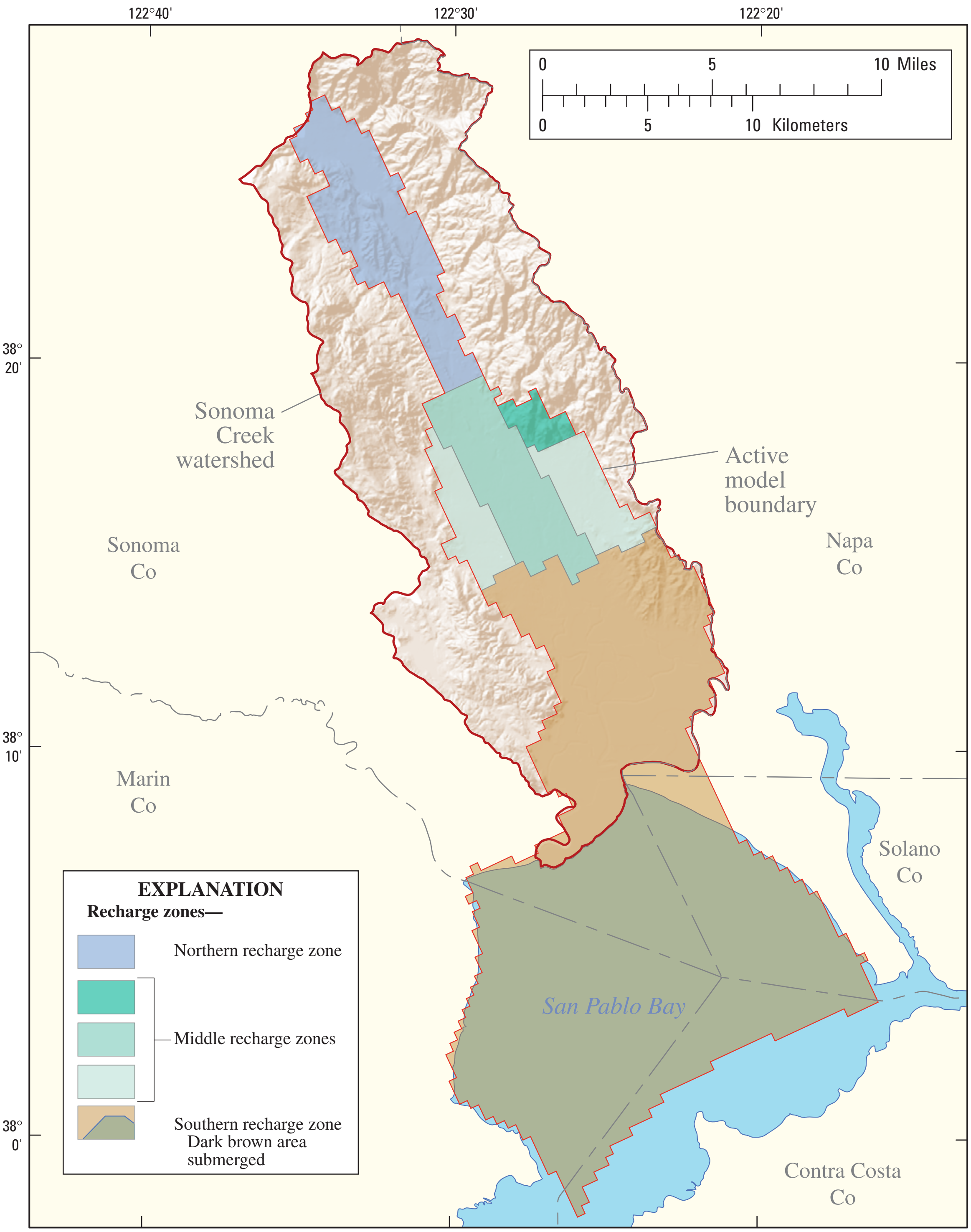
Potential sources of model outflow are natural discharge (evapotranspiration, stream leakage, drains, and subsurface discharge into San Pablo Bay) and pumping. It was assumed that evapotranspiration occurs along Sonoma Creek; however, during the modeling process it was found that simulating both evapotranspiration and stream leakage caused numerical instabilities in the model. Therefore, only stream leakage was simulated and it was assumed that any stream leakage out of the ground-water system included evapotranspiration. Note, it was assumed that any simulated drain outflow from the Bay Mud deposits includes evapotranspiration.

Annual pumpage was based on reported data and estimated values. The procedure for estimating pumpage for the model is described in *Appendix G*. As shown in *figure G-5* and *table G-2*, the estimated annual pumpage for the model area ranges from about 6.17×10^3 acre-ft in 1974 to about 8.43×10^3 acre-ft in 2000. Agricultural pumpage was estimated using land-use data for 4 different years spanning the model period, and interpolating between these years. This approach accounts for long-term trends in pumpage; however, interannual variability in pumpage is not addressed.

The annual pumpage was simulated using the Multi-Node Well Package (Halford and Hanson, 2002). In general, the Multi-Node Well Package distributes vertically the total pumpage based on the hydraulic conductivity of the model layers penetrated by the well and the screened interval of the well.

Model Calibration

The ground-water flow model of the Sonoma Valley ground-water basin was iteratively calibrated using a trial-and-error process in which the initial estimates of the aquifer properties were adjusted to improve the match between simulated hydraulic heads and measured ground-water levels. Measured ground-water levels for steady-state (pre-1975) conditions and for the period of 1975–2000 from 37 wells were used to calibrate the ground-water flow model. The iterative calibration process involved systematically adjusting the parameters to minimize hydrologic-budget error, match measured water levels, and simulate reasonable boundary fluxes.



Base from U.S. Geological Survey digital data, 1:250,000, 2003. State Plane Projection, Fipzone 402.
Shaded relief base from 1:250,000 scale Digital Elevation Model: sun illumination from northwest at 30 degrees above horizon

Figure 33. Areal recharge zones used in model parameterization, Sonoma County, California.

Table 6. Fraction of long-term average annual precipitation and estimated fraction of steady-state recharge in Sonoma Valley, Sonoma County, California, 1974–2000.

Calendar year	Fraction of annual mean precipitation	Fraction of annual mean precipitaiton normalized to 1974	Fraction of steady state recharge applied to model	Fraction of annual mean streamflow	Fraction of annual mean streamflow normalized to 1974
1974	0.81	1.00	1.00	1.10	1.00
1975	1.01	1.25	1.25	1.01	0.92
1976	0.38	0.47	0.47	0.05	0.05
1977	0.79	0.98	0.98	0.18	0.16
1978	1.02	1.26	1.26	1.36	1.24
1979	1.28	1.58	1.20	0.81	0.74
1980	0.86	1.06	1.06	1.33	1.21
1981	1.17	1.44	1.20	1.07	0.97
1982	1.58	1.95	1.20	2.09	1.90
1983	2.13	2.63	1.20	3.08	2.80
1984	0.74	0.91	0.91	0.46	0.42
1985	0.41	0.51	0.51	0.38	0.35
1986	1.13	1.40	1.20	2.05	1.86
1987	1.01	1.25	1.25	0.34	0.31
1988	0.65	0.80	0.80	0.33	0.30
1989	0.67	0.83	0.83	0.35	0.32
1990	0.61	0.75	0.75	0.23	0.21
1991	0.81	1.00	1.00	0.48	0.44
1992	1.19	1.47	1.20	0.50	0.45
1993	1.14	1.41	1.20	1.26	1.15
1994	0.76	0.94	0.94	0.27	0.25
1995	1.64	2.02	1.20	2.52	2.29
1996	1.53	1.89	1.20	1.42	1.29
1997	0.91	1.12	1.12	1.24	1.13
1998	1.60	1.98	1.20	1.93	1.75
1999	0.92	1.14	1.14	0.91	0.83
2000	0.99	1.22	1.22	0.75	0.68

Measured ground-water levels collected prior to 1975 were used to calibrate the ground-water flow model for steady-state conditions. Measured ground-water levels from 1975 to 2000 were used to calibrate the ground-water flow model for transient conditions. The variability in the simulated hydraulic heads is dependent on ground-water pumping, natural recharge and discharge, boundary conditions, hydraulic parameters (K, S_y, and S_s), stream stage, and fault parameters (hydraulic characteristic).

Final values of horizontal hydraulic conductivity range from 0.8 ft/d in layers 7 and 8 (lower geohydrologic unit) to 50 ft/d zone 7, along Sonoma Creek in layers 1 and 2 (upper geohydrologic unit) (table 5). In general, the final estimated values changed little from the initial values, except those for zones 3, 6, and 7 in model layers 1 and 2 (upper hydrogeologic unit). Zones 3 and 6 represent less consolidated alluvial material adjacent to Sonoma Creek which has greater hydraulic conductivity values. Zone 7 is immediately adjacent to Sonoma Creek and has the greatest final hydraulic conductivity value.

The initial estimate of the vertical hydraulic conductivity anisotropy ratio was assumed to equal 100:1, that is, the horizontal hydraulic conductivity was 100 times greater than the vertical hydraulic conductivity (*table 5*). The final anisotropy ratios, following model calibration, range from 10:1 to 500:1. In general, zones 2, 4, and 6 in model layers 3 through 6 (middle hydrogeologic unit) had anisotropy ratios greater than 100:1, whereas zones 3, 6, and 7 in model layers 1 and 2 had anisotropy ratios less than 100:1. The greater anisotropy ratios in zones 2, 4, and 6 may reflect greater consolidation or more low-permeability interbeds.

Both S_y and S_s are defined for model layer 1 because the layer was assumed to be unconfined (*table 5*). Specific storage was defined for model layers 2 through 8 because these layers were assumed to be confined. The final value for S_y in layer 1 was 0.1. The final values for S_s were 1.5×10^{-4}/ft for model layers 1 through 4 and 1.5×10^{-6}/ft for model layers 5 through 8.

The final values of steady-state areal recharge specified in the model are presented in table 5. Total recharge in the northern zone was 3.43×10^4 acre-ft/yr, total recharge in the middle zone was 2.98×10^3 acre-ft/yr, and recharge in the southern zone was set equal to zero (*fig. 33*).

Total steady-state recharge equals 3.70×10^4 acre-ft/yr. As described earlier, transient annual areal recharge was simulated as specified flux to model layer 1 on the basis of the relative amount of precipitation. During the calibration process, it was found that fractions greater than about 1.30 would result in simulated hydraulic heads that were above land surface; therefore, these fractions were reduced to 1.20 (*table 6*), implying that there is an upper bound on the amount of precipitation that can recharge the Sonoma Valley ground-water system in a given year.

The general-head-boundary hydraulic-conductance values were estimated through calibration such that the simulated steady-state hydraulic heads approximated measured steady-state water levels (pre-1975 ground-water levels). General-head boundaries were on the horizontal face at the top of model layer 1 underlying San Pablo Bay and the vertical face of the offshore boundary at San Pablo Bay (*fig. 29*). The depth of water in San Pablo Bay overlying model layer 1 varies spatially from about 2 to 80 ft (*fig. 29*). The water in San Pablo Bay was assumed to be seawater although it actually is a mix of seawater and freshwater the source of which is the San Francisco Bay delta. Seawater has a greater density than freshwater, and this greater density must be addressed when setting the value of external head at general-head boundaries. The equivalent freshwater head on the horizontal face of model layer 1 was set equal to 1.025 times the depth of water overlying the face. The depth of water in San Pablo Bay overlying the outcrop varies from about 30 to 70 ft. The thickness of model layer 1 at the outcrop is about 120 to 140 ft; therefore, it was assumed that water can be exchanged only across the vertical face of model layer 1. The head on the vertical boundary of model layer 1 was set equal to 1.025 times the sum of water depth and the bottom elevation of model layer 1. The initial hydraulic-conductance values for the horizontal and vertical faces were 1.34×10^4 and 1.30×10^2 ft^2/d, respectively, which allowed water to freely leave the basin. The final estimated hydraulic-conductance values for the horizontal and vertical faces were both equal to 1.00×10^{-2} ft^2/d.

The drain-conductance value was estimated through calibration such that the simulated steady-state hydraulic heads approximated measured steady-state water levels. The initial drain-conductance value was set equal to 1.34×10^4 ft^2/d, which allowed water to freely leave the basin. The final drain-conductance value was 0.10 ft^2/d.

The steady-state flow of Sonoma Creek at the point where the creek enters the domain of the simulation model along the northeastern side was estimated to equal 6.70×10^3 acre-ft/yr. This estimate is the sum of estimated mean annual runoff from three contributing subbasins located outside the area included in the model. To provide a means for the simulation model to represent variable annual discharge in Sonoma Creek, a multiplication factor was calculated for each year from 1974 to 2000. The factors are decimal values that are the ratio of total annual measured or estimated streamflow to the mean annual streamflow at the Agua Caliente gage, normalized so that the factor for 1974 is equal to 1.00 (*table 6*). The Agua Caliente gage was in operation from 1974 to 1981 and then discontinued until 2002. Streamflow at the Agua Caliente gage was estimated for the years 1982 to 2000 using a correlation between discharge in Sonoma Creek (USGS station 11458500) and Napa River (USGS station 11458000) for the period 1960 to 1981. The linear correlation of discharge between these two stations has an R^2 value of 0.98.

The streambed-conductance value was estimated through calibration such that the simulated steady-state hydraulic heads approximated measured steady-state water levels. The initial streambed-conductance value was set equal to 44.0 ft^2/d using the minimum vertical hydraulic conductivity of 0.01 ft/d and an assumed streambed thickness of 3 ft, which allowed little exchange between surface water and ground water. The final streambed-conductance value was 2.00×10^3 ft^2/d.

Ground-water flow across a simulated fault is proportional to the hydraulic characteristic (Hsieh and Freckleton, 1993). The parameter estimated during the calibration process was not the hydraulic characteristic but a multiplier of hydraulic characteristic, where the hydraulic characteristic is the hydraulic conductivity divided by the fault thickness adjusted by the angle that the fault crosses the model cell. The initial hydraulic-characteristic-multiplier value for the Eastside Fault was set such that the hydraulic characteristic was equal to the largest value of hydraulic conductivity adjacent to the fault (5 ft/d) divided by the assumed width of the fault (1 ft), allowing unrestricted hydraulic connection across the fault. To reproduce the measured water levels, it was necessary to simulate the fault by decreasing the initial hydraulic-characteristic-multiplier value by 11 orders of magnitude, 1.00×10^{-10}/d.

Simulated Hydraulic Heads

Areal Distribution: Steady State and 2000

Simulated hydraulic heads for model layer 2 and water-level measurements from selected wells for SS conditions (pre-1975) and at the end of the simulation period (2000) are shown in figure 34. Recall that the upper aquifer is simulated by model layers 1 and 2, and it was assumed that the simulated hydraulic heads for model layer 2 are representative of the upper aquifer. The simulated hydraulic heads for SS conditions for model layer 2 range from as high as 460 ft in the Kenwood/Los Guilicos area to less than 20 ft near the Bay Mud deposits (*fig. 34A*). The model results generally are consistent with measured water levels and indicate that ground water flows down valley from Kenwood/Los Guilicos toward San Pablo Bay discharging through the Bay Mud deposits or offshore in San Pablo Bay. Note that the water-level contours, based on limited data, shown in *figures 16* and *17* for 1950 and 1980, respectively, indicate flow convergent toward the axis of the valley, particularly south of El Verano. The simulated SS contours in *figure 34A* also show convergent flow, although much less pronounced. Specifically, the simulated water levels are underestimated near the model boundary east of Sonoma (for example, for wells 5N/5W-8Q1 and -21A1).

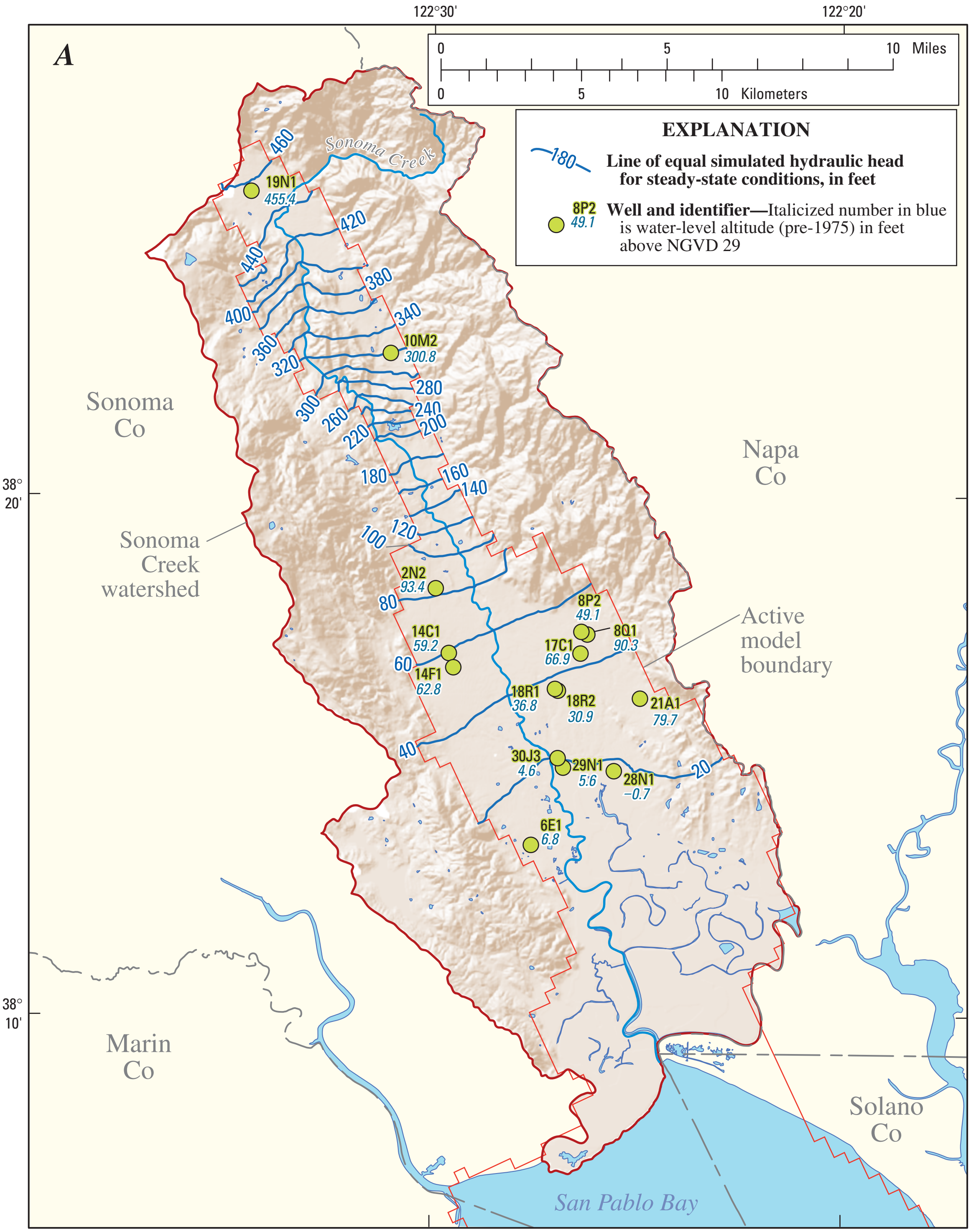
The simulated year 2000 hydraulic heads are little changed from the SS results, which is consistent with most measured water levels during that time period (*fig. 34B*). The simulated hydraulic heads for year 2000 in model layer 2 range from as high as 460 ft in the Kenwood/Los Guilicos area to less than 20 ft near the Bay Mud deposits. However, the contours are depressed east and south of the Sonoma area primarily owing to increased ground-water pumpage.

Simulated Hydrographs

Simulated hydraulic heads and measured water levels for selected wells are shown in *figure 35*. There are water-level trends that extend through the entire model period, multi-year variations, and seasonal fluctuations. The model cannot simulate any of the seasonal fluctuations shown in measured levels, because it simulates annual stress periods (*fig. 35*). There also are some multi-year periods of water-level declines that the model does not simulate.

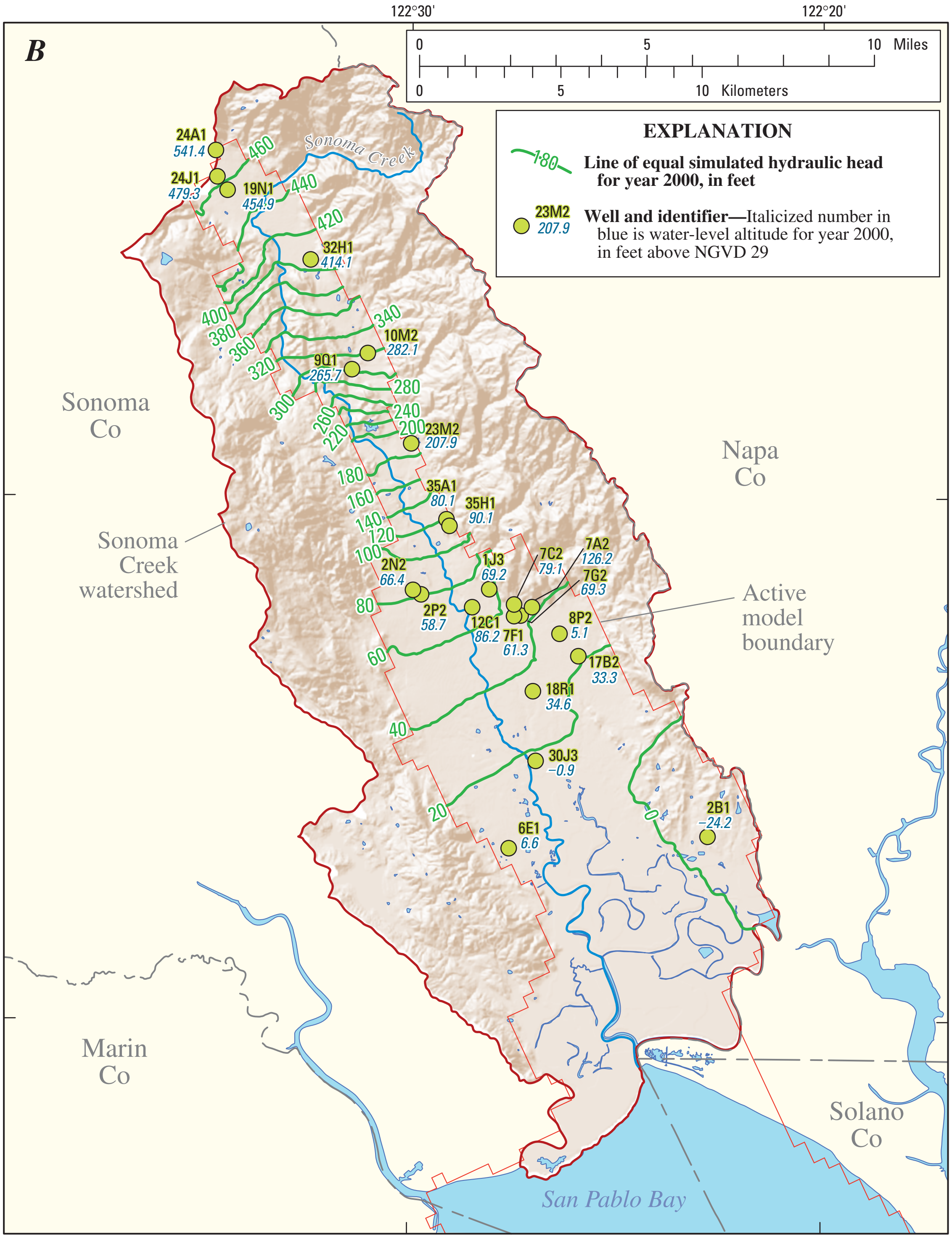
Wells 7N/6W-19N1 and 7N/7W-24J1 are located in the northern part of the valley in the Kenwood/Los Guilicos area (*fig. 29*). Well 19N1 is perforated in model layers 1 and 2; the simulated hydraulic heads follow the general trend of the measured water levels of this well (*fig. 35A*). However, the simulated hydraulic heads generally are higher and show greater temporal variability than the measured water levels (*fig. 35A*). Well 24J1 is perforated in model layer 1; the simulated hydraulic heads follow the general trend of the measured water levels (*fig. 35A*). However, the simulated values generally are lower and show greater temporal variability than the measured water levels.

Wells 6N/6W-10M2 and 23M2 are located in the north–central part of the valley in the Glen Ellen area (*fig. 29*). Well 10M2 is perforated in model layers 1 through 8; the simulated hydraulic heads for this well are about 20 to 40 ft higher than the measured water levels (*fig. 35B*). The simulated hydraulic heads for all the model layers diverge from the post-1996 data which show an overall water-level decline; this may be caused by an increase in pumpage that was not recorded. Well 23M2 is perforated in model layers 1 and 2 and the simulated hydraulic heads follow the general trend of the measured water levels; however, the simulated hydraulic heads are about 20 ft lower than the measured data.



Base from U.S. Geological Survey digital data, 1:250,000, 2003. State Plane Projection, Fipzone 402
Shaded relief base from 1:250,000 scale Digital Elevation Model: sun illumination from northwest at 30 degrees above horizon

Figure 34. Simulated hydraulic head for model layer 2 for (*A*) steady state and (*B*) 2000, Sonoma County, California.



Base from U.S. Geological Survey digital data, 1:250,000, 2003. State Plane Projection, Fipzone 402.
Shaded relief base from 1:250,000 scale Digital Elevation Model: sun illumination from northwest at 30 degrees above horizon

Figure 34.—Continued.

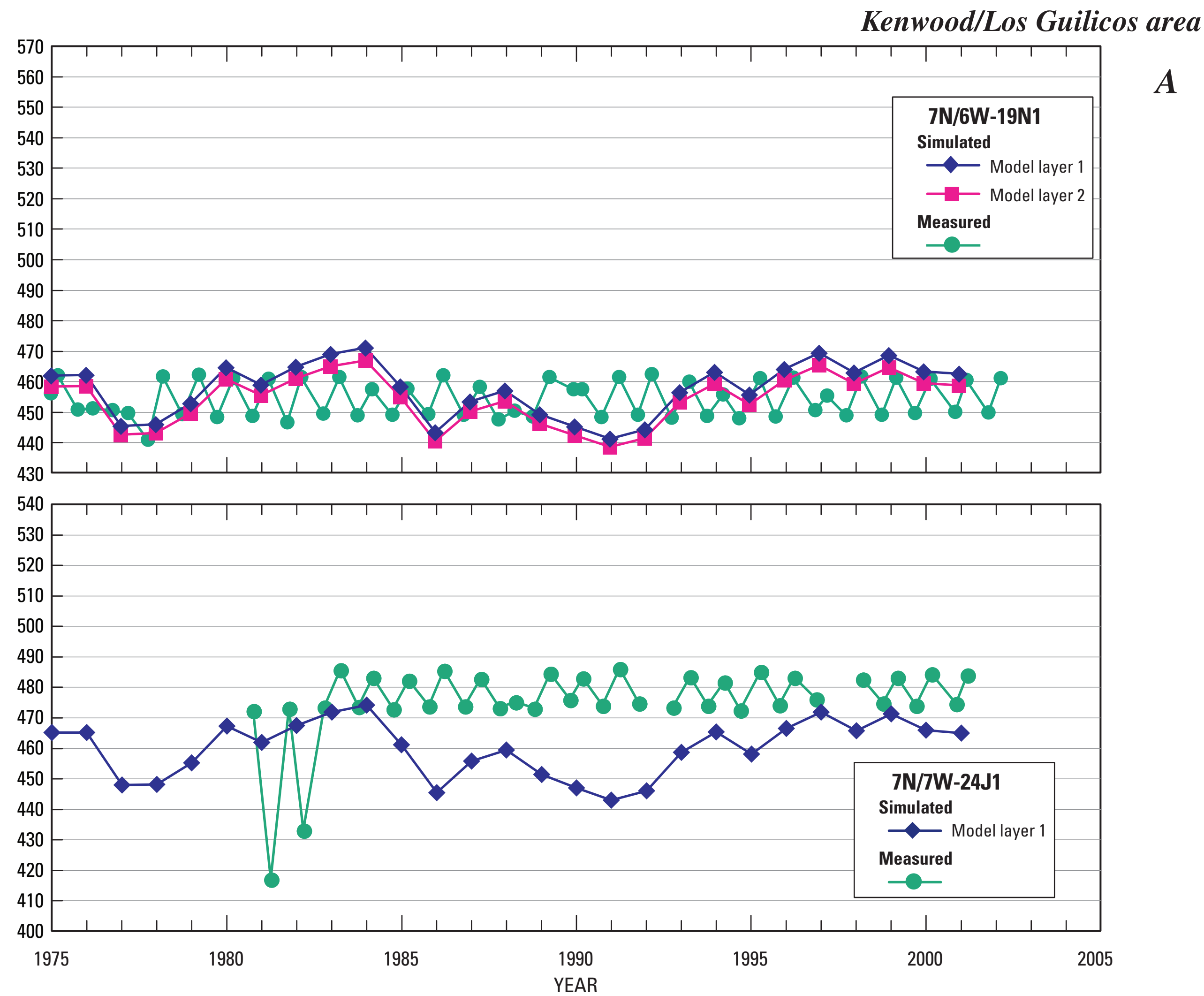


Figure 35. Measured water levels and simulated hydraulic heads for selected wells in the *A*. Kenwood/Guilicos, *B*. Glen Ellen, *C*. Sonoma, and *D*. Southern areas.

Wells 5N/6W-2N2, 5N/5W-8P2, 17B2, 17C1, and 18R1 are located in the Sonoma area (*fig. 29*). Wells 2N2 and 18R1 are located west of the Eastside Fault and wells 8P2, 17B2, and 17C1 are located east of the Eastside Fault. Well 2N2 is perforated in model layer 1 and 2; the simulated results for each layer are similar (*fig. 35C*). The simulated hydraulic heads for well 2N2 follow the general trend of the measured data. Well 8P2 is perforated in the model layers 2 through 4; the simulated hydraulic heads for this well closely follow the general trend of the measured data through the late-1980s (*fig. 35C*). After about 1987, the measured water levels show a general decline that is not matched in magnitude by the simulated hydraulic heads; however, the timing of the decline is matched by the simulated results. It is likely that there may be additional pumpage that is not incorporated into the model. Well 17B2 is perforated in model layers 3 through 6; the simulated hydraulic heads for this well follow the general trend of the measured water levels through the late-1980s (*fig. 35C*). After about 1987, the measured water levels show a general decline and a slight recovery starting about 1998 (*fig. 35C*). The decline and recovery are not matched by the simulated hydraulic heads. The measured water-level declines observed at wells 8P2 and 17B2 cannot be explained by the barrier effect of the inferred Eastside Fault; during the calibration, the hydraulic characteristic of the Eastside Fault was lowered to zero without effect. Well 17C1 is perforated in model layer 1; the simulated hydraulic heads for this well follow the general trend of the measured water levels through the early 1980s (*fig. 35C*); however, the simulated hydraulic heads do not match the measured water levels. In general, the simulated hydraulic heads are at least 35 ft lower than the measured water levels and the simulated results indicate a water-level decline starting in the mid-1980s that is not reflected in the measured data. Well 18R1 is perforated in model layers 1 and 2; the simulated hydraulic heads for each model layer for this well follow the general trend of the measured water levels (*fig. 35C*).

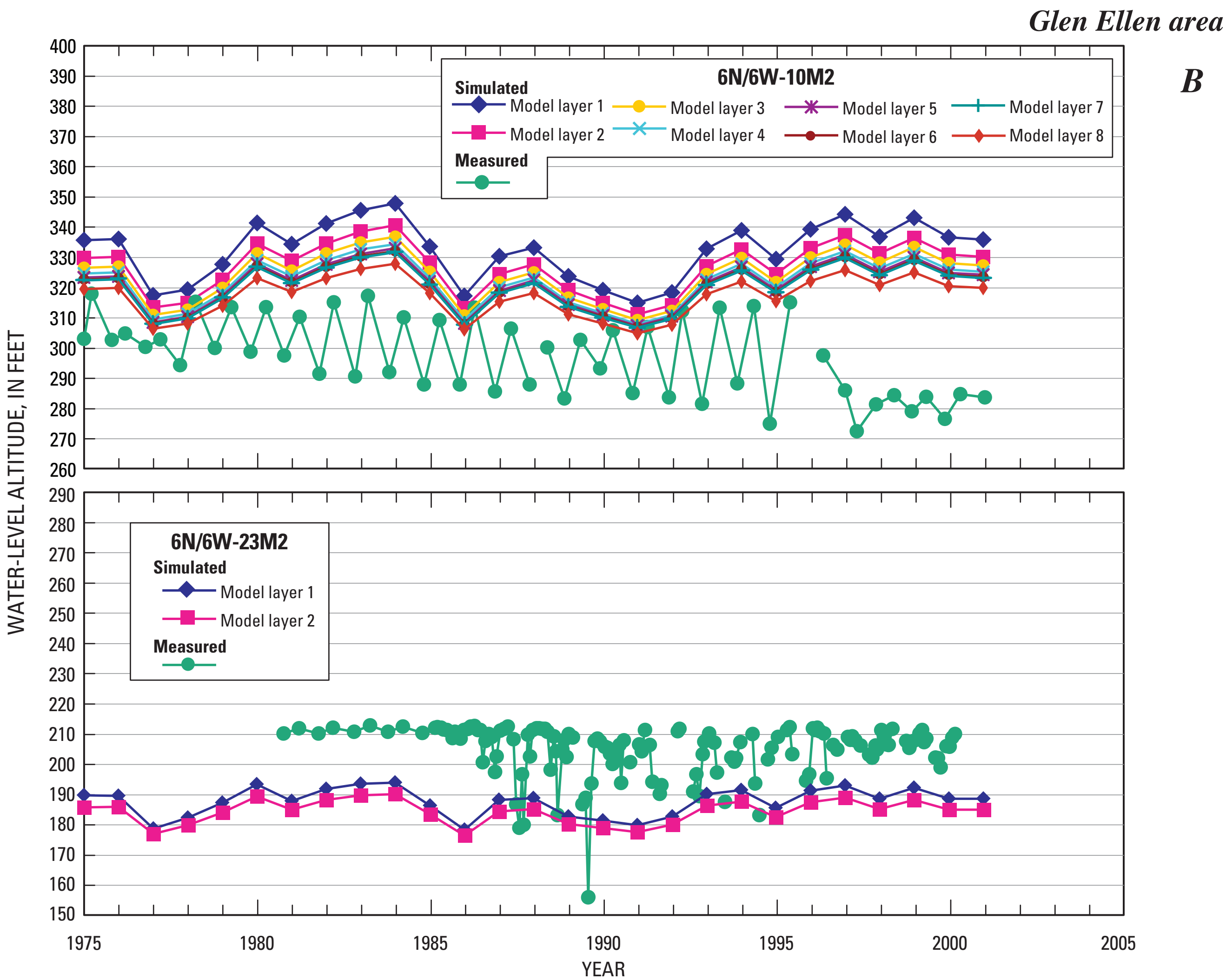


Figure 35.—Continued.

Wells 5N/5W-30J3, 4N/5W-6E1 and 4N/5W-2B1 are located in the Southern area (*fig. 29*). Well 30J3 is perforated in model layer 1; the simulated hydraulic heads for this well closely follows the general trend of the measured water levels; however, the simulated results generally are 10 to 15 ft higher than the measured water levels (*fig. 35D*). Well 6E1 is perforated in model layer 1; the simulated hydraulic heads for the well closely follow the trend of the measured water levels (*fig. 35D)*. Well 2B1 is perforated in model layers 1 through 4 and is located east of the Eastside Fault. The simulated hydraulic heads closely follow the general trend of the measured water levels through about 1989 when the measured water levels sharply decline (as much as 120 ft) (*fig. 35D*). As noted in the “Ground-Water Levels and Movement” section, the water-level decline is likely caused by pumpage that is not accounted for in the model. The timing of the drawdown and of the water-level recovery that started in 1996 is accurately simulated; however, the magnitude of the drawdown is not (*fig. 35D*).

There are limited data on depth-dependent water levels. The model simulates vertical differences between the upper and lower model layers to be as large as 10–20 ft. This is generally consistent with the sparse data on water-level differences between shallow and deep wells that are near each other. In some locations, however, measured vertical water- level differences are much greater (for example, 5N/6W-11C3–5, *fig. B1H*).

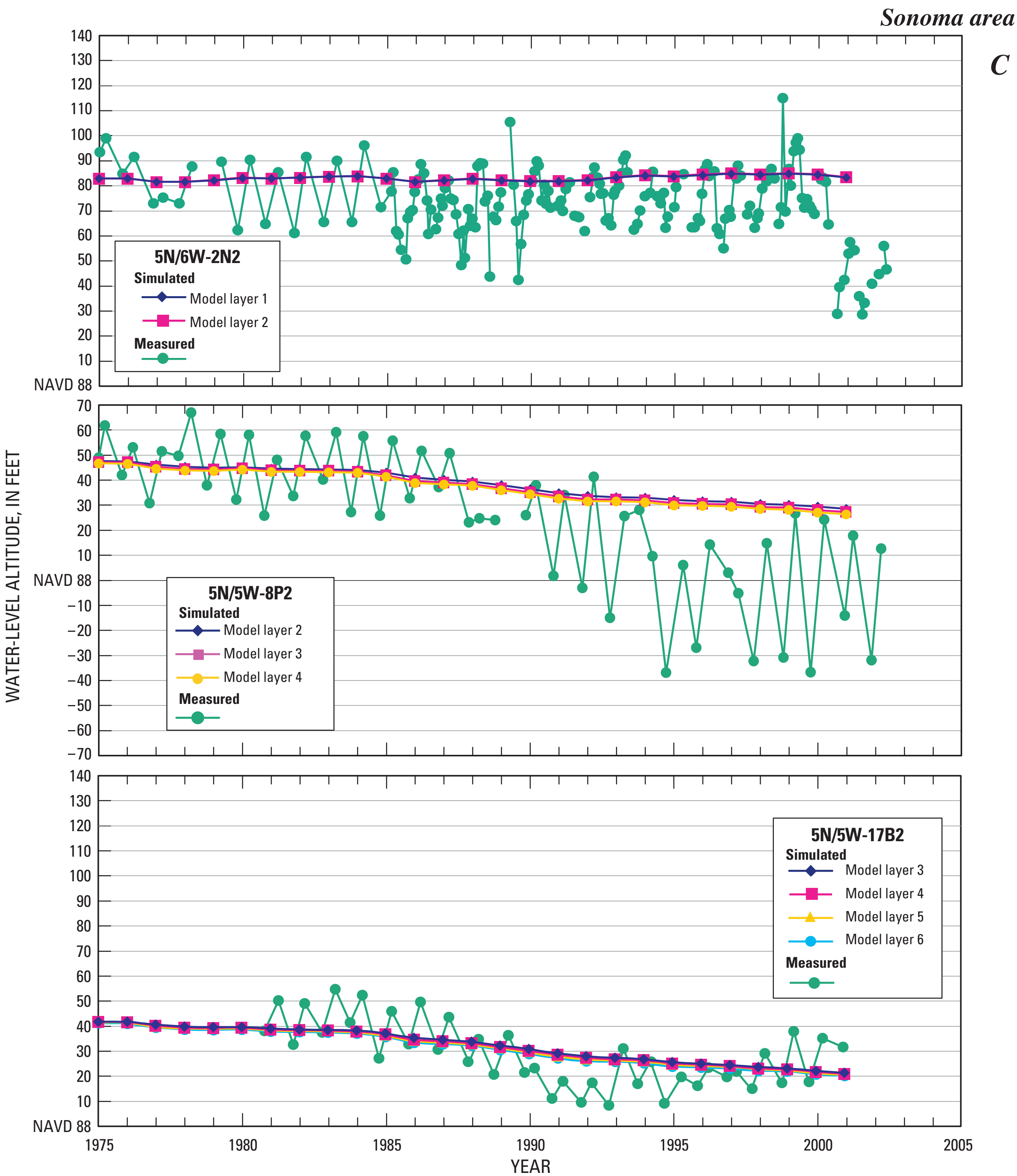


Figure 35.—Continued.

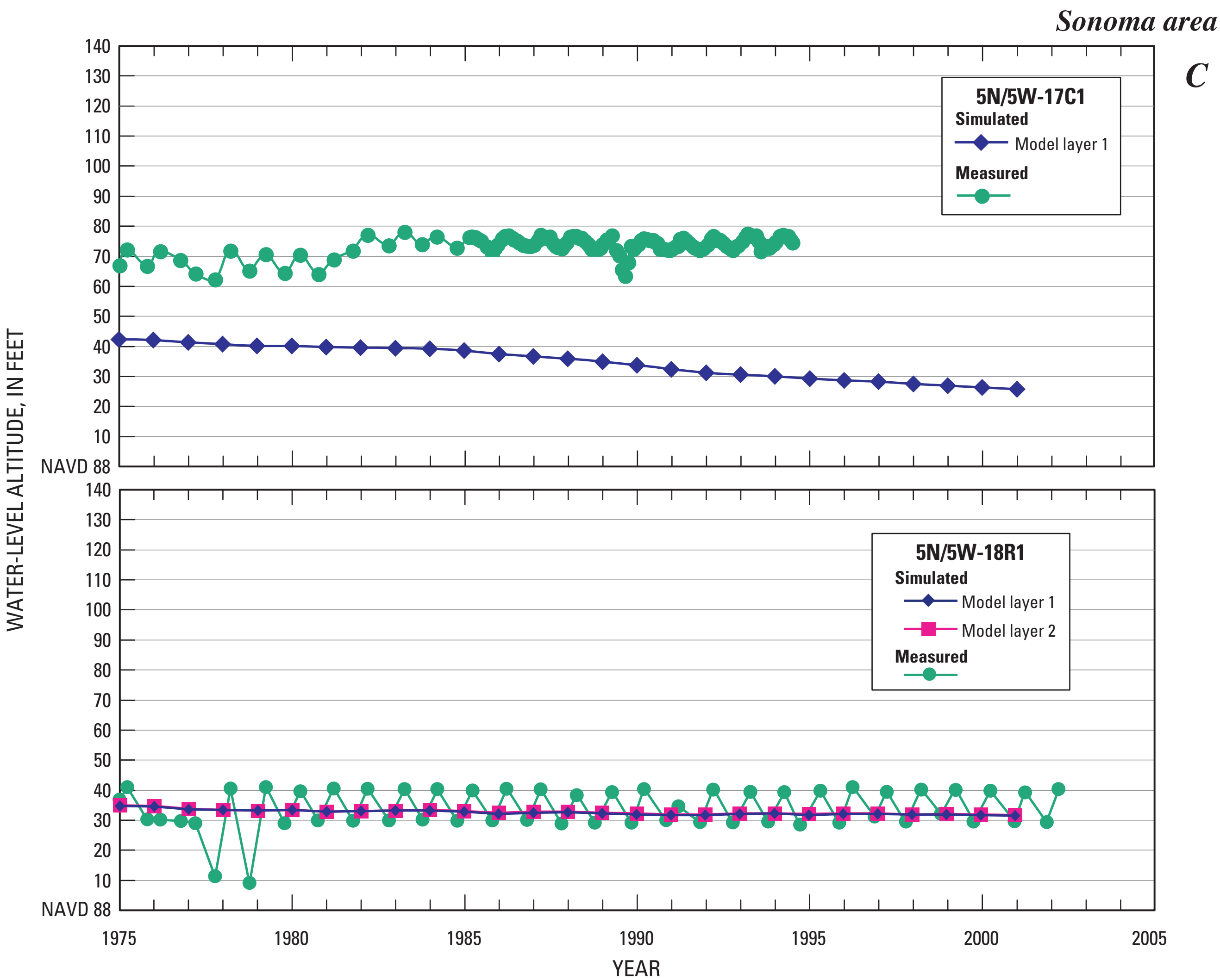


Figure 35.—Continued.

Simulated Water Budget

The simulated water budgets for steady-state conditions, end of the transient simulation (2000) and cumulative volumes from 1974–2000 are shown in *table 7*. For steady-state conditions, the total inflow rate (3.70×10^4 acre-ft/yr from natural recharge, 1.53×10^3 acre-ft/yr from San Pablo Bay, and 1.02×10^3 acre-ft/yr from Sonoma Creek) and outflow rate (1.50×10^3 to the Bay Mud deposits, 7.55×10^2 to San Pablo Bay, 3.12×10^4 to Sonoma Creek, and 6.10×10^3 to pumping) rates are both about 3.96×10^4 acre-ft/yr. As mentioned previously, simulated flow to Sonoma Creek includes both direct discharge to the creek as well as evapotranspiration adjacent to the creek. The results indicate that San Pablo Bay is a net source of 7.75×10^2 acre-ft/yr, and Sonoma Creek is a net sink of 3.02×10^4 acre-ft/yr. By definition, for steady-state conditions, there is no change in storage.

For year 2000 conditions, the inflow (3.66×10^4 from natural recharge, 1.57×10^3 from San Pablo Bay, and 1.27×10^3 from Sonoma Creek) and outflow (7.69×10^2 to the Bay Mud deposits, 7.55×10^2 to San Pablo Bay, 3.04×10^4 to Sonoma Creek, and 8.34×10^3 to pumping) rates are about 3.94×10^4 and 4.03×10^4 acre-ft/yr, respectively. Ground-water pumpage results in the removal of about 8.24×10^2 acre-ft/yr of water from ground-water storage, or storage depletion contributed about 10 percent of ground-water pumpage in 2000. The simulation results indicate that San Pablo Bay is a net source of 8.15×10^2 acre-ft/yr, and Sonoma Creek is a net sink of 2.91×10^4 acre-ft/yr.

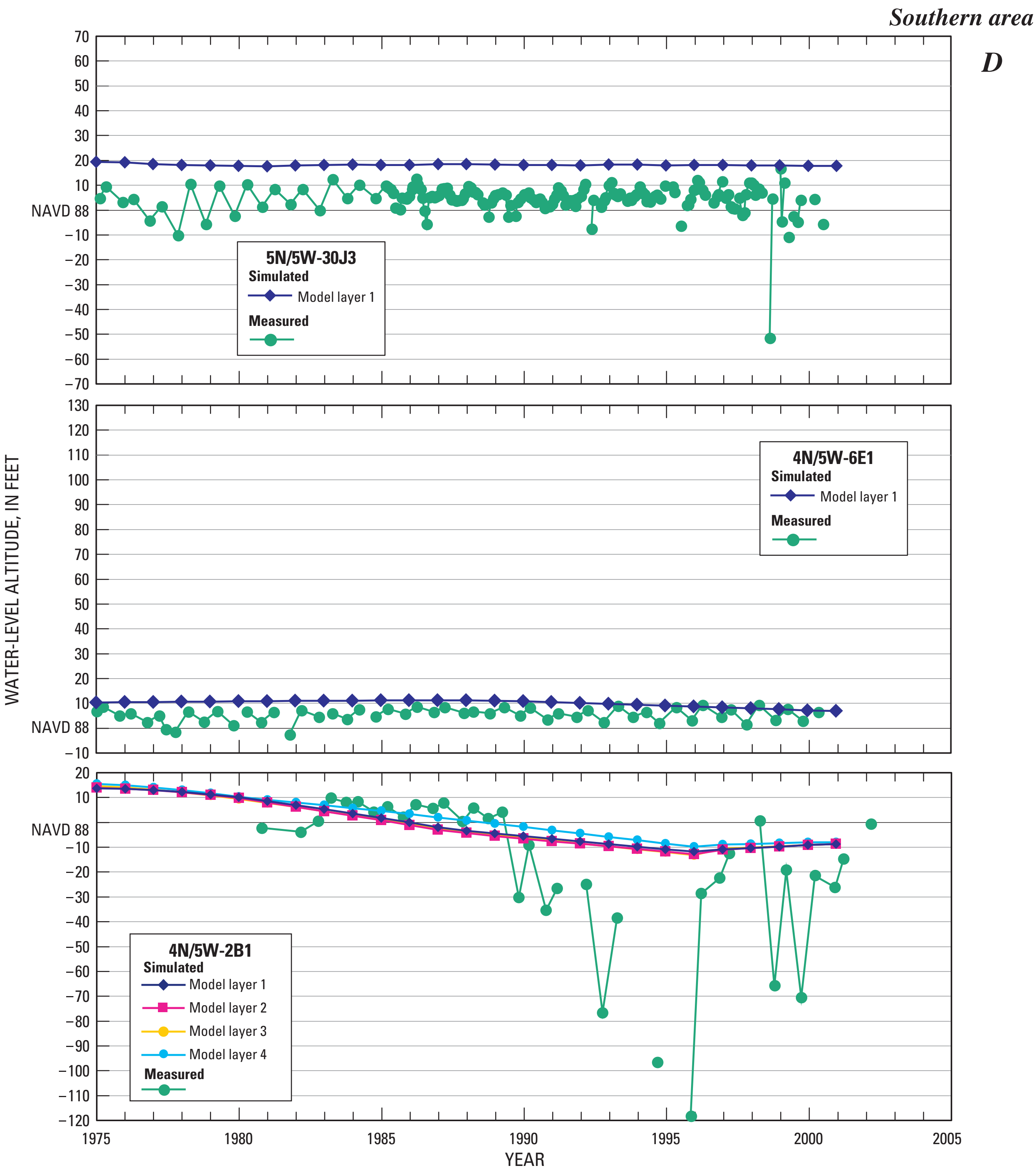


Figure 35.—Continued.

Table 7. Simulated water budget for Sonoma Valley, Sonoma County, California.

[acre-ft, acre feet; acre-ft/yr, acre feet per year]

Steady state (acre-ft/yr)			
	Inflow		
		Recharge	3.70×10^4
		Inflow from San Pablo Bay	1.53×10^3
		Stream	1.02×10^3
	Outflow		
		Drain to Bay-Mud deposits	1.50×10^3
		Outflow to San Pablo Bay	7.55×10^2
		Stream	3.12×10^4
		Well pumpage	6.10×10^3
2000 (acre-ft/yr)			
	Inflow		
		Recharge	3.66×10^4
		Inflow from San Pablo Bay	1.57×10^3
		Stream	1.27×10^3
	Outflow		
		Drain to Bay-Mud deposits	7.69×10^2
		Outflow to San Pablo Bay	7.55×10^2
		Stream	3.04×10^4
		Well pumpage	8.34×10^3
		Change in storage	-8.24×10^2
Cumulative (acre-ft)			
	Inflow		
		Recharge	9.05×10^5
		Inflow from San Pablo Bay	4.02×10^4
		Stream	3.60×10^4
	Outflow		
		Drain to Bay-Mud deposits	2.89×10^4
		Outflow to San Pablo Bay	1.96×10^4
		Stream	7.53×10^5
		Well pumpage	1.97×10^5
		Change in storage	-1.73×10^4

For the entire transient simulation period of 1975–2000, the cumulative inflow volume was about 9.81×10^5 acre-ft (9.05×10^5 acre-ft from natural recharge, 4.02×10^4 acre-ft from San Pablo Bay, and 3.60×10^4 from Sonoma Creek), and the cumulative outflow volume was about 1.00×10^6 acre-ft (2.89×10^4 to the Bay Mud deposits, 1.96×10^4 to San Pablo Bay, 7.53×10^5 to Sonoma Creek, and 1.97×10^5 to pumping). Ground-water pumpage results in the removal of about 1.73×10^4 acre-ft of water from ground-water storage, or storage depletion contributes about 9 percent of ground-water pumpage (*table 7*). This relatively small decrease in storage explains the localized nature of ground-water level declines in the basin.

Model Fit

Measured water levels and simulated hydraulic heads for 37 wells from steady state (pre-1975) to year 2000 closely follow a 1:1 correlation line (*fig. 36*). All the data would lie on the 1:1 correlation line if the model simulated the measured data perfectly. Simulated hydraulic heads are compared directly with measured water levels if the wells are perforated in a single model layer. However, for wells that perforate multiple model layers, the MF2K calculates a composite simulated equivalent hydraulic head that is a weighted function of the simulated hydraulic heads from the perforated model layers. The weights are functions of the perforated interval and the model layer hydraulic conductivity and sum to 1.0 (Hill and others, 2000). The composite simulated equivalent hydraulic heads are plotted with measured water levels in *figure 36A*. The sum of squared errors equals 2.13×10^6 ft^2 and, with 1,719 measured water levels, the root mean squared error (RMSE) equals 35.2 ft. Much of this error can be attributed to the simulated results for wells such as 6N/6W-10M2, 23M2, and 35A1 (not graphed); 5N/5W-8P2, 17B2, and 17C1; and 4N/5W-2B2. These wells had large errors because unknown phenomena caused higher than simulated water levels (23M2, 35A1, and 17C1), or because of an underestimation of pumpage which may have caused simulated hydraulic heads to be higher than measured water levels (10M2, 8P2, 17B2, and 2B2). Note that the errors at well 35A1 contribute more than 5 percent of the total sum of squared errors. In addition, the measured data reflect seasonal variability whereas the simulated results reflect average annual conditions resulting in a higher computed RMSE.

Another measure of model fit is to consider a plot of model residual (measured water levels minus simulated hydraulic heads) and simulated hydraulic heads (*fig. 36B*). Ideally, the model residuals should plot randomly about zero. Although the residuals show some clustering related to well location, the residuals are reasonably random.

Streamflow Gains and Losses

The streamflow gains and losses along the entire length of Sonoma Creek for steady-state and year 2000 conditions are presented in *figure 37*. In *figure 37*, a positive flux indicates that the ground-water system is gaining water from the stream and a negative value indicates that the stream is gaining water from the ground-water system. In general, the steady-state results agree with the seepage run results for this study (*fig. 14*). For example, the steady-state results indicate Sonoma Creek loses water to the ground-water system between sites S2 and S3 and gains water from the ground-water system between sites S3 and S4 (*fig. 37A*). The seepage run results do not clearly show a streamflow gain or loss between S4 and S10 (*fig. 14*); however, results of the model simulation do indicate gains and losses, but primarily gains, from the ground-water system. The seepage run results indicate that Sonoma Creek gains water from the ground-water system between sites S10 and S12, but model simulation results indicate a mix of gains and losses with 11 of the 19 model cells indicating flow from the ground-water system to the stream (*fig. 37A*). The simulated gains and losses for the year 2000 are similar to those for the steady-state period and are in general agreement with the seepage run results (*fig. 37B*).

The rigorous analysis of the routing of streamflow in Sonoma Creek was not possible because annual stress periods were used and the Streamflow-Routing Package is not a true surface-water flow model. However, this simulation results yields a general representation of the annual gains and losses to and from Sonoma Creek.

Sensitivity Analysis

Sensitivity analysis is a procedure that evaluates the model sensitivity to variations in the input parameters. The procedure involves keeping all input parameters constant except for the one being analyzed. For this study, there was a total of 39 parameters comprising horizontal and vertical hydraulic conductivity varied by aquifer and zone, storage (specific storage and specific yield) varied by aquifer, drain conductance, general-head conductance, recharge, hydraulic characteristic, and streambed conductance. MF2K was used to generate composite-scaled sensitivity values for each non-zero parameter. Composite-scaled sensitivities are calculated in MF2K for each parameter using the scaled sensitivities for all observations. Composite-scaled sensitivities are unitless and indicate the total amount of information provided by the observations for the estimation of one parameter (Hill, 1998). In general, the larger the value of the composite-scaled sensitivity for a particular parameter, the greater the model's sensitivity to changes in that parameter.

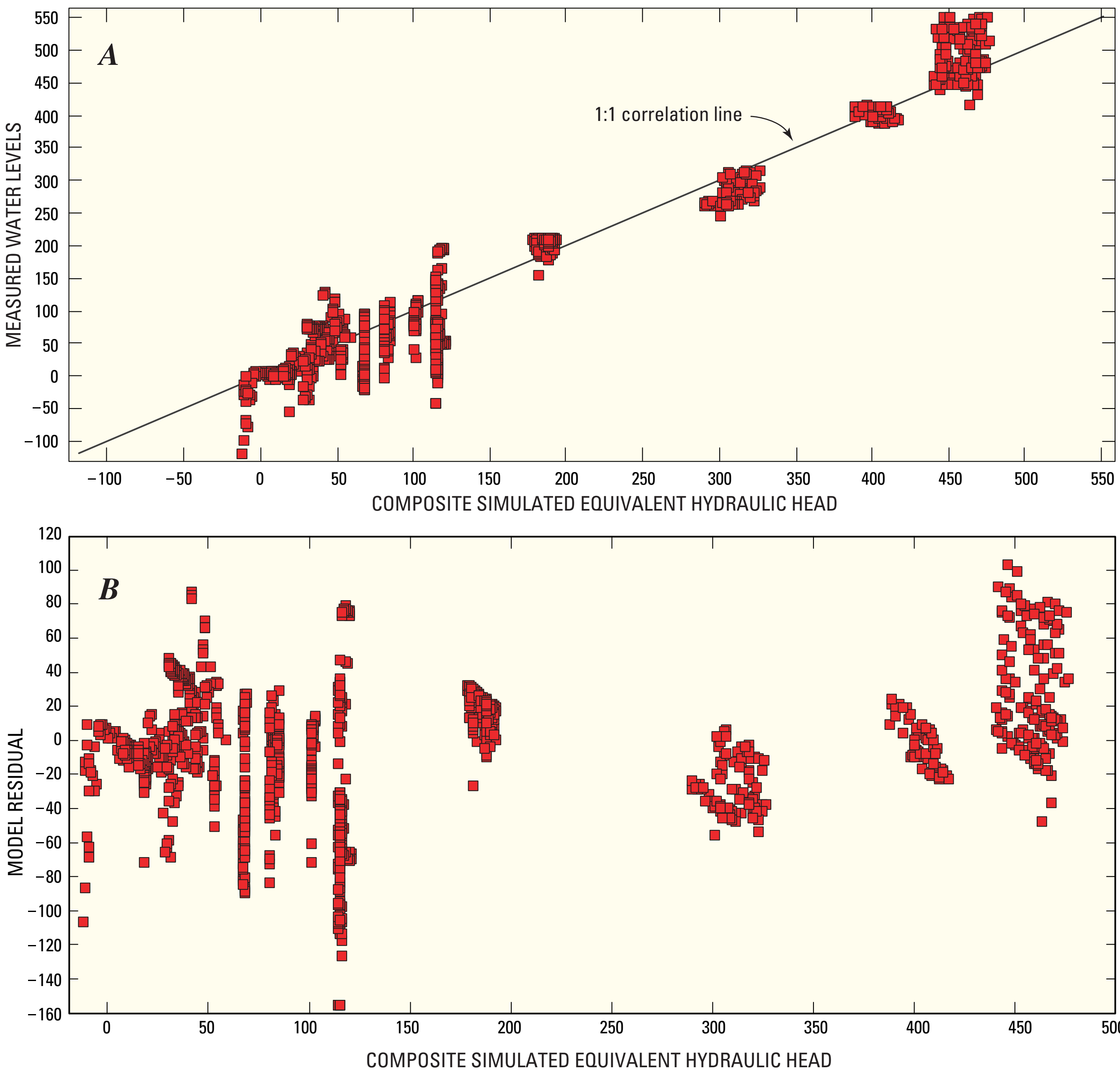
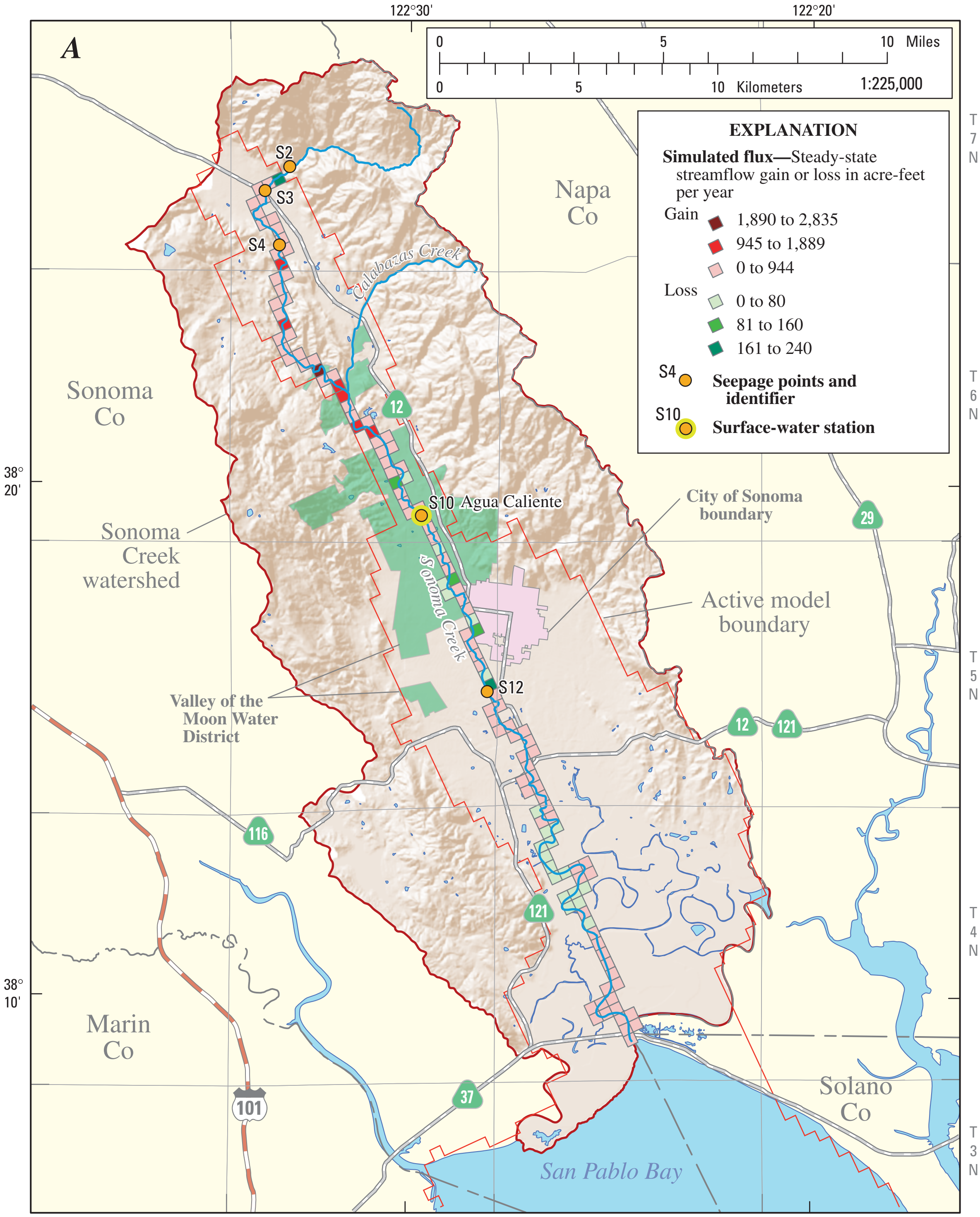
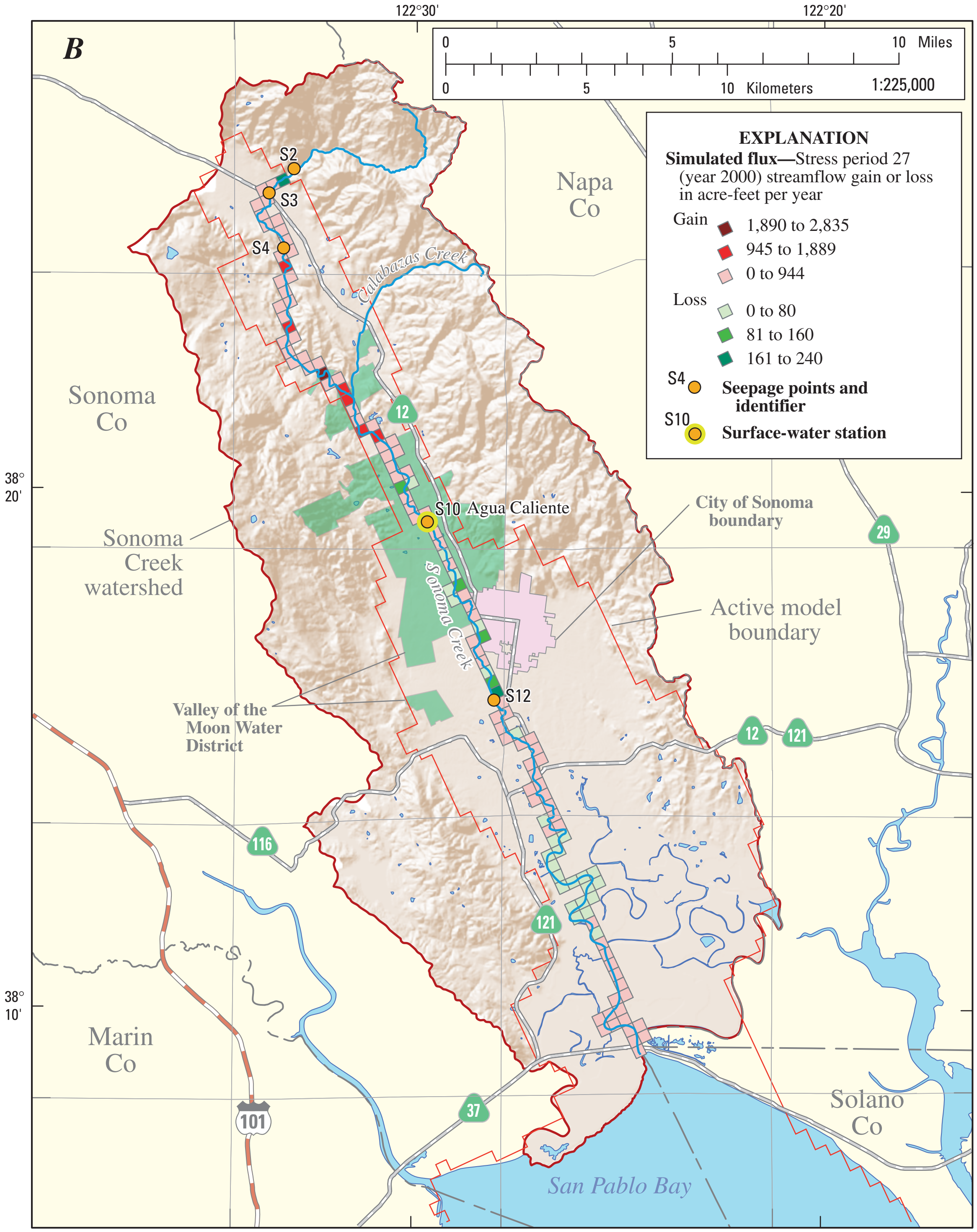


Figure 36. Composite simulated equivalent hydraulic heads for steady-state and transient conditions for wells in the Sonoma Valley area, Sonoma County, California compared with (*A*) measured water levels, and (*B*) model residual.



Base from U.S. Geological Survey digital data, 1:250,000, 2003. State Plane Projection, Fipzone 40.2
Shaded relief base from 1:250,000 scale Digital Elevation Model: sun illumination from northwest at 30 degrees above horizon

Figure 37. Simulated streamflow gains and losses along Sonoma Creek for *A*. steady-state and *B*. year 2000 conditions, Sonoma County, California.



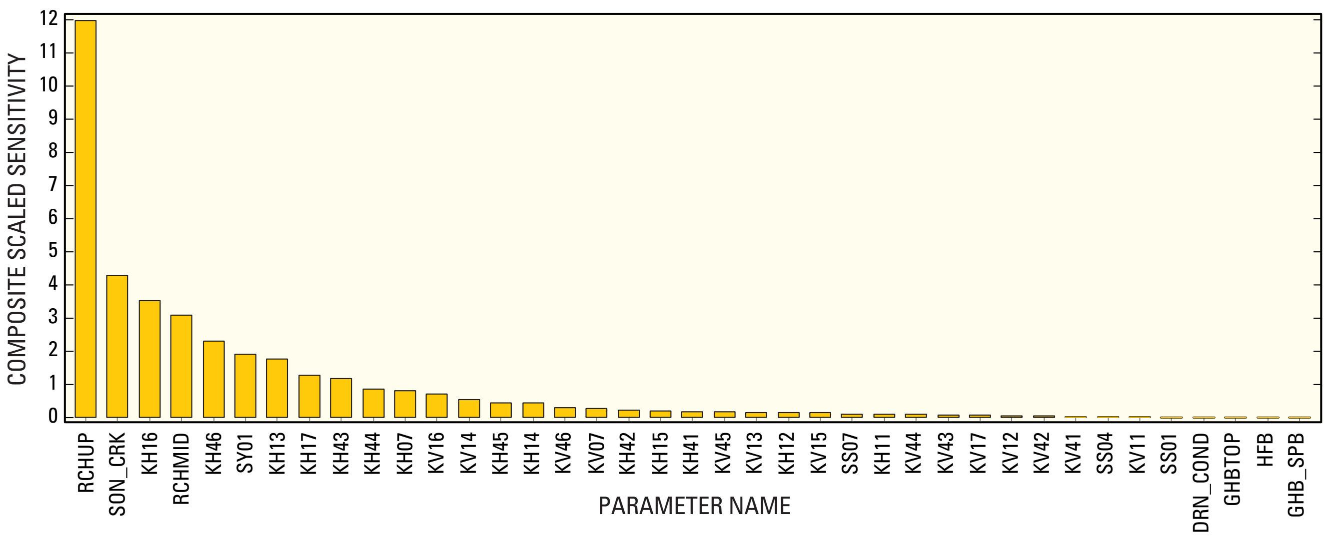
Base from U.S. Geological Survey digital data, 1:250,000, 2003. State Plane Projection, Fipzone 402.
Shaded relief base from 1:250,000 scale Digital Elevation Model: sun illumination from northwest at 30 degrees above horizon

Figure 37.—Continued.

The composite-scaled sensitivity values for all the parameters are shown in *figure 38*. The simulated hydraulic heads were most sensitive to the areal recharge parameter for the northern part of the basin, the streambed conductance in Sonoma Creek, the horizontal hydraulic conductivity of the upper hydrogeologic unit (model layers 1 and 2) in the Kenwood/Los Guilicos area (zone 6), the areal recharge parameter for the middle part of the basin, and the horizontal hydraulic conductivity of the middle hydrogeologic unit (model layers 3-6) in zone 6 (*fig. 38*). Owing to the model sensitivity to recharge and hydraulic properties in the northern part of the valley, additional data collection in this area would be most useful for improving the understanding of the ground-water system.

Uses and Limitations of the Ground-Water Flow Model

The simulation model developed for the Sonoma Valley synthesizes current data and understanding of the ground-water flow system. It provides a tool to begin assessing potential impacts of alternative future water management scenarios. Development of the model has also been useful for identifying key data gaps. The model provides a framework to build on as additional data are collected.



Parameter name	Description
RCHUP	Upper recharge zone multiplier
SON_CRK	Streambed conductance
KH16	Horizontal hydraulic conductivity: layers 1–2, zone 6
RCHMID	Middle recharge zone multiplier
KH46	Horizontal hydraulic conductivity: layers 3–6, zone 6
SY01	Specific yield: layer 1
KH13	Horizontal hydraulic conductivity: layers 1–2, zone 3
KH17	Horizontal hydraulic conductivity: layers 1–2, zone 7
KH43	Horizontal hydraulic conductivity: layers 3–6, zone 3
KH44	Horizontal hydraulic conductivity: layers 3–6, zone 4
KH07	Horizontal hydraulic conductivity: layers 7–8
KV16	Vertical hydraulic conductivity: layers 1–2, zone 6
KV14	Vertical hydraulic conductivity: layers 1–2, zone 4
KH45	Horizontal hydraulic conductivity: layers 3–6, zone 5
KH14	Horizontal hydraulic conductivity: layers 1–2, zone 4
KV46	Vertical hydraulic conductivity: layers 3–6, zone 6
KV07	Vertical hydraulic conductivity: layers 7–8
KH42	Horizontal hydraulic conductivity: layers 3–6, zone 2
KH15	Horizontal hydraulic conductivity: layers 1–2, zone 5
KH41	Horizontal hydraulic conductivity: layers 3–6, zone 1

Parameter name	Description
KV45	Vertical hydraulic conductivity: layers 3–6, zone 5
KV13	Vertical hydraulic conductivity: layers 1–2, zone 3
KH12	Horizontal hydraulic conductivity: layers 1–2, zone 2
KV15	Vertical hydraulic conductivity: layers 1–2, zone 5
SS07	Specific storage: layers 7–8
KH11	Horizontal hydraulic conductivity: layers 1–2, zone 1
KV44	Vertical hydraulic conductivity: layers 3–6, zone 4
KV43	Vertical hydraulic conductivity: layers 3–6, zone 3
KV17	Vertical hydraulic conductivity: layers 1–2, zone 7
KV12	Vertical hydraulic conductivity: layers 1–2, zone 2
KV42	Vertical hydraulic conductivity: layers 3–6, zone 2
KV41	Vertical hydraulic conductivity: layers 3–6, zone 1
SS04	Specific storage: layers 3–6
KV11	Vertical hydraulic conductivity: layers 1–2, zone 1
SS01	Specific storage: layers 1–2
DRN_COND	Drain conductance
GHBTOP	Hydraulic conductance for horizontal face
HFB	Fault hydraulic characteristic multiplier
GHB_SPB	Hydraulic conductance for vertical face

Figure 38. Composite-scaled sensitivities for the ground-water flow model of the Sonoma Valley, Sonoma County, California.

When applied carefully, a numerical ground-water flow model can be useful for simulating aquifer responses to various changes in aquifer stresses; however, a model is a highly idealized approximation of the actual system that is based on average and estimated conditions. Perhaps the greatest limitation of an idealized, lumped-parameter model is its failure to represent the complexity of a hydrogeologic system. The capability of the model to reliably reproduce aquifer responses is related to the accuracy of the input data used in the model calibration, and is inversely related to the magnitude of the proposed changes in the stresses being applied to the model as well as to the length of the simulation period.

MF2K is not designed to simulate the movement of water of different densities. It is not able to accurately simulate interactions of fresh ground water and saline water in and adjacent to San Pablo Bay; this is a source of uncertainty in simulation results. In addition, MF2K does not simulate the non-isothermal conditions that are present in parts of the Sonoma Valley.

For this study, the ground-water flow model was calibrated using manual trial-and-error techniques. Owing to the complexity and unknowns of the ground-water system being represented, model construction and calibration (formal or not) result in a non-unique product and model predictions that are subject to potentially large errors (Konikow and Bredehoeft, 1992). Automated approaches could be used in subsequent studies to more formally characterize uncertainties in the parameters and perhaps to improve the fit of the model to calibration data (Yeh, 1986).

There were significant data limitations of the model for the study area that affected the estimates of pumpage, recharge, streamflow, and hydrogeologic properties. As described in *Appendix G*, pumpage data were available only for the COS and the VOM wells; agricultural and domestic pumpage rates were not known and were estimated. In particular, it appears that there may be additional pumpage occurring that is not incorporated into the model. This could be due, in part, to the fact that the model does not account for any pumpage within the model area that may be providing water for irrigation outside the model area. This lack of data and the fact that the model uses annual stress periods may explain the underestimation of drawdown at some wells. The areal distribution of recharge was a simplification of average annual rates that were parameterized using multipliers to estimate the total average annual recharge. The model does not consider any deep lateral inflows (outflows) to the system. The availability of streamflow data was very limited because there was only one stream gage, located in the middle of the basin, making it difficult to model stream/aquifer interaction more realistically and making it necessary to assume average annual streamflow conditions. Although there are many wells in the ground-water basin, there were few geophysical data with which to better understand the hydrogeology and to better estimate hydrogeologic properties.

Summary

The Sonoma Creek watershed, an area of approximately 166 mi^2, is drained by Sonoma Creek. On the basis of long-term data, it was estimated that the watershed receives an average of 269,000 acre-ft of precipitation annually.

Land- and water-use patterns have changed since the 1970s. More land is being converted to agricultural from native vegetation. An increasing portion of the agricultural land is irrigated. Between 1974 and 2000 the area of irrigated agriculture (predominantly vineyards) within the area of the ground-water simulation model has more than tripled.

A significant component of the valley’s water supply is imported from outside the basin (primarily from the Russian River by way of SCWA’s Sonoma Aqueduct). The quantity of imported water averaged about 5,400 acre-ft between 1999 and 2003. Almost all the remaining water used in the study area is derived from wells. Estimated ground-water pumpage in the area of the simulation model increased from about 6,200 acre-ft in 1974 to about 8,400 acre-ft in 2000.

The ground-water basin includes all the rocks and sediments overlying the basement rocks which comprise Franciscan Complex, Coast Range Ophiolite, and Great Valley Sequence. Gravity data indicate the basin is as deep as 6,000 ft in the main part of Sonoma Valley and as much as 10,000 ft in the Kenwood area and along the edge of San Pablo Bay. The valley is a synform structure that has been faulted by strike-slip movement and high angle normal and reverse faults in the mountains on the southwest and northeast sides of the valley. Ground water is stored and transmitted through all the geologic units in the study area, but the most productive aquifers are the Sonoma Volcanics, the Glen Ellen Formation, the Huichica Formation, and the Quaternary alluvial units. All the formations contain variable but significant amounts of clay, which generally results in low permeability, low specific capacity, and low to modest well yields. For this report, the ground-water system was divided into three depth-based geohydrologic units: 0 to 200 ft below land surface (upper unit), 200 to 500 ft (middle unit), and greater than 500 ft (lower unit).

The general direction of ground-water movement is from the mountain ridges downslope toward the valley axis and from the northwest end of the valley southeastward toward San Pablo Bay. There was very little change in regional water levels between 1950 and 1980. Between 1980 and 2003, ground-water levels declined in some locations. Overall the water-level data show that large interannual changes have occurred in some areas along the west side of Sonoma Valley and in Sonoma during the post-1999 period.

Water-chemistry data for samples collected from 75 wells during 2002–04 indicate that water quality in the study area generally is acceptable for potable use. The water from some wells, however, contains one or more constituents in excess of the recommended standards for drinking water. Thirty-six samples from the 30 wells were analyzed for physical constituents (pH and specific conductance) and chemical constituents (sum of constituents [dissolved solids], chloride, fluoride, arsenic, boron, iron, and manganese). Results showed that 45 of the analytes had concentrations equaling or exceeding Federal and (or) State drinking-water standards and advisory levels (*Appendix D*). Wells with water having values equal to or in excess of standards and advisory levels were disproportionately from wells in the northern half of the Sonoma Valley; wells located in townships 6N and 7N were the source of 36 percent of all samples collected for major constituents, but were the source of 53 percent of all analyses having values equal to or in excess of standards and advisory levels. Ground-water depth intervals were more proportionately represented; wells less than 200 ft deep, 200 to 500 ft deep, greater than 500 ft deep and of questionable or unknown depth were the source of 28, 44, 22, and 6 percent, respectively, of all samples collected for major constituents. These depth categories constituted 22 percent (less than 200 ft), 36 percent (200 to 500 ft), 19 percent (greater than 500 ft) and 6 percent (questionable or unknown) or all analyses having values equal to or in excess of standards and advisory levels.

The chemical composition of water from creeks, springs, and wells sampled for major ions plot within three semi-distinct groups on the trilinear diagram. Group 1, which includes water from Sonoma Creek, springs, and most of the sampled wells in the valley, is characterized by a mixed-bicarbonate type water. Water in group 1 is generally drawn from shallow- and intermediate-depth wells, and from several deep wells located near the valley margins. Group 2 is characterized as a mixed type water with sodium and chloride as the predominant cation and anion, respectively. Samples in this group include water from mainly shallow and intermediate depth wells in areas identified as having saline or thermal ground water. Group 3 is characterized as sodium-bicarbonate type water and includes water from intermediate and deep wells in or near areas identified as having saline or thermal ground water.

Areas of saline ground water within the study area have long been known. The saline ground water is present in sediments that lie between the shore of San Pablo Bay and Schellville. The origin of the saline water is not known with certainty, but it may be attributed to modern saltwater intrusion from San Pablo Bay, shallow ground water affected by evaporation, connate ground water in areas with evaporites or marine sedimentary deposits, and (or) thermal waters. Additional chemical analyses, perhaps including the use of trace elements such as barium, boron, bromide and iodide, could help distinguish the sources of saline waters. Historical conductivity measurements from long-term water-chemistry monitoring wells indicate that the most significant changes in ground-water chemistry over the past 30 years occurred in the southern part of the Sonoma Valley. The conductivity of water in several wells has doubled, but these increases may not be entirely attributed to natural sources of salinity.

The historical areal extent of saline ground water located primarily south of Highway 12/121 did not change appreciably from the 1940s through 1982. Recent (2003) conductivity measurements, however, indicate that this area of high-salinity water may have shifted, expanding north of Highway 12/121 toward an area of depressed hydraulic head southeast of the city of Sonoma. In the vicinity of the intersections of Highways 12 and 121 and Sonoma Creek, the areal extent of the high-salinity ground water has receded.

Thermal waters are known to exist in several places along the eastside of Sonoma Valley, to the northwest of Glen Ellen, and in the Los Guilicos area. The occurrence of thermal water may partly be controlled by the Eastside Fault. This fault may provide a zone of fracturing that allows thermal water to rise to shallow depths from deeper sources. Mineralized zones within the fault zone could restrict the lateral movement of thermal waters toward the west. Sparse temperature data from wells southwest of the known occurrence of thermal waters suggest that thermal water may be present beneath a larger part of the valley than previously thought. Thermal water contains higher concentrations of dissolved elements than non-thermal waters because mineral solubilities generally increase with temperature. The presence of relatively high concentrations of dissolved solids, boron, and arsenic may restrict the use of thermal waters to low temperature heating and bathing.

The $\delta^{18}O$ and δD values for water samples plot on either side of and along the global meteoric water line. The $\delta^{18}O$ and δD values for ground-water samples collected from wells in the Sonoma Valley are somewhat lighter (more negative) then the $\delta^{18}O$ and δD values for surface-water samples collected in mid-November 2002 and late May through early June 2003. However, they are similar to the expected overall range of surface water values values based on isotopic data from a study in southeastern Napa County.

Water from most wells plot along the global meteoric water line indicating that recharge is derived primarily from the infiltration of precipitation or seepage from creeks. The scatter of data along the global meteoric water line suggests that the samples may represent different ground-water ages and (or) mixing of infiltrated surface water and precipitation with other contributing sources. Samples from shallow- and intermediate-depth wells located near Sonoma Creek and (or) near the northern margin of the bay-mud deposits plot to the right of the global meteoric water line, indicating that these samples are partly evaporated. Recharge waters not affected by evaporation (data plot to the left of the global meteoric water line) may occur in areas where precipitation and runoff infiltrate rapidly through coarse-grained alluvium or fractured rock and where there is negligible mixing with evaporated waters. These waters include samples from wells located near Sonoma Creek or its tributaries in the northern part of the Sonoma Valley, along the valley margins or in the Mayacmas and Sonoma Mountains, near mapped or inferred faults, and in the area of high-salinity ground water south of the city of Sonoma. The $\delta^{18}O$ and δD composition of water from sampled wells indicates that water from wells deeper than 200 ft is isotopically lighter than water from wells less than 200 ft deep, possibly indicating recharge under cooler and (or) wetter climatic conditions.

Data collected during the study were used to develop and calibrate a ground-water flow model of the Sonoma Creek watershed using MODFLOW-2000. The simulation period of the model was 1974–2000. The model was calibrated using a trial-and-error approach using water-level data collected between pre-1974 and 2000. In general, the calibrated model matched measured water-level declines. There were periods of water-level declines and recovery at selected wells that the model did not simulate. For the year 2000, the simulated total inflow was about 3.94×10^4 acre-ft/yr, of which 3.66×10^4 acre-ft/yr was from natural recharge, 1.57×10^3 acre-ft/yr was from San Pablo Bay, and 1.27×10^3 acre-ft/yr was from Sonoma Creek. The cumulative volume of water pumped from the ground-water basin between 1975 and 2000 was about 1.97×10^5 acre-ft; of this total pumpage, the model simulated that about 9 percent (1.73×10^4 acre-ft) was removed from storage. This relatively small decrease in storage explains the localized nature of water-level declines.

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Appendixes

Appendix A. Basement Rock Configuration Interpreted from Gravity Data

By Victoria E. Langenheim

Gravity Data

Gravity data were compiled and collected to help characterize the subsurface geometry of the Cenozoic sedimentary and volcanic rocks beneath the Sonoma Valley area. The gravitational attraction at any point depends on many factors, including the latitude and elevation of the measurement, earth tides, terrain, deep masses that isostatically support the terrain, and variations in density within the Earth's crust and upper mantle. The last of these quantities is of primary interest in geologic investigations and can be obtained by calculating and removing all other quantities. The resulting field is called the isostatic gravity field and reflects, to first order, density variations within the middle and upper crust (Simpson and others, 1986). Many of the gravity anomalies in Sonoma Valley are caused by the density contrast between basin fill composed of Cenozoic sedimentary and volcanic rocks and basement composed of Mesozoic Great Valley Sequence and Franciscan Complex. Density measurements of hand samples were made to determine sources of gravity anomalies and provide constraints on the porosity of the Sonoma Volcanics. The gravity data were inverted to create a basin thickness map of the study area.

About 1,790 gravity stations were used to produce an isostatic residual gravity map of the region (*fig. A-1*). The gravity map includes areas adjacent to the study area. Sources of data include surveys by the California Geological Survey (formerly known as the California Division of Mines and Geology: Chapman and Bishop, 1974; Youngs and others, 1985), Chevron (Smith, 1992), and the U.S. Geological Survey (this study).

Gravity stations are non-uniformly distributed in the region (*fig. A-1*). Station spacing is on average 1 station per 1 km^2, although the station spacing is as low as 1 station per 4 km^2 within parts of the Mayacmas Mountains and Sonoma Mountain. Detailed profiles within the central part of Sonoma Valley were collected to support geothermal resource assessments. Accuracy of the data is estimated to be on the order of 0.1 to 0.5 mGal.

Gravity data were reduced using the Geodetic Reference System of 1967 (International Union of Geodesy and Geophysics, 1971) and referenced to the International Gravity Standardization Net 1971 gravity datum (Morelli, 1974, p. 18). Gravity data were reduced to isostatic anomalies using a reduction density of 2,670 kg/m^3 and include earth-tide, instrument drift, free-air, Bouguer, latitude, curvature, and terrain corrections. An isostatic correction using a sea-level crustal thickness of 25 km (16 mi) and a mantle-crust density contrast of 400 kg/m^3 was applied to the gravity data to remove the long-wavelength gravitational effect of isostatic compensation of the crust due to topographic loading. *Figure A-1* shows the resulting gravity field, termed the isostatic residual gravity anomaly.

Terrain corrections were computed to a radial distance of 167 km (104 mi) and involved a three-part process: (1) Hayford-Bowie zones A and B, with an outer radius of 68 m (223 ft), were estimated in the field with the aid of tables and charts; (2) Hayford–Bowie zones C and D, with an outer radius of 590 m (1,936 ft), were computed using a 30-m (100-ft) digital elevation model; and (3) terrain corrections from a distance of 0.59 km (1,936 ft) to 167 km (104 mi) were calculated using a digital elevation model and a procedure by Plouff (1977). Total terrain corrections for the stations collected for this study ranged from 0 to 16.2 mGal, averaging 1.4 mGal. If the error resulting from the terrain correction was 5 to 10 percent of the total terrain correction, the largest error expected for the data was 1.6 mGal. However, the error resulting from the terrain correction was small (less than 0.2 mGal) for most of the stations due to low relief.

Density Data

The isostatic residual gravity data reflect subsurface crustal density variations and therefore knowledge of densities of exposed rock types are useful for determining the sources of gravity anomalies. Densities can also provide estimates of porosity for the various rock types. For the Sonoma Valley area, two main sources of density information are available: (1) density measurements of hand samples from this study and (2) density logs from drill holes (Brocher and others, 1997). Samples collected for this study were limited to Sonoma Volcanics and Great Valley Sequence rocks because of the difficulty of obtaining hand samples of young sedimentary rocks. *Table A-1* summarizes the density data of various rock types collected for this study, most of which was Sonoma Volcanics; all measurements are given in the appendix.

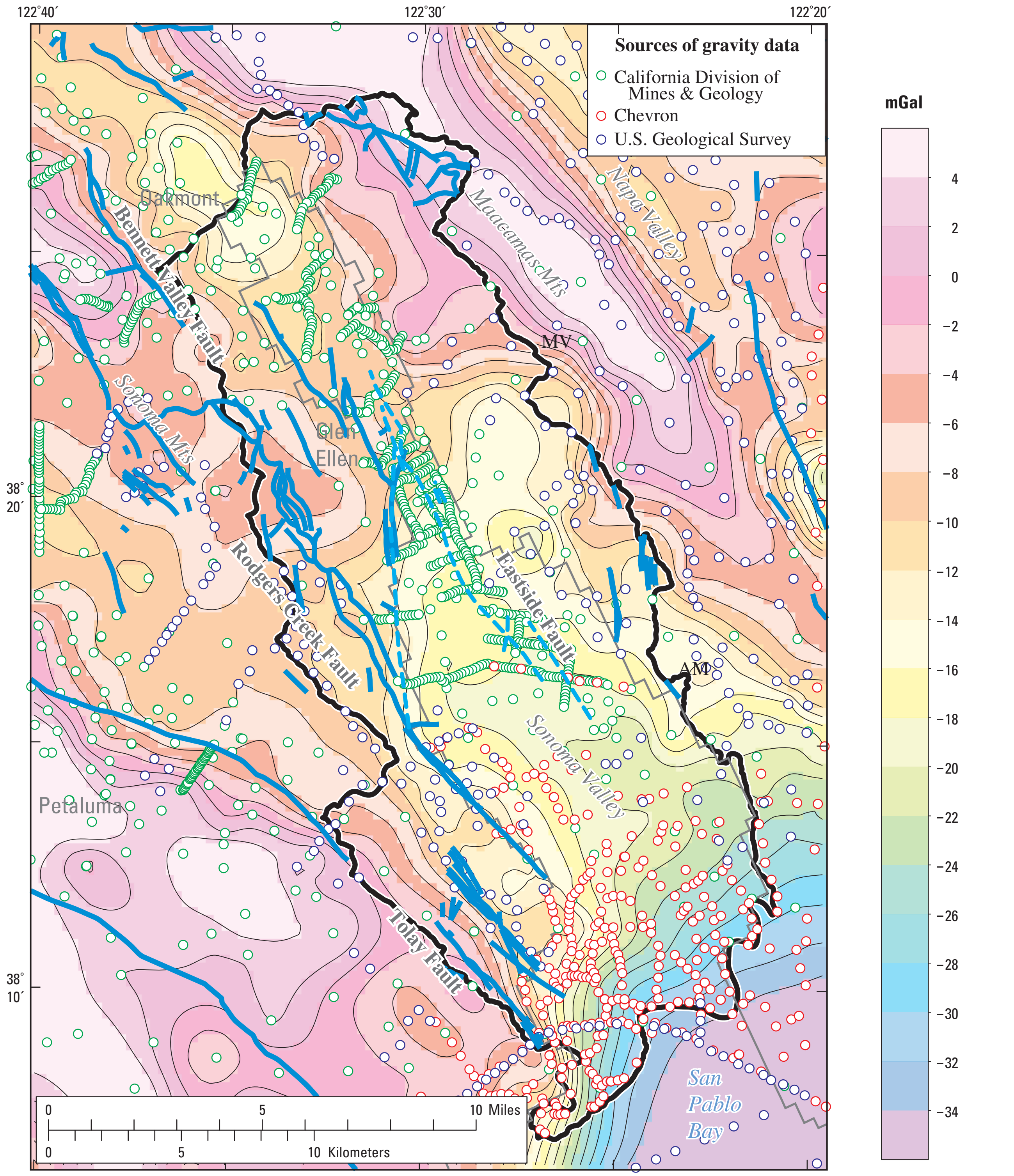

Figure A-1. Isostatic residual gravity in the Sonoma Valley area, Sonoma County, California. Black line is model boundary; thick blue lines, faults from California Department of Water Resources (1975) and Jennings (1994); dashed blue lines, faults from geophysical study of Campion and others (1984). AM, Arrowhead Mountain; MV, Mt. Veeder.

Table A-1. Densities of hand samples collected for this study of the Sonoma Valley area, Sonoma County, California.

[±, standard deviation; N, number of samples; kg/m^3, kilograms per cubic meter]

Rock type	Grain density range (in kg/m^3)	Average grain density (in kg/m^3)	Average saturated density (in kg/m^3)	Average dry bulk density (in kg/m^3)	Average porosity (in percent)
Sonoma Volcanics (N = 70)					
	1,570–2850	2,344 ± 272	2,214 ± 305	2,109 ± –367	10
Basalts (N = 21)	2,090–2850	2,519 ± 223	2,402 ± 290	2,318 ± 357	8 ± 8
Andesites (N = 8)	2,280–2830	2,508 ± 157	2,384 ± 196	2,298 ± 235	8 ± 5
Rhyolites (N = 23)	1,910–2590	2,358 ± 140	2,245 ± 141	2,163 ± 173	8 ± 5
Tuffs (N = 18)	1,570–2440	2,049 ± 252	1,881 ± 246	1,714 ± 309	16 ± 10
Great Valley sequence (N = 3)					
	2,570–2,670	2,610	2,560	2,523	3

In general, the volcanic flow rocks are denser than the tuffs or tuffaceous rocks. For the flow rocks, density increases as the mafic content of the rocks increases. Average densities for the non-tuff rocks increase with decreasing silica content. Basalts and basaltic-andesites have the highest densities, exceeding 2,800 kg/m^3, although the basalts are also characterized by a wide range of densities. The least dense sample of basalt is scoria, with a density of 2,040 kg/m^3 and a porosity of nearly 24 percent.

Tuffs are the least dense of the Sonoma Volcanics. They are also characterized by significantly higher porosities, averaging 16 percent. The most porous sample, a tuffaceous mudstone, has a porosity of 37 percent. Welded tuffs and vitrophyres, on the other hand, have porosities of 6 percent or less.

The density measurements of this study (*table A-1*) are broadly consistent with earlier data (Smith, 1992) and assumed densities (Campion and others, 1984). An average density of 2,400 kg/m^3 was measured from 2 formation density logs and 6 well cores of the Sonoma Volcanics (Smith, 1992), which compares reasonably with the average grain density of all the Sonoma Volcanic rocks measured in the hand samples (2,344 kg/m^3). Campion and others (1984) assumed a density of 2,250 kg/m^3 for the Sonoma Volcanics (excluding basalts). Smith (1992) lists average densities of 2,500 and 2,550 kg/m^3 for the Cretaceous Great Valley sedimentary rocks, which are slightly lower than the average grain density of 2,610 kg/m^3 based on only three samples. The hand sample measurements may be biased towards higher densities because of the relative ease of obtaining more consolidated samples. Both Campion and others (1984) and Smith (1992) assumed an average density of 2,650 kg/m^3 for the Franciscan Complex, although the average density locally may be higher because of dense greenstone.

Density logs from two drill holes in the vicinity of the Sonoma Valley area are available (Brocher and others, 1997). These logs provide critical information for how density varies with depth (Brocher and others, 1997). Densities in the Claremont Energy John Rice No. 1 well (latitude 38.34743; longitude –122.75268; total depth, 372 m or 1,220 ft) range from 1,900 to 2,100 kg/m^3 for an ~300-m-thick Quaternary sedimentary section above Franciscan basement. The Chevron Bethlehem No. 1 well (latitude, 37.99936; longitude, –122.33912; total depth, 3,048 m or 10,000 ft) penetrates approximately 1,200 m (3,900 ft) of Tertiary sedimentary rocks above 1,800 m (6000 ft) of Tertiary volcanics. Densities range from 1,800 to 2,380 kg/m^3 for the sedimentary section (see fig. 3 in Smith, 1992).

Gravity Anomalies

Positive gravity values (greater than 2–4 mGal) occur over areas of exposed Franciscan Complex and Great Valley sequence rocks in the Mayacmas Mountains and the area southwest of the city of Petaluma (*fig. A-1*). Moderately high values (–6 to –2 mGal) occur over Sonoma Mountain where Sonoma Volcanics are extensively exposed. Recently, serpentinite has been mapped in the Taylor Mountain area (R.J. McLaughlin, U.S. Geological Survey, oral commun., 2004), a few kilometers northwest of the study area, suggesting that shallow Franciscan basement may contribute to the high gravity values along the northwest part of the study area.

Low gravity values (less than –10 mGal) characterize much of Sonoma Valley. The low gravity values are separated into two lows by a north-northeast-striking gravity ridge near the town of Glen Ellen (Campion and others, 1984). The northern low is centered on the town of Oakmont and has northwest-striking, somewhat irregular margins. The southern low is more areally extensive and complex. It is the northern prong of a much more profound gravity low centered over San Pablo Bay along the southeast margin of the study area. The southwest margin of the southern Sonoma Valley gravity low appears to be stepped, with a strong gradient coincident with the Tolay Fault and a lesser gradient associated with the Rodgers Creek and Bennett Valley Faults. The western margin of the southern Sonoma Valley low changes to a more northerly strike at the latitude of 38°15’N. Campion and others (1984) interpreted this north-striking gradient as a fault (dashed red lines on fig. A1), which has been confirmed by mapping (Wagner and others, 2003). This structure appears to truncate southeast-striking magnetic anomalies west of the valley (U.S. Geological Survey, 1997). The eastern margin of the southern gravity low is irregular, but generally has a north to northwest strike. Detailed profiles indicate ~1 mGal step superposed on a gentle gradient along the east side of the valley which Campion and others (1984) named the East-side Fault. This fault also is locally expressed at the surface (Wagner and others, 2004). North of this fault is a north-striking gravity low that projects onto outcrops of Sonoma Volcanics as far north as Mt. Veeder.

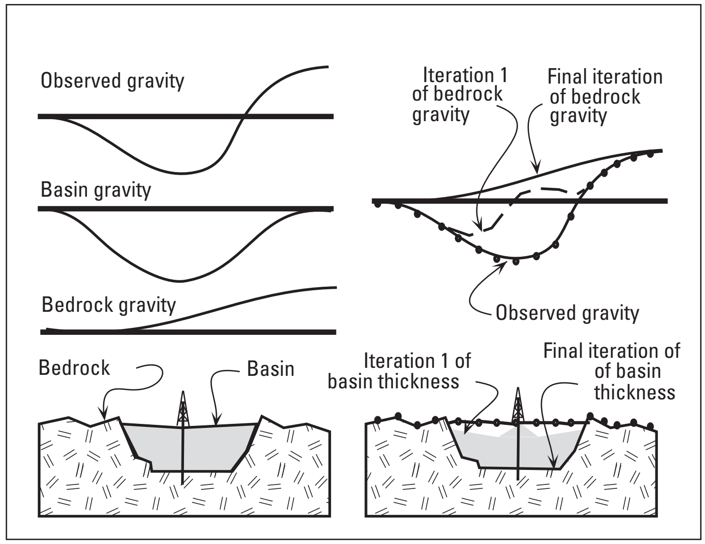

Figure A-2. Schematic representation of depth to bedrock method. (Panel on left represents contributions of basin and bedrock to the gravity field. Panel on right illustrates procedure that iterates difference between observed gravity field and regional bedrock field on the basis of bedrock gravity measurements and well constraints (modified after Blakely, unpub. data, 1999).

Depth to Basement Method

In this section, depth to pre-Cenozoic bedrock was calculated for the Sonoma Valley and vicinity to determine the geometry of bounding and internal faults. The inversion takes advantage of the large density contrast between dense pre-Cenozoic rocks (primarily the Franciscan Complex and ophiolite basement of the Great Valley sequence) and lighter Quaternary–Tertiary sedimentary rocks and Sonoma Volcanics.

Table A-2. Density-depth function for the Chevron Bethlehem No. 1 well in the Sonoma Valley area, Sonoma County, California.

[m, meter; kg/m^3, kilograms per cubic meter]

Depth range (in m)	Density contrast (in kg/m^3)
0–300	–480
300–1,300	–320
1,300–2,300	–270
2,300–3,300	–170
<3,300	–100

The method used for this study to estimate the thickness of Cenozoic rocks was developed by Jachens and Moring (1990) and modified to incorporate drill hole and other geophysical data (Bruce Chuchel, U.S. Geological Survey, unpub. data, 1996; *fig. A-2*). The inversion method allows the density of bedrock to vary horizontally as needed, whereas the density of basin-filling deposits is specified by a pre-determined density-depth relationship. The density-depth function (*table A-2*) was used for this study; it was based on a density log from the Chevron Bethlehem No. 1 well (Brocher and others, 1997). A first approximation of the bedrock gravity field was derived from gravity measurements made on exposed pre-Cenozoic rocks, augmented by appropriate bedrock gravity values calculated at sites where depth to bedrock was known. This approximation (which ignores the gravity effects of nearby basins) was subtracted from the observed gravity, which provided a first approximation of the basin gravity field. Using the specified density-depth relation, the thickness of the basin-fill deposits was calculated. The gravitational effect of this first approximation of the basin-fill layer was computed at each known bedrock station. This effect, in turn, was subtracted from the first approximation of the bedrock gravity field and the process is repeated until successive iterations produce no substantial changes in the bedrock gravity field.

This method has been shown to be effective in determining the general configuration of the pre-Cenozoic bedrock surface in Nevada (Phelps and others, 1999). They showed that the model bedrock surface of Yucca Flat (Nevada Test Site, northwest of Las Vegas, Nevada) was a reasonable approximation of the true surface, which was based on comparison with calculated basin depths from closely spaced drill holes. The predicted shape of the basin did not change significantly with additional well control. Furthermore, it appears that lateral variations in basin density, unless abrupt, do not change the overall modeled shape of the basin. Although the method is a good tool for predicting the shapes of basins, it can be less effective in estimating the magnitude of basin thickness, especially in basins containing thick basalt flows or in areas of poor well control.

Depth to Basement Results

A basin model (*fig. A-3*) was created using the density-depth function of the Chevron Bethlehem well (*table A-2*). Because of the wide range in density of the local Cenozoic volcanic rocks, the same density-depth relationship was assumed for Cenozoic volcanic rocks as for the Cenozoic sedimentary deposits. One might consider including the basalts with the pre-Cenozoic bedrock, but the limited and often laterally varying thickness of the basalt flows and the presence of lower density rocks (such as Tertiary sedimentary or volcanic rocks) beneath the basalts made this approach poorly constrained. The models utilize bedrock gravity stations to constrain the thickness of Cenozoic sediment and volcanic rocks.

The inversion presented here does not take into account lateral variations in the density of Cenozoic deposits, which may be an important source of error in the study area, particularly areas where these deposits are underlain by thick, dense basalt flows. The inversion will overestimate the thickness of basin fill in those areas underlain by light rock types (such as tuff) and underestimate the thickness in areas where there are thick accumulations of dense rock types (such as basalt). One area that suggests that dense basalt hides a more extensive thick tuff section may be the area north of the city of Sonoma (“A” on *fig. A-3*). Geologic mapping indicates that a tuffaceous section does underlie the basalt flows in places (Wagner and others, 2004).

Another source of error is the bedrock gravity field. The bedrock gravity field is reasonably well constrained by stations measured on bedrock in the Mayacmas Mountains and the hills southwest of the city of Petaluma. However, the broad area between these outcrops of Franciscan Complex is not constrained by any direct well information or bedrock gravity measurements. The presence of Franciscan bedrock on both sides of the valley with approximately the same isostatic residual gravity values suggests that the bedrock gravity field may be reasonably extrapolated through the valley.

The model was tested by comparing the predicted basin thickness with the minimum thickness of Cenozoic deposits measured in wells that did not bottom in pre-Cenozoic rock. Because there were few deep wells in the valley, this was not a robust test. For all but two wells (wells 2179 and McKenzie), the simulated bedrock surface was consistent with available well information. Well 2179 (mismatch 69 m) is located on a gravity high controlled only by stations west of the well, and well McKenzie, (mismatch 21 m) is located on a gradient in the bedrock gravity field.

The model shows that the Sonoma Valley is underlain by two main subbasins separated by a shallow bedrock ridge near the town of Glen Ellen. The ridge is at a depth of approximately 1,000 to 2,000 ft (300–600 m). Basalt flows crop out immediately west of the bedrock ridge, and their presence may lead to an underestimation of the thickness of the basin fill here if these rocks are dense and thick. However, if the flows are dense, they are likely impermeable, acting as hydrologic bedrock despite being Cenozoic in age.

The thickest basin fill is at the southern margin of the study area near San Pablo Bay, exceeding 10,000 ft (3,000 m). A series of subbasins extends northwest from San Pablo Bay into the central and eastern parts of Sonoma Valley. The Eastside Fault forms part of the eastern margins of these subbasins, and based on the inversion, the fault (or faults) extend another 7 to 8 km to the southeast. Along the western margin of Sonoma Valley is a 10-km-long, north-striking subbasin that is truncated on the south by the Rodgers Creek and Bennett Valley Faults.

The inversion predicts locally thick accumulations of volcanics on the east side of Sonoma Valley (“A” and “B” on *fig. A-3*). Area “A” is characterized by exposures of moderately dense andesite and basalt flows; the inversion predicts a substantial thickness of volcanics (8,000–10,000 ft; 2,400–3,000 m) beneath this area. The inversion may overestimate the thickness of fill in this area if these flow rocks conceal substantial amounts of tuff or other low-density rocks. If low-density rocks are present, they have relatively high porosity and may affect ground-water flow that moves from the Mayacmas Mountains into Sonoma Valley. The northern area, “B,” is characterized by exposures of rhyolite. Note that the gravity station coverage in this region is poor; anomaly shapes may change with more data (e.g., “A” and “B” may be connected). This accumulation may reflect a local volcanic center that fed rhyolite flows that cap ridges to the south toward Arrowhead Mountain (D. Wagner, California Geological Society, unpub. data, 2004).

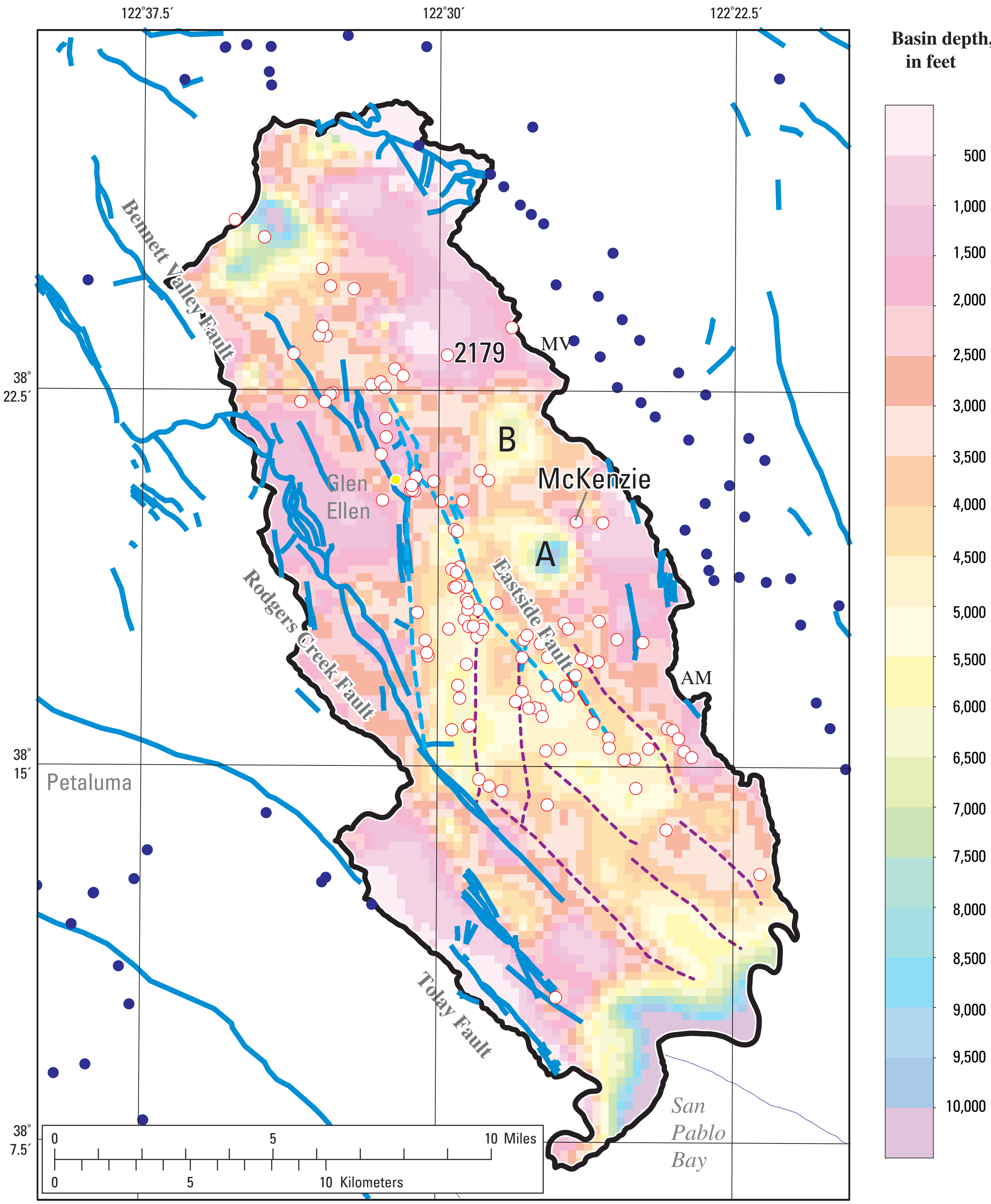

Figure A-3. Cenozoic basin thickness in the Sonoma Valley area, Sonoma County, California. (Thick blue lines, faults from California Department of Water Resources (1975) and Jennings (1994); dashed blue lines, faults from geophysical study of Campion and others (1984). All wells (circles) but 2179 and McKenzie are consistent with basin thickness model. "A" and "B" are on exposures of Sonoma Volcanics. Magenta dashed lines are inferred faults based on basin fill thickness variations. Purple circles are gravity measurements made on bedrock.

Appendix B. Water Levels at Selected Wells in the Sonoma Valley

Figure B-1. Periodic water levels in selected wells in the Sonoma Valley, Sonoma County, California: A, CADWR network, 1950s through 2004; B, CADWR network, southern area; C, CADWR network, Sonoma area; D, CADWR network, Glen Ellen area; E, CADWR network, Kenwood area; F, VOM primary network; G–K, VOM secondary network; L, city of Sonoma primary network, and M, city of Sonoma secondary network.

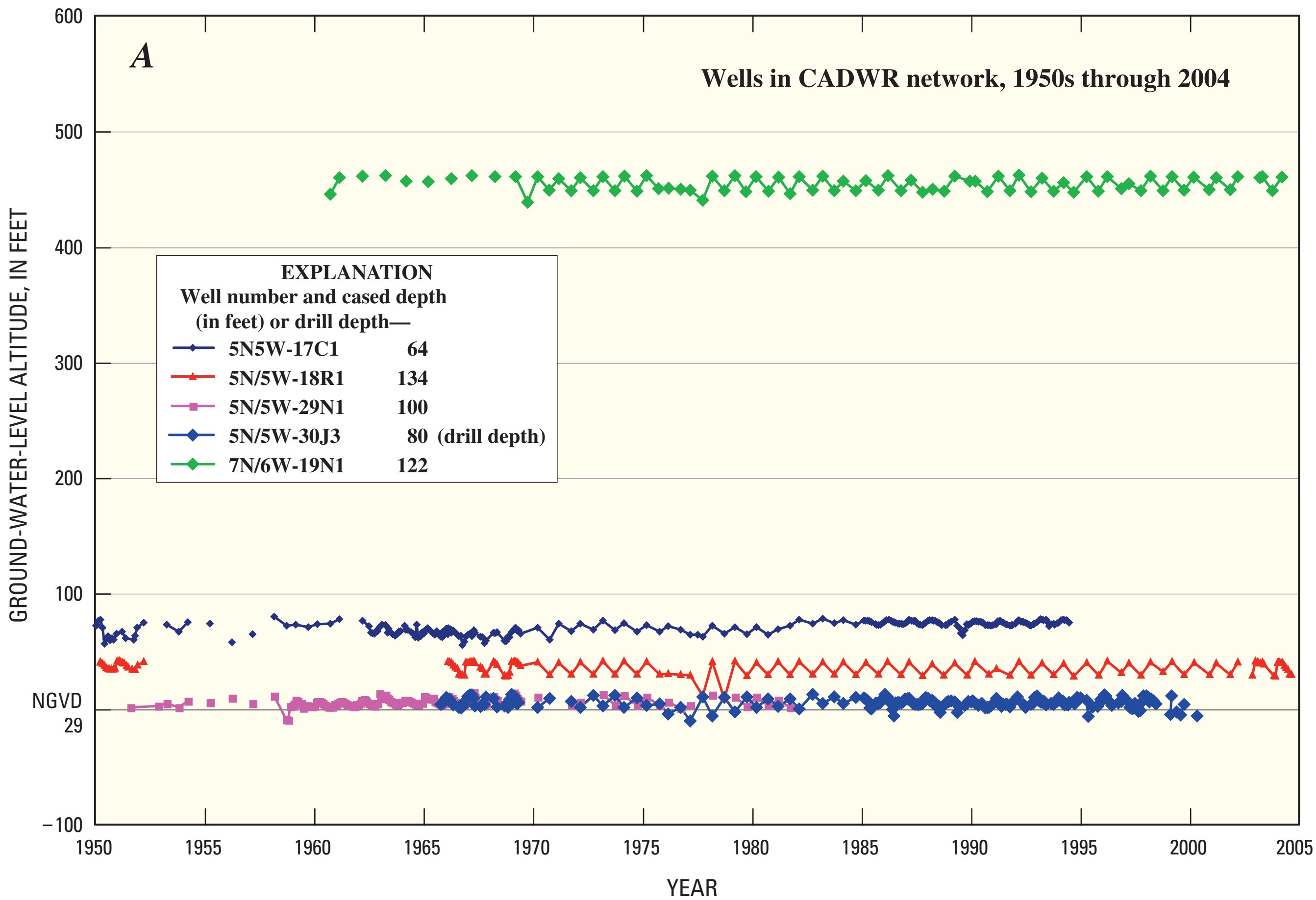

Figure B-1A.

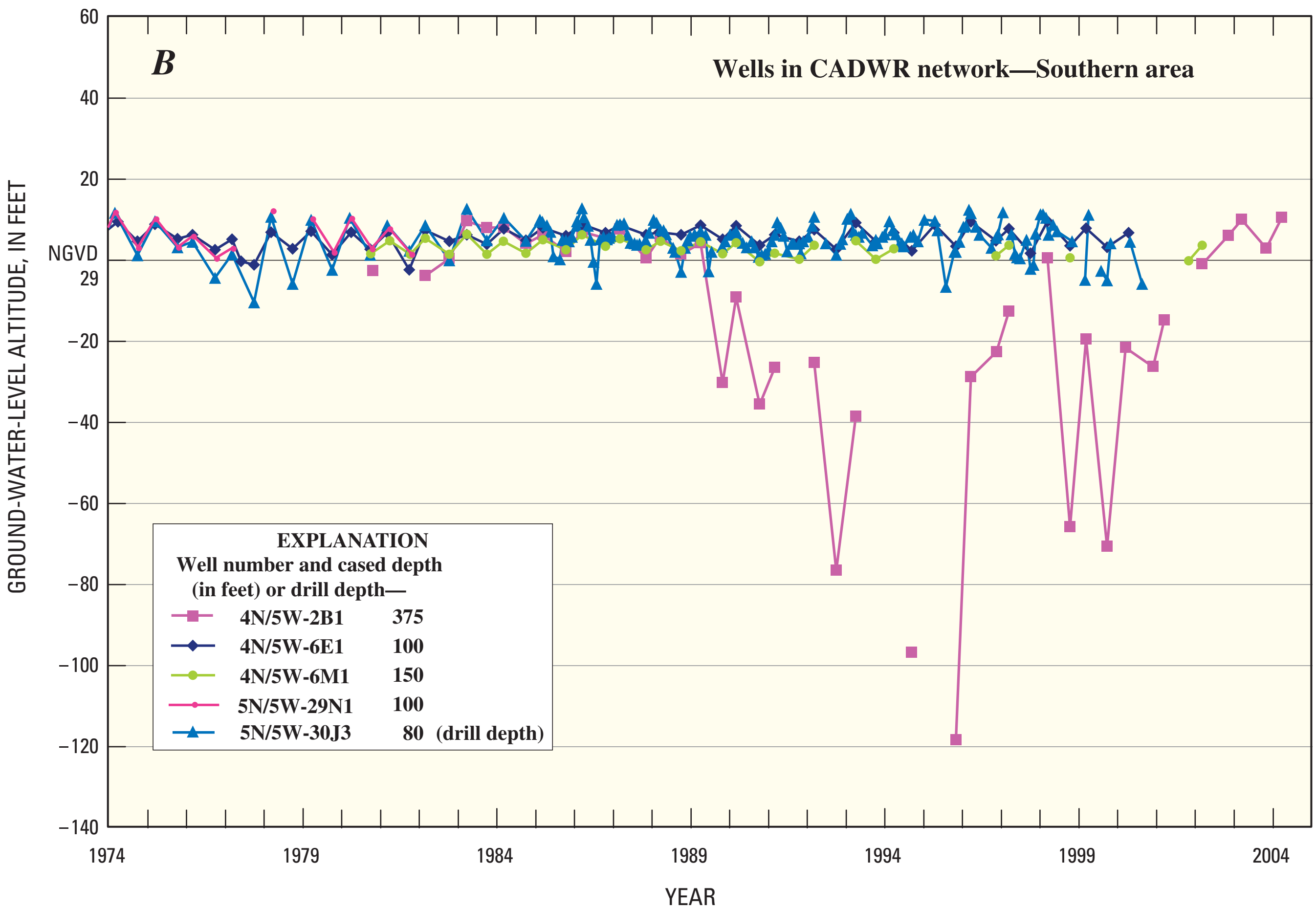
B
Wells in CADWR network—Southern area
60
40
20
NGVD 29
−20
−40
−60
−80
−100
−120
−140
GROUND-WATER-LEVEL ALTITUDE, IN FEET
1974
1979
1984
1989
1994
1999
2004
YEAR
EXPLANATION
Well number and cased depth (in feet) or drill depth—
4N/5W-2B1 375
4N/5W-6E1 100
4N/5W-6M1 150
5N/5W-29N1 100
5N/5W-30J3 80 (drill depth)

Figure B-1B.

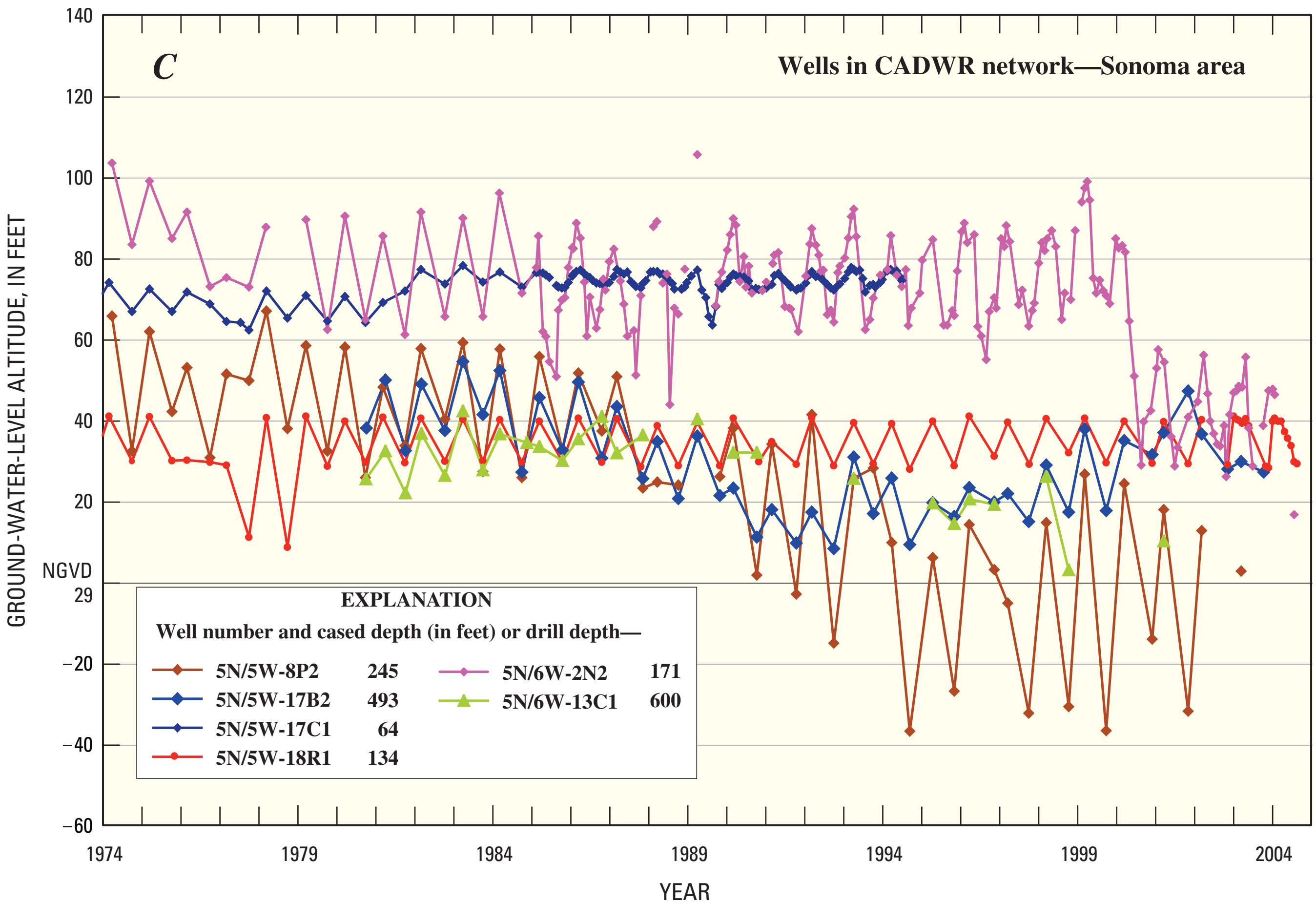
C
Wells in CADWR network—Sonoma area
GROUND-WATER-LEVEL ALTITUDE, IN FEET
140
120
100
80
60
40
20
NGVD 29
−20
−40
−60
1974
1979
1984
1989
1994
1999
2004
YEAR
EXPLANATION
Well number and cased depth (in feet) or drill depth—
5N/5W-8P2 245
5N/5W-17B2 493
5N/5W-17C1 64
5N/5W-18R1 134
5N/6W-2N2 171
5N/6W-13C1 600

Figure B-1C.

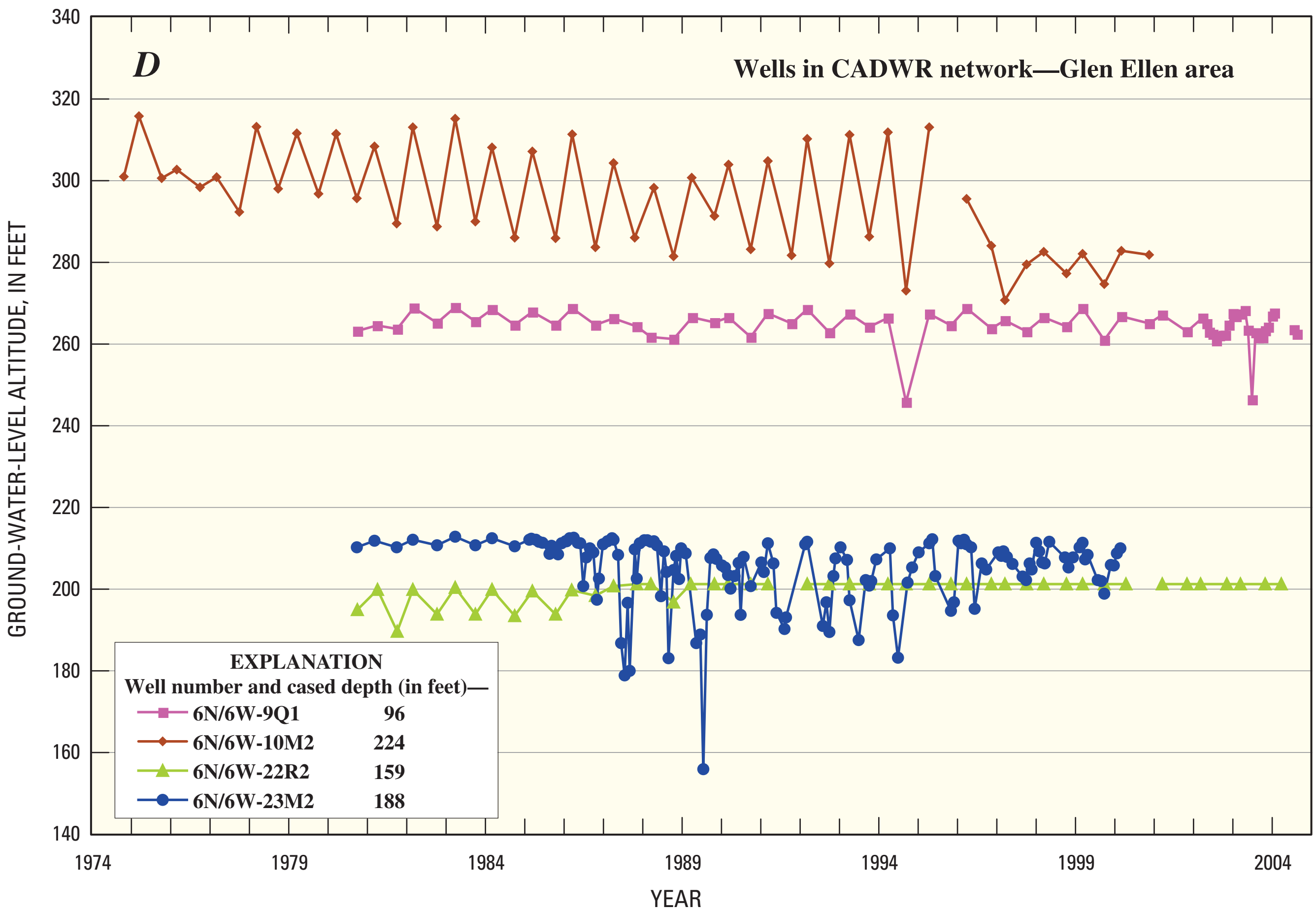
D
Wells in CADWR network—Glen Ellen area
GROUND-WATER-LEVEL ALTITUDE, IN FEET
340
320
300
280
260
240
220
200
180
160
140
1974
1979
1984
1989
1994
1999
2004
YEAR
EXPLANATION
Well number and cased depth (in feet)—
6N/6W-9Q1 96
6N/6W-10M2 224
6N/6W-22R2 159
6N/6W-23M2 188

Figure B-1D.

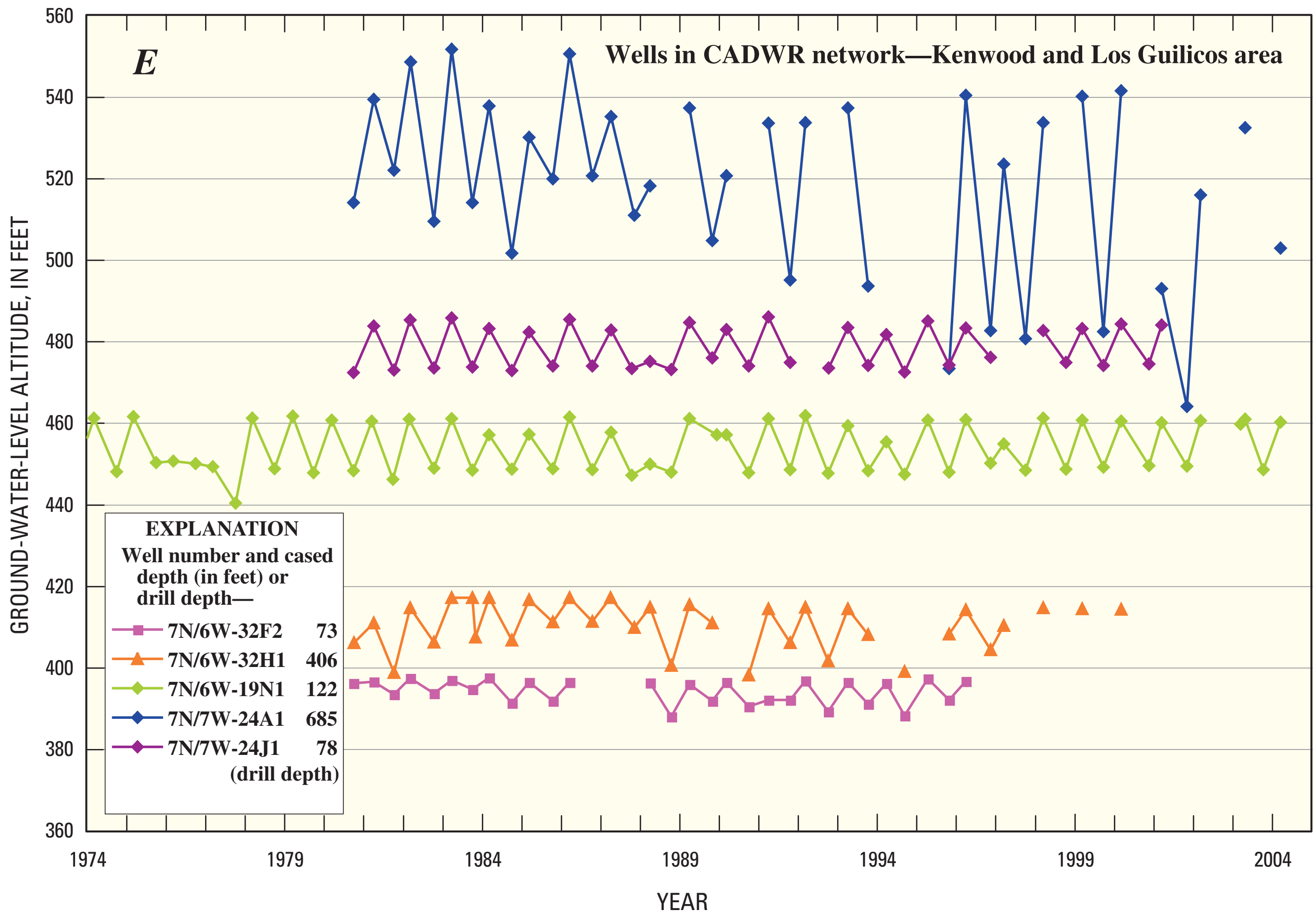
E
Wells in CADWR network—Kenwood and Los Guilicos area
GROUND-WATER-LEVEL ALTITUDE, IN FEET
560
540
520
500
480
460
440
420
400
380
360
1974
1979
1984
1989
1994
1999
2004
YEAR
EXPLANATION
Well number and cased depth (in feet) or drill depth—
7N/6W-32F2 73
7N/6W-32H1 406
7N/6W-19N1 122
7N/7W-24A1 685
7N/7W-24J1 78 (drill depth)

Figure B-1E.

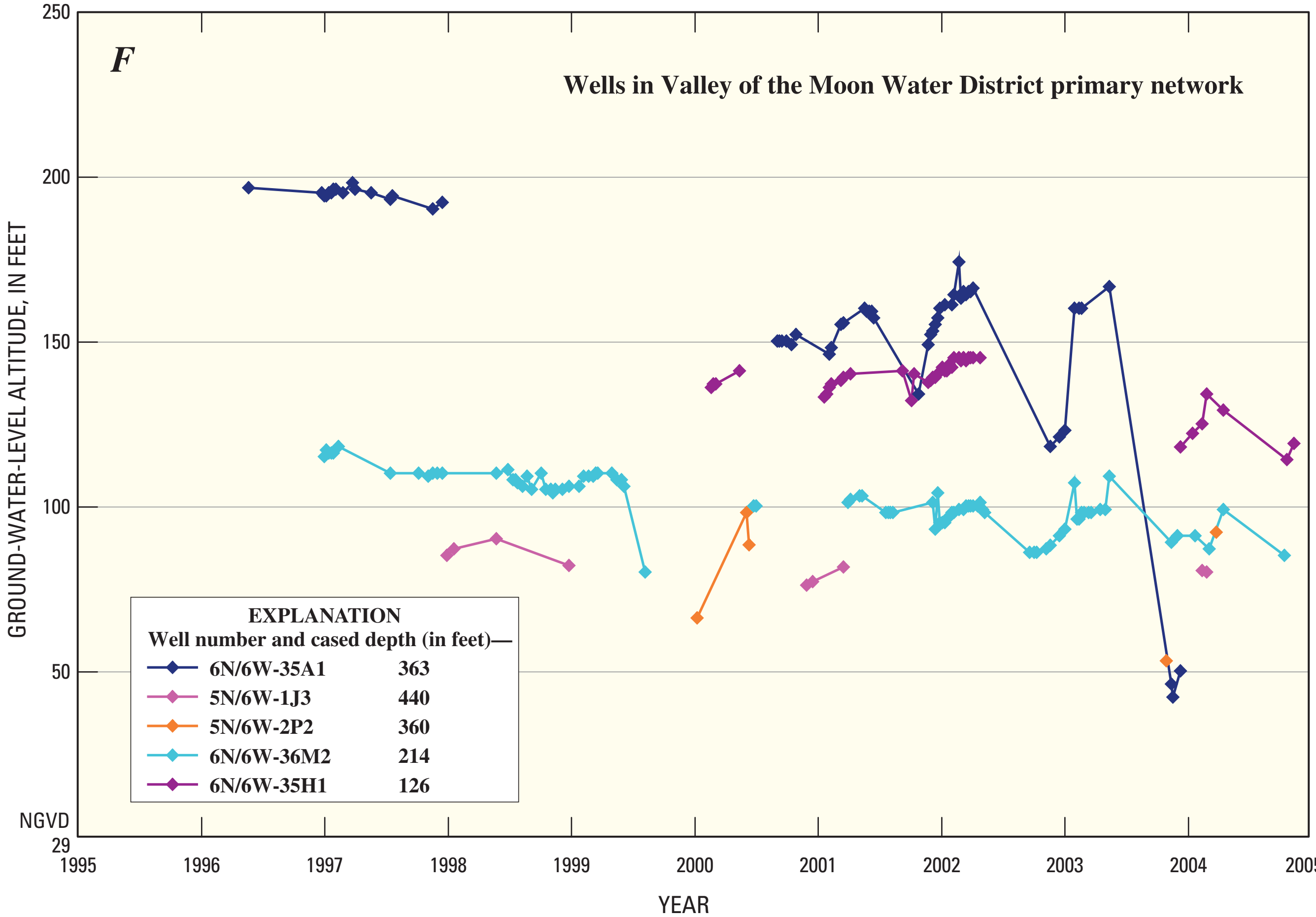
F
Wells in Valley of the Moon Water District primary network
GROUND-WATER-LEVEL ALTITUDE, IN FEET
250
200
150
100
50
NGVD 29
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
YEAR
EXPLANATION
Well number and cased depth (in feet)—
6N/6W-35A1 363
5N/6W-1J3 440
5N/6W-2P2 360
6N/6W-36M2 214
6N/6W-35H1 126

Figure B-1F.

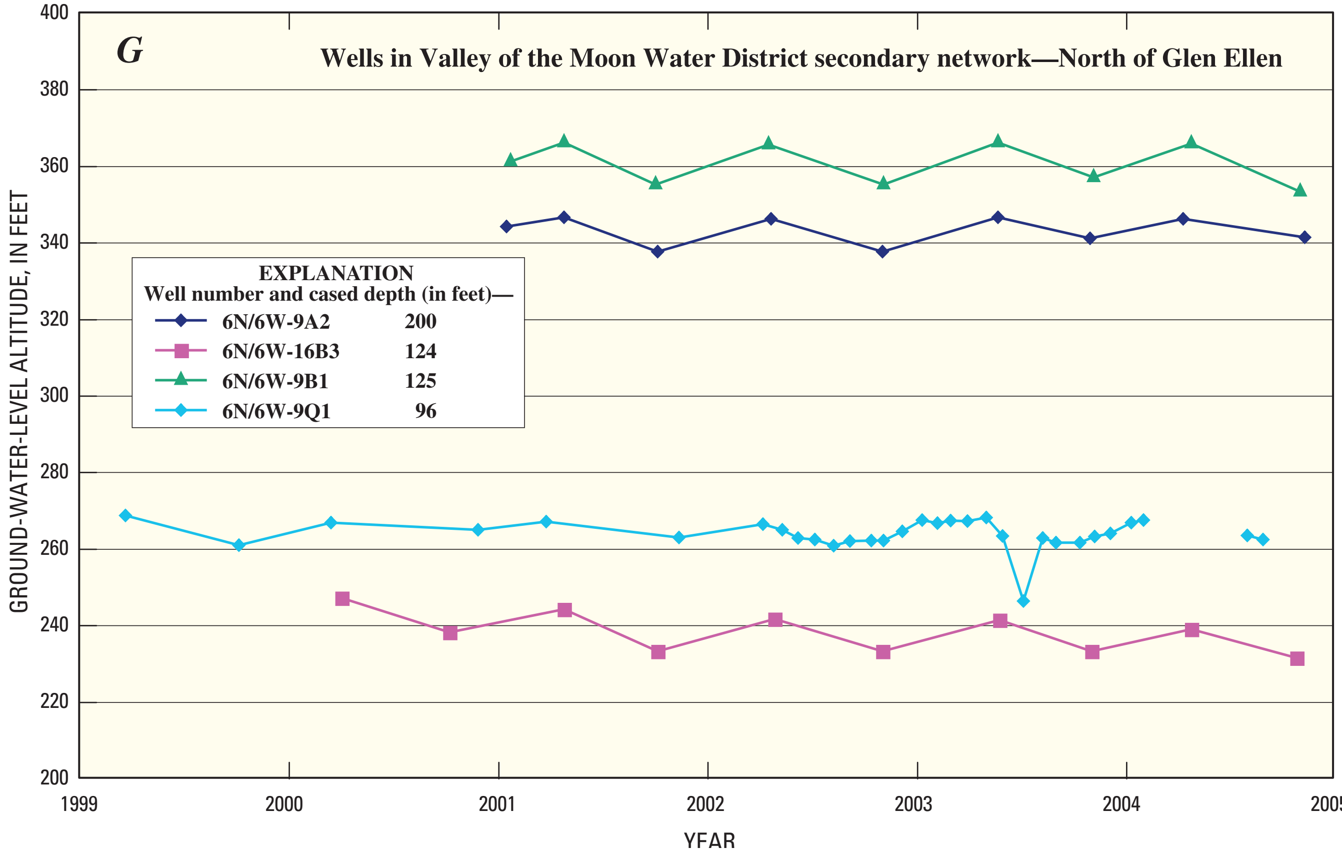
G
Wells in Valley of the Moon Water District secondary network—North of Glen Ellen
EXPLANATION
Well number and cased depth (in feet)—
6N/6W-9A2 200
6N/6W-16B3 124
6N/6W-9B1 125
6N/6W-9Q1 96
GROUND-WATER-LEVEL ALTITUDE, IN FEET
400
380
360
340
320
300
280
260
240
220
200
1999
2000
2001
2002
2003
2004
2005
YEAR

Figure B-1G.

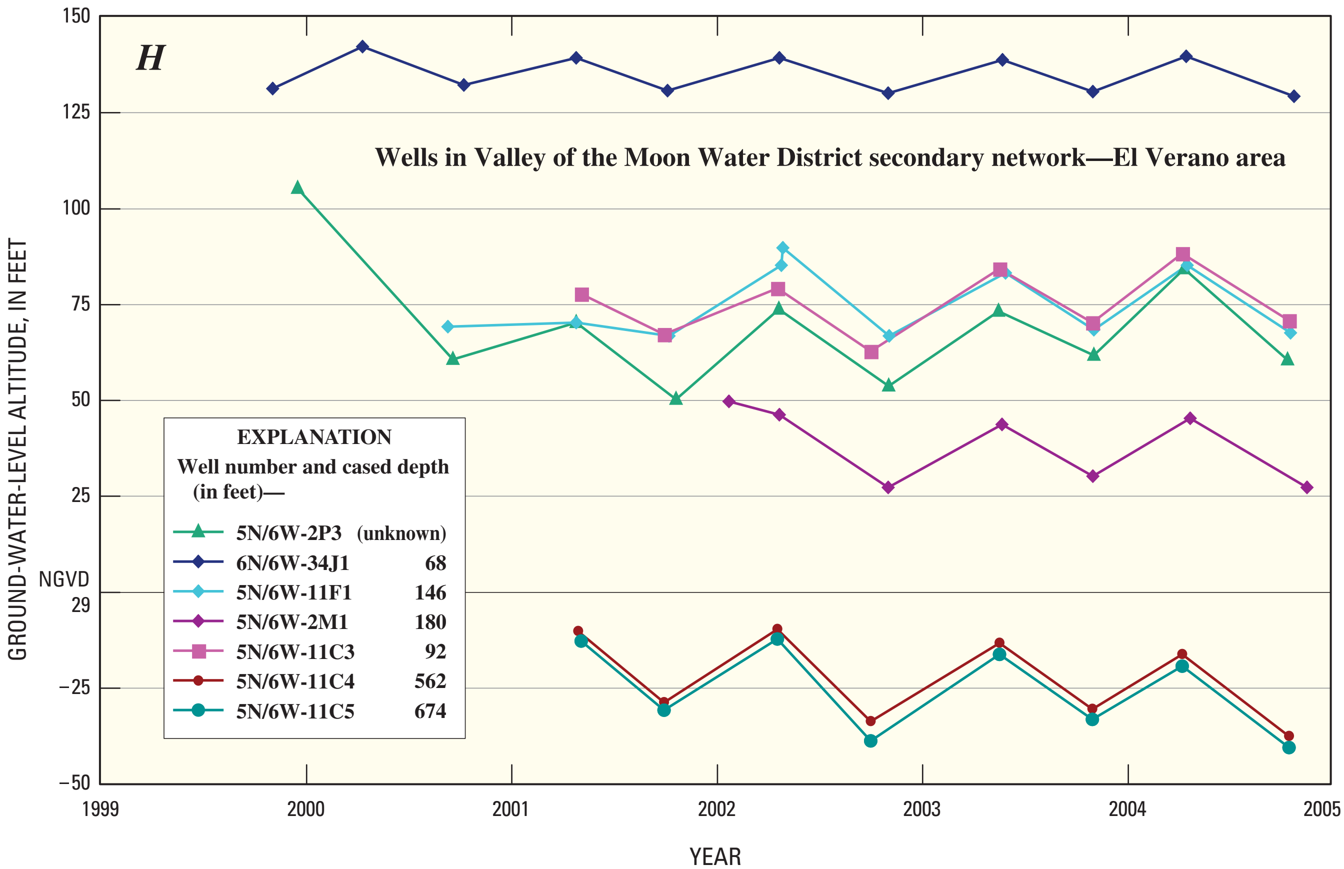
H
Wells in Valley of the Moon Water District secondary network—El Verano area
GROUND-WATER-LEVEL ALTITUDE, IN FEET
150
125
100
75
50
25
NGVD 29
−25
−50
1999
2000
2001
2002
2003
2004
2005
YEAR
EXPLANATION
Well number and cased depth (in feet)—
5N/6W-2P3 (unknown)
6N/6W-34J1 68
5N/6W-11F1 146
5N/6W-2M1 180
5N/6W-11C3 92
5N/6W-11C4 562
5N/6W-11C5 674

Figure B-1H.

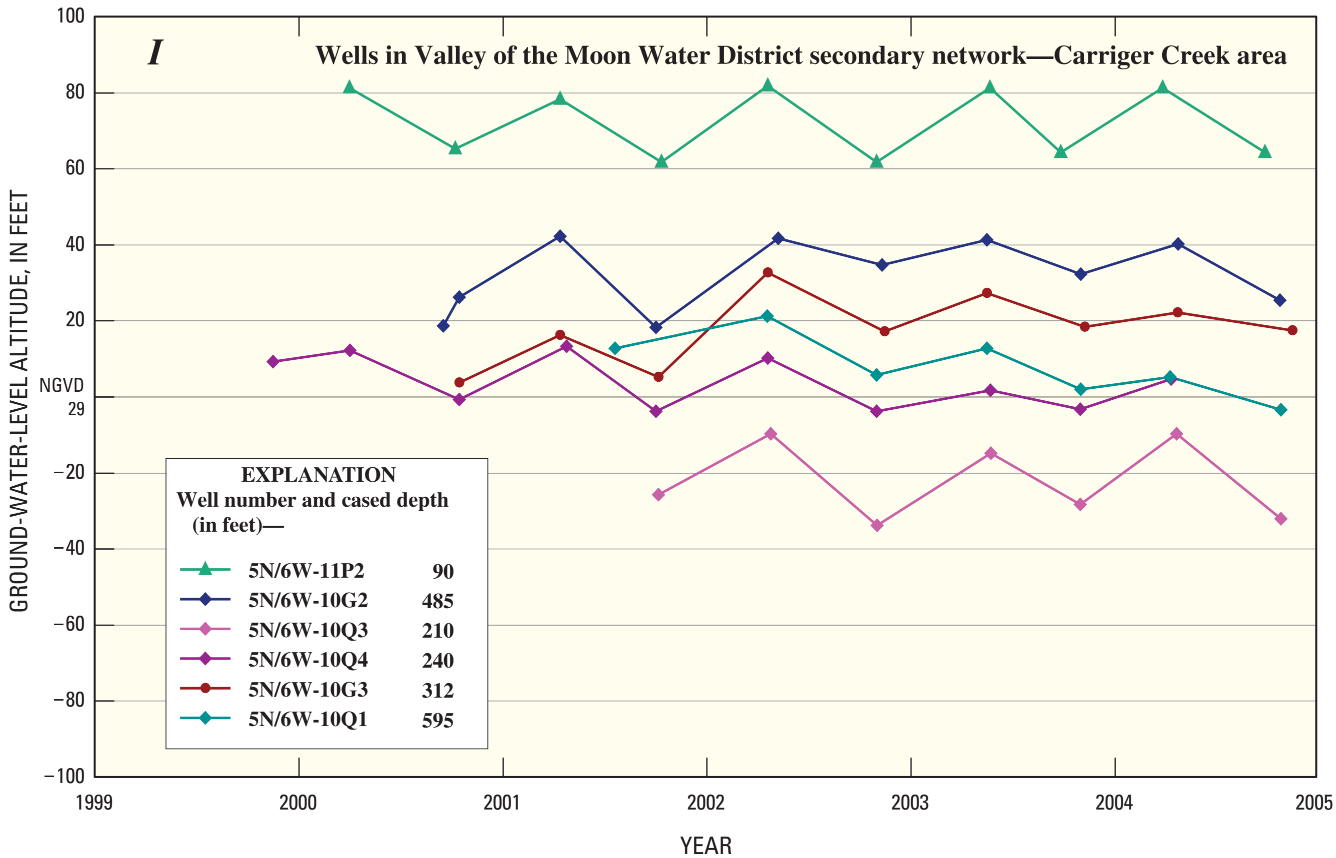
I
Wells in Valley of the Moon Water District secondary network—Carriger Creek area
GROUND-WATER-LEVEL ALTITUDE, IN FEET
100
80
60
40
20
NGVD 29
−20
−40
−60
−80
−100
1999
2000
2001
2002
2003
2004
2005
YEAR
EXPLANATION
Well number and cased depth (in feet)—
5N/6W-11P2 90
5N/6W-10G2 485
5N/6W-10Q3 210
5N/6W-10Q4 240
5N/6W-10G3 312
5N/6W-10Q1 595

Figure B-1I.

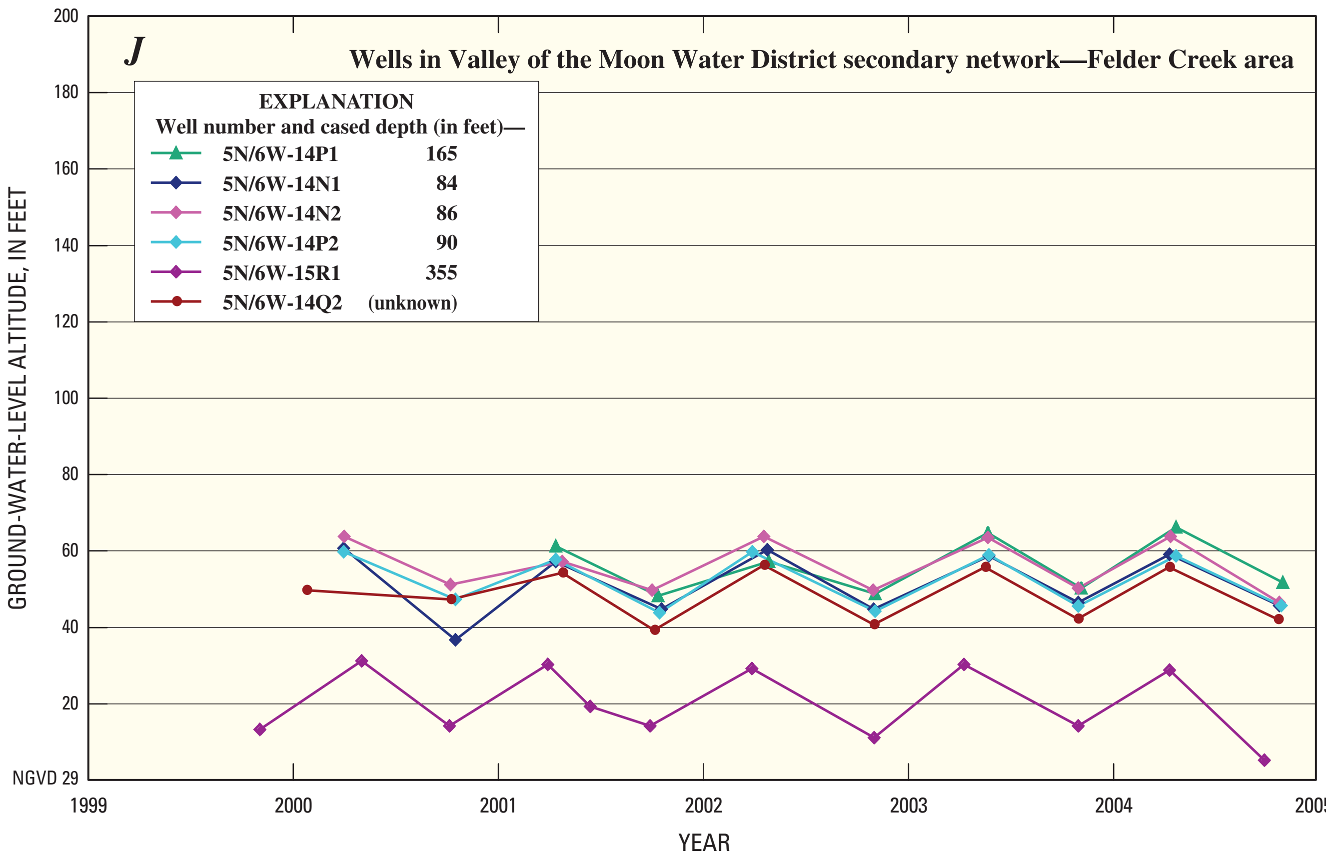
J
Wells in Valley of the Moon Water District secondary network—Felder Creek area
EXPLANATION
Well number and cased depth (in feet)—
5N/6W-14P1 165
5N/6W-14N1 84
5N/6W-14N2 86
5N/6W-14P2 90
5N/6W-15R1 355
5N/6W-14Q2 (unknown)
GROUND-WATER-LEVEL ALTITUDE, IN FEET
200
180
160
140
120
100
80
60
40
20
NGVD 29
1999
2000
2001
2002
2003
2004
2005
YEAR

Figure B-1J.

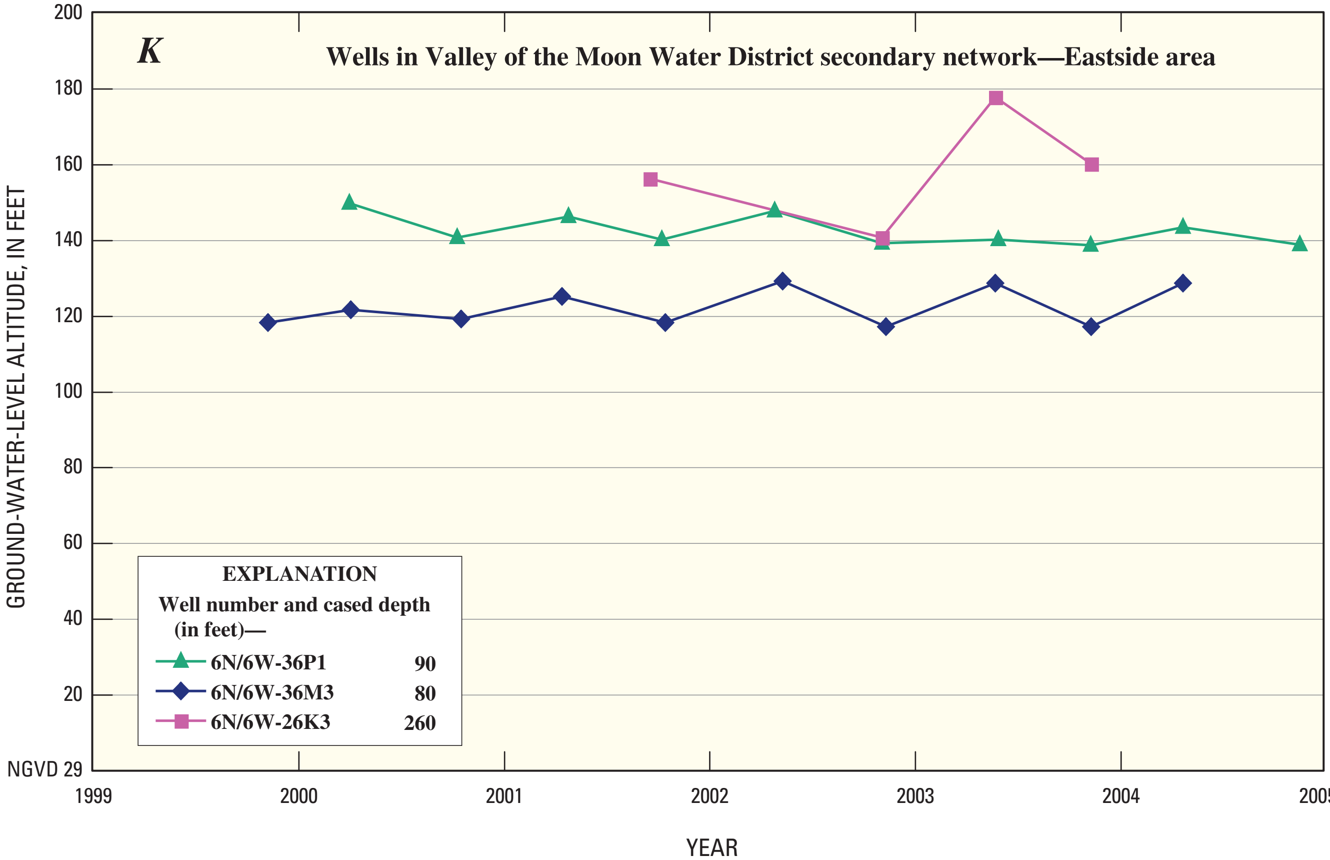
K
Wells in Valley of the Moon Water District secondary network—Eastside area
GROUND-WATER-LEVEL ALTITUDE, IN FEET
200
180
160
140
120
100
80
60
40
20
NGVD 29
1999
2000
2001
2002
2003
2004
2005
YEAR
EXPLANATION
Well number and cased depth (in feet)—
6N/6W-36P1 90
6N/6W-36M3 80
6N/6W-26K3 260

Figure B-1K.

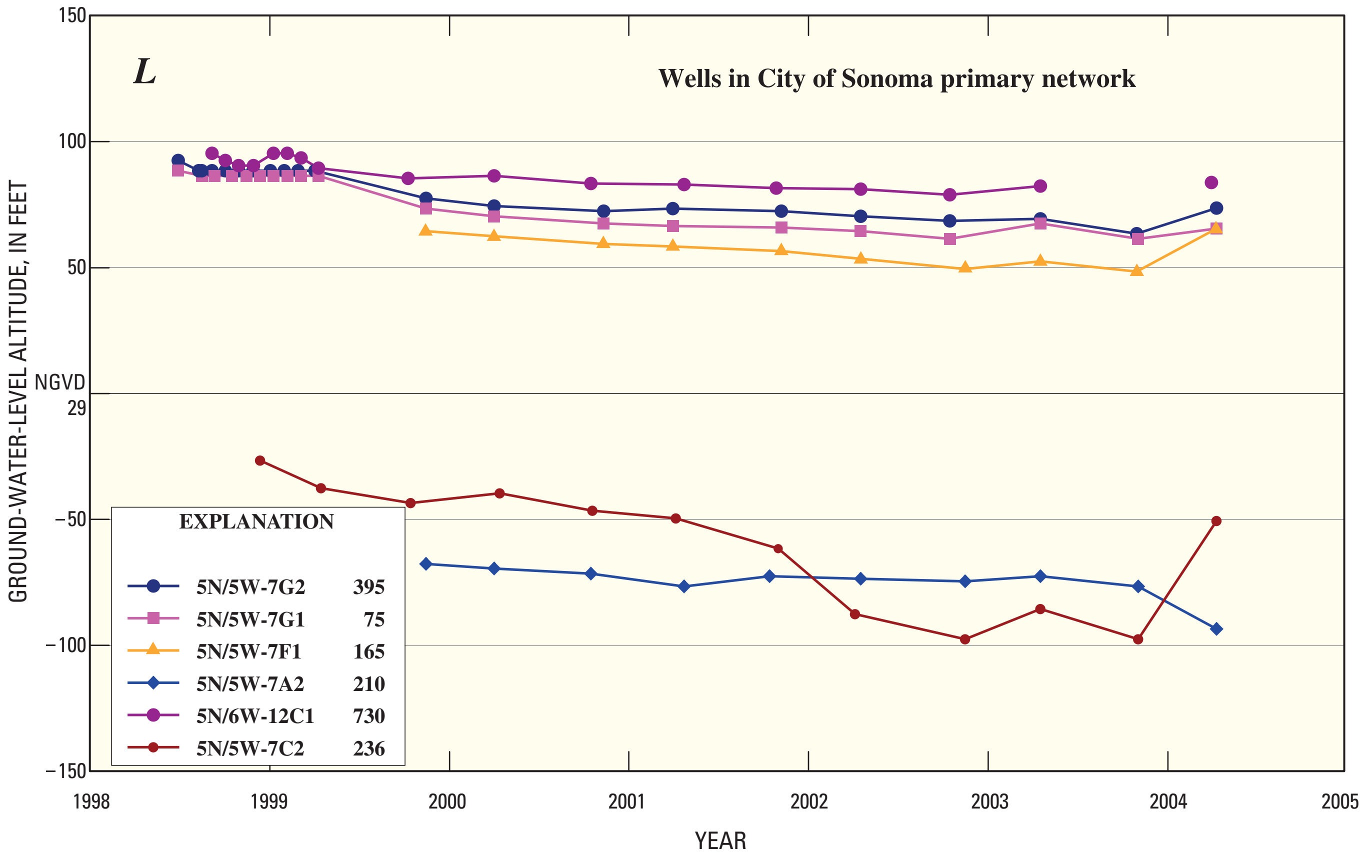
L
Wells in City of Sonoma primary network
GROUND-WATER-LEVEL ALTITUDE, IN FEET
150
100
50
NGVD 29
−50
−100
−150
1998
1999
2000
2001
2002
2003
2004
2005
YEAR
EXPLANATION
5N/5W-7G2 395
5N/5W-7G1 75
5N/5W-7F1 165
5N/5W-7A2 210
5N/6W-12C1 730
5N/5W-7C2 236

Figure B-1L.

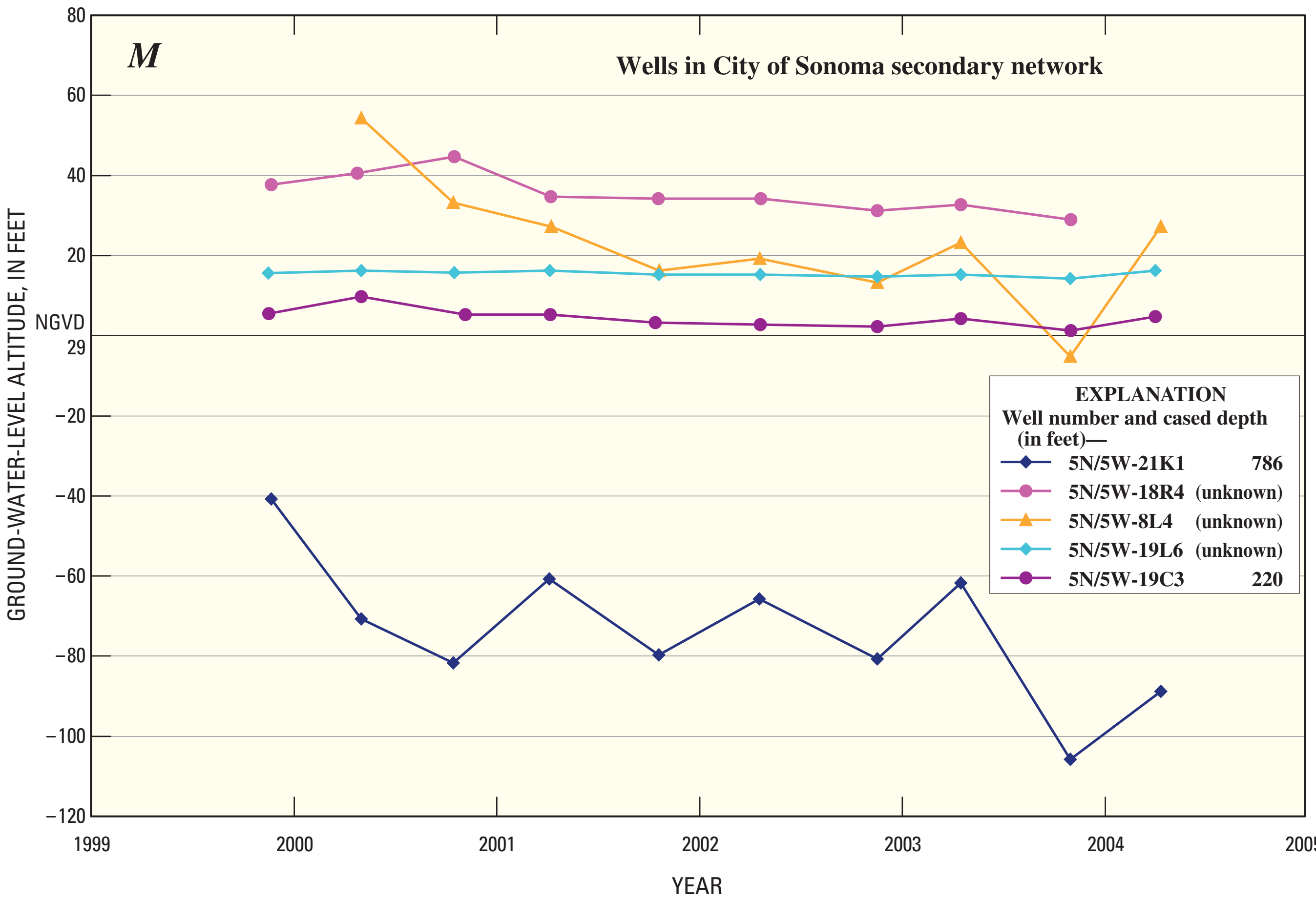
M
Wells in City of Sonoma secondary network
GROUND-WATER-LEVEL ALTITUDE, IN FEET
80
60
40
20
NGVD
29
−20
−40
−60
−80
−100
−120
1999
2000
2001
2002
2003
2004
2005
YEAR
EXPLANATION
Well number and cased depth (in feet)—
5N/5W-21K1 786
5N/5W-18R4 (unknown)
5N/5W-8L4 (unknown)
5N/5W-19L6 (unknown)
5N/5W-19C3 220

Figure B-1M

Appendix C. Construction data, and spring 2003 water levels for selected wells used for geologic cross sections, water-level monitoring, chemistry sampling, and temperature logging in the Sonoma Valley, Sonoma County, California.

[State well No.: See well-numbering diagram in text. See figures 9, 15, 18, 19, 26, and 34 for site locations. USGS (U.S. Geological Survey) identification number: the unique number for each site in USGS NWIS (National Water Information System) database. Depths in feet below land surface. Land surface altitude in feet above sea level. Altitude, altitude of potentiometric surface in feet above sea level which refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929). Status; R, recently pumped, otherwise static conditions or no data. Period of available water-level and water-chemistry, including temperature logging, data: year or multiple year period of data collection. Type of data included in this report for each well: GEO, geologic cross sections; WL, water level; WC, water chemistry; T, temperature logging. —, no data. Data sources: USGS, U.S. Geological Survey; CADMG, California Department of Conservation Division of Mines and Geology; CADWR, California Department of Water Resources; VOM, Valley of the Moon Water District; COS, City of Sonoma]

State well No.	USGS site identification No.	Depth drilled	Depth cased	Depth of top perforation	Depth of bottom perforation	Land surface altitude	Water level Spring 2003 (except where noted)				Period of data included in this report		Type of data included in this report	Data source
							Date	Depth	Altitude	Status	Water level	Chemistry		
4N/5W-2B1	—	375	375	41	290	50	03/27/03	40.3	10	—	1980–2004	—	WL	CADWR
4N/5W-2E1	381322122231801	400	318	140	302	25	08/19/03	75.4	[2]–50	R	2003	2003–04	WL, WC	USGS
4N/5W-2F1[1]	381326122225601	328	328	146	326	40	05/21/03	103.7	[2]–64	R	2003	2003	WL, WC	USGS
4N/5W-2R1[1]	381258122221901	1,255	700	100	700	10	—	—	—	—	—	2003	WC	USGS
4N/5W-6E1	—	100	100	70	100	27	—	—	—	—	1979–2000	—	WL	CADWR
4N/5W-6L1[1]	381313122271601	160	160	100	160	10	08/20/03	9.4	[2]1	R	2003	2003	WL, WC	USGS
4N/5W-6M1	—	230	150	40	150	17	03/27/03	14.5	2	—	1980–2004	—	WL	CADWR
4N/5W-6P2[1]	381250122273001	100	100	50	100	38	—	—	—	—	—	2003	WC	USGS
4N/5W-6P3[1]	381251122271701	420	340	120	340	31	—	—	—	—	—	2003–04	WC, T	USGS
4N/5W-7G1[1]	381228122270401	890	845	605	845	105	—	—	—	—	—	2003	WC	USGS
4N/5W-7K1[1]	381221122270801	770	560	260	560	60	—	—	—	—	—	2003	WC	USGS
4N/5W-14D2	—	1,620	620	260	620	3	—	—	—	—	—	—	GEO	CADWR
4N/5W-15K1[1]	381122122234301	—	—	—	—	0	05/15/03	–0.3	0	—	2003	2004	WL, WC	USGS
4N/5W-17M1	381120122262901	310	280	200	280	100	—	—	—	—	—	2003–04	WC	USGS
4N/5W-30M1[1]	380937122274101	385	375	70	365	300	—	—	—	—	—	2003	WC	USGS
4N/6W-1H1[1]	381322122280201	190	180	40	180	60	—	—	—	—	—	2003	WC	USGS
5N/5W-7A2	381754122265601	500	210	—	—	140	05/20/03	87.0	53	—	1999–2004	—	WL	USGS, COS
5N/5W-7C2	381757122272601	[3]250	236	140	236	120	04/23/03	84	36	—	1998–2004	—	WL	USGS, COS
5N/5W-7F1	381745122272701	263	165	—	—	95	05/15/03	24.9	70	—	1999–2004	—	WL	USGS, COS
5N/5W-7G1	381741122271901	221	75	—	—	95	05/20/03	24.0	71	—	1998–2004	—	WL	USGS, COS

See footnotes at end of table.

Appendix C. Construction data, and spring 2003 water levels for selected wells used for geologic cross sections, water-level monitoring, chemistry sampling, and temperature logging in the Sonoma Valley, Sonoma County, California—Continued.

[State well No.: See well-numbering diagram in text. See figures 9, 15, 18, 19, 26, and 34 for site locations. USGS (U.S. Geological Survey) identification number: the unique number for each site in USGS NWIS (National Water Information System) database. Depths in feet below land surface. Land surface altitude in feet above sea level. Altitude, altitude of potentiometric surface in feet above sea level which refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929). Status; R, recently pumped, otherwise static conditions or no data. Period of available water-level and water-chemistry, including temperature logging, data: year or multiple year period of data collection. Type of data included in this report for each well: GEO, geologic cross sections; WL, water level; WC, water chemistry; T, temperature logging. —, no data. Data sources: USGS, U.S. Geological Survey; CADMG, California Department of Conservation Division of Mines and Geology; CADWR, California Department of Water Resources; VOM, Valley of the Moon Water District; COS, City of Sonoma]

State well No.	USGS site identification No.	Depth drilled	Depth cased	Depth of top perfo-ration	Depth of bot-tom perfo-ration	Land surface altitude	Water level Spring 2003 (except where noted)				Period of data included in this report		Type of data included in this report	Data source
							Date	Depth	Altitude	Status	Water level	Chemistry		
5N/5W-7G2	381745122271301	405	395	100	395	98	05/20/03	24.8	73	—	1998–2004	—	WL	USGS, COS
5N/5W-8L4[1]	—	—	—	—	—	108	04/21/03	85	23	—	2000–04	—	WL	COS
5N/5W-8P2	381722122261901	250	245	170	240	100	05/13/03	119.3	[2]–19	R	1974–2003	1974–2002	WL, WC	USGS, CADWR
5N/5W-8Q1	381722122261001	—	500	—	—	107	—	—	—	—	1950–62	—	WL	USGS
5N/5W-17B2	—	493	493	330	470	88	03/27/03	58.2	30	—	1980–2004	—	WL	CADWR
5N/5W-17C1	381700122261401	70	64	—	—	85	—	—	—	—	1950–94	—	WL	USGS, CADWR
5N/5W-17E1[1]	381650122262701	861	666	473	646	69	05/20/03	85.3	–16	—	2003	—	WL, T	USGS
5N/5W-18D2	—	75	75	—	—	—	—	—	—	—	—	1969–2002	WC	CADWR
5N/5W-18R1	381618122265501	150	[4]134	15	—	43	05/06/03	2.6	40	—	1966–2004	—	WL, T	CADWR, USGS
5N/5W-18R2	381617122270001	—	[4]25	—	—	—	—	—	—	—	1950–52	—	WL	USGS
5N/5W-18R4[1]	—	—	—	—	—	50	04/21/03	17.5	32	—	1999–2004	—	WL	COS
5N/5W-19C3[1]	—	220	220	67	220	35	04/21/03	31	4	—	1999–2004	—	WL	COS
5N/5W-19L6[1]	—	—	—	—	—	38	04/21/03	23	15	—	1999–2004	—	WL	COS
5N/5W-19M1[1]	381539122274601	—	[4]150	—	—	35	—	—	—	—	—	2003	WC	USGS
5N/5W-19N1[1]	381528122273601	160	153	69	139	32	—	—	—	—	—	2003	WC	USGS
5N/5W-20J2[1]	381540122254701	418	414	114	414	30	07/15/03	85.1	[2]–55	R	2003	2003	WL, WC	USGS
5N/5W-20M1	381544122263801	770	770	210	770	30	—	—	—	—	—	2004	GEO, WC	USGS, CADWR
5N/5W-20P2[1]	381530122261301	—	—	—	—	26	—	—	—	—	—	2003	WC	USGS
5N/5W-20R1	381540122254702	504	449	—	—	32	07/15/03	75.7	[2]–44	—	2003	1969–2004	WL, WC, T	USGS, CADWR

See footnotes at end of table.

Appendix C. Construction data, and spring 2003 water levels for selected wells used for geologic cross sections, water-level monitoring, chemistry sampling, and temperature logging in the Sonoma Valley, Sonoma County, California—Continued.

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State well No.	USGS site identification No.	Depth drilled	Depth cased	Depth of top perfo-ration	Depth of bot-tom perfo-ration	Land surface altitude	Water level Spring 2003 (except where noted)				Period of data included in this report		Type of data included in this report	Data source
							Date	Depth	Altitude	Status	Water level	Chemistry		
5N/5W-21A1	381607122244901	—	[4]786	—	—	—	—	—	—	—	1950–52	—	WL	USGS
5N/5W-21K1[1]	—	508	507	307	507	69	04/21/03	131	–62	—	1999–2004	—	WL	COS
5N/5W-21P3[1]	381530122251601	—	[4]170	—	—	60	05/22/03	138.4	[2]–78	R	2003	2003	WL, WC	USGS
5N/5W-21P4[1]	381530122251602	500	500	400	500	60	—	—	—	—	—	2003	WC	USGS
5N/5W-21P5[1]	—	508	508	158	478	75	—	—	—	—	—	—	GEO	CADWR
5N/5W-22L1	—	542	—	—	—	—	—	—	—	—	—	—	GEO	CADWR
5N/5W-28N1	381442122253601	130	110	—	—	11	—	—	—	—	1946–70	1972–2002	WL, WC	USGS, CADWR
5N/5W-28P4[1]	381448122250501	500	500	400	500	28	09/04/03	116.9	[2]–89	—	2003	2003	WL, WC	USGS
5N/5W-28R1	381450122243701	280	280	80	270	70	05/13/03	46.6	[2]23	R	2003	1971–2003	WL, WC	USGS, CADWR
5N/5W-28R5[1]	381443122243801	—	[4]245	—	—	60	—	—	—	—	—	2003	WC	USGS
5N/5W-29N1	381452122264801	—	[4]100	—	—	16	—	—	—	—	1951–84	—	WL	USGS, CADWR
5N/5W-29P3[1]	381444122262101	—	[4]70	—	—	10	08/15/03	13.1	[2]–3	R	2003	2003	WL, WC	USGS
5N/5W-29P4[1]	381439122261101	—	[4]200	—	—	10	—	—	—	—	—	2003	WC	USGS
5N/5W-29Q1[1]	—	600	500	380	500	7	—	—	—	—	—	—	GEO	CADWR
5N/5W-29R6[1]	381445122254501	—	[4]120	—	—	10	—	—	—	—	—	2003	WC	USGS
5N/5W-29R7[1]	381443122254201	836	821	626	816	10	—	—	—	—	—	2003	WC	USGS
5N/5W-29R8[1]	381448122254201	—	[4]730	—	—	14	—	—	—	—	—	2003	WC	USGS
5N/5W-30C1[1]	381517122271601	—	[4]120	—	—	24	—	—	—	—	—	2003	WC	USGS
5N/5W-30H1[1]	381509122264801	356	104	24	104	20	05/13/03	12.9	[2]7	R	2003	2003	WL, WC	USGS
5N/5W-30J3	—	80	—	—	—	16	—	—	—	—	1965–2000	—	WL	CADWR
5N/5W-30M1[1]	381456122274001	—	[4]180	—	—	20	—	—	—	—	—	2003	WC	USGS

See footnotes at end of table.

Appendix C. Construction data, and spring 2003 water levels for selected wells used for geologic cross sections, water-level monitoring, chemistry sampling, and temperature logging in the Sonoma Valley, Sonoma County, California—Continued.

[State well No.: See well-numbering diagram in text. See figures 9, 15, 18, 19, 26, and 34 for site locations. USGS (U.S. Geological Survey) identification number: the unique number for each site in USGS NWIS (National Water Information System) database. Depths in feet below land surface. Land surface altitude in feet above sea level. Altitude, altitude of potentiometric surface in feet above sea level which refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929). Status; R, recently pumped, otherwise static conditions or no data. Period of available water-level and water-chemistry, including temperature logging, data: year or multiple year period of data collection. Type of data included in this report for each well: GEO, geologic cross sections; WL, water level; WC, water chemistry; T, temperature logging. —, no data. Data sources: USGS, U.S. Geological Survey; CADMG, California Department of Conservation Division of Mines and Geology; CADWR, California Department of Water Resources; VOM, Valley of the Moon Water District; COS, City of Sonoma]

State well No.	USGS site identification No.	Depth drilled	Depth cased	Depth of top perforation	Depth of bottom perforation	Land surface altitude	Water level Spring 2003 (except where noted)				Period of data included in this report		Type of data included in this report	Data source
							Date	Depth	Altitude	Status	Water level	Chemistry		
5N/5W-30R1[1]	381447122264301	—	—	—	—	13	—	—	—	—	—	2003	WC	USGS
5N/5W-30R2[1]	381439122264901	—	—	—	—	10	—	—	—	—	—	2003	WC	USGS
5N/5W-31J1[1]	381411122265201	450	450	370	450	7	—	—	—	—	—	2003	WC	USGS
5N/5W-31J2[1]	381404122264301	800	800	577	800	5	—	—	—	—	—	2003	WC	USGS
5N/5W-31P2[1]	381352122271901	—	[4]125	—	—	11	—	—	—	—	—	2003	WC	USGS
5N/5W-31P3[1]	381357122271801	300	175	60	175	10	08/20/03	17.4	[2]–7	R	2003	2003	WL, WC	USGS
5N/5W-32C1[1]	381438122262101	—	[4]150	—	—	9	—	—	—	—	—	2003	WC	USGS
5N/5W-33K7[1]	381408122250501	—	[4]300	—	—	5	08/19/03	6.0	[2]–1	—	2003	2003	WL, WC	USGS
5N/5W-33K8[1]	381415122251501	—	[4]60	—	—	5	—	—	—	—	—	2003	WC	USGS
5N/5W-33Q1[1]	381359122245001	—	—	—	—	8	08/13/03	7.6	[2]0	—	2003	2003	WL, WC	USGS
5N/5W-33R1[1]	381352122243901	—	—	—	—	12	07/15/03	Flowing	12	—	2003	2003	WL, WC	USGS
5N/5W-34M1[1]	381410122242301	—	[4]180	—	—	50	—	—	—	—	—	2003	WC	USGS
5N/6W-1J3	381814122275901	460	440	140	440	125	—	—	—	—	1996–2004	—	WL	VOM
5N/6W-1N1[1]	381809122284301	580	555	445	545	118	05/21/03	31.4	87	—	2002–04	2002–04	GEO, WL, WC, T	USGS, VOM
5N/6W-2A6[1]	381849122285901	1,000	—	—	—	105	—	—	—	—	—	2004	WC	USGS
5N/6W-2K1[1]	381819122291401	815	815	360	800	102	05/14/03	24.9	77	—	2003	—	WL	USGS
5N/6W-2M1[1]	—	—	[5]180	—	—	134	05/27/03	90.5	44	—	2002–04	—	WL	VOM
5N/6W-2N2	—	171	171	150	167	135	04/03/03	86.8	48	—	1974–2004	1972–2003	WL, WC	CADWR
5N/6W-2P2	381808122293801	425	360	60	350	118	—	—	—	—	2000–04	2004	WL, WC	USGS, VOM
5N/6W-2P3[1]	381809122293301	—	—	—	—	111	05/21/03	42	69	—	1999–2004	2002	WL, WC	USGS, VOM
5N/6W-3E1	381834122305401	790	790	690	790	277	—	—	—	—	—	2002–04	WC	USGS

See footnotes at end of table.

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State well No.	USGS site identification No.	Depth drilled	Depth cased	Depth of top perfo-ration	Depth of bot-tom perfo-ration	Land surface altitude	Water level Spring 2003 (except where noted)				Period of data included in this report		Type of data included in this report	Data source
							Date	Depth	Altitude	Status	Water level	Chemistry		
5N/6W-8B1	381749122323201	380	380	90	380	968	—	—	—	—	—	2004	WC	USGS
5N/6W-9J1[1]	—	—	[5]150	—	—	325	05/22/03	34.5	[2]290	—	1999–2004	—	WL	VOM
5N/6W-10G2[1]	—	485	485	365	485	185	05/22/03	144	41	—	2000–04	—	WL	VOM
5N/6W-10G3[1]	—	—	[5]312	—	—	200	05/22/03	173	27	—	2000–04	—	WL	VOM
5N/6W-10K1	—	239	—	—	—	—	—	—	—	—	—	—	GEO	CADWR
5N/6W-10K2[1]	—	740	735	235	735	207	05/28/03	224	–17	—	2002–04	—	WL	VOM
5N/6W-10L1[1]	—	725	708	168	708	213	—	—	—	—	—	—	GEO	CADWR
5N/6W-10Q1[1]	—	595	595	495	595	185	05/22/03	172.5	12	—	2001–04	—	WL	VOM
5N/6W-10Q2[1]	381712122301901	600	600	300	600	175	—	—	—	—	—	2002	WC	USGS
5N/6W-10Q3[1]	—	—	[5]210	—	—	175	05/29/03	190.1	–15	—	1999–2004	—	WL	VOM
5N/6W-10Q4[1]	—	—	[5]240	—	—	180	05/28/03	178.5	2	—	1999–2004	—	WL	VOM
5N/6W-11C3[1,6]	381758122293701	730	92	72	82	115	05/22/03	31	[7]84	—	2000–04	—	WL, T	USGS, VOM
5N/6W-11C4[1,6]	381758122293702	730	562	542	552	115	05/22/03	128.6	[2]–14	—	2000–04	—	WL, T	USGS, VOM
5N/6W-11C5[1,6]	381758122293703	730	674	654	664	115	05/22/03	131.6	[7]–17	—	2000–04	—	GEO, WL, T	USGS, VOM
5N/6W-11F1[1]	—	—	[5]146	—	—	108	06/02/03	25	83	—	2000–04	—	WL	VOM
5N/6W-11P2[1]	—	—	[5]90	—	—	120	05/27/03	39	81	—	2000–04	—	WL	VOM
5N/6W-12C1	381753122282501	730	730	530	730	95	04/23/03	12	83	—	1998–2004	—	WL	COS
5N/6W-12F1	—	113	113	—	—	80	—	—	—	—	—	1969–2002	WC	CADWR
5N/6W-12M1	—	60	58	49	57	80	—	—	—	—	—	1972–2003	WC	CADWR
5N/6W-13C1	381657122282601	600	600	420	580	65	05/15/03	57.4	[2]8	R	1980–2003	—	WL	USGS, CADWR

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State well No.	USGS site identification No.	Depth drilled	Depth cased	Depth of top perfo-ration	Depth of bot-tom perfo-ration	Land surface altitude	Water level Spring 2003 (except where noted)				Period of data included in this report		Type of data included in this report	Data source
							Date	Depth	Altitude	Status	Water level	Chemistry		
5N/6W-14C1	381657122293801	—	[4]116	—	—	112	—	—	—	—	1950–62	—	WL	USGS
5N/6W-14F1	381641122293401	—	[4]48	—	—	92	—	—	—	—	1950–52	—	WL	USGS
5N/6W-14N1[1]	—	—	[5]84	—	—	96	05/29/03	37.6	58	—	2000–04	—	WL	VOM
5N/6W-14N2[1]	—	—	[5]86	—	—	98	05/28/03	34.8	63	—	2000–04	—	WL	VOM
5N/6W-14P1[1]	—	—	[5]165	—	—	92	05/28/03	27.5	64	—	2001–04	—	WL	VOM
5N/6W-14P2[1]	—	—	[5]90	—	—	88	05/29/03	29.3	59	—	2000–04	—	WL	VOM
5N/6W-14Q2[1]	—	—	—	—	—	77	05/22/03	21.5	56	—	2000–04	—	WL	VOM
5N/6W-15R1[1]	—	—	[5]355	—	—	110	04/15/03	62	48	—	1999–2004	—	WL	VOM
5N/6W-24K2[1]	381544122280801	—	[4]130	—	—	38	—	—	—	—	—	2003	WC	USGS
5N/6W-24Q1[1]	381527122281601	—	[4]140	—	—	35	—	—	—	—	—	2003	WC	USGS
5N/6W-25P2	381438122283401	640	640	175	640	37	—	—	—	—	—	1969–2003	WC	USGS, CADWR
5N/6W-26A1[1]	381518122290401	—	[4]250	—	—	47	—	—	—	—	—	2003	WC	USGS
5N/6W-26B1	381517122291101	—	[4]100	—	—	53	—	—	—	—	—	2003	WC	USGS
5N/6W-36C2[1]	—	620	620	240	620	34	—	—	—	—	—	—	GEO	CADWR
6N/6W-5M1[1]	—	500	500	300	500	—	—	—	—	—	—	—	GEO	CADWR
6N/6W-9A1	382307122311301	265	258	41	258	320	05/29/03	9.1	311	—	2003	2003–04	WL, WC	USGS
6N/6W-9A2[1]	—	—	[5]200	—	—	355	05/27/03	8.5	346	—	2001–04	—	WL	VOM
6N/6W-9B1[1]	—	—	[5]125	—	—	395	05/27/03	29	366	—	2001–04	—	WL	VOM
6N/6W-9Q1	382227122312501	96	96	76	86	275	05/14/03	7.5	268	—	1980–2004	—	WL	USGS, CADWR
6N/6W-10M2	—	228	224	84	224	320	—	—	—	—	1974–2000	1975–2002	WL, WC	CADWR
6N/6W-10P1[1]	—	805	660	280	660	—	—	—	—	—	—	—	GEO	CADWR

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[State well No.: See well-numbering diagram in text. See figures 9, 15, 18, 19, 26, and 34 for site locations. USGS (U.S. Geological Survey) identification number: the unique number for each site in USGS NWIS (National Water Information System) database. Depths in feet below land surface. Land surface altitude in feet above sea level. Altitude, altitude of potentiometric surface in feet above sea level which refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929). Status; R, recently pumped, otherwise static conditions or no data. Period of available water-level and water-chemistry, including temperature logging, data: year or multiple year period of data collection. Type of data included in this report for each well: GEO, geologic cross sections; WL, water level; WC, water chemistry; T, temperature logging. —, no data. Data sources: USGS, U.S. Geological Survey; CADMG, California Department of Conservation Division of Mines and Geology; CADWR, California Department of Water Resources; VOM, Valley of the Moon Water District; COS, City of Sonoma]

State well No.	USGS site identification No.	Depth drilled	Depth cased	Depth of top perfo-ration	Depth of bot-tom perfo-ration	Land surface altitude	Water level Spring 2003 (except where noted)				Period of data included in this report		Type of data included in this report	Data source
							Date	Depth	Altitude	Status	Water level	Chemistry		
6N/6W-16B3[1]	382219122312501	—	[4]124	—	—	270	05/29/03	18.8	251	—	2000–04	2002	WL, WC	USGS, VOM
6N/6W-21R1[1]	—	1,430	1,430	—	—	320	—	—	—	—	—	—	GEO	CADMG
6N/6W-22J1[1]	382056122300501	—	[4]165	—	—	210	05/21/03	23.9	186	—	2003	—	WL	USGS
6N/6W-22Q1[1]	382045122302901	680	680	180	600	190	05/21/03	25.6	[2]164	R	2003	2003	WL, WC	USGS
6N/6W-22R2	—	175	159	—	—	200	03/27/03	Flowing	200	—	1980–2004	—	WL	CADWR
6N/6W-23M2	—	233	188	—	—	215	—	—	—	—	1974–2000	—	WL	CADWR
6N/6W-26E1	—	304	241	—	—	180	—	—	—	—	—	1969–2003	WC	CADWR
6N/6W-26K3[1]	—	—	[5]260	—	—	350	05/28/03	172.5	178	—	2001–04	—	WL	VOM
6N/6W-26Q10[1]	—	102	102	—	—	230	07/11/03	65.7	[2]164	—	2003–04	—	WL	VOM
6N/6W-34J1[1]	—	—	[5]68	—	—	160	05/28/03	21.5	138	—	1999–2004	—	WL	VOM
6N/6W-35A1[1]	381933122290801	363	363	95	363	260	05/21/03	93.5	167	—	1996–2004	—	WL	USGS, VOM
6N/6W-35A2[1]	—	200	200	20	200	260	05/22/03	100.5	160	—	2000–04	—	WL	VOM
6N/6W-35H1[1]	381927122285701	[8]141	[9]126	124	—	180	—	—	—	—	1996–2004	—	WL	VOM
6N/6W-35K1[1]	381916122292201	—	—	—	—	115	—	—	—	—	—	2004	WC	USGS
6N/6W-36J1	381906122274901	400	250	170	250	300	—	—	—	—	—	2004	WC	USGS
6N/6W-36M2[1]	381913122284001	—	214	140	214	230	05/21/03	120.9	109	—	1996–2004	—	WL	USGS, VOM
6N/6W-36M3[1]	—	—	[5]80	—	—	195	05/28/03	66.5	128	—	1999–2004	—	WL	VOM
6N/6W-36P1[1]	—	—	[5]90	—	—	185	06/02/03	50	135	—	2000–04	—	WL	VOM
6N/7W-2J3	382832122354301	510	510	330	510	1001	—	—	—	—	—	2004	WC	USGS
7N/6W-19N1	—	149	122	30	—	465	05/06/03	4.2	461	—	1950–2004	—	WL	CADWR
7N/6W-22E1	382614122310201	336	333	63	333	1190	05/14/03	12.7	[2]1,177	—	2003	2003	WL, WC	USGS

See footnotes at end of table.

Appendix C. Construction data, and spring 2003 water levels for selected wells used for geologic cross sections, water-level monitoring, chemistry sampling, and temperature logging in the Sonoma Valley, Sonoma County, California—Continued.

[State well No.: See well-numbering diagram in text. See figures 9, 15, 18, 19, 26, and 34 for site locations. USGS (U.S. Geological Survey) identification number: the unique number for each site in USGS NWIS (National Water Information System) database. Depths in feet below land surface. Land surface altitude in feet above sea level. Altitude, altitude of potentiometric surface in feet above sea level which refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929). Status; R, recently pumped, otherwise static conditions or no data. Period of available water-level and water-chemistry, including temperature logging, data: year or multiple year period of data collection. Type of data included in this report for each well: GEO, geologic cross sections; WL, water level; WC, water chemistry; T, temperature logging. —, no data. Data sources: USGS, U.S. Geological Survey; CADMG, California Department of Conservation Division of Mines and Geology; CADWR, California Department of Water Resources; VOM, Valley of the Moon Water District; COS, City of Sonoma]

State well No.	USGS site identification No.	Depth drilled	Depth cased	Depth of top perforation	Depth of bottom perforation	Land surface altitude	Water level Spring 2003 (except where noted)				Period of data included in this report		Type of data included in this report	Data source
							Date	Depth	Altitude	Status	Water level	Chemistry		
7N/6W-28M1	382517122321001	400	395	215	395	522	—	—	—	—	—	2004	WC	USGS
7N/6W-29E1[1]	—	400	400	180	400	—	—	—	—	—	—	—	GEO	CADWR
7N/6W-29M2[1]	382512122331101	—	372	50	372	427	—	—	—	—	—	2004	WC	USGS
7N/6W-29P1	382445122324901	112	112	63	70	410	05/29/03	25.7	384	—	2003	1971–2003	WL, WC	USGS, CADWR
7N/6W-29P3[1]	382500122330501	347	340	100	260	415	05/13/03	8.0	407	—	2003	2003	WL, WC	USGS
7N/6W-32F2	—	76	73	57	73	399	—	—	—	—	1980–96	—	WL	CADWR
7N/6W-32H1	382434122322801	406	[4]406	100	—	415	05/22/03	1.7	413	—	1980–2003	—	WL	USGS, CADWR
7N/6W-32P1[1]	—	805	805	700	805	—	—	—	—	—	—	—	GEO	CADWR
7N/7W-24A1	382636122344801	622	[10]585	—	—	560	05/13/03	36.0	524	—	1980–2004	2003	WL, WC	USGS, CADWR
7N/7W-24J1	—	78	—	—	—	490	—	—	—	—	1980–2001	—	WL	CADWR

[1]Projected state well number, verification pending.

[2]Measurement not included in the hydraulic-head contouring on figure 19.

[3]Drill depth of reconstructed well 236 ft. in 1999.

[4]Reported well depth; depth cased unknown.

[5]Well depth reported by owner via the Sonoma Ecology Center (SEC); depth cased unknown.

[6]One of three water-level observation wells constructed within a single borehole.

[7]Measurements for 5N/6W-11C3 and -11C5 averaged for hydraulic head contouring on figure 19.

[8]Extent of 1996 video log, but hole extends further to unknown depth.

[9]Bottom of sheared off casing per 1996 video log.

[10]Reported well and casing depth in 1990.

Appendix D. Field measurements and laboratory analyses of samples from streamflow-measurement stations, springs, and ground-water wells, Sonoma Valley, Sonoma County, California, 2002–04.

[See figure 20 for location of streamflow-measurement stations, springs, and wells. USGS (U.S. Geological Survey) identification number: the unique number for each site in USGS NWIS (National Water Information System) database. Collecting and analyzing agency: USGS, U.S. Geological Survey; CADWR, California Department of Water Resources. Parameter code, in brackets, is a five-digit number in the USGS computerized data system, National Water Information System (NWIS), used to uniquely identify a specific constituent or property. CADWR conductance measurements are referred to as electrical conductance (EC). CADWR alkalinities are laboratory values. $CaCO_3$, calcium carbonate; µS/cm, microsiemen per centimeter at 25°C; °C, degree Celsius; mg/L, milligram per liter; µg/L, microgram per liter; E, value estimated by the USGS National Water Quality Laboratory, Denver Colorado; (L), measured in laboratory; <, actual value is less than value shown; —, no data]

Stream site identifier or State well No. (abbreviated or local identifier)	USGS identification No.	Sample date	Collecting and analyzing agency	Oxygen, dissolved (mg/L) [00300]	pH, field (standard units) [00400]	Specific conductance, field (µS/cm) [00095]
Streamflow-measurement stations						
Sonoma Creek at Kenwood (KW)	382414122330701	11-20-2002	USGS	10.1	8.0	416
Sonoma Creek at Lawndale Road (S5)	382403122331101	06-06-2003	USGS	9.6	7.9	379
Sonoma Creek at Agua Caliente (S10)	11458500	11-19-2002	USGS	8.7	7.6	380
		06-05-2003	USGS	1.2	8.1	324
Springs						
6N/6W-19PS1	382045122335601	06-02-2003	USGS	—	7.2	293
7N/6W-22JS1	382602122301601	06-02-2003	USGS	—	6.8	154
Wells						
4N/5W-2E1	381322122231801	10-26-2004	USGS	—	7.9 (L)	[1]1,680
4N/5W-2F1	381326122225601	06-06-2003	USGS	2.0	7.2	[1]1,270
5N/5W-08P2	—	08-27-2002	CADWR	—	[2]7.2	[2]499
5N/5W-18D2	—	08-27-2002	CADWR	—	[2]6.6	[2]582
		08-30-2004	CADWR	—	[2]7.2	[2]643 (L)
5N/5W-20M1	381544122263801	10-20-2004	USGS	0.1	8.2	734
5N/5W-20R1	—	09-16-2003	CADWR	—	[2]7.6	[2]820
5N/5W-28N1	—	09-04-2002	CADWR	—	[2]7.3	[1,2]1,710
5N/5W-28R1	—	08-27-2002	CADWR	—	[2]7.7	[1,2]1,120
	—	09-01-2004	CADWR	—	[1,2]8.7	[1,2]1,230
5N/5W-30H1	381509122264801	06-05-2003	USGS	0.3	6.9	348
5N/6W-1N1	381809122284301	11-22-2002	USGS	0.6	7.7	231
5N/6W-2A6	381849122285901	10-20-2004	USGS	—	8.3	[1]2,020
5N/6W-2N2	—	09-16-2003	CADWR	—	—	[2]329 (L)
5N/6W-2P2	381808122293801	10-19-2004	USGS	3.5	6.8	345
5N/6W-2P3	381809122293301	11-21-2002	USGS	6.3	6.7	328
5N/6W-3E1	381834122305401	11-20-2002	USGS	1.1	7.4	378
		10-26-2004	USGS	—	7.4 (L)	383

See footnotes at end of table

Appendix D. Field measurements and laboratory analyses of samples from streamflow-measurement stations, springs, and ground-water wells, Sonoma Valley, Sonoma County, California, 2002–04—Continued.

[See figure 20 for location of streamflow-measurement stations, springs, and wells. USGS (U.S. Geological Survey) identification number: the unique number for each site in USGS NWIS (National Water Information System) database. Collecting and analyzing agency: USGS, U.S. Geological Survey; CADWR, California Department of Water Resources. Parameter code, in brackets, is a five-digit number in the USGS computerized data system, National Water Information System (NWIS), used to uniquely identify a specific constituent or property. CADWR conductance measurements are referred to as electrical conductance (EC). CADWR alkalinities are laboratory values. $CaCO_3$, calcium carbonate; µS/cm, microsiemen per centimeter at 25°C; °C, degree Celsius; mg/L, milligram per liter; µg/L, microgram per liter; E, value estimated by the USGS National Water Quality Laboratory, Denver Colorado; (L), measured in laboratory; <, actual value is less than value shown; —, no data]

Stream site identifier or State well No. (abbreviated or local identifier)	Sample date	Temperature, water °C [00010]	Hardness, total (mg/L as $CaCO_3$) [00900]	Calcium, dissolved (mg/L) [00915]	Magnesium, dissolved (mg/L) [00925]	Potassium, dissolved (mg/L) [00935]	Sodium, dissolved (mg/L) [00930]
			Streamflow-measurement stations				
Sonoma Creek at Kenwood (KW)	11-20-2002	10.5	190	21.1	33.5	1.62	14.7
Sonoma Creek at Lawndale Road (S5)	06-06-2003	16.0	180	20.5	31.6	1.22	11.7
Sonoma Creek at Agua Caliente (S10)	11-19-2002	11.5	130	21.3	19.6	2.49	25.3
	06-05-2003	17.5	140	21.3	21.7	2.23	15.7
			Springs				
6N/6W-19PS1	06-02-2003	16.0	140	25.6	17.3	2.23	8.93
7N/6W-22JS1	06-02-2003	16.0	55	12.2	6.02	2.05	9.02
			Wells				
4N/5W-2E1	10-26-2004	21.0	180	36.5	21.6	3.03	270
	06-06-2003	21.5	290	58.3	35.2	3.22	176
5N/5W-8P2	08-27-2002	[2]21.7	[2]50	[2]10	[2]6	[2]7.3	[2]83
5N/5W-18D2	08-27-2002	[2]18.9	[2]198	[2]33	[2]28	[2]2	[2]50
	08-30-2004	[2]19.3	[2]180	[2]31	[2]25	[2]1.8	[2]44
5N/5W-20M1	10-20-2004	25.5	22	6.26	1.51	2.29	177
5N/5W-20R1	09-16-2003	[2]19.4	[2]23	[2]6	[2]2	[2]1.6	[2]199
5N/5W-28N1	09-04-2002	[2]21.5	[2]413	[2]50	[2]70	[2]5.2	[2]169
5N/5W-28R1	08-27-2002	[2]21.1	[2]102	[2]21	[2]12	[2]1.6	[2]232
	09-01-2004	[2]20.0	[2]122	[2]24	[2]15	[2]1.6	[2]196
5N/5W-30H1	06-05-2003	19.0	130	14.7	21.5	2.79	25.1
5N/6W-1N1	11-22-2002	27.5	48	9.65	5.84	6.2	23.4
5N/6W-2A6	10-20-2004	41.5	23	9.01	0.078	20.2	381
5N/6W-2N2	09-16-2003	—	[2]86	[2]18	[2]10	[2]1.1	[2]33
5N/6W-2P2	10-19-2004	19.5	120	25.1	14.7	1.32	28.5
5N/6W-2P3	11-21-2002	18.5	140	26.1	17.2	1.13	22.9
5N/6W-3E1	11-20-2002	26.5	89	24.5	6.72	3.09	46.5
	10-26-2004	27.5	98	27.6	7.07	3.52	49.0

See footnotes at end of table

Appendix D. Field measurements and laboratory analyses of samples from streamflow-measurement stations, springs, and ground-water wells, Sonoma Valley, Sonoma County, California, 2002–04—Continued.

[See figure 20 for location of streamflow-measurement stations, springs, and wells. USGS (U.S. Geological Survey) identification number: the unique number for each site in USGS NWIS (National Water Information System) database. Collecting and analyzing agency: USGS, U.S. Geological Survey; CADWR, California Department of Water Resources. Parameter code, in brackets, is a five-digit number in the USGS computerized data system, National Water Information System (NWIS), used to uniquely identify a specific constituent or property. CADWR conductance measurements are referred to as electrical conductance (EC). CADWR alkalinities are laboratory values. $CaCO_3$, calcium carbonate; µS/cm, microsiemen per centimeter at 25°C; °C, degree Celsius; mg/L, milligram per liter; µg/L, microgram per liter; E, value estimated by the USGS National Water Quality Laboratory, Denver Colorado; (L), measured in laboratory; <, actual value is less than value shown; —, no data]

Stream site identifier or state well No. (abbreviated or local identifier)	Sample date	Alkalinity, field (mg/L as $CaCO_3$) [39086]	Bicarbonate (mg/L) [00453]	Bromide, dissolved (mg/L) [71870]	Chloride, dissolved (mg/L) [00940]	Fluoride, dissolved (mg/L) [00950]	Iodide, dissolved (mg/L) [71865]
Streamflow-measurement stations							
Sonoma Creek at Kenwood (KW)	11-20-2002	184	222	—	10.9	<0.2	—
Sonoma Creek at Lawndale Road (S5)	06-06-2003	167	203	0.02	8.64	<0.2	0.003
Sonoma Creek at Agua Caliente (S10)	11-19-2002	127	153	—	23.7	<0.2	—
	06-05-2003	130	160	E0.01	10.7	<0.2	0.003
Springs							
6N/6W-19PS1	06-02-2003	136	166	0.02	5.01	<0.2	<0.002
7N/6W-22JS1	06-02-2003	60	74	0.03	3.21	<0.2	<0.002
Wells							
4N/5W-2E1	10-26-2004	—	—	0.99	191	0.1	1.14
4N/5W-2F1	06-06-2003	274	335	0.50	214	0.2	0.225
5N/5W-8P2	08-27-2002	[2]165	[2,3]201	—	[2]38	—	—
5N/5W-18D2	08-27-2002	[2]184	[2,3]224	—	[2]44	—	—
	08-30-2004	[2]177	[2,3]216	—	[2]44	—	—
5N/5W-20M1	10-20-2004	[4]381	[3]451	0.10	25.5	0.4	0.138
5N/5W-20R1	09-16-2003	[2]380	[2,3]463	—	[2]57	—	—
5N/5W-28N1	09-04-2002	[2]157	[2,3]191	—	[1,2]415	—	—
5N/5W-28R1	08-27-2002	[2]382	[2,3]466	—	[2]122	—	—
	09-01-2004	[2]349	[2,3]426	—	[2]134	—	—
5N/5W-30H1	06-05-2003	119	146	0.10	25.9	0.2	0.007
5N/6W-1N1	11-22-2002	94	114	—	8.9	0.3	—
5N/6W-2A6	10-20-2004	—	—	2.44	[1]578	[1]8.5	1.61
5N/6W-2N2	09-16-2003	[2]116	[2,3]141	—	[2]18	—	—
5N/6W-2P2	10-19-2004		[3]150	0.12	23.0	0.2	0.002
5N/6W-2P3	11-21-2002	132	160	—	18.6	0.2	—
5N/6W-3E1	11-20-2002	171	208	—	8.05	0.2	—
	10-26-2004	—	—	0.16	7.70	0.2	0.010

See footnotes at end of table

Appendix D. Field measurements and laboratory analyses of samples from streamflow-measurement stations, springs, and ground-water wells, Sonoma Valley, Sonoma County, California, 2002–04—Continued.

[See figure 20 for location of streamflow-measurement stations, springs, and wells. USGS (U.S. Geological Survey) identification number: the unique number for each site in USGS NWIS (National Water Information System) database. Collecting and analyzing agency: USGS, U.S. Geological Survey; CADWR, California Department of Water Resources. Parameter code, in brackets, is a five-digit number in the USGS computerized data system, National Water Information System (NWIS), used to uniquely identify a specific constituent or property. CADWR conductance measurements are referred to as electrical conductance (EC). CADWR alkalinities are laboratory values. $CaCO_3$, calcium carbonate; µS/cm, microsiemen per centimeter at 25°C; °C, degree Celsius; mg/L, milligram per liter; µg/L, microgram per liter; E, value estimated by the USGS National Water Quality Laboratory, Denver Colorado; (L), measured in laboratory; <, actual value is less than value shown; —, no data]

Stream site identifier or state well No. (abbreviated or local identifier)	Sample date	Silica, dissolved (mg/L) [00955]	Sulfate, dissolved (mg/L) [00945]	Solids, sum of constituents, dissolved (mg/L) [70301]	Solids, residue on evaporation at 180°C (mg/L) [70300]	Nitrogen, ammonia, dissolved (mg/L) [00608]	Nitrite plus nitrate, dissolved (mg/L) [00631]
Streamflow-measurement stations							
Sonoma Creek at Kenwood (KW)	11-20-2002	51.5	22.7	269	269	<0.04	0.71
Sonoma Creek at Lawndale Road (S5)	06-06-2003	42.7	17.6	240	245	<0.04	1.31
Sonoma Creek at Agua Caliente (S10)	11-19-2002	37.0	30.0	235	248	<0.04	<0.06
	06-05-2003	32.6	18.7	203	210	<0.04	0.25
Springs							
6N/6W-19PS1	06-02-2003	55.6	10.1	207	200	<0.04	<0.06
7N/6W-22JS1	06-02-2003	56.1	3.3	138	135	<0.04	2.12
Wells							
4N/5W-2E1	10-26-2004	27.9	239	—	1,000	—	—
4N/5W-2F1	06-06-2003	43.6	44.8	752	738	E0.03	2.39
5N/5W-8P2	08-27-2002	—	[2]31	—	[2]336	—	—
5N/5W-18D2	08-27-2002	—	[2]24	—	[2]385	—	—
	08-30-2004	—	[2]27	—	[2]389	—	—
5N/5W-20M1	10-20-2004	52.9	1.7	501	503	0.22	E0.06
5N/5W-20R1	09-16-2003	—	[2]4	—	[2]532	—	—
5N/5W-28N1	09-04-2002	—	[2]43	—	[2]1,062	—	—
5N/5W-28R1	08-27-2002	—	[2]58	—	[2]729	—	—
	09-01-2004	—	[2]63	—	[2]712	—	—
5N/5W-30H1	06-05-2003	75.3	13.1	257	247	<0.04	1.35
5N/6W-1N1	11-22-2002	81.3	4.3	197	193	0.07	<0.06
5N/6W-2A6	10-20-2004	99.5	40.5	—	1,230	—	—
5N/6W-2N2	09-16-2003	—	[2]20	—	[2]219	—	—
5N/6W-2P2	10-19-2004	67.8	14.8	265	255	<0.04	3.22
5N/6W-2P3	11-21-2002	60.6	18.4	256	260	E0.03	2.77
5N/6W-3E1	11-20-2002	50.9	11.4	255	260	0.11	0.06
	10-26-2004	54.7	12.0	—	269	—	—

See footnotes at end of table

Appendix D. Field measurements and laboratory analyses of samples from streamflow-measurement stations, springs, and ground-water wells, Sonoma Valley, Sonoma County, California, 2002–04—Continued.

[See figure 20 for location of streamflow-measurement stations, springs, and wells. USGS (U.S. Geological Survey) identification number: the unique number for each site in USGS NWIS (National Water Information System) database. Collecting and analyzing agency: USGS, U.S. Geological Survey; CADWR, California Department of Water Resources. Parameter code, in brackets, is a five-digit number in the USGS computerized data system, National Water Information System (NWIS), used to uniquely identify a specific constituent or property. CADWR conductance measurements are referred to as electrical conductance (EC). CADWR alkalinities are laboratory values. $CaCO_3$, calcium carbonate; µS/cm, microsiemen per centimeter at 25°C; °C, degree Celsius; mg/L, milligram per liter; µg/L, microgram per liter; E, value estimated by the USGS National Water Quality Laboratory, Denver Colorado; (L), measured in laboratory; <, actual value is less than value shown; —, no data]

Stream site identifier or state well No. (abbreviated or local identifier)	Sample date	Nitrate, dissolved (mg/L)	Nitrogen, nitrite, dissolved (mg/L) [00613]	Phosphorus, ortho-phosphate, dissolved (mg/L) [00671]	Arsenic, dissolved (µg/L) [01000]	Barium, dissolved (µg/L) [01005]
Streamflow-measurement stations						
Sonoma Creek at Kenwood (KW)	11-20-2002	[6]3.2	E0.004	0.07	3	—
Sonoma Creek at Lawndale Road (S5)	06-06-2003	[6]5.9	<0.008	0.05	<2	53
Sonoma Creek at Agua Caliente (S10)	11-19-2002	[6]<0.3	<0.008	0.05	3	—
	06-05-2003	[6]1.1	<0.008	E0.01	E1	50
Springs						
6N/6W-19PS1	06-02-2003	[6]<0.3	<0.008	0.05	<2	6.0
7N/6W-22JS1	06-02-2003	[6]9.5	<0.008	0.09	<2	3.0
Wells						
4N/5W-2E1	10-26-2004	—	—	—	3	121
4N/5W-2F1	06-06-2003	[6]10.8	<0.008	0.11	E1	194
5N/5W-8P2	08-27-2002	[2]0.3	—	—	—	—
5N/5W-18D2	08-27-2002	[2]34.6	—	—	—	—
	08-30-2004	[2]35	—	—	—	—
5N/5W-20M1	10-20-2004	[6]<0.3	<0.008	0.15	[1]17	69
5N/5W-20R1	09-16-2003	[2]0.8	—	—	—	—
5N/5W-28N1	09-04-2002	[2]32.7	—	—	—	—
5N/5W-28R1	08-27-2002	[2]0.3	—	—	—	—
	09-01-2004	[2]0.9	—	—	—	—
5N/5W-30H1	06-05-2003	[6]6.1	<0.008	0.23	3	36
5N/6W-1N1	11-22-2002	[6]<0.3	<0.008	0.09	[1]11	—
5N/6W-2A6	10-20-2004	—	—	—	3	20
5N/6W-2N2	09-16-2003	10	—	—	—	—
5N/6W-2P2	10-19-2004	[6]14.5	<0.008	0.11	3	64
5N/6W-2P3	11-21-2002	[6]12.5	<0.008	0.11	4	—
5N/6W-3E1	11-20-2002	[6]0.3	<0.008	0.2	2	—
	10-26-2004	—	—	—	—	—

See footnotes at end of table

Appendix D. Field measurements and laboratory analyses of samples from streamflow-measurement stations, springs, and ground-water wells, Sonoma Valley, Sonoma County, California, 2002–04—Continued.

[See figure 20 for location of streamflow-measurement stations, springs, and wells. USGS (U.S. Geological Survey) identification number: the unique number for each site in USGS NWIS (National Water Information System) database. Collecting and analyzing agency: USGS, U.S. Geological Survey; CADWR, California Department of Water Resources. Parameter code, in brackets, is a five-digit number in the USGS computerized data system, National Water Information System (NWIS), used to uniquely identify a specific constituent or property. CADWR conductance measurements are referred to as electrical conductance (EC). CADWR alkalinities are laboratory values. $CaCO_3$, calcium carbonate; µS/cm, microsiemen per centimeter at 25°C; °C, degree Celsius; mg/L, milligram per liter; µg/L, microgram per liter; E, value estimated by the USGS National Water Quality Laboratory, Denver Colorado; (L), measured in laboratory; <, actual value is less than value shown; —, no data]

Stream site identifier or state well No. (abbreviated or local identifier)	Sample date	Boron, dissolved (µg/L) [01020]	Iron, Dissolved (µg/L) [01046]	Lithium, dissolved (µg/L) [01130]	Manganese, dissolved (µg/L) [01056]
Streamflow-measurement stations					
Sonoma Creek at Kenwood (KW)	11-20-2002	60	E5	8.8	5.9
Sonoma Creek at Lawndale Road (S5)	06-06-2003	50	18	4.2	6.3
Sonoma Creek at Agua Caliente (S10)	11-19-2002	300	20	11.3	14.6
	06-05-2003	130	13	8.0	6.6
Springs					
6N/6W-19PS1	06-02-2003	20	E5	13.2	0.5
7N/6W-22JS1	06-02-2003	10	<8	0.9	<0.4
Wells					
4N/5W-2E1	10-26-2004	820	[1]310	68.3	[1]135
4N/5W-2F1	06-06-2003	290	14	76.6	33.7
5N/5W-8P2	08-27-2002	[2]600	—	—	—
5N/5W-18D2	08-27-2002	[2]200	—	—	—
	08-30-2004	[2]100	—	—	—
5N/5W-20M1	10-20-2004	[7]3,830	12	61.3	14.5
5N/5W-20R1	09-16-2003	[2, 7]4,300	—	—	—
5N/5W-28N1	09-04-2002	[2]800	—	—	—
5N/5W-28R1	08-27-2002	[2, 7]1,000	—	—	—
	09-01-2004	[2]700	—	—	—
5N/5W-30H1	06-05-2003	100	<8	12.6	6.8
5N/6W-1N1	11-22-2002	180	192	152	[1]190
5N/6W-2A6	10-20-2004	[7]15,700	41	1,650	11.9
5N/6W-2N2	09-16-2003	[2]<100	—	—	—
5N/6W-2P2	10-19-2004	70	E6	25.6	6.4
5N/6W-2P3	11-21-2002	70	E8	14.9	E1.2
5N/6W-3E1	11-20-2002	90	40	52.7	[1]123
	10-26-2004	—	65	—	—

See footnotes at end of table

Appendix D. Field measurements and laboratory analyses of samples from streamflow-measurement stations, springs, and ground-water wells, Sonoma Valley, Sonoma County, California, 2002–04—Continued.

[See figure 20 for location of streamflow-measurement stations, springs, and wells. USGS (U.S. Geological Survey) identification number: the unique number for each site in USGS NWIS (National Water Information System) database. Collecting and analyzing agency: USGS, U.S. Geological Survey; CADWR, California Department of Water Resources. Parameter code, in brackets, is a five-digit number in the USGS computerized data system, National Water Information System (NWIS), used to uniquely identify a specific constituent or property. CADWR conductance measurements are referred to as electrical conductance (EC). CADWR alkalinities are laboratory values. $CaCO_3$, calcium carbonate; µS/cm, microsiemen per centimeter at 25°C; °C, degree Celsius; mg/L, milligram per liter; µg/L, microgram per liter; E, value estimated by the USGS National Water Quality Laboratory, Denver Colorado; (L), measured in laboratory; <, actual value is less than value shown; —, no data]

Stream site identifier or State well No. (abbreviated or local identifier)	USGS identification No.	Sample date	Collecting and analyzing agency	Oxygen, dissolved (mg/L) [00300]	pH, field (standard units) [00400]	Specific conductance, field (µS/cm) [00095]
Wells						
5N/6W-10Q2	381712122301901	11-22-2002	USGS	0.4	7.4	344
5N/6W-12F1	381742122282901	08-27-2002	CADWR	—	[2]7.0	[2]875
	381742122282901	08-30-2004	CADWR	—	[2]7.4	[2]867
5N/6W-12M1	381729122284601	09-16-2003	CADWR	—	[2]7.2	[2]800
5N/6W-25P2	381438122283401	09-04-2002	CADWR	—	[2]8.0	[2]556
6N/6W-9A1	382307122311301	06-04-2003	USGS	1.1	7.2	229
		10-18-2004	USGS	0.2	7.3	211
6N/6W-10M2	382245122305801	08-27-2002	CADWR	—	[2]6.8	[2]488
		08-30-2004	CADWR	—	[2]7.2	[2]502
6N/6W-16B3	382219122312501	11-21-2002	USGS	2.8	[1]8.8	533
6N/6W-22Q1	382045122302901	06-04-2003	USGS	0.1	7.3	457
6N/6W-26E1	382017122295301	09-16-2003	CADWR	—	[2]6.8 (L)	[2]377 (L)
6N/6W-35K1	381916122292201	10-20-2004	USGS	—	7.5	[1]1,290
6N/6W-36J1	381906122274901	11-04-2004	USGS	2.9	7.4	222
7N/6W-22E1	382614122310201	06-02-2003	USGS	0.1	7.2	215
7N/6W-29P1	382445122324901	09-11-2003	CADWR	—	[1,2]6.2 (L)	[2]243 (L)
7N/6W-29P3	382500122330501	06-03-2003	USGS	1.2	7.3	382
7N/7W-24A1	382636122344801	06-03-2003	USGS	5.8	[1]6.1	124

See footnotes at end of table

Appendix D. Field measurements and laboratory analyses of samples from streamflow-measurement stations, springs, and ground-water wells, Sonoma Valley, Sonoma County, California, 2002–04—Continued.

[See figure 20 for location of streamflow-measurement stations, springs, and wells. USGS (U.S. Geological Survey) identification number: the unique number for each site in USGS NWIS (National Water Information System) database. Collecting and analyzing agency: USGS, U.S. Geological Survey; CADWR, California Department of Water Resources. Parameter code, in brackets, is a five-digit number in the USGS computerized data system, National Water Information System (NWIS), used to uniquely identify a specific constituent or property. CADWR conductance measurements are referred to as electrical conductance (EC). CADWR alkalinities are laboratory values. $CaCO_3$, calcium carbonate; µS/cm, microsiemen per centimeter at 25°C; °C, degree Celsius; mg/L, milligram per liter; µg/L, microgram per liter; E, value estimated by the USGS National Water Quality Laboratory, Denver Colorado; (L), measured in laboratory; <, actual value is less than value shown; —, no data]

Stream site identifier or State well No. (abbreviated or local identifier)	Sample date	Temperature, water °C [00010]	Hardness, total (mg/L as $CaCO_3$) [00900]	Calcium, dissolved (mg/L) [00915]	Magnesium, dissolved (mg/L) [00925]	Potassium, dissolved (mg/L) [00935]	Sodium, dissolved (mg/L) [00930]
Wells							
5N/6W-10Q2	11-22-2002	22.0	120	25.3	13.7	2.34	26
5N/6W-12F1	08-27-2002	[2]19.1	[2]263	[2]41	[2]39	[2]4.8	[2]92
	08-30-2004	[2]20.3	[2]215	[2]35	[2]31	[2]4.2	[2]84
5N/6W-12M1	09-16-2003	[2]18.3	[2]303	[2]39	[2]50	[2]4.4	[2]62
5N/6W-25P2	09-04-2002	[2]22.0	[2]12	[2]3	[2]1	[2]2.5	[2]122
6N/6W-9A1	06-04-2003	20.0	55	9.97	7.34	5.48	26.1
	10-18-2004	19.5	49	9.14	6.26	4.7	23.4
6N/6W-10M2	08-27-2002	[2]19.6	[2]134	[2]24	[2]18	[2]5.1	[2]48
	08-30-2004	[2]19.1	[2]108	[2]21	[2]15	[2]4.5	[2]44
6N/6W-16B3	11-21-2002	20.0	8	2.41	0.38	4.95	112
6N/6W-22Q1	06-04-2003	25.0	32	6.73	3.59	10.0	85.5
6N/6W-26E1	09-16-2003	—	[2]12	[2]3	[2]1	[2]7.9	[2]77
6N/6W-35K1	10-20-2004	34.5	130	39.7	6.33	17.5	208
6N/6W-36J1	11-04-2004	25.0	39	8.96	4.09	4.34	31.3
7N/6W-22E1	06-02-2003	15.5	79	10.8	12.5	4.07	14.8
7N/6W-29P1	09-11-2003	—	[2]100	[2]17	[2]14	[2]2.1	[2]17
7N/6W-29P3	06-03-2003	21.5	120	17.7	17.3	3.74	38.9
7N/7W-24A1	06-03-2003	21.0	33	6.76	3.83	3.43	12.5

See footnotes at end of table

Appendix D. Field measurements and laboratory analyses of samples from streamflow-measurement stations, springs, and ground-water wells, Sonoma Valley, Sonoma County, California, 2002–04—Continued.

[See figure 20 for location of streamflow-measurement stations, springs, and wells. USGS (U.S. Geological Survey) identification number: the unique number for each site in USGS NWIS (National Water Information System) database. Collecting and analyzing agency: USGS, U.S. Geological Survey; CADWR, California Department of Water Resources. Parameter code, in brackets, is a five-digit number in the USGS computerized data system, National Water Information System (NWIS), used to uniquely identify a specific constituent or property. CADWR conductance measurements are referred to as electrical conductance (EC). CADWR alkalinities are laboratory values. $CaCO_3$, calcium carbonate; µS/cm, microsiemen per centimeter at 25°C; °C, degree Celsius; mg/L, milligram per liter; µg/L, microgram per liter; E, value estimated by the USGS National Water Quality Laboratory, Denver Colorado; (L), measured in laboratory; <, actual value is less than value shown; —, no data]

Stream site identifier or state well No. (abbreviated or local identifier)	Sample date	Alkalinity, field (mg/L as $CaCO_3$) [39086]	Bicarbonate (mg/L) [00453]	Bromide, dissolved (mg/L) [71870]	Chloride, dissolved (mg/L) [00940]	Fluoride, dissolved (mg/L) [00950]	Iodide, dissolved (mg/L) [71865]
Wells							
5N/6W-10Q2	11-22-2002	162	197	—	9.12	0.2	—
5N/6W-12F1	08-27-2002	341	[2,3]416	—	[2]77	—	—
	08-30-2004	317	[2,3]387	—	[2]66	—	—
5N/6W-12M1	09-16-2003	380	[2,3]463	—	[2]40	—	—
5N/6W-25P2	09-04-2002	266	[2,3]324	—	[2]22	—	—
6N/6W-9A1	06-04-2003	95	116	0.07	12.8	0.3	0.03
	10-18-2004	[4]90	[3]110	0.07	10.6	0.3	0.02
6N/6W-10M2	08-27-2002	98	[2,3]120	—	[2]75	—	—
	08-30-2004	94	[2,3]115	—	[2]71	—	—
6N/6W-16B3	11-21-2002	200	228	—	48.6	0.5	—
6N/6W-22Q1	06-04-2003	135	165	0.22	55.7	0.5	0.083
6N/6W-26E1	09-16-2003	127	[2,3]155	—	[2]41	—	—
6N/6W-35K1	10-20-2004	[5]114 (L)	[2]139	0.37	[1]255	[1]2.0	0.190
6N/6W-36J1	11-04-2004	[4]102	[2]123	0.03	4.62	0.3	E0.001
7N/6W-22E1	06-02-2003	111	136	0.02	4.31	0.2	0.004
7N/6W-29P1	09-11-2003	127	[2,3]155	—	[2]6	—	—
7N/6W-29P3	06-03-2003	184	224	0.07	9.25	0.3	0.032
7N/7W-24A1	06-03-2003	51	62	0.02	5.11	<0.2	E0.002

See footnotes at end of table

Appendix D. Field measurements and laboratory analyses of samples from streamflow-measurement stations, springs, and ground-water wells, Sonoma Valley, Sonoma County, California, 2002–04—Continued.

[See figure 20 for location of streamflow-measurement stations, springs, and wells. USGS (U.S. Geological Survey) identification number: the unique number for each site in USGS NWIS (National Water Information System) database. Collecting and analyzing agency: USGS, U.S. Geological Survey; CADWR, California Department of Water Resources. Parameter code, in brackets, is a five-digit number in the USGS computerized data system, National Water Information System (NWIS), used to uniquely identify a specific constituent or property. CADWR conductance measurements are referred to as electrical conductance (EC). CADWR alkalinities are laboratory values. $CaCO_3$, calcium carbonate; µS/cm, microsiemen per centimeter at 25°C; °C, degree Celsius; mg/L, milligram per liter; µg/L, microgram per liter; E, value estimated by the USGS National Water Quality Laboratory, Denver Colorado; (L), measured in laboratory; <, actual value is less than value shown; —, no data]

Stream site identifier or state well No. (abbreviated or local identifier)	Sample date	Silica, dissolved (mg/L) [00955]	Sulfate, dissolved (mg/L) [00945]	Solids, sum of constituents, dissolved (mg/L) [70301]	Solids, residue on evaporation at 180°C (mg/L) [70300]	Nitrogen, ammonia, dissolved (mg/L) [00608]	Nitrite plus nitrate as N, dissolved (mg/L) [00631]
Wells							
5N/6W-10Q2	11-22-2002	64.3	4.2	243	242	<0.04	0.07
5N/6W-12F1	08-27-2002	—	[2]19	—	[2]539	—	—
	08-30-2004	—	[2]20	—	[2]487	—	—
5N/6W-12M1	09-16-2003	—	[2]17	—	[2]485	—	—
5N/6W-25P2	09-04-2002	—	[2]6	—	[2]372	—	—
6N/6W-9A1	06-04-2003	80.6	2.5	205	195	0.08	<0.06
	10-18-2004	85.3	2.6	199	185	0.07	<0.06
6N/6W-10M2	08-27-2002	—	[2]27	—	[2]316	—	—
	08-30-2004	—	[2]26	—	[2]305	—	—
6N/6W-16B3	11-21-2002	39.6	<0.2	—	359	0.11	<0.06
6N/6W-22Q1	06-04-2003	79.9	5.6	332	329	0.20	E0.05
6N/6W-26E1	09-16-2003	—	[2]3	—	[2]252	—	—
6N/6W-35K1	10-20-2004	85.6	14.0	[1]702	673	—	—
6N/6W-36J1	11-04-2004	87.0	4.6	207	197	<0.04	0.10
7N/6W-22E1	06-02-2003	58.1	0.3	176	158	0.67	<0.06
7N/6W-29P1	09-11-2003	—	[2]<1	—	[2]164	—	—
7N/6W-29P3	06-03-2003	72.5	4.1	275	262	0.07	<0.06
7N/7W-24A1	06-03-2003	70.1	2.7	137	142	<0.04	0.36

See footnotes at end of table

Appendix D. Field measurements and laboratory analyses of samples from streamflow-measurement stations, springs, and ground-water wells, Sonoma Valley, Sonoma County, California, 2002–04—Continued.

[See figure 20 for location of streamflow-measurement stations, springs, and wells. USGS (U.S. Geological Survey) identification number: the unique number for each site in USGS NWIS (National Water Information System) database. Collecting and analyzing agency: USGS, U.S. Geological Survey; CADWR, California Department of Water Resources. Parameter code, in brackets, is a five-digit number in the USGS computerized data system, National Water Information System (NWIS), used to uniquely identify a specific constituent or property. CADWR conductance measurements are referred to as electrical conductance (EC). CADWR alkalinities are laboratory values. $CaCO_3$, calcium carbonate; µS/cm, microsiemen per centimeter at 25°C; °C, degree Celsius; mg/L, milligram per liter; µg/L, microgram per liter; E, value estimated by the USGS National Water Quality Laboratory, Denver Colorado; (L), measured in laboratory; <, actual value is less than value shown; —, no data]

Stream site identifier or state well No. (abbreviated or local identifier)	Sample date	Nitrate, dissolved (mg/L)	Nitrogen, nitrite, dissolved (mg/L) [00613]	Phosphorus, ortho-phosphate, dissolved (mg/L) [00671]	Arsenic, dissolved (µg/L) [01000]	Barium, dissolved (µg/L) [01005]
Wells						
5N/6W-10Q2	11-22-2002	[6]0.3	E0.006	0.13	7	—
5N/6W-12F1	08-27-2002	[2]<0.1	—	—	—	—
	08-30-2004	[2]0.9	—	—	—	—
5N/6W-12M1	09-16-2003	[2]0.1	—	—	—	—
5N/6W-25P2	09-04-2002	[2]0.2	—	—	—	—
6N/6W-9A1	06-04-2003	[6]<0.3	<0.008	0.28	6	38
	10-18-2004	[6]<0.3	<0.008	0.32	7	35
6N/6W-10M2	08-27-2002	[2]<0.1	—	—	—	—
	08-30-2004	[2]1	—	—	—	—
6N/6W-16B3	11-21-2002	[6]<0.3	<0.008	0.05	9	—
6N/6W-22Q1	06-04-2003	[6]<0.3	<0.008	0.24	4	98
6N/6W-26E1	09-16-2003	[2]0.2	—	—	—	—
6N/6W-35K1	10-20-2004	—	—	—	[1]12	14
6N/6W-36J1	11-04-2004	[6]0.4	<0.008	0.061	6	9
7N/6W-22E1	06-02-2003	[6]<0.3	<0.008	0.38	<2	82
7N/6W-29P1	09-11-2003	[2]<0.1	—	—	—	—
7N/6W-29P3	06-03-2003	[6]<0.3	<0.008	0.21	2	42
7N/7W-24A1	06-03-2003	[6]1.6	<0.008	0.06	E2	10

See footnotes at end of table

Appendix D. Field measurements and laboratory analyses of samples from streamflow-measurement stations, springs, and ground-water wells, Sonoma Valley, Sonoma County, California, 2002–04—Continued.

[See figure 20 for location of streamflow-measurement stations, springs, and wells. USGS (U.S. Geological Survey) identification number: the unique number for each site in USGS NWIS (National Water Information System) database. Collecting and analyzing agency: USGS, U.S. Geological Survey; CADWR, California Department of Water Resources. Parameter code, in brackets, is a five-digit number in the USGS computerized data system, National Water Information System (NWIS), used to uniquely identify a specific constituent or property. CADWR conductance measurements are referred to as electrical conductance (EC). CADWR alkalinities are laboratory values. $CaCO_3$, calcium carbonate; µS/cm, microsiemen per centimeter at 25°C; °C, degree Celsius; mg/L, milligram per liter; µg/L, microgram per liter; E, value estimated by the USGS National Water Quality Laboratory, Denver Colorado; (L), measured in laboratory; <, actual value is less than value shown; —, no data]

Stream site identifier or state well No. (abbreviated or local identifier)	Sample date	Boron, dissolved (µg/L) [01020]	Iron, dissolved (µg/L) [01046]	Lithium, dissolved (µg/L) [01130]	Manganese, dissolved (µg/L) [01056]
Wells					
5N/6W-10Q2	11-22-2002	160	<10	28.8	[1]55.1
5N/6W-12F1	08-27-2002	[2]700	—	—	—
	08-30-2004	[2]600	—	—	—
5N/6W-12M1	09-16-2003	[2]300	—	—	—
5N/6W-25P2	09-04-2002	[2,7]1,100	—	—	—
6N/6W-9A1	06-04-2003	160	[1]845	4.9	[1]540
	10-18-2004	120	[1]999	4.7	[1]434
6N/6W-10M2	08-27-2002	[2]<100	—	—	—
	08-30-2004	[2]<100	—	—	—
6N/6W-16B3	11-21-2002	[7]5,780	<10	22	31.8
6N/6W-22Q1	06-04-2003	[7]1,350	[1]499	39	[1]313
6N/6W-26E1	09-16-2003	[2,7]1,300	—	—	—
6N/6W-35K1	10-20-2004	[7]3,570	[1]302	703	373
6N/6W-36J1	11-04-2004	70	E4.0	42.3	0.3
7N/6W-22E1	06-02-2003	50	1,480	1.1	[1]390
7N/6W-29P1	09-11-2003	[2]<100	—	—	—
7N/6W-29P3	06-03-2003	110	20	9.6	[1]399
7N/7W-24A1	06-03-2003	20	13	20.9	1.5

[1]Value equals or exceeds the maximum contaminant level (MCL) or is outside of the acceptable range for primary or secondary Federal and State drinking-water standards (California Department of Health Services, 2003; U.S. Environmental Protection Agency, 2002).

[2]Data provided by CADWR; not in USGS NWIS (National Water Information System) database.

[3]Bicarbonate value calculated from alkalinity.

[4]Parameter code 29802 in USGS NWIS database.

[5]Parameter code 29801 in USGS NWIS database.

[6]Nitrate value calculated from nitrite plus nitrate as N.

[7]Value equals or exceeds the State notification level (California Department of Health Services, 2005).

Appendix E. Summary of specific conductance and temperature measurements in samples from springs, ground-water wells, and miscellaneous sources, Sonoma Valley, Sonoma County, California, 1969–2004.

[See figures 20 and 27 for locations of springs, wells, and miscellaneous sites. USGS (U.S. Geological Survey) identification number: the unique number for each site in USGS NWIS (National Water Information System) database. Collecting and analyzing agency: USGS, U.S. Geological Survey; CADWR, California Department of Water Resources. Parameter code, in brackets, is a five-digit number in the USGS computerized data system, National Water Information System (NWIS), used to uniquely identify a specific constituent or property. CADWR conductance measurements represent electrical conductance (EC). °C, degrees Celsius; ft^3/s, cubic feet per second; L, laboratory value; µS/cm, microsiemen per centimeter at 25°C; mm/dd/yyyy, month/day/year; —, no data]

Stream site identifier or State well No. (abbreviated or local identifier)	USGS Identification No.	Sample date (mm/dd/yyyy)	Collecting and analyzing agency	Field measurements: Specific conductance, field (µS/cm) [00095]	Field measurements: Temperature, water °C [00010]
Springs					
4N/5W-30NS1	380932122273701	09-02-2003	USGS	222	—
4N/5W-30PS1	380926122271901	09-02-2003	USGS	[1]2,200	26.5
6N/6W-5FS1	382338122330301	07-15-2003	USGS	986	32.0
6N/6W-19PS1	382045122335601	06-02-2003	USGS	293	16.0
7N/6W-22JS1	382602122301601	06-02-2003	USGS	154	16.0
Wells					
4N/5W-2E1	381322122231801	09-03-2003	USGS	1,270	21.5
		10-26-2004	USGS	1,680	21.0
4N/5W-2F1	381326122225601	06-06-2003	USGS	1,270	21.5
		09-03-2003	USGS	1,170	21.0
4N/5W-2R1	381258122221901	09-03-2003	USGS	[2]942	[2]23.0
4N/5W-6L1	381313122271601	09-03-2003	USGS	555	19.5
4N5W-6P2	381250122273001	09-02-2003	USGS	820	26.0
4N/5W-6P3	381251122271701	09-02-2003	USGS	784	33.5
4N/5W-7G1	381228122270401	09-03-2003	USGS	589	35.0
4N/5W-7K1	381221122270801	09-02-2003	USGS	461	29.5
4N/5W-15K1	381122122234301	08-03-2004	USGS	[3]1,240	—
4N/5W-17M1	381120122262901	09-03-2003	USGS	544	24.5
		09-28-2004	USGS	544	24.0
4N/5W-30M1	380937122274101	09-02-2003	USGS	638	19.5
4N/6W-1H1	381322122280201	09-02-2003	USGS	417	23.5
5N/5W-8P2	—	08-01-1974	CADWR	[4]521(L)	—
		07-01-1976	CADWR	[4]505(L)	—
		08-14-1978	CADWR	[4]505(L)	—
		07-11-1980	CADWR	[4]506(L)	—
		09-30-1982	CADWR	[4]489(L)	—
		08-08-1984	CADWR	[4]474(L)	—
		08-13-1986	CADWR	[4]491(L)	—
		08-09-1988	CADWR	[4]476(L)	—
		09-18-1991	CADWR	[4]507(L)	—

See footnotes at end of table

Appendix E. Summary of specific conductance and temperature measurements in samples from springs, ground-water wells, and miscellaneous sources, Sonoma Valley, Sonoma County, California, 1969–2004—Continued.

[See figures 20 and 27 for locations of springs, wells, and miscellaneous sites. USGS (U.S. Geological Survey) identification number: the unique number for each site in USGS NWIS (National Water Information System) database. Collecting and analyzing agency: USGS, U.S. Geological Survey; CADWR, California Department of Water Resources. Parameter code, in brackets, is a five-digit number in the USGS computerized data system, National Water Information System (NWIS), used to uniquely identify a specific constituent or property. CADWR conductance measurements represent electrical conductance (EC). °C, degrees Celsius; ft^3/s, cubic feet per second; L, laboratory value; µS/cm, microsiemen per centimeter at 25°C; mm/dd/yyyy, month/day/year; —, no data]

Stream site identifier or State well No. (abbreviated or local identifier)	USGS Identification No.	Sample date (mm/dd/yyyy)	Collecting and analyzing agency	Field measurements: Specific conductance, field (µS/cm) [00095]	Field measurements: Temperature, water °C [00010]
5N/5W-8P2		09-16-1993	CADWR	[4]487(L)	—
		08-28-1996	CADWR	[4]522(L)	—
		08-24-1998	CADWR	[4]490(L)	—
		08-27-2002	CADWR	[4]509(L)	—
5N/5W-18D2		08-08-1969	CADWR	[4]519(L)	—
		07-28-1970	CADWR	[4]512(L)	—
		08-01-1974	CADWR	[4]514(L)	—
		07-31-1979	CADWR	[4]490(L)	—
		07-16-1981	CADWR	[4]495(L)	—
		07-06-1983	CADWR	[4]500(L)	—
		08-08-1985	CADWR	[4]507(L)	—
		09-16-1987	CADWR	[4]510(L)	—
		07-26-1989	CADWR	[4]530(L)	—
		09-18-1991	CADWR	[4]551(L)	—
		09-16-1993	CADWR	[4]564(L)	—
		08-28-1996	CADWR	[4]601(L)	—
		08-24-1998	CADWR	[4]594(L)	—
		08-27-2002	CADWR	[4]602(L)	—
		08-30-2004	CADWR	[4]643(L)	—
5N/5W-19M1		09-05-2003	USGS	554	21.0
5N/5W-19N1		09-05-2003	USGS	[2]554	[2]17.0
5N/5W-20J2		09-03-2003	USGS	858	25.5
5N/5W-20M1		10-20-2004	USGS	734	25.5
5N/5W-20P2		09-04-2003	USGS	245	20.0
5N/5W-20R1		08-07-1969	CADWR	[4]811(L)	—
		07-28-1970	CADWR	[4]804(L)	—
		06-03-1975	CADWR	[4]823(L)	—
		07-11-1980	CADWR	[4]834(L)	—
		09-30-1982	CADWR	[4]945(L)	—
		08-08-1984	CADWR	[4]832(L)	—
		08-13-1986	CADWR	[4]871(L)	—

See footnotes at end of table

Appendix E. Summary of specific conductance and temperature measurements in samples from springs, ground-water wells, and miscellaneous sources, Sonoma Valley, Sonoma County, California, 1969–2004—Continued.

[See figures 20 and 27 for locations of springs, wells, and miscellaneous sites. USGS (U.S. Geological Survey) identification number: the unique number for each site in USGS NWIS (National Water Information System) database. Collecting and analyzing agency: USGS, U.S. Geological Survey; CADWR, California Department of Water Resources. Parameter code, in brackets, is a five-digit number in the USGS computerized data system, National Water Information System (NWIS), used to uniquely identify a specific constituent or property. CADWR conductance measurements represent electrical conductance (EC). °C, degrees Celsius; ft^3/s, cubic feet per second; L, laboratory value; µS/cm, microsiemen per centimeter at 25°C; mm/dd/yyyy, month/day/year; —, no data]

Stream site identifier or State well No. (abbreviated or local identifier)	USGS Identification No.	Sample date (mm/dd/yyyy)	Collecting and analyzing agency	Field measurements: Specific conductance, field (µS/cm) [00095]	Field measurements: Temperature, water °C [00010]
5N/5W-20R1		08-09-1988	CADWR	[4]850(L)	—
		08-02-1990	CADWR	[4]880(L)	—
		07-23-1992	CADWR	[4]877(L)	—
		08-25-1995	CADWR	[4]866(L)	—
		08-29-1997	CADWR	[4]842(L	—
		08-12-1999	CADWR	[4]856(L)	—
		11-15-2001	CADWR	[4]855(L)	—
		09-16-2003	CADWR	[4]855(L)	—
5N/5W-21P3	381530122251601	09-03-2003	USGS	1,180	22.0
5N/5W-21P4	381530122251602	12-18-2003	USGS	490	21.0
5N/5W-28N1	—	08-17-1972	CADWR	[4]994(L)	—
		08-01-1974	CADWR	[4]1,190(L)	—
		07-01-1976	CADWR	[4]1,240(L)	—
		08-14-1978	CADWR	[4]1,420(L)	—
		07-11-1980	CADWR	[4]1,110(L)	—
		09-29-1982	CADWR	[4]1,090(L)	—
		08-08-1984	CADWR	[4]1,120(L)	—
		08-13-1986	CADWR	[4]1,090(L)	—
		08-02-1990	CADWR	[4]1,020(L)	—
		08-29-1996	CADWR	[4]1,080(L)	—
		08-24-1998	CADWR	[4]1,110(L)	—
		09-04-2002	CADWR	[4]1,780(L)	—
5N/5W-28P4	381448122250501	09-04-2003	USGS	1,390	23.5
5N/5W-28R1	—	07-29-1971	CADWR	[4]1,020(L)	—
		07-30-1973	CADWR	[4]1,070(L)	—
		06-03-1975	CADWR	[4]1,070(L)	—
		08-09-1977	CADWR	[4]1,100(L)	—
		07-31-1979	CADWR	[4]1,120(L)	—
		07-16-1981	CADWR	[4]1,120(L)	—
		07-05-1983	CADWR	[4]1,070(L)	—
		08-08-1985	CADWR	[4]1,080(L)	—

See footnotes at end of table

Appendix E. Summary of specific conductance and temperature measurements in samples from springs, ground-water wells, and miscellaneous sources, Sonoma Valley, Sonoma County, California, 1969–2004—Continued.

[See figures 20 and 27 for locations of springs, wells, and miscellaneous sites. USGS (U.S. Geological Survey) identification number: the unique number for each site in USGS NWIS (National Water Information System) database. Collecting and analyzing agency: USGS, U.S. Geological Survey; CADWR, California Department of Water Resources. Parameter code, in brackets, is a five-digit number in the USGS computerized data system, National Water Information System (NWIS), used to uniquely identify a specific constituent or property. CADWR conductance measurements represent electrical conductance (EC). °C, degrees Celsius; ft^3/s, cubic feet per second; L, laboratory value; µS/cm, microsiemen per centimeter at 25°C; mm/dd/yyyy, month/day/year; —, no data]

Stream site identifier or State well No. (abbreviated or local identifier)	USGS Identification No.	Sample date (mm/dd/yyyy)	Collecting and analyzing agency	Field measurements: Specific conductance, field (µS/cm) [00095]	Field measurements: Temperature, water °C [00010]
5N/5W-28R1	—	09-16-1987	CADWR	[4]1,110(L)	—
		07-26-1989	CADWR	[4]1,130(L)	—
		09-18-1991	CADWR	[4]1,150(L)	—
		09-16-1993	CADWR	[4]1,150(L)	—
		08-28-1996	CADWR	[4]1,170(L)	—
		08-24-1998	CADWR	[4]1,160(L)	—
		08-27-2002	CADWR	[4]1,190(L)	—
	381450122243701	09-03-2003	USGS	1,180	21.0
		09-01-2004	CADWR	[4]1,290(L)	—
5N/5W-28R5	381443122243801	09-03-2003	USGS	920	20.5
5N/5W-29P3	381444122262101	09-04-2003	USGS	315	17.5
5N/5W-29P4	381439122261101	09-05-2003	USGS	1,170	18.5
5N/5W-29R6	381445122254501	09-04-2003	USGS	720	18.5
5N/5W-29R7	381443122254201	09-04-2003	USGS	1,560	23.0
5N/5W-29R8	381448122254201	09-04-2003	USGS	910	23.5
5N/5W-30C1	381517122271601	09-05-2003	USGS	543	17.5
5N/5W-30H1	381509122264801	06-05-2003	USGS	348	19.0
		09-04-2003	USGS	464	19.5
5N/5W-30M1	381456122274001	09-05-2003	USGS	[2]575	—
5N/5W-30R1	81447122264301	9-04-2003	USGS	850	18.0
N/5W-30R2	381439122264901	09-04-2003	USGS	571	17.5
5N/5W-31J1	381411122265201	09-02-2003	USGS	880	25.0
5N/5W-31J2	381404122264301	09-02-2003	USGS	880	36.0
5N/5W-31P2	381352122271901	9-02-2003	USGS	700	19.0
5N/5W-31P3	381357122271801	09-02-2003	USGS	583	19.0
5N/5W-32C1	381438122262101	09-04-2003	USGS	[2]315	[2]19.0
N/5W-33K7	81408122250501	09-03-2003	USGS	1,090	18.5
N/5W-33K8	81415122251501	09-03-2003	USGS	904	19.0
5N/5W-33Q1	381359122245001	09-03-2003	USGS	940	18.5
5N/5W-33R1	381352122243901	09-03-2003	USGS	[5]1,900	[5]22.0
5N/5W-34M1	381410122242301	09-03-2003	USGS	1,290	23.0

See footnotes at end of table

Appendix E. Summary of specific conductance and temperature measurements in samples from springs, ground-water wells, and miscellaneous sources, Sonoma Valley, Sonoma County, California, 1969–2004—Continued.

[See figures 20 and 27 for locations of springs, wells, and miscellaneous sites. USGS (U.S. Geological Survey) identification number: the unique number for each site in USGS NWIS (National Water Information System) database. Collecting and analyzing agency: USGS, U.S. Geological Survey; CADWR, California Department of Water Resources. Parameter code, in brackets, is a five-digit number in the USGS computerized data system, National Water Information System (NWIS), used to uniquely identify a specific constituent or property. CADWR conductance measurements represent electrical conductance (EC). °C, degrees Celsius; ft^3/s, cubic feet per second; L, laboratory value; µS/cm, microsiemen per centimeter at 25°C; mm/dd/yyyy, month/day/year; —, no data]

Stream site identifier or State well No. (abbreviated or local identifier)	USGS Identification No.	Sample date (mm/dd/yyyy)	Collecting and analyzing agency	Field measurements: Specific conductance, field (µS/cm) [00095]	Field measurements: Temperature, water °C [00010]
5N/6W-2A6	381849122285901	10-20-2004	USGS	2,020	41.5
5N/6W-2N2	—	8-17-1972	CADWR	[4] 288(L)	—
		08-01-1974	CADWR	[4] 280(L)	—
		07-01-1976	CADWR	[4] 286(L)	—
		08-14-1978	CADWR	[4] 294(L)	—
		07-11-1980	CADWR	[4] 306(L)	—
		09-30-1982	CADWR	[4] 281(L)	—
		08-08-1984	CADWR	[4] 287(L)	—
		08-13-1986	CADWR	[4] 287(L)	—
		08-09-1988	CADWR	[4] 280(L)	—
		08-02-1990	CADWR	[4] 297(L)	—
		07-23-1992	CADWR	[4] 303(L)	—
		08-28-1995	CADWR	[4] 294(L)	—
		08-29-1997	CADWR	[4] 303(L)	—
		08-12-1999	CADWR	[4] 307(L)	—
		11-05-2001	CADWR	[4] 334(L)	—
		09-16-2003	CADWR	[4] 329(L)	—
5N/6W-2P2	381808122293801	10-19-2004	USGS	345	19.5
5N/6W-2P3	381809122293301	11-21-2002	USGS	328	18.5
5N/6W-3E1	381834122305401	11-20-2002	USGS	378	26.5
		10-26-2004	USGS	383	27.5
5N/6W-8B1	381749122323201	09-29-2004	USGS	296	22.0
5N/6W-10Q2	381712122301901	11-22-2002	USGS	344	22.0
5N/6W-12F1	—	08-08-1969	CADWR	[4] 420(L)	—
		07-29-1971	CADWR	[4] 462(L)	—
		07-30-1973	CADWR	[4] 464(L)	—
		06-03-1975	CADWR	[4] 821(L)	—
		08-09-1977	CADWR	[4] 462(L)	—
		07-31-1979	CADWR	[4] 908(L)	—
		07-16-1981	CADWR	[4] 748(L)	—
		07-06-1983	CADWR	[4] 1,090(L)	—

See footnotes at end of table

Appendix E. Summary of specific conductance and temperature measurements in samples from springs, ground-water wells, and miscellaneous sources, Sonoma Valley, Sonoma County, California, 1969–2004—Continued.

[See figures 20 and 27 for locations of springs, wells, and miscellaneous sites. USGS (U.S. Geological Survey) identification number: the unique number for each site in USGS NWIS (National Water Information System) database. Collecting and analyzing agency: USGS, U.S. Geological Survey; CADWR, California Department of Water Resources. Parameter code, in brackets, is a five-digit number in the USGS computerized data system, National Water Information System (NWIS), used to uniquely identify a specific constituent or property. CADWR conductance measurements represent electrical conductance (EC). °C, degrees Celsius; ft^3/s, cubic feet per second; L, laboratory value; µS/cm, microsiemen per centimeter at 25°C; mm/dd/yyyy, month/day/year; —, no data]

Stream site identifier or State well No. (abbreviated or local identifier)	USGS Identification No.	Sample date (mm/dd/yyyy)	Collecting and analyzing agency	Field measurements: Specific conductance, field (µS/cm) [00095]	Field measurements: Temperature, water °C [00010]
5N/6W-12F1	—	07-26-1989	CADWR	[4]897(L)	—
		09-18-1991	CADWR	[4]1,440(L)	—
		09-16-1993	CADWR	[4]887(L)	—
		08-29-1996	CADWR	[4]941(L)	—
		08-24-1998	CADWR	[4]895(L)	—
		08-27-2002	CADWR	[4]886(L)	—
		08-30-2004	CADWR	[4]888(L)	—
5N/6W-12M1	—	08-17-1972	CADWR	[4]478(L)	—
		08-01-1974	CADWR	[4]536(L)	—
		07-01-1976	CADWR	[4]561(L)	—
		08-14-1978	CADWR	[4]607(L)	—
		07-11-1980	CADWR	[4]873(L)	—
		09-30-1982	CADWR	[4]752(L)	—
		08-08-1984	CADWR	[4]861(L)	—
		08-13-1986	CADWR	[4]789(L)	—
		08-09-1988	CADWR	[4]745(L)	—
		08-02-1990	CADWR	[4]865(L)	—
		07-23-1992	CADWR	[4]873(L)	—
		08-25-1995	CADWR	[4]936(L)	—
		08-29-1997	CADWR	[4]845(L)	—
		08-12-1999	CADWR	[4]866(L)	—
		11-15-2001	CADWR	[4]850(L)	—
		09-16-2003	CADWR	[4]806(L)	—
5N/6W-24K2	381544122280801	09-05-2003	USGS	661	17.5
5N/6W-24Q1	381527122281601	09-05-2003	USGS	371	18.0
5N/6W-25P2	—	08-07-1969	CADWR	[4]540(L)	—
		07-28-1970	CADWR	[4]540(L)	—
		07-30-1973	CADWR	[4]562(L)	—
		06-03-1975	CADWR	[4]559(L)	—
		08-09-1977	CADWR	[4]565(L)	—
		07-31-1979	CADWR	[4]566(L)	—

See footnotes at end of table

Appendix E. Summary of specific conductance and temperature measurements in samples from springs, ground-water wells, and miscellaneous sources, Sonoma Valley, Sonoma County, California, 1969–2004—Continued.

[See figures 20 and 27 for locations of springs, wells, and miscellaneous sites. USGS (U.S. Geological Survey) identification number: the unique number for each site in USGS NWIS (National Water Information System) database. Collecting and analyzing agency: USGS, U.S. Geological Survey; CADWR, California Department of Water Resources. Parameter code, in brackets, is a five-digit number in the USGS computerized data system, National Water Information System (NWIS), used to uniquely identify a specific constituent or property. CADWR conductance measurements represent electrical conductance (EC). °C, degrees Celsius; ft^3/s, cubic feet per second; L, laboratory value; µS/cm, microsiemen per centimeter at 25°C; mm/dd/yyyy, month/day/year; —, no data]

Stream site identifier or State well No. (abbreviated or local identifier)	USGS Identification No.	Sample date (mm/dd/yyyy)	Collecting and analyzing agency	Field measurements: Specific conductance, field (µS/cm) [00095]	Field measurements: Temperature, water °C [00010]
5N/6W-25P2	—	07-21-1981	CADWR	[4]564(L)	—
		07-06-1983	CADWR	[4]566(L)	—
		07-26-1989	CADWR	[4]585(L)	—
		09-18-1991	CADWR	[4]574(L)	—
		08-29-1996	CADWR	[4]578(L)	—
		08-24-1998	CADWR	[4]563(L)	—
		09-04-2002	CADWR	[4]572(L)	—
	381438122283401	09-04-2003	USGS	556	26.5
5N/6W-26A1	381518122290401	09-04-2003	USGS	307	19.0
5N/6W-26B1	381517122291101	09-04-2003	USGS	440	19.5
6N/6W-9A1	382307122311301	06-04-2003	USGS	229	20.0
		10-18-2004	USGS	211	19.5
6N/6W-10M2	—	06-03-1975	CADWR	[4]258(L)	—
		08-09-1977	CADWR	[4]275(L)	—
		07-19-1979	CADWR	[4]274(L)	—
		07-16-1981	CADWR	[4]276(L)	—
		07-06-1983	CADWR	[4]281(L)	—
		08-08-1985	CADWR	[4]299(L)	—
		09-14-1987	CADWR	[4]306(L)	—
		07-26-1989	CADWR	[4]306(L)	—
		09-18-1991	CADWR	[4]352(L)	—
		09-16-1993	CADWR	[4]340(L)	—
		08-29-1996	CADWR	[4]338(L)	—
		08-24-1998	CADWR	[4]353(L)	—
6N/6W-10M2	—	08-27-2002	CADWR	[4]504(L)	—
		08-30-2004	CADWR	[4]504(L)	—
6N/6W-16B3	382219122312501	11-21-2002	USGS	533	20.0
6N/6W-22Q1	382045122302901	06-04-2003	USGS	457	25.0
6N/6W-26E1	—	08-15-1969	CADWR	[4]412(L)	—
		07-28-1970	CADWR	[4]411(L)	—
		07-29-1971	CADWR	[4]409(L)	—

See footnotes at end of table

Appendix E. Summary of specific conductance and temperature measurements in samples from springs, ground-water wells, and miscellaneous sources, Sonoma Valley, Sonoma County, California, 1969–2004—Continued.

[See figures 20 and 27 for locations of springs, wells, and miscellaneous sites. USGS (U.S. Geological Survey) identification number: the unique number for each site in USGS NWIS (National Water Information System) database. Collecting and analyzing agency: USGS, U.S. Geological Survey; CADWR, California Department of Water Resources. Parameter code, in brackets, is a five-digit number in the USGS computerized data system, National Water Information System (NWIS), used to uniquely identify a specific constituent or property. CADWR conductance measurements represent electrical conductance (EC). °C, degrees Celsius; ft^3/s, cubic feet per second; L, laboratory value; µS/cm, microsiemen per centimeter at 25°C; mm/dd/yyyy, month/day/year; —, no data]

Stream site identifier or State well No. (abbreviated or local identifier)	USGS Identification No.	Sample date (mm/dd/yyyy)	Collecting and analyzing agency	Field measurements: Specific conductance, field (µS/cm) [00095]	Field measurements: Temperature, water °C [00010]
6N/6W-26E1	—	08-01-1974	CADWR	[4]416(L)	—
		08-09-1977	CADWR	[4]408(L)	—
		07-19-1979	CADWR	[4]399(L)	—
		09-30-1982	CADWR	[4]385(L)	—
		08-08-1984	CADWR	[4]393(L)	—
		08-13-1986	CADWR	[4]388(L)	—
		08-10-1988	CADWR	[4]380(L)	—
		08-02-1990	CADWR	[4]390(L)	—
		07-23-1992	CADWR	[4]385(L)	—
		08-25-1995	CADWR	[4]376(L)	—
		08-29-1997	CADWR	[4]381(L)	—
		08-12-1999	CADWR	[4]434(L)	—
		09-16-2003	CADWR	[4]377(L)	—
6N/6W-35K1	381916122292201	10-20-2004	USGS	1,290	34.5
6N/6W-36J1	381906122274901	11-04-2004	USGS	222	25.0
6N/7W-2J3	382832122354301	09-27-2004	USGS	138	20.0
7N/6W-22E1	382614122310201	06-02-2003	USGS	215	15.5
7N/6W-28M1	382517122321001	09-29-2004	USGS	215	22.5
7N/6W-29M2	382512122331101	09-28-2004	USGS	408	17.5
7N/6W-29P1	—	07-28-1971	CADWR	[4]233(L)	—
		07-26-1973	CADWR	[4]238(L)	—
		06-05-1975	CADWR	[4]225(L)	—
		08-04-1977	CADWR	[4]202(L)	—
		07-13-1979	CADWR	[4]213(L)	—
		07-10-1981	CADWR	[4]215(L)	—
		07-06-1983	CADWR	[4]222(L)	—
		08-28-1985	CADWR	[4]236(L)	—
		08-20-1987	CADWR	[4]248(L)	—
		07-26-1989	CADWR	[4]249(L)	—
		09-18-1991	CADWR	[4]231(L)	—

See footnotes at end of table

Appendix E. Summary of specific conductance and temperature measurements in samples from springs, ground-water wells, and miscellaneous sources, Sonoma Valley, Sonoma County, California, 1969–2004—Continued.

[See figures 20 and 27 for locations of springs, wells, and miscellaneous sites. USGS (U.S. Geological Survey) identification number: the unique number for each site in USGS NWIS (National Water Information System) database. Collecting and analyzing agency: USGS, U.S. Geological Survey; CADWR, California Department of Water Resources. Parameter code, in brackets, is a five-digit number in the USGS computerized data system, National Water Information System (NWIS), used to uniquely identify a specific constituent or property. CADWR conductance measurements represent electrical conductance (EC). °C, degrees Celsius; ft^3/s, cubic feet per second; L, laboratory value; µS/cm, microsiemen per centimeter at 25°C; mm/dd/yyyy, month/day/year; —, no data]

Stream site identifier or State well No. (abbreviated or local identifier)	USGS Identification No.	Sample date (mm/dd/yyyy)	Collecting and analyzing agency	Field measurements: Specific conductance, field (µS/cm) [00095]	Field measurements: Temperature, water °C [00010]
7N/6W-29P1	—	09-16-1993	CADWR	[4]232(L)	—
		08-29-1996	CADWR	[4]236(L)	—
		08-12-1999	CADWR	[4]237(L)	—
		09-11-2003	CADWR	[4]243(L)	—
7N/6W-29P3	382500122330501	06-03-2003	USGS	382	21.5
7N/7W-24A1	382636122344801	06-03-2003	USGS	124	21.0
Miscellaneous					
Sonoma Valley aqueduct water at Sonoma tank (SA)	381801122274201	12-18-2003	USGS	281	14.5
Napa-Sonoma Marshes at Tolay Creek and Hwy 37 (NSM)	380900122261901	12-18-2003	USGS	[1]22,000	8.5

[1]Uncalibrated value.

[2]Measured sample may represent water from well pressure tank.

[3]Standing water in sounding tube measured.

[4]Data provided by CADWR; not in USGS NWIS (National Water Information System) database.

[5]Artesian well; in-situ measurements taken approximately one foot below top of open well casing.

Appendix F. Summary of delta deuterium and delta oxygen-18 values in samples from streamflow-measurement stations, springs, ground-water wells, and miscellaneous sources, Sonoma Valley, Sonoma County, California, 2002–04.

[See figure 20 for location of stream-flow measurement stations, springs, wells, and miscellaneous sites. USGS (U.S. Geological Survey) identification number: the unique number for each site in USGS NWIS (National Water Information System) database. Per mil, parts per thousand. SVTP, Sonoma Valley wastewater treatment plant; mm/dd/yyyy, month/day/year]

Stream site identifier or State well No. (abbreviated or local identifier)	USGS Identification No.	Sample date (mm/dd/yyyy)	Delta deuterium (per mil) [82082]	Delta oxygen-18 (per mil) [82085]
Sonoma Creek and tributaries				
Sonoma Creek at Kenwood (KW)	382414122330701	11-20-2002	–39.7	–6.06
Sonoma Creek in Sugar Loaf Park (S1)	382614122305601	05-28-2003	–40.7	–6.68
Sonoma Creek at Hwy 12–bridge (S3)	382539122333401	05-28-2003	–40.1	–6.54
Sonoma Creek at Mound Avenue (S4)	382435122331201	05-28-2003	–40.3	–6.41
Sonoma Creek at Lawndale Road and Warm Springs (S5)	382403122331101	05-28-2003	–41.1	–6.45
		06-06-2003	–40.5	–6.37
Sonoma Creek at Agua Caliente (S10)	11458500	11-19-2002	–33.0	–5.09
		06-05-2003	–39.7	–6.20
Sonoma Creek at Verano Road (S11)	381811122285801	05-30-2003	–38.9	–6.30
Calabazas Creek upstream site below confluence (T6)	382352122304301	05-29-2003	–40.3	–6.63
Springs				
4N/5W-30PS1	380926122271901	09-02-2003	–38.8	–5.36
6N/6W-5FS1	382338122330301	07-15-2003	–45.3	–6.99
6N/6W-19PS1	382045122335601	06-02-2003	–43.2	–7.05
7N/6W-22JS1	382602122301601	06-02-2003	–43.1	–6.85
Wells				
4N/5W-2E1	381322122231801	10-26-2004	–47.8	–7.18
4N/5W-2F1	381326122225601	06-06-2003	–44.2	–6.54
		09-03-2003	–40.2	–6.21
4N/5W-7G1	381228122270401	09-03-2003	–46.2	–7.25
4N/5W-17M1	381120122262901	09-03-2003	–44.1	–6.82
		09-28-2004	–44.8	–6.86
4N/5W-30M1	380937122274101	09-02-2003	–39.7	–6.44
5N/5W-20M1	381544122263801	10-20-2004	–50.4	–7.75
5N/5W-21P3	381530122251601	09-03-2003	–50.1	–7.57
5N/5W-21P4	381530122251602	12-18-2003	–49.4	–7.59
5N/5W-28R1	381450122243701	09-03-2003	–42.9	–6.58
5N/5W-29P3	381444122262101	09-04-2003	–38.9	–6.07
5N/5W-29P4	381439122261101	09-05-2003	–38.6	–6.04

Appendix F. Summary of delta deuterium and delta oxygen-18 values in samples from streamflow-measurement stations, springs, ground-water wells, and miscellaneous sources, Sonoma Valley, Sonoma County, California, 2002–04—Continued.

[See figure 20 for location of stream-flow measurement stations, springs, wells, and miscellaneous sites. USGS (U.S. Geological Survey) identification number: the unique number for each site in USGS NWIS (National Water Information System) database. Per mil, parts per thousand. SVTP, Sonoma Valley wastewater treatment plant; mm/dd/yyyy, month/day/year]

Stream site identifier or State well No. (abbreviated or local identifier)	USGS Identification No.	Sample date (mm/dd/yyyy)	Delta deuterium (per mil) [82082]	Delta oxygen-18 (per mil) [82085]
		Wells		
5N/5W-29R6	381445122254501	09-04-2003	–38.1	–5.98
5N/5W-29R7	381443122254201	09-04-2003	–44.8	–6.95
5N/5W-30H1	381509122264801	06-05-2003	–38.4	–5.52
		09-04-2003	–37.6	–5.58
5N/5W-31P3	381357122271801	09-02-2003	–39.5	–6.02
5N/5W-33K7	381408122250501	09-03-2003	–42.5	–6.50
5N/6W-2A6	381849122285901	10-20-2004	–52.0	–7.64
5N/6W-2P2	381808122293801	10-19-2004	–39.0	–6.00
5N/6W-2P3	381809122293301	11-21-2002	–39.6	–6.11
5N/6W-3E1	381834122305401	10-26-2004	–40.1	–6.32
5N/6W-8B1	381749122323201	09-29-2004	–41.7	–6.82
5N/6W-10Q2	381712122301901	11-22-2002	–41.5	–6.62
6N/6W-9A1	382307122311301	06-04-2003	–47.9	–7.24
		10-18-2004	–46.5	–7.12
6N/6W-16B3	382219122312501	11-21-2002	–45.0	–7.01
6N/6W-22Q1	382045122302901	06-04-2003	–44.4	–6.82
6N/6W-35K1	381916122292201	10-20-2004	–41.7	–6.09
6N/6W-36J1	381906122274901	11-04-2004	–45.0	–6.98
6N/7W-2J3	382832122354301	09-27-2004	–42.5	–6.68
7N/6W-22E1	382614122310201	06-02-2003	–43.6	–6.97
7N/6W-28M1	382517122321001	09-29-2004	–41.7	–6.63
7N/6W-29M2	382512122331101	09-28-2004	–42.0	–6.73
7N/6W-29P3	382500122330501	06-03-2003	–50.1	–7.56
7N/7W-24A1	382636122344801	06-03-2003	–42.5	–6.62
		Miscellaneous		
Reclaimed water (SVTP)	—	06-05-2003	–42.6	–6.42
Sonoma Valley aqueduct water at Sonoma tank (SA)	381801122274201	12-18-2003	–44.4	–6.61
Napa-Sonoma Marshes at Tolay Creek and Hwy 37 (NSM)	380900122261901	12-18-2003	–21.9	–3.08

Appendix G. Methodology for Estimating Pumpage for the Ground-Water Simulation Model

The demand for fresh water in Sonoma Valley is primarily for irrigation of agriculture and for domestic use (*fig. G-1*). Local streamflow and precipitation did not meet fresh water demands in the model area during 1974–2000. Local sources are supplemented by imported and reclaimed water. Since 1963, water supply has been delivered by aqueduct from the Russian River to the valley (currently about 5,400 acre-ft/yr) (Beach, 2002) or pumped from ground water. Aqueduct water is delivered for domestic use to purveyor areas by the city of Sonoma and by the Valley of the Moon Water District (VOM; fig. 1.1). The city of Sonoma and the VOM, water districts further supplement domestic water deliveries from large public-supply wells located within the valley (*fig. G-2*). Outside these purveyor areas, demand for domestic use is supplemented by private wells. Irrigation water for agricultural crops comes primarily from wells, followed by rainfall or small local diversions from Sonoma Creek. The amount of irrigated acreage increased throughout the modeling period. During this period, farmers converted from higher water-consuming crops (pasture) to lower water-consuming crops (vineyards) (*table G-1*, *fig. G-3*). In addition, areas of native vegetation have been converted to vineyards, and population has increased (*fig. G-4*). During the modeling period and within the model area, crop irrigation water demand has continued to far exceed demand for domestic use.

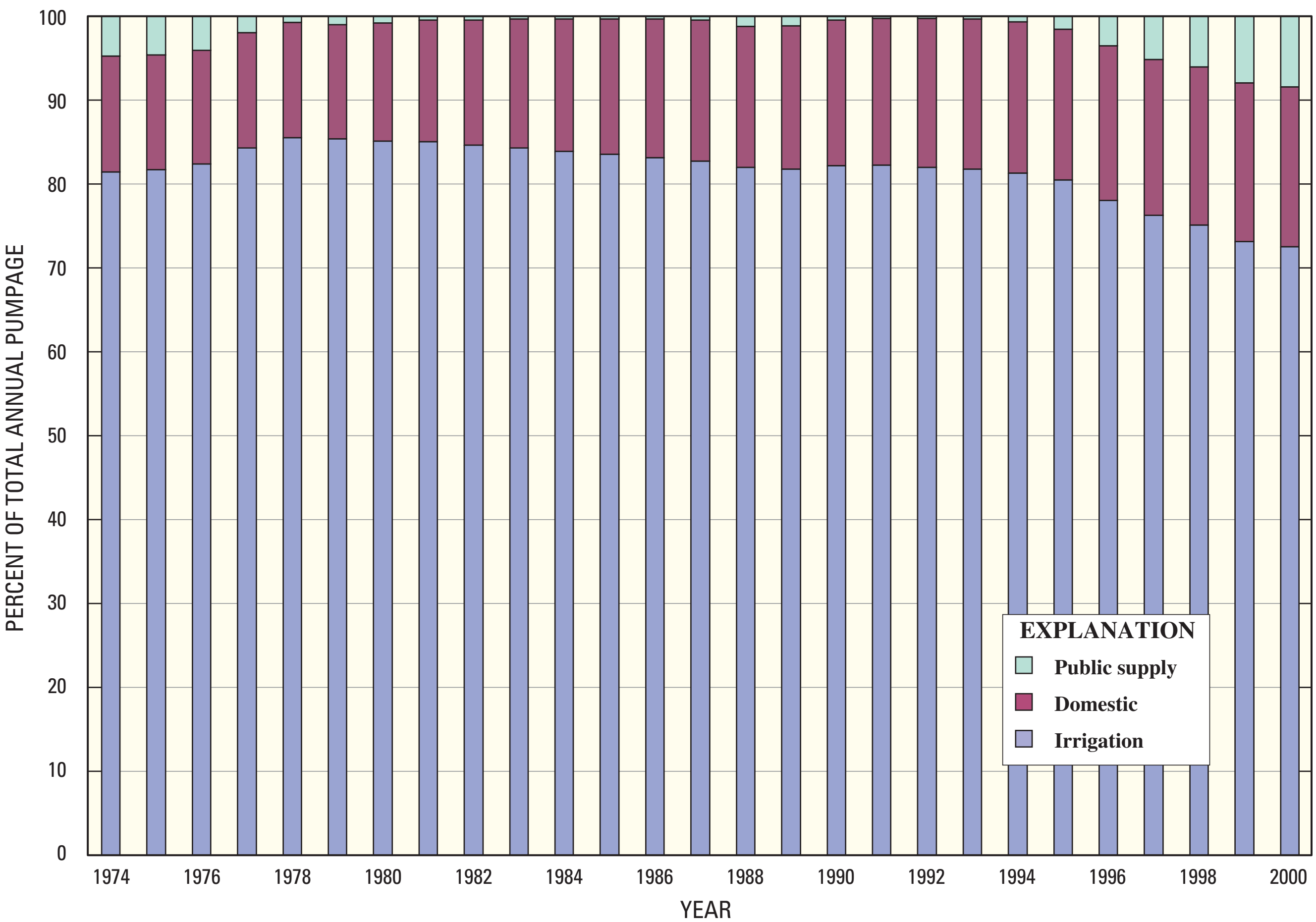

Figure G-1. Percent of estimated annual pumpage by water-use type within the ground-water flow model area, 1974– 2000, Sonoma Valley, Sonoma County, California.

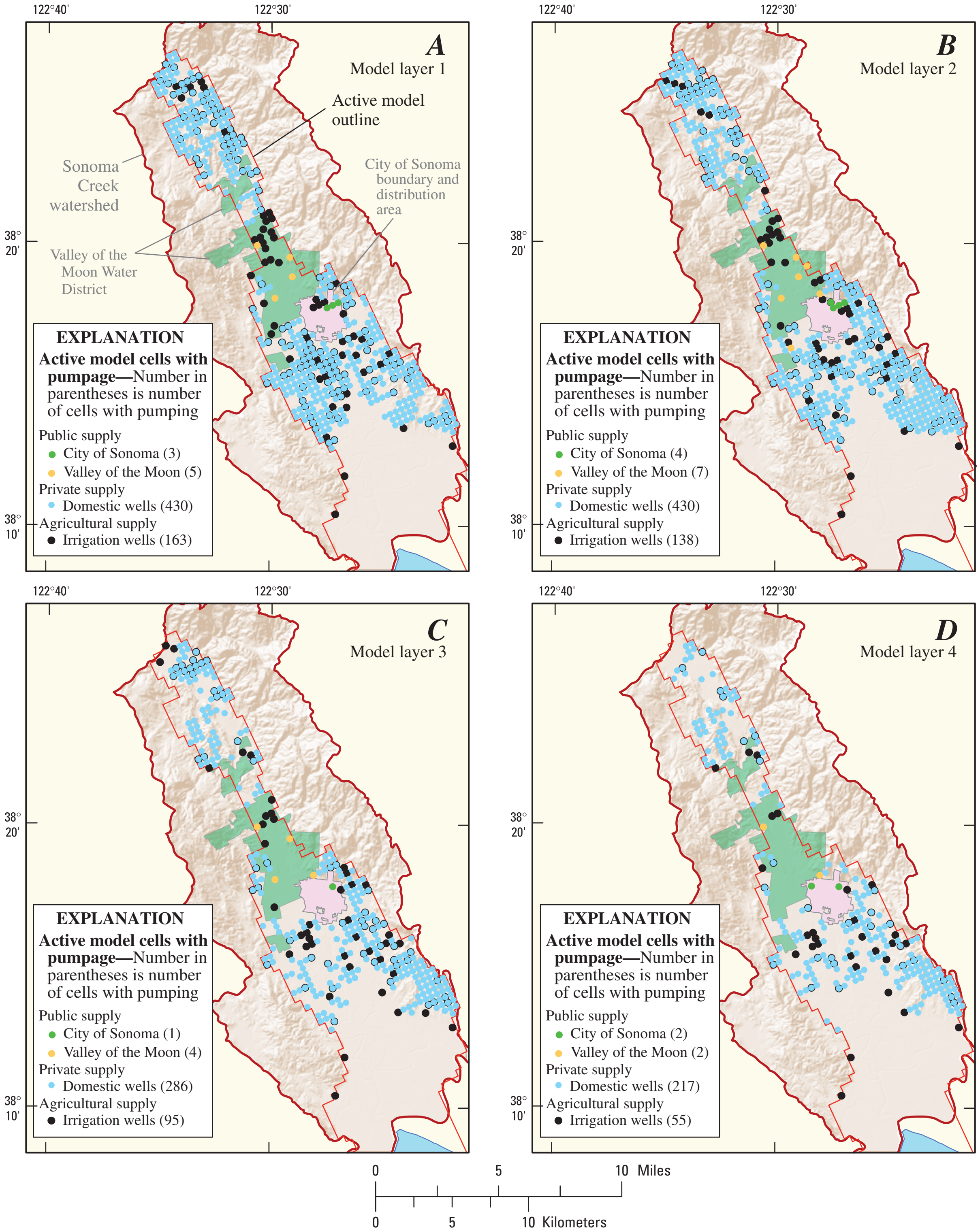

Figure G-2. Active model cells with pumpage in the ground-water flow model of Sonoma Valley, Sonoma County, California. A. layer 1. B, layer 2; C. layer 3. D. layer 4. E. layer 5. F. layer 6. G, layer 7. and H. layer 8.

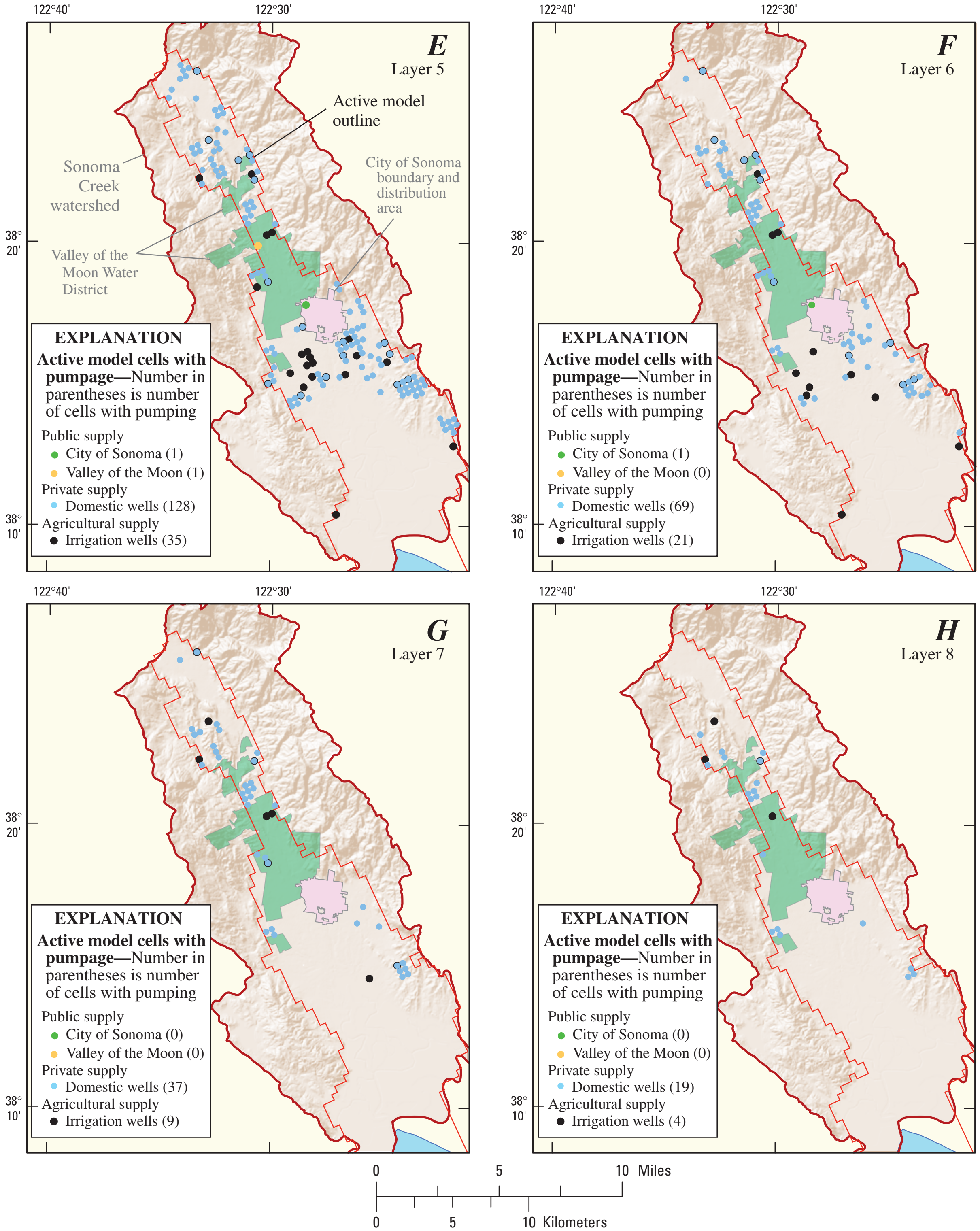

Figure G-2.—Continued.

Table G-1. Estimated irrigated lands by crop type, and annual applied water estimates, years, for Sonoma Valley, Sonoma County, California, 1974, 1979, 1986, and 1999.

Crop class	Year				
	1974	1979	1986	1999	Applied water[1]
	(Acres irrigated[2])				(feet/year)
Citrus, deciduous and field	367	946	130	31	2.0
Pasture and lawn	990	818	856	249	3.3
Grain[3]	0	0	0	409	0.4
Truck	0	9	28	50	1.7
Vineyard	1,468	3,073	5,104	9815	0.6
Vineyard and orchard	239	0	0	0	0.6
Total acres	3,063	4,847	6,118	10,556	

[1]Scott Matyac, California Department of Water Resources, unpub. data, 2005.

[2]Estimated from California Department of Water Resources, 1974, 1979, 1986, and 1999, unpublished crop surveys of Sonoma County, Division of Planning and Local Assistance, Sacramento.

[3]Grains are winter crops and watered largely from precipitation. In 1999, the land-use survey documented some fields as receiving supplemental irrigation water.

For modeling purposes, quantities of pumpage in the model area were needed to identify discharge from the ground-water system. Specifically, discharge (pumpage) measurements over the calibration period, accurate well locations, and the depth of perforated intervals are required in order to integrate pumpage into the model. Construction information was needed to determine the stratigraphy at the well to identify which aquifer (simulated in the model as a series of layers) that the well was pumping water from. In this model area, very little reported pumpage existed, records of well locations were missing or in error, and in some cases, wells with known locations were missing construction information (Ann Roth, California Department of Water Resources, unpub. data, 2003). Therefore, for this study, pumpage was reconstructed for irrigation, domestic and public supply wells based on methods described in previous work (Koczot, 1996; Woolfenden and Koczot, 2001; Hanson and others, 2003). Details specific to this study are described in the following sections. A geographic information system (GIS) was used to manage spatial data to compute pumpage estimates and to characterize the study and model area in terms of land-use water-demand categories, topography, altitudes, geology, and the distribution of precipitation and runoff.

Pumpage from Irrigation Wells

No reported pumpage for irrigation exists, and a public record of the locations of these wells are incomplete. Therefore, an estimate of irrigation demand was used as a surrogate for pumpage for irrigation. Irrigation demand for the model area for 1974–2000 was reconstructed from areas of irrigated crop types identified in the California Department of Water Resources land-use surveys (California Department of Water Resources, 1974, 1979, 1986, and 1999, unpublished crop surveys of Sonoma County, Division of Planning and Local Assistance, Sacramento) and from established estimates of the depth of applied water by crop type (*table G-1*, *fig. G-3*; Scott Matyac, California Department of Water Resources, unpub. data, 2005). Areas designated ‘fallow’ were assumed to be non-irrigated. A volume estimate of applied water was calculated for each land-use polygon by multiplying the polygon area by the applied water estimates for the crop type (*table G-1*). Because vineyards are the dominant crop type and are typically under-watered to stress plants to create better grapes, 100-percent irrigation efficiency was assumed so that no irrigation return flow existed in the valley. Figure G-3 shows the land-use map crop designations as they changed through the surveys. Vineyard has the highest acreage but a low applied water rate of about 0.6 acre-ft/yr. Pasture and lawns require the highest amount of applied water at 3.3 acre-ft/yr. The existing record of well locations and well-use types (Ann Roth, California Department of Water Resources, unpub. data, 2003) was mapped according to complete or partial tax assessors’ parcel numbers or State well identification numbers. These well locations were used to identify irrigation wells built near the area represented by the polygon for irrigated land use. These wells were then ‘moved’ by assigning their location to a model grid cell within the irrigated polygon, assuming that the location of the irrigated polygon was more accurate then the well location. Construction information, as available, was assumed to be accurate at the new model grid location. If a known well with land-use type “irrigation” was not located near the irrigated polygon, other known wells nearby were used instead. The assumption was made that construction for these wells accurately simulated the construction for the assumed irrigation well.

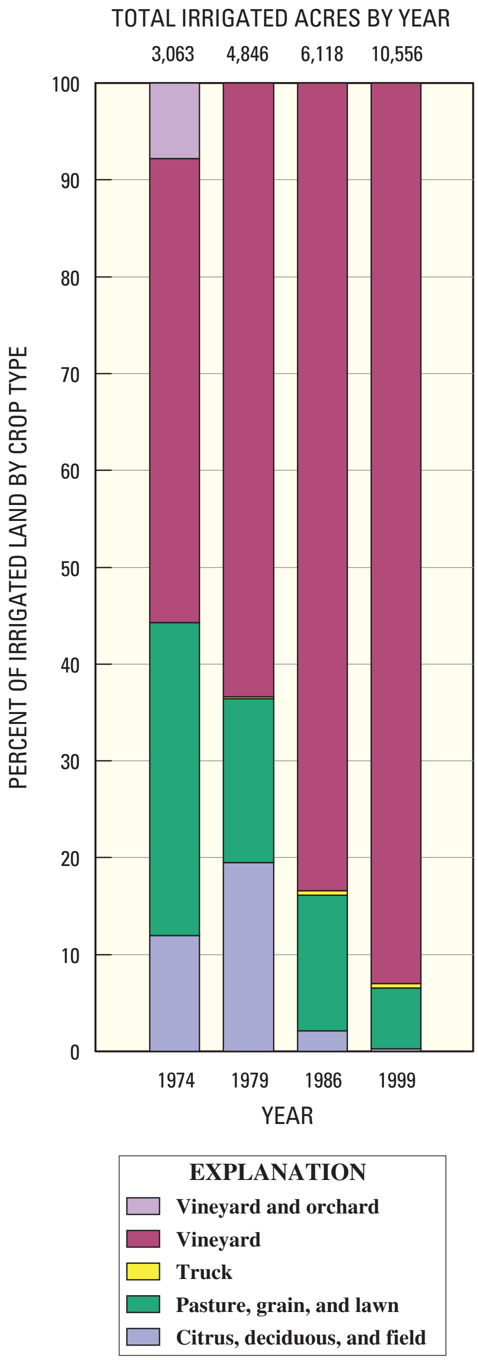

Figure G-3. Irrigated lands by crop type and total irrigated acreage in Sonoma Valley, Sonoma County, California. Data from the California Department of Water Resources, land-use surveys, 1974, 1979, 1986, and 1999.

If a known well was missing construction information, construction information from neighboring wells was used, making the assumption that stratigraphy and water yield did not change between these locations. Total annual pumpage was computed from the irrigated polygon that was assigned to a well. The well was assigned to a model grid row and column. The amount of pumpage coming from each model layer was computed by multiplying the total estimated amount of applied water by the weighted percentage of the length of perforated interval in each model layer. This was done for all four land-use layers (1974, 1979, 1986, 1999). Further, deliveries of reclaimed water to vineyards in the south were accounted for so that in these areas some pumpage ceased (1996–2000). The assumption was made that the reclaimed water met the crop irrigation demands. The modeling period of record was completed by linearly interpolating between pumpage values estimated from the land-use layers. Pumpage in the year 2000 was assumed to be equivalent to 1999. Note that these estimates of agricultural pumpage do not account for any pumpage within the model area that provides water for irrigation outside the model area.

Pumpage from Private Domestic Wells

As noted previously, the VOM and the city of Sonoma Water Districts deliver Russian River water primarily for domestic use within their purveyor areas. With exception of a few suburban blocks in the VOM area (*fig. G-2*), customers within this area are on public supply. Therefore, for purposes of this study, it was assumed that no additional pumpage, except for the few suburban blocks in the VOM (*fig. G-2*), occurs within these purveyor areas. Private domestic use was computed for the remaining portions of the model area by estimating population for each model grid cell from a 2000 census map. The 2000 population totals for each cell were multiplied by an estimate of domestic consumption of 0.19 acre-ft/yr/person, as computed for the study area (California Department of Water Resources, 1994). These totals were pro-rated to the years 1970, 1980, and 1990 using ratios of the 2000 population census totals for each of these three population censuses. Construction details were derived from known wells near or inside the model grid cell. The assumption was made that the construction of nearby wells reasonably represented construction for a domestic well within the cell. The modeling period of record was completed by interpolating between these pro-rated values for each of the model grid cells assigned with domestic pumpage. Pumpage was tied to model layers using the method noted previously for irrigation wells. A limitation of this technique is that it did not capture the variance in population growth within the valley. Population and irrigated acreage estimates are presented in *figure G-4*.

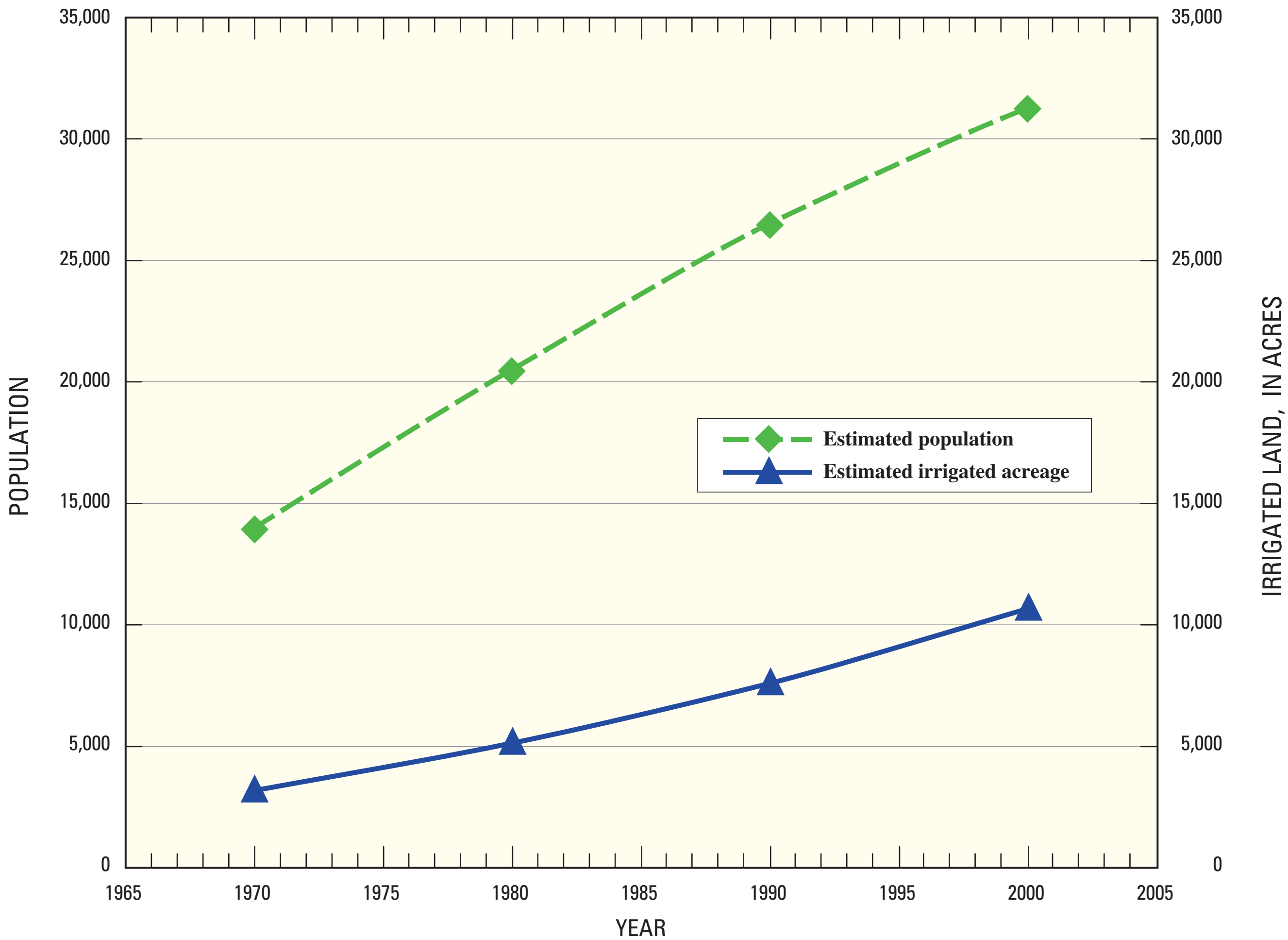

Figure G-4. Estimated population growth and irrigated lands in Sonoma Valley, Sonoma County, California.

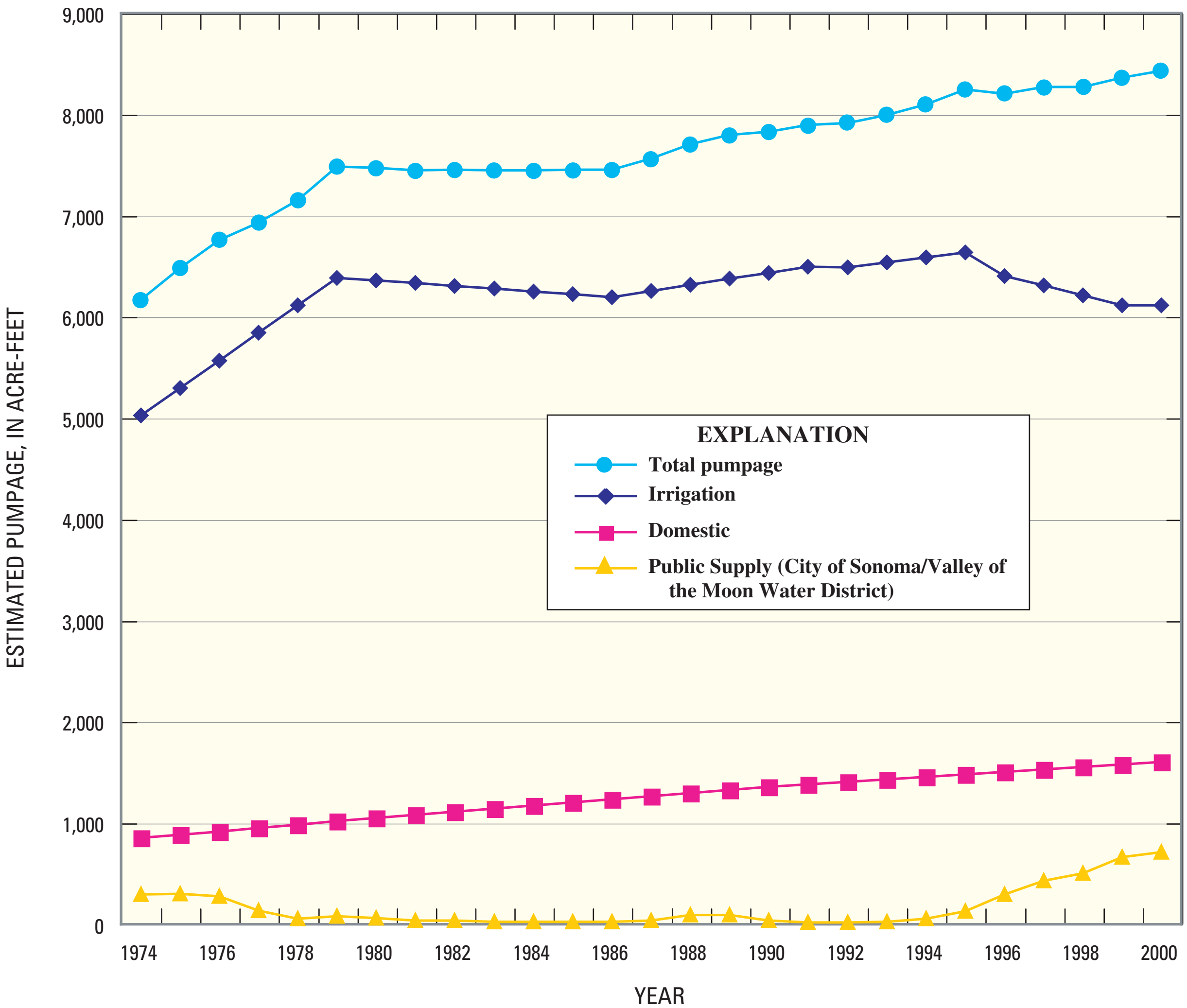

Figure G-5. Estimated pumpage by water-use type for Sonoma Valley, Sonoma County, California, 1974–2000.

Pumpage from Public-Supply Wells

Unlike pumpage for irrigation and private domestic use outside the VOM and the city of Sonoma purveyor areas (*fig. G-5*), a known record of pumpage for public-supply wells exists. Further, accurate well locations and general construction information is also known. Therefore, no estimations or interpolations were required. These data were used to assign the annual pumpage to a model grid cell and model layers using methods noted previously.

Summary of Results of Constructing a Pumpage File

The percent of total annual pumpage by water-use type is presented in *figure G-1* for the modeling period 1974 to 2000. By far, the largest demand on ground water in the modeling area is estimated to be for crop irrigation. Public-supply pumpage mostly comes from the VOM. Estimated pumpage in acre-feet is presented in *figure G-5*. The decline in irrigation demand from 1996 through 2000 is due to the introduction of reclaimed water replacing irrigation wells. It was estimated that reclaimed water deliveries ranged from about 400 acre/ft in 1996 to about 860 acre-ft in 2000. Total estimates of pumpage in acre-ft/yr by water-use type is presented in *table G-2*.

Table G-2. Estimated annual pumpage by year and water-use type for the Sonoma Valley area, Sonoma County, California, 1974–2000.

[All values are in acre-feet; VOM, Valley of the Moon Water District]

Use type	Year								
	1974	1975	1976	1977	1978	1979	1980	1981	1982
Irrigation	5,024	5,296	5,568	5,841	6,113	6,385	6,358	6,331	6,304
Domestic	851	884	917	950	984	1,017	1,051	1,081	1,112
Public supply (city of Sonoma/VOM)	293	301	274	138	54	78	62	35	35
Total pumpage in model area	6,168	6,481	6,760	6,929	7,151	7,480	7,471	7,447	7,451

Use type	Year								
	1983	1984	1985	1986	1987	1988	1989	1990	1991
Irrigation	6,277	6,249	6,222	6,195	6,254	6,314	6,374	6,434	6,494
Domestic	1,143	1,174	1,205	1,236	1,267	1,298	1,329	1,360	1,384
Public supply (city of Sonoma/VOM)	25	25	24	24	38	92	92	35	19
Total pumpage in model area	7,445	7,448	7,451	7,455	7,560	7,704	7,795	7,828	7,897

Use type	Year								
	1992	1993	1994	1995	1996	1997	1998	1999	2000
Irrigation	6,487	6,535	6,584	6,632	6,403	6,306	6,209	6,113	6,113
Domestic	1,409	1,434	1,458	1,483	1,508	1,532	1,557	1,581	1,606
Public supply (city of Sonoma/VOM)	19	26	54	129	292	429	501	664	710
Total pumpage in model area	7,914	7,995	8,096	8,244	8,203	8,268	8,267	8,358	8,429