

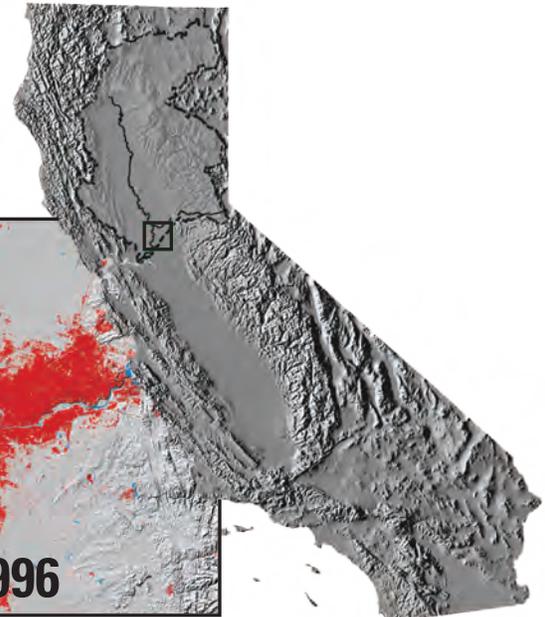
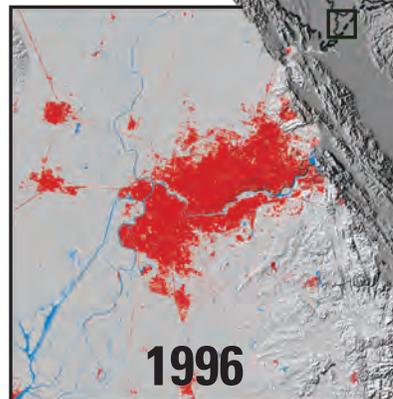
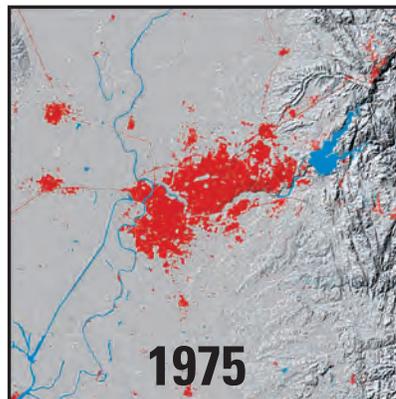
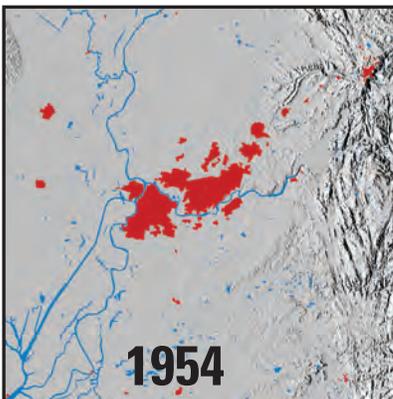
Assessment of Shallow Ground-Water Quality in Recently Urbanized Areas of Sacramento, California, 1998

NATIONAL WATER-QUALITY ASSESSMENT PROGRAM

Scientific Investigations
Report 2005-5148



Urban Growth



Urban growth maps on front cover from: Preliminary Assessment of Urban Growth in California's Central Valley at <http://ceres.ca.gov/calsip/cv/> (used with permission from William Acevedo, U.S. Geological Survey).

Assessment of Shallow Ground-Water Quality in Recently Urbanized Areas of Sacramento, California, 1998

By Jennifer L. Shelton

Scientific Investigations Report 2005-5148

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

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
million gallons per day (Mgal/d)	0.04381	cubic meter per second
square hectometer (hm ²)	2.471	acre
square kilometer (km ²)	247.1	acre
centimeter (cm)	0.3937	inch
meter (m)	3.281	foot
kilometer (km)	0.6214	mile
square kilometer (km ²)	0.3861	square mile
liter (L)	0.2642	gallon
cubic meter (m ³)	264.2	gallon
cubic meter per second (m ³ /s)	22.83	million gallons per day (Mgal/d)
kilogram (kg)	2.205	pound avoirdupois

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

$$^{\circ}\text{F} = (1.8 \times ^{\circ}\text{C}) + 32$$

Sea level: In this report, “sea level” refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929. Altitude, as used in this report, refers to distance above or below vertical datum.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius ($\mu\text{S}/\text{cm}$ at 25 °C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter ($\mu\text{g}/\text{L}$).

Abbreviations and Acronyms

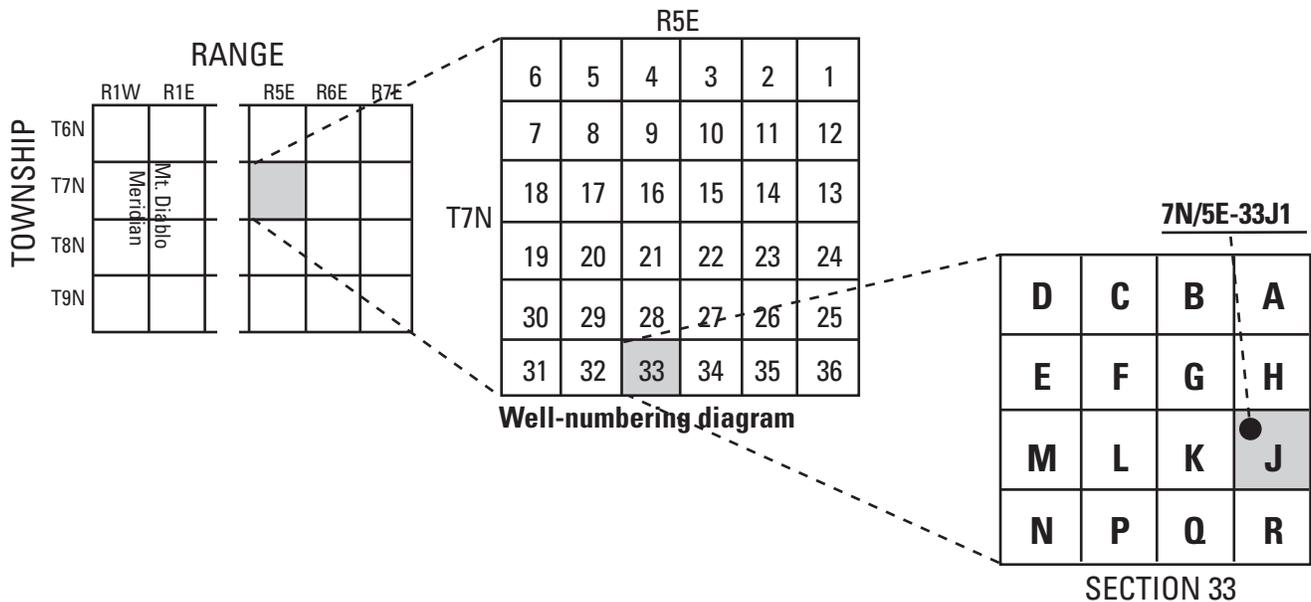
α , significance level
 cps, counts per second
 g/kg, gram per kilogram
 mL, milliliter
 mS/m, millisiemens per meter
 ppbv, parts per billion volume
 CA DHS, California Department of Health Services
 DOC, dissolved organic carbon
 E, estimated
 EM, electromagnetic
 GC/MS, gas chromatography/mass spectrometry
 HCl, hydrochloric acid
 HPLC, high-performance liquid chromatography
 LRL, laboratory reporting level
 LULC, land use land cover
 MCL, maximum contaminant level
 MTBE, methy *tert*-butyl ether
 NAWQA, National Water-Quality Assessment program
 NWQL, USGS National Water-Quality Laboratory
 NWIS, National Water Information System
 ODEX, down-hole air hammer rotary
 PCE, tetrachloroethene
 PVC, polyvinyl chloride

QC, quality control
 TDS, total dissolved solids
 TU, tritium unit
 USEPA, U.S. Environmental Protection Agency
 USGS, U.S. Geological Survey
 VOC, volatile organic compound

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. Wells in the study area are referenced to the Mount Diablo base line and meridian. Well numbers consist of 15 characters and follow the format 007N005E033J01M. In this report, well numbers are abbreviated and written 7N/5E-33J1.

The USGS station identification number for wells is principally for correlation and retrieval of computerized data and is not considered a State location number. Station 38245012153601, as an example, indicates latitude 38°24'50", longitude 121°25'36", and sequence 01.



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Assessment of Shallow Ground-Water Quality in Recently Urbanized Areas of Sacramento, California, 1998

By Jennifer L. Shelton

Abstract

Evidence for anthropogenic impact on shallow ground-water quality beneath recently developed urban areas of Sacramento, California, has been observed in the sampling results from 19 monitoring wells in 1998. Eight volatile organic compounds (VOCs), four pesticides, and one pesticide transformation product were detected in low concentrations, and nitrate, as nitrogen, was detected in elevated concentrations; all of these concentrations were below National and State primary and secondary maximum contaminant levels. VOC results from this study are more consistent with the results from urban areas nationwide than from agricultural areas in the Central Valley, indicating that shallow ground-water quality has been impacted by urbanization. VOCs detected may be attributed to either the chlorination of drinking water, such as trichloromethane (chloroform) detected in 16 samples, or to the use of gasoline additives, such as methyl *tert*-butyl ether (MTBE), detected in 2 samples. Pesticides detected may be attributed to use on household lawns and gardens and rights-of-way, such as atrazine detected in three samples, or to past agricultural practices, and potentially to ground-water/surface-water interactions, such as bentazon detected in one sample from a well adjacent to the Sacramento River and downstream from where bentazon historically was used on rice. Concentrations of nitrate may be attributed to natural sources, animal waste, old septic tanks, and fertilizers used on lawns and gardens or previously used on agricultural crops. Seven sample concentrations of nitrate, as nitrogen, exceeded 3.0 milligrams per liter, a level that may indicate impact from human activities.

Ground-water recharge from rainfall or surface-water runoff also may contribute to the concentrations of VOCs and pesticides observed in ground water. Most VOCs and pesticides detected in ground-water samples also were detected in air and surface-water samples collected at sites within or adjacent to the recently developed urban areas.

Five arsenic sample concentrations exceeded the U.S. Environmental Protection Agency (USEPA) primary maximum contaminant level (MCL) of 10 milligrams per liter adopted in 2001. Measurements that exceeded USEPA or California Department of Health Services recommended

secondary maximum contaminant levels include manganese, iron, chloride, total dissolved solids, and specific conductance. These exceedances are probably a result of natural processes.

Variations in stable isotope ratios of hydrogen ($^2\text{H}/^1\text{H}$) and oxygen ($^{18}\text{O}/^{16}\text{O}$) may indicate different sources or a mixing of recharge waters to the urban ground water. These variations also may indicate recharge directly from surface water in one well adjacent to the Sacramento River. Tritium concentrations indicate that most shallow ground water has been recharged since the mid-1950s, and tritium/helium-3 age dates suggest that recharge has occurred in the last 2 to 30 years in some areas. In areas where water table depths exceed 20 meters and wells are deeper, ground-water recharge may have occurred prior to 1950, but low concentrations of pesticides and VOCs detected in these deeper wells indicate a mixing of younger and older waters.

Overall, the recently urbanized areas can be divided into two groups. One group contains wells where few VOCs and pesticides were detected, nitrate mostly was not detected, and National and State maximum contaminant levels, including the USEPA MCL for arsenic, were exceeded; these wells are adjacent to rivers and generally are characterized by younger water, shallow (1 to 4 meters) water table, chemically reducing conditions, finer grained sediments, and higher organics in the soils. In contrast, the other group contains wells where more VOCs, pesticides, and elevated nitrate concentrations were detected; these wells are farther from rivers and are generally characterized by a mixture of young and old waters, intermediate to deep (7 to 35 meters) water table due to ground-water pumpage, oxygenated ground water, and coarser grained sediments.

Nitrate and specific conductance data for shallow wells sampled from 1970–98 in Sacramento County were compiled to examine the effects of urbanization on ground-water quality over the time since urban development has taken place. These data show that nitrate concentrations increased from the 1980s to the 1990s. This result may be due to the higher number of shallow wells that were sampled in the 1990s than in previous decades.

Introduction

Increasing rates of urbanization may affect the quality of ground water and could potentially contribute to the degradation of drinking-water resources. The effects of urban development on ground-water quality were assessed by the presence or absence of anthropogenic compounds associated with urban land use or by identifying elevated concentrations of naturally occurring compounds that may result from activities associated with urban land use. Ground-water quality beneath urban areas has been assessed in other U.S. Geological Survey studies throughout the United States (Berndt and others, 1998; Bevan and others, 1998; Dennehy and others, 1998; Wall and others, 1998; Land and others, 1999; Squillace and others, 1999). In these studies, the effects of urban development on ground-water quality were identified generally by the detection of volatile organic compounds, pesticides, and (or) elevated nitrate, trace-element, or dissolved organic carbon concentrations.

Ground water is a significant source of drinking water and agricultural supply in the Sacramento Valley, California, located in the central part of the Sacramento River Basin and the northern part of the Central Valley (*fig. 1*). The quality of ground water in the Sacramento Valley has been studied and evaluated for domestic and agricultural uses (Bader, 1967; California Department of Water Resources, 1974, 1978; Fogelman, 1976, 1978; Johnson, 1985; Bertoldi and others, 1991), but these studies have not addressed the quality of shallow ground water associated with urban land use in the metropolitan area of Sacramento.

The purpose of this study was to assess the quality of shallow ground water in newly developed urban areas—defined as residential and commercial areas for the purposes of this study—and to evaluate the factors that may affect ground-water quality. Urban areas developed between 5 and 25 years ago were selected because it takes some time for new development to affect shallow ground-water quality and because urban areas developed more than 25 years ago may have undergone multiple land-use changes, which would make it difficult to assess the effects of recent urban development. Understanding the shallow ground-water quality beneath newly developing urban areas is important for planning and implementing wellhead protection of municipal and private supply wells. An assessment of shallow ground-water quality in these newly developed urban areas also may assist in locating wells needed for future drinking-water supplies by assessing the potential effects on deeper ground-water quality.

This study is one of the U.S. Geological Survey (USGS) National Water-Quality Assessment (NAWQA) Program

ground-water studies in the Sacramento River Basin. The NAWQA Program is designed to assess the status of and trends in the quality of the Nation's ground- and surface-water resources and to link the status and trends with an understanding of the natural and human factors that affect the quality of water (Gilliom and others, 1995). As part of the NAWQA Program design, the focus of this study was to target areas of recently recharged ground water in metropolitan urban areas developed during the last 5 to 25 years. Population density has been related to contamination of shallow ground water (Squillace and Price, 1996), and therefore NAWQA has given large metropolitan areas priority for urban land-use studies. Sacramento is the largest city in the Sacramento River Basin and was selected for an urban land-use study because it has a high population density, depth to water is relatively shallow, and ground water is thought to be connected to surface waters used for public supply (Domagalski and others, 1998).

Purpose and Scope

The purpose of this report is to describe the quality of shallow ground water beneath primarily residential areas developed 5 to 25 years ago in the Sacramento metropolitan area and to examine natural and human factors that may affect the presence of selected chemical constituents. This report presents the results of analyses of volatile organic compounds (VOCs), pesticides, elevated nitrate concentrations, and exceedances of U.S. Environmental Protection Agency (USEPA) or California Department of Health Services (CA DHS) primary and secondary maximum contaminant levels (MCLs). Results were compared to earlier agricultural studies in the Central Valley and agricultural and urban studies nationwide. Characteristics with the potential to indicate vulnerability to contamination such as depth to water, well depth, soil texture and chemistry, alluvial sediment texture, and ground-water age and chemistry were examined.

A total of 19 monitoring wells were sampled in the summer of 1998. The entire data set for these wells is given by Domagalski and others (2000).

Acknowledgments

This study could not have been completed without the cooperation of the following park districts, which allowed the USGS to install and sample monitoring wells on their properties: City of Sacramento, Neighborhood Services Department; Elk Grove Community Services District, Department of Parks and Recreation; and Sunrise Park and Recreation District.

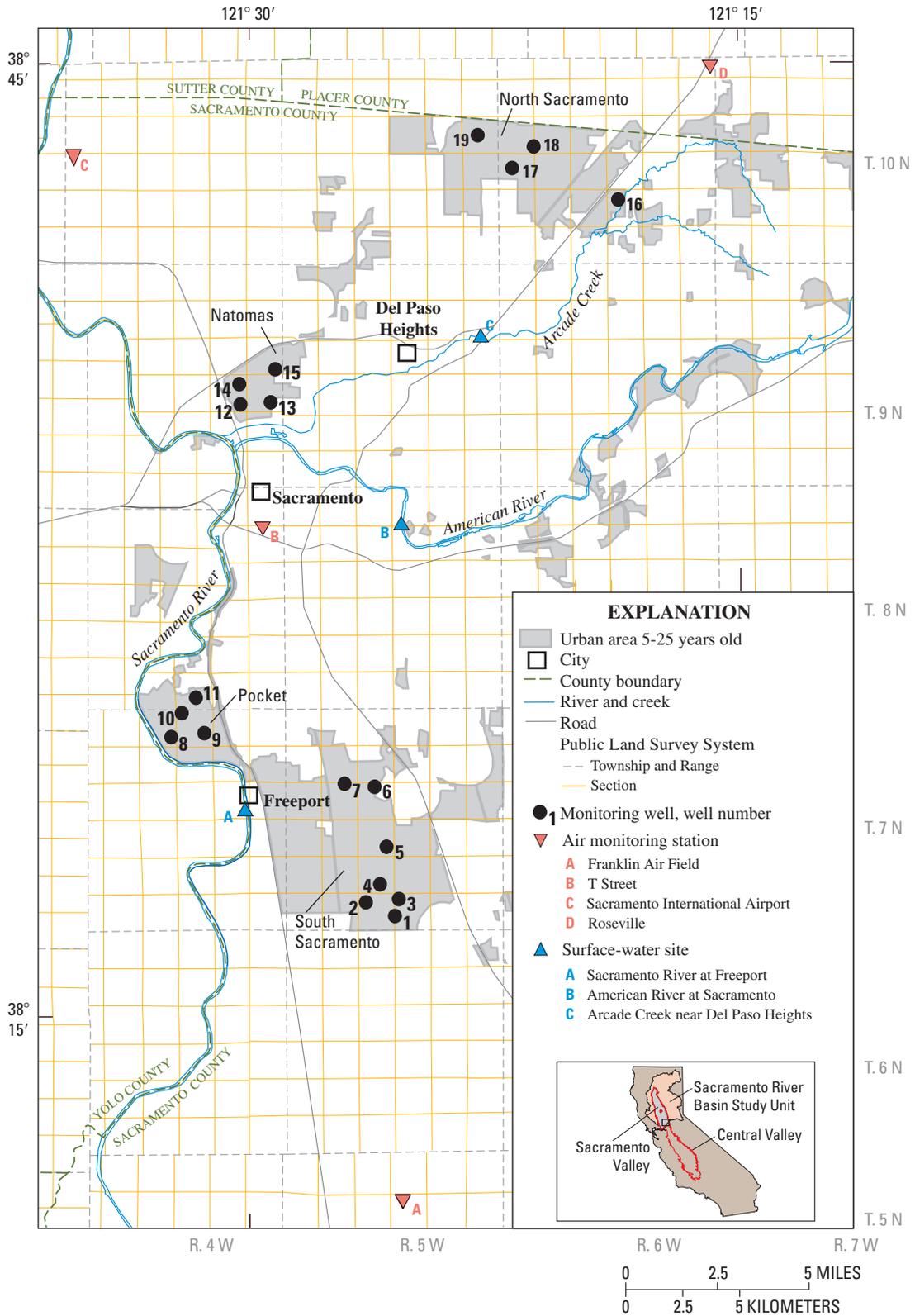


Figure 1. Location of sampling sites and study area (5- to 25-year-old urban areas), Sacramento, California.

Description of the Urban Study Area

As part of the NAWQA study design, the urban study area includes primarily residential areas developed 5 to 25 years ago in the Sacramento metropolitan area. The urban study area is located in the southern part of the Sacramento River Basin and predominantly within Sacramento County (*fig. 1*). For this report, four subareas have been defined on the basis of the location of wells. They will be referred to as the south Sacramento area (wells 1–7), the Pocket area (wells 8–11), the Natomas area (wells 12–15), and the north Sacramento area (wells 16–19). The environmental setting can influence ground-water quality and is briefly described in this section for the urban study area and the surrounding Sacramento County area. The environmental setting for the Sacramento River Basin is described in detail by Domagalski and others (1998).

Climate

Average annual precipitation for Sacramento County is 46 cm (Earthinfo, 1996), but extremes ranged from 18 cm in 1976 to 96 cm in 1983. Eighty-eight percent of the long-term average annual precipitation falls between November and April. Temperature extremes in Sacramento County ranged from -7.8°C to 46°C between 1961 and 1990 (Western Regional Climate Center, 1997). A normal year evapotranspiration value, based on long-term records of climatic data, for Sacramento County is approximately 132 cm (California Department of Water Resources, 1992). Fluctuations in rainfall and temperature can affect the quality of ground water by influencing the amount of volatile organic compounds (VOCs) in rainfall, volatilization of VOCs to the atmosphere, seasonal loadings of pesticides in rainfall, and relative amounts of runoff and infiltration. Sorption and denitrification processes also may be affected by the climate and can affect the likelihood of detecting VOCs, pesticides, or nitrate. Precipitation, soil characteristics, and evapotranspiration data can be used to estimate a recharge rate and the traveltime that it would take for water to reach the water table.

Population

In the 1980s the population growth rate in the greater Sacramento region was greater than the growth rate for the State of California (Sacramento Area Commerce Trade Organization, 1998). In 1980, the population of Sacramento County was about 783,000; by 1995, it had increased to more than 1,100,000, a 41-percent increase. The Sacramento County

population increased 17.5 percent from 1,041,219 to 1,223,499 between 1990 and 2000 (U.S. Bureau of Census, 2005).

The study area has been divided into primarily large census blocks by the U.S. Bureau of Census (1991), as shown by the 1990 census data (*fig. 2A,B*). Total population in each census block was greater than 5,000 people in 1990 for most of the study area (*fig. 2A*). Population density by census block ranged from 100 to 5,000 people per km^2 over most of the study area in 1990 (*fig. 2B*). The south Sacramento area in the southern part of the study area has the least number of people per area (100–499 people per km^2), which may reflect the least amount of urban development and a change in land use from agriculture to urban that is still in progress.

Land and Water Use

Between 1975 and 1993, the amount of land area used for agriculture decreased as the urban population increased and spread outward from the center of Sacramento. In 1975, the recently urbanized areas studied in this report were almost entirely cropland and pasture except for a few small areas of urban use and rangeland, and very small areas of confined feeding operations (*fig. 3*). By 1993, land use in the study area was almost all urban (*fig. 4*). Urban development in the southern Sacramento area is the most recent compared to other parts of the urban study area. Land use in the study area is primarily residential; however, some agricultural land-use areas still surround urban areas and areas adjacent to the Sacramento River.

Total fresh-water use in Sacramento County in 1995 was about $3.3 \times 10^6 \text{ m}^3/\text{d}$ (876 Mgal/d); 40 percent was supplied by ground water (U.S. Geological Survey, 1995). Public-supplied water accounted for about 38 percent of the total water use, of which ground water supplied about 44 percent ($0.55 \times 10^6 \text{ m}^3/\text{d}$ or 145 Mgal/d). Self-supplied water accounted for about 62 percent of the total water use, of which ground water supplied about 37 percent ($0.76 \times 10^6 \text{ m}^3/\text{d}$ or 201 Mgal/d). Public-supplied water is withdrawn by water suppliers and delivered to users for a variety of uses, such as domestic, commercial, industrial, and public water use (Solley and others, 1998). Self-supplied water is withdrawn from a surface- or ground-water source by a user and was used primarily for irrigation, commercial, industrial, and livestock water uses. Irrigation accounted for about 51 percent of the total water use and irrigated about 640 km^2 (158,000 acres). Ground water supplied about 37 percent ($0.63 \times 10^6 \text{ m}^3/\text{d}$ or 166 Mgal/d) of the water used for irrigation.

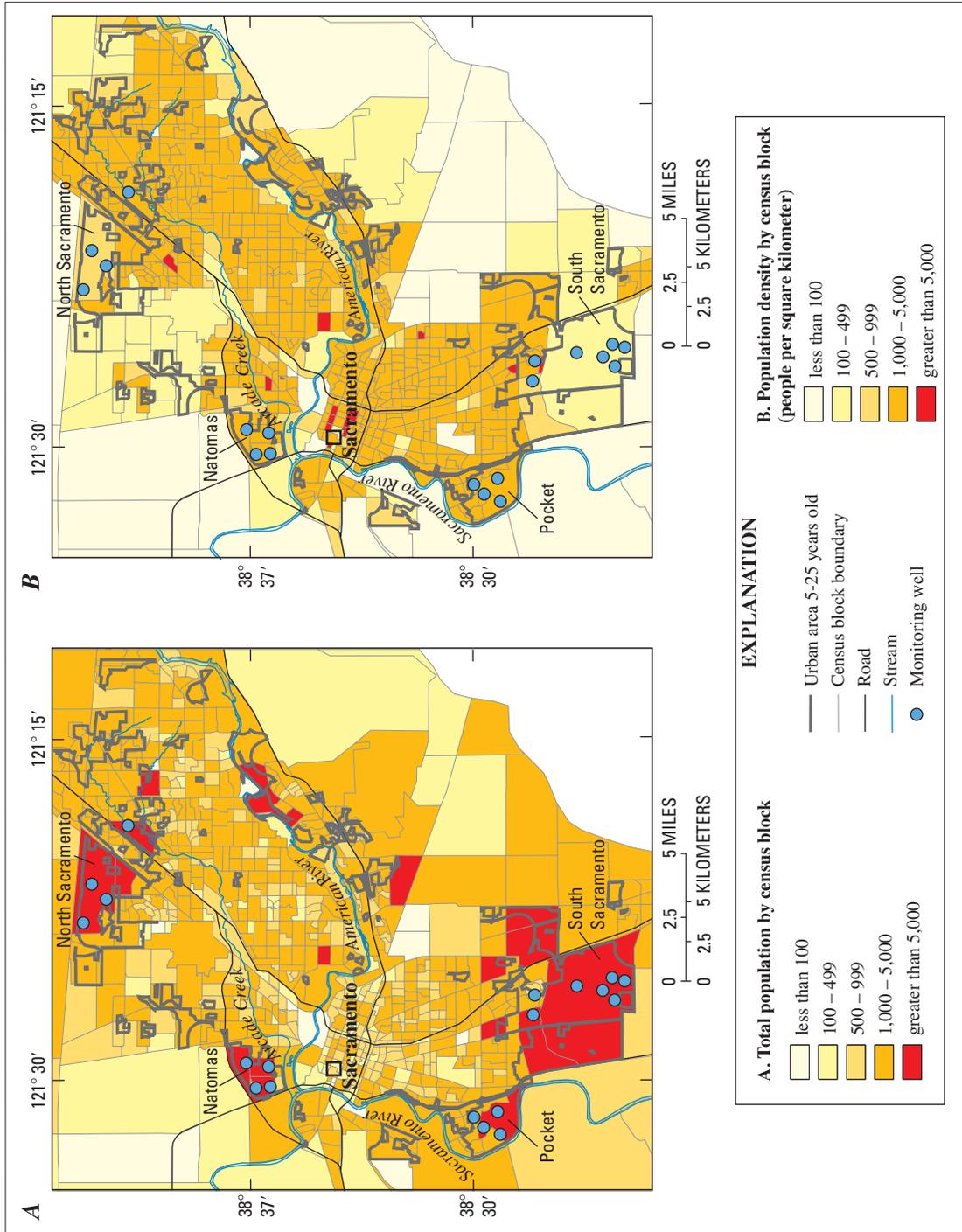


Figure 2. Total population (A) and population density (B) by census block boundaries in 1990, Sacramento, California (data from U.S. Bureau of Census, 1991).

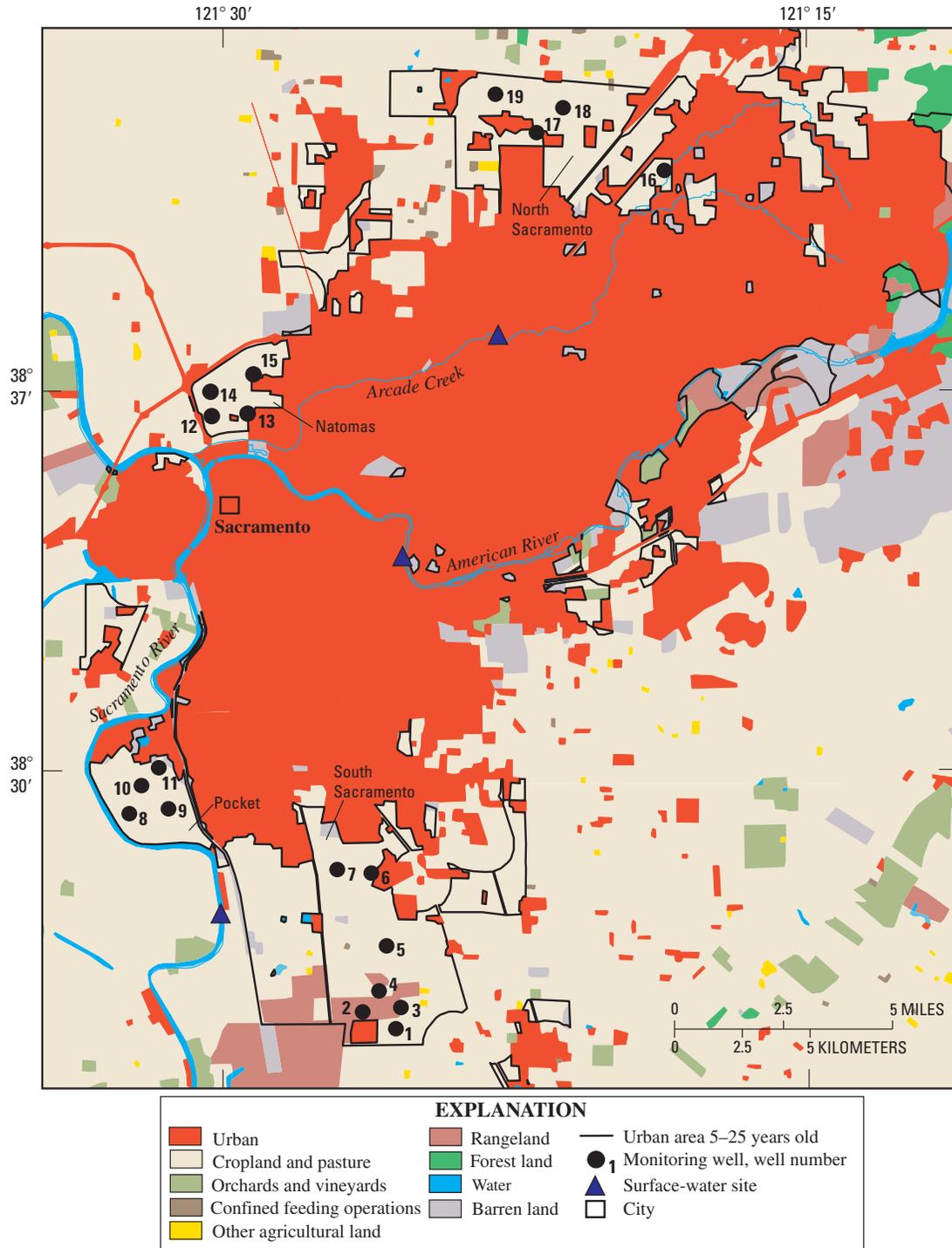


Figure 3. Types of land use in 1975, Sacramento, California (data from Geographic Information Retrieval and Analysis System or GIRAS) (from U.S. Geological Survey, 1998).

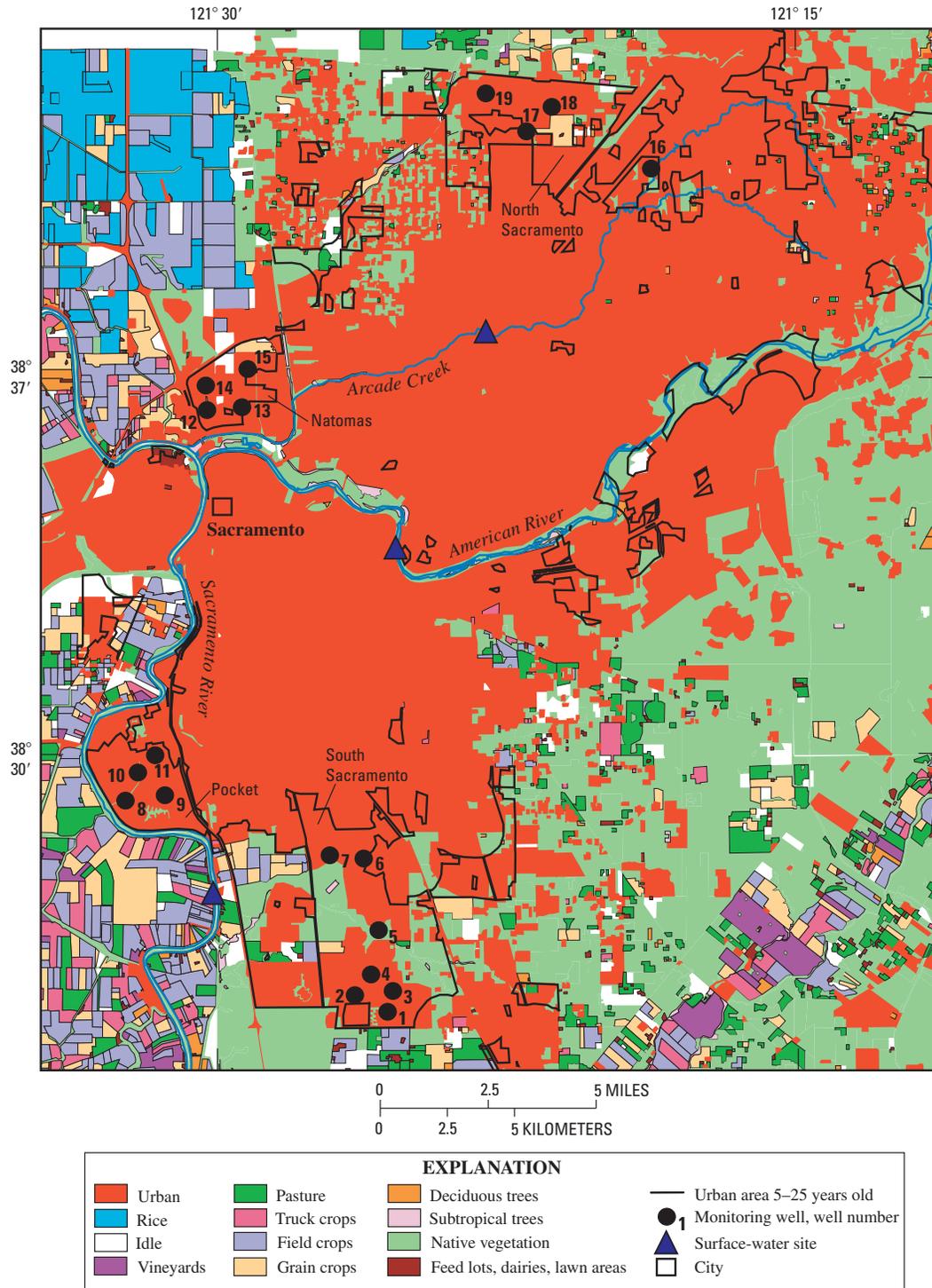


Figure 4. Types of land use in 1993, Sacramento, California (from California Department of Water Resources, 1993).

Two water-use categories in the USGS Water Use Program contribute to the total urban water use as defined by this report—domestic and commercial. Domestic water use accounted for about 28 percent of the total water use, of which ground water supplied about 44 percent (0.41×10^6 m³/d or 108 Mgal/d) in 1995 in Sacramento County. Domestic water use is water used for household purposes, such as indoor plumbing, drinking water, and lawn and garden irrigation. More than 99 percent of the domestic water use was public supplied and it served about 1,115,000 people. Commercial water use accounted for about 11 percent of the total water use, of which 44 percent (0.076×10^6 m³/d or 20 Mgal/d) was supplied by ground water. Water used for commercial purposes was supplied almost equally by public suppliers (0.17×10^6 m³/d or 46 Mgal/d) and self suppliers (0.18×10^6 m³/d or 47 Mgal/d), but surface water was the sole source of the self-supplied commercial water use.

Hydrogeology

The study area is located primarily east of the Sacramento River, in the southeast part of the Sacramento Valley. The Sacramento Valley occupies the northern third of the Central Valley, an asymmetric structural trough filled with hundreds of meters of sediment derived primarily from the Sierra Nevada to the east of the Sacramento River and from the Coast Ranges to the west (Page, 1986). Piper and others (1939), Olmsted and Davis (1961), and Page (1986) have described Sacramento Valley geology, but the smallest scale of surficial geologic units is described by Helley and Harwood (1985) and is summarized below.

There are four different types of Quaternary surficial geologic deposits in the study area (*fig. 5*). These include the lower member of the Riverbank Formation consisting of red semiconsolidated gravel, sand, and silt; undivided Basin deposits consisting of fine-grained silt and clay; alluvium consisting of unweathered gravel, sand, and silt; and the Turlock Lake Formation consisting of deeply weathered and dissected arkosic gravels with minor resistant metamorphic rock fragments and quartz pebbles, sand, and silt (Helley and Harwood, 1985). Soils are predominantly fine grained with slow to very slow infiltration rates (Tugel, 1993).

The top 60 m of the aquifer generally is unconfined (Bertoldi and others, 1991), but because of the discontinuity of clay lenses, there is not a well-defined lower boundary for the unconfined interval. Water-level information for the urban study area is minimal. Regional water-level data from 1977 to 1995 for the Sacramento County area indicate that depth to water from land surface (water table depth) varies from less

than 1.5 m to greater than 69 m in areas with high pumping rates (Eric Senter, California Department of Water Resources, computer files and written commun., 1997). A map of equal elevation of ground-water levels for the spring of 1968 (California Department of Water Resources, 1974) indicates that pumping depressions have a maximum depth of only 15 m, in contrast to the data from 1977 to 1995 that indicate pumping depressions as deep as about 61 m. Thus, shallow ground-water levels have declined significantly in some areas since recent urban development has occurred.

Study Design and Methods

An important goal for the NAWQA program is to be able to compare results from study areas across the Nation. This is accomplished by using a nationally consistent study design and nationally consistent data collection protocols, described below.

Delineation of the Urban Land-Use Study Area

Five- to twenty-five-year-old urban land-use areas were delineated from a national database of land-use and land-cover (LULC) digital data and 1990 census block data (Anderson and others, 1976; Hitt, 1994; U.S. Geological Survey, 1998). The LULC data represent the highest resolution, nationally consistent classification of land use and land cover available in 1997 (when data were compiled for this study) for the United States (Gilliom and Thelin, 1997). LULC land-use data were derived from polygons of land use and land cover that were determined from the photo interpretation of color-infrared aerial photographs taken in the mid-1970s. The study area consists of formerly nonurban land-use areas identified from the LULC data for 1975 (*fig. 3*) that were converted to urban land use as indicated by 1990 census block data (Hitt, 1994). This procedure for delineating recently urbanized areas was checked against a 1993 land-use map produced by the California Department of Water Resources (*fig. 4*). The comparison verifies NAWQA's minimum 5-year-old age requirement by showing the presence of urban land use in 1993 (5 years before sampling in 1998). According to NAWQA design, the central downtown, industrial areas, railroads, freeways, and areas of known point-source contamination were avoided in order to better assess the effects of recently urbanized land use on ground-water quality.

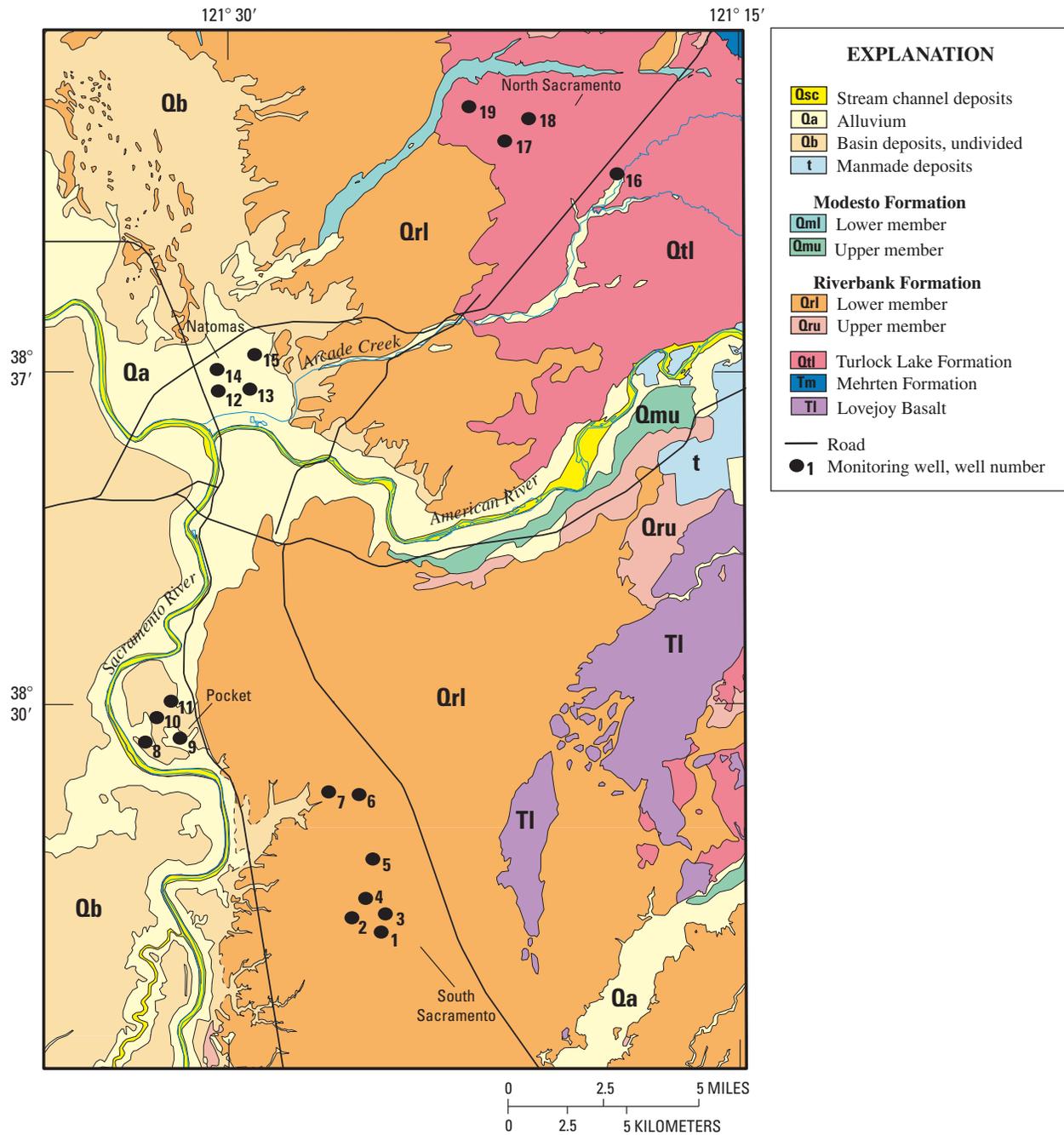


Figure 5. Surficial geology in Sacramento, California (from Helley and Harwood, 1985).

Well Site Selection, Installation, and Construction

A ground-water monitoring network consisting of 19 randomly distributed shallow wells (*fig. 6*) was established. A computer program (Scott, 1990) was used to divide the urban land-use study area into equal-area units, or cells, and an attempt was made to locate a potential drill site in each cell. After equal-area cells were determined, the area was field checked to verify the presence of urban land use. As a result of field verification, the western half of the South Sacramento subarea was eliminated (*fig. 6*) because it contained mostly agricultural land use. Potential drill sites were identified at sites that contained a minimum threshold of 75 percent or greater residential and (or) commercial land use within a 500-m radius (Squillace and Price, 1996). These procedures reduced the area to be included in the study area and resulted in the target areas where wells were drilled. All sites were located in small local parks and greenbelts with little to no development, surrounded by residential and school land uses and a small amount of commercial land use.

Prior to drilling, water-level data were obtained from the California Department of Water Resources to determine the lowest known water-table depth in the targeted urban study area (Eric Senter, California Department of Water Resources,

computer files and written commun., 1997). Water-table maps were created for spring and winter periods for wells screened in the unconfined aquifer. Driller's logs also were compiled for other wells drilled in the same vicinity as the targeted drill sites and screened in the unconfined aquifer to obtain the lowest known water levels in the study area. Although ancillary water-level data for the targeted drill site areas were sparse, the data were used as a guide to estimate the lowest known water-table depth in the vicinity of the drill sites. As part of NAWQA protocol (Squillace and Price, 1996), wells were drilled to a depth estimated to place screened intervals 1.5 m below the lowest known water-table depth. Well depths range from 11.1 to 61.0 m below land surface.

Three different drilling methods were used during construction of the new wells (*table 1*). Most of the wells (14 out of 19) were augered because this method is least invasive to the aquifer materials. Mud rotary drilling was necessary for four wells in areas with deeper water tables. At these wells, a sodium bromide tracer was added to the drilling mud to identify and minimize the presence of drilling mud left behind in the formation. After construction, wells were pumped until the concentration of the tracer was below one part per million. The down-hole air hammer (ODEX) drilling method was used to install one well when aquifer materials were too coarse to auger. An air filter was used with the ODEX equipment to filter out contamination from lubricants.

Table 1. Location and construction information for monitoring wells sampled in recently urbanized areas of Sacramento, California.

[See *fig. 1* for well locations. State well no.: See well-numbering diagram on p. ix. Altitude of land surface is in meters above National Geodetic Vertical Datum of 1929 (NGVD29). ODEX, down-hole air hammer rotary]

Well number	State well number	USGS station number	Subarea	Altitude of land surface (meters)	Depth to water (meters)	Depth to top of screened interval (meters)	Depth to bottom of screened interval (meters)	Drilling method
1	7N/5E-33J1	382450121253601	South Sacramento	7.9	27.2	35.7	40.2	Auger
2	7N/5E-33D1	382515121262501	South Sacramento	7.0	20.4	25.6	30.2	Auger
3	7N/5E-34D1	382517121252601	South Sacramento	8.2	25.8	26.5	31.1	Auger
4	7N/5E-28Q1	382537121260001	South Sacramento	7.3	20.6	27.0	31.5	Auger
5	7N/5E-21R1	382629121254801	South Sacramento	5.2	16.0	18.6	20.1	Auger
6	7N/5E-16C1	382757121261101	South Sacramento	4.9	12.0	14.8	17.8	Auger; ODEX
7	7N/5E-17B1	382800121270701	South Sacramento	3.7	7.13	8.23	11.3	Auger
8	7N/3E-4J1	382906121322201	Pocket	1.2	2.45	6.70	9.75	Auger
9	7N/4E-3K2	382911121312301	Pocket	2.1	1.40	8.38	9.91	Auger
10	8N/3E-3D1	382941121320501	Pocket	1.2	1.09	6.86	9.91	Auger
11	8N/4E-34K1	383000121313601	Pocket	1.2	1.65	7.01	10.1	Auger
12	9N/4E-23R2	383655121301601	Natomas	4.3	2.92	10.0	13.1	Auger
13	9N/4E-24Q1	383659121292201	Natomas	4.3	4.65	8.38	11.4	Auger
14	9N/4E-23A1	383727121301801	Natomas	3.7	3.42	8.08	9.60	Auger
15	9N/4E-13R1	383746121291101	Natomas	3.7	4.14	8.23	11.3	Auger
16	10N/6E-27F1	384145121184101	North Sacramento	37.2	43.3	55.8	58.8	Mud rotary
17	10N/6E-19F1	384234121215601	North Sacramento	41.1	49.2	50.6	53.6	Mud rotary
18	10N/6E-18R1	384303121211701	North Sacramento	41.1	52.7	54.9	59.4	Mud rotary
19	10N/5E-13F1	384318121230001	North Sacramento	32.3	39.5	46.0	49.1	Mud rotary

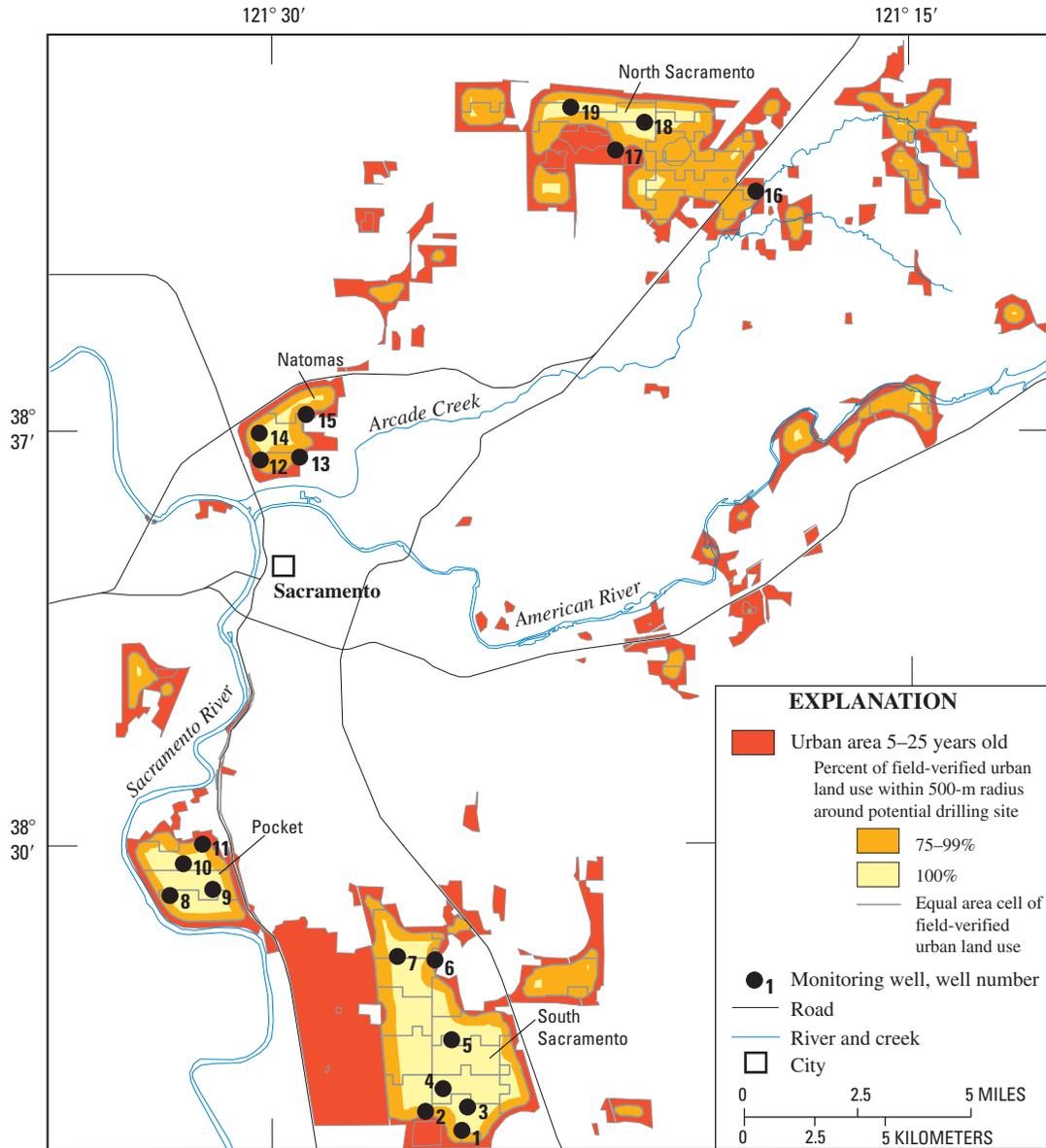


Figure 6. Urban land-use study area and the resulting monitoring well network, Sacramento, California.

Wells were completed using a 5-cm-diameter, threaded, schedule-40 PVC (polyvinyl chloride) casing, which, along with drilling equipment, was steam cleaned prior to installation. Well screen intervals were 1.5 to 4.6 m in length; variations occurred due to the presence or lack of available water-level information needed to place the screened interval 1.5 m below the lowest known water table and (or) on-site drilling observations indicating possible low yielding wells. All wells were pumped until turbidity measurements stabilized at a relatively low level (usually one Formazin turbidity unit) or, for the mud rotary completed wells, until drilling-mud tracer concentrations fell below one part per million. Full details of well installation protocols are given by Lapham and others (1995).

Sample Collection and Analyses

Aquifer characteristics were defined by the collection and analysis of soil samples, drill cuttings descriptions, and evaluation of borehole geophysical logs at each well. These characteristics were used to better explain the factors influencing the presence or absence of contaminants. Water samples were collected from each well to assess the quality of shallow ground water, to investigate stable isotopic signatures that may indicate recharge patterns, and to estimate the age of the water.

Sediment Samples

Samples of surface soil and drill cuttings were collected to measure soil pH, determine the percentage of organic and inorganic carbon, and characterize the sediment texture. Sediment samples were collected for these analyses during well drilling from all wells except the mud rotary drilled wells in the north Sacramento area. County soil survey data were compiled for each well site to provide a complete data set.

Soil pH was measured with an Orion model 250A portable pH meter after mixing sediment samples with deionized water on a one-to-one weight basis. Sediment samples were sent to the USGS National Water Quality Laboratory (NWQL) to analyze for the percentage of organic and inorganic carbon, using standard methods (Wershaw and others, 1987). These data were collected to explain possible degradation mechanisms for certain volatile organic compounds (VOCs).

Drill cuttings were collected and observations of drilling-equipment response were recorded to provide information on lithology, mineralogy, grain-size distribution, moisture content, and permeability. Electromagnetic (EM) induction, and natural-gamma geophysical logs also were used to characterize aquifer texture at each well.

Ground-Water Samples

Ground-water samples were collected from the 19 wells in the summer of 1998, using protocols developed by the NAWQA Program and adopted by the USGS to minimize contamination during sampling and to promote the collection of high-quality, consistent ground-water data among NAWQA study areas throughout the Nation (Koterba and others, 1995; U.S. Geological Survey, variously dated). Prior to sample collection, pH, dissolved oxygen, specific conductance, temperature, and turbidity were measured until values or concentrations were stable, generally after pumping three casing volumes. Samples were collected after each well was purged to ensure that the sample was from ground water in the aquifer and not from water stored in the well casing. A Grundfos Redi-Flow submersible impeller pump with collection lines made of Teflon was used to sample each well. These collection lines minimize cross-contamination from organic compounds. Samples were collected and preserved inside chamber bags to minimize airborne contamination. After collection, samples were stored in ice chests and mailed to the laboratory using overnight delivery to minimize changes in water chemistry until they could be analyzed.

Samples were analyzed for a variety of constituents, including VOCs, pesticides, nutrients, major ions, trace elements, dissolved organic carbon, stable isotopes, tritium, and tritium/helium-3. Most analyses were completed at the NWQL except for stable isotopes, which were analyzed at the USGS Stable Isotope Laboratory in Reston, Virginia, and tritium and tritium/helium-3, which were analyzed at the Lamont-Doherty Earth Observatory of Columbia University.

Unfiltered samples were collected in triplicate and analyzed for a suite of 86 VOCs (*table 2*). These samples were preserved with hydrochloric acid (HCl) in 40-mL vials with lids designed to minimize loss from volatilization. VOC samples were analyzed using a gas chromatograph/mass spectrometer (GC/MS) purge-and-trap method (Connor and others, 1998). This method was improved to allow the reporting of semiquantitative results for VOCs identified by the method but detected at a concentration below laboratory reporting level (LRL). Concentrations below LRLs were reported as estimated (E), indicating that they were present in the sample but the concentrations were estimated.

Pesticide samples were collected and filtered using a 0.7-micron baked glass-fiber filter to obtain two approximately 1-L samples for the analysis of 83 compounds (*table 3*). Two methods were used to analyze each pesticide sample: 47 compounds were analyzed using C-18 solid-phase extraction and capillary column GC/MS (Lindley and others, 1994; Zaugg and others, 1995), and 39 compounds were analyzed using Carbopak-B solid-phase extraction and high-performance liquid chromatography (HPLC) (Werner and others, 1996). Three compounds are included in the suites analyzed in both methods: carbaryl, carbofuran, and linuron.

Table 2. Volatile organic compounds analyzed in ground-water samples, Sacramento, California.

[IUPAC, International Union of Pure and Applied Chemistry nomenclature; CAS #, Chemical Abstract Service number; [0.044], laboratory reporting level, in microgram per liter]

IUPAC name, by compound class	CAS #	IUPAC name, by compound class	CAS #
Halogenated alkanes			
1,1,1,2-Tetrachloroethane [0.044]	630-20-6	Bromodichloromethane [0.048]	75-27-4
1,1,1-Trichloroethane [0.032]	71-55-6	Bromomethane [0.15]	74-83-9
1,1,2,2-Tetrachloroethane [0.13]	79-34-5	Chlorodibromomethane [0.18]	124-48-1
1,1,2-Trichloro-1,2,2-trifluoroethane [0.32]	76-13-1	Chloroethane [0.12]	75-00-3
1,1,2-Trichloroethane [0.064]	79-00-5	Chloromethane (Methyl chloride) [0.25]	74-87-3
1,1-Dichloroethane [0.066]	75-34-3	Dibromomethane [0.05]	74-95-3
1,2,3-Trichloropropane [0.16]	96-18-4	Dichlorodifluoromethane (CFC 12) [0.14]	75-71-8
1,2-Dibromo-3-chloropropane (DBCP) [0.21]	96-12-8	Dichloromethane (Methylene chloride) [0.38]	75-09-2
1,2-Dibromoethane (EDB) [0.036]	106-93-4	Hexachloroethane [0.36]	67-72-1
1,2-Dichloroethane [0.13]	107-06-2	Iodomethane (Methyl Iodide) [0.21]	74-88-4
1,2-Dichloropropane [0.068]	78-87-5	Tetrachloromethane (Carbon tetrachloride) [0.088]	56-23-5
1,3-Dichloropropane [0.12]	142-28-9	Tribromomethane (Bromoform) [0.1]	75-25-2
2,2-Dichloropropane [0.078]	594-20-7	Trichlorofluoromethane (CFC 11) [0.09]	75-69-4
Bromochloromethane [0.044]	74-97-5	Trichloromethane (Chloroform) [0.052]	67-66-3
Halogenated alkenes			
1,1-Dichloroethene [0.044]	75-35-4	Trichloroethene (TCE) [0.038]	79-01-6
1,1-Dichloropropene [0.026]	563-58-6	<i>cis</i> -1,2-Dichloroethene [0.038]	156-59-2
3-Chloropropene (Allyl chloride) [0.2]	107-05-1	<i>cis</i> -1,3-Dichloropropene [0.09]	10061-01-5
Bromoethene (Vinyl bromide) [0.1]	593-60-2	<i>trans</i> -1,2-Dichloroethene [0.032]	156-60-5
Chloroethene (Vinyl chloride) [0.11]	75-01-4	<i>trans</i> -1,3-Dichloropropene [0.13]	10061-02-6
Hexachlorobutadiene [0.14]	87-68-3	<i>trans</i> -1,4-Dichloro-2-butene [0.7]	110-57-6
Tetrachloroethene (PCE) [0.10]	127-18-4		
Aromatic hydrocarbons			
Benzene [0.10]	71-43-2	Styrene [0.042]	100-42-5
Naphthalene [0.25]	91-20-3		
Alkyl benzenes			
1,2,3,4-Tetramethylbenzene [0.23]	488-23-3	Ethylbenzene [0.03]	100-41-4
1,2,3,5-Tetramethylbenzene [0.24]	527-53-7	Isopropylbenzene [0.032]	98-82-8
1,2,3-Trimethylbenzene [0.12]	526-73-8	Methylbenzene (Toluene) [0.05]	108-88-3
1,2,4-Trimethylbenzene [0.056]	95-63-6	<i>n</i> -Butylbenzene [0.19]	104-51-8
1,2-Dimethylbenzene (<i>ortho</i> -Xylene) [0.06]	95-47-6	<i>n</i> -Propylbenzene [0.042]	103-65-1
1,3,5-Trimethylbenzene [0.044]	108-67-8	<i>p</i> -Isopropyltoluene [0.11]	99-87-6
1,3-Dimethylbenzene (<i>meta</i> -Xylene) [0.06]	108-38-3	<i>sec</i> -Butylbenzene [0.048]	135-98-8
1,4-Dimethylbenzene (<i>para</i> -Xylene) [0.06]	106-42-3	<i>tert</i> -Butylbenzene [0.1]	98-06-6
2-Ethyltoluene (<i>o</i> -Ethyl toluene) [0.10]	611-14-3		
Halogenated aromatics			
1,2,3-Trichlorobenzene [0.27]	87-61-6	2-Chlorotoluene [0.042]	95-49-8
1,2,4-Trichlorobenzene [0.19]	120-82-1	4-Chlorotoluene [0.056]	106-43-4
1,2-Dichlorobenzene [0.048]	95-50-1	Bromobenzene [0.036]	108-86-1
1,3-Dichlorobenzene [0.054]	541-73-1	Chlorobenzene [0.028]	108-90-7
1,4-Dichlorobenzene [0.05]	106-46-7		
Ethers and other oxygenated compounds			
2-Butanone [1.6]	78-93-3	Diisopropyl ether (DIPE) [0.098]	108-20-3
2-Hexanone [0.7]	591-78-6	Ethyl <i>tert</i> -butyl ether (ETBE) [0.054]	637-92-3
4-Methyl-2-pentanone (MIBK) [0.37]	108-10-1	Methyl <i>tert</i> -butyl ether (MTBE) [0.17]	1634-04-4
Acetone [5]	67-64-1	<i>tert</i> -Amyl methyl ether (TAME) [0.11]	994-05-8
Diethyl ether [0.17]	60-29-7	Tetrahydrofuran [9]	109-99-9
Others			
2-Propenenitrile (Acrylonitrile) [1.2]	107-13-1	Methyl acrylate [1.4]	96-33-3
Carbon disulfide [0.37]	75-15-0	Methyl acrylonitrile [0.57]	126-98-7
Ethyl methacrylate [0.28]	97-63-2	Methyl methacrylate [0.35]	80-62-6

Table 3. Pesticides analyzed in ground-water samples, Sacramento, California.

[*, transformation product; CAS #, Chemical Abstract Service number; [0.04] laboratory reporting level, in microgram per liter]

Compound	CAS #	Compound	CAS #	Compound	CAS #
Amides					
Alachlor [0.002] ¹	15972-60-8	Napropamide [0.003] ¹	15299-99-7	Propanil [0.004] ¹	709-98-8
Metolachlor [0.002] ¹	51218-45-2	Propachlor [0.007] ¹	1918-16-7	Pronamide [0.003] ¹	23950-58-5
Carbamates					
Aldicarb [0.55] ²	116-06-3	Carbofuran, 3-Hydroxy* [0.014] ²	16655-82-6	Pebulate [0.004] ¹	1114-71-2
Aldicarb sulfone* [0.10] ²	1646-88-4	EPTC [0.002] ¹	759-94-4	Propham [0.035] ²	122-42-9
Aldicarb sulfoxide* [0.021] ²	1646-87-3	Methiocarb [0.026] ²	2032-65-7	Propoxur [0.035] ²	114-26-1
Butylate [0.002] ¹	2008-41-5	Methomyl [0.017] ²	16752-77-5	Thiobencarb [0.002] ¹	28249-77-6
Carbaryl [0.003] ¹ , [0.008] ²	63-25-2	Molinate [0.004] ¹	2212-67-1	Triallate [0.001] ¹	2303-17-5
Carbofuran [0.003] ¹ , [0.12] ²	1563-66-2	Oxamyl [0.018] ²	23135-22-0		
Chlorophenoxy herbicides					
2,4,5-T [0.035] ²	93-76-5	Dacthal, mono-acid* [0.017] ²	887-54-7	MCPB [0.14] ²	94-81-5
2,4-D (acid) [0.15] ²	94-75-7	Dichlorprop (2,4-DP) [0.032] ²	120-36-5	Silvex (2,4,5-TP) [0.021] ²	93-72-1
2,4-DB [0.24] ²	94-82-6	MCPA [0.17] ²	94-74-6	Triclopyr [0.25] ²	55335-06-3
Dinitroanilines					
Benfluralin [0.002] ¹	1861-40-1	Trifluralin [0.002] ¹	1582-09-8	Pendimethalin [0.004] ¹	40487-42-1
Ethafuralin [0.004] ¹	55283-68-6	Oryzalin [0.31] ²	19044-88-3		
Organochlorines					
Chlorothalonil [0.48] ²	1897-45-6	Dichlobenil [1.2] ²	1194-65-6	alpha-HCH* [0.002] ¹	319-84-6
Dacthal (DCPA) [0.002] ¹	1861-32-1	Dieldrin [0.001] ¹	60-57-1	Lindane [0.004] ¹	58-89-9
<i>p,p'</i> -DDE* [0.006] ¹	72-55-9				
Organophosphates					
Azinphos-methyl [0.001] ¹	86-50-0	Ethoprop [0.003] ¹	13194-48-4	Parathion [0.004] ¹	56-38-2
Chlorpyrifos [0.004] ¹	2921-88-2	Fonofos [0.003] ¹	944-22-9	Phorate [0.002] ¹	298-02-2
Diazinon [0.002] ¹	333-41-5	Malathion [0.005] ¹	121-75-5	Terbufos [0.013] ¹	13071-79-9
Disulfoton [0.017] ¹	298-04-4	Methyl parathion [0.006] ¹	298-00-0		
Triazine herbicides					
Atrazine [0.001] ¹	1912-24-9	Cyanazine [0.004] ¹	21725-46-2	Prometon [0.018] ¹	1610-18-0
Atrazine, desethyl* [0.002] ¹	6190-65-4	Metribuzin [0.004] ¹	21087-64-9	Simazine [0.005] ¹	122-34-9
Uracils					
Bromacil [0.035] ²	314-40-9	Terbacil [0.007] ¹	5902-51-2		
Ureas					
Fenuron [0.013] ²	101-42-8	Fluometuron [0.035] ²	2164-17-2	Neburon [0.015] ²	555-37-3
Diuron [0.02] ²	330-54-1	Linuron [0.002] ¹ , [0.018] ²	330-55-2	Tebuthiuron [0.01] ¹	34014-18-1
Miscellaneous					
2,6-Diethylalane* [0.003] ¹	579-66-8	Chloramben [0.42] ²	133-90-4	DNOC [0.42] ²	534-52-1
Acetochlor [0.002] ¹	34256-82-1	cis-Permethrin [0.005] ¹	54774-45-7	Norflurazon [0.024] ²	27314-13-2
Acifluorfen [0.035] ²	50594-66-6	Clopyralid [0.23] ²	1702-17-6	Picloram [0.05] ²	1918-02-1
Bentazon [0.014] ²	25057-89-0	Dicamba [0.035] ²	1918-00-9	Propargite [0.013] ¹	2312-35-8
Bromoxynil [0.035] ²	1689-84-5	Dinoseb [0.035] ²	88-85-7		

¹Solid-phase extraction and gas chromatography/mass spectrometry (GC/MS), corresponds to the laboratory reporting level.²Solid-phase extraction and high-performance liquid chromatography (HPLC), corresponds to the laboratory reporting level.

Nitrate, major-ion, and trace-element samples were filtered using a 0.45-micron pleated capsule filter and were analyzed using colorimetry and atomic absorption spectrometry methods (Fishman and Friedman, 1989; Patton and Truitt, 1992; Fishman, 1993). Dissolved organic carbon samples were analyzed using ultraviolet-promoted persulfate oxidation and infrared spectrometry methods (Brenton and Arnett, 1993). Total dissolved-solids (TDS) concentrations were determined by the laboratory by evaporating an aliquot of water for 1 hour at 180°C and weighing the residue.

Stable-isotope ratios of hydrogen ($^2\text{H}/^1\text{H}$) and oxygen ($^{18}\text{O}/^{16}\text{O}$) were analyzed using hydrogen equilibrium and mass spectrometry (Coplen and others, 1991) and carbon dioxide equilibrium (Epstein and Mayeda, 1953).

Tritium/helium-3 ($^3\text{H}/^3\text{He}$) isotope samples were collected in duplicate copper tubes by flushing the tubes with the sample while tapping them until air bubbles were removed and then crimping the ends of the tubes to keep the sample sealed from the atmosphere. Samples for tritium (^3H) were collected in duplicate to accompany each set of copper tube samples. These samples were collected by filling a 1-L, high-density polyethylene bottle using caps that prevent contact with air. The $^3\text{H}/^3\text{He}$ method of analysis (Plummer and Mullin, 1997) is used to determine the age of the water or when the sample water was recharged and isolated from the atmosphere. Tritium/helium-3 analysis is a multi-step process accomplished by extracting helium isotopes, separating water vapor, neon, and other gases, and measuring the amount of helium and neon. As ^3H decays, it produces ^3He , so by measuring the current concentrations of ^3H and ^3He in ground water and using the known decay rate or half life of 12.43 years, the initial ^3H content can be back calculated (Bayer and others, 1989; Schlosser and others, 1989; Solomon and Sudicky, 1992; Solomon and others, 1993).

Quality-Control Data

Quality-control (QC) samples were collected to qualify the interpretation of environmental data (samples from wells) and to identify the sources and magnitude of bias and variability in that data. Three types of QC samples were collected and analyzed: Blank samples, spiked samples, and duplicate samples. Collection, preservation, and analysis of QC samples followed the same methods described for environmental samples. A description of the QC sample design and a summary of the QC results are presented below. All of the data for the Sacramento River Basin NAWQA are available in Domagalski and others (2000) and all of the quality-control results are available in Munday and Domagalski (2003).

Blank and spike samples were collected to estimate bias. Blank samples (blanks) consisted of different grades of purified water, tested to be free of the analytes of interest. Four different types of blanks were collected: field (four samples),

source solution (four samples), equipment (one sample), and trip (one sample). Field blanks measure the overall bias of the environmental data, and the other types of blanks measure specific sources of bias associated with the blank water and with various aspects of sampling, processing, transportation, and laboratory analysis. Field blanks were collected by pumping purified water through sampling lines, after environmental samples were collected and the equipment was cleaned, to test the effectiveness of equipment cleaning procedures in preventing cross contamination between wells and to determine if samples were exposed to atmospheric contamination during sampling. Source-solution blanks were collected by pouring purified water directly into the sample bottle, after environmental samples were collected, to test for contamination in the water used for the field blank. An equipment blank was collected prior to the start of the sampling season to determine if the sampling equipment was a source of contamination to the environmental samples. A trip blank was collected in a controlled environment and transported with a set of environmental samples to the laboratory to test for contamination in the transportation of samples and sample containers.

Field-spiked samples (spikes) are environmental samples fortified with a spike solution that contains known concentrations of target analytes (a subset of compounds included in the analysis). Spikes are analyzed to test for bias from interference with the ground-water sample matrix or degradation of target-analyte concentration after sample collection. The concentration of the analytes detected in the spikes is compared to the known concentration, so a recovery rate can be determined for each analyte in the spike solution. Recovery rates are determined for every pesticide and VOC by the NWQL from samples spiked in the laboratory. Recovery rates for each analyte are published as part of the method of analysis documentation.

The NWQL also adds surrogate compounds to all environmental and QC samples to monitor compound recovery and potential effects. A surrogate is a compound that is expected to perform similarly to the compounds being analyzed in a laboratory method. The surrogate is not normally found in the environment and can be used to monitor the recovery efficiency of analytical processes.

Duplicate samples (duplicates) were collected to estimate variability. Duplicates are two environmental samples collected sequentially and processed identically. Duplicate spikes also were collected to estimate variability in the recovery of spiked analytes contained in the spike solution.

Volatile Organic Compounds

Very low concentrations of VOCs were detected in several blanks, although the random occurrence of these detections does not appear to compromise the validity of the data set. One equipment blank, four field blanks, and one trip blank were analyzed for VOCs.

Trichloromethane (chloroform), the most frequently detected VOC in the environmental samples, was detected in the equipment blank at a concentration of 0.334 µg/L. The source of this detection may have resulted from using chlorinated tap water as a first rinse through the sampling lines, a procedure that was discontinued thereafter. Trichloromethane also was detected in two of the four field blanks, the first and third, at low concentrations (E0.064 and E0.006 µg/L; E = estimated), but was not detected in the accompanying environmental samples collected just prior to the field blanks. This may indicate that the detections in the field blanks are an artifact of the cleaning process, or occurred because of atmospheric contamination or contamination during transport. Two of the four field blanks in which trichloromethane was not detected were collected immediately after environmental samples with detectable concentrations of trichloromethane. Trichloromethane was not detected in the trip blank, which would indicate that contamination of this compound did not occur during transportation.

Two other VOCs that were detected in field blanks also were detected in environmental samples. Carbon disulfide was detected in the first field blank at a concentration of E0.02 µg/L, although it was not detected in the accompanying environmental sample taken at the same well. Possible sources of this detection are unknown. Chloromethane (methyl chloride) was detected in the third field blank at a concentration of E0.01 µg/L, although it was not detected in the accompanying environmental sample taken at the same well. Chloromethane was also detected in one environmental sample at a concentration of E0.02 µg/L. Contamination from this analyte can occur from degraded HCl (used to preserve VOC samples) if it has been exposed to light or warm conditions for long periods of time (Connor and others, 1998). Contamination from HCl seems unlikely because HCl was used to preserve all VOC samples and chloromethane was detected only in one field blank and one environmental sample.

Five of the eight VOCs detected in environmental samples were not detected in any of the blanks. They included bromodichloromethane, tetrachloroethene, 1,1,1-trichloroethane, iodomethane, and methyl *tert*-butyl ether (MTBE). Overall, the VOC sample collection, processing, and field-cleaning procedures were successful in minimizing environmental sample contamination and carryover.

Three VOC spike and spike replicates were collected and analyzed. The calculated percent recoveries of the VOCs contained in the spike solution were comparable to the percent recoveries reported for the method of analysis by the laboratory (Connor and others, 1998). The spike recovery for trichloromethane, the most frequently detected VOC in the environmental samples, was 101 percent.

Percent recoveries of the surrogates were also calculated by the laboratory to test method performance. Surrogate recoveries ranged from 73 to 123 percent for the 19 environmental samples.

In addition to QC samples collected for this study, the laboratory also analyzes QC samples on a routine basis to

identify any possible sources of contamination from the sample analysis, including sources of interference from preservation, carryover, or the chemistry of the sample matrix. Environmental or QC samples that contained hydrogen sulfide or were foamy, for example, were diluted at least one to four times prior to analysis because the presence of hydrogen sulfide interferes with the response of the mass spectrometer (Connor and others, 1998). VOC samples from all four wells in the Pocket area and one well in the Natomas area (*fig. 6*) were diluted to prevent interference with the mass spectrometer. Sample results from these wells may be biased low because the laboratory reporting limits were raised owing to the sample dilution. Two of the samples did not contain any VOCs, but trichloromethane was detected in three of these five samples.

Pesticides

One equipment blank and four field blanks resulted in only one detection of dichloroprop at a concentration of 0.04 µg/L. Dichloroprop was not detected in any of the environmental samples. The detection of only one pesticide indicates that the sample collection, processing, and field-cleaning procedures were successful in minimizing environmental sample contamination or carryover.

Four spikes were collected and analyzed for 47 analytes using the GC/MS method. Of these 47 analytes, the mean recovery value for 32 ranged from 71 to 110 percent, for 10 was below 70 percent, and for 5 was greater than 110 percent. This range of values for spike recovery is similar to those typically reported by the NWQL (Zaugg and others, 1995). Detections of 5 of the 15 analytes—azinphos-methyl, carbaryl, carbofuran, desethyl atrazine, and terbacil—are reported by the laboratory as estimated because they are known to have poor analytical performance in the GC/MS procedure. Desethyl atrazine is the only analyte with low or high recovery that was detected in any environmental samples. Atrazine, simazine, and tebuthiuron were detected in environmental samples and had mean spike recoveries of 80, 76, and 85 percent, respectively.

Four spikes were collected and analyzed for 39 analytes using the HPLC method. The mean recoveries were variable, ranging from 38 to 98 percent (Werner and others, 1996). In general, precision and recovery for most HPLC analytes were consistent and high enough so that they could be used reliably in the data analysis. Several analytes consistently had poor precision and recoveries, including aldicarb, aldicarb sulfone, aldicarb sulfoxide, chlorothalonil, dichlobenil, and 4,6 dinitro-*o*-creosol (DNOC). There is a greater chance of these analytes being reported as “false negative.” The only HPLC analyte detected in any environmental samples was bentazon. The calculated mean spike recovery for bentazon in this study was 62 percent, which is comparable to the mean recovery of 60 percent reported by the NWQL (Werner and others, 1996).

Surrogate recovery data from the GC/MS-analyzed and HPLC-analyzed environmental samples show that the method performance was adequate. The mean recovery values for diazinon-d₁₀, *alpha*-HCH-d₆, and terbuthylazine were all above 70 percent. The mean recovery for 4-bromo-3,5-dimethylphenyl-n-methylcarbamate (BDMC) was 89 percent for 14 of the 19 environmental samples, and was slightly greater than 100 percent for 5 of the 19 environmental samples. High surrogate recovery may be due to interference with the sample matrix or from an interference peak that was somewhat coeluted with the surrogate.

Nitrate

An equipment blank and four field blanks resulted in only one detection of nitrate at a concentration of 0.085 mg/L, as nitrogen. The method detection limit for nitrate is 0.05 mg/L. Nitrate was not detected in the accompanying environmental sample collected at the same well. This indicates that the sample collection, processing, and field-cleaning procedures were successful in minimizing environmental sample contamination and carryover of nitrate.

Duplicate ground-water samples were collected sequentially from four wells and analyzed for nitrate. Concentrations were identical for two of the nitrate duplicates and were within 0.04 mg/L for the other two duplicates. The small variability between duplicate samples indicates a high degree of precision in the collection, processing, and analysis of nitrate samples.

Major Ions, Trace Elements, and Dissolved Organic Carbon

One equipment blank, four field blanks, four source-solution blanks, and four duplicates were collected for analysis of major ions, trace elements, and dissolved organic carbon (DOC). QC results for major ions and trace elements will be limited to the eight constituents discussed in this report, including arsenic, calcium, chloride, iron, magnesium, manganese, sodium, and sulfate. Of these eight constituents, only calcium was detected in the equipment blank (0.025 mg/L) and in the first field blank (0.004 mg/L). DOC was not detected in any of the source-solution blanks, but was detected in the equipment blank (0.6 mg/L) and in the four field blanks (0.20 to 0.70 mg/L) at low levels that overlap environmental concentrations (0.2 to 4.9 mg/L). DOC contamination in equipment and field blanks is likely due to cleaning methods that used methanol to prevent carryover contamination between environmental samples. It is possible that more water is needed to effectively rinse methanol residue before equipment and field blank collection, whereas

insufficient rinsing likely is not an issue with environmental samples because a minimum of three well casing volumes of water are pumped through the sampling lines and tubing prior to environmental sample collection. The blank results indicate that the sample collection, processing, and field-cleaning procedures were successful in minimizing environmental sample contamination and carryover of these constituents.

Results from the four major-ion, trace-element, and DOC duplicates indicate a high degree of precision in the collection, processing, and analysis of these samples and a very small amount of temporal variation during sample collection. Duplicate concentrations were identical or less than 0.5 concentration units apart for all of the major-ions, trace-elements, and DOC analyses.

Determination of Hydrogeologic and Well-Construction Variables

Data on depth to water, well depth, depth to top of screened interval, percent organic matter in soil, soil pH, percent clay in soil, soil permeability, electromagnetic conductivity, and natural gamma were compiled for each well site. These variables were compiled to evaluate whether differences in ground-water quality can be attributed to differences in hydrogeologic and well-construction characteristics. The methods used to compile these variables are described below.

The depth to water below land surface was measured in all wells to the nearest hundredth of a foot upon completion of each well, during well development, and at the time of sample collection. There were no large fluctuations in these water-level measurements for each well. Depth to water, well depth, and depth to top of screened interval were used in the statistical analysis for this report.

Sediment properties are presented from two sources: direct measurements of sediment samples collected from drill cuttings at depths ranging from 1.5 to 28 m, and the Sacramento County Soil Survey report (Tugel, 1993). It was not possible to collect a complete set of direct measurements for every well because mud rotary drilling methods were used at some sites and because of contamination from mixing of cuttings samples from different depths at a drill site as the cuttings came out of the well. Soil properties from the Sacramento County Soil Survey report were used in statistical analyses. The highest percentage of organic matter, the lowest soil pH, the highest percentage clay, and the lowest soil permeability values were chosen from the range of values in the Sacramento County Soil Survey report to reflect the most limiting soil layer that could have controlled the degradation of contaminants or the overall rate at which ground water was recharged.

At each well site, two types of borehole geophysical logs were run: electromagnetic (EM) induction and natural gamma. The EM-induction tool measures the EM conductivity of fluid and sediment surrounding the borehole. A high conductivity response generally is attributed to silt or clay, but the specific conductance of pore water can also affect the EM conductivity measured by an induction logger. Natural-gamma logs record the amount of gamma radiation emitted by geologic materials. Potassium-40 and products of the uranium and thorium decay series are the gamma-emitting radioisotopes that occur naturally in geologic materials. In general, clay-rich sediments emit relatively higher gamma radiation than do other sediments because of a relative abundance of potassium or uranium and thorium in fine-grained sediments (Keys, 1990).

Three hydrogeologic facies were determined on the basis of sediment texture, sediment descriptions from drill cuttings, observations of drilling rates, and borehole geophysical logs. Sediment samples and drilling observations were compared with the borehole geophysical logs to identify the texture for intervals where cuttings were not collected.

Statistical Methods

Nonparametric statistical methods were used in this report because the data set is small, most of the data are not normally distributed, and some data are censored to either the detection limit or the highest concentration detected in a blank sample. Nonparametric tests exhibit greater power than parametric tests in the presence of skewness and outliers, which are characteristics common to most water-resources data (Helsel and Hirsch, 1992). The significance level, used for hypothesis testing in this report, is 5 percent ($\alpha = 0.05$).

The Spearman's rho was used to evaluate the correlation of two variables (Iman and Conover, 1983). The Kruskal-Wallis test, an analysis of variance, was used to test the differences between more than two groups of data (Iman and Conover, 1983). When the results from the Kruskal-Wallis test indicated a significant difference between the multiple groups, the multistage Kruskal-Wallis test was used (Helsel and Hirsch, 1992) to determine whether a significant difference exists between two groups. The significance level used in this report for the multi-stage Kruskal-Wallis test is $\alpha_p = 0.03$. For compounds with reported concentrations that were less than the detection limit, a concentration of one-half the detection limit was used in the statistical analyses.

Multivariate statistical methods were used in this study to simultaneously investigate the influence of a large number of variables on the presence or absence of contaminants, develop hypotheses about relations between water-quality and hydrogeologic variables, and determine which variables explain most of the variance in the data set. In principal components analysis, groups of related variables are called components or eigenvectors and each component is viewed as a weighted

combination of the input variables. Associated with each derived component is a quantity known as an eigenvalue, which corresponds to the equivalent number of variables that the component represents (Kachigan, 1986). Principal components analysis involves interpretation of the eigenvalues and eigenvectors from the variance-covariance matrix (Davis, 1973). The contribution of a particular sediment texture or water-quality constituent to a component can be estimated by the value's loading on the eigenvector. This allows grouping and strength of grouping to be simultaneously examined for a large number of interrelated variables.

Ground-Water Quality

Water-quality results from the 19 well samples will be presented in this section, including ground-water characteristics, VOCs, pesticides, and nitrate. Median concentrations of some constituents will be compared to national medians derived from NAWQA studies. Constituent concentrations and values for selected ground-water properties will be compared to drinking-water standards. A comprehensive data report for the Sacramento River Basin NAWQA study can be viewed or downloaded from the Internet (Domagalski and others, 2000).

Ground-Water Characteristics

General ground-water characteristics summarized in this section include depth to water, specific conductance, dissolved oxygen, selected trace-element concentrations, major-ion chemistry, and hardness. Depth to water ranged from 1.09 to 52.7 m below land surface (*table 1*). Depth to water was shallower in the wells near the Sacramento and American Rivers in the Pocket and Natomas areas and deeper in the wells in the south and north Sacramento areas (*table 1*).

Specific conductance values ranged from 202 to 2,920 $\mu\text{S}/\text{cm}$, with a median of 545 $\mu\text{S}/\text{cm}$. In general, specific conductance was highest in ground-water samples from wells in the Pocket and Natomas areas (*fig. 7*). Median values for specific conductance at these wells were more than two times higher than the median for ground-water samples at all the wells, with one exception. The lowest specific conductance was measured in a well in the Pocket area, well 8, that is closest to the Sacramento River.

Dissolved-oxygen concentrations at all 19 wells ranged from 0.2 to 7.0 mg/L, with a median of 3.4 mg/L. Median dissolved-oxygen concentrations in samples from the eight wells in the Pocket and Natomas areas, however, were less than 1 mg/L. Five well samples were considered to be chemically reduced because dissolved-oxygen concentrations were less than or equal to 1 mg/L; in addition, concentrations of iron or manganese were high (over 300 $\mu\text{g}/\text{L}$) in four of these wells.

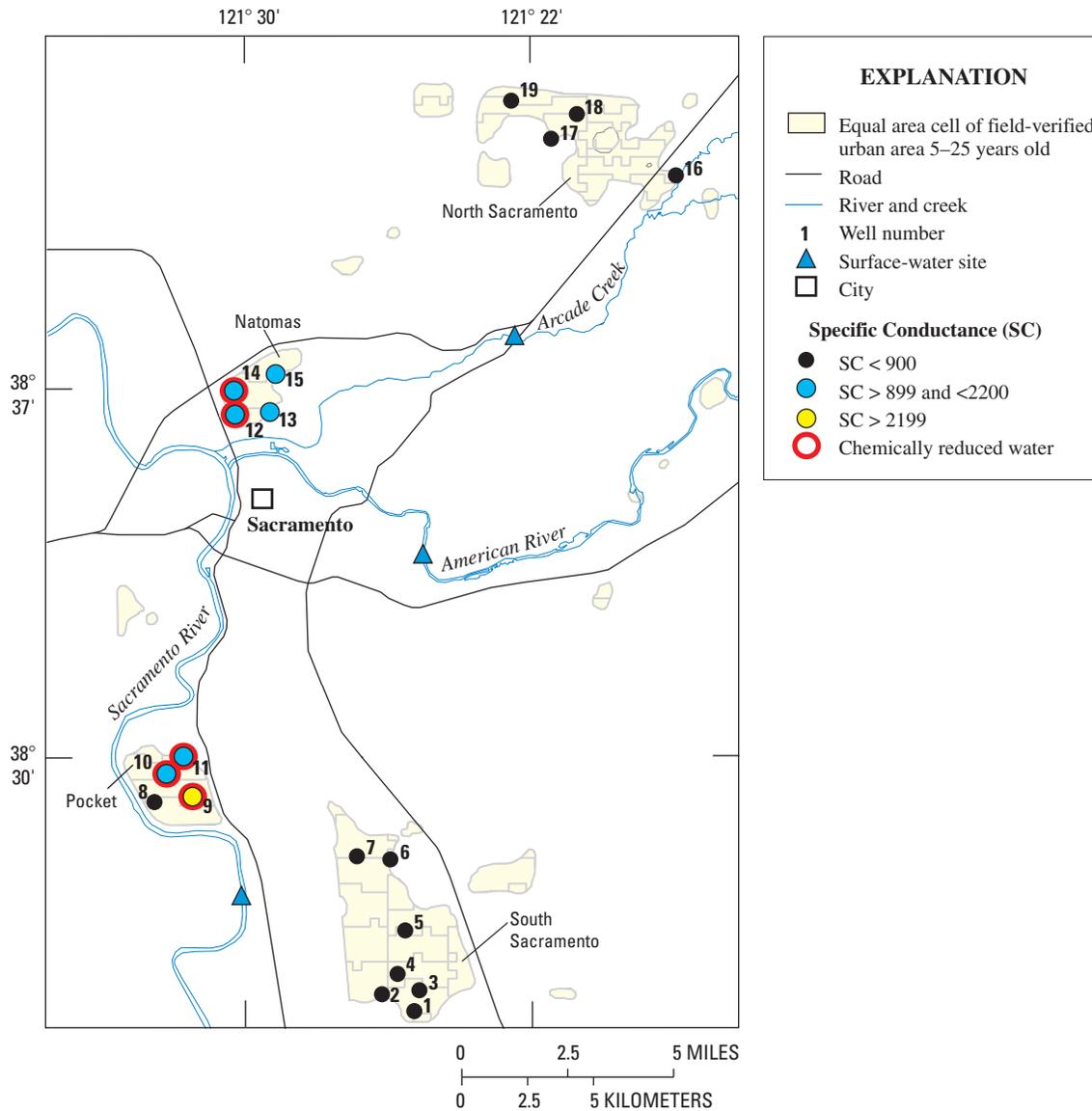


Figure 7. Range of specific conductance values, in microsiemens per centimeter at 25°C, observed in ground-water samples, and wells with chemically reduced waters, Sacramento, California.

In general, the major-ion chemistry of ground water from urban wells is similar to the major-ion chemistry found in ground water on the entire east side of the Sacramento Valley (Hull, 1984), with bicarbonate as the dominant anion and calcium and magnesium as the co-dominant cations. There are a few exceptions where chloride is the dominant anion or where sodium is the dominant cation (fig. 8). Although the major-ion chemistry is similar for the urban wells, the concentrations of the major ions are more variable in ground water from wells in the Pocket and Natomas areas than from the wells in the south and north Sacramento areas.

Calcium and magnesium contribute to the hardness of water, which can be an important water-quality characteristic to water users. Hardness, an indicator of water's ability to form residues with soaps or to form encrustations in pipes, is calculated by multiplying the sum of milliequivalents per liter of calcium and magnesium by 50, and is expressed as milligrams per liter of calcium carbonate (CaCO_3) (Hem, 1985). All of the ground-water samples were at least moderately hard (61 to 120 mg/L as CaCO_3) and most, 12 of 19, were very hard (greater than 180 mg/L as CaCO_3).

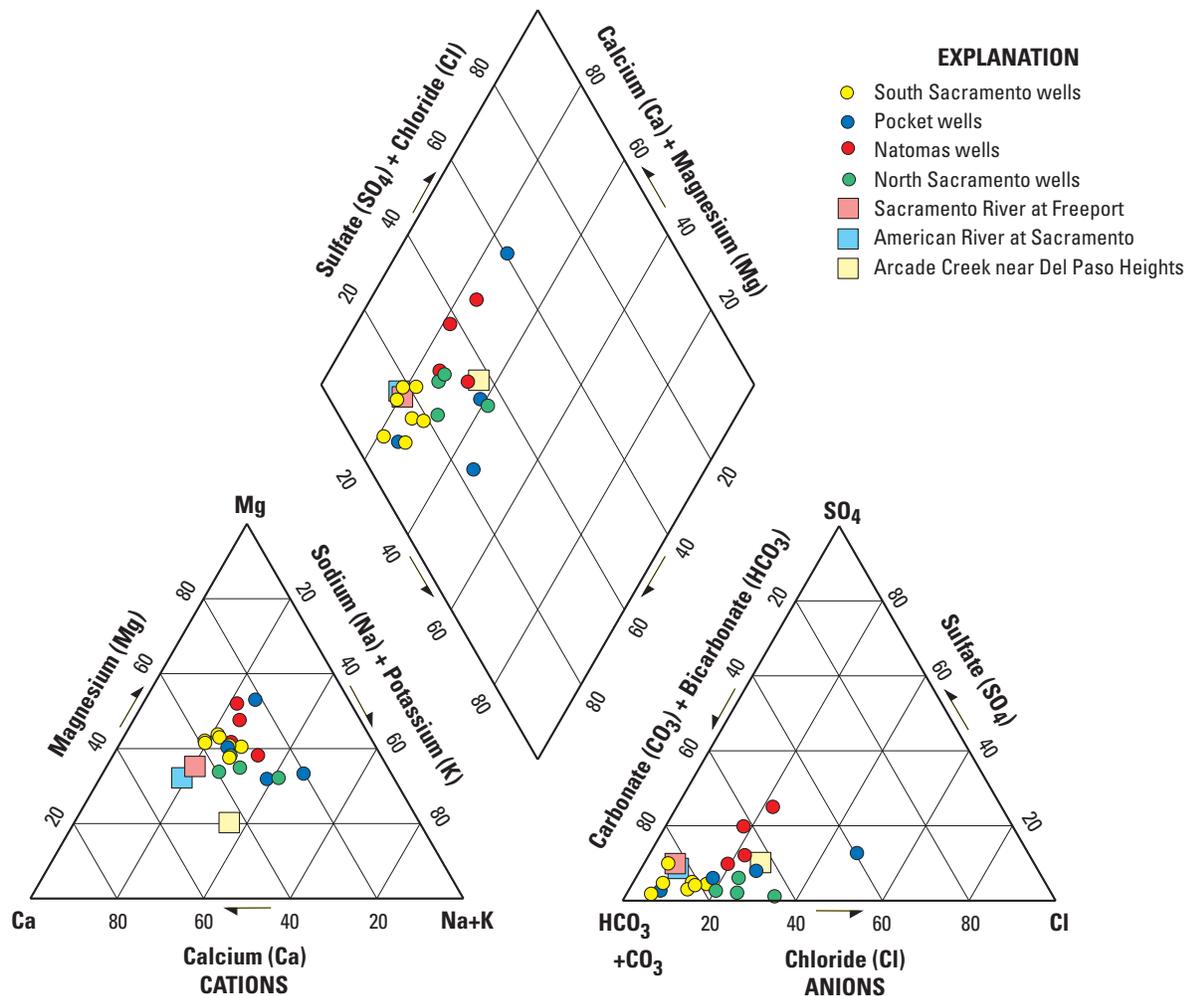


Figure 8. Piper diagram showing major-ion composition, in percent milliequivalents per liter, of water samples from wells and surface-water sites, Sacramento, California.

Volatile Organic Compounds

VOCs are widely used, and are significant potential contaminants because they can be mobile, persistent, and toxic. VOCs can be found in dry-cleaning and pharmaceutical products, refrigerants, paints, adhesives, plastics, fuels and exhaust fumes, solvent degreasers, pesticides, and fumigants (Howard, 1991; Majewski and Capel, 1995; Barbash and Resek, 1996; Squillace and others, 1999). Some VOCs, such as trichloromethane, also are common byproducts of the disinfection of drinking water with chlorine.

Ground-water samples from 16 (84 percent) of the 19 wells sampled contained one or more VOCs (table 4); VOCs were detected in all the wells in the south Sacramento area (fig. 9). Almost all of these detections were at low levels, with only 11 percent above 1 $\mu\text{g/L}$. Two or more VOCs were detected in samples from five (26 percent) of the wells, all of which are in the south Sacramento and Natomas areas (table 4

and fig. 9). The highest concentrations were also found in samples from wells in these two areas. The laboratory reporting limits were elevated for five samples because the samples had to be diluted during analysis due to sample matrix interference with laboratory instruments. This may have affected the frequency of VOC detection for four wells in the Pocket area and one well in the Natomas area; however, one VOC was detected in three of the wells.

Eight of the 86 VOCs analyzed (table 2) were detected: four at concentrations above the laboratory reporting limit (LRL), and four only at concentrations below the LRL and reported as estimated (table 4). Of the eight VOCs detected, six are either regulated or have been assigned proposed regulations by the U.S. Environmental Protection Agency (USEPA). The maximum concentrations of all the VOCs detected were at least five times lower than any National or State maximum contaminant levels (table 4).

Table 4. Volatile organic compounds detected in ground-water samples, Sacramento, California.

[See *fig. 1* for well locations. IUPAC, International Union of Pure and Applied Chemistry nomenclature; $\mu\text{g/L}$, microgram per liter; —, not established; detected compounds are reported for all 19 samples; E, detection reported as estimated if concentration is less than the laboratory reporting level]

Volatile organic compound (VOC) detected		Number of wells with a detection	Well numbers with detections	All detected concentrations		Drinking-water standard ($\mu\text{g/L}$)
IUPAC name	Common name			Median ($\mu\text{g/L}$)	Maximum ($\mu\text{g/L}$)	
Trichloromethane	Chloroform	16	1, 2, 3, 4, 5, 6, 7, 8, 10, 11, 13, 15, 16, 17, 18, 19	0.062	5.05	¹ 80
Bromodichloromethane	Dichlorobromomethane	3	6, 13, 15	.094	.136	¹ 80
Methyl <i>tert</i> -butyl ether	MTBE	2	5, 6	.79	1.5	² 13
Tetrachloroethene	Tetrachloroethylene, PCE	2	3, 13	.49	.98	^{1,2} 25
1,1,1-Trichloroethane	1,1,1-TCE Methylchloroform	1	6	E.008	E.008	^{1,2} 200
Carbon disulfide	Carbon disulfide	1	5	E.05	E.05	—
Chloromethane	Methyl chloride	1	13	E.02	E.02	—
Iodomethane	Methyl iodide	1	5	E.06	E.06	—

¹U.S. Environmental Protection Agency (USEPA) primary maximum contaminant level (MCL) (USEPA website accessed May 3, 2004).

²California Department of Health Services (CA DHS) primary MCL (CA DHS website accessed August 3, 2004).

The four VOCs detected at the highest concentrations were the same VOCs detected in two or more samples (table 4). Trichloromethane (chloroform), a trihalomethane and a disinfection byproduct, was the most frequently detected VOC, detected at the highest concentration, and detected in all of the samples that had any detections of VOCs. Bromodichloromethane, also a trihalomethane and a disinfection byproduct, was detected in samples from three wells in the south Sacramento and Natomas areas. The fuel oxygenate methyl *tert*-butyl ether (MTBE) was detected in two wells, both located in the south Sacramento area. Tetrachloroethene (PCE), a solvent, also was detected in two wells in the south Sacramento and Natomas areas.

The most frequently detected VOCs are similar to those found in ground-water samples from monitoring, domestic, and public supply wells in urban areas representative of a wide range of hydrogeologic conditions across the United States (Squillace and others, 1999). Three of the four VOCs detected in two or more samples in this study—trichloromethane, MTBE, and PCE—were detected in 10 percent or more of the 225 to 405 samples from urban areas across the United States. The percentages of detections for trichloromethane, MTBE, and PCE in this study were 21, 5, and 5, respectively, and in urban areas nationwide were 26, 17, and 17, respectively, when the concentrations of detections are censored at a reporting limit of 0.2 $\mu\text{g/L}$.

In contrast, the VOCs detected in this study were not frequently detected in a total of 86 samples from domestic wells in predominantly agricultural areas in the San Joaquin and southeast Sacramento Valleys (Dubrovsky and others, 1998; Domagalski and others, 2000). The percentages of detections for trichloromethane, MTBE, and PCE in these primarily agricultural areas were 2, 0, and 3, respectively, even with uncensored, lower reporting limits.

VOC results from this study are more consistent with results from urban areas nationwide than from agricultural areas in the San Joaquin and southeast Sacramento Valleys. In addition, the frequent occurrence of trichloromethane and MTBE in urban areas and the near exclusion of them in agricultural areas indicates that the presence of those VOCs in this study represents an urban signature in the quality of the ground water. Overall, the VOC results from this study suggest that ground-water quality has been impacted by urbanization.

Pesticides

Pesticides are applied on agricultural crops, on roadsides, on canal or ditch edges (rights-of-way), and frequently on lawns and gardens. The three general types of pesticides, categorized by use, are herbicides, insecticides, and fumigants. In 1993, about 450 million kilograms of pesticides were applied in the United States to control weeds, insects, and other pests (Barbash and Resek, 1996). Half of the total amount of pesticides was applied for home and garden use, and of this home and garden use, over half the mass was herbicides and insecticides.

Many classes of pesticides are categorized based on chemical properties. Pesticides analyzed in this study are listed in *table 3*. Four pesticides and one pesticide transformation product, all of which are herbicides, were detected at low concentrations in 32 percent (6 out of 19) of the ground-water samples (*table 5*). All of these herbicides are regulated by the USEPA and the California Department of Health Services (CA DHS), but no drinking-water standards were exceeded (U.S. Environmental Protection Agency, 1996; California Department of Water Resources, 1997). All concentrations were at least two orders of magnitude lower than drinking-water standards (*table 5*).

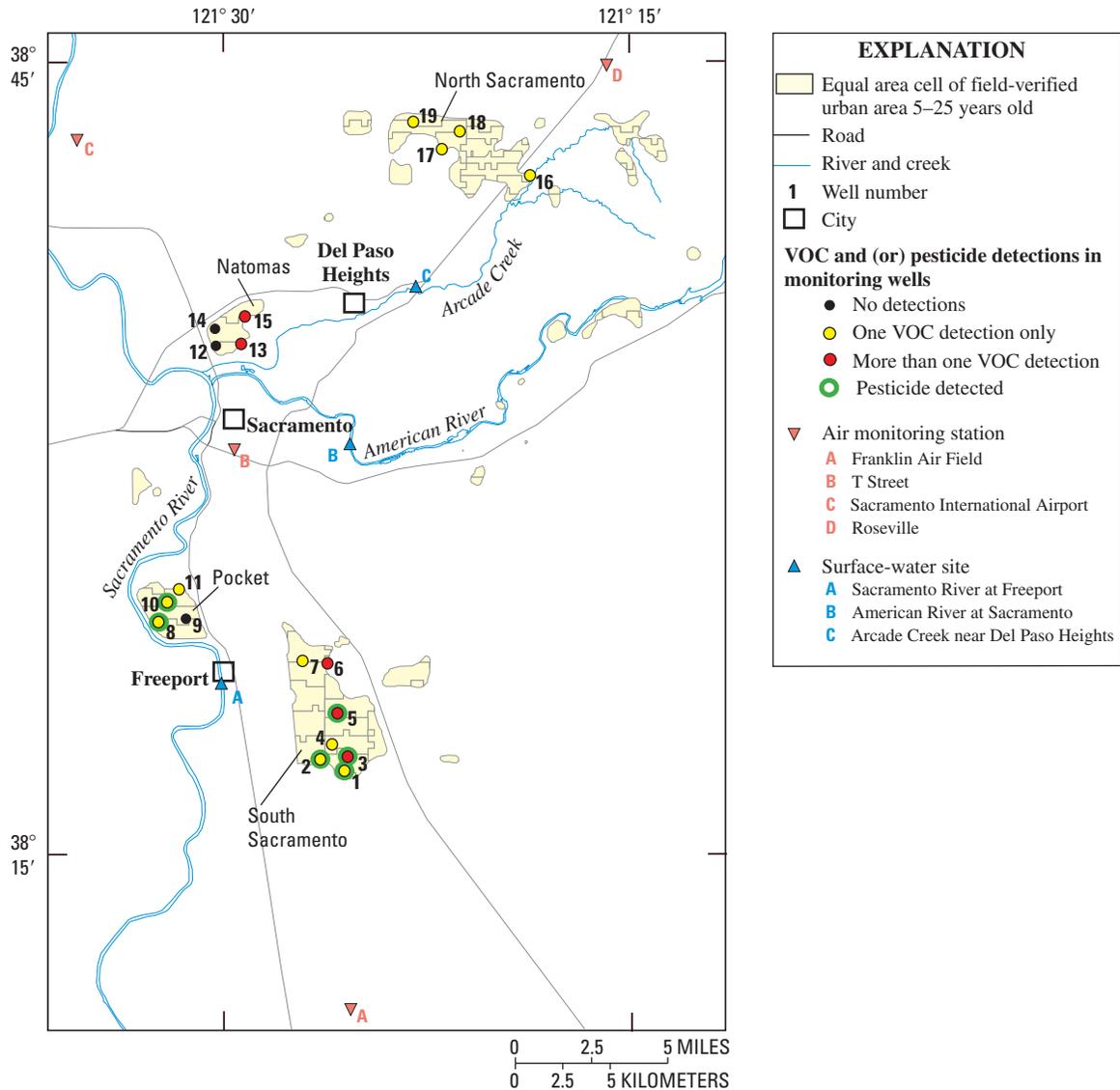


Figure 9. Ground-water samples with volatile organic compound (VOC) and pesticide detections, Sacramento, California.

Most pesticide detections were from samples at wells in the south Sacramento area (fig. 9). Only atrazine and desethyl atrazine were detected in more than one ground-water sample and were detected together in samples from the same three wells in the south Sacramento area (table 5). The principal use of atrazine in Sacramento County was on rights-of-way, but it also was commonly used on agricultural crops. Desethyl atrazine is a transformation product of atrazine, and in this report, detections of atrazine and desethyl atrazine were counted as a single detection in statistical analyses. Concentrations of desethyl atrazine are reported as estimated by the laboratory due to poor method performance. Simazine, in addition to atrazine and desethyl atrazine, was detected in the sample from well 5, the only well with more than one pesticide detection.

Bentazon and tebuthiuron were detected in samples from two different wells (wells 8 and 10) in the Pocket area (table 5,

fig. 9). Tebuthiuron, a broad-spectrum herbicide used to control weeds in noncropland areas, rangeland, rights-of-way, and industrial sites, was detected in well 10. Bentazon was detected in well 8, located closest to the Sacramento River. Bentazon was predominantly used on rice, grown north of the urban area and adjacent to the Sacramento River within the Sacramento River Basin, until it was suspended in 1989 and formally banned in 1992. Bentazon has been detected in the Sacramento River and its tributaries (California Department of Food and Agriculture, 1987, 1989; Bennett, 1995; Domagalski and others, 2000; California Department of Pesticide Regulation, 2001) and in shallow wells (Domagalski and others, 2000; Schuette and others, 2003), suggesting that the detection in the well in the Pocket area is a result of movement of surface water into the shallow aquifer.

Table 5. Pesticides detected in ground-water samples in 1998, and the amount of detected pesticides applied in Sacramento County, California, in 1991 and 1996.

[See *fig. 1* for well locations. $\mu\text{g/L}$, microgram per liter; *, transformation product; detected compounds are reported for all 19 samples; E, detections reported as estimated if concentration is less than laboratory reporting level; —, not established; amount of pesticide applied is from California Department of Pesticide Regulation data base]

Pesticide detected	Number of wells with a detection	Well numbers with detections	Median of detected concentrations ($\mu\text{g/L}$)	Maximum concentration detected ($\mu\text{g/L}$)	Drinking-water standard ($\mu\text{g/L}$)	Amount, in kilograms, applied in Sacramento County	
						1991	1996
Atrazine	3	2, 3, 5	0.016	0.025	¹ 3, ² 1	9,075	5,334
Atrazine, desethyl*	4	1, 2, 3, 5	.012	E.016	—	0	0
Simazine	1	5	.010	.010	^{1,2} 4	7,132	3,257
Tebuthiuron	1	10	.024	.024	—	287	253
Bentazon	1	8	.060	.060	² 18	0	0

¹2004 U.S. Environmental Protection Agency (USEPA) primary maximum contaminant level (MCL) (USEPA website accessed May 3, 2004).

²2003 California Department of Health Services (CA DHS) primary MCL (Title 22, CA DHS website accessed September 12, 2003).

The pesticides detected in this study also were detected in ground-water samples collected from monitoring and domestic wells in urban and agricultural areas representative of a wide range of hydrogeologic conditions across the United States (Dubrovsky and others, 1998; Domagalski and others, 2000; Kolpin, 2001). Nationwide, atrazine, desethyl atrazine, simazine, and bentazon were detected more frequently in samples collected in agricultural areas (44 percent, 43 percent, 21 percent, and 4 percent, respectively) than in urban areas (31 percent, 29 percent, 19 percent, and 3 percent, respectively) (Kolpin, 2001). Atrazine, desethyl atrazine, and simazine were also the most frequently detected pesticides in shallow domestic wells in agricultural areas in the San Joaquin Valley (25 percent, 25 percent, and 37 percent, respectively; Burow and others, 1998) and among the most frequently detected pesticides in shallow monitoring wells in rice areas (31 percent, 29 percent, and 19 percent, respectively), with bentazon the most frequently detected (71 percent; Dawson, 2001). However, tebuthiuron was detected more frequently in wells in urban areas (7 percent) than in agricultural areas (2 percent) nationwide and was the only pesticide that was detected in this study but not detected in agricultural areas in the San Joaquin Valley and rice areas in the Sacramento Valley (Dubrovsky and others, 1998; Dawson, 2001).

The relatively low frequency of occurrence of atrazine, desethyl atrazine, and simazine in this study (16 percent, 21 percent, and 5 percent, respectively) is more consistent with the results from urban areas nationwide than from agricultural areas nationwide and it is lower than the results from the San Joaquin and Sacramento Valley agricultural areas. The higher frequency of tebuthiuron in urban areas than in agricultural areas nationwide and the exclusion of tebuthiuron in agricultural areas locally may suggest that its presence in this study could act as an indicator of urban impact on shallow water quality.

Nitrate

Elevated nitrate concentrations in ground water can be a threat to public health because they can cause serious health problems in infants, including methemoglobinemia (Comly, 1945). The USEPA and CA DHS primary MCL for nitrate is 10 mg/L, as nitrogen. This MCL concentration originally was chosen because there were no known cases of infant methemoglobinemia below that level (Comly, 1945). Naturally occurring nitrogen compounds include nitrite, nitrate, and ammonium, although nitrate is the dominant species in oxygenated ground water. In this study, nitrite was detected at low concentrations (0.012 to 0.027 mg/L) in samples from wells in the south Sacramento, Pocket, and Natomas areas (wells 1, 2, 3, 10, and 14). Concentrations of nitrite plus nitrate, as nitrogen, will be referred to as nitrate in this report because nitrite concentrations were low and account for less than 0.5 percent of the total nitrate plus nitrite concentrations in samples where nitrite was detected. Ammonium concentrations were also low and did not exceed 0.787 mg/L.

Nitrate concentrations exceeded the LRL of 0.05 mg/L in 14 (74 percent) of the 19 ground-water samples at concentrations ranging from 0.69 to 8.0 mg/L, with a median detected concentration of 2.9 mg/L. Half of the detected nitrate concentrations were elevated, exceeding 3.0 mg/L (*fig. 10*). Concentrations of nitrate above 3.0 mg/L may represent ground water that is affected by anthropogenic factors (Hull, 1984; Madison and Brunett, 1985; Mueller and Helsel, 1996).

The highest concentrations of nitrate were detected in samples from wells in the south Sacramento and Natomas areas. Of the seven wells with elevated nitrate concentrations—concentrations greater than 3.0 mg/L—three were in the south Sacramento area, three were in the Natomas area, and one was in the north Sacramento area (*fig. 10*).

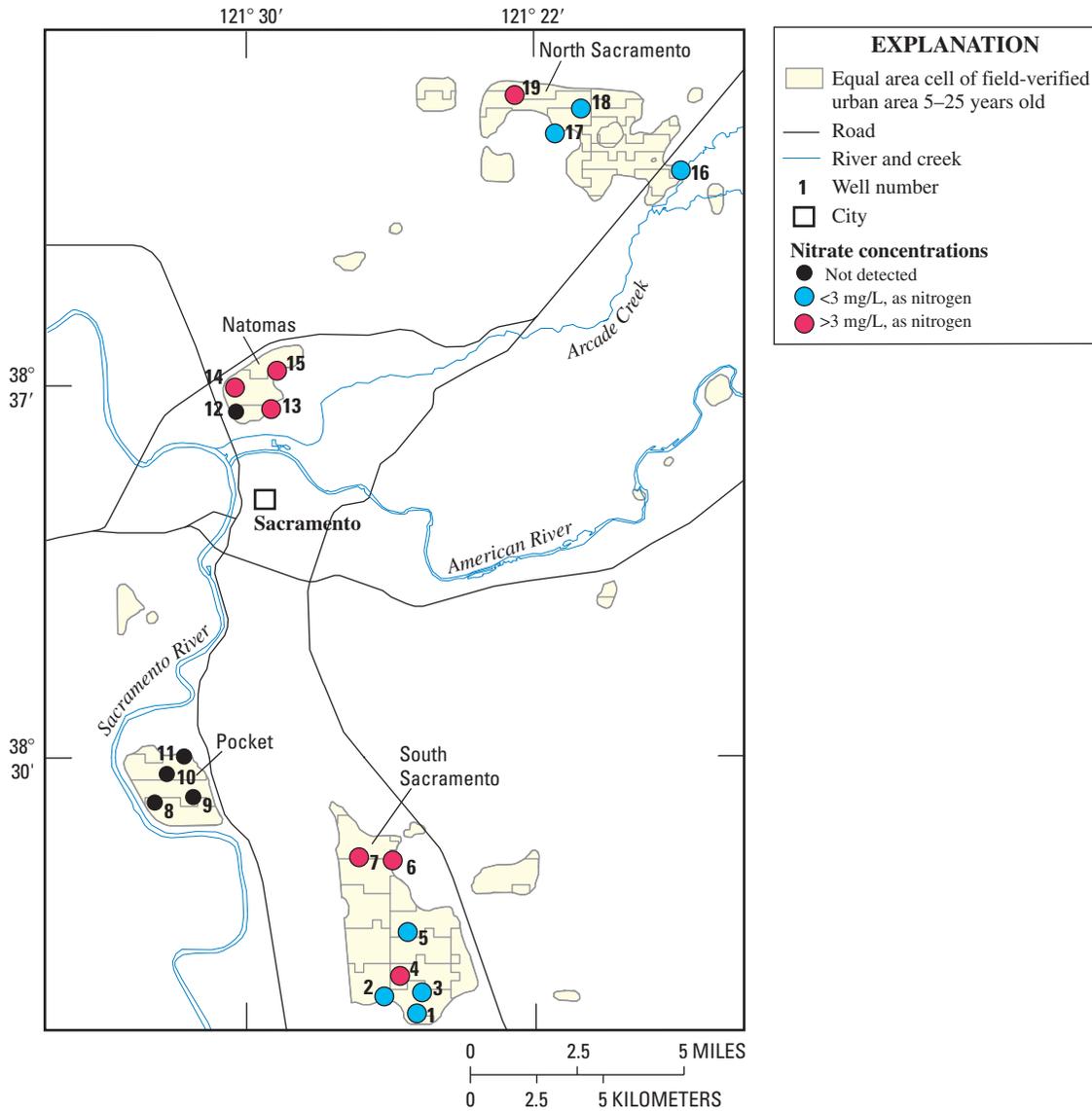


Figure 10. Range of nitrate concentrations, in milligrams per liter (mg/L), detected in ground-water samples, Sacramento, California.

Nitrate concentrations ranged from 0.69 to 7.6 mg/L in the seven wells in the south Sacramento area, with a median concentration of 2.6 mg/L. Nitrate concentrations ranged from 5.8 to 8.0 mg/L in the three wells in the Natomas area, with a median concentration of 6.1 mg/L. Nitrate concentrations ranged from 2.0 to 3.6 mg/L in the four wells in the north Sacramento area, with a median concentration of 2.2 mg/L. Nitrate was not detected in samples from five wells (fig. 10): four in the Pocket area and one in the Natomas area. Water samples from these wells were chemically reduced (fig. 7), with the exception of well 8. The lack of any detectable nitrate at these wells may be due to removal by denitrification.

The median concentration of detected nitrate (2.9 mg/L) in the Sacramento urban study sites was lower than the

median concentration detected in agricultural areas nationwide (3.4 mg/L), but higher than the median concentration detected in urban areas nationwide (1.8 mg/L), according to a national analysis of nutrients in ground water (Mueller and others, 1995). The median nitrate concentration in this study was lower than the medians in 20 samples each from three different agricultural land-use settings (vineyard, 4.6 mg/L; almond, 10 mg/L; and a combined crop grouping of corn, alfalfa, and vegetables, 6.2 mg/L) in the San Joaquin Valley (Buraw and others, 1998), but higher than the median nitrate concentration in rice areas (2 mg/L) in the Sacramento Valley and higher than in agricultural or nonurban areas (1.8 mg/L) in the south-eastern Sacramento Valley (Domagalski and others, 2000).

Elevated nitrate concentrations and pesticide detections do not co-occur. Nitrate was either less than 3 mg/L or not detected above 0.05 mg/L in samples from six sites where pesticides were detected (figs. 9 and 10). Elevated nitrate concentrations do not appear to be due to past agricultural land use.

Drinking-Water Standards Exceeded

Nine well samples contained levels exceeding National or State primary or secondary maximum contaminant levels of one or more of the following: arsenic, manganese, iron, chloride, total dissolved solids, and specific conductance (table 6). However, the only contaminant exceeding the USEPA primary MCL was arsenic (MCL 10 µg/L), in five samples from wells in the Pocket and Natomas areas (wells 8–12). Elevated levels of arsenic, manganese, and iron are likely from natural sources due to reduced chemical conditions near the confluence of the Sacramento and American Rivers.

Arsenic can occur naturally in sulfide minerals, including arsenopyrite, can be sorbed on iron hydroxides or grain surfaces, and can occur as a component of pesticides (Hem, 1985). The presence of hydrogen sulfide (characterized by the odor of rotten eggs) noted during the sampling of five wells (wells 8–12) indicates reducing chemical conditions in the ground water where the MCL for arsenic was exceeded. Co-occurrence of reducing conditions and high arsenic suggests that arsenic is being released to solution by the dissolution of

iron hydroxide grain-surface coatings. At least one previous ground-water study in the Sacramento area has reported two wells with concentrations of arsenic greater than the USEPA primary MCL, but the wells were in southwest Sacramento County south of the urban study area, near the confluence of the Sacramento and San Joaquin Rivers (Johnson, 1985).

Eight ground-water samples contained concentrations of manganese that exceeded the USEPA and CA DHS secondary maximum contaminant levels (table 6). Secondary maximum contaminant levels (secondary MCLs) are intended to protect public welfare and to assure a supply of potable water (California Department of Water Resources, 1997; California Department of Health Services, 2003). Secondary MCLs are applied at the entry point to the distribution system and generally address the taste, odor, or appearance of drinking water. Federal secondary MCLs are nonenforceable, but State secondary MCLs are enforceable for all new water systems and new sources added to existing systems. Four of the samples with manganese concentrations greater than the secondary MCLs were from wells (8–11) in the Pocket area, two from wells (12 and 14) in the Natomas area, and two from wells (2 and 5) in the south Sacramento area. Five samples from wells (8–12) in the Pocket and Natomas areas also contained concentrations of iron that exceeded the USEPA and CA DHS secondary MCLs (table 6). Elevated concentrations of iron and manganese in ground water have been reported in previous ground-water studies in Sacramento County (California Department of Water Resources, 1974; Johnson, 1985).

Table 6. Water-quality parameters in ground-water samples that exceeded drinking-water standards, Sacramento, California.

[See fig. 1 for well locations. Concentrations are in microgram per liter, except where noted. mg/L, milligram per liter]

Water-quality parameter	Number of samples exceeding drinking-water standards	Well numbers with exceedances	All detected concentrations		Drinking-water standard
			Median	Maximum	
Arsenic	5	8, 9, 10, 11, 12	5.0	62	¹ 10; ² 50
Manganese	8	2, 5, 8, 9, 10, 11, 12, 14	255	9,830	^{3,4} 50
Iron	5	8, 9, 10, 11, 12	2,400	9,200	^{3,4} 300
Chloride, in mg/L	1	9	27	610	³ 250; ⁵ 250 500 600
Total dissolved solids, in mg/L	8	6, 9, 10, 11, 12, 13, 14,15	344	2,000	³ 500; ⁵ 500 1,000 1,500
Specific conductance, in microsiemens per centimeter at 25°Celsius	7	9, 10, 11, 12, 13, 14,15	545	2,920	⁵ 900 1,600 2,200

¹2004 U.S. Environmental Protection Agency (USEPA) primary maximum contaminant level (MCL), as of Jan. 23, 2006, adopted Jan. 22, 2001 (USEPA web page accessed Aug. 3, 2004).

²2004 California Department of Health Services (CA DHS) primary MCL (CA DHS website accessed Aug. 3, 2004; Title 22 dated Sept. 12, 2003).

³2004 USEPA secondary MCL (USEPA web page accessed Aug. 3, 2004).

⁴2004 CA DHS secondary MCL (CA DHS website accessed Aug. 3, 2004; Title 22 dated Sept. 12, 2003).

⁵2004 CA DHS secondary MCL ranges: recommended, upper, and short term (CA DHS website accessed Aug. 3, 2004; Title 22 dated Sept. 12, 2003).

Samples from wells in the south Sacramento (well 6), Pocket (wells 9, 10, and 11), and Natomas (wells 12–15) areas exceeded the secondary MCL (500 mg/L) for total dissolved solids (TDS) (*table 6*). TDS concentrations in wells from the urban study areas are higher than previously reported for ground-water samples from wells in the same or adjacent areas, except for the high concentrations reported in wells along the Sacramento River (Johnson, 1985). One of the ground-water samples from well 9 in the Pocket area exceeded the USEPA secondary MCL and the CA DHS recommended secondary MCL (250 mg/L) for chloride (*table 6*).

Specific conductance values exceeded secondary MCLs determined by the CA DHS (*table 6*) in samples from seven wells (wells 9–15) in the Pocket and Natomas areas. The three levels of secondary MCLs in *table 6* indicate recommended, upper, and short-term limits (California Department of Water Resources, 1997). Specific conductance was highest in samples from wells in the Pocket and Natomas areas adjacent to the Sacramento and American Rivers (*fig. 7*); the lowest specific conductance was measured in the sample from the well (well 8) in the Pocket area that is closest to the Sacramento River.

Factors Affecting Ground-Water Quality

Physical and chemical factors were evaluated relative to ground-water quality to explain the presence or absence of contaminants in shallow ground water. These factors include ground-water age, land use, detections of contaminants at air and surface-water sampling sites within and adjacent to the urban study area, and various hydrogeologic and chemical variables. Ground-water age dating can be used to define the time of ground-water recharge (age of the ground water) and to estimate ground-water residence time. Land-use patterns can indicate possible sources of contaminants to ground-water quality. Detections of contaminants at nearby air and surface-water sampling sites may suggest possible sources or transport mechanisms of contaminants to ground water. Hydrogeologic and chemical factors, including depth to water, soil texture and chemistry, borehole texture and geophysical data, stable isotope ratios, and characterization of chemically reducing environments, can influence the occurrence and sources of contaminants. These factors can impede the movement of contaminants; control sorption, dispersion, or volatilization of chemicals; provide evidence for sources of recharge; and cause

chemical or biological transformation. A multivariate analysis was used to investigate factors that contribute to or explain the occurrence of contaminants in ground water.

Ground-Water Age

Tritium/helium-3 ($^3\text{H}/^3\text{He}$) and tritium (^3H) data were used to estimate the age of the ground water and to verify whether or not the ground water was recently recharged. A recharge estimate based on a ground-water budget also was determined for the area around one well. The potential effect of the age of the ground water was examined with respect to the occurrence of anthropogenic compounds such as pesticides or VOCs.

The age given by age dating refers to the time elapsed since the water was recharged at the water table and isolated from the atmosphere. Traveltime of the water through the unsaturated zone is not included in the age. Samples were collected and analyzed for $^3\text{H}/^3\text{He}$ to determine if ground waters were recharged within the time in which urbanization has occurred, approximately within the last 30 years. Results from the $^3\text{H}/^3\text{He}$ analyses show that ground water was recharged within the last 37 years in the samples from 6 of the 19 wells in the south Sacramento, Pocket, and Natomas areas (*table 7*). Most of the well samples could not be dated using $^3\text{H}/^3\text{He}$ analyses. Potential complications to $^3\text{H}/^3\text{He}$ dating include corrections for sources and sinks of additional ^3He in ground water other than tritiogenic ^3He , accounting for dispersive mixing of ^3H and ^3He along the flow path, and the potential for mixing of waters of different ages over the length of the screened interval.

Samples were collected and analyzed for tritium (^3H) to define the age of the water relative to 1953—that is, pre or post 1953, the start of nuclear bomb testing. Results from the ^3H analyses show that most (13 of the 19 samples) of the ground water was recharged after 1953. Thirteen of the samples contain tritium concentrations greater than 1 TU (*table 7*). Concentrations below 1 TU in the Sacramento area are considered to be natural or not from nuclear weapons testing (Niel Plummer, U.S. Geological Survey, oral commun., 1999) and indicate that the ground water was recharged prior to 1953. Ground-water samples from two wells in the south Sacramento area (wells 1 and 3) and all four wells in the north Sacramento area (wells 16–19) contain tritium concentrations below 1 TU.

Table 7. Estimated age of ground water from tritium and tritium/helium-3 analyses in ground-water samples, Sacramento, California.[See *fig. 1* for well locations. TU, tritium unit; —, no data]

Well number	Date sampled	Tritium, dissolved (TU)	Accuracy of tritium, dissolved (TU)	Estimated age date	Calculated tritium/helium-3 age date	Accuracy of tritium/helium-3 age (years)	Assigned tritium/helium-3 age date
1	07/16/98	0.94	± 0.04	pre 1953	—	—	—
2	07/14/98	1.2	±.04	post 1953	—	—	—
3	07/15/98	.91	±.04	pre 1953	—	—	—
4	07/13/98	1.3	±.09	post 1953	—	—	—
5	07/20/98	4.0	±.08	post 1953	1998.4	±1.4	1998
6	07/21/98	4.9	±.10	post 1953	—	—	—
7	07/22/98	4.0	±.08	post 1953	—	—	—
8	06/18/98	4.8	±.10	post 1953	1994.3	±.24	1994
9	06/22/98	1.6	±.05	post 1953	—	—	—
10	06/17/98	6.9	±.14	post 1953	—	—	—
11	06/16/98	5.2	±.10	post 1953	1988.5	±.57	1988
12	08/03/98	4.2	±.08	post 1953	—	—	—
13	08/05/98	5.2	±.10	post 1953	1991.7	±.28	1992
14	08/06/98	4.8	±.10	post 1953	1965.8	±.52	1966
15	08/04/98	3.8	±.08	post 1953	1960.6	±.52	1961
16	08/17/98	.45	±.04	pre 1953	—	—	—
17	08/20/98	—	—	pre 1953	—	—	—
18	08/18/98	.13	±.07	pre 1953	—	—	—
19	08/19/98	.13	±.03	pre 1953	—	—	—

To evaluate an approximate age range of the ground-water samples that were not dated using the $^3\text{H}/^3\text{He}$ dating technique and to verify that ground water was recharged since urbanization, tritium concentrations were compared with atmospheric tritium concentrations deposited through rainfall. *Figure 11* shows the tritium deposition in Sacramento estimated each year from 1953 to 1983 (Michel, 1989), and from 1984 to 1998, estimated from recent tritium measurements made in Portland, Oregon (R.L. Michel, U.S. Geological Survey, written commun., 1999). The Portland data are an estimate for the maximum tritium deposition level in Sacramento. Estimated tritium concentration in precipitation was consistently between 4 and 8 TU from 1984 through 1993 and was between 4 and 8 TU for brief periods of time between 1953 and 1984. Comparatively, samples with tritium concentrations in this range that were not dated with $^3\text{H}/^3\text{He}$ age dating methods likely contain water recharged since about 1980 (wells 6, 7, 10, and 12; *table 7*).

Wells with no reliable $^3\text{H}/^3\text{He}$ age date were categorized as pre or post 1953 on the basis of whether the tritium concentration was less than or greater than 1 TU. Samples from at least four wells were reliably dated to have recharged within the last 10 years: well 5 in the south Sacramento area, wells 8 and 11 in the Pocket area, and well 13 in the Natomas area. The six oldest ground-water samples were collected from wells 16–19 in the north Sacramento area and from wells 1 and 3 in the south Sacramento area. These six wells with ground water recharged prior to 1953 are the wells where the depth to water is greatest.

A recharge estimate based on a ground-water budget was calculated for well 3 to provide an independent check on the pre-1953 estimated age dates for the wells in the south Sacramento area. If the independent recharge estimate, which takes into account the traveltime from the land surface to the depth of the screened interval, indicated that the recharge water reached the water table before the start of nuclear testing, then this would provide an additional piece of information suggesting that the water was recharged prior to 1953.

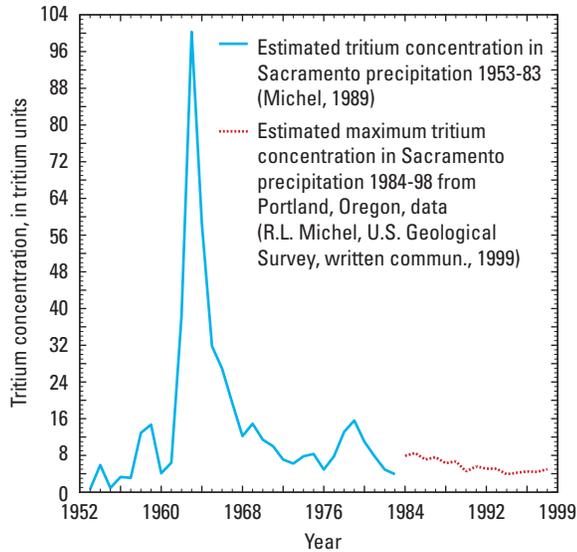


Figure 11. Annual tritium deposition in Sacramento, California, in 1953–83.

In order to determine a ground-water budget for the area around well 3, minimum and maximum soil-moisture content estimates were obtained (Maserjian, 1993) and assigned to the textural facies categories classified by comparing drill-cutting descriptions with EM induction and natural-gamma logs throughout the borehole. This resulted in an estimate of the range of the total volume of water in the sediment above the depth to water in the well. A normal evapotranspiration value (from long-term averages) was used and multiplied by the crop coefficient for pasture; values were obtained from the California Department of Water Resources (1992 and 1994). Average monthly precipitation values were used for Sacramento County for the period of record from 1878 to 1994, obtained from Earthinfo (1996). The calculated approximate amount of time it would take water to recharge at well 3 varied from 56 to 129 years. This assumes vertical recharge and does not take into account any sources of recharge moving laterally, which would influence this traveltime estimate.

Most of the VOCs that were detected were in ground waters recharged since 1953. Ground waters from two of the three wells with the most VOC detections (wells 5 and 13; *table 4*) were recharged in the last 10 years (*table 7*). Ground water from the third well with the most VOC detections (well 6) was not dated with $^3\text{H}/^3\text{He}$, but was recharged after 1953. Coarse-grained aquifer material was encountered during the installation of this well, which may allow recharge to occur at a more rapid rate and result in younger water.

Trichloromethane was detected in ground water recharged prior to 1953 (wells 1, 3, and 16–19). Also, tetrachloroethene was detected in one ground-water sample (well 3) dated to have recharged prior to 1953. This detection may result from a mixing of young and old water recharging that well.

Pesticides were detected primarily in wells with ground waters that have recharged in the last 50 years, except for two detections in the oldest ground-water samples collected from

the deepest wells in the south Sacramento area (wells 1 and 3). Atrazine and its transformation product desethyl atrazine were detected at wells 2, 3, and 5, and desethyl atrazine also was detected at well 1 (*table 5*). Ground water from wells 1 and 3 contained low tritium concentrations and was recharged prior to 1953, but ground water from well 5 was dated to have recharged in 1998. Sources of recharge water to the wells with ^3H concentrations less than 1 TU may be mixed, in which case the more recently recharged water probably contained the VOCs and pesticides.

Most of the elevated nitrate concentrations occurred in samples from wells where ground water was recently recharged (*fig. 10* and *table 7*). Nitrate was greater than 3 mg/L in six wells recharged since 1953 and in only one well recharged before 1953. Nitrate was less than 3 mg/L in five wells recharged before 1953, and in two wells recharged since 1953. Nitrate was not detected in wells with low dissolved oxygen and elevated iron and manganese concentrations, reflecting reducing conditions that first consume the available oxygen and then the nitrate.

Results from $^3\text{H}/^3\text{He}$ and ^3H samples indicate that most (13 of the 19) ground-water samples were from recently recharged water—recharged after 1953. Also, well samples with the most VOC and pesticide detections and highest concentrations of nitrate were from recently recharged ground waters. The mixing of waters captured from different depths over the length of a well's screened interval may affect the estimated ages of the ground water. The detection of trichloromethane in all six samples that are estimated to have recharged prior to 1953 and the detections of atrazine or desethyl atrazine in two of those six samples may indicate that at least some component of young water may have been captured in these samples.

Land Use

Land uses surrounding the monitoring wells were documented at three different spatial scales and time periods to evaluate possible sources of contaminants associated with various land-use practices. Data were compiled to characterize the specific types of land use present. Urban, cropland, and miscellaneous other land uses in 1975 were identified for the Sacramento River Basin using 1:100,000 scale maps and satellite imagery data (U.S. Geological Survey, 1998). Crop type classifications as well as other land uses in 1993 were mapped by the California Department of Water Resources (1993) on 1:24,000 scale maps. Detailed land uses in a 500-m radius around each well were mapped in 1998 on aerial photos with an approximate scale of 1:20,000. These land uses may help to identify potential sources, but the percentages of total urban or agricultural land use around a well were not significantly correlated with the presence or absence of VOCs or pesticides, elevated nitrate concentrations, or drinking-water-standard exceedances.

Prior to extensive urban development in the Sacramento River Basin, cropland and livestock were the primary land uses and livelihoods (Bryan, 1923; California Department of Public Works, 1931). Cropland and pasture continued to be the primary land uses in the urban study area until as recently as 1975 (fig. 3). By 1993, most of these land uses had been converted to urban, except for grain crops in the south Sacramento, Natomas, and north Sacramento areas; field crops in the south Sacramento area and a small amount in the Natomas area; pasture in the south Sacramento area; and some native vegetation throughout the urban study area (fig. 4). Livestock is another type of agricultural commodity present in 1993 in Sacramento County (fig. 4). A small amount of the feedlot land-use category was present in the south Sacramento area in 1993 and was adjacent to the south Sacramento, Natomas, and north Sacramento areas (fig. 4).

In 1998, the primary type of land use in a 500-m radius around all the monitoring wells in this study was residential (table 8). There was a variety of other types of urban land uses immediately surrounding the wells in a 500-m radius. More than half of the wells are near rights-of-way (primarily roadways and highways, lined canals, and pump or electrical substations), about half are adjacent to schools, and about one-fifth have commercial land use within the 500-m radius (table 8). All of the wells are located on land owned by local

park districts, but none of the park sites are highly developed. Some differences in park land use between the well locations are not listed in table 8: over half of the sites are in green, open-space areas adjacent to houses or in greenbelts (wells 16–19); approximately one-fifth of the wells are adjacent to creeks (wells 5, 12, 14, and 16), and two are on barren, undeveloped park land surrounded by urban land uses (wells 17 and 18). While there are minor differences between these urban settings, between 52 and 86 percent of the 500-m radius land area surrounding every well is residential land use. All wells are also either on or surrounded by irrigated landscaping.

Agricultural and urban sources of VOCs, pesticides, and nitrate were investigated because urbanization has accelerated since 1975, and cropland and pasture were still present in 1993 in the urban study area and still existed adjacent to the urban study area in 1998. Six of the eight VOCs detected in the ground-water samples are known to be used in agricultural practices (trichloromethane, chloromethane, tetrachloroethene, carbon disulfide, 1,1,1-trichloroethane, and MTBE). Trichloromethane and chloromethane can be found in fumigants and solvents. In addition, carbon disulfide is found in soil conditioners and in herbicide propellants. MTBE is found in fuels, and while typically thought to be associated with urban land use could also be associated with agricultural fuel storage tanks, machinery, and vehicles.

Table 8. Land uses in 1998 within a 500-meter radius around each well, Sacramento, California.

[See fig. 1 for well locations. Land use is in percentage of land area surrounding well]

Well number	Urban land uses							Total urban	Other land uses			Total for all land uses
	Residential	Park	School/church	Commercial	Rights-of-way	Miscellaneous	Barren		Open water	Riparian	General miscellaneous	
1	80.3	9.7	5.0	0.0	0.0	1.4	3.7	100	0.0	0.0	0.0	100
2	85.1	5.6	.0	3.8	.0	2.3	3.2	100	.0	.0	.0	100
3	80.9	10.4	.0	.0	4.2	2.9	.0	98	.0	.0	1.6	100
4	81.6	5.6	12.8	.0	.0	.0	.0	100	.0	0.0	.0	100
5	51.9	29.4	.0	.0	2.6	3.6	.0	88	.0	12.5	.0	100
6	79.4	.0	13.6	.0	2.9	2.8	.0	99	.0	.0	1.4	100
7	75.4	.0	.0	.0	.0	5.8	18.8	100	.0	.0	.0	100
8	76.8	7.7	5.1	1.9	8.5	.0	.0	100	.0	.0	.0	100
9	81.2	0.0	.0	.0	5.5	11.6	.0	98	.0	.0	1.7	100
10	80.0	10.5	.0	.0	4.2	2.0	.0	97	3.1	.0	.0	100
11	78.6	10.4	5.6	.0	3.5	1.2	.0	99	.0	.0	.7	100
12	63.3	5.2	5.8	.0	8.5	4.8	7.4	95	.0	.0	5.1	100
13	84.0	8.0	6.4	.0	.0	1.6	.0	100	.0	.0	.0	100
14	86.0	.0	5.0	.0	4.3	4.7	.0	100	.0	.0	.0	100
15	78.6	6.2	2.9	.0	5.5	2.9	4.0	100	.0	.0	.0	100
16	79.7	.0	2.7	.0	.0	.0	2.1	85	15.5	.0	.0	100
17	60.1	4.5	.0	5.6	2.1	3.0	24.6	100	.0	.0	.0	100
18	66.6	16.6	.0	.0	5.3	1.6	9.9	100	.0	.0	.0	100
19	72.6	6.2	17.3	0.9	.0	2.2	.0	99	.0	.0	.9	100

One likely source of the two most frequently detected VOCs in the ground-water samples—trichloromethane and bromodichloromethane—may be from by-products of the chlorination of tap water used to water lawns and gardens. Other sources of trichloromethane include fumigants, fire extinguishers, and chlorinated wastewater from sewage treatment plants (Howard, 1991). The other two VOCs detected in more than one ground-water sample are MTBE and tetrachloroethene. MTBE is a gasoline additive and tetrachloroethene is used primarily in dry cleaning operations and in metal degreasing. Iodomethane, carbon disulfide, and chloromethane, detected in one ground-water sample each, are used in medicine, soil conditioners, and herbicide propellants, respectively. No wells had any known ground-water contamination problems, and no existing dry cleaners or gas stations are located within the 500-m radius surrounding the wells.

Pesticide-use data were compiled for Sacramento County for the oldest (1991) and most recent (1996) years available in digital format in 1998 (California Department of Pesticide Regulation, 1991, 1996). County totals are presented (*table 5*) to provide some information on use of these pesticides in the urban study area.

In 1991, atrazine and simazine were the top two pesticides applied in Sacramento County (California Department of Pesticide Regulation, 1991). Over 9,000 kg of atrazine was applied, of which approximately 62 percent was applied to field and grain crops. Of the total amount applied of each pesticide detected in this study, use on rights-of-way and on uncultivated nonagricultural areas comprised 37 percent of the total atrazine, 67 percent of the total simazine, and 68 percent of the total tebuthiuron applications. Pesticide use for landscape maintenance and ornamental turf comprised 0.74 percent of the total atrazine, 3.9 of the total simazine, and 32 percent of the total tebuthiuron. Pesticide detections in this study may have resulted from these nonagricultural uses.

The most recent pesticide-use data (1996) available for Sacramento County show almost a 50 percent reduction in the amount of atrazine and simazine applications relative to the 1991 data (California Department of Pesticide Regulation, 1996). In 1996, the total amount of atrazine applied in Sacramento County (*table 5*) was about 5,300 kg, all of which was applied to field, grain, and uncultivated nonagricultural areas. The amount of simazine applied in Sacramento County in 1996 (*table 5*) was about 3,200 kg, of which 77 percent was applied to processed grapes and deciduous trees. These crops were not present in the urban study area in 1993 (*fig. 4*).

Sources of pesticides detected in this study (*table 5*) may include applications on field and grain crops, agricultural and (or) urban rights-of-way areas, uncultivated nonagricultural areas, landscape maintenance and ornamental turf areas, and rice. Samples with atrazine or desethyl atrazine detections were collected from wells (wells 1, 2, 3, 5) in the south Sacramento area where cropland and rangeland were present in 1975 (*fig. 3*) and primarily urban land use and field and grain crops were present in 1993 (*fig. 4*). The largest amount of simazine and tebuthiuron used in 1991 was applied on

rights-of-way and uncultivated nonagricultural areas in Sacramento County. Simazine was detected in the sample from well 5 in the south Sacramento area. The largest amount of tebuthiuron was applied on landscape maintenance and ornamental turf areas in 1996. Tebuthiuron was detected in the sample from well 10 in the Pocket area. The only known use of bentazon was as a rice herbicide from 1978 to 1989, after which it was suspended and subsequently banned. Rice has been grown along the Sacramento River levees, but in 1993 the most dense area of rice land use was north of the urban study area (*fig. 4*). Bentazon was detected in one sample from well 8 in the Pocket area. One mode of transport of this pesticide to the well sample may be the Sacramento River. Bentazon has been detected in the Sacramento River and its tributaries (California Department of Food and Agriculture, 1987, 1989; Domagalski and others, 2000), and the stable isotope data for this well clearly indicates recharge from the river.

Elevated nitrate concentrations, above 3 mg/L as nitrogen, were detected in samples from wells in the south Sacramento, Natomas, and north Sacramento areas (*fig. 10*). None of the detections co-occur at a well where a pesticide was detected, indicating no association between elevated nitrate concentrations and agricultural crops. Sources may include dissolution of minerals, decomposition of plants, sewage wastewater, or animal excrement.

Air and Surface-Water Quality

VOC and pesticide data from air and surface-water sampling sites were compared with similar data from the wells to evaluate possible sources of these compounds to the shallow ground water. VOCs and pesticides present in air and surface-water bodies can be transported to the aquifer (Pankow and others, 1997; Lopes and Bender, 1998). Although the specific sources of ground-water recharge have not been verified in this study, rainfall recharges water supplies (both surface and ground water) by direct deposition, runoff, and infiltration. Surface water also can contribute to water recharged to the aquifer. These processes of recharge are possible contributors of observed VOCs and pesticides in this study.

VOCs or pesticides were collected at four air sampling sites located adjacent to the study area (*fig. 1*). Air VOC samples were collected at one site—Roseville. Air VOC samples were 24-hour composites collected every 24th day from August 1997 through September 1998. Air pesticide samples were collected at three sites—Franklin Air Field, T Street, and Sacramento International Airport. Air pesticide samples were weekly composites collected from December 1995 through June 1997. Sorbent sample collection methods were used to detect a wide range of VOCs (Pankow and others, 1998) and pesticides (Majewski and others, 1998; Foreman and others, 2000) to ensure reproducible and quantitative results.

Six of the eight VOCs detected in the wells (*table 4*) also were detected routinely in the air samples collected at the Roseville site. The VOCs detected in the air samples include trichloromethane, MTBE, tetrachloroethene, 1,1,1-trichloroethane, carbon disulfide, and chloromethane (D. Bender, U.S. Geological Survey, written commun., 1999). Bromodichloromethane was not detected in the air samples and methyl iodide was not analyzed. Trichloromethane was the most frequently detected VOC in ground water and was detected in 84 percent of the wells at low concentrations. The average concentration of trichloromethane in air was 0.028 parts per billion volume (ppbv) with a standard deviation of 0.015 ppbv. This is only slightly less than the 1996 statewide average concentration of trichloromethane in air, which was 0.036 ppbv with a standard deviation of 0.031 ppbv (California Environmental Protection Agency, 1997).

Three of the four pesticides detected in the wells (*table 5*) also were detected routinely in the air samples collected at the Franklin Air Field, T Street, and Sacramento International Airport sites. Pesticides detected in the air samples include atrazine, simazine, and tebuthiuron (M.S. Majewski, U.S. Geological Survey, written commun., 1999). Atrazine was the most frequently detected pesticide in both ground-water and air samples.

Surface water containing VOCs and pesticides is a potential source for contaminants detected in the wells. Surface-water sites in and around the urban study area at which water-quality samples were collected by the NAWQA study include the Sacramento River at Freeport, the American River at Sacramento, and Arcade Creek near Del Paso Heights (*fig. 1*). The same methods were used to analyze the surface-water samples as were used for the samples collected at the wells.

Arcade Creek was the Sacramento River Basin NAWQA site chosen to indicate surface-water quality in an urban area and was the only surface-water site where VOC samples were collected and analyzed. Samples were collected monthly from November 1996 through April 1998. Almost all the VOCs detected in the wells also were detected in Arcade Creek in low concentrations, including trichloromethane, MTBE, tetrachloroethene, carbon disulfide, and chloromethane. MTBE was the most frequently detected VOC, detected in 100 percent of the samples, with a maximum concentration of 1.20 µg/L. Trichloromethane was detected in 84 percent of the samples, with a maximum concentration of E0.100 µg/L (estimated).

Samples were collected monthly and analyzed for pesticides at all three of the surface-water sites from January 1997 through April 1998. Pesticides detected in the wells were also detected in Arcade Creek at low concentrations, including atrazine, simazine, and tebuthiuron with maximum concentrations of 0.027, 0.190, and 0.078 µg/L, respectively. Atrazine, desethyl atrazine, simazine, and bentazon were detected in the Sacramento River at Freeport with maximum concentrations of E0.002, E0.001, 0.020, and E0.002 µg/L, respectively. Bentazon was detected at well 8 in the Pocket area, which

is located very close to the Sacramento River at Freeport. Samples collected from the American River at Sacramento were analyzed by the GC/MS method (*table 3*). None of the pesticides detected in the wells were detected in the samples from the American River at Sacramento during February 1996 through April 1998.

The limited amount of data on current VOC and pesticide concentrations in air and surface waters within the urban study area shows that some of the most frequently detected VOCs and pesticides in ground-water samples also were detected in air and surface-water samples. This suggests that air or surface water may be potential sources of these contaminants in ground water. However, a comparison of the concentrations of VOCs and pesticides detected in air and in surface waters with those detected in ground waters indicates that air and surface water alone could not account for all of the ground-water detections because most of the concentrations were greater in ground water. Furthermore, air and surface-water quality have changed over time, so the concentrations of pesticides and VOCs detected in samples collected in approximately the two years prior to when ground-water sample collection took place likely do not represent the same concentrations present when ground water was being recharged throughout most of the study area.

Physical and Chemical Factors

Physical and chemical data were compiled to assess how they may affect the occurrence of VOCs, pesticides, elevated nitrate concentrations, and exceedances of drinking-water standards in the ground-water samples. Concentrations in ground water may be affected by the rate and amount of a constituent leaching beyond the root zone. Transport to the water table can be inhibited by impeding clay or silt layers as well as by the depth to the water table from land surface. Nitrate concentrations and pesticide occurrence have been linked to well construction and hydrogeologic characteristics, such as well depth and sediment texture (Nightingale and Bianchi, 1980; Knox and Moody, 1991; Koterba and others, 1993; Troiano and others, 1994; MacLeod and others, 1995; Mueller and others, 1995; Barbash and Resek, 1996). Chemical factors—such as isotopic chemistry, specific conductance, and reducing conditions—that indicate the source of recharge, length of ground-water residence time, and possible effects from agricultural and urban land uses were examined. Chemical data were evaluated for each ground-water sample and for air and surface-water samples collected in and adjacent to the study area. Although the study area is located within one physiographic province, interpretation of geochemistry in the Sacramento urban area is complex due to the physiographic confluence of river channels, flood-plain deposits and alluvial channels, presence of major rivers, and location at the distal end of an alluvial fan.

Physical Factors

A series of comparisons were made to investigate correlations between ground-water quality and physical factors, such as well construction characteristics and variables that describe the hydrogeologic setting. Well construction characteristics evaluated for each well site include depth to water, depth to the top of the screened interval below the water table, length of the screened interval, and well depth. Hydrogeologic variables evaluated were soil pH, percent organic matter of surface soils, permeability, percent clay, inorganic and organic carbon content of borehole cuttings, texture or lithologic facies penetrated by each borehole, percentages of hydrogeologic facies by borehole footage, and general depositional environments.

Depth to the top of the screened interval below the water table was negatively correlated with the number of VOCs detected ($p = 0.02$, $\rho = -0.53$). This correlation supports the prevailing thought that contaminants occur in greater frequency near the surface of the water table (Barbash and Resek, 1996). Ground-water samples with the most VOC detections (*table 4, fig. 9*) occurred in samples from wells in the south Sacramento area (wells 3, 5, and 6) and in the Natomas area (wells 13 and 15). These are not the wells with the smallest depth-to-water measurements of all 19 wells (*table 1*); therefore, there must be other variables that help to explain the occurrence of VOCs.

Depth to water and well depth were positively correlated with a presence or absence variable indicating whether or not a VOC was detected in each ground-water sample ($p = 0.054$, $\rho = 0.45$, and $p = 0.047$, $\rho = 0.46$; respectively). This correlation is counter to the idea that VOCs are more likely to occur where the water table is shallow or in the shallowest wells. This correlation reflects the fact that at least one VOC was detected in almost every well, including the wells with the deepest depth to water (*table 1, fig. 9*), and that the only wells with no VOC detections are among the wells with the shallowest depth to water. These wells with no VOC detections are located adjacent to the rivers at a potential ground-water discharge zone or where ground-water/surface-water interaction may occur, and are not located near any pumping depressions. Most of the wells with more than one VOC detection are not located close to rivers, are characterized by intermediate depth to water (*table 1 and fig. 9*), and are located in the south Sacramento area where pumping depressions have been noted. Perhaps whether or not VOCs were detected from wells in this study may have to do with the amount of pumping in the vicinity of the well, which may be increased by rapid urbanization or by the position of the well in the flow system.

Detections of constituents in concentrations exceeding drinking water standards primarily occurred in samples from wells where the depth to water was shallowest (*tables 1 and 6*) near the confluence of the Sacramento and American Rivers. Ground water tends to be chemically reduced (*fig. 7*) in these areas near rivers that historically have flooded and are

at the end of the flow path from the Sierras, so shallow depth to water cannot solely explain these exceedances. Elevated levels of manganese and iron are typically found in chemically reduced waters (Hem, 1985), and elevated levels of chloride, TDS, and specific conductance are typically found in evaporative environments and in ground water with longer residence times such as at the end of a flow path. These natural processes likely affected the elevated measurements of the constituents exceeding drinking water standards in the study area.

Surface-soil pH and organic matter data were compiled from the Sacramento County soil survey maps (Tugel, 1993) to document the potential for leaching and degradation of organic compounds (*table 9*). Surface-soil pH values from soil maps for the south Sacramento area (wells 1-7) were slightly acidic, which may indicate a higher susceptibility to the leaching of organic substances from the land surface. The measured pH of the uppermost soil in drill cuttings from this project, however, was consistently more basic than indicated on the soil maps for the south Sacramento area. Most of the pesticide detections were from samples from south Sacramento wells. Organic matter content can also affect the transport and degradation of compounds. The maximum organic matter present in surface soils was relatively low (1 to 5 percent) at most sites, but was relatively high (10 percent) at three sites in the Pocket area (*table 9*). Organic matter may provide a substrate for bacteria that reduce nitrate in ground water or soil water, and may be associated with chemically reduced waters and elevated levels of trace elements, TDS, and specific conductance. In samples from the three Pocket area wells, nitrate was not detected (*fig. 10*), ground water was chemically reduced at two wells (*fig. 7*), arsenic was detected over the USEPA primary MCL, and other drinking-water standards were exceeded (*table 6*). These factors may influence the presence of certain compounds, but clearly do not account for all detections or the absence of detections.

Infiltration rates at the land surface are most likely inhibited by the low permeability and relatively high percentage of clay in the surface soil, although these factors were relatively consistent among the wells. Minimum permeability of the surface soil was low (0.91 to 1.8 cm per day) at most wells, but high (18 cm per day) at two wells (wells 7 and 9) in the south Sacramento and Pocket areas (*table 9*). The maximum clay percentage of the surface soil was high (50 to 60 percent) at most wells, but low (25 to 35 percent) at five wells (wells 9, 16-19) in the Pocket and north Sacramento areas. The minimum permeability and maximum clay percentage of the surface soils do not appear to influence the presence or absence of VOCs, pesticides, or elevated nitrate concentrations in most of the wells. Perhaps either deeper unsaturated zone sediments or nonvertical recharge patterns—such as from ground-water/surface-water interaction or long lateral flow paths—are more controlling factors on ground-water quality.

Table 9. Sediment data from County soil survey report, drill cuttings analyses, and borehole logs, Sacramento, California.

[See *fig. 1* for well locations. m, meter; cm, centimeter; g/kg, gram per kilogram; —, not analyzed]

Well number	Soil survey of Sacramento County (Tugel, 1993)							Drill cuttings and borehole geophysical logs					
	Surface soil depth (m)	Surface soil pH	Surface soil maximum organic matter (percent)	Depth (m)	Minimum pH	Minimum permeability (cm/day)	Maximum clay (percent)	Surface soil pH (0-0.61 m)	Sample depth (m)	Inorganic carbon (g/kg)	Organic carbon (g/kg)	Hydrogeologic facies	
												Silt and clay (percent of well depth)	Coarse sand and/or gravel/cobble (percent of well depth)
1	0-0.61	5.6-6.5	1	0-1.5	5.6	0.91	50	6.8	9.1	<0.1	0.38	67	0
2	0-0.30	5.6-6.5	1	0-1.5	5.6	.91	50	7.4	—	—	—	26	18
3	0-0.30	5.6-6.5	1	0-1.5	5.6	.91	50	7.9	—	—	—	54	6
4	0-0.61	5.6-6.5	1	0-1.5	5.6	.91	50	7.8	2.4-9.1, 27-28	<.1, <.1	.42, .15	39	12
5	0-1.2	6.1-8.4	4	0-1.5	6.1	1.8	60	—	5.2	<.1	.52	12	30
6	0-0.30	6.1-7.3	2	0-1.5	6.1	1.8	60	7.6	7.6-8.2, 17	<.1, <.1	.22, .54	17	24
7	0-0.30	6.1-8.4	5	0-1.5	6.1	1.8	60	—	2.1, 6.1-7.6	2.2, <.1	1.3, .36	63	0
8	0-0.61	6.1-7.8	10	0-1.5	6.1	1.8	55	7.6	1.5, 9.1	<.1, <.1	4.0, .63	32	0
9	0-0.30	7.4-8.4	1	0-1.5	7.4	1.8	25	7.9	1.8	<.1	14.0	100	0
10	0-0.61	6.1-7.8	10	0-1.5	6.1	1.8	55	7.4	1.5-1.8	<.1	8.1	56	0
11	0-0.61	6.1-7.8	10	0-1.5	6.1	1.8	55	7.9	7.6	<.1	1.7	85	0
12	0-0.21	6.1-7.8	1	0-1.5	6.1	1.8	55	7.1	2.1-2.4	<.1	3.3	100	0
13	0-0.21	6.1-7.8	1	0-1.5	6.1	1.8	55	6.9	7.0-8.5	<.1	.98	62	0
14	0-0.21	6.1-7.8	1	0-1.5	6.1	1.8	55	—	2.1, 9.4	2.9, <.1	5.0, .35	33	25
15	0-0.21	6.1-7.8	1	0-1.5	6.1	1.8	55	—	6.1	<.1	.36	67	10
16	0-0.21	5.6-7.3	2	0-0.91	5.6	.91	35	—	—	—	—	64	5
17	0-0.21	5.6-7.3	2	0-0.91	5.6	.91	35	—	—	—	—	17	3
18	0-0.30	5.6-7.3	2	0-0.91	5.6	.91	35	—	—	—	—	20	13
19	0-0.30	5.6-7.3	2	0-0.91	5.6	.91	35	—	—	—	—	33	9

Results from the analyses of the drill cuttings (*table 9*) were compiled to provide data for deeper parts of the unsaturated zone and the aquifer. The measured surface soil pH was neutral to slightly alkaline (6.8-7.9), and the aquifer materials were low in inorganic carbon (<0.1-2.9 g/kg) and highly variable in organic carbon content (0.15-14 g/kg). High organic content in the sediment may be related to the depositional environment and may contribute to chemically reducing conditions where elevated levels of trace elements can occur and nitrate can be reduced. The sites with the highest soil organic carbon content are near the Sacramento and American Rivers at wells in the Pocket and Natomas areas where the ground water tends to be chemically reduced (*fig. 7*), most of the elevated levels of trace elements exceeding drinking-water standards were measured (*table 6*), and the only samples with no nitrate detections were collected (*fig. 10*).

The texture of the deeper parts of the unsaturated zone and the aquifer do not consistently reflect the texture observed in the surface soils. Textural information from drill cuttings and borehole geophysical logs were compiled and hydrogeologic facies were defined for every well (*fig. 12*). The EM conductivity and natural-gamma data are plotted, along with the three different hydrogeologic facies and the position of the water table. The EM conductivity of the sediments varies from less than 20 to about 200 mS/m overall, and the natural gamma varies from about 20 to 200 counts per second (cps). High EM conductivity of the sediments at wells in the Pocket and Natomas areas may be related to the specific conductance in the ground-water samples (*fig. 7*) at these same wells.

A. Wells in South Sacramento subarea

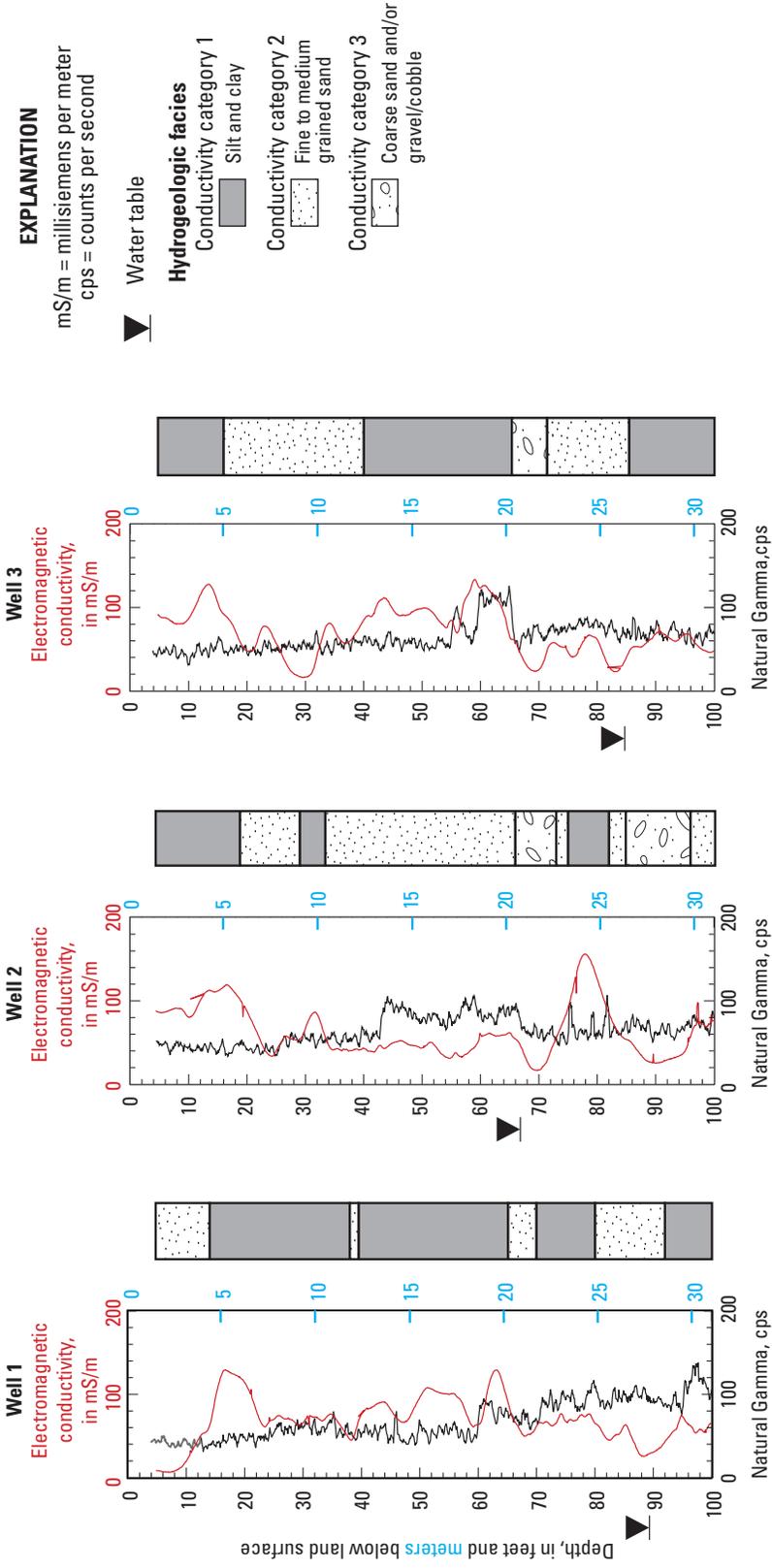


Figure 12. Hydrogeologic facies interpretations and accompanying borehole electromagnetic conductivity and natural gamma logs for wells, Sacramento, California.

A. Wells in South Sacramento subarea—continued

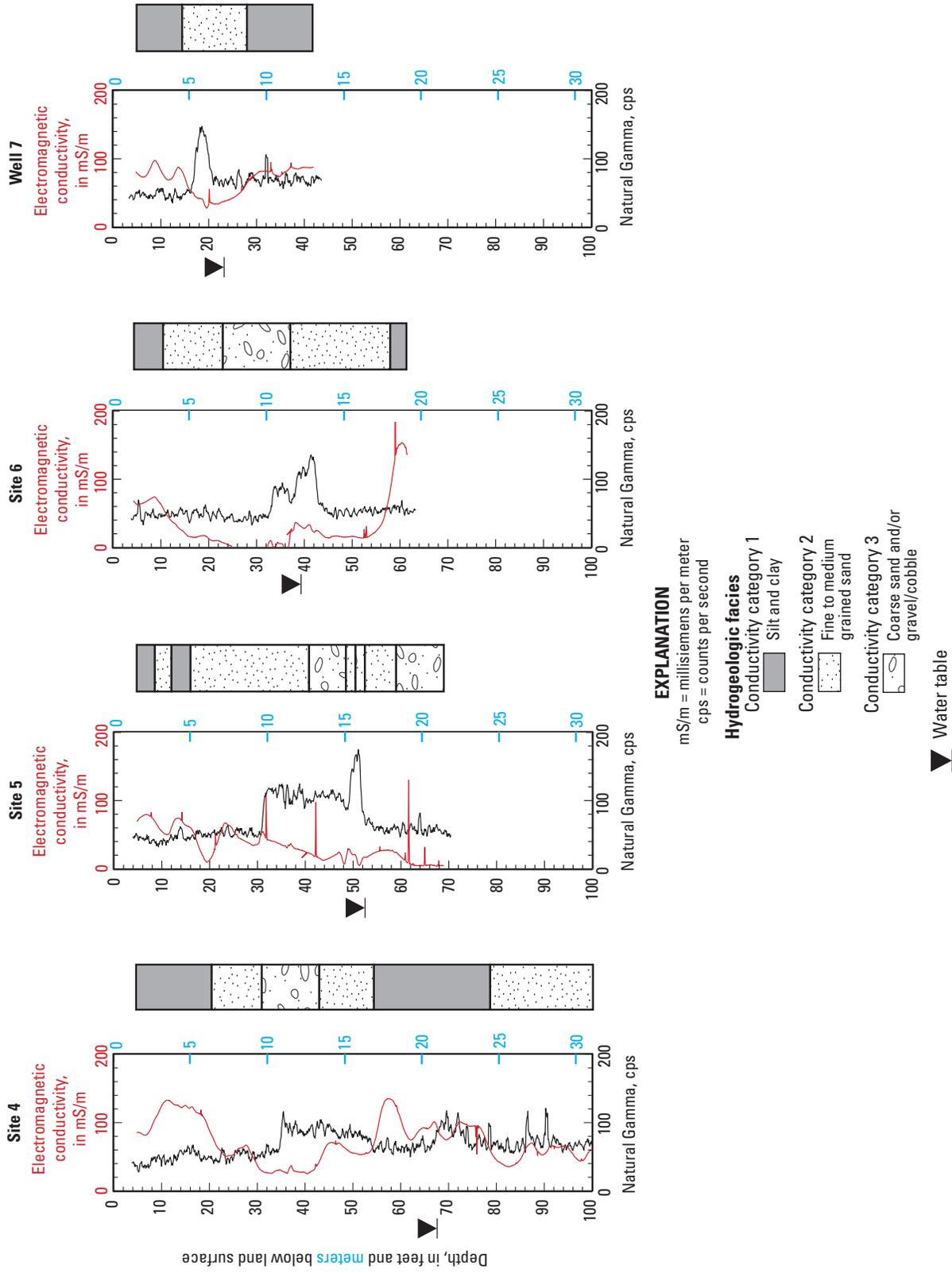


Figure 12—Continued.

B. Wells in Pocket subarea

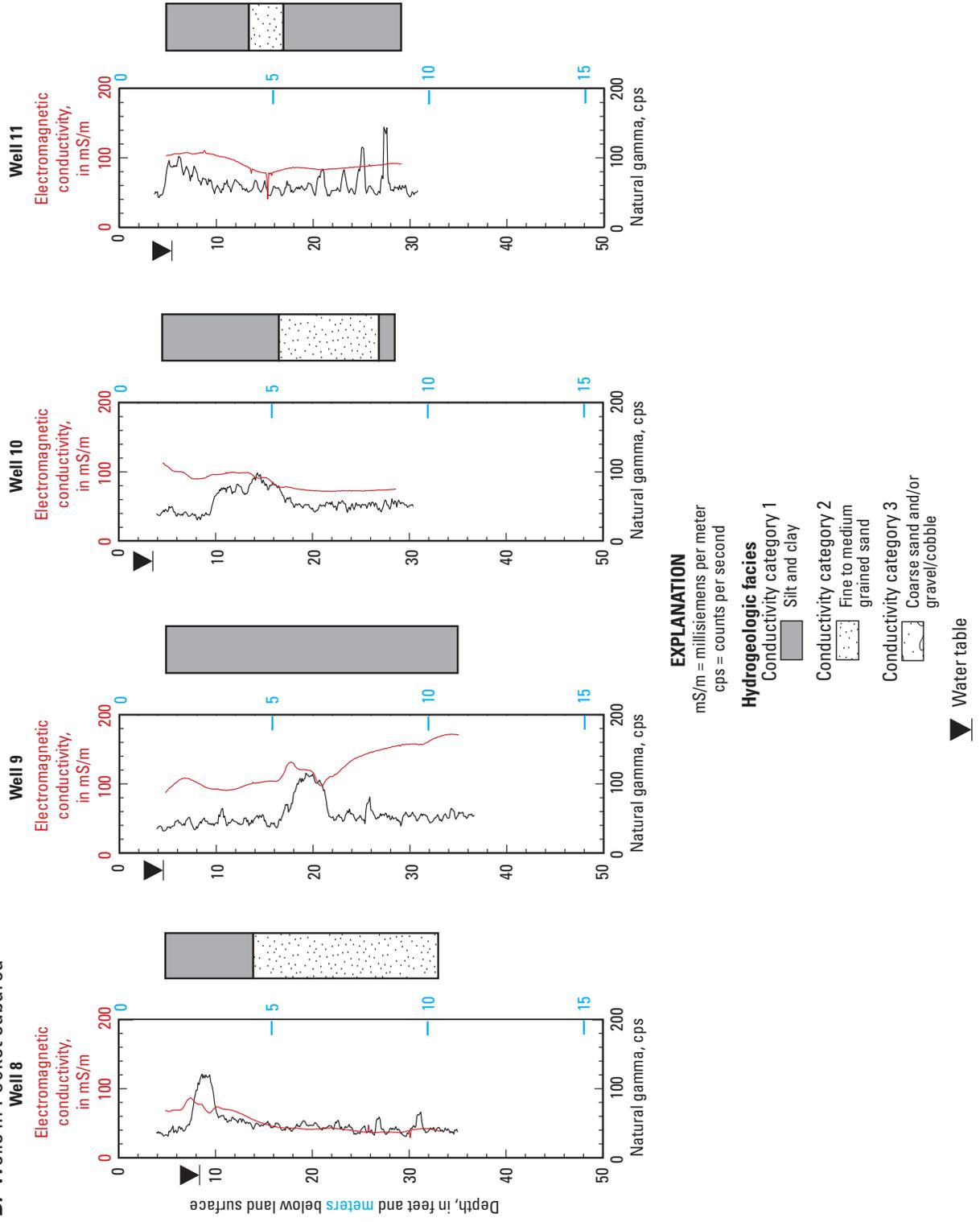


Figure 12—Continued.

C. Wells in Natomas subarea

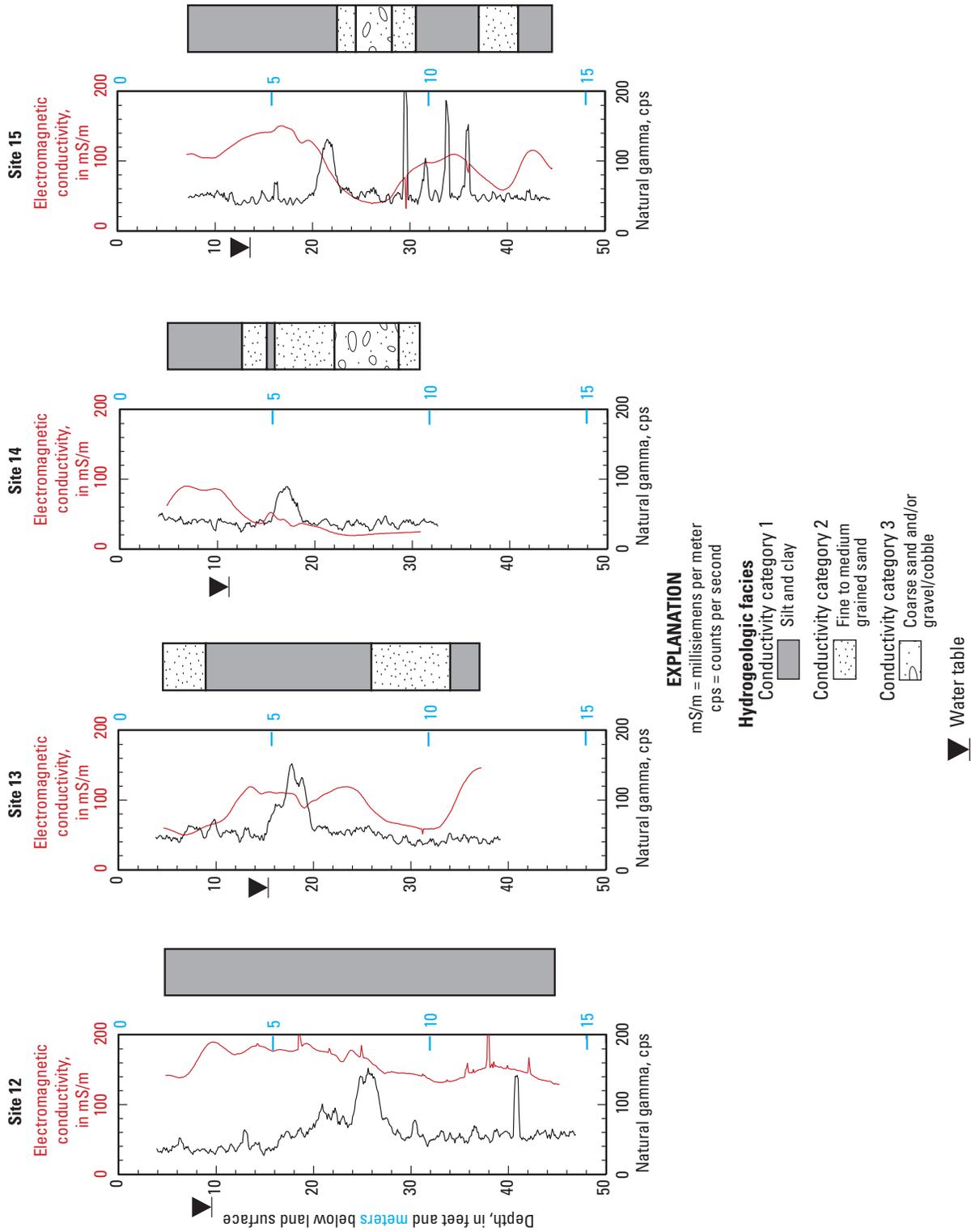


Figure 12—Continued.

D. Wells in North Sacramento subarea

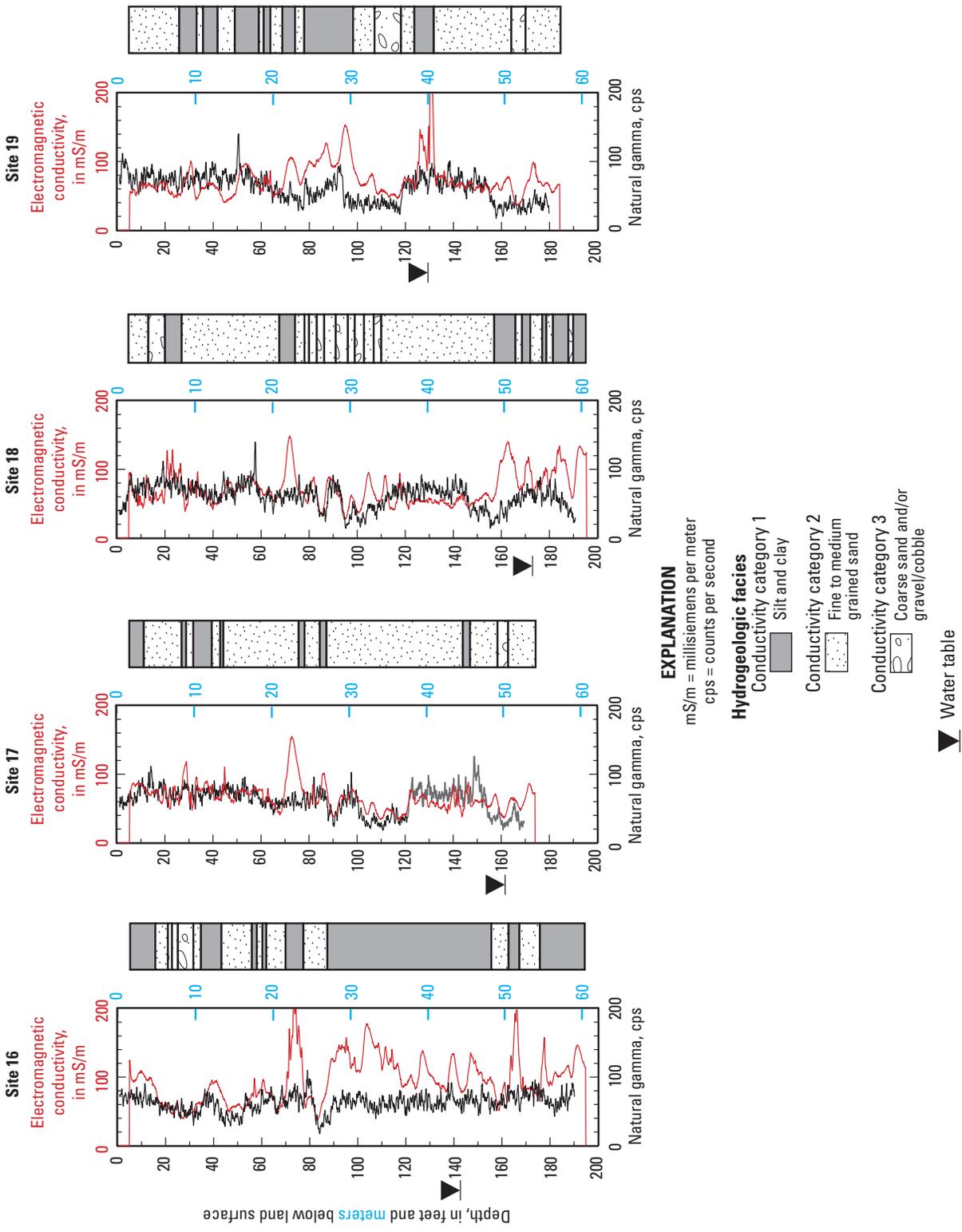


Figure 12—Continued.

In general, there are more fine-grained sediments at wells where elevated levels of trace elements were detected and the most drinking-water standards were exceeded, but the amount of fine-grained materials varies widely at wells where VOCs and pesticides were detected. The sedimentary textures observed in the drill cuttings are predominantly very fine-grained sand, silt, and clay, interlayered with fine- to coarse-grained sand, gravel, and cobble. These textures are typical of the fluvial-dominated alluvial fans of the Riverbank and Turlock Lake Formations, flood-basin deposits, and alluvium (*fig. 5*). Three textural categories were distinguished based on analyses of drill cuttings, behavior of drilling equipment, and EM conductivity logs. The three conductivity categories, in increasing order of hydraulic transmissive properties, are Category 1: silt and clay; Category 2: fine to medium sand; and Category 3: coarse sand and (or) gravel/cobble. The occurrence of each category was calculated as a percentage using the footage of each textural category and the total footage of the borehole log. These textural categories were interpreted as hydrogeologic facies assuming that each facies was deposited by similar sedimentary processes and has similar hydraulic properties.

The least transmissive category is “silt and clay,” Category 1, which consists of various combinations of silt mixed with very fine sand, silt mixed with clay, and clay. Sediments of this texture were found in the borehole materials at every well (*table 9; fig. 12*) in various amounts ranging from 12 to 100 percent of the total footage of borehole material. Some of the layers of clay found at wells in the Pocket and Natomas areas were blue to bluish gray, indicating probable deposition in reducing environments. Category 1 also was most abundant (32 to 100 percent of the total footage) in borehole material from wells in those areas, ranging in thickness from 0.3 to 12 m and making up the entire borehole material from well 9 in the Pocket area and well 12 in the Natomas area. No VOCs or pesticides were detected in samples from these two wells (*fig. 9*), ground waters were chemically reduced, and the USEPA primary MCL for arsenic was exceeded in addition to other drinking water standards (*table 6*).

Most of the sites with fine-grained materials are near the Sacramento and American Rivers at wells in the Pocket and Natomas areas with the shallowest depth to water and where all samples with chemically reduced waters were identified, most elevated trace elements were detected, and all samples with no detectable nitrate were found.

The most transmissive conductivity category is “coarse sand and (or) gravel/cobble,” Category 3. Some zones of this material contain minor interstitial amounts of very fine sand, silt, and clay. Sediments of this texture were found in the borehole materials at 11 wells, most of which are in the south Sacramento (5 wells) and north Sacramento (4 wells) areas (*table 9, fig. 12*). Well 6 contained large cobbles at a depth that may correspond to a previous channel of the American River that is now buried, according to plots by the California Depart-

ment of Water Resources (1974) of where previous channels of the American River are thought to exist.

Three boreholes contained more than 20 percent of the coarse Category 3 material, two in the south Sacramento area (wells 5 and 6) and one in the Natomas area (well 14; *table 9, fig. 12*). Four VOCs, including MTBE, were detected in each of the samples from the two wells in the south Sacramento area, but no VOCs were detected in the sample from the well in the Natomas area where the ground water was chemically reduced. The only sample with more than one pesticide detection was from well 5, where the borehole material contained the greatest amount (30 percent) of coarse material, but no pesticides were detected in samples from the other two wells that have more than 20 percent of coarse material. Drinking water standard exceedances at these three wells included manganese at well 5, TDS at well 6, and manganese, TDS, and specific conductance at well 14.

There is a clear relation between ground-water quality and physical factors. In the south Sacramento area, where most of the VOCs, pesticides, and elevated nitrate were detected, the depth to water and well depth are intermediate, surface soil pH is slightly acidic (Tugel, 1993), organic matter content in the surface soil is low (Tugel, 1993), organic carbon content is low, and the texture of the aquifer material penetrated by the boreholes is the most coarse-grained. In contrast, in the Pocket and Natomas area wells where only one or no VOCs were detected and pesticides or nitrate were typically not detected, the depth to water and well depth are shallow, organic matter content in the surface soil is high, organic carbon content is high, and the texture of the aquifer material penetrated by the boreholes is generally more fine-grained; however, all of the primary MCL arsenic exceedances and most of the other drinking water standard exceedances occurred in samples from these wells.

Chemical Factors

A series of comparisons were made to investigate correlations between ground-water quality and chemical factors, such as isotopic chemistry, specific conductance, and reducing conditions. Isotopic ratios of hydrogen (delta deuterium) and oxygen (delta oxygen -18) in samples from 17 of the wells and from the 3 surface-water sites were compared to the average proportions in precipitation, as defined by the global meteoric water line (Craig, 1961) (*fig. 13*), to investigate the effects of different sources of recharge water on ground-water quality. Most of the isotopic ratios do not plot on the global meteoric water line, which likely is an indication of variability due to the geographic area and not an indication of evaporation. The spread of the data points along the global meteoric water line may indicate the variability in recharge sources among the sites.

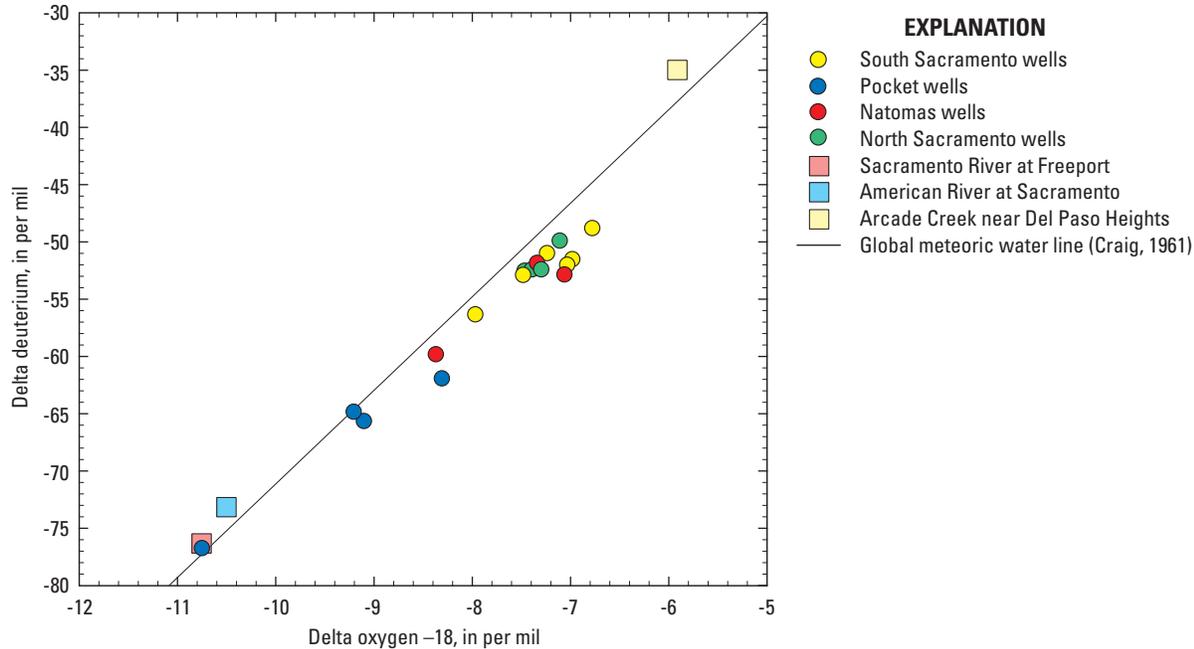


Figure 13. Relation between stable isotopes in ground water and surface water in Sacramento, California.

Samples from the Sacramento and American Rivers, plotted in the bottom left corner of *figure 13*, are isotopically lighter or more depleted than most of the well samples clustered in the mid to top right corner. The sample from Arcade Creek, plotted in the top right corner, is isotopically heavier or more enriched than all of the ground-water samples. The fact that most of the well samples are isotopically heavier than the river samples and lighter than the Arcade Creek sample may indicate multiple sources of recharge or a mixing of recharge water to these areas. Movement of surface water toward the ground water (recharge) or movement of the ground water to the land surface (discharge) may change over time. Areas where ground water is recharged or discharged also may have changed over time, which would result in multiple sources of recharge water to the wells.

Most ground-water samples from the south Sacramento, north Sacramento, and Natomas areas are grouped together in the upper right corner of the plot, with two exceptions. The samples from well 6 in the south Sacramento area and well 13 in the Natomas area, which are isotopically lighter, plot more towards the lower left. Well 6 is the site that may be located in the old buried American River channel, so the water that is recharging this well may include water from the American River.

Well samples from the Pocket and Natomas areas show the most variability in isotopic ratios, which may suggest local differences in the source of recharge water to these wells and (or) ground-water recharge or discharge. The only well sample in the dataset that shows a clear isotopic signature is the sample from well 8 in the Pocket area, which plots directly on top of the sample from the Sacramento River at Freeport

site. This indicates that the Sacramento River is the source of recharge water to well 8.

At well 8, the specific conductance value is very low compared to the other well samples from the Pocket area, but is similar to the specific conductance value of approximately 200 $\mu\text{S}/\text{cm}$ found in all the samples from the Sacramento River at Freeport site (Domagalski and others, 2000). This similarity in specific conductance between well 8 and the Sacramento River is another indication that the Sacramento River is the source of recharge water to well 8.

Isotopic results show that water in the wells is a mixture of more enriched, locally derived runoff (represented by the Arcade Creek data), and the more depleted surface water in the Sacramento and American Rivers that originated in the Sierras. Four Pocket and one Natomas area well samples are the most depleted, which is consistent with the proximity of these areas to the rivers. South Sacramento and north Sacramento well samples are the most enriched, which is consistent with the greater distances of these areas from the rivers.

Reducing conditions were identified to evaluate their effects on the occurrence of VOCs and pesticides, elevated nitrate concentrations, and exceedances of drinking-water standards. Reducing conditions exist in wells in the Pocket and Natomas areas adjacent to the Sacramento and American Rivers. This has been previously documented in ground-water studies in the Sacramento Valley (California Department of Water Resources, 1974; Hull, 1984; Johnson, 1985). For this report, reducing conditions were defined to be dissolved-oxygen concentrations less than or equal to 1 mg/L and elevated concentrations of both iron and manganese.

Reducing conditions were present in samples from wells in the Pocket area (wells 9–11) and the Natomas area (wells 12 and 14) (fig. 7). The occurrence of chemically reduced conditions at wells in the Pocket and Natomas areas is consistent with the presence of fine-grained textures, high maximum organic matter content, high organic carbon, the least VOC detections, the most nondetections of nitrate, high arsenic concentrations, and the most drinking water standard exceedances.

Multivariate Analysis

Principal components analysis was used to examine relations between a large number of chemical and physical variables and to identify those variables that explain the maximum variability in the data set. Principal components analysis summarizes the variance-covariance or correlation structure of a data set by identifying major axes or principal components of variation within the data set (Davis, 1973). The first principal component explains the most variability in a data set and each remaining component explains a lesser amount of variability until the total variance is explained. The absolute value of the variable “loading” expresses the magnitude of association

between a principal component and a variable. A positive or negative correlation between variables loading on the same principal component is indicated by the sign of the loading. Correlations between variables that explain the maximum variability in the data set can be interpreted in terms of geochemical and hydrogeologic characteristics that influence the presence or absence of certain constituents in ground water.

Twenty variables were selected for principal components analysis (table 10) based on their potential to indicate reducing conditions or characterize general water-quality, ground-water residence time in the aquifer, or alluvial sediment texture. The values for the variables differ by several orders of magnitude, so prior to analysis the data were transformed to standardized form with a mean of zero and a variance of one (Davis, 1973).

The first two principal components (I and II) explain 64 percent of the variance in the data and the third and fourth account for an additional 18 percent (table 10). The first four principal components describe most of the variance in the data and an addition of any more components would account for less variance than an individual variable. Variable scores were computed and plotted for principal components I and II and for each ground-water sample (fig. 14).

Table 10. Principal components analysis variables and loadings for monitoring wells, Sacramento, California.

[{46%}, percent of total variance explained; —, loadings with absolute values greater than 0.20; $\mu\text{S/cm}$, microsiemens per centimeter at 25°Celsius; mg/L , milligram per liter; $\mu\text{g/L}$, microgram per liter]

Variable	Loadings for principal components with eigenvalues greater than 1.0			
	I {46%}	II {18%}	III {11%}	IV {7%}
Specific conductance (mS/cm)	0.31	—	—	—
Sodium (mg/L)	0.31	—	—	—
Bicarbonate (mg/L)	0.30	—	—	—
Minimum soil pH (standard units)	0.29	—	—	0.26
Chloride (mg/L)	0.28	0.21	—	0.22
Dissolved organic carbon (mg/L)	0.27	—	-0.20	0.20
Electrical conductivity category 1 (percentage of fine-grained texture over borehole depth)	0.25	—	—	-0.39
Minimum soil permeability (centimeters per hour)	0.24	0.21	—	0.35
Iron (mg/L)	0.23	—	-0.30	—
Manganese (mg/L)	0.22	—	—	—
Dissolved oxygen (mg/L)	-0.27	—	—	—
Depth to water (meters below land surface)	-0.25	0.32	—	—
Depth to top of screened interval (meters below land surface)	-0.23	0.34	—	—
Maximum clay in soil (percent)	—	-0.47	—	—
Tritium (tritium unit)	—	-0.41	—	—
Number of volatile organic compound detections	—	-0.28	—	0.28
Number of pesticide detections	—	-0.22	-0.36	0.39
Maximum organic matter in soil (percent)	—	-0.21	-0.47	—
Nitrate (mg/L)	—	—	0.53	—
Electrical conductivity category 3 (percentage of coarse-grained texture over borehole depth)	—	—	0.26	0.46

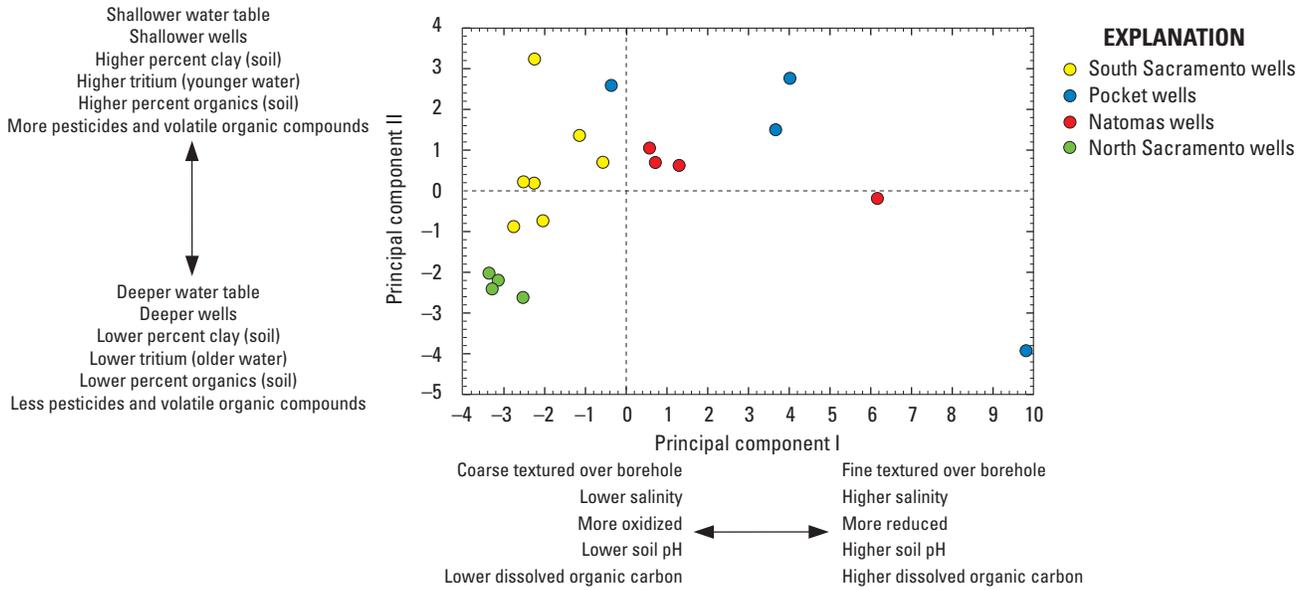


Figure 14. Variable scores for each ground-water sample for principal components I and II, Sacramento, California.

Most of the variables with positive loadings (greater than or equal to the absolute value of 0.20) on component I reflect increased salinity and more reduced geochemical conditions. Other variables with positive loadings on component I influence the adsorption and degradation of some compounds and characterize the alluvial sediment texture in the aquifer. Fine-grained alluvial sediment texture, geochemically reduced waters, and higher soil pH and dissolved DOC are characteristic of most of the wells in the Pocket and Natomas areas (fig. 14). Variables with negative loadings on component I reflect geochemically oxidized conditions. Coarse-grained alluvial sediment texture, geochemically oxidized waters, and lower soil pH and dissolved DOC are characteristic of the wells in the south and north Sacramento areas.

Component II has positive and negative loadings that reflect the influences of soil texture, length of time ground water has been isolated from the atmosphere (age of the water), soil chemistry, depth to water, and the occurrence of VOCs and pesticides. In general, shallow to intermediate water tables, higher percent clay and organics in soils, young waters, and more VOCs and pesticides are characteristic of most of the wells in the south Sacramento, Natomas, and Pocket areas. In contrast, deeper water tables, lower percent clay and organics in soils, older waters, and less VOCs and pesticides are characteristic of wells in the north Sacramento area. Depth to water, percent clay, and age as indicated by tritium concentration are consistent with the locations of wells along the regional flow system.

Multivariate analysis indicates that most of the elevated nitrate concentrations and detections of VOCs and pesticides occur in oxic waters where depth to water is shallow to

intermediate, and tritium is relatively high—that is, younger post bomb waters. These conditions are characteristic of the south Sacramento area wells and the wells in the Natomas area that are farthest from the Sacramento River. Higher salinity and reduced geochemical waters are associated with finer-grained alluvial textures. These conditions characterize most of the Pocket and some of the Natomas area wells where drinking water standards associated with saline and reduced waters (arsenic, manganese, iron, chloride, total dissolved solids, and specific conductance) were exceeded.

Reduced waters and fine-grained alluvial sediment textures at the Pocket and Natomas wells are consistent with the location of the wells in the depositional environments and flow system. Reduced conditions and dissolved organic carbon in the Pocket area are consistent with flood basin deposits and to a lesser extent the alluvial deposits in the Natomas area (fig. 5). In addition, reduced conditions and high salinity are at the distal end of the regional flow system. In contrast, wells in the north and south Sacramento areas are in the coarser-grained alluvial sediment textures and are more oxidized, which is consistent with older alluvial fan deposits. The historical regional flow system and sources of recharge have been modified, as indicated by the presence of young water in the flood basin and alluvial deposits. The presence of young water is consistent with the detections of pesticides and VOCs in all areas. The lack of elevated nitrate, pesticides, and VOCs other than trichloromethane is more consistent with older water in wells higher up on the alluvial fan. The geologic map and well locations describe to great extent the geochemistry and distribution of natural and anthropogenic contaminants.

Nitrate and Specific Conductance in Ground Water by Land Use and Decade

Ground-water-quality data collected from 1970 through 1998 for shallow wells in and adjacent to the urban study area were compiled to examine the effects of urban land use on ground-water quality over the time since urban development has taken place. Previous studies in the Sacramento County area have identified the occurrence of elevated concentrations of iron, manganese, TDS, and a few elevated concentrations of nitrate in well samples (California Department of Water Resources, 1974 and 1978; Hull, 1984; Johnson, 1985), but there has been limited data available for time-trend analysis and comparisons by land use.

Data were compiled from the USGS National Water Information System (NWIS) data base for all wells in Sacramento County less than 76 m deep. A 76-m maximum depth was chosen to incorporate the deepest wells from this urban study and to represent wells sampled in the unconfined aquifer. Water-quality data collected in all three decades were limited. No analyses of VOCs or pesticides were available until the 1990s, and analyses of constituents other than nitrate and specific conductance in the urban well samples were available only for one decade or another, but not all three decades. Nitrate and specific conductance data were available for at least 30 samples per decade. Ideally, to investigate possible trends over time, wells would be chosen that were of the same depth and location. Unfortunately, that was not possible because of limitations in the number of shallow wells sampled in Sacramento County in the 1970s and 1980s. An additional bias exists in that most of the wells sampled in the 1980s are located along the Sacramento River and in the south Sacramento area. The well depths were significantly different by decade ($p = 0.002$), which also may conflict with interpretations drawn from this time-trend analysis. This analysis was another tool to describe changes in ground-water quality in recently urbanized areas over the time period in which urban development has occurred.

Wells were divided into three groups consisting of data collected in the 1970s, 1980s, and 1990s to evaluate differences by decade. Categories of land use present in 1975 (*fig. 3*) and 1993 (*fig. 4*) were modified into three categories of land use: agriculture, urban, or other. Cropland and pasture or any type of crop, livestock, and associated agricultural dwellings such as a farmstead were grouped as "agriculture." Land-use codes equal to "agriculture," "urban," or "other" were assigned to each sample according to the location of the well on the modified land-use plots. These land-use code designations were assigned to each sample using 1975 land-use codes for wells sampled in the 1970s and 1980s and using 1993 land-use codes for wells sampled in the 1990s.

Nitrate

There was a significant difference ($p = 0.003$; Kruskal-Wallis test) between the median nitrate concentrations from samples collected in the 1970s, 1980s, and 1990s. Boxplots of median nitrate concentrations show that median concentrations decreased from the 1970s to the 1980s and increased from the 1980s to the 1990s across all land-use types (*fig. 15A*). The median nitrate concentration was 0.66 mg/L, as nitrogen, in the 18 samples collected in the 1970s, 0.11 mg/L, as nitrogen, in the 62 samples collected in the 1980s, and 2.1 mg/L, as nitrogen, in the 30 samples collected in the 1990s.

A multi-stage Kruskal-Wallis statistical test was performed to investigate in which decades the nitrate concentrations were significantly different. The only statistically significant difference among decades was in the well samples collected in the 1980s and those collected in the 1990s ($p = 0.002$; multi-stage Kruskal-Wallis test). The higher median nitrate concentration in the samples collected in the 1990s may result from a bias in well depth, land use, or spatial location of wells sampled in each decade. The depths of the wells sampled in the 1990s are significantly different than the depths of the wells sampled in the 1970s or the 1980s (each $p < 0.001$). The wells sampled in the 1990s are the shallowest, with a median well depth of 33 m, and most (63 percent) are in areas of urban land use. The median well depth of wells sampled in the 1980s was 49 m, and most (67 percent) are in areas of agricultural land use, along the Sacramento River, and in south Sacramento. The sites sampled in the 1980s were potentially comprised of ground waters that were reducing, which would have resulted in lower nitrate concentrations. The median well depth of wells sampled in the 1970s was 53 m. Resampling of the same wells would be required to determine if the apparent increase in nitrate between the decades was in fact caused by the differences in well depths or the hydrogeochemical setting.

Median nitrate concentrations were also compared by land use and decade (*fig. 15B*). There were not enough (less than ten) well samples collected in "agriculture" or "urban" land-use areas in the 1970s, or in "agriculture" land-use areas in the 1990s to create boxplots, so statistical analyses were not completed. In the 1980s, median nitrate concentration was highest in samples from wells in "urban" land-use code designations. In the 1990s, median nitrate concentration was highest in samples from wells in "agricultural" land-use code designations, but there were only two wells in that land-use category sampled in that decade.

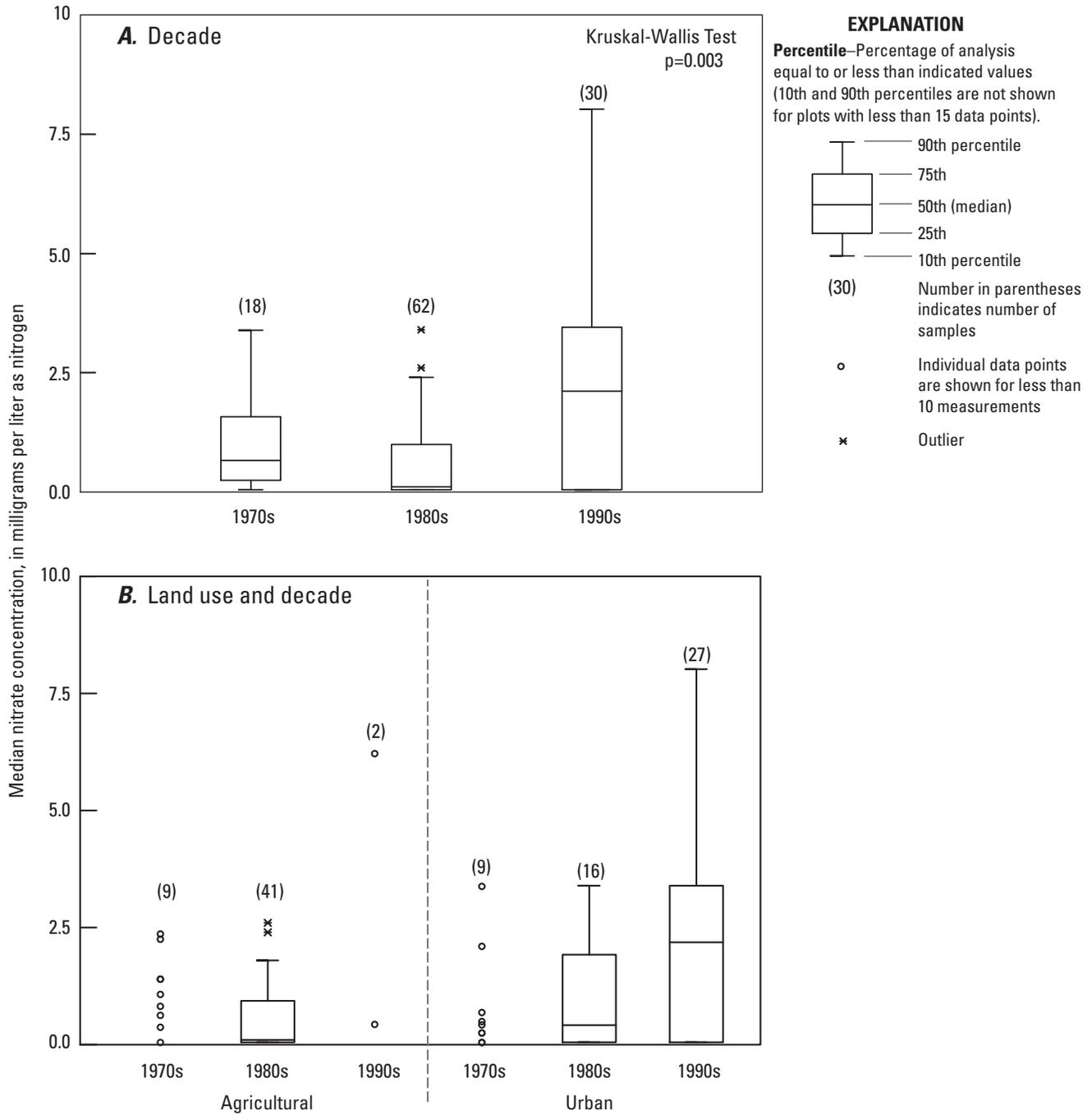


Figure 15. Boxplots of median nitrate concentration by decade (A) and by decade with land use (B) for samples collected in 1970s, 1980s, and 1990s, Sacramento, California.

Specific Conductance

Specific conductance in samples collected in the 1970s, 1980s, and 1990s did not differ significantly although the median specific conductance was higher in the samples collected in the 1990s (464 $\mu\text{S}/\text{cm}$) than in the 1970s (328 $\mu\text{S}/\text{cm}$) or the 1980s (299 $\mu\text{S}/\text{cm}$).

Specific conductance in ground-water samples collected from wells located in “agriculture” and “urban” land-use code designations were grouped by decade to compare the effects of land use by decade. There was no significant difference in median specific conductance between samples from wells in “agriculture” and “urban” land-use areas within any of the decades sampled although the median specific conductance is higher in the samples from wells in the “urban” land-use code designations.

Summary and Conclusions

An assessment was completed of shallow ground-water quality in 1998 in primarily residential urban areas developed over the previous 5 to 25 years in Sacramento, California. The results of this study were used to relate shallow ground-water quality to natural and human factors in an attempt to understand the processes that govern the occurrence and concentration of selected chemical constituents. Detections of VOCs, pesticides, and elevated nitrate concentrations in samples collected in 1998 from 19 monitoring wells are evidence of anthropogenic impact on the quality of shallow ground water underlying this recently urbanized region. VOC results from this study are more consistent with results from urban areas nationwide than from agricultural areas in the Central Valley, indicating that shallow ground-water quality has been impacted by urbanization.

Ground-water samples from 16 of the 19 wells contained one or more VOCs at low concentrations, with only 2 of the samples above 1 $\mu\text{g}/\text{L}$. The maximum concentration of any detected VOC was at least five times lower than the USEPA or the CA DHS primary MCLs. Two or more VOCs were detected in samples from five of the sampled wells, all of which are in the south Sacramento and Natomas areas. Eight of the 86 VOCs analyzed were detected; 4 were detected in 2 or more samples—trichloromethane (84 percent), bromodichloromethane (16 percent), MTBE (11 percent), and PCE (11 percent).

Four VOCs detected at the highest concentrations were the same VOCs detected in two or more samples. This group of the most frequently detected VOCs is similar to those found in ground-water samples from urban areas representative of a wide range of hydrogeologic conditions across the United States. In contrast, the most frequently detected VOCs in this study were not the most frequently detected VOCs in domestic wells in agricultural and nonurban areas in the San Joaquin and southeast Sacramento Valleys. In addition, the

prevalence of disinfection byproducts (trichloromethane and bromodichloromethane), the solvent PCE, and the fuel oxygenate MTBE in urban areas and the near exclusion of them in agricultural or nonurban areas indicate that the presence of those VOCs in this study may show an urban signature in the quality of the ground water. Overall, the VOC results from this study suggest that ground-water quality has been affected by urban land use.

Four herbicides (atrazine, simazine, tebuthiuron, and bentazon) and one herbicide transformation product (desethyl atrazine) were detected in ground-water samples from 6 of the 19 wells at low concentrations in the south Sacramento and Pocket areas. None of the detected concentrations were above 1 $\mu\text{g}/\text{L}$, and the maximum concentration of any detection was at least three times lower than the USEPA or CA DHS primary MCLs.

Only atrazine and desethyl atrazine, a transformation product of atrazine, were detected in more than one sample. Desethyl atrazine was detected the most frequently and co-occurred with atrazine in three samples from the south Sacramento area. Simazine, atrazine, and desethyl atrazine were detected in the sample from well 5 in the south Sacramento area, which was the only sample with more than one herbicide detection. Bentazon and tebuthiuron were detected in the Pocket area. The banned rice herbicide, bentazon, was detected at the well closest to the Sacramento River with the isotopic signature of water similar to the river. Bentazon also has been detected historically in the Sacramento River, its tributaries, and shallow ground-water wells. Bentazon may have been transported in the Sacramento River down from where it was applied historically on rice and recharged to the well.

The herbicides detected in this study were also detected in agricultural and urban areas representative of a wide range of hydrogeologic settings in the United States; however, most were detected more frequently in agricultural areas than in urban areas. Pesticide results are more consistent with urban areas nationwide than agricultural areas and are lower than agricultural areas in the San Joaquin and southeast Sacramento Valleys.

Nitrate (dissolved nitrate plus nitrite, as nitrogen) was detected in 14 of the 19 samples at concentrations ranging from 0.69 to 8.0 mg/L , with a median of 2.9 mg/L . Four of the five samples in which nitrate was not detected were from the Pocket area and one was from the Natomas area. Ground-water samples from these sites were chemically reduced and thus the lack of detectable nitrate may be due to removal by denitrification. Half of the detected nitrate concentrations were elevated, exceeding 3.0 mg/L , suggesting impact by anthropogenic factors (Hull, 1984; Madison and Brunett, 1985; Mueller and Helsel, 1996). Elevated nitrate concentrations occurred in three samples each from the south Sacramento and Natomas areas and in one sample from the north Sacramento area. Elevated nitrate concentrations and pesticide detections do not co-occur. Pesticides were only detected at sites in which nitrate was either not detected or was detected below 3.0 mg/L .

The median detected nitrate concentration was low compared to the median concentration detected in agricultural areas nationwide, but was higher than in urban areas nationwide. However, the median nitrate concentration in this study was lower than the median in agricultural land-use settings in the San Joaquin Valley, but higher than the median in agricultural and nonurban areas in the southeast Sacramento Valley. The results of the nitrate data are not consistent with agricultural or urban areas nationwide or with agricultural or nonurban areas in the San Joaquin and Sacramento Valleys. However, the absence of any pesticide detections in samples with elevated nitrate concentrations may indicate that elevated nitrate concentrations are not due to agricultural land use.

The USEPA primary MCL for arsenic of 10 µg/L was exceeded in 5 of the 19 samples. USEPA and CA DHS secondary MCLs were exceeded for manganese, iron, and specific conductance. Almost all of the samples with these exceedances were from sites in the Pocket and Natomas areas. The elevated levels of these constituents are likely from natural sources at the distal end of the regional flow path near the confluence of the Sacramento and American Rivers.

Tritium/helium-3 and tritium analyses used to date the age of the ground-water samples verify that at least 13 of the 19 wells were recently recharged, that is recharged after 1953. Most VOC and pesticide detections and all elevated nitrate concentrations occurred in ground waters recharged since 1953. However, trichloromethane was detected in all six samples in which ground water was recharged prior to 1953. In addition, atrazine and desethyl atrazine was detected in both samples from the south Sacramento area in which ground water was recharged prior to 1953. The detections of VOCs and pesticides in the ground-water samples with estimated recharge dates prior to 1953 may indicate that at least some component of young water may be captured by those samples.

The limited amount of data on current VOC and pesticide concentrations in air and surface water within the urban study area shows that air and surface water may be potential sources for these contaminants in ground water because some of the most frequently detected VOCs and pesticides in ground-water samples are also detected in air and surface-water samples. Concentrations, however, are higher in ground water than in air or surface water, which indicates that air and surface water alone could not account for the concentrations present in ground water. Furthermore, air and surface-water quality have changed over time, so the concentrations in these samples likely do not represent the same concentrations present when ground water was being recharged.

Physical factors were examined with respect to their effect on ground-water quality. Depth to the top of the screened interval below the water table was inversely correlated with the number of VOCs detected. In contrast, depth to water and well depth was directly correlated with the detection of any VOC in each ground-water sample. However, wells with the shallowest depth to water and no VOC detections are located adjacent to the confluence of the Sacramento and American Rivers, which is at the distal end of the regional

ground-water flow path and an area of ground-water/surface-water interaction.

In general, in the south Sacramento area—where most of the VOCs, pesticides, and elevated nitrate detections occurred—the depth to water and well depth are intermediate, surface soil pH is slightly acidic, organic matter content in the surface soil is low, organic carbon content is low, and the texture of the aquifer material penetrated by the boreholes is the most coarse-grained. In contrast, in the Pocket and Natomas area—where only one or no VOCs were detected and pesticides or nitrate were typically not detected—the depth to water and well depth are shallow, organic matter content in the surface soil is high, organic carbon content is high, and the texture of the aquifer material penetrated by the boreholes is generally more fine-grained.

Chemical factors were examined with respect to their effect on ground-water quality. The stable isotope data show that water in the wells is a mixture of more enriched, locally derived runoff (represented by Arcade Creek) and the more depleted surface waters in the Sacramento and American Rivers that originated in the Sierras. In general, ground waters from the Pocket and Natomas areas are the most depleted, which is consistent with the proximity of these areas to the rivers; ground waters from the south and north Sacramento areas are the most enriched, which is consistent with the greater distances of these areas from the rivers. The ground-water sample from the well in the Pocket area closest to the Sacramento River in which bentazon was detected shows an isotopic signature and low specific conductance characteristic of the Sacramento River. This indicates that the source of recharge water to that well is primarily from the river and that the source of bentazon also may be from the river.

Reducing conditions were present in ground waters in the Pocket and Natomas areas. At these sites the MCL of 10 µg/L was exceeded for arsenic and the secondary MCLs were exceeded for manganese, iron, chloride, TDS, and specific conductance. Reducing conditions also may account for the absence of nitrate in the ground-water samples due to denitrification.

Results from the principal components analysis illustrate the correlations between the depositional environment, position of the well in a regional flow system, and water quality. The first two principal components account for 64 percent of the variance in the data set. In general, shallower water tables, shallower wells, higher salinity, and more reduced waters were shown to be associated with fine-grained alluvial textures typical of the depositional environment near the rivers and of the water chemistry at the distal end of the regional flow system. These conditions characterize most of the Pocket and some of the Natomas area wells where few VOCs and pesticides were detected, nitrate was mostly not detected, and the USEPA MCL for arsenic was exceeded. Pesticides and VOCs tended to occur in samples from wells where depth to water was intermediate, the ground water is oxic, and there is more clay and organics in the surface soils. These conditions predominate in most of the south Sacramento wells, and

some of the Natomas area wells. Tritium concentrations were relatively high in the south Sacramento, Pocket, and Natomas areas, indicating some portion of the water sampled was recently recharged. Deeper water tables, deeper wells, and more oxic and older ground water was typical of wells in the north Sacramento area where only trichloromethane was detected and no pesticides were detected, elevated nitrate was detected in one sample, and no MCL exceedances occurred.

Analysis of historical data available in the USGS NWIS database on nitrate and specific conductance for shallow wells (less than 76 m deep) in Sacramento County sampled from 1970 through 1998 indicates that nitrate concentrations increased from the 1980s to the 1990s. This may be due to a bias in the location of the network of wells with respect to land use or chemically reduced settings or a bias in the well depths of wells sampled in the different decades or a downward movement of nitrate.

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