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Assessing the Susceptibility to Contamination of Two Aquifer Systems Used for Public Water Supply in the Modesto and Fresno Metropolitan Areas, California, 2001 and 2002

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

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By Michael T. Wright, Kenneth Belitz, and Tyler Johnson

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Conversion Factors, Water-Quality Information, and Abbreviations and Acronyms

Inch/Pound to SI

Multiply	By	To obtain
acre	4,047	square meter (m^2)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year (m^3/yr)
foot (ft)	0.3048	meter (m)
inch (in.)	2.54	centimeter (cm)
mile (mi)	1.609	kilometer (km)
picocurie per liter (pCi/L)	0.037	becquerel per liter (Bq/L)

SI to Inch/Pound

Multiply	By	To obtain
liter (L)	0.2642	gallon (gal)
meter (m)	3.281	foot (ft)
milliliter (ml)	0.0338	ounce (oz)

Water-Quality Information

Concentrations of chemical constituents in water are given in milligrams per liter (mg/L) or micrograms per liter (µg/L). Milligrams per liter is approximately equivalent to parts per million. Micrograms per liter is approximately equivalent to parts per billion.

Data for the isotopes oxygen-18 and deuterium are reported in delta (δ) notation as per mil (parts per thousand); tritium data are reported in picocuries per liter (pCi/L).

Abbreviations and Acronyms

bls	below land surface
BTEX	benzene, toluene, ethyltoluene, xylenes
CAS	California Aquifer Susceptibility
DBCP	1, 2-dibromo-3-chloropropane
DHS	Department of Health Services
DWR	Department of Water Resources
EPA	U.S. Environmental Protection Agency
GAMA	Ground-Water Ambient Monitoring
GEIMS	Geographic Environmental Information Management System
GMWL	global meteoric water line
LLNL	Lawrence Livermore National Laboratory
LRL	laboratory reporting level
LT-MDL	long-term method detection limit
LUFT	leaking underground fuel tank
MCL	maximum contaminant level
MDL	method detection limit
MTBE	methyl *tert*-butyl ether
NAWQA	National Water Quality Assessment Program
NWIS	National Water Information System
NWQL	National Water Quality Laboratory
PCE	tetrachloroethylene
QC	Quality Control
SWRCB	California State Water Resources Control Board
TCE	trichloroethylene
THM	trihalomethane
VOC	volatile organic compound
USGS	U.S. Geological Survey

Assessing the Susceptibility to Contamination of Two Aquifer Systems Used for Public Water Supply in the Modesto and Fresno Metropolitan Areas, California, 2001 and 2002

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Abstract

Ground-water samples were collected from 90 active public supply wells in the Fresno and Modesto metropolitan areas as part of the California Aquifer Susceptibility (CAS) program. The CAS program was formed to examine the susceptibility to contamination of aquifers that are tapped by public supply wells to serve the citizens of California. The objectives of the program are twofold: (1) to evaluate the quality of ground water used for public supply using volatile organic compound (VOC) concentrations in ground-water samples and (2) to determine if the occurrence and distribution of low level VOCs in ground water and characteristics, such as land use, can be used to predict aquifer susceptibility to contamination from anthropogenic activities occurring at, or near, land surface. An evaluation was made of the relation between VOC occurrence and the explanatory variables: depth to the top of the uppermost well perforation, land use, relative ground-water age, high nitrate concentrations, density of leaking underground fuel tanks (LUFT), and source of recharge water.

VOCs were detected in 92 percent of the wells sampled in Modesto and in 72 percent of the wells sampled in Fresno. Trihalomethanes (THM) and solvents were frequently detected in both study areas. Conversely, the gasoline components—benzene, toluene ethylbenzene, and xylenes (BTEX)—were rarely, if at all, detected, even though LUFTs were scattered throughout both study areas. The rare occurrence of BTEX compounds may be the result of their low solubility and labile nature in the subsurface environment.

Samples were analyzed for 85 VOCs; 25 were detected in at least one sample. The concentrations of nearly all VOCs detected were at least an order of magnitude below action levels set by drinking water standards. Concentrations of four VOCs exceeded federal and state maximum contaminant levels (MCL): the solvent trichloroethylene (TCE) and the fumigant 1, 2-dibromo-3-chloropropane (DBCP) in Fresno, and the solvents TCE and tetrachloroethylene (PCE) in Modesto. Chloroform, which is a by product of water disinfection and a constituent used in industrial processes since the 1920s, was the most frequently detected compound, whereas the gasoline oxygenate methyl *tert*-butyl ether (MTBE), which has been in widespread production and use only since the 1990s, was detected in only 2 percent of the samples.

Downward migration of contaminants appears to be a viable pathway of contamination in the unconfined and semi-confined aquifers underlying the Fresno and Modesto study areas. Within the individual study areas, VOCs were detected more frequently and in greater numbers in shallower wells than in deeper wells. Additionally, VOCs were detected more frequently and in greater numbers in Modesto than in Fresno. Wells sampled in Modesto were significantly shallower than the wells sampled in Fresno; the other explanatory variables examined in this report were not significantly different between the two study areas.

VOCs occurred more frequently in younger ground water (water recharged after 1952) than in older ground water (water recharged prior to 1952). Additionally, wells withdrawing younger ground water had a higher number of VOCs detected per well than did wells withdrawing older ground water. Younger ground water was at or near the land surface during a period when VOCs came into widespread production and use. Therefore, wells from which younger ground water is withdrawn may be more susceptible to contamination.

Of the explanatory variables examined in this study, land use was the best predictor of aquifer susceptibility in the Fresno and Modesto study areas. VOCs were detected more frequently in wells located in heavily urbanized areas. The number of VOCs detected in ground water was positively correlated to the degree of urbanization. VOCs are produced and used primarily in urban land use settings; therefore, aquifers underlying urban areas may be more susceptible to contamination from these compounds.

Other variables had little or no predictability. Overall, the presence of high nitrate concentrations was only marginally useful in predicting aquifer susceptibility to VOC contamination. In Fresno, nitrate concentrations had a moderate correlation to VOC occurrence in ground water, whereas in Modesto, nitrate concentrations did not predict VOC occurrence. The density of LUFTs and the stable isotopic content of ground

water were not good predictors of VOC occurrence in Fresno and Modesto ground water. LUFT density was not useful because gasoline components comprised less than 2 percent of the VOCs detected in the study areas. Source of recharge water is indicated by stable isotope ratios. The presence or absence of VOCs in ground-water samples was not correlated with stable isotope values. Therefore, source of recharge water was not important in predicting aquifer susceptibility in the Fresno and Modesto study areas.

Introduction

California depends heavily on ground water to supply its growing population. In 1995, California withdrew 4,450 acre-ft of fresh ground water per day from its aquifers (Solley and others, 1998), which is approximately 19 percent of the total ground water withdrawn in the United States each day. Out of the 4,450 acre-ft, 827 acre-ft were withdrawn by public supply wells and used primarily for domestic purposes. It is in urban areas where the majority of ground water is withdrawn by public supply wells. Aquifers located beneath urban areas can be susceptible to contamination from volatile organic compounds (VOCs) from point and non-point sources (Grady and Casey, 2001). VOCs are a class of anthropogenic compounds that are used widely in urban areas and that have contaminated ground-water supplies. Recently, public supply wells contaminated with the gasoline oxygenate MTBE have been closed in Santa Monica, Sacramento, and many other areas in California (California State Water Resources Control Board, 2001).

Because anthropogenic compounds were detected in ground water used for public supply, the California State Water Resources Control Board (SWRCB) created the Ground-Water Ambient Monitoring (GAMA) Program. The objectives of the program are twofold: (1) to evaluate the quality of ground water used for public supply by using VOC concentrations found in ground-water samples and (2) to determine if the occurrence and distribution of low level VOCs in ground water and characteristics, such as land use, can be used to predict aquifer susceptibility to contamination from anthropogenic activities occurring at or near land surface. The California Aquifer Susceptibility (CAS) assessment is the component of GAMA that is examining the susceptibility of aquifers serving the citizens of California by way of production wells. The U.S. Geological Survey (USGS) is partnering with the California State Water Resources Control Board (SWRCB), the California Department of Health Services (DHS), the California Department of Water Resources (DWR), and Lawrence Livermore National Laboratory (LLNL) to complete the CAS assessment.

This report presents the results and analyses of the occurrence and distribution of VOCs, tritium, nitrate, and stable isotopes in two aquifer systems in the San Joaquin Valley. These two aquifer systems serve the San Joaquin Valley metropolitan areas of Fresno and Modesto. Forty public supply wells were sampled in Modesto in the spring of 2001, and 50 public supply wells were sampled in Fresno in the summer of 2002. USGS laboratories analyzed ground-water samples for stable isotopes and VOCs; the tritium content of the samples was determined by LLNL. Nitrate values were obtained from the California DHS database. The California DHS regularly monitors public supply wells for a variety of chemical constituents in order to assure compliance with federal and state drinking water standards.

Hydrogeologic Setting

The Fresno and Modesto metropolitan areas are within the Kings and Modesto ground-water basins, respectively (*fig. 1*). The Kings ground-water basin is part of the Tulare Lake Hydrologic Region, and the Modesto ground-water basin is part of the San Joaquin Hydrologic Region (California Department of Water Resources, 2003). These two hydrologic regions are within the San Joaquin Valley, which is bordered by the Coast Ranges to the west and the Sierra Nevada to the east. The San Joaquin Valley is a structural trough that is filled with sediments up to 6 mi thick that consist of intercalated lenses of gravel, sand, silt, and clay (Page, 1986).

The Fresno metropolitan area (*fig. 2*) is located within the Kings ground-water basin. The Kings Basin is bordered by the San Joaquin River to the north and partially by the Kings River to the south (California Department of Water Resources, 2003). The local climate consists of hot, dry summers and wetter, mild winters. The mean annual precipitation is approximately 10 inches, with rainfall increasing in an easterly direction toward the higher elevations of the Sierra Nevada (Page and LeBlanc, 1969). More than 90 percent of the precipitation falls between October and April. Fresno is the most populated area within the Kings ground-water basin with a population of approximately 440,000 in 2002 (City of Fresno, 2003a). The sole source of public water supply for the city of Fresno is ground water (City of Fresno, 2003b). In 2002, the city of Fresno withdrew over 167,220 acre-ft of ground water (City of Fresno, 2003c).

The Kings ground-water basin is composed of unconsolidated deposits of continental origin. The main water-bearing unit of the aquifer consists of older alluvium that extends from the base of the Sierra Nevada to beyond the western boundary of the city of Fresno. These sedimentary deposits are an intercalated fill of permeable sand and gravel strata layered with relatively impermeable lenses of silt and clay. Ground water is mostly unconfined, although there are areas where partially confined conditions exist because of the lenticular nature of the aquifer matrix (Muir, 1977). The base of the fresh water aquifer (fresh water being defined as having less than 2,000 mg/L dissolved solids) ranges from approximately 900 ft below land surface (bls) near the Sierra Nevada to approximately 2,000 ft bls near the city of Fresno. The movement of ground water in the Kings Basin generally is to the
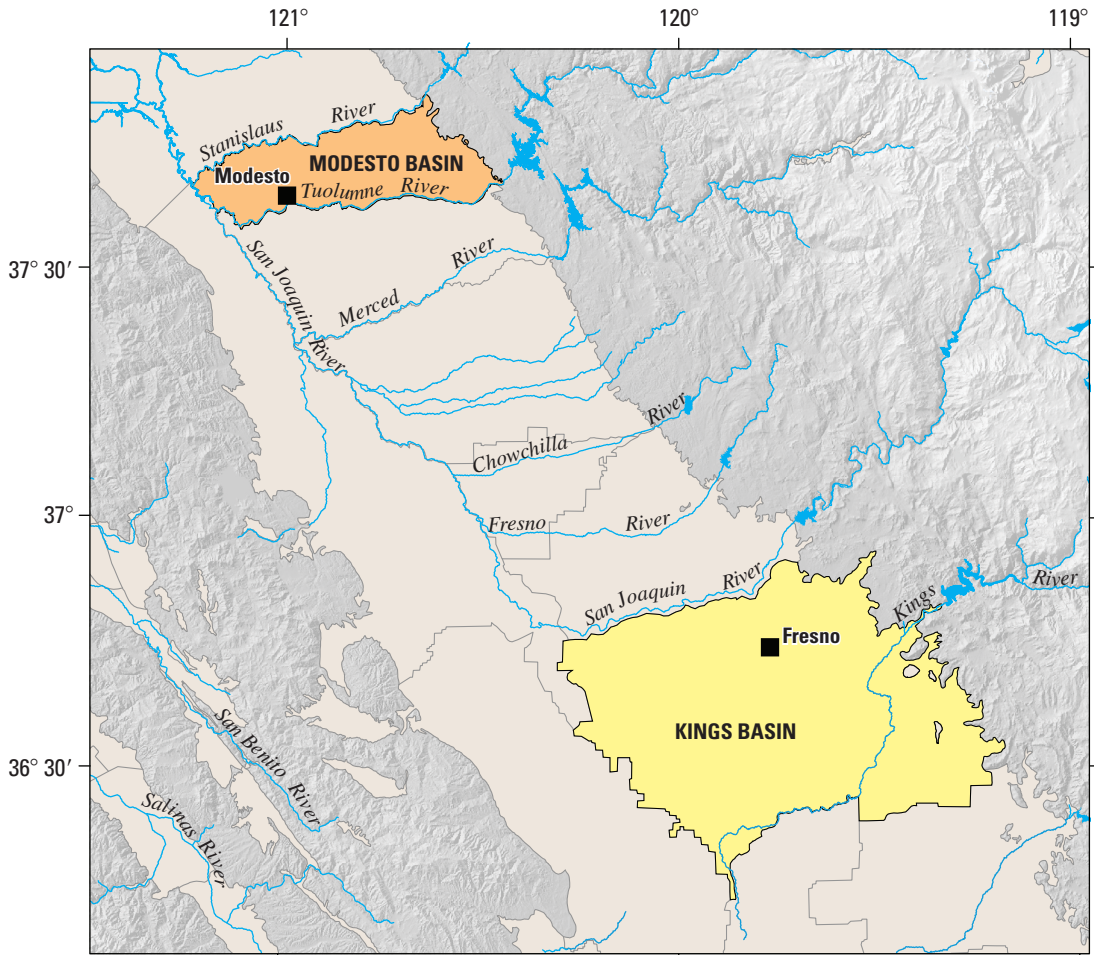
Figure 1.   Location of Fresno and Modesto study areas, the Kings and Modesto ground-water basins, and alluvial deposits in California.

DWR, California Department of Water Resources.

southwest towards the axis of the valley. However, a large cone of depression exists under the city of Fresno owing to ground-water withdrawals; this change in hydraulic gradient causes a shift in ground-water movement around the Fresno metropolitan area to a northwesterly direction. Recharge in the ground-water basin is from precipitation; seepage from rivers, streams, and irrigation canals; and deep percolation of irrigation water (California Department of Water Resources, 2003). The Kings ground-water basin is also replenished through engineered recharge that occurs by way of a 200-acre spreading basin located on the eastern portion of the city of Fresno; this recharge water is composed of runoff from the nearby Sierra Nevada.
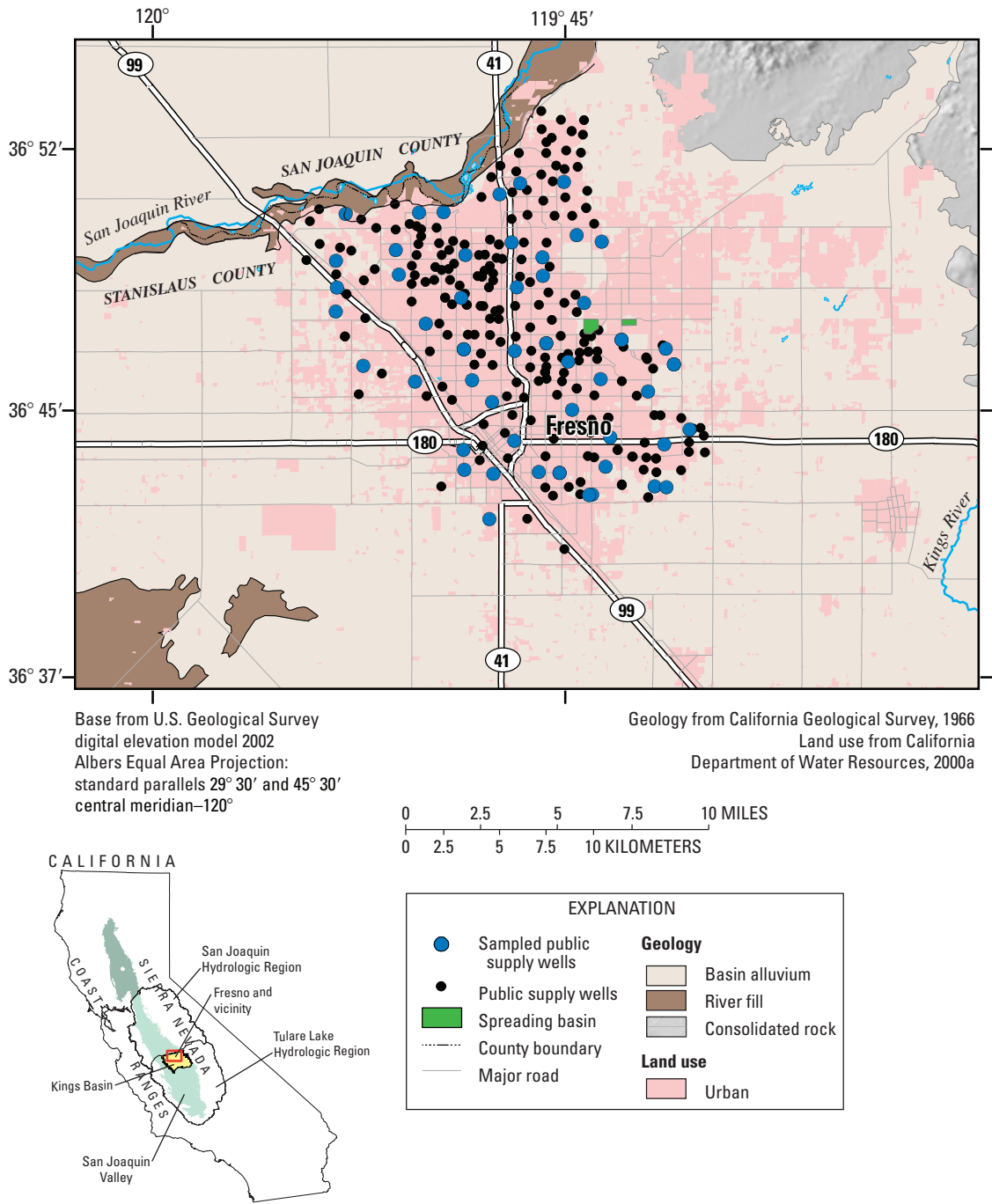
Figure 2.   Study area showing urban land use areas and locations of public supply wells that were sampled in July and August 2002 in metropolitan Fresno, California.

The Modesto metropolitan area (*fig. 3*) is within the Modesto ground-water basin. The Stanislaus River forms the northern border of the basin; the Tuolumne River flows parallel to, and just north of, its southern border. The local climate is very similar to the climate in Fresno, although

Modesto receives a couple more inches of rainfall annually (California Department of Water Resources, 2003). Modesto is the most populated area within the Modesto ground-water basin. In 2002, the population of Modesto was 203,300 (City of Modesto, 2004a). Ground water provides the majority of
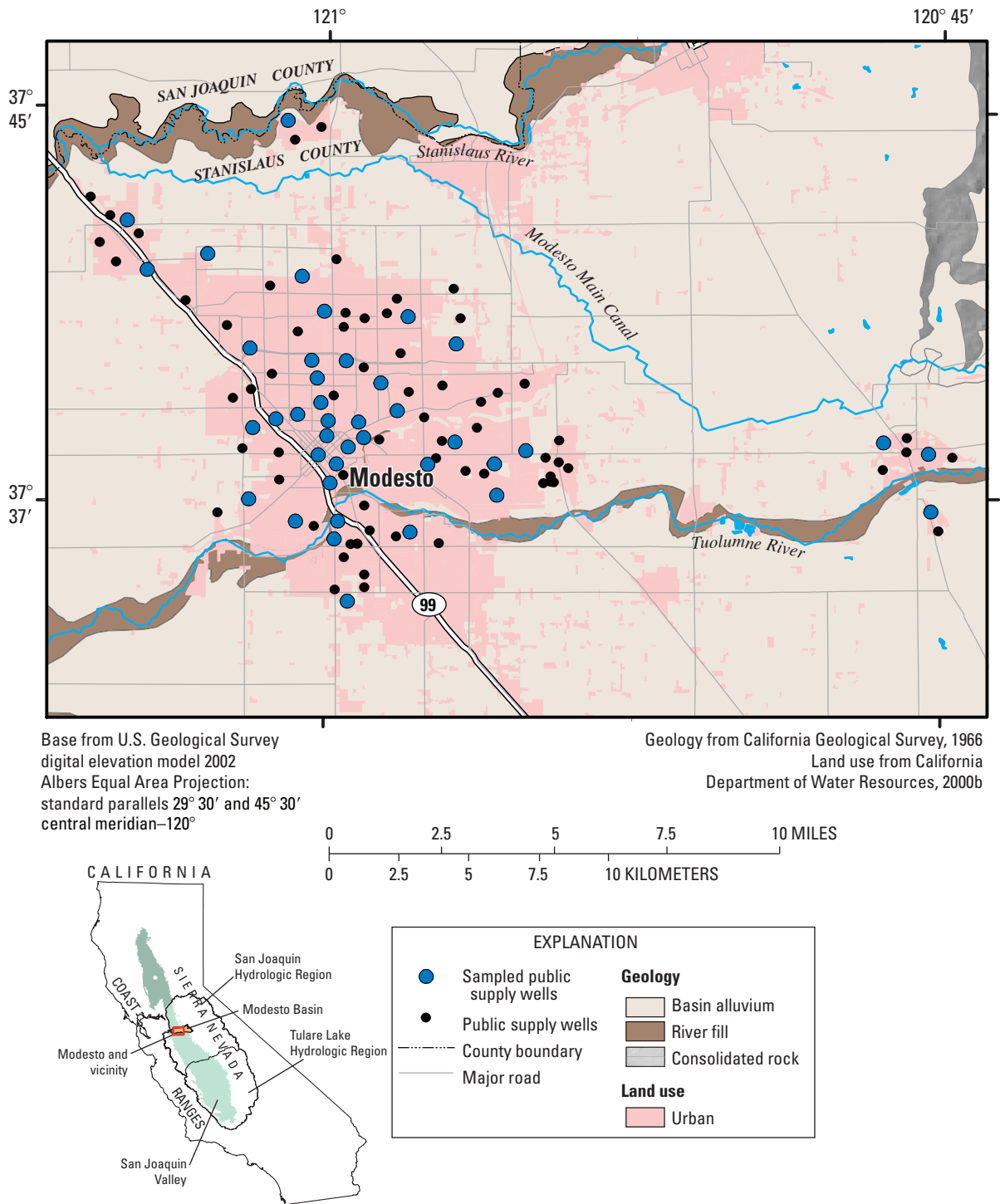
Figure 3.   Study area showing urban land use areas and locations of public supply wells that were sampled in March and April 2001 in metropolitan Modesto, California.

domestic, public water supply in the Modesto metropolitan area, with over 49,660 acre-ft per year withdrawn from the Modesto ground-water basin (City of Modesto, 2004b).

Ground water in the Modesto basin primarily is in the unconfined to partially confined part of the aquifer that is composed of unconsolidated to semi-consolidated deposits (Karen Burow, U.S. Geological Survey, written commun., 2004). Consolidated deposits of continental origin lie in the eastern portion of the basin and generally yield low quantities of water to wells; these deposits consist of poorly sorted gravel, sand, silt, and clay. Continental deposits are near the surface in the eastern part of the basin and at depths of over 400 ft bls in the western part of the basin. In the western half of the basin, older alluvium composed of intercalated layers of gravel, sand, silt, and clay is up to 400 ft thick (Davis and others, 1959). Confined conditions occur in the southwestern part of the basin where the aquifer lies beneath the Corcoran Clay, which extends from approximately 150 to 250 ft bls (California Department of Water Resources, 2003). The rest of the aquifer system is mostly unconfined, except where clay and silt lenses create partially confined conditions. The base of the fresh water aquifer is approximately 700 to 900 ft bls just west of the city (Page and Balding, 1973); at the time this report was written, no data had been found that delineates the base of the fresh water aquifer underlying the city proper. Ground-water flow in the Modesto Basin generally is to the southwest, towards the axis of the valley. Aquifer recharge in the basin is from precipitation; seepage from rivers, streams, and irrigation canals; and deep percolation of irrigation water.

Approach

The CAS assessment has been utilizing low-level VOC analyses to identify public supply wells that are already affected by contamination, but at concentrations well below federal and state maximum contaminant levels (MCL). The MCL is the highest level of a contaminant that is allowed in drinking water and is an enforceable standard (U.S. Environmental Protection Agency, 2002). *Table 1* shows the suite of 85 VOCs analyzed for at the USGS National Water Quality Laboratory (NWQL), along with their primary use or source. In this report, all detections of VOCs, whether above or below laboratory reporting level (LRL), were used in calculating detection frequencies and in statistical tests.

The NWQL uses LRLs for reporting non-detections, but is also able to semi-quantitatively detect compounds below the LRL. The LRL and long-term method detection limit (LT-MDL) are calculated based on quality control experiments conducted by the NWQL. The LT-MDL mitigates the reporting of false positive readings. The risk of reporting a false positive concentration equal to or greater than the LT-MDL when the compound is not present is 1 percent or less. The LRL (LRL = $2 \times$ LT-MDL) is used to minimize the chance of reporting a false negative reading. The risk of reporting a false

negative is 1 percent or less when the actual concentration is equal to or greater than the LRL (Childress and others, 1999).

The CAS assessment also has been utilizing the tritium content of samples to identify young ground water. Young ground water is generally thought to be more susceptible to contamination owing to the prevalent use of regulated chemicals (VOCs) during the last approximately 50 years. Additionally, natural processes of attenuation have more time to reduce contaminant concentrations in ground water that remains in the aquifer system for longer periods. Ground-water samples collected during the CAS assessment were analyzed for the stable isotopes of water—deuterium and oxygen-18. Stable isotopes can help determine the source of recharge water to an aquifer system. Knowing the source of recharge water may aid in identifying pathways of aquifer contamination.

In addition to the aforementioned chemical components, this study also examined nitrate concentrations found in ground water underlying the Fresno and Modesto study areas. Nitrate analyses required no extra sampling since a large and readily accessible amount of water-quality data for public supply wells is available in the California DHS public supply well database. High nitrate concentrations were examined to determine the ability to predict the occurrence of VOCs. Relatively high nitrate concentrations may occur in ground water due to anthropogenic activities at or near the land surface and thus may be a useful tool in predicting the occurrence of other anthropogenic compounds.

Besides examining the chemical composition of ground water, the explanatory variables of well depth, which is defined as the depth to the top of the uppermost perforation, and land use were studied in order to determine their ability to predict ground-water contamination and aquifer susceptibility. This is an approach used by the USGS National Water Quality Assessment (NAWQA) Program. One objective of the NAWQA Program is to examine how factors such as depth to the top of the uppermost perforation and land use are related to ground-water quality and aquifer susceptibility (Gilliom and others, 1995). Previous NAWQA studies of unconfined aquifers have shown a negative correlation between depth to the top of the uppermost perforation and VOC occurrence and distribution (Clawges and others, 1999). The shallower a well's perforations are, the shorter the distance a contaminant must travel from its source at or near the land surface.

NAWQA studies have also shown that type of land use—for example, urban or agriculture—can be correlated with VOC occurrence and distribution in unconfined aquifers (Squillace and others, 2002). Wells located in urban areas may have more detections of anthropogenic compounds, such as VOCs, compared to wells located in less urbanized or more agricultural/rural areas. This may occur because VOCs generally are manufactured and used more frequently in urbanized settings. Because this study was done using only public supply wells located in primarily urban areas, only the degree of urbanization was used to examine the relation between land use and ground-water quality.

Table 1. Volatile organic compounds, primary source or use, Chemical Abstract Service number, and laboratory reporting limits for the U.S. Geological Survey National Water Quality Laboratory analytical schedule 2020.

[VOC, volatile organic compound; CAS, Chemical Abstract Service; μg/L, microgram per liter]

VOC	Primary use or source	CAS number	Laboratory reporting limits	
			Fresno study μg/L	Modesto study μg/L
1,1-Dichloroethane	Solvent	75-34-3	0.035	0.035
1,1-Dichloroethylene (DCE)	Organic synthesis	75-35-4	.04	.04
1,1-Dichloropropene	Organic synthesis	563-58-6	.05	.026
1,1,1,2-Tetrachloroethane	Solvent	630-20-6	.03	.03
1,1,2,2-Tetrachloroethane	Solvent	79-34-5	.09	.09
1,1,1-Trichloroethane (TCA)	Solvent	71-55-6	.032	.032
1,1,2-Trichloroethane	Solvent	79-00-5	.06	.06
1,1,2-Trichlorotrifluoroethane (CFC-113)	Refrigerant	76-13-1	.06	.06
1,2-Dibromo-3-chloropropane (DBCP)	Fumigant	96-12-8	.5	.21
1,2-Dibromoethane	Solvent	106-93-4	.036	.036
1,2-Dichlorobenzene	Solvent	95-50-1	.031	.031
1,2-Dichloroethane	Solvent	107-06-2	.13	.13
1,2-Dichloropropane	Solvent	78-87-5	.029	.029
1,2,3,4-Tetramethylbenzene	Hydrocarbon	488-23-3	.23	.23
1,2,3,5-Tetramethylbenzene (isodurene)	Hydrocarbon	527-53-7	.2	.2
1,2,3-Trichlorobenzene	Organic synthesis	87-61-6	.27	.27
1,2,3-Trichloropropane	Solvent	96-18-4	.16	.16
1,2,3-Trimethylbenzene	Gasoline	526-73-8	.12	.12
1,2,4-Trichlorobenzene	Solvent	120-82-1	.07	.19
1,2,4-Trimethylbenzene	Organic synthesis	95-63-6	.056	.056
1,3-Dichlorobenzene	Solvent	541-73-1	.03	.03
1,3-Dichloropropane	Organic synthesis	142-28-9	.12	.12
1,3,5-Trimethylbenzene	Gasoline	108-67-8	.044	.044
1,4-Dichlorobenzene	Fumigant	106-46-7	.05	.05
2,2-Dichloropropane	Organic synthesis	594-20-7	.05	.05
2-Butanone	Solvent	78-93-3	5	1.6
2-Chlorotoluene	Solvent	95-49-8	.026	.026
2-Hexanone	Solvent	591-78-6	.7	.7
3-Chloropropene	Organic synthesis	107-05-1	.07	.07
4-Chlorotoluene	Solvent	106-43-4	.05	.06
4-Isopropyl-1-methylbenzene	Organic synthesis	99-87-6	.07	.07
4-Methyl-2-pentanone	Solvent	108-10-1	.37	.37
Acetone	Solvent	67-64-1	7	7
Acrylonitrile	Organic synthesis	107-13-1	1.2	1.2
Benzene	Gasoline	71-43-2	.035	.035
Bromobenzene	Solvent	108-86-1	.036	.036
Bromochloromethane	Organic synthesis	74-97-5	.07	.044
Bromodichloromethane	Disinfection by-product	75-27-4	.048	.048
Bromoethene	Fire retardant	593-60-2	.11	.1
Bromoform (tribromomethane)	Disinfection by-product	75-25-2	.06	.06
Bromomethane	Fumigant	74-83-9	.26	.26
Butylbenzene	Organic synthesis	104-51-8	.19	.19
Carbon disulfide	Organic synthesis	75-15-0	.07	.07
Chlorobenzene	Solvent	108-90-7	.028	.028
Chloroethane	Solvent	75-00-3	.12	.12
Chloroform (trichloromethane)	Disinfection by-product	67-66-3	.024	.024
Chloromethane	Refrigerant	74-87-3	.17	.25
cis-1,2-Dichloroethylene	Solvent	156-59-2	.038	.038
cis-1,3-Dichloropropene	Fumigant	10061-01-5	.09	.09
Dibromochloromethane	Disinfection by-product	124-48-1	.18	.18
Dibromomethane	Solvent	74-95-3	.05	.05
Dichlorodifluoromethane (CFC-12)	Refrigerant	75-71-8	.18	.27
Dichloromethane (methylene chloride)	Solvent	75-09-2	.16	.16
Diethyl ether	Solvent	60-29-7	.17	.17
Diisopropyl ether	Gasoline	108-20-3	.1	.1
Ethyl methacrylate	Organic synthesis	97-63-2	.18	.18
Ethyl tert-butyl ether (ETBE)	Gasoline	637-92-3	.05	.054

Table 1. Volatile organic compounds, predominant source or use, Chemical Abstract Service number, and laboratory reporting limits for the U.S. Geological Survey National Water Quality Laboratory analytical schedule 2020.—Continued

[VOC, volatile organic compound; CAS, Chemical Abstract Service; μg/L, microgram per liter]

VOC	Primary use or source	CAS number	Laboratory reporting limits	
			Fresno study μg/L	Modesto study μg/L
Ethylbenzene	Gasoline	100-41-4	0.03	0.03
Hexachlorobutadiene	Organic synthesis	87-68-3	.14	.14
Hexachloroethane	Solvent	67-72-1	.19	.19
Isopropylbenzene	Organic synthesis	98-82-8	.06	.032
m- and *p*-Xylene	Gasoline	108-38-3/106-42-3	.06	.06
Methyl acrylate	Organic synthesis	96-33-3	2	1.4
Methyl acrylonitrile	Organic synthesis	126-98-7	.6	.6
Methyl iodide	Organic synthesis	74-88-4	.25	.12
Methyl methacrylate	Organic synthesis	80-62-6	.35	.35
Methyl *tert*-butyl ether (MTBE)	Gasoline	1634-04-4	.17	.17
Naphthalene	Organic synthesis	91-20-3	.5	.25
n-Propylbenzene	Solvent	103-65-1	.042	.042
o-Ethyl toluene	Hydrocarbon	611-14-3	.06	.06
o-Xylene	Gasoline	95-47-6	.07	.038
sec-Butylbenzene	Organic synthesis	135-98-8	.032	.032
Styrene	Organic synthesis	100-42-5	.042	.042
tert-Amyl methyl ether	Gasoline	994-05-8	.08	.11
tert-Butylbenzene	Organic synthesis	98-06-6	.048	.06
Tetrachloroethylene (PCE)	Solvent	127-18-4	.027	.1
Tetrachloromethane (carbon tetrachloride)	Solvent	56-23-5	.06	.06
Tetrahydrofuran	Solvent	109-99-9	2.2	2.2
Toluene	Gasoline	108-88-3	.05	.05
trans-1,2-Dichloroethylene	Solvent	156-60-5	.032	.032
trans-1,3-Dichloropropene	Fumigant	10061-02-6	.09	.09
trans-1,4-Dichloro-2-butene	Organic synthesis	110-57-6	.7	.7
Trichloroethylene (TCE)	Solvent	79-01-6	.038	.038
Trichlorofluoromethane (CFC-11)	Refrigerant	75-69-4	.09	.09
Vinyl chloride	Organic synthesis	75-01-4	.11	.11

Another explanatory variable examined for its ability to predict ground-water contamination was the density, or number, of leaking underground fuel tanks (LUFTs) located near public supply wells. LUFTs are sites where chemicals, primarily gasoline and diesel fuel, are known to have been released into the environment. LUFTs can introduce gasoline components such as benzene, toluene, ethylbenzene, and xylenes (BTEX), as well as the gasoline oxygenate methyl *tert*-butyl ether or MTBE into the subsurface environment (Moran and others, 1999; Johnson and others, 2000). Therefore, the density of LUFTs within a prescribed distance of each well sampled was studied to determine if this is an effective indicator of ground-water contamination by VOCs.

Methods

Well Selection

Wells for both CAS studies were selected by using a grid-based random sampling design (Scott, 1990) with grids consisting of 50 equal area cells. Suitable wells were chosen using an inventory obtained from the USGS National Water Information System (NWIS) and information provided by the water purveyors for the cities of Modesto and Fresno. Wells were randomly selected in each cell to statistically represent the zone of ground water tapped by the majority of public supply wells in the area. Those wells were then ranked based on the total number of wells chosen for a particular cell. Only wells that had construction information (screened intervals, depth of perforations, and date constructed) available were considered for sampling. Depth to the top of the uppermost perforation of the wells sampled ranged from 74 to 248 ft (median = 124.5 ft) and 116 to 445 ft (median = 188.5 ft) for the Modesto and Fresno study areas, respectively. Selected construction information for the wells sampled can be found in *appendix 1*.

Sample Collection

Forty wells in the Modesto area were sampled during a 2-week period in March and April, 2001. Fifty wells in the Fresno area were sampled during a 2-week period in July 2002. Each of the wells was sampled for VOCs, stable isotopes of water, and tritium. Procedures utilized by the USGS NAWQA Program were implemented in this study to mitigate the potential for airborne contamination of samples and (or)

cross contamination between wells (Koterba and others, 1995; U.S. Geological Survey, 1998; U.S. Geological Survey, 1999). These procedures also helped assure that a representative sample of ground water would be collected at each site. Each public supply well was pumped for at least 20 minutes in order to purge a minimum of three casing volumes before sampling. Samples were collected by affixing tubing to the sampling port closest to the well head. All samples were unfiltered and collected before any type of chemical treatment, such as chlorination, was done to the well water.

Either tygon or copper tubing was used for collecting VOC samples for this study. Tygon tubing was used because it is flexible and available in different diameters, which is important because sampling ports have spigots with different diameters. However, tygon tubing is not a preferred sampler material when collecting VOCs because it may leach plasticizers and thus contaminate the sample (U.S. Geological Survey, 1998). To avoid this problem, only high purity, plasticizer-free tygon tubing was used in this study (Cole Parmer, 2004). Before going into the field, sample tubing was cleaned according to procedures implemented by the NAWQA Program (Koterba and others, 1995).

Volatile organic compounds were collected in 40-ml sample vials that were purged using three vial volumes of sample water and then bottom filled to eliminate headspace. Drops of one-to-one (1:1) hydrochloric acid were added to the sample to decrease the pH to 2 or less, and the sample was put on ice and shipped for analysis. To collect stable isotopes of water, a 60-ml clear glass bottle was filled with unfiltered water, sealed with a conical cap, and secured with electrical tape to prevent leakage and evaporation. Tritium samples were collected by filling 1-L amber bottles with unfiltered water, closing each using a cap with a conical insert and then securing it with electrical tape. VOCs, stable isotopes, and tritium concentrations were determined by analytical methods similar to those used by the NAWQA Program (Coplen and others, 1991; Conner and others, 1998; Hudson and others, 2002). VOC analyses were done at the NWQL in Denver, Colorado; stable isotopic analyses were done at the USGS stable isotope laboratory in Reston, Virginia; and tritium analyses were done at LLNL in Livermore, California.

Quality Control

Blank Data

Blank samples were collected at 10 percent of the well sites to determine if contaminants were introduced during sample collection, processing, storage, transportation, and laboratory analysis. Only VOC-free water (blank water) was used in the preparation of blanks. Four types of quality-control blanks were collected in Modesto: equipment, trip, field, and source solution. Only field and source blanks were collected in Fresno. Equipment blanks were collected to determine if the sampling equipment introduced contamination. Trip

blanks were collected to determine if shipping, handling, and intermittent storage of sample containers produced bias. Field blanks were processed at the sampling location to determine if procedures used during sample collection and laboratory analysis introduced contamination and if cleaning procedures were effective. Source solution blanks were prepared to verify that the blank water used for the field, trip, and equipment blanks had no concentrations of VOCs detectable at the laboratory-reporting limit (LRL).

Field blanks were collected at the sampling site by pouring blank water directly from its original storage container through clean sampling equipment and into sample vials. Source-solution blanks also were collected at the sampling site by pouring blank water directly into sample vials that were then stored, shipped, and analyzed in the same manner as the environmental samples. Equipment blanks were collected in the same manner as field blanks, but were processed under controlled conditions away from the sampling site. Trip blanks consisted of blank water in a sealed sample vial that was kept with the other sample vials from the start of the field activities through laboratory analysis.

A VOC detected in an environmental sample was considered a result of contamination if the following criteria were met: (1) the VOC was detected in a quality-control blank, but not in the associated source solution blank, (2) the VOC detected in the quality-control blank was also detected in environmental samples, and (3) the minimum concentration detected in environmental samples was lower than the maximum concentration detected in quality-control blanks. Contamination was indicated when the concentration of VOCs in quality-control blanks was as high as or higher than the concentration in the environmental samples (Dawson and others, 2003). Samples that were determined to have a detection of one or more specific VOCs resulting from contamination were censored, and subsequently any VOC in question was reported as not being detected for the sample in question.

Surrogate Data

Surrogate data were used to calculate percentage recoveries for VOCs detected in the CAS study. Surrogate compounds are not normally found in the environment and are used to identify potential problems associated with laboratory analyses. Potential problems include matrix interferences (such as high levels of dissolved organic carbon) that produce a positive bias, and incomplete laboratory recovery (such as improper maintenance and calibration of analytical equipment) that produces a negative bias. In the laboratory, three surrogates (1,2-dichloroethane-d_4, toluene-d_8, and p-bromofluorobenzene) were added to each quality control (QC) and environmental sample, and their percentage recoveries were reported along with targeted VOC concentrations. A 70- to 130-percent recovery of surrogates is considered acceptable; values outside this range indicate possible problems with the analytical procedure (Conner and others, 1998).

Determination and Use of Categorical Variables

Well Depth

Wells were put into one of two depth categories, shallow or deep, depending on the depth to the top of their uppermost perforation. Shallow and deep categories were demarcated by the median depth to the top of the uppermost perforation for each particular study area; wells having a depth less than the median value were categorized as shallow; wells having a depth greater than the median value were categorized as deep. Information on the depth of well perforations was obtained from the city water purveyors for Fresno and Modesto, as well as the California Department of Water Resources and USGS databases.

Land Use

In order to assign a land-use category to a public supply well, a circular buffer (radius = 500 m) was placed around each well sampled and the percentages of land-use types (urban, agriculture, or native vegetation) within that buffer zone were calculated. The land use category was then based on the dominant type within each well's buffer area (Koterba, 1998). Because the predominant land use type within the buffered areas for both Fresno and Modesto was urban, wells were categorized as either high or low in their degree of urbanization. The median percentage of urban land use for all the buffered areas in a particular basin was used to divide wells into high and low urban land use categories. The median percentage of urban land use in Modesto was 100 percent and in Fresno, 95 percent. Land use data were obtained from the California Department of Water Resources for the Fresno (California Department of Water Resources, 2000a) and the Modesto (California Department of Water Resources, 2000b) study areas.

Leaking Underground Fuel Tanks

Wells were classified into one of two LUFT categories, high density or low density, depending on the number of LUFTs contained within the buffer zone associated with each well. The number of LUFTs assigned to each well sampled was determined in much the same way as the amount of urban land use assigned to each well; circular buffers (radius = 500 m) were placed around each well and the number of LUFTs within the buffer zone was tabulated. The location and chemical content of LUFTs for each of the study areas was obtained from the SWRCB Geographic Environmental Information Management System (GEIMS), a data warehouse which tracks regulatory data about underground fuel tanks, fuel pipelines, and public drinking water supplies (California State Water Resources Control Board, 2004).

Determining the Presence of Young Ground Water

Tritium concentrations were used to determine whether ground-water samples contained a component of young ground water (water recharged within the last approximately 50 years) or the sample consisted only of old ground water recharged prior to that 50 year period. Tritium is introduced into ground water when atmospheric tritium replaces hydrogen atoms in rain and snowfall, and this precipitation then infiltrates the soil. The primary source of atmospheric tritium is cosmic rays bombarding water vapor in the atmosphere (Thatcher, 1962). However, thermonuclear weapons testing in the 1950s and 1960s produced elevated levels of tritium in the atmosphere and thus elevated tritium levels in ground water; by 1963, the extensive testing of thermonuclear weapons ended. Atmospheric tritium levels in the northern hemisphere reached a maximum in 1963, and levels of tritium in the atmosphere and ground water are now approaching background levels.

Young ground water that has been at the land surface within the last 50 years is thought to be more susceptible to contamination due to the widespread production and use of VOCs during this period. A tritium concentration of 1.0 picocurie per liter (pCi/L) was used as the demarcation between young and old ground water (Michel, 1989; Michel and Schroeder, 1994). Ground water with tritium concentrations above the 1.0-pCi/L threshold is referred to as young, and ground water with tritium concentrations that fall below the threshold is referred to as old.

Determining the Presence of High Nitrate Concentrations

Nitrate concentrations were analyzed as predictors of aquifer contamination from VOCs. Relatively high nitrate concentrations in ground water may indicate that an aquifer has been influenced by anthropogenic activities taking place at or near the land surface. Therefore, ground water that is relatively high in nitrate may also contain other anthropogenic contaminants, such as VOCs. The median nitrate value for all wells sampled in each study area was used to place wells into one of two categories: wells with high nitrate concentrations or wells with low nitrate concentrations. Each study area was evaluated individually and assigned its own median nitrate value. Nitrate values for individual wells were determined by using the median nitrate concentration of analyses performed within the previous 12 months of this study. Nitrate-as-nitrogen concentrations were used for the analyses in this report, but for simplicity are referred to as nitrate concentrations.

Censoring of Data in the Fresno Study Area

The explanatory variables of well depth and land use had a statistically significant negative correlation to one another

in the Fresno study area (Kendall's tau test, p = 0.05). Deeper wells tended to be located in less urbanized areas, whereas shallower wells tended to be located in more urbanized areas. Because of this correlation, a meaningful analysis of the relation between VOC occurrence, tritium levels, nitrate concentrations, and the explanatory variables of well depth and land use was not possible. To solve this problem, wells were systematically censored (removed from the data set) until there was no statistically significant correlation between the explanatory variables of well depth and land use. A correlation was not considered statistically significant if the p-value for a Kendall's tau test was greater than 0.1.

The following steps were used to censor wells: (1) wells were sorted in ascending order based on depth to the top of the uppermost perforation; (2) wells were divided into two depth categories (see determination of well depth categories above), shallow and deep; (3) the shallowest well, from the shallow depth category, with the highest percentage of urban land use (see determination of land use category above) was censored; (4) the deepest well, from the deep depth category, with the lowest percentage of urban land use was censored; and (5) well depth and land use were again compared to determine if a statistically significant correlation existed in the new censored data set. If a statistically significant correlation between well depth and land use was not found, no additional wells were censored. If a statistically significant correlation still existed, then steps 3–5 were repeated until there was no significant correlation between well depth and land use in the Fresno study area.

Four out of 50 wells were censored in order to reduce the correlation between well depth and land use in the Fresno study area (Kendall's tau test, p-value = 0.12). The censored data set was used only to examine the relation between the explanatory variables of well depth and land use, and the occurrence and distribution of VOCs, tritium, and nitrate.

Stable Isotopes and Source of Ground-Water Recharge

The source of ground-water recharge can be inferred by determining the stable isotopic content of local ground and surface waters. Two naturally occurring stable isotopes of hydrogen and oxygen are deuterium and oxygen-18, respectively. Deuterium and oxygen-18 are heavier than the more abundant protium and oxygen-16 isotopes and readily substitute for these lighter isotopes in water molecules. The mass differences created by isotopic substitution in the water molecule allow for a measurable fractionation during physical hydrological processes (Clark and Fritz, 1997). The relative abundance of these isotopes is expressed as a ratio in delta notation, which is often plotted next to the linear global meteoric water line (GMWL). The GMWL defines the relation between deuterium and oxygen-18 in the global fresh surface waters and is an average of many local and regional water lines (Craig, 1961). Owing to physical hydrological processes,

such as evaporation, mixing, and precipitation, deviations from the GMWL will occur. These deviations can provide insight into the source of the water recharging an aquifer system and, thereby, possibly identify pathways of contamination.

Statistical Analysis and the Use of Boxplots

Nonparametric statistics were used in this study to examine the relations between explanatory variables, such as degree of urbanization, and response variables, such as number of VOC detections. For ground-water samples that had nondetectable concentrations of tritium or nitrate, a value of one-half the method detection limit (MDL) was used to compute test statistics and create plots. Scatter plots were the first step used to analyze the existing correlations between variables. Scatter plots are used to visually examine the data because relying solely on the value of the correlation coefficient to measure relation strength can be misleading (Helsel and Hirsch, 1992). The correlation coefficient is used to indicate the strength of the association between two continuous variables

Kendall's tau test was the rank order statistical test used to examine the correlation between occurrence and distribution of chemical components and the explanatory variables of depth to the top of the uppermost perforation, land use, tritium levels, nitrate concentrations, and LUFT density. Explanatory variables were also grouped into categories (see Determination and Use of Categorical Variables above) and compared to one another using the Wilcoxon rank sum test. The Wilcoxon rank sum test is a nonparametric, median test statistic that compares two independent data groups (categories) to determine if one group contains larger values than the other. For example, if wells are grouped based on depth to the top of the uppermost perforation, this test could determine whether wells grouped in the shallow category or the deep category tend to have a higher number of VOCs detected per well.

The results of Kendall's tau and the Wilcoxon rank sum statistical tests were considered significant if the null hypothesis was rejected at least 95 percent of the time (p-value = 0.05). The null hypothesis for Kendall's tau test is that there is no significant correlation between the two continuous variables being tested. The null hypothesis for the Wilcoxon rank sum test is that there is no significant difference between the observations of the two independent data groups being tested.

Boxplots were used to analyze and display data in this report. A boxplot is a convenient way to look at the characteristics of a data set. The boxed portion of a boxplot contains 50 percent of the data points, that is, the values located between the 25th and 75th percentiles of the data set. The median value is identified by a solid line through the box. The lines or "whiskers" extending from the end of the boxes expand out to the extreme values of the data set that are no more than 1.5 times the length of the interquartile range. Any values beyond 1.5 times the interquartile range (outliers) are marked with a solid line not connected by a whisker to the box (Venables and Ripley, 1999).

Results

VOC Detections in Quality-Control and Associated Environmental Samples

A summary of the results of the quality control (QC) and associated environmental samples can be found in *appendix 2*. Three VOCs (toluene, tetrachloroethylene (PCE), and dichloromethane were detected in 7 QC blanks (4 field, 1 source solution, 1 equipment, and 1 trip) collected for the Modesto study. Dichloromethane was detected in 1 field blank (0.02 μg/L) and the associated source-solution blank (0.02 μg/L), but not in the paired environmental sample. Consequently, environmental data for dichloromethane were not censored. Tetrachloroethylene was detected in two field blanks, but not in the associated source solution blanks. Both field blanks had PCE concentrations of 0.02 μg/L. Six environmental samples had PCE concentrations less than or equal to 0.02 μg/L. These PCE detections were censored and counted as nondetections. Toluene was detected in 3 blanks: 1 field blank (0.01 μg/L), 1 trip blank (0.02 μg/L), and 1 equipment blank (0.03 μg/L). Toluene was detected in two environmental samples (both at 0.01 μg/L). Because the equipment and trip blanks had higher concentrations of toluene than either of the environmental samples, both environmental toluene detections were counted as nondetections. None of the QC blanks collected as part of the Fresno study had VOC detections.

All but two samples (one environmental sample and one field blank) analyzed for the Fresno study had surrogate recoveries within acceptable limits (70 to 130 percent). The environmental sample had a high recovery (133 percent) of the surrogate 1, 2-dichloroethane-d_4. The VOCs chloroform and PCE were detected in this environmental sample. Therefore, these compounds may have been present in the sample at a lower concentration than is reported. Both of these VOC concentrations were listed as estimated values in the USGS database and, on the basis of the QC data, were not censored further. The field blank also had a high recovery (138 percent) of the surrogate 1,2-dichloroethane-d_4. No VOCs were detected in this QC sample. All surrogate recoveries for the Modesto CAS data were within the accepted limits.

Occurrence of VOCs, Tritium, and Nitrate

Detection frequencies for VOCs, class of VOCs, and tritium at levels greater than or equal to 1.0 pCi/L in the Fresno and the Modesto study areas are shown in *figure 4*. Overall, VOCs were detected more frequently in Modesto (92 percent) than in Fresno (72 percent). The class of VOCs known as trihalomethanes (THMs) was detected more frequently in Modesto (92 percent) than in Fresno (56 percent). Solvents also were detected more frequently in Modesto (70 percent) than in Fresno (58 percent). In Fresno, BTEX compounds were rarely detected (2 percent), whereas MTBE was not detected at all.

Conversely, MTBE was detected in Modesto (5 percent), whereas BTEX compounds were not detected at all.

The prevalence of THMs in ground water used for public supply has been documented (Stackelberg and others, 2000; Shelton and others, 2001). A review of the occurrence and distribution of VOCs in ground-water supplies (Westrick, 1984) stated that the most frequently detected VOC class was THMs. THMs are formed when water containing organic matter, including drinking water and wastewater, is disinfected. These compounds may be introduced into aquifers through landscape irrigation, leaking drinking water and storm drain infrastructure, and disposal of treated wastewater. In a national survey of drinking-water sources, THMs were detected frequently in samples taken from public water systems that relied strictly on ground water; the larger the system, the more frequently THMs were detected (Grady, 2003). Therefore, it is reasonable to expect THMs to be the class of VOCs detected most frequently in the ground-water supplies of the large public water systems serving the Fresno and Modesto metropolitan areas.

Solvents are used in a wide variety applications ranging from metal degreasing to dry cleaning (Thiros, 2000). These compounds and their degradation products have been detected frequently during previous studies of ground-water quality (Stackelberg and others, 2000; Hamlin and others, 2002). In a national study that analyzed the VOC content of untreated, ambient ground water in nearly 3,000 wells, solvents were detected more frequently in wells associated with urban use than with agricultural land use (Squillace and others 1999).

In contrast, the VOCs commonly referred to as BTEX compounds and the gasoline oxygenate MTBE are not frequently detected in the wells sampled in the Fresno and Modesto study areas. The low detection frequencies for the BTEX compounds may be a synergistic effect that is due to their relatively low solubility and labile nature, whereas the low detection frequencies of MTBE may be due to the fact that compound has been in heavy production and use only since the early 1990s (Schwarzenbach and others, 1993; Grady and Casey, 2001). Therefore, it may not have reached the depths of the aquifers sampled in this study in any appreciable quantities. The detection frequencies for BTEX and MTBE compounds in this study were similar to the frequencies reported by Moran and others (2003), who analyzed the results obtained by the USGS NAWQA Program (1993–2002) and source-water survey (1999-2000).

Tritium at levels greater than 1.0 pCi/L was frequently detected in both the Fresno (92 percent) and the Modesto (90 percent) study areas. The median tritium levels found in Fresno wells was 10.9 pCi/L and 11.9 pCi/L for Modesto wells (appendix 3a). These tritium levels show that some fraction of the ground water withdrawn from these basins has been recharged since the 1950s. The median concentration of nitrate found in Fresno was 3.3 mg/L and in Modesto, 3.4 mg/L (*appendix 3b*). The similarity in nitrate detections in the two basins may be due to the similarity in land uses. Land use has been shown to be an important explanatory variable in predicting the concentrations
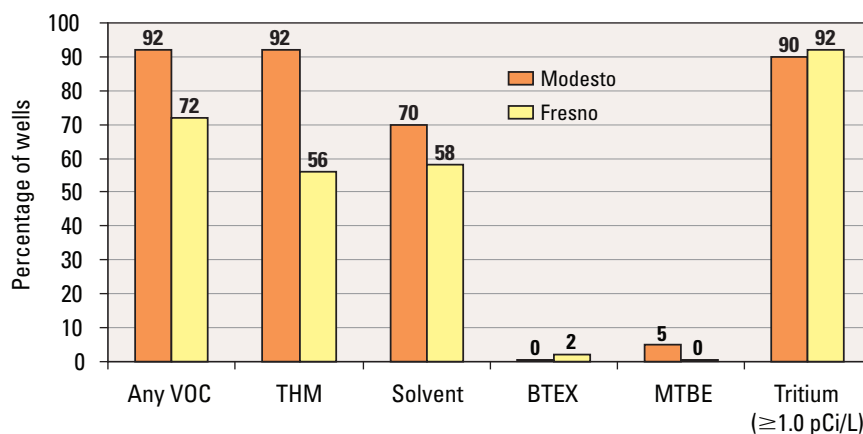
Figure 4. Detection frequencies of volatile organic compounds, classes of volatile organic compounds, and tritium for wells sampled in the Fresno and Modesto study areas, California, in 2002 and 2001, respectively.
VOC, volatile organic compound; THM, trihalomethane; BTEX, benzene, toluene, ethyltoluene, xylenes; MTBE, methyl *tert*-butyl ether. ≥, less than or equal to; pCi/L, picocurie per liter.

of nitrate in ground water (Eckhardt and Stackelberg, 1995; Tesoriero and Voss, 1997).

Detection Frequency of Individual VOCs

Figure 5 shows the detection frequencies for individual VOCs in the Fresno and Modesto study areas. Twenty-five different VOCs were detected in Fresno and Modesto (*appendixes 4a* and *4b*). Seven of the 25 VOCs identified in Modesto samples were frequently detected and 3 of the 19 VOCs identified in Fresno samples were frequently detected. VOCs were considered frequently detected if they were identified in at least 20 percent of the wells sampled. In Modesto, the disinfection by-products chloroform, bromodichloromethane, bromoform, and dibromochloromethane, commonly referred to as THMs, were among the frequently detected VOCs, as were the solvents PCE, TCE, and dibromomethane. Frequently detected VOCs in Fresno included the THM chloroform, as well as the solvents PCE and 1, 2-dichloropropane. In contrast, the soil fumigant 1, 2-dibromo-3-chloropropane (DBCP) was rarely detected in either the Modesto (2 percent) or the Fresno (2 percent) study area. DBCP is a pesticide that was used to control nematodes in the agricultural areas of California. This carcinogenic compound has been detected frequently in drinking water wells in the San Joaquin Valley (Burow and others, 1999).

Chloroform was also the most frequently detected VOC in untreated, ambient ground water that was studied as part of the NAWQA Program from 1985 to 1995. The production of chloroform has been documented in the United States since the 1920s and is primarily used in the synthesis of the refrigerant hydrochlorofluorocarbon or HCFC-22 (IARC, 1979). Chloroform, bromodichloromethane, bromoform, and dibromochloromethane are commonly formed during the chlorination process used to disinfect drinking and reclaimed water

(Grady and Casey, 2000). This process has been used for much of the 20th century (White, 1972; Chlorine Chemistry Council, 2004). Therefore, activities like landscape irrigation and disposal of reclaimed water may increase chloroform concentrations in ground water.

The solvents PCE and TCE have been detected frequently during previous studies of ground-water quality (Grady and Casey, 2000; Hamlin and others, 2002). These solvents are among the most widely produced chlorinated organics and have many commercial and industrial uses (Stackelberg and others, 2000). These chlorinated organics are hydrophobic and denser than water; thus, they primarily move through the unsaturated zone as a distinct liquid phase. When these compounds migrate downward, they frequently become trapped in soil pores only later to be slowly dissolved by water percolating through the soil profile. Because of these chemical properties, solvents like PCE and TCE can bring about large and persistent plumes of ground-water contamination (Broholm and others, 1999).

Almost all VOC detections in this study were at least an order of magnitude (factor of 10) below maximum safe concentrations set by federal and state drinking water regulations. Only four wells had a detection that exceeded drinking water standards; one TCE detection (59.6 μg/L) and one DBCP detection (0.6 μg/L) in Fresno, and one TCE detection (6.1 μg/L) and one PCE detection (5.6 μg/L) in Modesto (*appendix 4b*). The MCL set by the U.S. Environmental Protection Agency (EPA) and the state of California for TCE and PCE is 5 μg/L; the MCL for DBCP is 0.2 μg/L.

TCE concentrations in the DHS database for the well in Fresno also exceeded the MCL; however, DBCP concentrations did not. The ground water withdrawn by the two wells in Fresno with TCE and DBCP concentrations that exceeded the MCL are treated so that federal and state regulations are
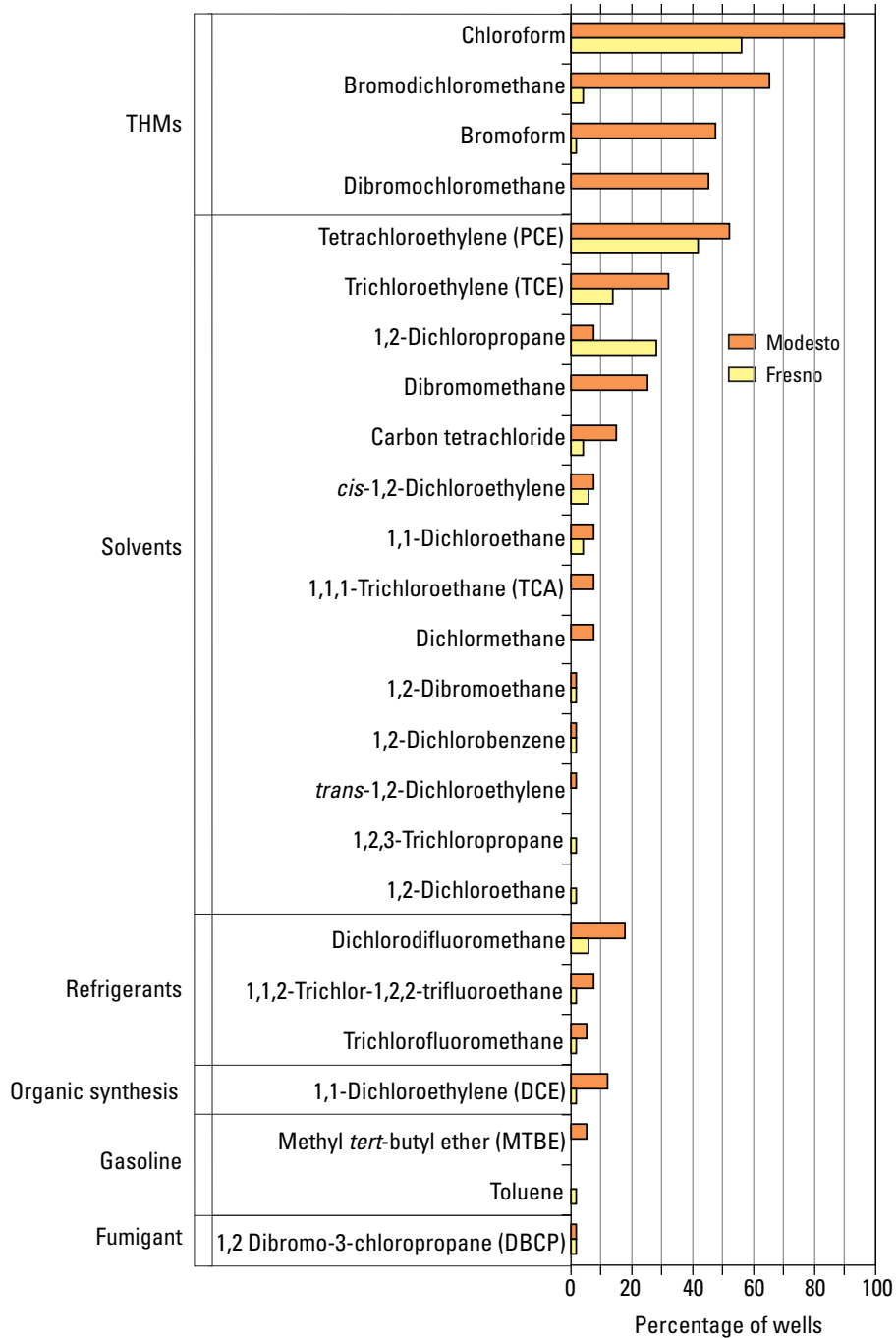
Figure 5. Detection frequencies of volatile organic compounds, divided by class, in samples collected in the Fresno and Modesto study areas, California, in 2002 and 2001, respectively.
Not detected where not shown.

met before delivery to the public (Bob Little, city of Fresno, oral commun., 2004). The TCE and PCE concentrations in the DHS database for the wells in Modesto did not exceed the MCL prior to sampling. After sampling, the TCE concentration did exceed the MCL in the DHS database; the PCE concentration did not. Ground water from the two wells in Modesto with TCE and PCE concentrations that exceeded the MCL are not being used; these wells will not be used until the ground water can be treated to meet federal and state regulations (Lanora E. Hill, oral commun, 2004).

Relation between VOC Occurrence, Young Ground Water, and Nitrate Concentration

In Fresno, wells withdrawing young ground water had a higher detection frequency of VOCs (68 percent) than wells withdrawing old ground water (40 percent). Modesto wells withdrawing young ground water also had a higher detection frequency of VOCs (94 percent) than wells withdrawing older ground water (75 percent). The distribution of the number of VOCs detected in wells withdrawing young versus old ground water in the Fresno and the Modesto study areas are shown in *figures 6A* and 6B, respectively. There was a significantly higher number of VOC detections in Fresno wells withdrawing young ground water than in wells withdrawing old ground water (p = 0.05, Wilcoxon rank sum test). In Modesto, there was a significant positive correlation between number of VOCs detected and tritium levels (p = 0.04, Kendall's tau test). Of the wells that had at least one VOC detection, 94 percent of the wells in Fresno and 92 percent of the wells in Modesto were also withdrawing young ground water.

These results indicate that young ground water is more susceptible to contamination than old ground water. Young ground water has been at or near the land surface while anthropogenic compounds like VOCs have been in widespread production and use. Additionally, the younger the ground water, the less time that processes of natural attenuation have had to reduce contaminant concentrations. Even though the results indicate that young ground water is more susceptible than old ground water to VOC contamination, these data do show that old ground water can be contaminated.
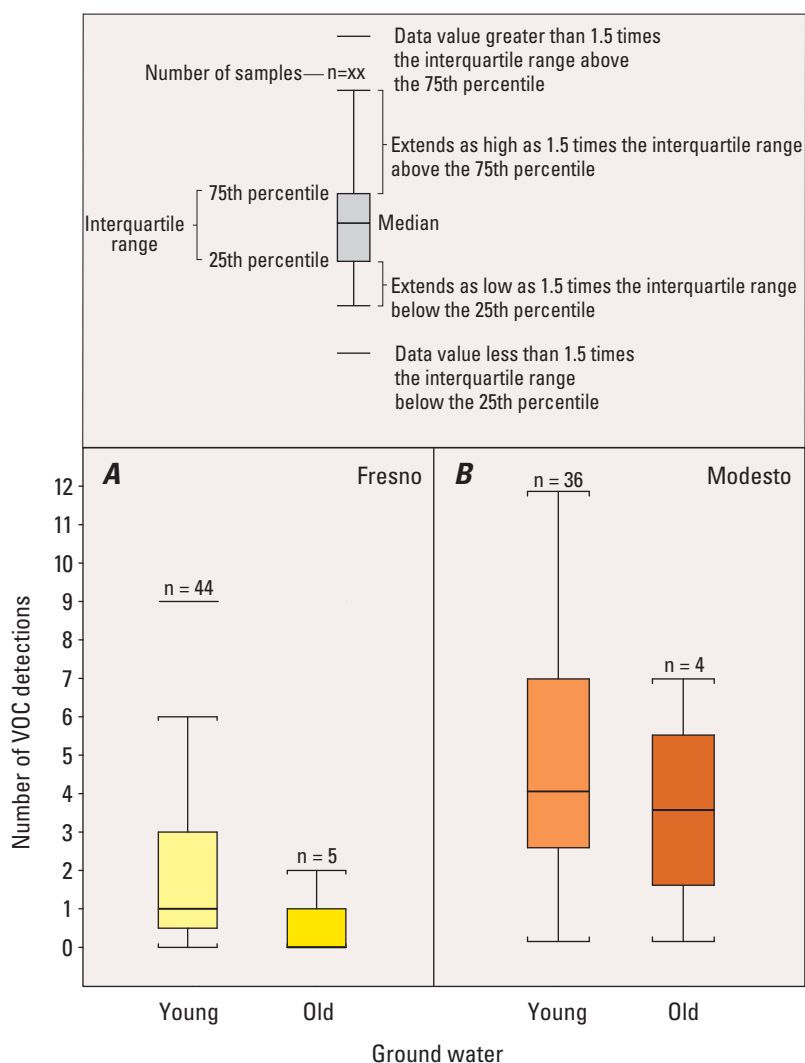
Figure 6. The number of volatile organic compounds (VOCs) detected in wells categorized by relative ground-water age in (**A**) the Fresno and (**B**) the Modesto study areas, California, in 2002 and 2001, respectively. n is the number of wells.

Contamination of old ground water may be caused by point source contamination and (or) preferential flow paths that may aid in transporting liquids relatively quickly from the land surface to the water table. Point sources of contamination may include hazardous materials spills, leaking storage tanks, or improper disposal of VOC laden waste. Preferential flow paths in these ground-water basins may arise from the improper sealing of abandoned and destroyed wells, and (or) the improper placement, or lack, of sanitary seals in active public supply wells.

In Fresno, VOCs were detected more frequently in wells with high nitrate concentrations (80 percent) than in wells with low nitrate concentrations (68 percent). In Modesto, wells with high nitrate concentrations had slightly higher detection frequencies of VOCs (95 percent) than wells with low nitrate concentrations (90 percent). The distribution of the number of VOC detections for samples with high and with low nitrate concentrations are shown in *figure 7*. In Fresno, the statistical significance of the difference between the number of VOCs detected in wells with high nitrate and wells with low nitrate was borderline (p = 0.07, Wilcoxon rank sum test). In Modesto, there was no statistical significance between the number of VOCs detected in the high and the low nitrate wells (p = 0.33, Wilcoxon rank sum test).
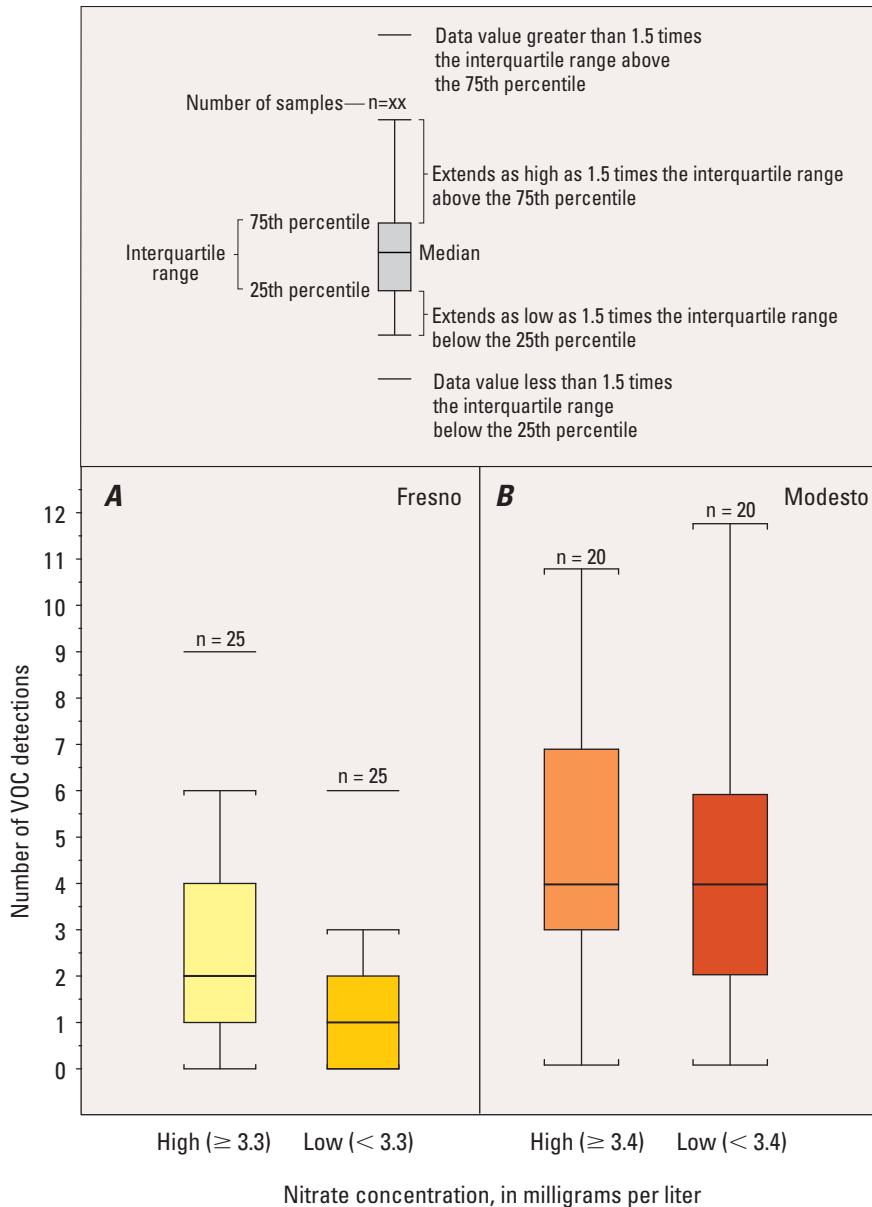
Figure 7.   The number of volatile organic compounds (VOCs) detected in wells categorized by nitrate concentration in (**A**) the Fresno and (**B**) the Modesto study areas, California, in 2002 and 2001, respectively.
n is the number of wells. ≥, greater than or equal to; <, less than.

The absence of a significant positive correlation between nitrate concentrations and the number of VOCs detected in ground water may be due to the labile nature of nitrate under certain natural conditions. Anaerobic denitrification by bacteria has been shown to be a viable process for removing nitrate in ground water (Korom, 1992). A study of the terminal electron accepting processes in several San Joaquin Valley ground-water basins showed that favorable conditions existed for nitrate removal by denitrification (Chapelle and others, 1995). Therefore, the process of denitrification may remove nitrate from ground water while VOC concentrations are left largely unchanged.

Depth to the Top of the Uppermost Perforation as an Explanatory Variable

The detection frequencies for VOCs, tritium at levels greater than or equal to 1.0 pCi/L, and high nitrate concentrations in shallow and deep wells in Fresno are shown in *figure 8A*. VOCs were detected more frequently in shallow wells (86 percent) than in deep wells (67 percent). *Figure 9A* shows the distribution of the number of VOC detections for shallow and deep wells in the Fresno study area. The

number of VOCs detected had a statistically significant negative correlation to well depth (*table 2*). These results indicate that depth to the top of the uppermost perforation is a good predictor of VOC occurrence in the Fresno study area.

Tritium at levels greater than or equal to 1.0 pCi/L was detected more frequently in shallow wells (95 percent) than in deep wells (87 percent) in Fresno. A statistically significant negative correlation was found between depth to the uppermost perforation and tritium levels (*table 2*). High nitrate concentrations also were detected in shallow wells (54 percent) more frequently than in deep wells (42 percent). The median value of nitrate concentrations was greater in shallow wells than in deep wells; however, the difference in concentrations is not statistically significant (*table 2*). Tritium levels and nitrate concentrations detected in Fresno show that shallow wells contain younger water with higher concentrations of nitrate than deep wells, which indicates that wells perforated at shallow depths are more susceptible to influences occurring at or near the land surface than wells screened at deeper depths.

The detection frequencies for VOCs, tritium at levels greater than or equal to 1.0 pCi/L, and high nitrate concentrations in shallow and deep wells in Modesto are shown in *figure 8B*. VOCs were detected more frequently in shallow wells (95 percent) than in deep wells (90 percent), and the
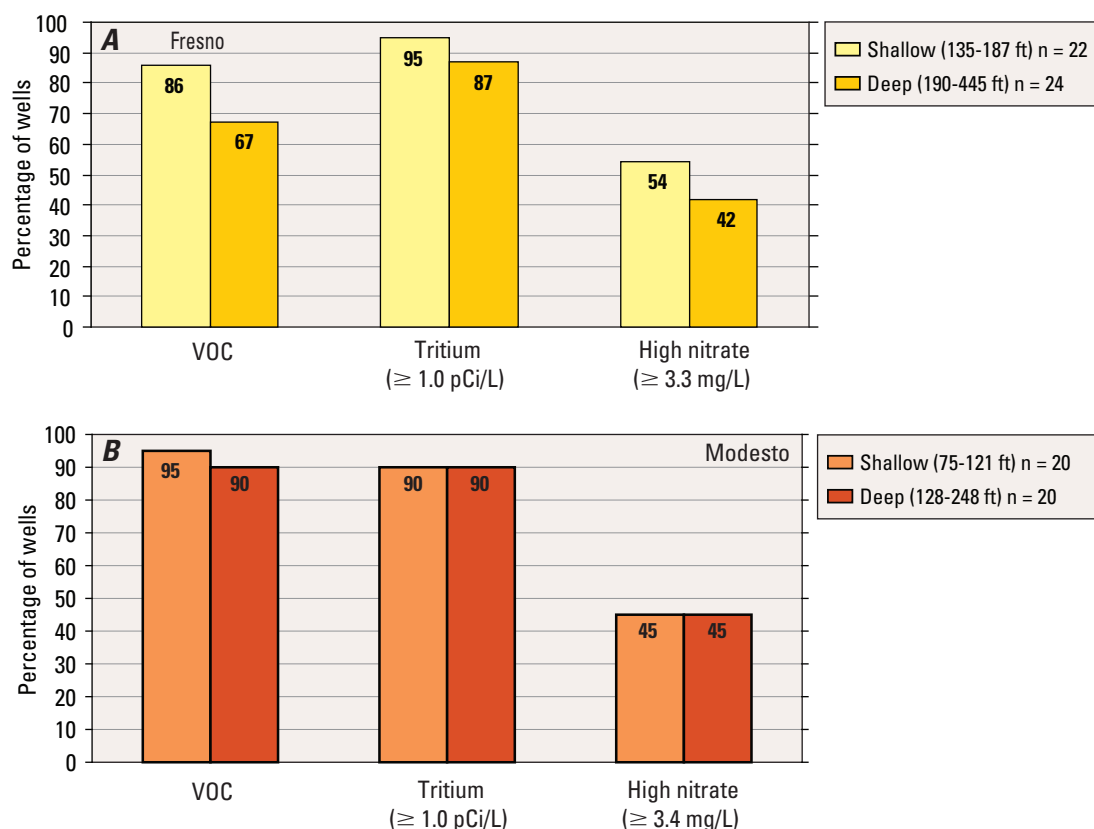
Figure 8. Detection frequencies of volatile organic compounds (VOCs), tritium, and nitrate in shallow and deep wells sampled in (**A**) the Fresno and (**B**) the Modesto study areas, California, in 2002 and 2001, respectively.
n is the number of wells. ft, foot; mg/L, milligram per liter; pCi/L, picocurie per liter; ≥, greater than or equal to.
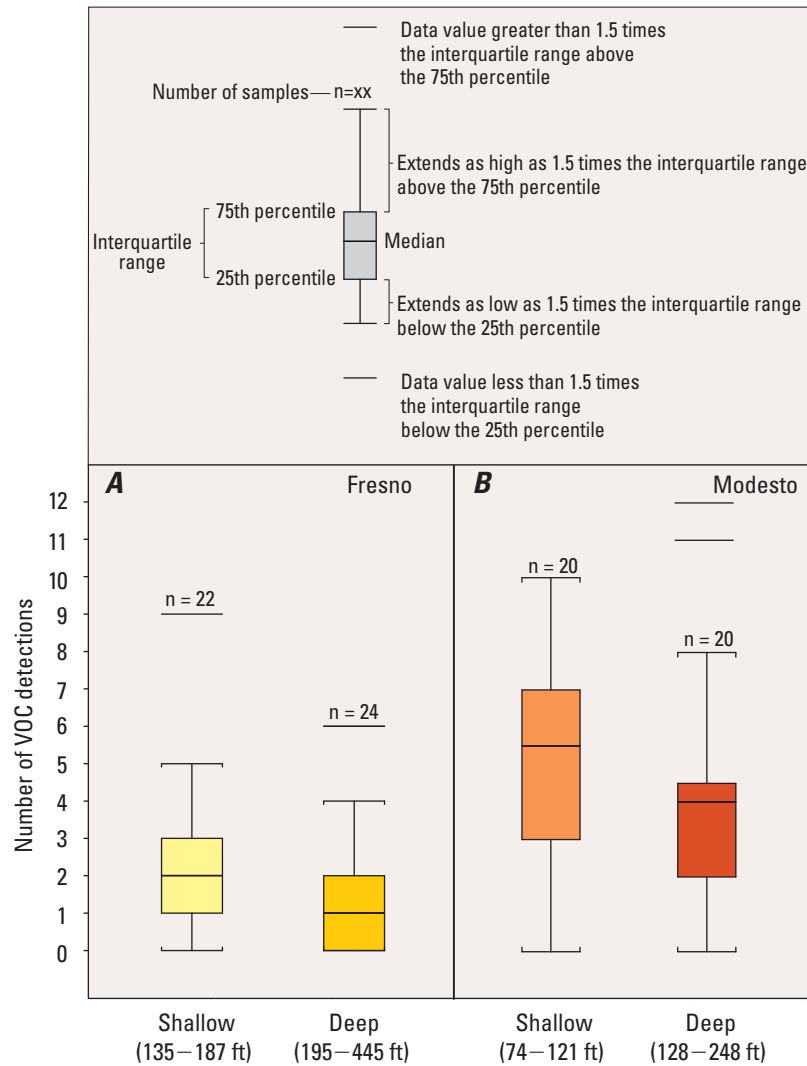
Figure 9.   The number of volatile organic compounds (VOCs) detected in shallow and deep wells sampled in (**A**) the Fresno and (**B**) the Modesto study areas, California, in 2002 and 2001, respectively.
n is the number of wells. ft, foot.

Table 2.   Median value for the number of volatile organic compound detections, tritium levels, and nitrate concentrations in samples collected in shallow and deep wells in Fresno and Modesto, California, in 2002 and 2001, respectively.

[Depth categories are demarcated by the median depth to the top of the uppermost perforation for all wells in each study area. VOC, volatile organic compound. Nitrate-N, nitrate nitrogen. ft, foot; pCi/L, picocurie per liter; mg/L, milligram per liter]

	Fresno			**Modesto**		
	Shallow (135–187 ft)	**Deep (190–445 ft)**	**p-value**	**Shallow (74–121 ft)**	**Deep (128–248 ft)**	**p-value**
VOCs (detections)	2	1	[1]0.04	5.5	4	[2]0.04
Tritium (pCi/L)	14	8.4	[1].02	10.3	14.7	[2].4
Nitrate-N (mg/L)	4	3.1	[2].1	3.6	3.5	[2].5

[1]Statistical test: Kendall's tau.
[2]Statistical test: Wilcoxon rank sum.

number of VOCs detected was significantly greater in shallow wells (*table 2*). *Figure 9B* shows the distribution of the number of VOC detections for shallow and deep wells in the Modesto study area. These results indicate that depth to the top of the uppermost perforation is a good predictor of VOC occurrence in the Modesto study area. Tritium at levels greater than or equal to 1.0 pCi/L were detected as frequently in deep wells as in shallow wells (90 percent); the median levels were higher for the deep wells, but the difference was not statistically significant (*table 2*).

In Modesto, high nitrate concentrations were detected just as frequently in deep wells as in shallow wells (45 percent) (*fig. 8B*). Median nitrate concentrations in shallow wells were higher than those in deep wells, but the difference was not statistically significant (*table 2*). The fact that the occurrence and distribution of tritium and nitrate were not significantly correlated to depth in Modesto indicates young water has infiltrated the depths of the aquifer sampled in this study; even so, VOCs occurred more frequently in the shallow wells of Modesto. This finding may be a result of the partially confined nature of the aquifer system in the Modesto study area and (or) the hydrophobic properties of VOCs, which allow contaminants to adsorb to the aquifer matrix and then only slowly be released into aqueous phase over time.

The differences in VOC occurrence and distribution between the Modesto and Fresno study areas are likely due to differences in the depth to the top of the uppermost perforations of the wells. *Figure 10* shows that land use, tritium levels, and nitrate concentrations in Fresno and Modesto were very similar, whereas the depth to the top of the uppermost perforation was significantly less for the wells in Modesto than for the wells in Fresno. The number of VOCs detected per well was greater in Modesto than in Fresno (p < 0.01, Wilcoxon rank sum test), indicating that depth to the top of the uppermost perforation is an important explanatory variable in predicting the occurrence and distribution of VOCs. Other studies of ground-water quality in partially confined and unconfined aquifers also have shown that wells screened at shallower depths tend to have a higher frequency of VOC detections than wells screened at deeper depths (Clawges and others, 1999).

Land Use as an Explanatory Variable

For wells in areas of high and low urban land use in Fresno, the detection frequencies for VOCs, tritium at levels greater than or equal to 1.0 pCi/L, and high nitrate concentrations are shown in *figure 11A*. VOCs were detected more frequently in high urban land use wells (96 percent) than in low urban land use wells (56 percent). The number of VOCs detected showed a statistically significant positive correlation with urban land use (*table 3*). The history of a compound's production and use may be the best predictor of its occurrence in the environment. Therefore, it is reasonable to expect VOCs to occur more frequently in wells that are located in more urbanized areas, where these compounds are most often used

(Moran and others, 2002). Analysis of ground-water quality data collected from across the nation by the USGS NAWQA Program has shown that VOCs are detected more frequently in wells that are located in densely populated, urbanized areas than in less populated, rural areas (Squillace and others, 1999).

Tritium was detected at levels greater than or equal to 1.0 pCi/L almost as often in low urban land use wells (83 percent) as in high urban land use wells (95 percent) in Fresno (*fig.11A*). Tritium levels did not have a significant statistical correlation with urban land use (*table 3*). High nitrate concentrations were detected more frequently in high urban land use wells (61 percent) than in low urban land use wells (35 percent) (*fig. 11A*); the difference in concentration was statistically significant (*table 3*). In urban areas, nitrate can be introduced into the subsurface environment by several pathways, such as leaking wastewater infrastructure, disposal of wastewater via percolation ponds, fertilization of residential lawns and gardens, and septic tank systems. High nitrate values in urbanized areas may also be a legacy of agricultural activities.

The detection frequencies for VOCs, tritium at levels greater than or equal to 1.0 pCi/L, and nitrate in high and low urban use wells in Modesto are shown in *figure 11B*. VOCs were detected in 100 percent of the wells located within high urban land use areas and in 84 percent of the wells located within low urban land use areas. VOC detections showed a significant positive correlation to urban land use in Modesto (*table 3*). Tritium was detected at levels greater than or equal to 1.0 pCi/L less frequently in low urban land use wells (84 percent) than in high urban land use wells (95 percent), but the difference in the median tritium level between high and low urban land use wells was not statistically significant (*table 3*). High nitrate concentrations were detected more frequently in low urban land use wells (53 percent) than in high urban land use wells (48 percent). However, the difference in median nitrate concentrations between the two land use categories was not statistically significant (*table 3*).

LUFT Density as an Explanatory Variable

Analysis of LUFT data showed that 99.6 percent of the underground storage tanks located within the study areas contained gasoline, diesel fuel, or other petroleum distillates (California State Water Resources Control Board, 2004). A total of three gasoline components were detected in 3 of the 90 wells sampled in the Fresno and Modesto study areas. Because gasoline components were rarely detected, LUFT density was not analyzed as a explanatory variable (*appendix 4*).

Stable Isotopic Content of Ground Water as an Explanatory Variable

Ground-water recharge in Fresno and Modesto occurs through several processes: infiltration of local precipitation, percolation from streams and rivers, percolation from urban and
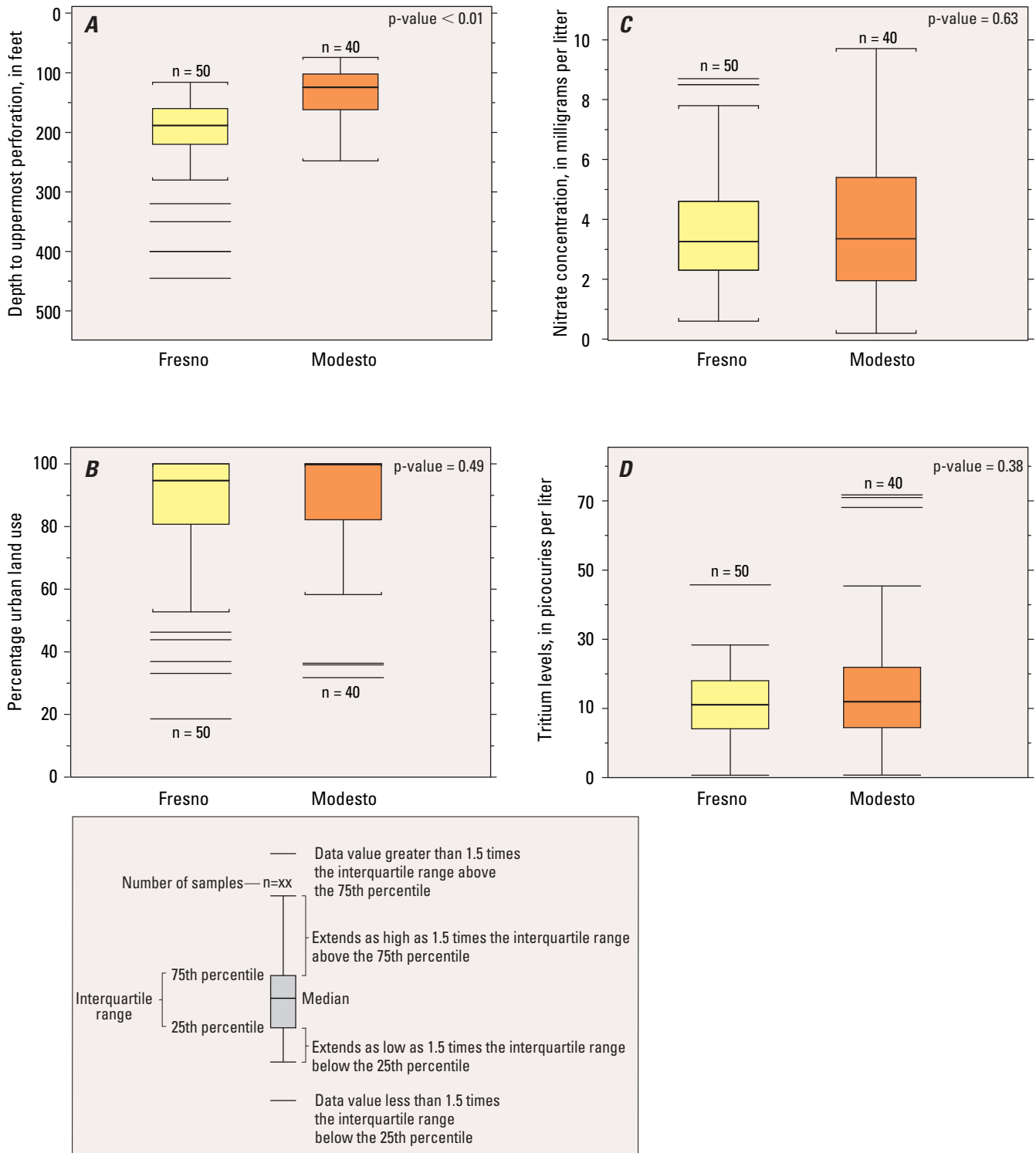
Figure 10. Distribution of depth to the top of the uppermost perforation, percentage urban land use, nitrate concentration, and tritium levels in the Fresno and Modesto study areas, California, in 2002 and 2001, respectively.
p-values indicate the statistical significance of the difference in distribution between the study areas. n is the number of wells.
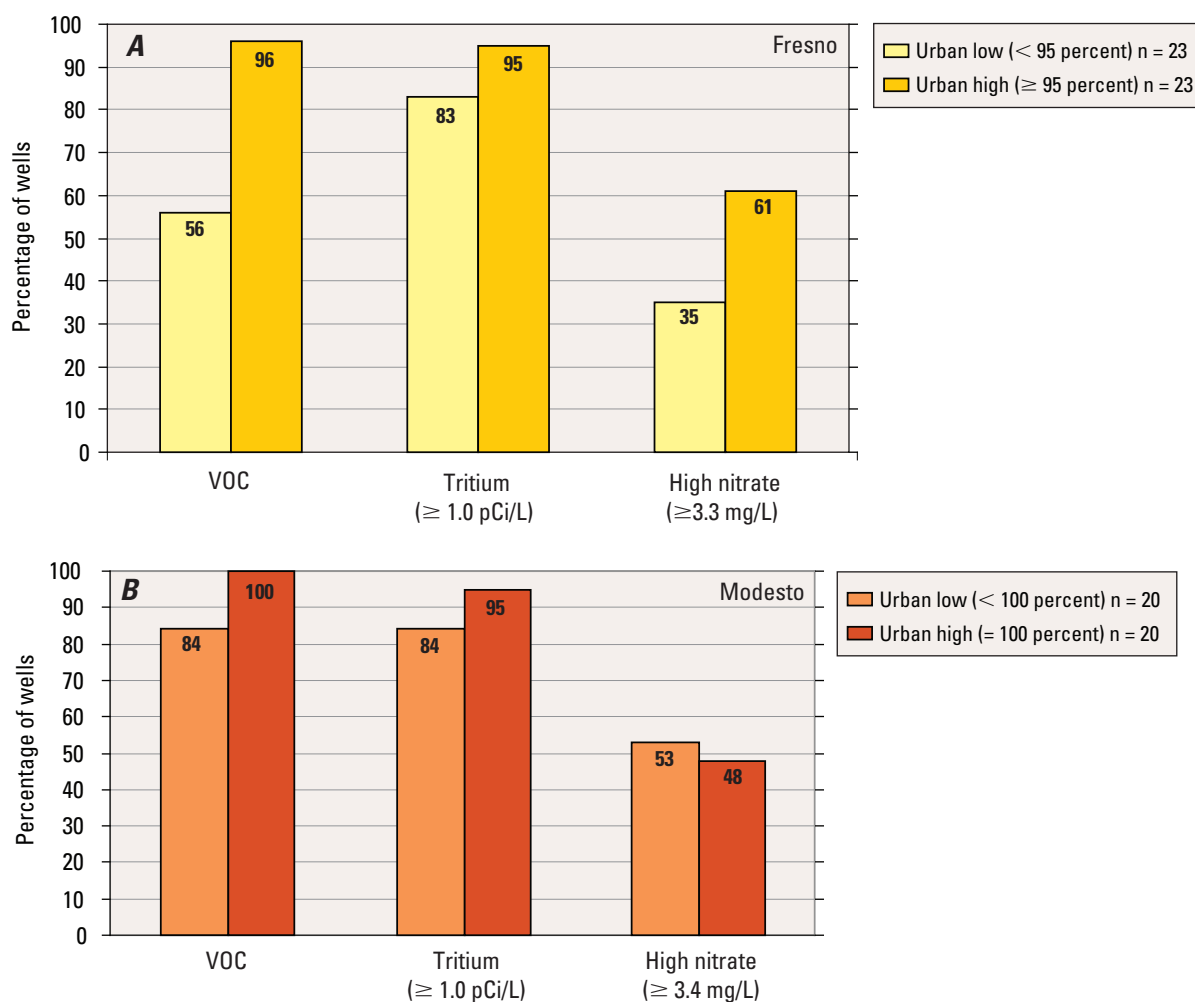
Figure 11. Detection frequencies of volatile organic compounds, tritium, and nitrate by urban land use category in wells sampled in (**A**) the Fresno, and (**B**) the Modesto study areas, California, in 2002 and 2001, respectively. n is the number of wells in each category; ft, foot; mg/L, milligram per liter; pCi/L, picocurie per liter; ≥, greater than or equal to.

Table 3. Median value for the number of volatile organic compound detections, tritium levels, and nitrate concentrations by degree of urbanization for samples collected in the Fresno and Modesto study areas, California, in 2002 and 2001, respectively.

[Degree of urbanization is demarcated by the median percentage of urbanized land occupying in a circular buffer zone around each well in each study area. VOC, volatile organic compound. Nitrate-N, nitrate nitrogen. pCi/L, picocurie per liter. mg/L, milligram per liter. <, less than; ≥, greater than or equal to]

	Fresno			Modesto		
	Urban low (< 95 percent)	Urban high (≥ 95 percent)	p-value	Urban low (< 100 percent)	Urban high (100 percent)	p-value
VOCs (detections)	1	2	[1]<0.01	4	5	[1]0.05
Tritium (pCi/L)	10.5	10.9	[2].30	17.6	9.6	[2].14
Nitrate-N (mg/L)	2.7	4.1	[1].04	3.5	3	[2].30

[1]Statistical test: Kendall's tau.
[2]Statistical test: Wilcoxon rank sum.

agricultural irrigation, and engineered recharge by spreading basins (Fresno study area only). Generally speaking, regional precipitation becomes isotopically lighter as it moves eastward from the low elevations of the San Joaquin Valley trough to the high elevations of the Sierra Nevada (Clark and Fritz, 1997). Ground water recharged by local precipitation, which falls at low elevations is more isotopically enriched (less negative) than ground water recharged by rivers, agricultural irrigation,

and engineered recharge operations because the source of water recharged by the latter is mostly from precipitation that has fallen in the higher elevations of the Sierra Nevada and is therefore isotopically depleted (more negative). *Figure 12* shows plots of the isotopic composition of ground-water samples collected from the Fresno and Modesto study areas. Samples are differentiated based on whether or not VOCs were detected.
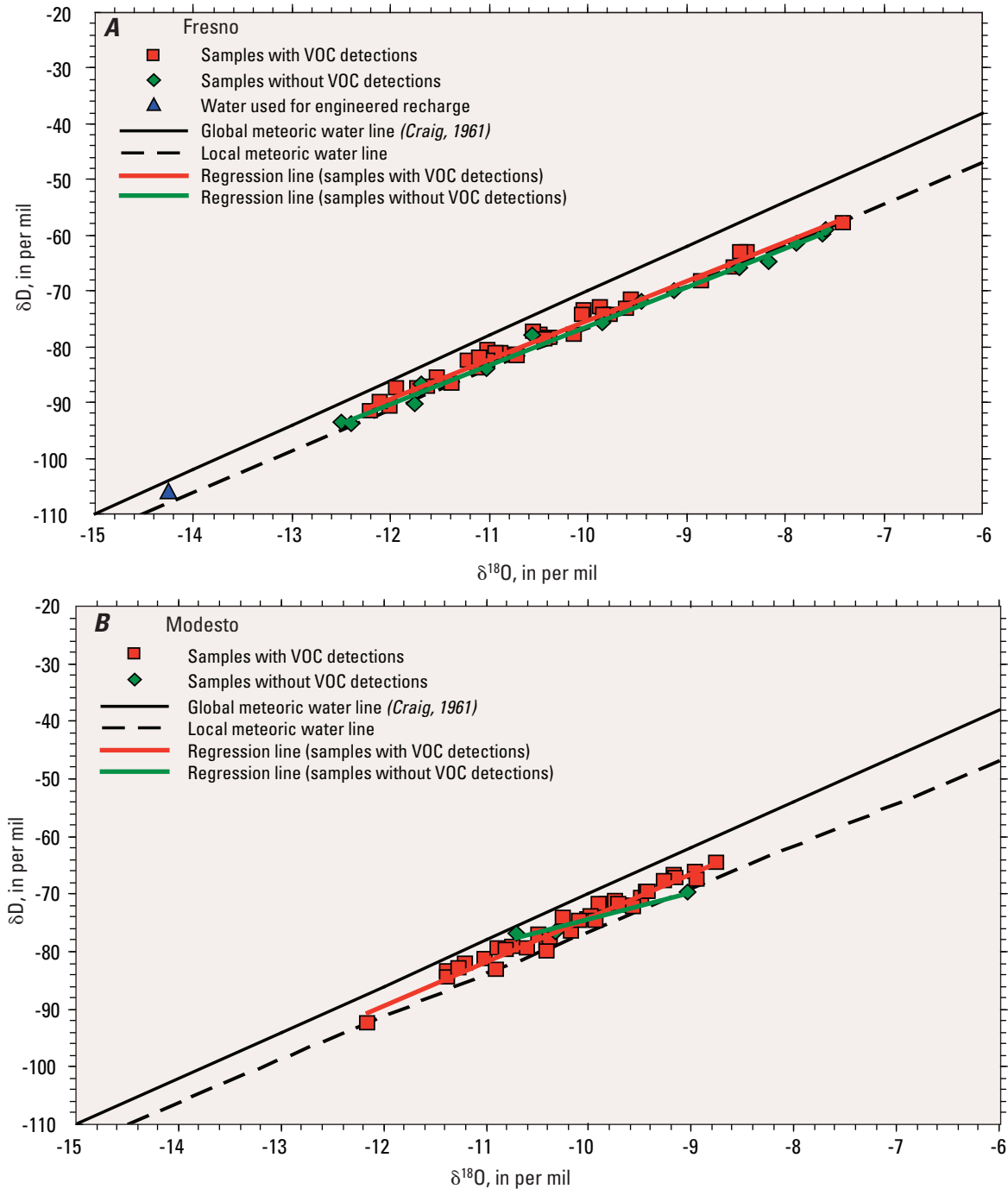
Figure 12.   Scatter plot of delta oxygen-18 ($\delta^{18}O$) versus delta deuterium (δD) for samples with and without volatile organic compounds (VOCs) collected in (**A**) the Fresno and (**B**) the Modesto study areas, California, in 2002 and 2001, respectively.

Stable isotopic composition of ground-water samples in Fresno plots over a wide range of values that are nearly parallel and close to the GMWL (*fig. 12A*), indicating a mixture of recharge from local precipitation and recharge from Sierra Nevada runoff. Samples that have no VOC detections plot within the same range of isotopic values as samples with VOC detections. In addition, the regression lines for samples with VOC detections and samples without VOC detections are nearly coincident with one another and with the local meteoric water line. This suggests that the source of ground-water recharge is not an important factor in predicting VOC occurrence and distribution in Fresno.

In Modesto, the isotopic composition of ground water also plots over a wide range of values that are parallel and close to the GMWL (*fig. 12B*), indicating a mixture of recharge water from local precipitation and Sierra Nevada runoff. Samples with detections of VOCs and samples without detections of VOCs plot over a similar range of values. The regression lines for these two sample types are almost coincident, indicating that the source of ground water is not an important factor in predicting the occurrence and distribution of VOCs in Modesto.

Summary and Conclusions

A total of 90 public supply wells were sampled in the Fresno and Modesto study areas; 50 wells were sampled in the Fresno study area, and 40 wells were sampled in the Modesto study area. Thirty-six of the 50 wells sampled in Fresno had at least one volatile organic compound (VOC) detection; one well contained trichloroethylene (TCE), the concentration of which was nearly 12 times the maximum contaminant level. Another well in Fresno contained the fumigant 1, 2-dibromo-3-chloropropane (DBCP) at 3 times the MCL. Thirty-seven of the 40 wells sampled in Modesto had at least one VOC detection; 2 of these wells had one detection each that just exceeded the MCL. The exceedances were concentrations of the solvents TCE and tetrachloroethylene (PCE).

Twenty-five of the 85 VOCs analyzed for in this study were detected in ground-water samples. Eight of these 25 were frequently detected (more than 20 percent) in the wells sampled. Trihalomethanes (THM), primarily chloroform, accounted for half of these frequently detected compounds; solvents, primarily PCE, accounted for the other half. In contrast to THMs and solvents, the gasoline components BTEX (benzene, toluene, ethyltoluene, xylenes) and MTBE (methyl *tert*-butyl ether) were rarely detected. Two wells in Modesto had detections of MTBE, and one well in Fresno had a detection of the BTEX compound toluene, suggesting that these are not contaminants of concern in these study areas.

The explanatory factors of relative ground-water age, depth to the top of the uppermost perforation, and land use are good predictors of aquifer susceptibility in both the Fresno and the Modesto study areas. VOCs were detected more frequently in wells withdrawing young ground water (water recharged after 1952) than in wells withdrawing old ground water (water recharged before 1952). Wells withdrawing young ground water also have a higher number of VOCs detections than wells withdrawing old ground water. The detection of VOCs in wells withdrawing old ground water implies that point sources of contamination and (or) preferential flow paths may be, or may have been, pathways of contamination in these study areas. These results indicate that wells withdrawing young ground water are more susceptible to contamination than wells withdrawing old ground water.

VOCs were detected more frequently in shallow than in deep wells in the Fresno and the Modesto study areas, indicating that the downward migration of contaminants is a viable pathway for aquifer contamination. These results suggest that depth to the top of the uppermost perforation is an important variable to consider when determining aquifer susceptibility. This is most likely especially true in unconfined and partly confined aquifer systems that are not only found in these study areas, but in many areas throughout California where ground water is an important source of public supply.

Land use showed the strongest correlation to VOC occurrence of all the explanatory variables analyzed in this study. Urban land use was the major type of land use in both the Fresno and the Modesto study areas. The history of production and use of a compound may be the ultimate predictor of whether or not it will be found in the environment. In urban areas, activities are diverse and require the use of many VOCs; these chemicals can be introduced into the subsurface environment through spills, storage tank leaks, and improper disposal. Therefore, it is reasonable to expect VOCs to be primarily associated with urban land use, just as it may be reasonable to expect pesticides to be primarily associated with agricultural land use.

Overall, nitrate concentration was only a marginally useful predictor of VOC occurrence in this study; VOCs were not significantly correlated to higher nitrate concentrations in either study area. The relation between VOCs and nitrate may be a reflection of the labile nature of nitrate under the anaerobic conditions that often occur in aquifer systems. Stable isotopic content of ground water and LUFT density were not useful in the prediction of aquifer susceptibility in the Fresno and the Modesto study areas. Stable isotopic content of samples did not provide insight into the susceptibility to contamination; samples with VOC detections spanned the range of isotopic values that composed the local meteoric water lines in Fresno and Modesto, and therefore did not implicate a specific source of water that may be more susceptible to contamination than other water sources. The density of LUFTs was not important simply because the compounds stored in these tanks were rarely detected in ground-water samples. Gasoline components accounted for less the 2 percent of the VOCs detected.

References Cited

Broholm, K., Feenstra, S., and Cherry, J.A., 1999, Solvent release into a sandy aquifer. 1. Overview of source distribution and dissolution behavior: Environmental Science and Technology. v. 33, no. 5, p. 681-690.

Burow, K.R., Panshin, S.Y., Dubrovsky, N.,M., VanBrocklin, D., and Fogg, G.E., 1999, Evaluation of processes affecting 1,2-dibromo-3-chloropropane (DBCP) concentrations in found water in the eastern San Joaquin Valley, California: Analysis of chemical data and ground-water flow and transport situations: Water Resources Investigation Report 99-4059, 57 p.

California Department of Water Resources, 2000a, Department of Water Resources, Division of Planning and Local Assistance, Land Use Data: accessed January 2003 at *http://www.waterplan.water.ca.gov/landwateruse/landuse/counties/pdf/94fr.htm.*

California Department of Water Resources, 2000b Department of Water Resources, Division of Planning and Local Assistance, Land Use Data: accessed January 2003 at *http://www.waterplan.water.ca.gov/landwateruse/landuse/counties/pdf/96ss.htm.*

California Department of Water Resources, 2003, California's Groundwater Bulletin 118, 246 p.

California Geological Survey, 1966, Geologic Map of California, San Jose sheet: California Department of Conservation, scale 1:250,000, 2 sheets.

California State Water Resources Control Board, 2001, Ambient groundwater monitoring and assessment program: accessed January 26, 2004, at *http://www.swrcb.ca.gov/gama/.*

California State Water Resources Control Board, 2004, Geotracker: accessed February 24, 2004, at *http://www.geotracker.swrcb.ca.gov/about.htm.*

Chapelle, F.H., McMahon, P.B., Dubrovsky, N.M., Fujii, R.F., Oaksford, E.T., and Vroblesky, D.A., 1995, Deducing the distribution of terminal electron-accepting processes in hydrologically diverse groundwater systems: Water Resources Research, v. 31, no. 2, p. 359-371.

Childress, C.J.O., Foreman, W.T., Connor, B.F., and Maloney, T.J., 1999, New reporting procedures based on long-term method detection levels and some considerations for interpretations of water-quality data provided by the U.S. Geological Survey National Water Quality Laboratory: Open-File Report, 99-0193, 19 p.

Chlorine Chemistry Council, 2004, accessed January 14, 2004, at *http://c3.org/chlorine_knowledge_center/wastewatercl.html.*

City of Fresno, 2003a, Population web page: accessed July 3 2003, available for download at *http://www.fresno.gov/econdev/demographics/population.htm.*

City of Fresno, 2003b, Water Info web page: accessed July 3, 2003, at *http://www.fresno.gov/public_utilities/water/water_info.asp.*

City of Fresno, 2003c, Water Production web page: accessed June 13, 2004, at *http://www.fresno.gov/public_utilities/water/water_production.asp.*

City of Modesto, 2004a, Community and Economic Development web page: accessed June 12, 2003, at *http://www.modestogov.com/ed/demographics/population.asp.*

City of Modesto, 2004b, Water Division Consumer Confidence Report 2004: accessed September 8, 2004, at *http://www.ci.modesto.ca.us/pwd/forms/pdf/CCR_04.pdf.*

Clark, I.D., and Fritz, P., 1997, Environmental isotopes in hydrology: Boca Raton, Fla., Lewis Publishers, 328 p.

Clawges, R.M., Stackelberg, P.E., Ayers, M.A., and Vowinkel, E.F., 1999, Nitrate, volatile organic compounds, and pesticides in ground water—A summary of selected studies from New Jersey and Long Island, New York: Water Resources Investigation Report 99-4027, 32 p.

Cole Parmer, Online catalog for Tygon tubing: accessed April 20, 2004, at *http://www.coleparmer.com/catalog/0102_pdf/U-2027.pdf.*

Connor, B.F., Rose, D.L., Noriega, M.C., Murtagh, L.K., and Abney, S.R., 1998, Methods of analysis by the U.S. Geological Survey National Water Quality Laboratory: Determination of 86 volatile organic compounds in water by gas chromatography/mass spectrometry, including detections less than reporting limits: U.S. Geological Survey Open-File Report 97-829, 78 p.

Coplen, T.B., Wildman, J.D., and Chen, J., 1991, Improvements in the gaseous hydrogen-water equilibrium technique for hydrogen isotope analysis: Analytical Chemistry, v. 63, p. 910-912.

Craig, H., 1961, Isotopic variations in meteoric waters: Science, v. 133, p. 1702-1703.

Davis, G.H., Green, J.H., Olmsted, F.H., and Brown, D.W., 1959, Ground-Water Conditions and Storage Capacity in the San Joaquin Valley, California: Water-Supply Paper 1469, 287 p.

Dawson, B.J., Belitz, K., Land, Michael, and Danskin, W.R., 2003, Stable isotopes and volatile organic compounds along seven ground-water flowpaths in divergent and convergent flow systems, Southern California, 2000: Water Resources Investigation Report 03-4059, 79 p.

Eckhardt, D.A.V., and Stackelberg, P.E., 1995, Relation of ground-water quality to land use on Long Island, New York: Ground Water, v. 33, no. 6, p. 1019-1033.

Gilliom, R.J., Alley, W.M., and Gurtz, M.E., 1995, Design of the National Water-Quality Assessment Program: Occurrence and distribution of water-quality conditions: U.S. Geological Survey Circular 1112, 33 p.

Grady, S.J., 2003, National survey of methyl *tert*-butyl ether and other volatile organic compounds in drinking-water sources: Results of the random survey: U.S. Geological Survey Water-Resources Investigations Report 02-4079, 85 p.

Grady, S.J., and Casey, G.D., 2001, Occurrence and distribution of methyl *tert*-butyl ether and other volatile organic compounds in drinking water in the Northeast and Mid-Atlantic regions of the United States, 1993-98: U.S. Geological Survey Water-Resources Investigations Report 00–4228, 123 p.

Hamlin, S.N., Belitz, K., Kraja, S., and Dawson, B., 2002, Ground-water quality in the Santa Ana watershed, California: Overview and data summary: U.S. Geological Survey Water-Resources Investigations Report 02–4243, 137 p.

Helsel, D.R., and Hirsch, R.M., 1992, Statistical Methods in Water Resources: Amsterdam, The Netherlands, Elsevier Science Publishers, 522 p.

Hudson, G.B., Moran, J.E., and Eaton, G.F., 2002, Interpretation of titium-^{3}helium groundwater ages and associated dissolved noble gas results from public water supply wells in the Los Angeles physiographic basin: Lawrence Livermore National Laboratory, Report UCRL-AR-151447, 25 p.

IARC, International Agency for Research on Cancer, 1979, IARC monographs on the evaluation of the carcinogenic risk of chemicals to humans: Some halogenated hydrocarbons, Lyon, France, v. 20, 609 p.

Johnson, R., Pankow, J.F., Bender, D.A. Price, C.V., and Zogorski, J.S., 2000, MTBE—To what extent will past releases contaminate community water supply wells?: Environmental Science and Technology, v. 34, no. 9, p. 210A-217A.

Korom, S.F., 1992, Natural denitrification in the saturated zone: A review water resources research: v. 28, no. 6, p. 1657-1668.

Koterba, M.T., 1998, Ground-water data-collection protocols and procedures for the National Water-Quality Assessment Program: Collection, documentation, and compilation of required site, well, subsurface, and landscape data for wells: U.S. Geological Survey Water-Resources Investigations Report 98–4107, 91 p.

Koterba, M.T., Wilde, F.D., and Lapham, W.W., 1995, Ground-water data-collection protocols and procedures for the National Water-Quality Assessment Program: Collection and documentation of water-quality samples and related data: U.S. Geological Survey Open-File Report 95–399, 113 p.

Michel, R., 1989, Tritium deposition in the continental United States, 1953-83: U.S. Geological Survey Water-Resources Investigations Report 89–4072, 46 p.

Michel, R., and Schroeder, R., 1994, Use of long-term tritium records from the Colorado River to determine timescales for hydrologic processes associated with irrigation in the Imperial Valley, California: Applied Geochemistry v. 9, p. 387-401.

Moran, M.J., Lapham, W.W., Rowe, B.L., and Zogorski, J.S., 2002, Occurrence and status of volatile organic compounds in ground water from rural, untreated, self-supplied domestic wells in the United States, 1986-99: U.S. Geological Survey Water-Resources Investigations Report 02–4085, 51 p.

Moran, M.J., Zogorski, J.S., and Squillace, P.J., 1999, MTBE in ground water of the United States—Occurrence, potential sources, and long range transport, *in* Water resources management: Source of supply challenges: Proceedings, September 26-29, 1999, Norfolk, Virginia: Denver, Colo., American Water Works Association, CD–ROM.

Moran, M.J., Zogorski, J.S., and Squillace, P.J., 2003, Occurrence and implications of methyl tert-butyl ether and gasoline hydrocarbons in ground water and source water in the United States and in drinking water in 12 Northeast and Mid-Atlantic states, 1993-2002: U.S. Geological Survey Water-Resources Investigations Report 03–4200, 26 p.

Muir, K.S., 1977, Ground water in the Fresno area, California: U.S. Geological Survey Water-Resources Investigations Report 77–59, 22 p.

Page, R.W., 1986, Geology of the fresh ground-water basin of the Central Valley, California, with texture maps and sections: U.S. Geological Survey Professional Paper 1401-C, 54 p., 5 pls. in pocket.

Page, R.W., and Balding, G.O., 1973, Geology and quality of water in the Modesto–Merced area, San Joaquin Valley, California, with a brief section on hydrology: U.S. Geological Survey Water-Resources Investigations Report 73–6, 98 p.

Page, R.W., and LeBlanc, R.A., 1969, Geology, hydrology, and water quality in the Fresno area, California: U.S. Geological Survey Open-File Report, 70 p.

Schwarzenbach, R.P., Gschwend, P.M., and Imboden, D., 1993, Environmental Organic Chemistry: New York, John Wiley and Sons, Inc., 681 p.

Scott, J.C., 1990, Computerized stratified random site selection approaches for design of a ground-water quality sampling network: U.S. Geological Survey Water-Resources Investigations Report 90–4101, 109 p.

Shelton, J.L., Burow, K.R., Belitz, Kenneth, Dubrovsky, N.M., Land, Michael, and Gronberg, J.M., 2001, Low-level volatile organic compounds in active public supply wells as ground-water tracers in the Los Angeles physiographic basin, California, 2000: U.S. Geological Survey Water-Resources Investigations Report 01–4188, 29 p.

Solley, W.B., Pierce, R.R., Perlman, H.A., 1998, Estimated use of water in the United States in 1995: U.S. Geological Survey Circular 1200, 71 p.

Squillace, P.J., Moran, M.J., Price, C.V., Clawges, R.M, and Zogorski, J.S., 1999, Volatile organic compounds in untreated ambient groundwater of the United States, 1985-1995: Environmental Science and Technology, v. 33, no. 23, p. 4176-4187.

Squillace, P.J., Scott, J.C., Moran, M.J., Nolan, B.T., and Kolpin, D.W., 2002, VOCs, pesticides, nitrate, and their mixtures in groundwater used for drinking water in the United States: Environmental Science and Technology, v. 36, no. 9, p. 1923-1930.

Stackleberg, P.E., Kauffman, L.J., Baehr, A.L., and Ayers, M.A., 2000, Comparison of nitrate, pesticides, and volatile organic compounds in samples from monitoring and public-supply wells, Kirkwood-Cohansey aquifer system, southern New Jersey: U.S. Geological Survey Water-Resources Investigations Report 00–4123, 78 p.

Tesoriero, A.J., and Voss, F.D., 1997, Predicting the probability of elevated nitrate concentrations in the Puget Sound Basin; implications for aquifer susceptibility and vulnerability: Ground Water, v. 35, no. 6, p. 1029-1039.

Thatcher, L.L., 1962, The distribution of tritium fallout in precipitation over North America: Louvain, Belgium, International Association, Hydrological Sciences, Publication no. 7, p. 48-58.

Thiros, S.A., 2000, Quality of shallow ground water in areas of recent residential and commercial development in Salt Lake Valley, Utah, 1999: U.S. Geological Survey Fact Sheet 106–00, 6 p.

U.S. Environmental Protection Agency, 2002, List of drinking water contaminants & MCLs: accessed February 2004 at *http://www.epa.gov/safewater/mcl.html*.

U.S. Geological Survey, 1998, National Field Manual for the collection of water quality data: U.S. Geological Survey Techniques of Water Resources Investigations, book 9, variously paged.

U.S. Geological Survey, 1999, National Field Manual for the collection of water quality data: U.S. Geological Survey Techniques of Water Resources Investigations, book 9, variously paged.

Venables, W.N., and Ripley, B.D., 1999, Modern applied statistic with S-Plus (3d ed.): New York, Springer-Verlag, 501 p.

Westrick, J.J, Mello, J.W., and Thomas, R.F., 1984, The groundwater supply survey: Journal of the American Water Works Association, p. 52-59.

White, G.C., 1972, Handbook of chlorination: New York, Van Nostrand Reinhold Company, 744 p.

Appendixes

Appendix 1. Identification and construction information for sampled wells in the Fresno and Modesto study areas, California, in 2002 and 2001, respectively.

[CAS, California Aquifer Susceptibility program; LSD, land surface datum; FRCAS, Fresno study area; MODCAS, Modesto study area. ft, foot; --, no data]

CAS identification No.	Well depth (ft below LSD)	Top perforation (ft below LSD)	Bottom perforation, (ft below LSD)	CAS identification No.	Well depth (ft below LSD)	Top perforation (ft below LSD)	Bottom perforation, (ft below LSD)
FRCAS-01	450	180	450	FRCAS-46	340	195	202
FRCAS-02	510	235	500	FRCAS-47	302	140	300
FRCAS-03	760	200	400	FRCAS-48	630	190	620
FRCAS-04	447	225	447	FRCAS-49	420	140	420
FRCAS-05	430	190	430	FRCAS-50	371	187	246
FRCAS-06	770	180	760	MODCAS-01	92	92	118
FRCAS-07	420	150	420	MODCAS-02	136	92	138
FRCAS-08	332	192	248	MODCAS-03	231	137	225
FRCAS-09	156	220	257	MODCAS-04	109	109	--
FRCAS-10	610	250	600	MODCAS-05	152	104	148
FRCAS-11	312	176	--	MODCAS-06	296	200	292
FRCAS-12	681	213	670	MODCAS-07	133	133	--
FRCAS-13	480	180	470	MODCAS-08	104	104	332
FRCAS-14	270	152	268	MODCAS-09	100	100	--
FRCAS-15	332	116	220	MODCAS-10	234	175	234
FRCAS-16	500	175	500	MODCAS-11	244	104	232
FRCAS-17	397	294	387	MODCAS-12	294	144	294
FRCAS-18	410	160	400	MODCAS-13	242	104	194
FRCAS-19	580	350	570	MODCAS-14	277	106	277
FRCAS-20	660	400	640	MODCAS-15	391	91	366
FRCAS-21	550	445	540	MODCAS-16	295	200	292
FRCAS-22	420	150	240	MODCAS-17	255	92	216
FRCAS-23	409	168	409	MODCAS-18	260	160	210
FRCAS-24	402	172	402	MODCAS-19	263	180	--
FRCAS-25	355	135	345	MODCAS-20	189	121	149
FRCAS-26	440	200	440	MODCAS-21	312	74	274
FRCAS-27	390	180	390	MODCAS-22	204	116	120
FRCAS-28	203	160	168	MODCAS-23	100	100	112
FRCAS-29	262	226	231.5	MODCAS-24	172	132	164
FRCAS-30	650	320	640	MODCAS-25	138	197	226
FRCAS-31	440	270	440	MODCAS-26	128	128	--
FRCAS-32	213.5	208	213.5	MODCAS-27	123	94	123
FRCAS-33	540	150	510	MODCAS-28	302	96	278
FRCAS-34	430	210	430	MODCAS-29	415	110	410
FRCAS-35	294	154	294	MODCAS-30	280	164	276
FRCAS-36	280	146	259	MODCAS-31	322	130	320
FRCAS-37	396	200	301	MODCAS-32	305	145	305
FRCAS-38	520	190	510	MODCAS-33	268	228	268
FRCAS-39	450	150	450	MODCAS-34	256	248	256
FRCAS-40	640	150	630	MODCAS-35	275	139	271
FRCAS-41	500	265	500	MODCAS-36	221	105	213
FRCAS-42	270	200	260	MODCAS-37	255	180	255
FRCAS-43	--	158	266	MODCAS-38	233	97	229
FRCAS-44	510	280	500	MODCAS-39	245	129	241
FRCAS-45	735	400	725	MODCAS-40	265	180	260

Appendix 2. Summary of volatile organic compounds detected in quality-control blanks and associated environmental samples for the Fresno and Modesto study areas, California, in 2002 and 2001, respectively.

[VOC, volatile organic compound; FRCAS, Fresno study area; MODCAS, Modesto study area; µg/L, microgram per liter; na, not applicable]

Study/VOC	Quality-control blanks			Maximum concentration (µg/L detected in blank samples)	Minimum concentration (µg/L detected in environmental samples)	Number of potentially affected environmental samples	Number of environmental samples flagged
	Number of equipment blank detections/ analyses	Number of trip blank detections/ analyses	Number of field blank detections/ analyses				
FRCAS							
No detections	na	na	0/5	na	na	na	na
MODCAS							
Methylbenzene (toluene)	1/1	1/1	1/4	0.03	0.01	2	2
Tetrachloroethene (PCE)	0/1	0/1	2/4	.02	.01	6	6
Dichloromethane, µg/L (Methylene chloride)	0/1	0/1	1/[1]4	.02	.05	3	0

[1]VOC also detected in associated source solution blank.

Appendix 3a. Isotopic content of environmental samples collected in the Fresno and Modesto study areas, California, in 2002 and 2001, respectively.

[Number in parentheses is the data parameter code, a five-digit code used in the U.S. Geological Survey's computerized data system, National Water Information System, to uniquely identify a specific constituent or property. Tritium levels were determined by Lawrence Livermore National Laboratory. CAS, California Aquifer Susceptibility program; FRCAS, Fresno study area; MODCAS, Modesto study area. per mil, parts per thousand; pCi/L, picocurie per liter; <1.0, below method detection limits (MDL) (0.5 pCi/L was used to compute statistical analysis of tritium data that was below MDL). --, no data]

CAS identification No.	Deuterium/ protium, ratio per mil (82082)	Oxygen-18/ oxygen-16, ratio per mil (82085)	Tritium level (pCi/L)	CAS identification No.	Deuterium/ protium, ratio per mil (82082)	Oxygen-18/ oxygen-16, ratio per mil (82085)	Tritium level (pCi/L)
FRCAS-01	-61.5	-7.88	5.14	FRCAS-46	-82	-11.1	9.64
FRCAS-02	-74.3	-9.77	4.09	FRCAS-47	-63	-8.38	22.81
FRCAS-03	-81.1	-10.88	6.83	FRCAS-48	-68.4	-8.85	6.82
FRCAS-04	-85.5	-11.53	22.00	FRCAS-49	-63.2	-8.45	18.25
FRCAS-05	-87.4	-11.72	8.35	FRCAS-50	-84	-11.03	9.87
FRCAS-06	-90.1	-12.11	<1.0	MODCAS-01	-73.9	-9.98	2.22
FRCAS-07	-81.7	-10.71	16.53	MODCAS-02	-81.3	-11.01	9.54
FRCAS-08	-58.9	-7.59	16.90	MODCAS-03	-82.8	-11.26	22.52
FRCAS-09	-65.7	-8.52	11.09	MODCAS-04	-79.4	-10.88	17.48
FRCAS-10	-74.2	-9.83	2.69	MODCAS-05	-74.8	-9.93	9.68
FRCAS-11	-84	-11.11	10.90	MODCAS-06	-72.3	-9.56	18.71
FRCAS-12	-71.5	-9.56	14.63	MODCAS-07	-71.9	-9.7	5.27
FRCAS-13	-73	-9.87	16.19	MODCAS-08	-77.7	-10.37	31.69
FRCAS-14	-80.7	-11.02	18.01	MODCAS-09	-92.6	-12.15	9.18
FRCAS-15	-77.8	-10.48	21.89	MODCAS-10	-76.5	-10.16	12.96
FRCAS-16	-58	-7.41	10.49	MODCAS-11	-72	-9.61	14.03
FRCAS-17	-86.8	-11.69	19.59	MODCAS-12	-66.8	-9.17	16.36
FRCAS-18	-78.4	-10.38	2.12	MODCAS-13	-69.7	-9.44	3.58
FRCAS-19	-71.8	-9.46	<1.0	MODCAS-14	-66.3	-8.96	7.34
FRCAS-20	-59.8	-7.62	3.76	MODCAS-15	-67.4	-8.94	3.33
FRCAS-21	-74.2	-10.06	<1.0	MODCAS-16	-71.7	-9.82	17.63
FRCAS-22	-77.9	-10.13	4.10	MODCAS-17	-74.5	-10.01	16.32
FRCAS-23	-93.6	-12.5	1.78	MODCAS-18	-67.8	-9.26	1.79
FRCAS-24	-93.9	-12.4	12.13	MODCAS-19	-67.3	-9.15	5.34
FRCAS-25	-82.5	-11.21	19.10	MODCAS-20	-80.1	-10.4	17.77
FRCAS-26	-81.4	-10.77	<1.0	MODCAS-21	-64.5	-8.75	10.92
FRCAS-27	-77.3	-10.55	6.06	MODCAS-22	-71.7	-9.76	<1.0
FRCAS-28	-82.1	-11.1	2.36	MODCAS-23	-71.3	-9.73	<1.0
FRCAS-29	-77.9	-10.56	4.64	MODCAS-24	-79.8	-10.8	31.70
FRCAS-30	-81.1	-10.93	<1.0	MODCAS-25	-83.1	-10.89	1.53
FRCAS-31	-75.8	-9.85	2.40	MODCAS-26	-84.6	-11.38	21.21
FRCAS-32	-65.9	-8.47	28.32	MODCAS-27	-83.5	-11.38	39.44
FRCAS-33	-91.5	-12.21	24.55	MODCAS-28	-70.7	-9.48	26.25
FRCAS-34	-78.6	-10.44	11.31	MODCAS-29	-76.9	-10.7	1.00
FRCAS-35	-74.3	-9.84	18.20	MODCAS-30	-82	-11.2	<1.0
FRCAS-36	-64.6	-8.17	16.53	MODCAS-31	-79.1	-10.74	5.29
FRCAS-37	-90.9	-12.01	--	MODCAS-32	-78.3	-10.41	20.74
FRCAS-38	-73.4	-10.03	13.11	MODCAS-33	-77	-10.49	45.40
FRCAS-39	-87.1	-11.63	45.73	MODCAS-34	-71.8	-9.89	70.97
FRCAS-40	-86.6	-11.37	9.28	MODCAS-35	-74.2	-10.24	5.92
FRCAS-41	-69.9	-9.13	19.83	MODCAS-36	-79.5	-10.6	71.71
FRCAS-42	-82.5	-11.02	15.75	MODCAS-37	-69.6	-9.42	9.59
FRCAS-43	-73.3	-9.61	15.92	MODCAS-38	-74.7	-10.09	68.14
FRCAS-44	-90.3	-11.75	15.90	MODCAS-39	-69.6	-9.04	37.87
FRCAS-45	-87.6	-11.94	1.08	MODCAS-40	-76.6	-10.32	<1.0

Appendix 3b. Nitrate concentrations obtained from the California Department of Health Services database for wells sampled.

[Nitrate concentration is the median value of all analyses completed in the 12-month period before sampling. CAS, California Aquifer Susceptibility program; Nitrate-N, nitrate nitrogen; FRCAS, Fresno study area; MODCAS, Modesto study area. mg/L, milligram per liter]

CAS identification No.	Nitrate-N, mg/L	CAS identification No.	Nitrate-N, mg/L
FRCAS-01	4.07	FRCAS-46	5.65
FRCAS-02	2.71	FRCAS-47	3.84
FRCAS-03	2.03	FRCAS-48	3.84
FRCAS-04	2.26	FRCAS-49	3.16
FRCAS-05	1.81	FRCAS-50	3.16
FRCAS-06	1.81	MODCAS-01	1.75
FRCAS-07	1.58	MODCAS-02	6.38
FRCAS-08	3.16	MODCAS-03	4.15
FRCAS-09	4.07	MODCAS-04	2.75
FRCAS-10	4.75	MODCAS-05	3.53
FRCAS-11	1.58	MODCAS-06	3.45
FRCAS-12	1.81	MODCAS-07	.74
FRCAS-13	.68	MODCAS-08	2.01
FRCAS-14	3.84	MODCAS-09	1.84
FRCAS-15	9.94	MODCAS-10	3.73
FRCAS-16	2.94	MODCAS-11	3.62
FRCAS-17	5.88	MODCAS-12	9.29
FRCAS-18	8.36	MODCAS-13	2.99
FRCAS-19	2.71	MODCAS-14	.88
FRCAS-20	2.94	MODCAS-15	8.28
FRCAS-21	.90	MODCAS-16	4.14
FRCAS-22	5.42	MODCAS-17	2.15
FRCAS-23	4.97	MODCAS-18	1.00
FRCAS-24	4.97	MODCAS-19	6.63
FRCAS-25	6.55	MODCAS-20	.23
FRCAS-26	3.39	MODCAS-21	4.03
FRCAS-27	3.39	MODCAS-22	5.02
FRCAS-28	4.52	MODCAS-23	9.51
FRCAS-29	5.42	MODCAS-24	4.75
FRCAS-30	4.52	MODCAS-25	.23
FRCAS-31	7.46	MODCAS-26	4.00
FRCAS-32	2.94	MODCAS-27	5.74
FRCAS-33	4.52	MODCAS-28	6.00
FRCAS-34	2.03	MODCAS-29	1.84
FRCAS-35	1.13	MODCAS-30	2.77
FRCAS-36	6.33	MODCAS-31	2.53
FRCAS-37	5.42	MODCAS-32	1.31
FRCAS-38	.68	MODCAS-33	3.61
FRCAS-39	4.52	MODCAS-34	1.95
FRCAS-40	2.26	MODCAS-35	3.47
FRCAS-41	3.16	MODCAS-36	4.72
FRCAS-42	.90	MODCAS-37	1.95
FRCAS-43	6.33	MODCAS-38	4.04
FRCAS-44	2.03	MODCAS-39	1.08
FRCAS-45	4.07	MODCAS-40	5.40

Appendix 4a. Wells with volatile organic compound detections in the Fresno study area, California, 2002.

[CAS, California Aquifer Susceptibility program. ymd, year, month, day. Percentage values are detection frequencies. Number in parentheses is the data parameter code, a five-digit code used in the U.S. Geological Survey computerized data system, National Water Information System, to uniquely identify a specific constituent or property. LRL, laboratory reporting limit; FRCAS, Fresno study area. µg/L, microgram per liter; VOC, volatile organic compound; E, estimated value; --, not detected]

| CAS identification No. | Date (ymd) | Time | Disinfection byproduct (56 percent) | | | | | | | Solvent (58 percent) | | | | | |
			Trichloromethane (Chloroform), µg/L (32106)	Bromodichloromethane, µg/L (32101)	Bromoform (Tribromomethane), µg/L (32104)	Tetrachloroethylene (PCE), µg/L (34475)	1,2-Dichloropropane, µg/L (34541)	Trichloroethylene (TCE), µg/L (39180)	cis-1,2-Dichloroethylene, µg/L (77093)	Tetrachloromethane (Carbon tetrachloride), µg/L (32102)	1,1-Dichloroethane, µg/L (34496)	1,2-Dibromoethane, µg/L (77651)	1,2-Dichlorobenzene, µg/L (34536)	1,2,3-Trichloropropane, µg/L (77443)	1,2-Dichloroethane, µg/L (32103)
LRL			<0.024	<0.048	<0.06	<0.027	<0.029	<0.038	<0.038	<0.06	<0.035	<0.036	<0.031	<0.16	<0.13
FRCAS-01	20020715	0800	E0.01	--	--	E0.01	E0.04	--	--	--	--	--	--	--	--
FRCAS-02	20020715	0930	--	--	--	--	E.01	--	--	--	--	--	--	--	--
FRCAS-03	20020715	1100	--	--	--	--	E.02	--	--	--	--	--	--	--	--
FRCAS-04	20020715	1140	E.01	--	--	--	E.01	--	--	--	--	--	--	--	--
FRCAS-05	20020715	1240	E.02	--	--	--	--	--	--	--	--	--	--	--	--
FRCAS-06	20020715	1340	--	--	--	--	E.02	--	--	--	--	--	--	--	--
FRCAS-07	20020715	1440	E.03	--	--	--	E.01	--	--	--	--	--	--	--	--
FRCAS-08	20020716	0820	E.09	E0.01	--	E.05	E.02	E0.06	--	--	--	--	E0.01	--	--
FRCAS-09	20020716	0940	E.03	--	--	E.02	E.02	--	--	--	--	--	--	--	--
FRCAS-10	20020716	1040	E.07	--	--	.20	E.02	.18	1.11	--	--	--	--	--	--
FRCAS-11	20020716	1140	E.02	--	--	E.03	--	--	--	--	--	--	--	--	--
FRCAS-12	20020716	1300	--	--	--	--	E.02	--	--	--	--	--	--	--	--
FRCAS-14	20020716	1530	.16	--	--	1.42	--	59.55	E.09	--	--	--	--	--	--
FRCAS-15	20020717	0830	E.02	--	--	--	--	--	--	--	--	--	--	--	--
FRCAS-16	20020717	0950	--	--	--	E.01	E.04	--	--	--	--	--	--	--	--
FRCAS-18	20020717	1140	--	--	--	--	--	--	--	--	--	--	--	--	--
FRCAS-23	20020718	1030	E.02	E.04	--	E.02	E.02	E.09	.11	--	--	--	--	--	--
FRCAS-25	20020718	1130	.21	--	E0.07	.38	--	E.05	--	--	E0.04	E0.05	--	--	--
FRCAS-26	20020718	1250	E.02	--	--	.79	--	--	--	E0.05	--	--	--	--	0.14
FRCAS-27	20020718	1340	E.03	--	--	E.05	--	--	--	E.07	--	--	--	--	--
FRCAS-28	20020718	1500	E.07	--	--	E.03	--	--	--	--	--	--	--	--	--
FRCAS-29	20020719	0810	E.04	--	--	E.02	--	--	--	--	--	--	--	--	--
FRCAS-31	20020719	1020	--	--	--	--	--	--	--	--	--	--	--	--	--
FRCAS-32	20020729	0820	E.09	--	--	.42	--	--	--	--	--	--	--	--	--
FRCAS-33	20020729	1120	E.01	--	--	--	--	--	--	--	--	--	--	--	--
FRCAS-34	20020729	1250	E.10	--	--	--	--	--	--	--	--	--	--	--	--
FRCAS-35	20020729	1410	E.08	--	--	E.04	--	E.04	--	--	--	--	--	--	--
FRCAS-36	20020730	0800	E.06	--	--	.11	.16	E.03	--	--	E.03	--	--	0.35	--
FRCAS-37	20020730	0850	E.04	--	--	.20	--	--	--	--	--	--	--	--	--
FRCAS-40	20020730	1240	--	--	--	.10	--	--	--	--	--	--	--	--	--
FRCAS-42	20020730	1450	E.03	--	--	--	--	--	--	--	--	--	--	--	--
FRCAS-43	20020731	0810	E.05	--	--	--	--	--	--	--	--	--	--	--	--
FRCAS-46	20020731	1210	E.04	--	--	E.06	--	--	--	--	--	--	--	--	--
FRCAS-47	20020731	1340	E.03	--	--	--	--	--	--	--	--	--	--	--	--
FRCAS-49	20020801	0810	E.05	--	--	E.02	--	--	--	--	--	--	--	--	--
FRCAS-50	20020801	0920	E.02	--	--	E.03	E.03	--	--	--	--	--	--	--	--
Wells with VOC detections			28	2	1	21	14	7	3	2	2	1	1	1	1
Detection frequency (percentage)			56	4	2	42	28	14	6	4	4	2	2	2	2

Appendix 4a. Wells with volatile organic compound detections in the Fresno study area, California, 2002. —Continued

[CAS, California Aquifer Susceptibility program. ymd, year, month, day. Percentage values are detection frequencies. Number in parentheses is the data parameter code, a five-digit code used in the U.S. Geological Survey computerized data system, National Water Information System, to uniquely identify a specific constituent or property. LRL, laboratory reporting limit; FRCAS, Fresno study area. µg/L, microgram per liter; VOC, volatile organic compound; E, estimated value; --, not detected]

CAS identification No.	Date (ymd)	Time	Dichloro-difluoromethane (CFC-12), µg/L (34668)	Refrigerant (10 percent) 1,1,2-Trichloro-trifluoroethane (CFC-113), µg/L (77652)	Trichloro-fluoromethane (CFC-11), µg/L (34488)	Organic synthesis (2 percent) 1,1-Dichloroethylene (DCE), µg/L (34501)	Fumigant (2 percent) 1,2-Dibromo-3-chloropropane (DBCP), µg/L (82625)	Gasoline (2 percent) Methylbenzene (Toluene), µg/L (34010)	Number of VOCs detected
LRL			**<0.18**	**<0.06**	**<0.09**	**<0.04**	**<0.5**	**<0.05**	
FRCAS-01	20020715	0800	E0.08	--	--	--	--	--	4
FRCAS-02	20020715	0930	--	--	--	--	--	--	1
FRCAS-03	20020715	1100	--	--	--	--	--	--	1
FRCAS-04	20020715	1140	--	--	--	--	--	--	2
FRCAS-05	20020715	1240	--	--	--	--	--	--	1
FRCAS-06	20020715	1340	--	--	--	--	--	--	1
FRCAS-07	20020715	1440	--	--	--	--	--	--	2
FRCAS-08	20020716	0820	--	--	--	--	--	--	6
FRCAS-09	20020716	0940	--	--	--	--	--	--	3
FRCAS-10	20020716	1040	E17.97	--	--	--	--	--	6
FRCAS-11	20020716	1140	--	--	--	--	--	--	2
FRCAS-12	20020716	1300	--	--	--	--	--	--	1
FRCAS-14	20020716	1530	E.16	--	--	--	--	--	5
FRCAS-15	20020717	0830	--	--	--	--	--	--	1
FRCAS-16	20020717	0950	--	--	--	--	--	--	2
FRCAS-18	20020717	1140	--	--	--	--	0.65	--	1
FRCAS-23	20020718	1030	--	--	--	E0.04	--	--	4
FRCAS-25	20020718	1130	--	--	--	--	--	--	9
FRCAS-26	20020718	1250	--	--	--	--	--	--	2
FRCAS-27	20020718	1340	--	--	--	--	--	--	3
FRCAS-28	20020718	1500	--	--	--	--	--	--	3
FRCAS-29	20020719	0810	--	--	--	--	--	--	2
FRCAS-31	20020719	1020	--	--	--	--	--	--	1
FRCAS-32	20020729	0820	--	--	--	--	--	--	2
FRCAS-33	20020729	1120	--	--	--	--	--	--	1
FRCAS-34	20020729	1250	--	--	--	--	--	--	1
FRCAS-35	20020729	1410	--	--	--	--	--	--	2
FRCAS-36	20020730	0800	--	E0.07	--	--	--	--	5
FRCAS-37	20020730	0850	--	--	--	--	--	--	4
FRCAS-40	20020730	1240	--	--	--	--	--	--	1
FRCAS-42	20020730	1450	--	--	--	--	--	--	2
FRCAS-43	20020731	0810	--	--	--	--	--	--	1
FRCAS-46	20020731	1210	--	--	E0.08	--	--	E0.01	4
FRCAS-47	20020731	1340	--	--	--	--	--	--	1
FRCAS-49	20020801	0810	--	--	--	--	--	--	2
FRCAS-50	20020801	0920	--	--	--	--	--	--	3
Wells with VOC detections			3	1	1	1	1	1	
Detection frequency (percentage)			6	2	2	2	2	2	

Appendix 4b. Wells with volatile organic compound detections in the Modesto study area, California, 2001.

[CAS, California Aquifer Susceptibility program. ymd, year, month, day. Percentage values are detection frequencies. Number in parentheses is the data parameter code, a five-digit code used in the U.S. Geological Survey computerized data system, National Water Information System, to uniquely identify a specific constituent or property. LRL, laboratory reporting limit; MODCAS, Modesto study area. μg/L, microgram per liter; VOC, volatile organic compound; E, estimated value; --, not detected]

CAS identification No.	Date (ymd)	Time	Disinfection byproduct (92 percent)				Solvent (70 percent)							
			Chloroform (Trichloromethane), μg/L (32106)	Bromodichloromethane, μg/L (32101)	Bromoform (Tribromomethane), μg/L (32104)	Dibromochloromethane, μg/L (32105)	Tetrachloroethylene (PCE), μg/L (34475)	Trichloroethylene (TCE), μg/L (39180)	Dibromomethane, μg/L (30217)	Tetrachloromethane (Carbon tetrachloride), μg/L (32102)	1,2-Dichloropropane, μg/L (34541)	cis-1,2-Dichloroethylene, μg/L (77093)	1,1-Dichloroethane, μg/L (34496)	1,1,1-Trichloroethane (TCA), μg/L (34506)
LRL			<0.024	<0.048	<0.06	<0.18	<0.1	<0.038	<0.05	<0.06	<0.029	<0.038	<0.035	<0.032
MODCAS-01	20010327	0830	E0.09	--	--	--	--	--	--	0.12	--	--	--	--
MODCAS-02	20010327	1030	1.20	E0.08	--	--	0.81	E0.01	--	.32	--	--	--	--
MODCAS-03	20010327	1230	.59	E.06	--	--	E.04	E.03	--	--	--	--	--	--
MODCAS-04	20010327	1330	E.03	--	--	--	.22	E.01	--	--	E0.04	--	--	--
MODCAS-05	20010328	0800	.21	E.02	E0.09	--	E.04	--	--	E.02	--	--	--	--
MODCAS-06	20010328	0940	--	--	E.07	--	--	--	--	--	--	--	--	--
MODCAS-07	20010328	1050	E.02	E.02	--	--	--	--	--	--	--	--	--	--
MODCAS-08	20010328	1230	E.02	--	--	--	.31	E.01	--	--	--	--	--	--
MODCAS-09	20010328	1340	E.02	--	--	--	--	--	--	--	--	--	--	--
MODCAS-10	20010329	0800	.31	E.03	--	--	--	--	--	--	--	--	E0.05	--
MODCAS-11	20010329	0920	1.86	.25	E.08	E0.13	E.03	E.02	E0.03	--	--	--	--	--
MODCAS-12	20010329	1020	2.58	.16	--	--	5.60	--	--	--	--	--	--	--
MODCAS-13	20010330	0820	.97	.21	E.07	E.10	E.04	--	E.05	--	--	--	--	E0.01
MODCAS-14	20010330	0920	4.53	.61	.43	.41	.13	--	E.05	--	--	--	--	--
MODCAS-15	20010330	1020	.45	E.04	--	--	--	--	--	--	--	--	--	--
MODCAS-16	20010330	1110	1.19	.19	.21	E.16	E.04	6.13	--	--	--	E0.02	--	E.09
MODCAS-17	20010403	0820	2.14	.29	.91	.18	.18	E.03	E.08	.99	--	--	--	--
MODCAS-18	20010403	0930	E.08	--	--	--	--	--	--	--	--	--	--	--
MODCAS-19	20010403	1130	.15	--	--	--	.71	--	--	--	--	--	--	--
MODCAS-20	20010403	1330	18.14	1.04	--	E.07	3.29	.21	E.03	E.05	--	--	--	--
MODCAS-21	20010404	0820	1.85	.18	.40	E.12	1.57	--	--	--	--	.25	--	E.01
MODCAS-22	20010404	1020	5.25	.73	.23	.34	.50	--	E.05	--	--	--	--	--
MODCAS-23	20010404	1230	.17	--	--	--	.13	E.01	--	--	--	--	--	--
MODCAS-24	20010404	1350	E.07	--	--	--	E.04	--	--	--	--	--	--	--
MODCAS-25	20010405	0820	1.19	E.09	--	--	--	--	--	--	--	--	--	--
MODCAS-26	20010405	1030	1.98	.34	.47	E.16	.15	E.10	E.05	--	E.08	--	--	--
MODCAS-27	20010405	1130	1.59	.23	1.29	.31	.17	E.02	.13	--	--	--	E.02	--
MODCAS-28	20010406	0830	3.85	.49	.54	.44	.12	--	--	--	--	--	--	--
MODCAS-30	20010406	1100	.48	.11	.19	E.12	--	--	--	--	--	--	--	--
MODCAS-31	20010406	1220	5.04	.93	.37	.63	--	--	--	--	--	--	--	--
MODCAS-32	20010410	0840	.67	.12	.32	E.15	1.96	3.01	E.06	--	--	E.03	E.02	--
MODCAS-33	20010410	1000	1.50	.32	1.19	.35	--	--	--	--	E.03	--	--	--
MODCAS-34	20010410	1110	1.79	.39	1.64	.45	--	--	E.10	--	--	--	--	--
MODCAS-35	20010410	1240	E.08	E.03	--	--	--	--	--	--	--	--	--	--
MODCAS-36	20010410	1420	E.09	--	.21	E.05	--	E.01	--	E.09	--	--	--	--
MODCAS-37	20010411	0830	6.12	.56	.10	E.18	--	--	--	--	--	--	--	--
MODCAS-38	20010411	0940	E.04	--	--	--	--	--	--	--	--	--	--	--
Wells with VOC detections			36	26	19	18	21	13	10	6	3	3	3	3
Detection frequency (percent)			90	65	48	45	52	32	25	15	8	8	8	8

Appendix 4b. Wells with volatile organic compound detections in the Modesto study area, California, 2001.—Continued

[CAS, California Aquifer Susceptibility program. ymd, year, month, day. Percentage values are detection frequencies. Number in parentheses is the data parameter code, a five-digit code used in the U.S. Geological Survey computerized data system, National Water Information System, to uniquely identify a specific constituent or property. LRL, laboratory reporting limit; MODCAS, Modesto study area. μg/L, microgram per liter; VOC, volatile organic compound; E, estimated value; --, not detected]

CAS identification No.	Date (ymd)	Time	Solvent (70 percent) Dichloromethane (Methylene chloride), μg/L (34423)	Solvent 1,2-Dibromoethane, μg/L (77651)	Solvent 1,2-Dichlorobenzene, μg/L (34536)	Solvent trans-1,2-Dichloroethylene, μg/L (34546)	Dichlorodifluoromethane (CFC-12), μg/L (34668)	Refrigerant (25 percent) 1,1,2-Trichlorotrifluoroethane (CFC-113), μg/L (77652)	Refrigerant Trichlorofluoromethane (CFC-11), μg/L (34488)	Organic Synthesis (2 percent) 1,1-Dichloroethylene (DCE), μg/L (34501)	Gasoline (5 percent) Methyl tert-butyl ether (MTBE), μg/L (78032)	Fumigant (2 percent) 1,2-Dibromo-3-chloropropane (DBCP), μg/L (82625)	Number of VOCs detected
LRL			**<0.16**	**<0.036**	**<0.031**	**<0.032**	**<0.27**	**<0.06**	**<0.09**	**<0.04**	**<0.17**	**<0.21**	
MODCAS-01	20010327	0830	--	--	--	--	--	--	0.27	--	--	--	3
MODCAS-02	20010327	1030	--	--	E0.01	--	E0.74	--	.15	--	--	--	8
MODCAS-03	20010327	1230	--	E0.03	--	--	--	--	--	--	--	--	4
MODCAS-04	20010327	1330	--	--	--	--	--	--	--	--	--	--	5
MODCAS-05	20010328	0800	--	--	--	--	--	--	--	--	--	--	5
MODCAS-06	20010328	0940	--	--	--	--	--	--	--	--	--	--	1
MODCAS-07	20010328	1050	--	--	--	--	--	--	--	--	--	--	2
MODCAS-08	20010328	1230	--	--	--	--	E.06	0.25	--	E0.028	--	--	5
MODCAS-09	20010328	1340	--	--	--	--	--	--	--	--	--	--	2
MODCAS-10	20010329	0800	--	--	--	--	--	--	--	E.049	--	--	4
MODCAS-11	20010329	0920	--	--	--	--	--	--	--	--	--	--	7
MODCAS-12	20010329	1020	--	--	--	--	--	--	--	--	E0.06	--	4
MODCAS-13	20010330	0820	--	--	--	--	--	--	--	--	--	--	6
MODCAS-14	20010330	0920	--	--	--	--	--	--	--	--	--	--	6
MODCAS-15	20010330	1020	--	--	--	--	--	--	--	--	--	--	3
MODCAS-16	20010330	1110	--	--	--	E0.02	E.92	15.49	--	E.095	--	--	11
MODCAS-17	20010403	0820	--	--	--	--	--	--	--	--	--	--	9
MODCAS-18	20010403	0930	--	--	--	--	E.07	--	--	--	--	--	1
MODCAS-19	20010403	1130	--	--	--	--	--	--	--	--	--	--	3
MODCAS-20	20010403	1330	0.23	--	--	--	--	--	--	E.021	E.07	--	10
MODCAS-21	20010404	0820	--	--	--	--	--	--	--	--	--	--	7
MODCAS-22	20010404	1020	--	--	--	--	E.14	--	--	--	--	--	7
MODCAS-23	20010404	1230	--	--	--	--	--	--	--	--	--	--	3
MODCAS-24	20010404	1350	--	--	--	--	--	--	--	--	--	--	2
MODCAS-25	20010405	0820	--	--	--	--	--	--	--	--	--	--	2
MODCAS-26	20010405	1030	E.06	--	--	--	--	--	--	--	--	--	8
MODCAS-27	20010405	1130	E.05	--	--	--	--	--	--	--	--	--	9
MODCAS-28	20010406	0830	--	--	--	--	E.07	--	--	--	--	--	7
MODCAS-30	20010406	1100	--	--	--	--	--	--	--	--	--	--	4
MODCAS-31	20010406	1220	--	--	--	--	--	--	--	--	--	--	4
MODCAS-32	20010410	0840	--	--	--	--	E.06	E.01	--	E.036	--	--	12
MODCAS-33	20010410	1000	--	--	--	--	--	--	--	--	--	0.26	6
MODCAS-34	20010410	1110	--	--	--	--	--	--	--	--	--	--	5
MODCAS-35	20010410	1240	--	--	--	--	--	--	--	--	--	--	3
MODCAS-36	20010410	1420	--	--	--	--	--	--	--	--	--	--	4
MODCAS-37	20010411	0830	--	--	--	--	--	--	--	--	--	--	4
MODCAS-38	20010411	0940	--	--	--	--	--	--	--	--	--	--	1
Wells with VOC detections			3	1	1	1	7	3	2	5	2	1	
Detection frequency (percent)			8	2	2	2	18	8	5	12	5	2	

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