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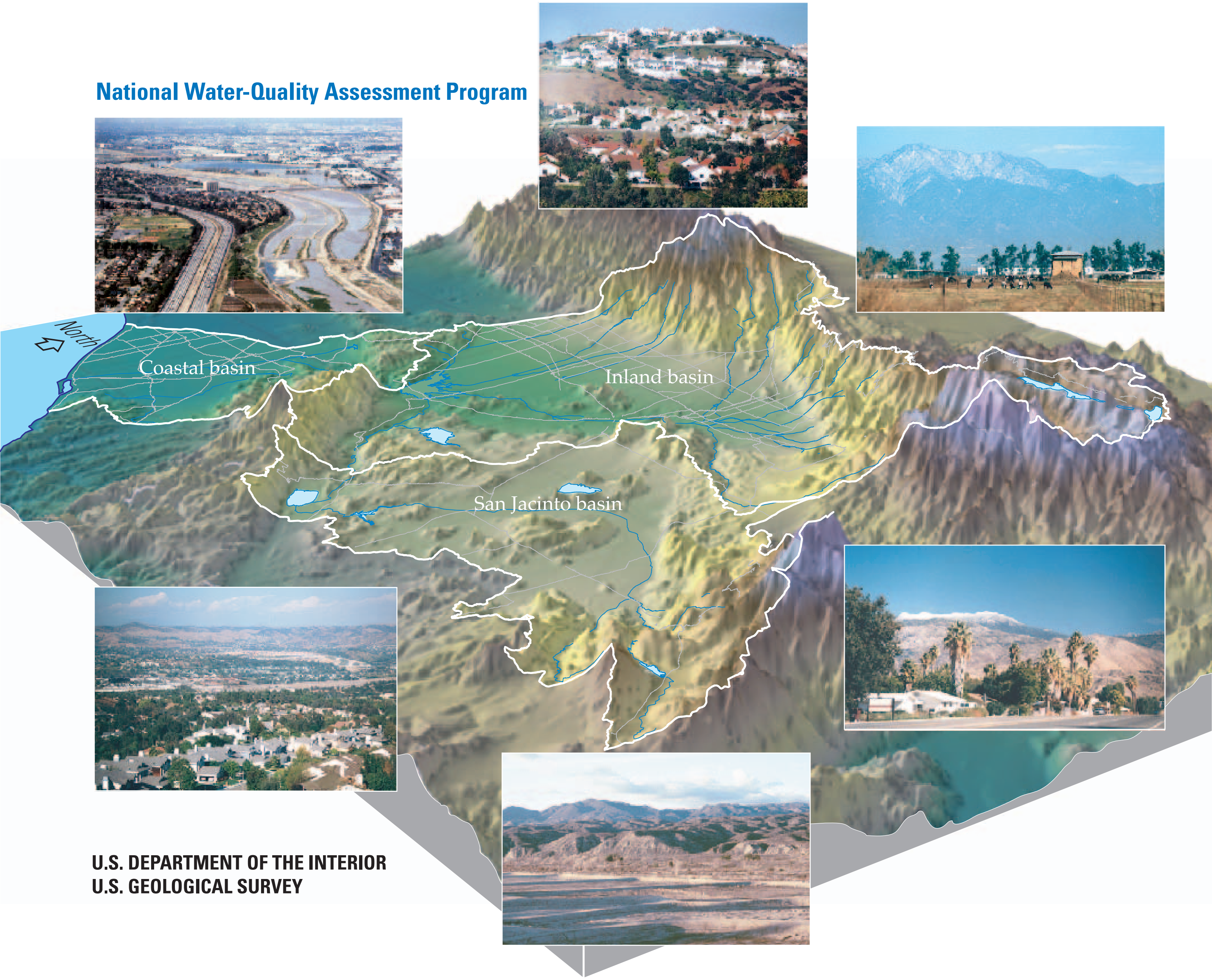
Occurrence and Distribution of Volatile Organic Compounds and Pesticides in Ground Water in Relation to Hydrogeologic Characteristics and Land Use in the Santa Ana Basin, Southern California

Scientific Investigations Report 2005-5032

National Water-Quality Assessment Program



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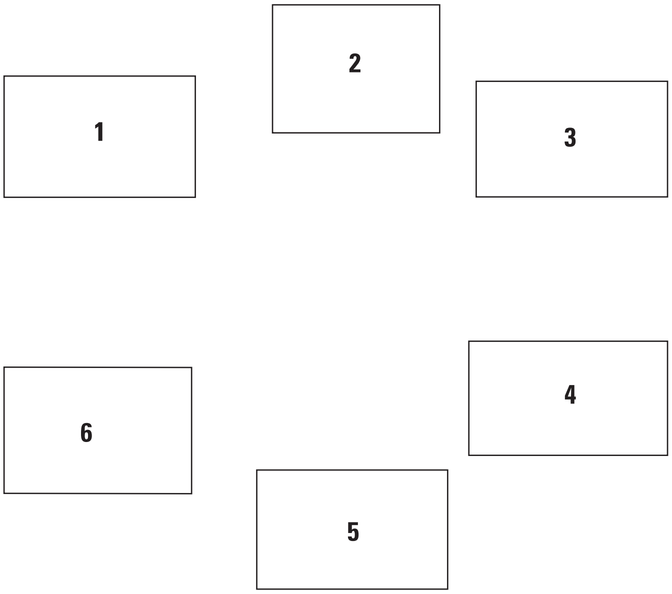

Cover Photographs
Clockwise from upper left:

1 Recharge facilities on Santa Ana River. Photo courtesy of Orange County Water District.

2 Urban development, Yorba Linda area. Photo: Phil Contreras, USGS

3 Dairy farm with San Gabriel Mountains in background. Photo: Phil Contreras, USGS

4 Looking east toward the San Jacinto Mountains from Hemet. Photo: Phil Contreras, USGS

5 Recharge facilities on the San Jacinto River. Photo: Barbara Dawson, USGS

6 Urban development overlooking the Santa Ana River near Yorba Linda. Photo: Phil Contreras, USGS

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By Scott N. Hamlin, Kenneth Belitz, and Tyler Johnson

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Conversion Factors, Vertical Datum, and Abbreviations

Multiply	By	To obtain
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per year (hm^3/yr)
foot (ft)	0.3048	meter (m)
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)

Multiply	By	To obtain
kilometer (km)	0.62137	mile (mi)
square kilometer (km^2)	0.3861	square mile (mi^2)
meter (m)	3.28084	feet (ft)

In the text, Inch/Pound units are used, except for the NAWQA contributory area near wells which was defined by a 500-meter radius.

Vertical Datum

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

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

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

Abbreviations

CAS	California Aquifer Susceptibility
CFC-11	(Freon 11) trichlorofluoromethane
CFC-12	(Freon 12) dichlorofluoromethane
CFC-113	(Freon 113) 1,1,2-trichlorofluoroethane
DCE	1,1-dichloroethene
LRL	laboratory reporting limit
MTBE	methyl tert-butyl ether
NAWQA	National Water-Quality Assessment (Program)
NWQL	National Water Quality Laboratory
OCCAS	Orange County California Aquifer Susceptibility (program)
PCE	tetrachloroethene (or tetrachloroethylene)
pCi/L	picocuries per liter
SAR	Santa Ana River
SUS	subunit survey

TCA	1,1,1-trichloroethane
TCE	trichloroethene (or trichloroethylene)
TDS	total dissolved solids
TIN	total inorganic nitrogen
VOC	volatile organic compound

Organizations

EMWD	Eastern Municipal Water District
OCWD	Orange County Water District
SAWPA	Santa Ana Watershed Project Authority
USGS	U.S. Geological Survey

Occurrence and Distribution of Volatile Organic Compounds and Pesticides in Ground Water in Relation to Hydrogeologic Characteristics and Land Use in the Santa Ana Basin, Southern California

By Scott N. Hamlin, Kenneth Belitz, and Tyler Johnson

Abstract

This report presents an evaluation of the occurrence and distribution of VOCs and pesticides in the Santa Ana ground-water basins in relation to two types of explanatory factors: hydrogeologic characteristics and land use. The Santa Ana Basin is subdivided into the San Jacinto, the Inland, and the Coastal ground-water basins. Most wells sampled were deep and used for public supply. Data from regional studies were used to evaluate the occurrence and distribution of pesticides and volatile organic compounds (VOCs) in relation to hydrogeologic characteristics and land uses that could potentially explain variations between basins. Additional data from special studies (flow path and aquifer susceptibility) were used to evaluate potential factors affecting water quality for individual basins. The hydrogeologic characteristics evaluated in this report were hydrogeologic setting, ground-water age, depth to the top of the well screen (top of well perforations), and proximity to engineered recharge facilities. Urban land use, agricultural land use, and population density were characterized within a 500-meter radius of sampled wells and at the basin scale.

Aquifers in the San Jacinto Basin are generally unconfined, and major land-use categories are urban (33 percent), agricultural (37 percent), and undeveloped (25 percent). Recharge is primarily from the overlying landscape, but engineered recharge is locally important in the Hemet area. VOCs and pesticides were detected more frequently in younger ground water (less than 50 years old) than in older ground water, and more frequently in shallower wells than deeper wells; the numbers of VOCs and pesticides detected also were significantly higher in the younger ground water and in the shallower wells. In the Hemet area of the San Jacinto Basin, VOCs and pesticides were detected more frequently in wells proximal to engineered recharge facilities than in distal wells. These patterns illustrate the importance of proximity to sources of recharge in relation to the occurrence and distribution of VOCs and pesticides in ground water.

Aquifers in the Inland Basin also are generally unconfined, and the major land-use category is urban (58 percent), with lesser amounts of agricultural (13 percent) and undeveloped (28 percent) land. Recharge is from engineered facilities that utilize local runoff and imported water and from vertical infiltration. VOCs and pesticides were detected more frequently in younger ground water than in older ground water, and more frequently in shallower wells than deeper wells. The number of VOCs detected per well also was significantly higher in the younger ground water and in the shallower wells. Several solvent plumes extending between 5 and 10 kilometers illustrate the large distances that contaminants travel in basins with intensive use of ground water.

Aquifers in the Coastal Basin, in contrast to the other basins, are generally confined. Land use in the basin is largely urban (80 percent), with lesser amounts of agricultural (7 percent) and undeveloped (12 percent) land. Recharge is primarily from engineered facilities that utilize water diverted from the Santa Ana River and imported water. Consequently, VOCs and pesticides were detected more frequently in wells proximal to engineered recharge facilities than in distal wells. These compounds were also detected more frequently in the unconfined area than in the confined area of the basin. In the confined area, the numbers of VOCs and pesticides detected per well were not significantly different in wells with shallower and deeper screens. This distribution reflects the dominance of lateral flow and insulation from overlying land use in the confined aquifers of the Coastal Basin.

In the unconfined area of the Coastal Basin, the numbers of VOCs and pesticides detected per well were significantly higher in shallower wells than in deeper wells. VOC and pesticide detections were not statistically correlated to urban land use, agricultural land use, or population density near the sampled wells, in contrast to national findings.

Nationally, positive correlations have been observed between the percentage of urban land use near sampled wells (500 meters) and pesticide and VOC detection frequencies in shallow ground water. Similarly, national studies have shown correlation between the percentage of agricultural land use near sampled wells and pesticide detection frequency. In contrast, pesticide and VOC detections in the Santa Ana ground-water basins were not positively correlated with urban land use, agricultural land use, or population density near the sampled wells. These contrasts with national findings could be due to differences in the types of wells sampled in the Santa Ana ground-water basins: deep, production wells compared with shallow, domestic wells in the national evaluation. The capture zones for these deep wells are complex (asymmetrical) and commonly extend beyond 500 meters, more than 10 kilometers in some cases as illustrated by solvent plumes. Another explanation for the contrasts with national findings, particularly in the San Jacinto Basin, is that current land use may not reflect land use at the time of recharge. An additional explanation for the lack of agreement with national findings in the Coastal Basin is the predominance of confined aquifers that are insulated from overlying land use.

Introduction

Description of Study Area

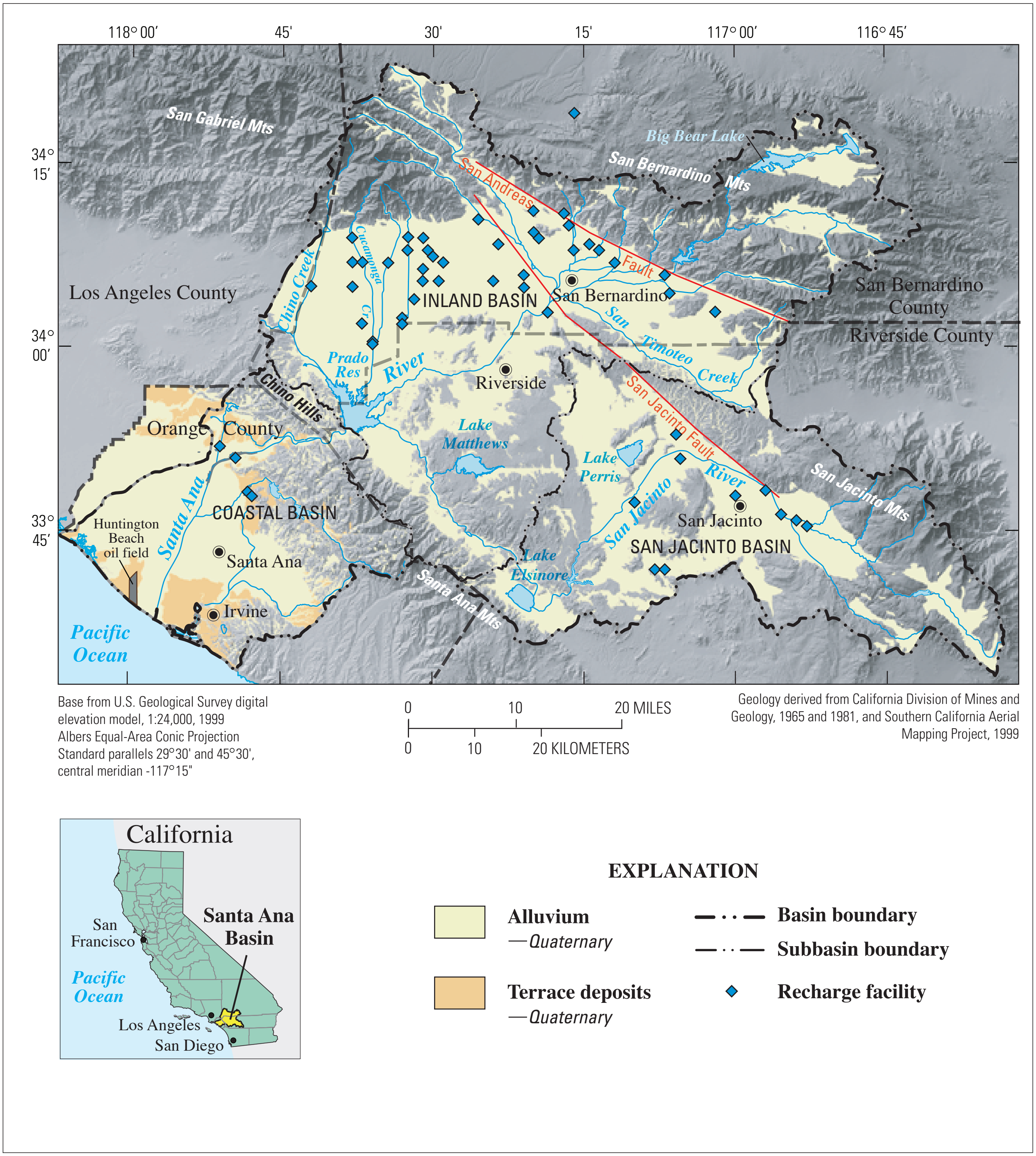
The Santa Ana Basin is located in southern California between Los Angeles and San Diego (*fig. 1*). The 2,700-mi^2 watershed is home to nearly 5 million people, and the population is expected to increase by more than 50 percent by the year 2020. During the same period, water demand is expected to increase by somewhat less than 50 percent (Santa Ana Watershed Project Authority [SAWPA], 1998). The Santa Ana Basin includes parts of Orange, San Bernardino, Riverside, and Los Angeles Counties. Population density for the entire study area is 1,500 people per mi^2; excluding areas too steep to develop, the population density is about 3,000 people per mi^2. In the city of Santa Ana, the population density is as high as 20,000 people per mi^2 (California Department of Finance, accessed March 3, 2005).

The Santa Ana River is the largest stream system in southern California, beginning in the San Bernardino Mountains (which reach altitudes exceeding 10,000 ft above sea level [NAVD, 1988]) and flowing more than 100 mi to the Pacific Ocean near Huntington Beach. The climate is Mediterranean with hot, dry summers and cool, wet winters. Average annual rainfall ranges from 12 in. in the coastal plain and 18 in. in the inland valley to 40 in. in the San Bernardino Mountains.

Ground water is the main source of supply in the watershed, providing about two-thirds of the total water used (about 1.2 million acre-ft/yr). Imported water from northern California and the Colorado River accounts for about one-quarter of the total consumptive demand. Local surface water provides the remaining supply. Urban water use (63 percent) exceeds agricultural water use (28 percent of total use) in the study area (Hamlin and others, 1999).

The Santa Ana Basin can be subdivided into three primary ground-water basins: the San Jacinto Basin, the Inland Basin, and the Coastal Basin *(fig.1)*. Relatively impervious hills and mountains bound water-bearing deposits in the alluvium-filled basins. Urban and agricultural land uses occur primarily in the alluvium-filled valleys and the coastal plain. Land use in the watershed is about 35 percent urban; 10 percent agricultural; and 55 percent open space, primarily steep mountain slopes (Belitz and others, 2004).

Numerous studies of ground-water quality have been conducted in the Santa Ana Basin. The Santa Ana Watershed Project Authority (SAWPA) was formed to protect water quality in the basin. To help local agencies manage water resources in the basin, SAWPA has produced a report that summarizes water use, water quality, water-quality issues, and the water budget (Santa Ana Watershed Project Authority, 1998). SAWPA has identified two primary water-quality issues: high concentrations of total dissolved solids (TDS) and total inorganic nitrogen (TIN). A task force was formed to study and address these issues and has produced a report that describes the distribution, variation, and management alternatives for TDS and TIN in surface and ground water (Wildermuth Environmental, 2000). Ground-water quality in the Santa Ana Basin is discussed in relation to drinking water standards in a report completed for the U.S. Geological Survey (USGS) National Water-Quality Assessment Program (NAWQA) (Hamlin, 2002).



Base from U.S. Geological Survey digital elevation model, 1:24,000, 1999
Albers Equal-Area Conic Projection
Standard parallels 29°30' and 45°30', central meridian -117°15"

Geology derived from California Division of Mines and Geology, 1965 and 1981, and Southern California Aerial Mapping Project, 1999

Figure 1. Location of the study area and the distribution of alluvial deposits in the Santa Ana Basin, southern California.

Many previous studies address water-quality issues specific to the individual ground-water basins. Several USGS studies have been done in cooperation with the Eastern Municipal Water District (EMWD) to describe geohydrology and water quality in the San Jacinto Basin (Burton and others, 1996; Kaehler and others, 1998; Kaehler and Belitz, 2003). The USGS has also completed studies in the Inland Basin in cooperation with local water agencies to investigate nitrate and volatile organic compound (VOC) contamination of ground water, to evaluate ground-water chemistry and recharge, and to optimize ground-water use and pumping (Klein and Bradford 1980; Duell and Schroeder, 1989; Danskin and Freckleton, 1992; Rees and others, 1994; Woolfenden and Kadhim, 1997; Izbicki and others, 1998). The Orange County Water District (OCWD) manages and monitors ground water in the Coastal Basin. The OCWD has published several reports that describe VOC plumes, water quality, and geohydrology in the Coastal Basin (Herndon and Reilly, 1989; Carlson and others, 1991; Herndon and Goodrich, 1991; Herndon and others, 1997). General water quality in the Coastal Basin is described in reports by the USGS: a description of geohydrology and characterization of seawater intrusion (Poland, 1959) and a description of aquifers and evaluation of ground-water quality in the Irvine subbasin (Singer, 1973). The USGS has also evaluated the occurrence of VOCs and pesticides in ground water to help assess the potential, or susceptibility, for contamination of ground water in the Coastal Basin (Shelton and others, 2001), and in flow paths in the Coastal and Inland Basins (Dawson and others, 2003).

Purpose and Scope

The purpose of this report is to evaluate the occurrence and distribution of VOCs and pesticides in the Santa Ana ground-water basins in relation to two types of explanatory factors: hydrogeologic characteristics and land use. This evaluation was based on chemical analyses of water samples primarily from deep, public-supply wells for water-quality studies done from 1999 to 2001 as part of the USGS's NAWQA program (Hamlin and others, 2002). The hydrogeologic characteristics include setting (unconfined versus confined), ground-water age (based on tritium concentration), depth to well screen (top of well perforations), and proximity to engineered (or artificial) recharge facilities.

A particular land use may be a source of VOCs and/or pesticides. Land use was evaluated at two scales: the entire basin (basin scale) and within 500 m of the sampled wells (well scale). Evaluation of land use within 500 m of sampled wells was consistent with the approach generally used in NAWQA studies (Koterba, 1998). Land-use factors evaluated at each scale were the percentage of urban land, the percentage of agricultural land, and the population density. Land use can be considered as a surrogate for sources of contamination. The size (and shape) of the area around a well that may contribute contaminants presumably ranges between the well scale (within 500 m) and the basin scale (tens of thousands of meters). It is beyond the scope of the present study to use ground-water flow modeling to assess the size and shape of contributing areas for individual wells sampled.

Acknowledgments

The authors thank the many water purveyors and companies that allowed the USGS to sample their wells: Agri Empire, Cucamonga County Water District, Diamond Brothers, East Orange Water Company, East Valley Water District, Elsinore Valley Municipal Water District, Fontana Water Company, Irvine Ranch Water District, Jurupa Community Services District, Lake Hemet Municipal Water District, Mesa Consolidated Water District, Serrano Water District, Southern California Water Company, The Irvine Company, University of California at Riverside, West San Bernardino County Water District, Yucaipa Valley Water District; and the cities of Anaheim, Chino Hills, Colton, Corona, Fountain Valley, Garden Grove, Hemet, Huntington Beach, Newport Beach, Nuevo, Ontario, Orange, Pomona, Redlands, Riverside, San Bernardino, San Jacinto, Santa Ana, Tustin, and Westminster.

We also thank the water districts that coordinated sampling efforts within their boundaries: Orange County Water District in the Coastal Basin and Eastern Municipal Water District in the San Jacinto Basin. Without their cooperation, this study would not have been possible.

Approach

Data from two different types of studies were used in this report (Hamlin and others, 2002). Subunit surveys (SUS) utilized randomized, spatially distributed sampling networks in each of the ground-water basins, and thus provided an unbiased assessment of the resource. Data from the SUS studies were used to assess water quality within basins and to compare water quality between basins. Data from special studies (flow path and aquifer susceptibility) were used, along with the SUS data, to evaluate explanatory factors affecting water quality. Most of the wells sampled for the SUS and special studies are deep and are used for public supply.

The San Jacinto, Inland, and Coastal Basins were described and compared with respect to hydrogeologic characteristics (degree of aquifer confinement, depth to the top of well perforations, and proximity to engineered recharge), land use (urban and agricultural), and population density. These factors were evaluated and compared at the basin scale. In addition, land-use factors and population density were evaluated at the well scale.

Whether an aquifer is unconfined or confined can affect the distribution of anthropogenic compounds in ground water. In most cases, VOCs and pesticides are expected to occur more frequently in unconfined aquifers than in confined aquifers (Squillace and others, 2002), and the basins are qualitatively compared with respect to degree of aquifer confinement.

Whether a well screen is shallow or deep can be an important explanatory factor in the distribution of anthropogenic compounds. Wells are classified as “shallow” or as “deep” relative to the median value for depth to the top perforation. In unconfined aquifers, shallow wells are generally closer to sources of recharge and to overlying sources of contamination than are deep wells. As a consequence, VOCs and pesticides are expected to occur more frequently in shallow wells (Squillace and others, 2002). Depths of wells sampled for the SUS studies were compared for the ground-water basins.

Proximity to engineered recharge facilities can be an important explanatory factor in the Coastal Basin and in the Hemet area of the San Jacinto Basin. Wells near recharge facilities were classified as “proximal” and more distant wells were classified as “distal.” Engineered recharge of aquifers can introduce trace amounts of VOCs and pesticides into ground water (Shelton and others, 2001; Dawson and others, 2003). Anthropogenic compounds may be widely distributed in ground water as recharged water moves through the flow system. The relative amount of engineered recharge (ground-water use) was compared for the ground-water basins.

Water from shallow wells and wells proximal to recharge facilities is generally younger than water from deep wells and wells distal from recharge facilities. In this study, the presence of tritium at concentrations at or above 1 pCi/L was taken as an indicator of “young” water recharged since the early 1950s; other samples were defined as “old.” Concentrations of tritium higher than 1 pCi/L were produced during atmospheric nuclear tests that began in the early 1950s; tritium concentrations have been decreasing since atmospheric tests were banned in 1963. In the comparison of ground-water basins, the relative amount of young water was used as an indicator of engineered recharge.

Urban and agricultural land uses are potential explanatory factors because they indicate whether or not anthropogenic compounds have been used. Population density reflects urban land use and can also be an explanatory factor. The data were compiled from the Southern California Association of Governments database (1993) and included various urban classifications, agricultural land, and vacant land (Southern California Association of Governments, accessed March 3, 2005). Land use and population density were evaluated at the basin scale and the well scale.

At the well scale, land use and population density were classified within a 500-m (1,640-ft) radius around each well sampled using procedures recommended by the NAWQA program (Koterba, 1998). In this report, land use and population density within the 500-m radius are classified as “near” the well. On a national basis, evaluation of NAWQA data indicated a positive correlation between VOC occurrence in ground water and urban land use; pesticide occurrence was associated with both agricultural and urban land uses (Squillace and others, 1999; Squillace and others, 2002). These national results were based on an analysis of land use within a 500-m (1,640-ft) radius of shallow, domestic wells. The national evaluation also found that water quality from the domestic wells can be different from public supply wells for several reasons, including generally shallower depth and lower pumping rates. Public supply wells can have high pumping rates and large capture zones, which can increase the number of potential contamination sources (Stackleberg and others, 2001).

The current study evaluates the relation of VOC and pesticide occurrence to land use at the basin scale and at the well scale; the actual scale of the capture zones for the sampled wells lies somewhere between the two. An important component of the current study was to evaluate whether land use and population density within a 500-m (1,640-ft) radius of the deep wells sampled is an explanatory factor for the occurrence and distribution of VOCs and pesticides.

Water quality was evaluated primarily in terms of detection frequency and number of compounds detected per well. Detection frequencies were used to qualitatively determine whether or not the potential explanatory factors control the occurrence and distribution of VOCs and pesticides. The number of compounds detected per well was evaluated with nonparametric statistical tests to quantitatively determine whether or not the potential explanatory factors can predict the distribution of VOCs and pesticides.

Two nonparametric statistical tests were used to quantitatively evaluate the significance of the potential explanatory factors (Helsel and Hirsch, 1992). The Wilcoxon test (two-sided test) was used to assess the significance of differences between two groups of wells. If the Wilcoxon test indicated a significant difference between groups of data, Kendall’s test was used to evaluate potential correlation between explanatory variables and response variables (detections of VOCs and pesticides). Probability values (p) less than 0.05 (95-percent confidence level) are taken as a strong correlation (Savoca and others, 2000). P values between 0.05 and 0.10 (90-percent confidence level) indicate a weaker correlation.

All detections of VOCs and pesticides, whether above or below laboratory reporting limits (LRLs), were used in calculating detection frequencies and in nonparametric statistical tests. The USGS National Water Quality Laboratory (NWQL) uses LRLs for reporting nondetections, but is able to quantify detections of compounds below the LRL (Childress and others, 1999). If a water sample has a compound at a concentration above the LRL, the NWQL has a high degree of confidence that that the compound will be detected in that sample under routine operating conditions. If a water sample has a concentration lower than the LRL, the NWQL does not have a high degree of confidence that that compound will be routinely detected. To reflect that uncertainty, the NWQL reports nondetections as less-than values rather than reporting them as zeros. Under some conditions, the NWQL can quantify detections below the LRL; in those cases, the NWQL reports detections as estimated values.

Description and Comparison of Explanatory Factors in the Ground-Water Basins

The Santa Ana Basin includes three ground-water basins: the San Jacinto, Inland, and Coastal Basins. In this section, the hydrogeology of each of the basins is briefly described. In addition, the basins are compared with one another with respect to selected potential explanatory factors. Selected explanatory factors are listed by ground-water basin and compiled in the appendix.

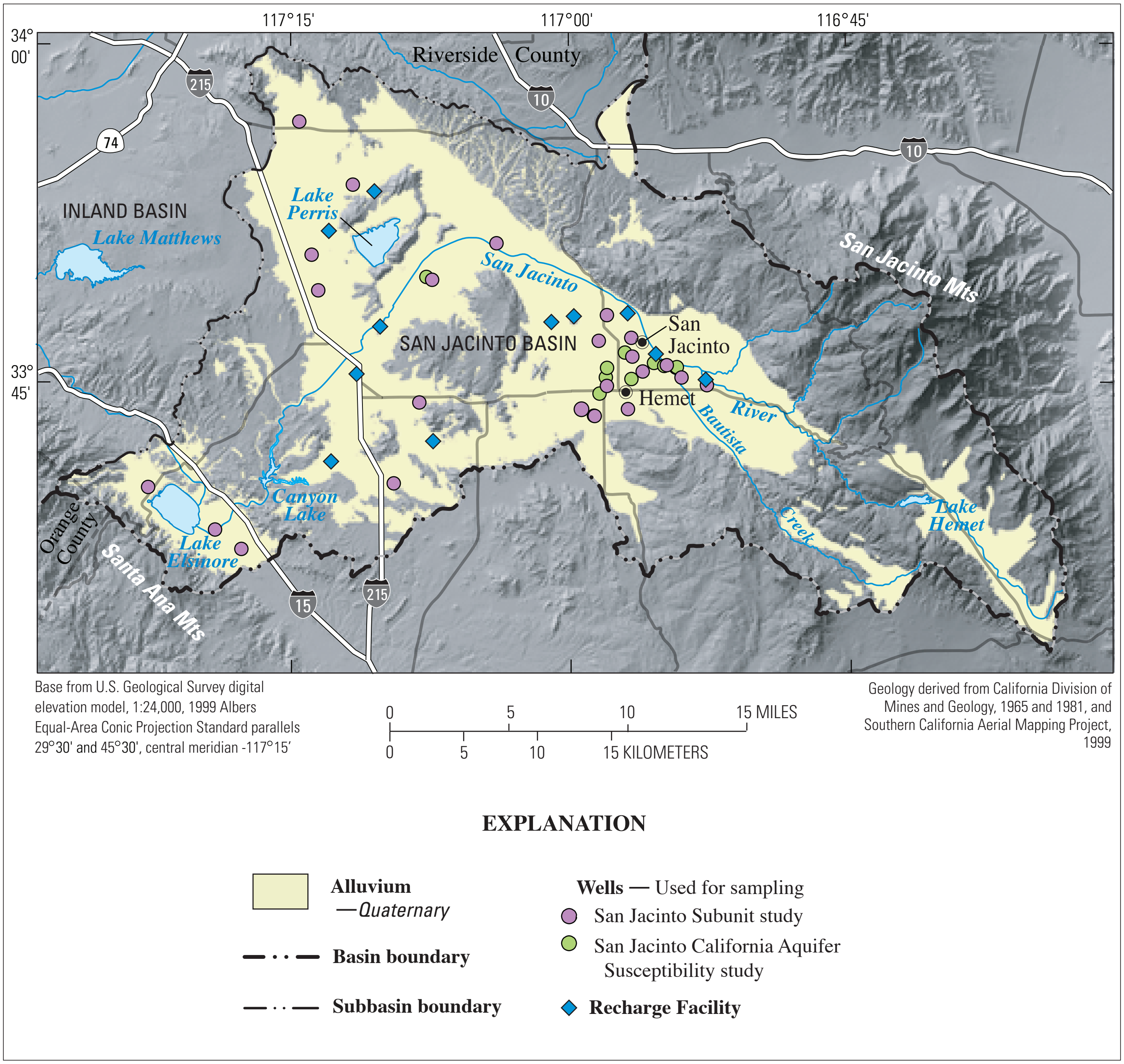
Figure 2 shows the location of the San Jacinto Basin. The aquifers in this basin are generally unconfined and consist of a series of interconnected alluvium-filled valleys bounded by steep-sided bedrock mountains and hills. The thickness of deposits in these valleys typically ranges from 200 to 1,000 ft (Eastern Municipal Water District, 2002). Collectively, alluvium covers about one-half of the total area in the subunit. Prior to development, recharge to the local aquifers was from infiltration of mountain streams, primarily the San Jacinto River. Presently, sources of recharge include irrigation return flows, engineered (artificial) recharge facilities (*fig. 2*), and infiltration from streams. Water levels in sampled wells ranged from 90 to 540 ft below land surface, with an average depth of 230 ft. The basin is virtually closed; ground-water discharge occurs primarily by ground-water pumping.

Figure 3 shows the location of the Inland Basin. The aquifers of this basin generally are unconfined and comprise several subbasins filled with alluvial deposits eroded from the surrounding mountains. The thickness of these deposits ranges from less than 200 to more than 1,000 ft (Dutcher and Garrett, 1963). Recharge to the basin varies seasonally and is largely from infiltration of runoff from the San Gabriel and San Bernardino Mountains. Much of the runoff is diverted into storm-detention basins, which also operate as ground-water recharge facilities (*fig. 3*). Surface water imported from northern California and the Colorado River is also used to recharge the ground-water basin. Incidental recharge occurs from landscape irrigation. Water levels in sampled wells ranged from 20 to 560 ft below land surface, with an average depth of 200 ft. Ground-water discharge occurs primarily by pumping for public supply (fig. 3). Several VOC plumes in the basin define ground-water flow paths.

The Coastal Basin is subdivided into the Main and Irvine Basins (*fig. 4*; Singer, 1973). The Main Basin was divided, on the basis of relative abundance of shallow clay layers, into unconfined (forebay) and confined (pressure) areas (California Department of Public Works, 1934). The unconfined area is small (28 percent) compared with the confined area (72 percent) (*fig. 4*). Within this basin, the thickness of freshwater-bearing deposits is as great as 4,000 ft (California Department of Water Resources, 1967). Almost all recharge in the basin is from engineered facilities located within and along the Santa Ana River and along Santiago Creek (Herndon and others, 1997). Ground-water discharge occurs primarily by pumping for public supply. Water levels in sampled wells ranged from 20 to 230 ft below land surface, with an average depth of 100 ft.

VOCs and pesticides were detected more frequently in younger ground water (recharged since the early 1950s) than in older ground water. In the three ground-water basins, VOCs were detected in 88 percent of the younger samples and in 36 percent of the older samples. Pesticides were detected in 72 percent of the younger samples and in 14 percent of the older samples.

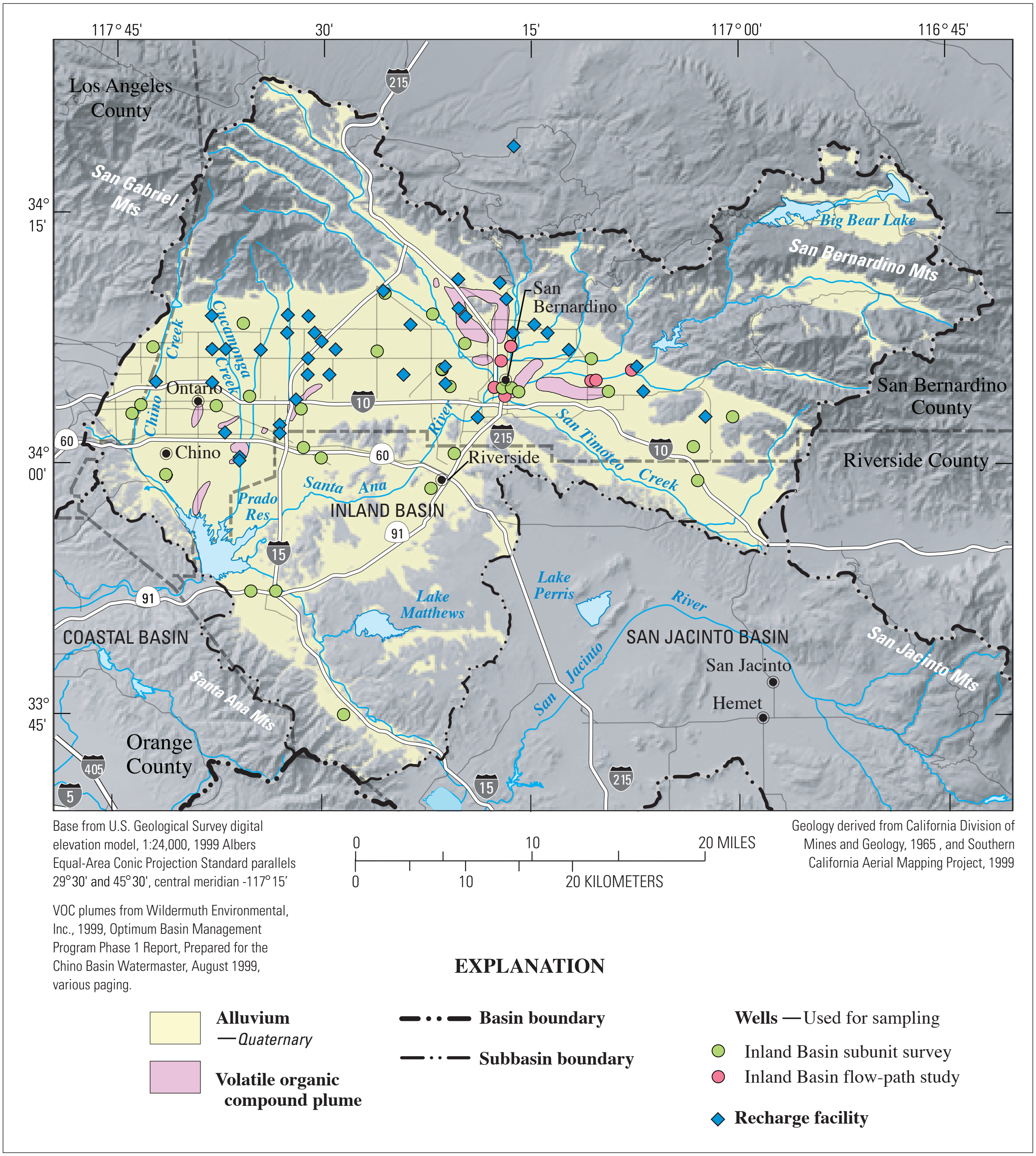
Data from wells sampled for the three subunit surveys were used to compare one basin with another. Depth to the top of the well screen can be an important explanatory factor for the occurrence of VOCs and pesticides, particularly in unconfined aquifers. The median depth to the top of the well screen is 270 ft in the San Jacinto Basin, 240 ft in the Inland Basin, and 388 ft in the Coastal Basin (*fig. 5*). The depths to the tops of the well screens are significantly deeper in the Coastal Basin than in either the San Jacinto Basin or Inland Basin (*table 1; fig. 5*). Total well depths range from 328 to 1720 ft in the San Jacinto Basin, from 225 to 1,180 ft in the Inland Basin, and from 98 to 1,550 ft in the Coastal Basin. Median total depths of sampled wells are 696 ft in the San Jacinto Basin, 585 ft in the Inland Basin, and 910 ft in the Coastal Basin.



Base from U.S. Geological Survey digital elevation model, 1:24,000, 1999 Albers Equal-Area Conic Projection Standard parallels 29°30' and 45°30', central meridian -117°15'

Geology derived from California Division of Mines and Geology, 1965 and 1981, and Southern California Aerial Mapping Project, 1999

Figure 2. Location of the San Jacinto Basin and wells within this subbasin of the Santa Ana Basin, southern California.



Base from U.S. Geological Survey digital elevation model, 1:24,000, 1999 Albers Equal-Area Conic Projection Standard parallels 29°30' and 45°30', central meridian -117°15'

VOC plumes from Wildermuth Environmental, Inc., 1999, Optimum Basin Management Program Phase 1 Report, Prepared for the Chino Basin Watermaster, August 1999, various paging.

Geology derived from California Division of Mines and Geology, 1965 , and Southern California Aerial Mapping Project, 1999

Figure 3. Location of the Inland Basin and of wells within this subbasin of the Santa Ana Basin, southern California.

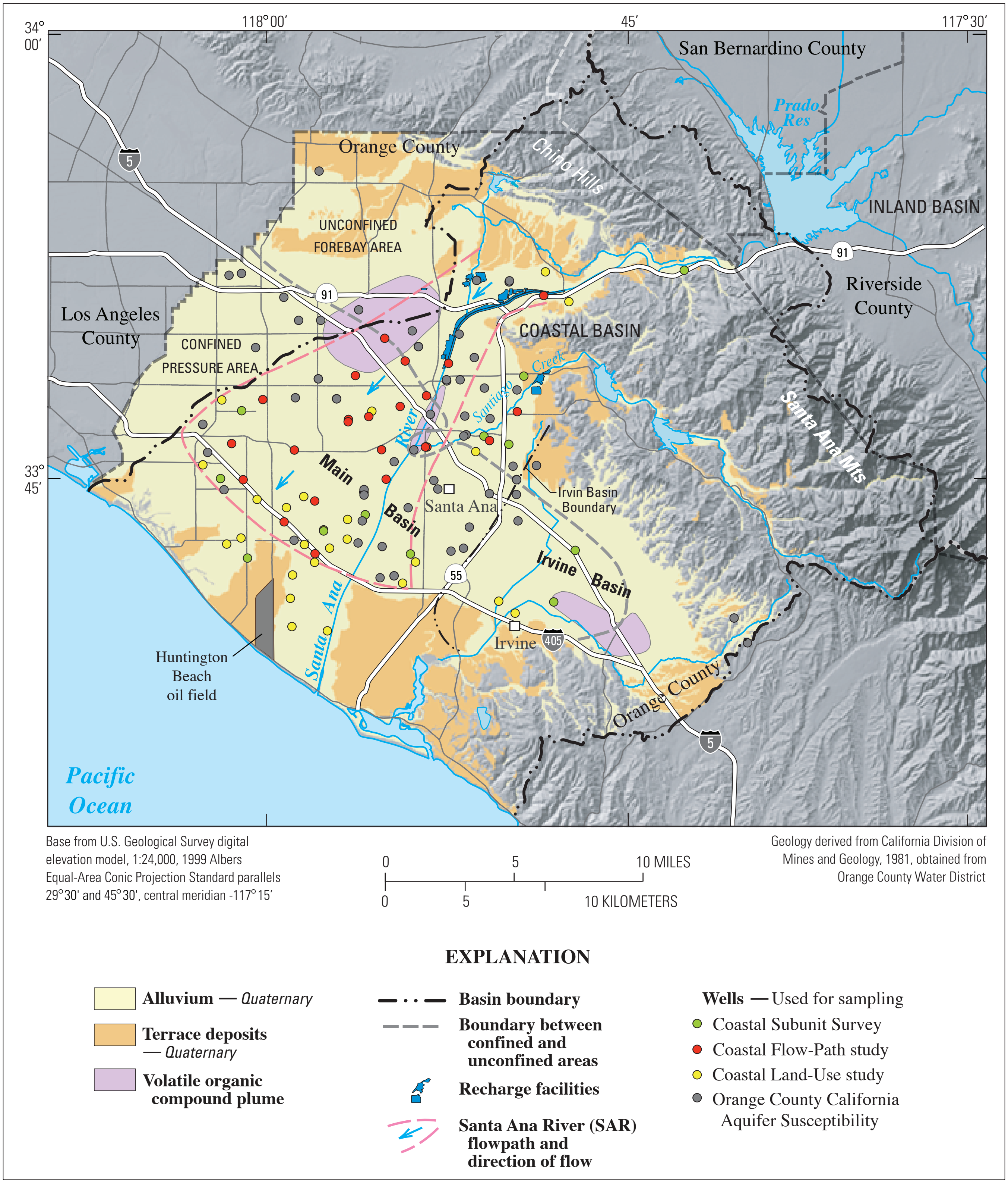


Figure 4. Location of the Coastal Basin and of wells within this subbasin of the Santa Ana Basin, southern California.

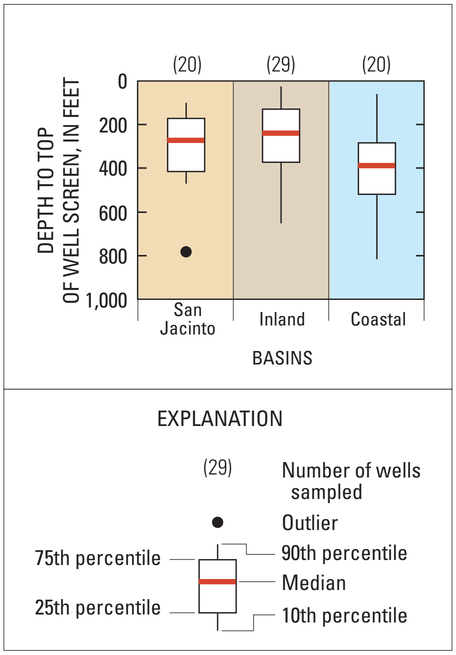


Figure 5. Depth to the top of the well screen grouped by subunit surveys for the three subbasins of the Santa Ana Basin, southern California.

Table 1. Statistical comparison of depth to the top of well screen, percent urban land use, percent agricultural land use, number of volatile organic compounds (VOCs) detected per well, and number of pesticides detected per well for the San Jacinto, Inland, and Coastal Basins, within the Santa Ana Basin, southern California.

[p value, probability value; Wilcoxon p value less than or equal to 0.10 indicates a significant difference between basins (green shading); ft, feet; mi^2, square mile]

Explanatory factors and response variables	Basins compared by Wilcoxon test (p values):		
	San Jacinto and Inland	San Jacinto and Coastal	Inland and Coastal
Depth to top of well screen, ft below land surface	0.38	0.05	0.006
Percent urban land use[1] (within 500-meter radius of well)	0.37	0.08	0.29
Percent agricultural land use (within 500-meter radius of well)	0.29	0.01	0.08
Percent undeveloped land (within 500-meter radius of well)	0.99	0.001	0.001
Population density, people per mi^2 (within 500-meter radius of well)	0.31	0.000	0.0001
Number of VOCs detected (per well)	0.005	0.13	0.19
Number of pesticides detected (per well)	0.0006	0.11	0.0001

[1] Urban land use includes residental, commercial, industrial, military, and transportation.

Within the Coastal Basin, the depths to the tops of the well screens in the unconfined and confined areas are not significantly different (p = 0.80, Wilcoxon test; *fig. 6A*). Similarly, when the comparison between unconfined and confined areas is restricted to wells in the Santa Ana River flow path, depths to well screens are not statistically different (p = 0.67, Wilcoxon test; *fig. 6B*).

Nationally, land use is an important explanatory factor for the occurrence of VOCs and pesticides (Squillace and others, 2002). At the basin scale, the percentage of urban land was highest in the Coastal Basin (80 percent), followed by the Inland Basin (58 percent), and the San Jacinto Basin (33 percent). Within each basin, the median value for urban land use near the wells (within a 500-m radius of the wellhead) was greater than the percentage in the basins as a whole. The median value for the wells was highest for the Coastal Basin (90 percent) and was about the same for the Inland and San Jacinto Basins (75 percent) (*fig. 7A*; *table 1*). Development in the ground-water basins has followed a general trend of increasing urbanization of agricultural and undeveloped land.

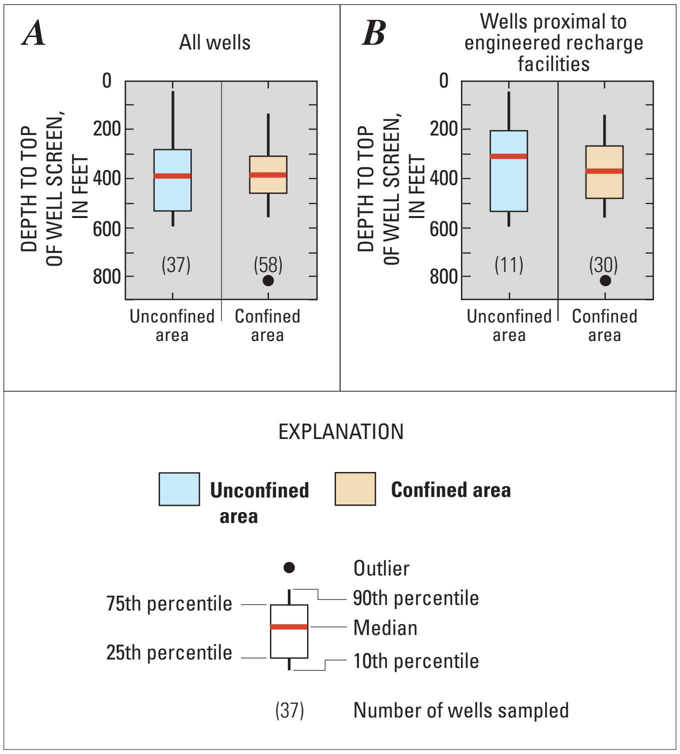


Figure 6. Depth to the top of the well screen grouped by unconfined and confined areas of the Coastal Basin within the Santa Ana Basin, southern California. *A*, all wells. *B*, wells proximal to engineered (artificial) recharge facilities.

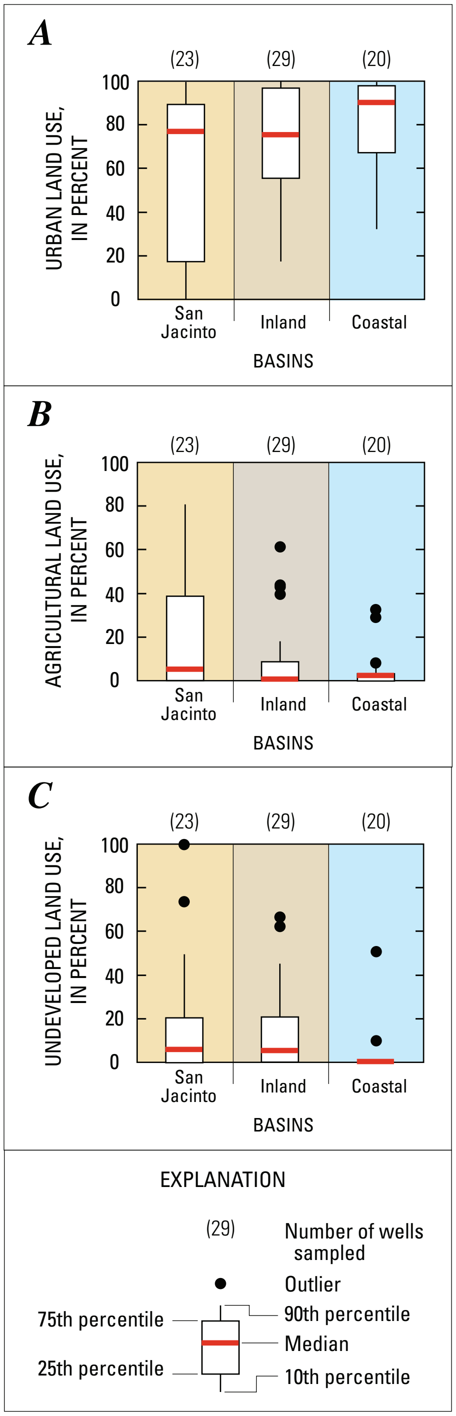


Figure 7. Land use in a 500-meter radius of wells sampled, grouped by subunit surveys for the three subbasins of the Santa Ana Basin, southern California. *A*, Percent urban use. *B*, Percent agriculture use. *C*, Percent undeveloped.

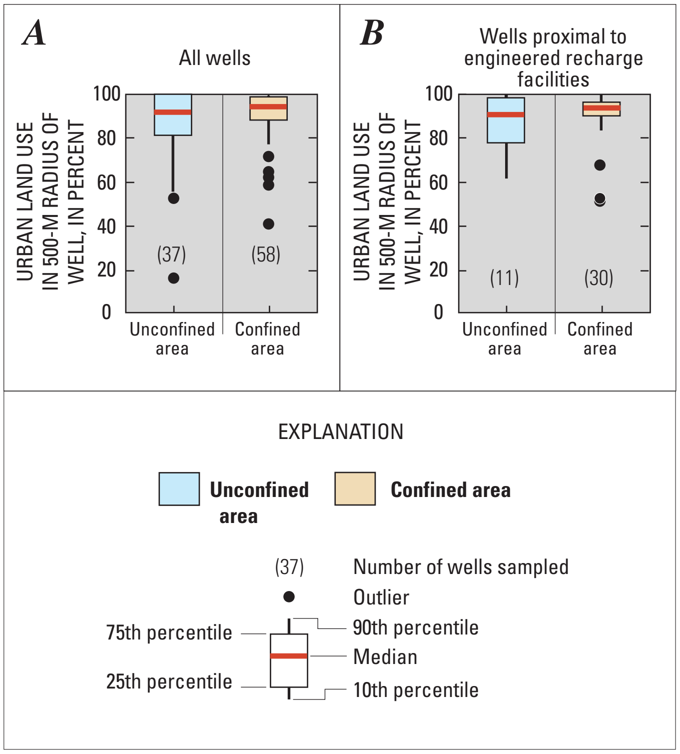


Figure 8. Percentage of urban land use in a 500-meter radius of wells sampled, grouped by unconfined and confined areas in the Coastal Basin of the Santa Ana Basin, southern California. *A*, all wells. *B*, wells proximal to engineered (artificial) recharge facilities.

Urban land use was further evaluated in the Coastal Basin in relation to hydrogeologic setting. For all wells sampled (*fig. 8A*), the percentage of urban land use was not significantly different in the unconfined and confined areas of the basin (p = 0.77, Wilcoxon test). Similarly, for wells proximal to recharge facilities (*fig. 8B*), urban land use was not significantly different in unconfined and confined areas (p = 0.80, Wilcoxon test).

Nationally, population density is an important explanatory factor for the occurrence of VOCs and pesticides (Squillace and others, 1999; Squillace and others, 2002). Population density in the year 2000 was highest in the Coastal Basin (3,160 people per km^2), intermediate in the Inland Basin (1,620 people per km^2), and lowest in the San Jacinto Basin (560 people per km^2) (*fig. 9A*). The median population density near the sampled wells is lower than that for the basins as a whole and shows a similar pattern (*fig. 9B*); the median population density near the sampled wells is 350 people per km^2 for the San Jacinto Basin, 795 people per km^2 for the Inland Basin, and 2,110 people per km^2 for the Coastal Basin. The population density in the Coastal Basin is significantly higher than that of the San Jacinto and Inland Basins; the population density near sampled wells is not significantly different than that of the San Jacinto and Inland Basins (*table 1*).

During the past 30 years, the Coastal Basin has been the most densely populated, and the San Jacinto Basin has been the least densely populated (*fig. 9A*). In addition, the 1970 population density in the Coastal Basin (1,797 people per km^2) is higher than the 2000 population density in either the San Jacinto or the Inland basins. Historical variation in population density indicates the duration and relative amount of urban land use, and may be used to evaluate the occurrence of anthropogenic compounds.

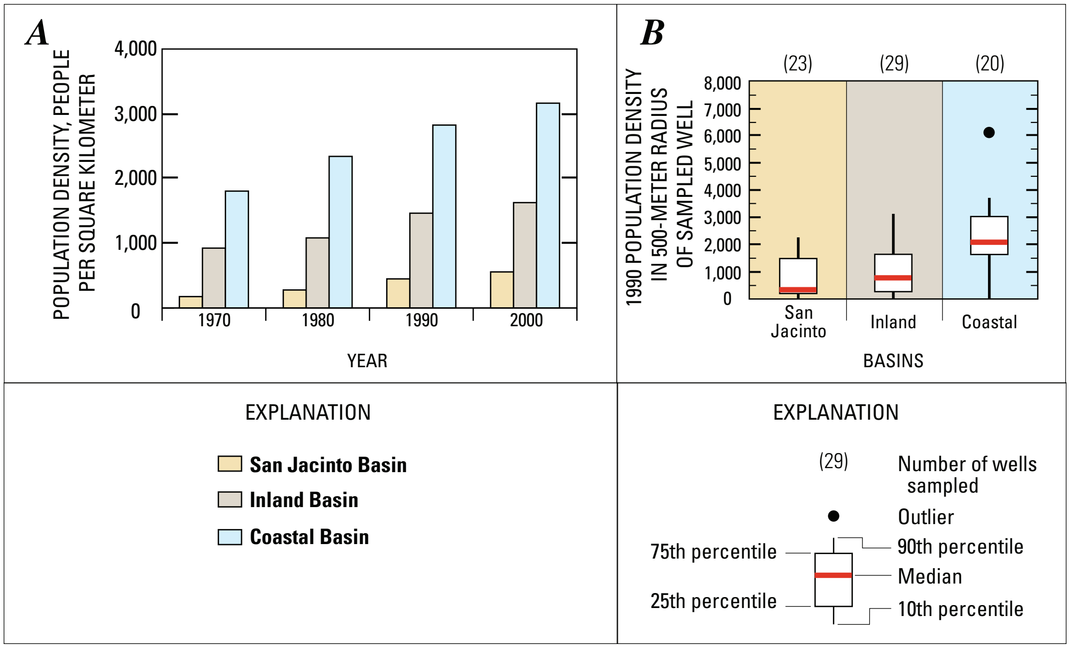


Figure 9. Population density grouped by subunit surveys for the three subbasins of the Santa Ana Basin, southern California. *A*, Population density per square kilometer. *B*, Population density for 1990 within a 500-meter radius of sampled wells.

The percentage of industrial and military land use was highest for the Coastal Basin (13 percent), intermediate for the Inland Basin (6 percent), and lowest for the San Jacinto Basin (3 percent). In contrast, the median percentage of industrial and military land use near the sampled wells was highest for the Inland Basin (14 percent), followed by the San Jacinto Basin (3 percent), and the Coastal Basin (2 percent). Numerous solvent plumes associated with industrial and military facilities have been documented in the Inland Basin (Wildermuth Environmental, 1999; Hamlin and others, 2002; Dawson and others, 2003).

The percentage of agricultural land use was highest in the San Jacinto Basin (39 percent), followed by the Inland Basin (13 percent), and the Coastal Basin (7 percent). The median percentage of agricultural land use near the sampled wells was lower than that for the basins as a whole and was highest for the San Jacinto Basin (6 percent), followed by the Inland (1 percent) and Coastal (0 percent) basins (*fig. 7B*; table 1). Agricultural land use is inversely proportional to the degree of urbanization in the basins (*fig. 7A,B*). Prior to urbanization, agricultural land use was important in the Inland and Coastal Basins.

The percentage of undeveloped land is highest in the Inland Basin (28 percent), followed closely by the San Jacinto Basin (25 percent), and is lowest in the Coastal Basin (12 percent). Median values are lower near sampled wells than in the basins as a whole. The median values near the sampled wells (*fig. 7C*; *table 1*) are identical for the San Jacinto and Inland Basins (6 percent). The median percentage near wells sampled in the Coastal Basin is zero percent; only two of the 20 wells sampled had any undeveloped land (10 and 51 percent) within a 500-m radius.

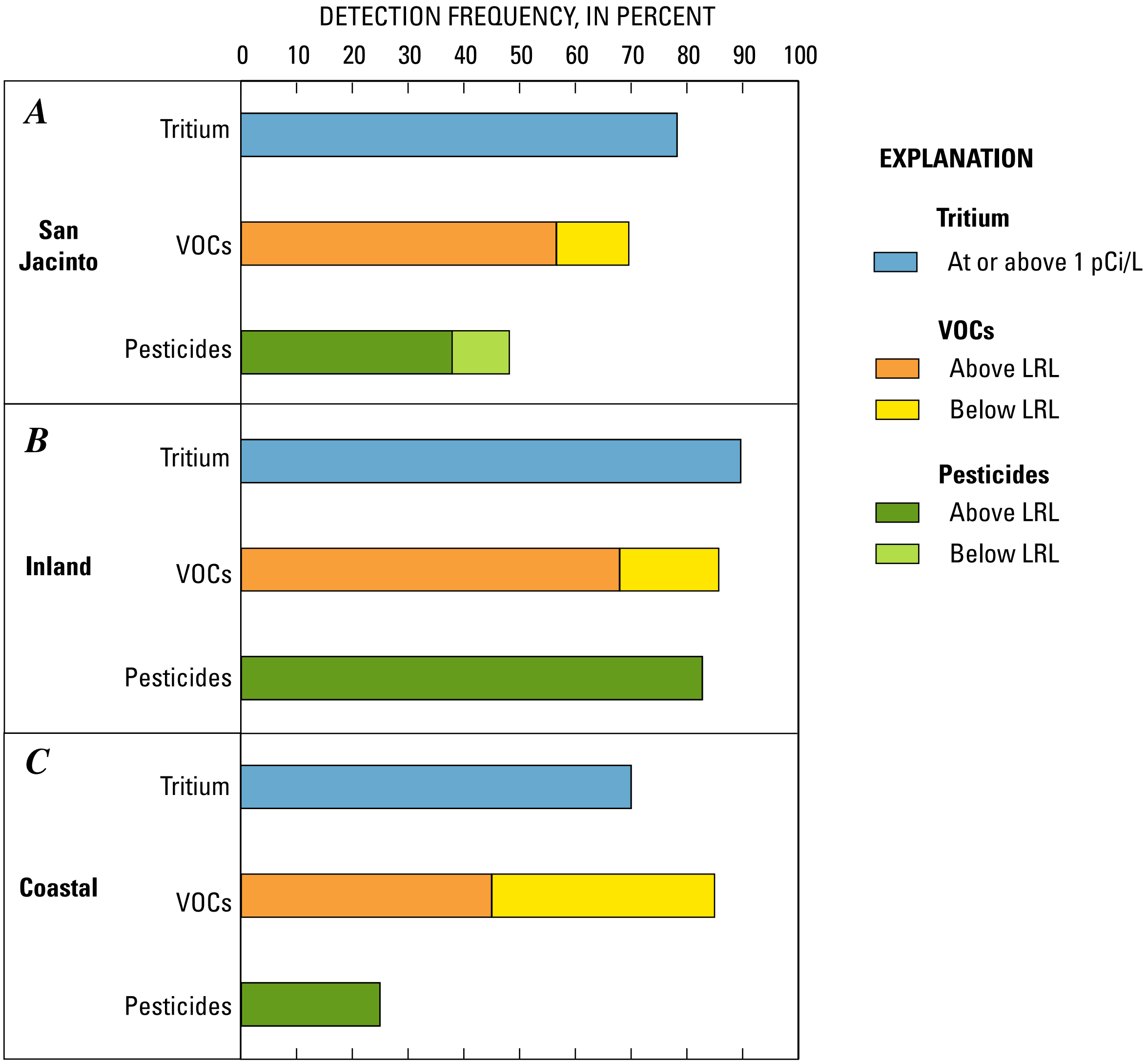


Figure 10. Detection frequencies for tritium at or above 1 pCi/L and for volatile organic compounds (VOCs) and pesticides above and below the laboratory reporting limit (LRL) for the three subbasins of the Santa Ana Basin, southern California. *A*, San Jacinto Basin. *B*, Inland Basin. *C*, Coastal Basin.

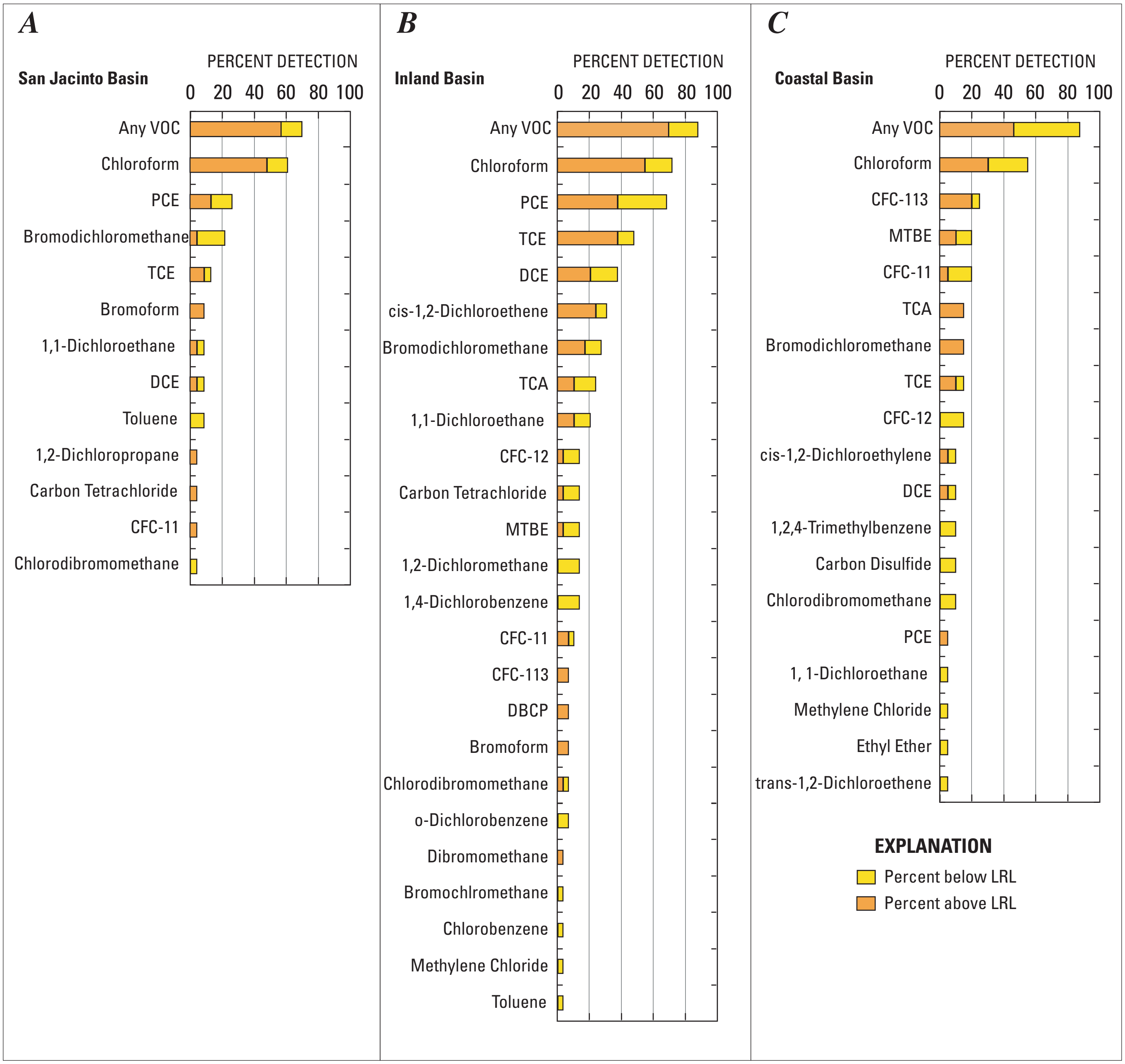


Figure 11. Detection frequencies for volatile organic compounds (VOCs) by individual compound for the three subbasins of the Santa Ana Basin, southern California. *A*, San Jacinto Basin. *B*, Inland Basin. *C*, Coastal Basin.

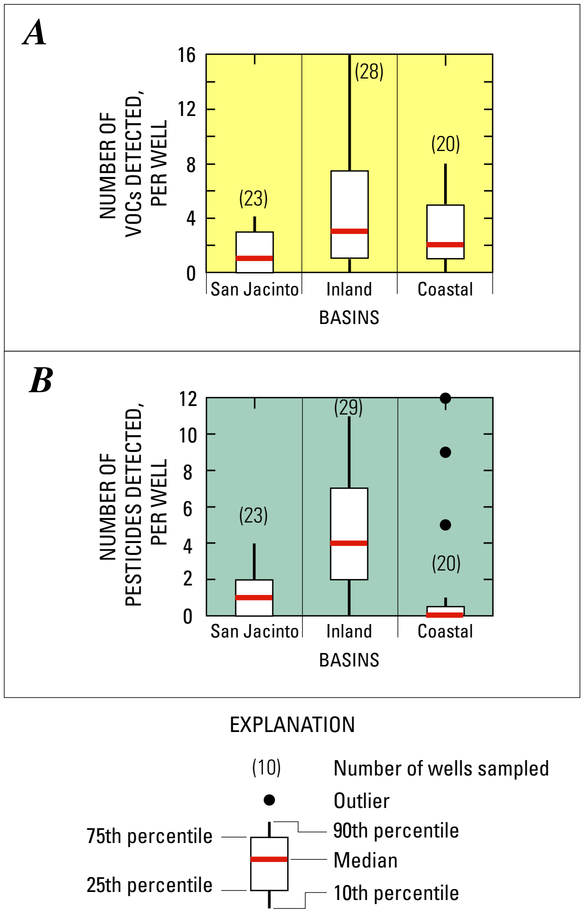


Figure 12. (*A*) number of volatile organic compounds (VOCs) detected and (*B*) number of pesticides detected in the San Jacinto, Inland, and Coastal Basins within the Santa Ana Basin, southern California.

To ensure that the potential explanatory factors were not statistically related, Kendall's test was used to evaluate the potential correlation of depth to the top of the well screen with land use. For depth to the top of the well screen in the San Jacinto Basin, p values were 0.77 for urban land use and 0.53 for agricultural land use. For depth to the top of the well screen in the Inland Basin, p values were 0.97 for urban land use and 0.68 for agricultural land use. For depth to the top of the well screen in the Coastal Basin, p values were 0.80 for urban and 0.26 for agricultural land use. These results indicate that the depth to the top of the well screen and land use are not correlated.

Occurrence and Distribution of VOCs and Pesticides in the San Jacinto Basin

Detection Frequencies of Tritium, VOCs, and Pesticides

Tritium was the most frequently detected anthropogenic compound in the San Jacinto Basin; pesticides were least frequently detected (*fig. 10*). Tritium was detected in 78 percent of the wells sampled in the basin, indicating that the ground water was mostly young (recharged during the past 50 years). VOCs were detected in 70 percent of the wells sampled, which may reflect mostly urban land use near the wells. Pesticides were detected in 48 percent of the wells sampled. In some cases, pesticide detections may reflect agricultural land that has been recently urbanized, a common trend in the San Jacinto Basin.

In the San Jacinto Basin, the most commonly detected VOCs (more than 20 percent of the sampled wells) were the disinfection byproducts chloroform and bromodichloromethane and the solvent PCE (*fig. 11A*). Recharge of ground water by chlorinated water, particularly in the Hemet area, is a potential source of disinfection byproducts in the sampled wells. The number of VOCs detected per well was significantly lower in the San Jacinto Basin than in the Inland Basin, but not different from that for the Coastal Basin (*fig. 12A*; *table 1*). The lower number of VOCs detected per well may reflect the relatively low percentage of urban land use (33 percent, low population density (*fig. 2*), and the absence of large solvent plumes in the areas of the San Jacinto Basin that were sampled (*fig. 2*).

Table 2. Detection frequencies for volatile organic compounds (VOCs) and pesticides in younger and older ground water in the San Jacinto, Inland, and Coastal Basins, within the Santa Ana Basin, southern California.

[Younger ground water (recharged since the 1950s) is defined by a tritium concentration at or above 1 pCi/L]

Basin	VOCs		Pesticides	
	Younger	Older	Younger	Older
San Jacinto	83	20	72	20
Inland	92	33	88	33
Coastal	90	50	36	0
All basins	88	36	72	14

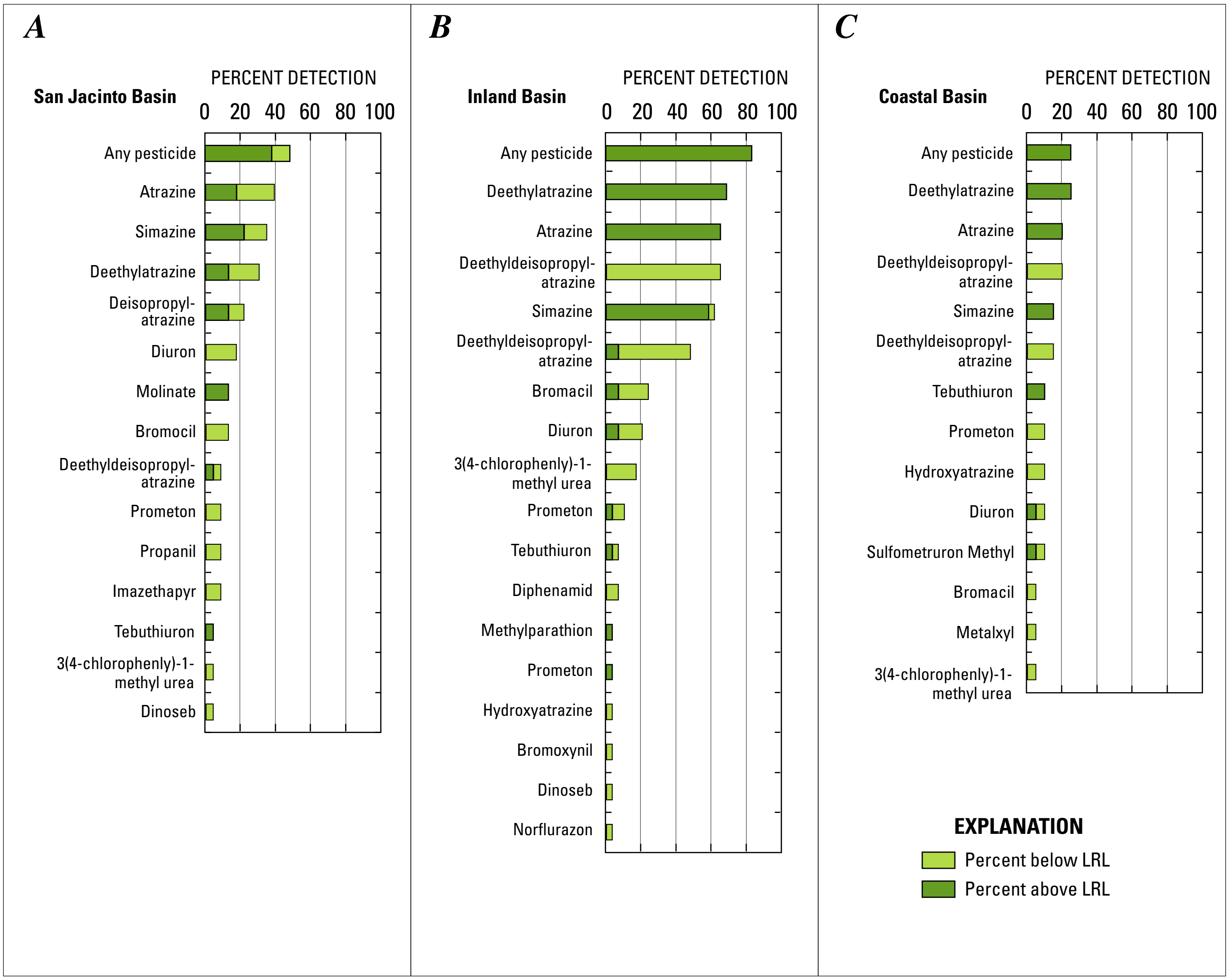


Figure 13. Detection frequencies for pesticide compounds by individual compound above and below the laboratory reporting limit (LRL) for the three subbasins of the Santa Ana Basin, southern California. *A*, San Jacinto Basin. *B*, Inland Basin. *C*, Coastal Basin.

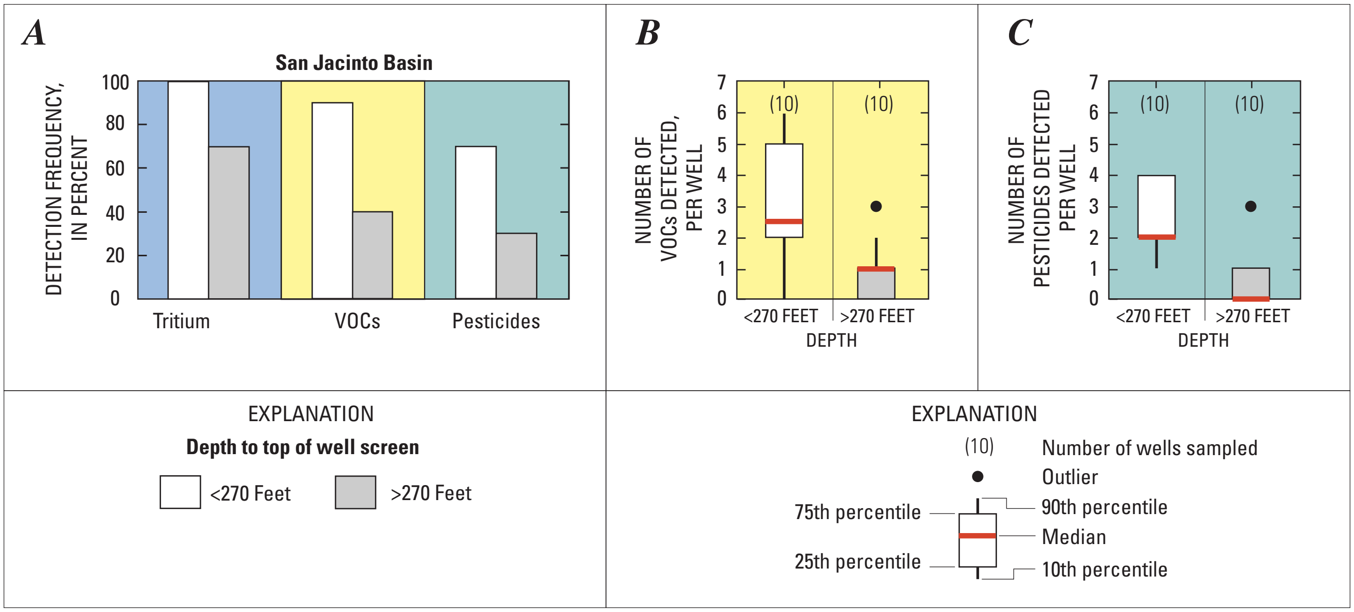


Figure 14. (*A*) detection frequencies for tritium, volatile organic compounds (VOCs), and pesticides; (*B*) number of VOCs detected, and (*C*) number of pesticides detected grouped by depth to the top of the well screen in the San Jacinto Basin.

The most commonly detected pesticides were the herbicides atrazine and simazine and the atrazine degradation products deethylatrazine and deisopropylatrazine (*fig. 13A*). Atrazine was detected more frequently than its daughter product deethylatrazine in the San Jacinto Basin, in contrast to detections in the other ground-water basins, indicating a shorter residence time in ground water.

Pesticides were detected less frequently in the San Jacinto Basin than in the Inland Basin (*fig. 10*), even though both basins are unconfined and the San Jacinto Basin has a higher percentage of agricultural land use. In addition, the number of pesticides detected per well was significantly lower in the San Jacinto Basin than in the Inland Basin (*table 1*; *fig. 12B*). The lower detection frequency, and the lower number of pesticides detected per well, may reflect the lower use of ground water (less pumping and engineered recharge) and consequently the lower flow (and transport) rates for the San Jacinto Basin than for the Inland Basin. Pesticides were detected more frequently in the San Jacinto Basin than in the Coastal Basin (fig. 10); the higher detection frequency is consistent with the basin being unconfined and having more agricultural land use. In addition, the median number of pesticides detected per well in the San Jacinto Basin was higher than that for the Coastal Basin (*table 1*; *fig. 12B*); however, the difference was not statistically significant (*table 1*). The pesticide data for the Coastal Basin were not suitable for basin-to-basin comparison; several wells located near recharge facilities had outliers with more than four detections per well (*fig. 12B*).

Relation to Ground-Water Age and Depth to the Top of the Well Screen

In the San Jacinto Basin, VOCs and pesticides were detected more frequently in younger ground water than older ground water (*table 2*). VOCs were detected in 83 percent of the younger samples and in 20 percent of the older samples. Similarly, pesticides were detected in 72 percent of the younger samples, and in 20 percent of the older samples. The higher detection frequencies in younger ground water suggest that these compounds have been introduced to the aquifer system since the early 1950s. The presence of VOCs and pesticides in older ground water may reflect the use of these compounds prior to the early 1950s. Alternatively, these compounds may have been introduced directly into older ground water from surface or shallow sources via well-bore leakage.

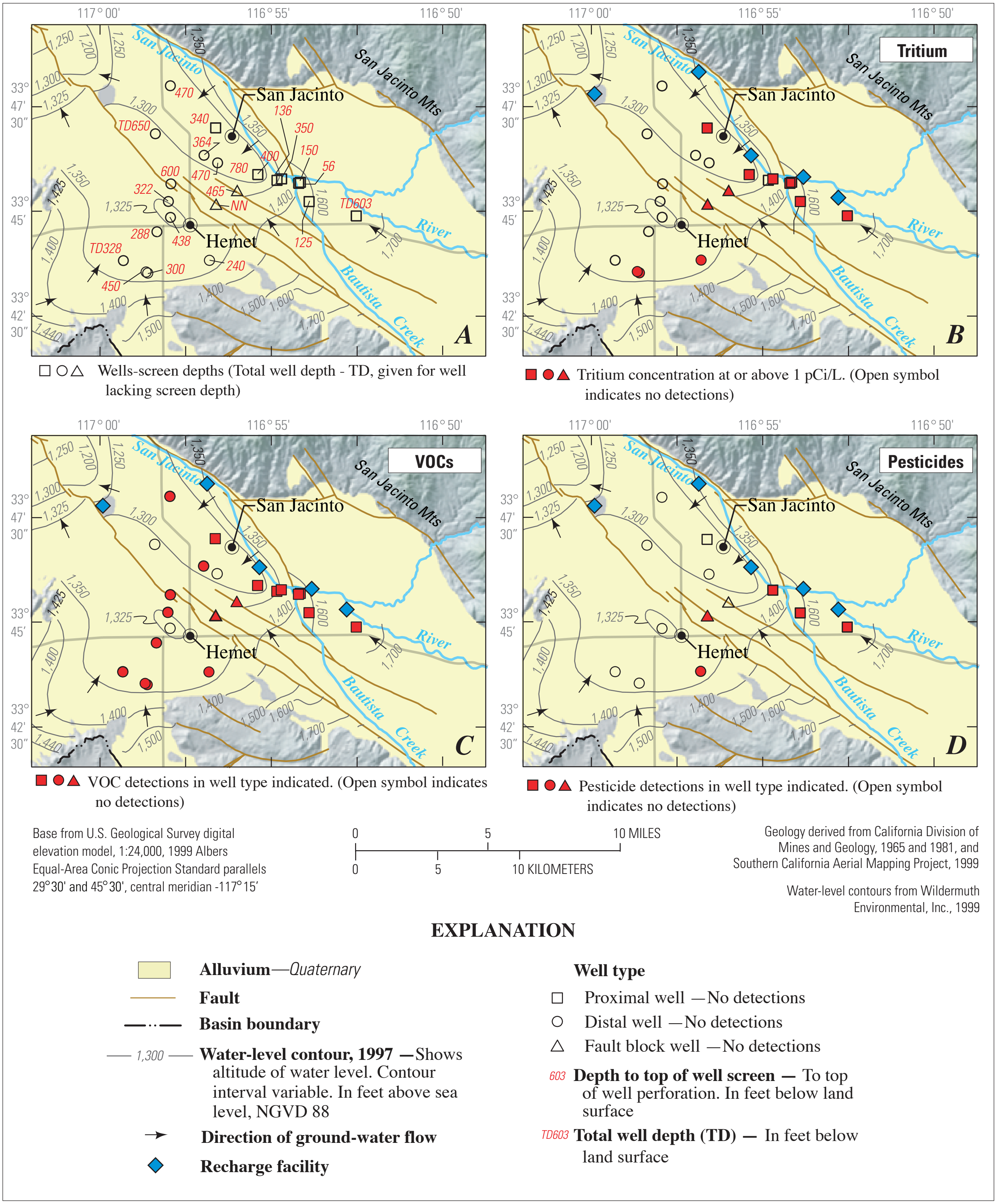
In the San Jacinto Basin, tritium was detected more frequently in shallower wells than in deeper wells (*fig. 14A*). Tritium was detected in all (100 percent) of the shallower wells and 70 percent of the deeper wells. The more frequent detection of tritium in shallower wells suggests that recharge to the ground-water flow system is primarily from above.

VOC detection frequency was higher in shallower wells (90 percent) than in deeper wells (40 percent; *fig. 14A*). In addition, the number of VOCs detected per well was significantly higher in shallower wells than in deep wells (*fig. 14B; table 3*), and inversely correlated to well-screen depth (*table 3*).

Table 3. Statistical tests for difference between groups of data (Wilcoxon test) and for correlation (Kendall's test) of potential explanatory factors with the number of VOCs detected and number of pesticides detected in the San Jacinto, Inland, and Coastal Basins, within the Santa Ana Basin, southern California.

[Kendall's test was only done when Wilcoxon test indicated significant difference between groups of data; p value, probability value; p values less than or equal to 0.10 indicate significant difference or correlation (green shading); —, not calculated; proximal, near recharge facilities]

Ground-water basin	Compound category	Explanatory variable	Wilcoxon test p value	Kendall's test p value	Kendall's tau
San Jacinto	VOCs	Screen depth	0.01	0.04	–0.33
	Pesticides	Screen depth	0.001	0.02	–0.36
	VOCs	Percent urban land use	0.85	—	—
	Pesticides	Percent urban land use	0.04	0.09	–0.25
	VOCs	Percent agricultural land use	0.41	—	—
	Pesticides	Percent agricultural land use	0.5	—	—
	VOCs	Population density (by median)	0.27	—	—
	Pesticides	Population density (by median)	0.04	0.01	–0.36
San Jacinto, Hemet area	VOCs	Screen depth (by median)	0.1	0.07	–0.28
	Pesticides	Screen depth (by median)	0.04	0.04	–0.44
	VOCs	Proximity to recharge	0.68	—	—
	Pesticides	Proximity to recharge	0.07	—	—
Inland	VOCs	Screen depth (by median)	0.19	—	—
	Pesticides	Screen depth (by median)	0.65	—	—
	VOCs	Screen depth (by <150, >350)	0.01	0.1	–0.3
	Pesticides	Screen depth (by <150, >350)	0.2	—	—
	VOCs	Percent urban land use	0.5	—	—
	Pesticides	Percent urban land use	0.46	—	—
	VOCs	Percent agricultural land use	0.68	—	—
	Pesticides	Percent agricultural land use	0.46	—	—
	VOCs	Population density (by median)	0.66	—	—
	Pesticides	Population density (by median)	1	—	—
Coastal	VOCs	Unconfined vs confined areas	0.05	—	—
	Pesticides	Unconfined vs confined areas	0.02	—	—
	VOCs	Proximity to recharge facilities	0	—	—
	Pesticides	Proximity to recharge facilities	0.07	—	—
	VOCs	Percent urban land use	0.86	—	—
	Pesticides	Percent urban land use	0.32	—	—
	VOCs	Population density (by median)	0.59		
	Pesticides	Population density (by median)	0.49		
Coastal, proximal	VOCs	Unconfined vs confined areas	0.08	—	—
	Pesticides	Unconfined vs confined areas	0.0006	—	—
Coastal, unconfined	VOCs	Screen depth	0.01	0.03	–0.26
	Pesticides	Screen depth	0.03	0.2	–0.24
	VOCs	Proximity to recharge facilities	0.01	—	—
	Pesticides	Proximity to recharge facilities	0.01	—	—
	VOCs	Percent urban land use	0.6	—	—
	Pesticides	Percent urban land use	1	—	—
	VOCx	Population density (by median)	0.69	—	—
	Pesticides	Population density (by median)	0.44	—	—
Coastal, confined	VOCs	Screen depth	0.19	—	—
	Pesticides	Screen depth	0.17	—	—
	VOCs	Proximity to recharge facilities	0.01	—	—
	Pesticides	Proximity to recharge facilities	0.27	—	—



□ ○ △ Wells-screen depths (Total well depth - TD, given for well lacking screen depth)

🟥 ● ▲ Tritium concentration at or above 1 pCi/L. (Open symbol indicates no detections)

🟥 ● ▲ VOC detections in well type indicated. (Open symbol indicates no detections)

🟥 ● ▲ Pesticide detections in well type indicated. (Open symbol indicates no detections)

Base from U.S. Geological Survey digital elevation model, 1:24,000, 1999 Albers Equal-Area Conic Projection Standard parallels 29°30' and 45°30', central meridian -117°15'

Geology derived from California Division of Mines and Geology, 1965 and 1981, and Southern California Aerial Mapping Project, 1999

Water-level contours from Wildermuth Environmental, Inc., 1999

EXPLANATION

🟨 **Alluvium**—*Quaternary*

Fault

Basin boundary

1,300 **Water-level contour, 1997** —Shows altitude of water level. Contour interval variable. In feet above sea level, NGVD 88

Direction of ground-water flow

◆ **Recharge facility**

Well type

□ Proximal well —No detections

○ Distal well —No detections

△ Fault block well —No detections

603 **Depth to top of well screen** — To top of well perforation. In feet below land surface

TD603 **Total well depth (TD)** — In feet below land surface

Figure 15. (*A*) Water-level contours and depths to the tops of well screens, and distribution of (*B*) tritium, (*C*) VOCs, and (*D*) pesticides in the Hemet area of the San Jacinto Basin of the Santa Ana Basin, southern California.

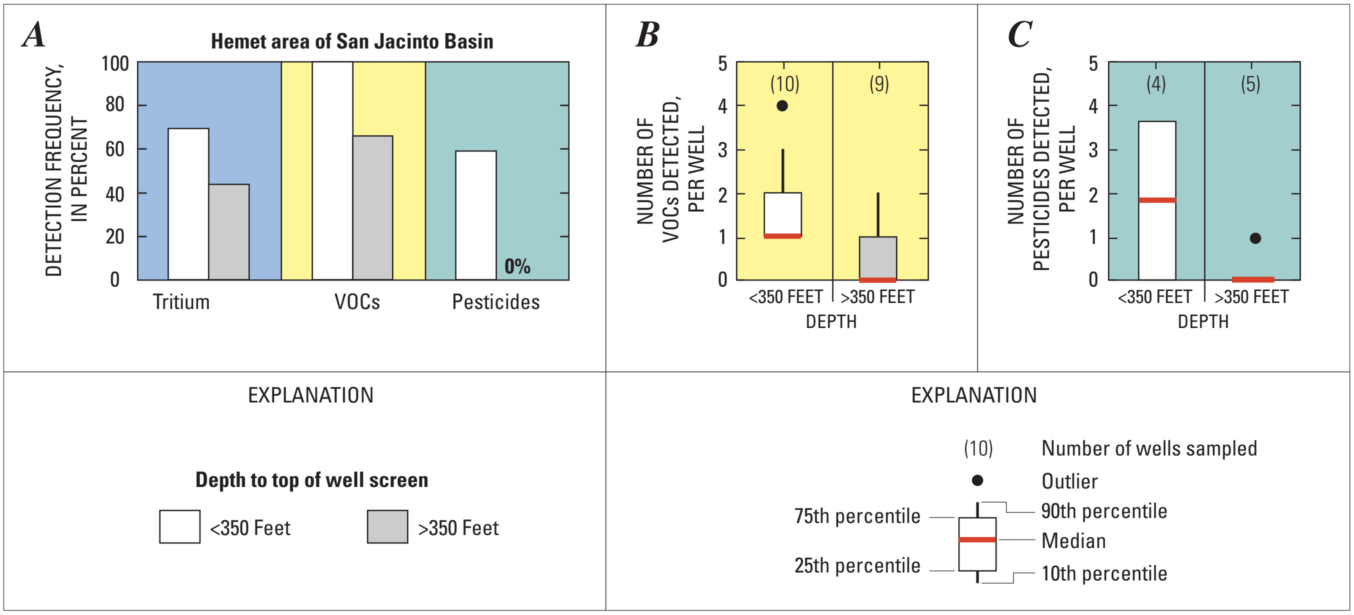


Figure 16. (*A*) Detection frequencies for tritium, volatile organic compounds (VOCs), and pesticides; (*B*) number of VOCs detected, and (*C*) number of pesticides detected by depth to the top of the well screen in the Hemet area of the San Jacinto Basin of the Santa Ana Basin, southern California.

Pesticides, like VOCS, were more frequently detected in shallower wells (70 percent) than in deeper wells (30 percent; *fig. 14A*). In addition, the number of pesticides detected per well was significantly higher in shallower wells than in deeper wells, and inversely correlated to well-screen depth (*table 3*; *fig. 14C*).

The inverse correlation of VOC and pesticide occurrence with depth to the top of the well screen indicates that shallower wells tend to be more susceptible to contamination than deeper wells in the San Jacinto Basin. This correlation could be due to the proximity of the well screen to the sources of these compounds at the land surface or due to the presence of these compounds in younger recharge. In addition, the less frequent occurrence of VOCs and pesticides in deeper wells could reflect degradation of these compounds during transport through the aquifer system.

Relation to Engineered Recharge in the Hemet Area

The distribution of VOCs and pesticides in ground water in the Hemet area of the San Jacinto Basin reflects proximity to sources of recharge (*fig. 15*). These sources include natural and engineered infiltration of water along the San Jacinto River, and natural infiltration along Bautista Creek. Recharge facilities located in and along the San Jacinto River take advantage of coarse soils and the availability of water. Water used for recharge may include water imported from northern California and from the Colorado River, as well as reclaimed wastewater (Williams and others, 1993). In the Hemet area, ground-water flow is generally from the San Jacinto River toward the city of Hemet where there is a large depression in water levels due to municipal pumping (*fig. 15A*; Rees and others, 1994).

In the Hemet area, tritium was detected more frequently in shallower wells (70 percent) than in deeper wells (44 percent; *fig. 16A*). The more frequent detection of tritium in shallower wells suggests recharge by younger water, primarily from above. However, the shallower wells are also located closer to engineered recharge sources than are the deeper wells ($p = 0.04$; Wilcoxon test).

Tritium was detected more frequently in water from wells near sources of engineered recharge (90 percent) than in wells farther from recharge sources (30 percent; *fig. 17A*). Based on detection frequency, proximity to sources of engineered recharge appears to be a more important factor than well-screen depth for explaining the presence or absence of younger ground water in the Hemet area.

Tritium was detected in two wells located relatively far from sources of recharge (triangle symbols, *fig. 15B*). These detections may reflect preferential flow along faults because they are moderately deep (*fig. 15A*) and not likely affected by sources near the wellhead. Each well is located along a fault that is crossed by Bautista Creek, which may be a source of recharge.

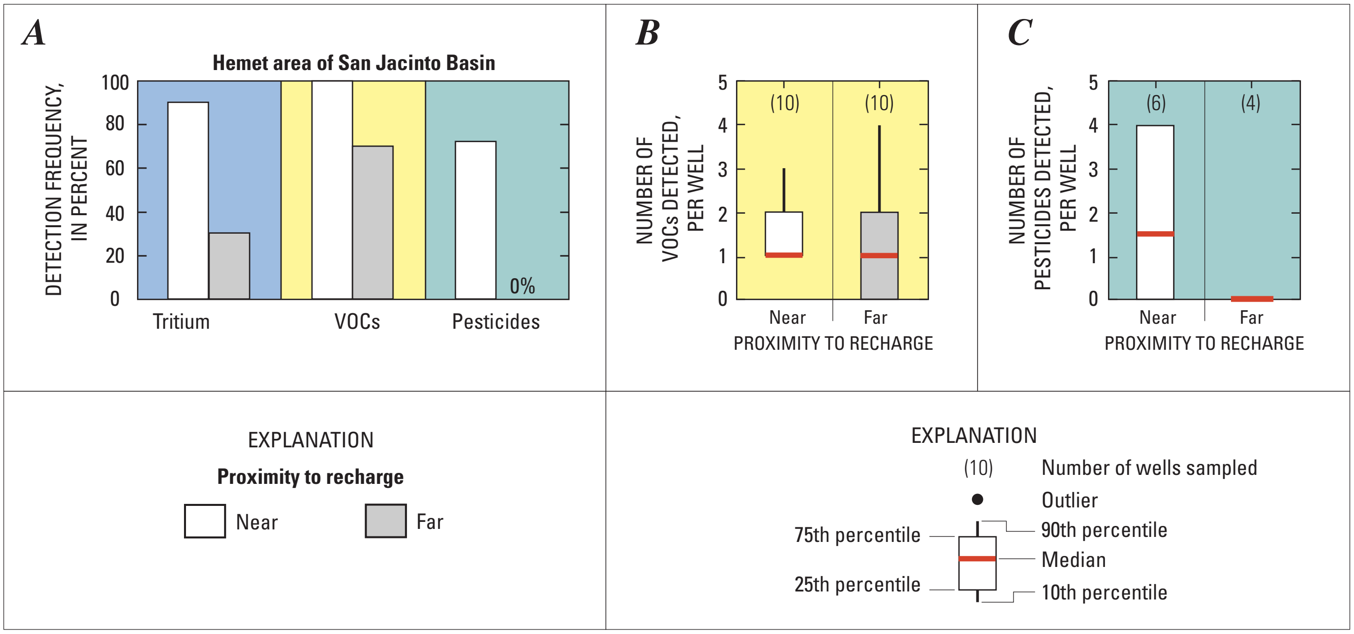


Figure 17. (*A*) Detection frequencies for tritium, volatile organic compounds (VOCs), and pesticides; (*B*) number of VOCs detected per well, and (*C*) number of pesticides detected by proximity to engineered recharge facilities in the Hemet area of the San Jacinto Basin of the Santa Ana Basin, southern California.

VOCs were detected more frequently in shallower wells (100 percent) than in deeper wells (67 percent; *fig. 16A*) in the Hemet area. In addition, the number of VOCs detected per well (*fig. 16B*) was significantly higher in shallow wells than in deeper wells, and was inversely correlated with screen depth (*table 3*). Although VOCs were detected more frequently in wells near engineered recharge sources (100 percent) than in distal wells (70 percent; *fig. 17A*), the number of VOCs detected per well was not statistically different between the two areas (*table 3*). Based on detection frequency, screen depth and proximity to sources of recharge are about equal in their ability to explain VOC occurrence in the Hemet area. Based on the number of VOCs detected per well, however, screen depth is the more important explanatory factor.

In contrast to other areas of the Santa Ana Basin, VOCs occur over a more widespread area than tritium in the Hemet area (*fig. 15C*). Of the 11 wells without detections of tritium in the Hemet area, 8 of them contained at least one VOC. The more widespread distribution of VOCs in this area could be due to the use of VOCs prior to the early 1950s or could be due to the introduction of VOCs into older ground water as a result of recharge from the overlying landscape. For example, chloroform, widely used since the 1920s, was detected in four wells and could have entered the ground-water flow system prior to the introduction of tritium. In contrast, TCE has been widely used only since the 1960s (Stackelberg and others, 2000) and was detected in one sample of older ground water. Other VOCs detected in older ground water were 1,2-dichloropropane (2 wells), cis-1,2-DCE (1 well), PCE (1 well), and tetrahydrofuran (1 well); the production and use of these compounds postdates the generation of anthropogenic tritium in the early 1950s. One additional VOC was detected in older ground water: carbon disulfide, which can occur naturally or as a product of organic synthesis. The lack of tritium detections and the widespread occurrence of VOCs used only since the 1960s in older ground water indicates that VOCs migrate downward from the land surface into older ground water in the Hemet area.

Pesticides were detected more frequently in shallower wells (60 percent) than in deeper wells (no detections; *fig. 16A*). In addition, the number of pesticides detected per well was significantly higher in the shallower wells and was inversely correlated with screen depth (*table 3*; *fig. 16C*). These results indicate that well-screen depth is an explanatory factor for the occurrence of pesticides in the Hemet area.

Pesticides were detected in all the wells located near sources of recharge and in none of the distal wells (*fig. 17A*). In addition, the number of pesticides detected per well was significantly higher in the wells near sources of recharge than in distal wells (*fig. 17C*; *table 3*). These results indicate that proximity to sources of recharge is an explanatory factor for the occurrence of pesticides in the Hemet area.

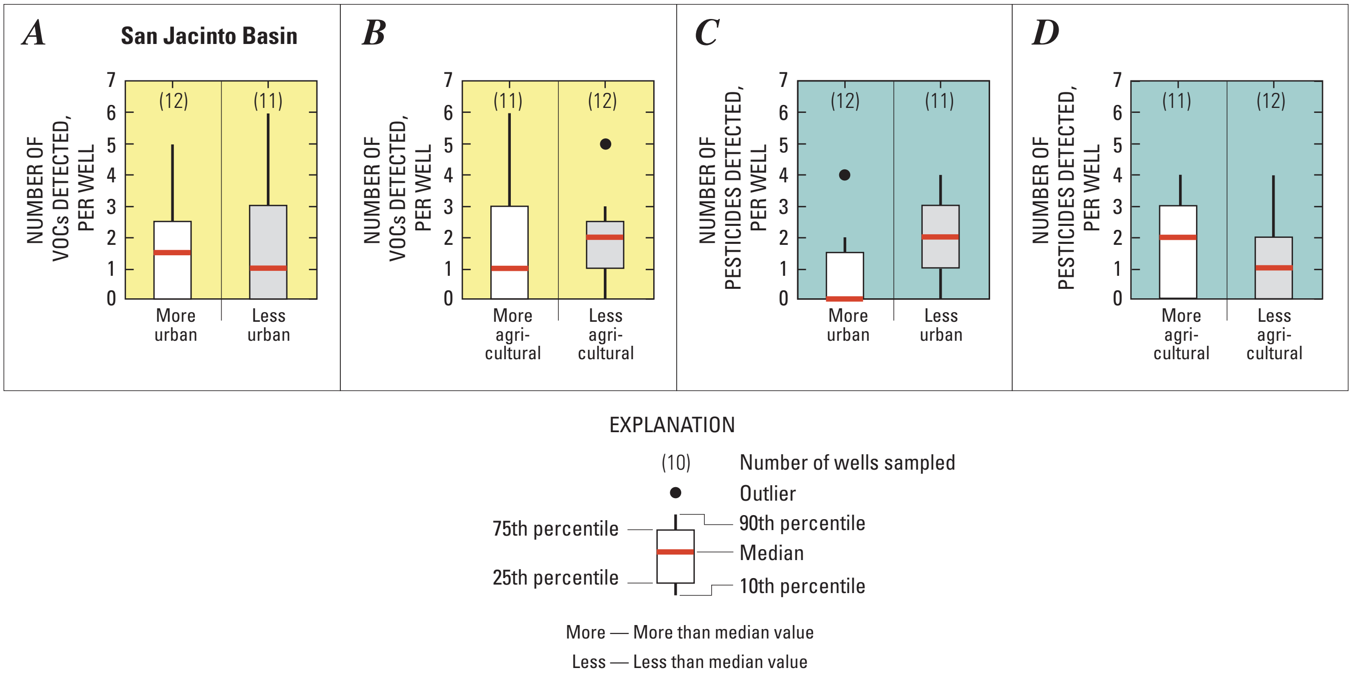


Figure 18. Number of compounds detected in the San Jacinto Basin of the Santa Ana Basin, southern California. *A*, Number of VOCs detected per well for urban use. *B*, Number of VOCs detected for agricultural land use. *C*, Number of pesticides detected for urban use. *D*, Number of pesticides detected for agricultural land use.

Relation to Land Use and Population Density

The San Jacinto Basin as a whole is the least urbanized (33 percent) of the Santa Ana ground-water basins and has the highest percentage of land used for agricultural purposes (37 percent). However, the median percentage of urbanized land within a 500-m (1,640-ft) radius of the sampled wells—75 percent— (*fig. 7A*) is relatively high because public-supply wells tend to be located in urbanized areas in proximity to highest demand. The median percentage of agricultural land use near the sampled wells in the San Jacinto Basin (6 percent) was higher than that for the Inland (1 percent) and Coastal (0 percent) Basins, but was much less than that for the basin as a whole (37 percent). Compared with the other ground-water basins, the San Jacinto Basin has had the least amount, and shortest history, of urban development. Urban development in the basins is mirrored by growth in population density (*fig. 9A*).

VOC detection frequencies in the San Jacinto Basin were lower for wells classified as more urban than for wells classified as less urban, 67 percent as compared with 73 percent. In addition, the number of VOCs detected per well was not statistically different between the two groups (*fig. 18A*; *table 3*). The absence of correlation between urban land use and VOC occurrence contrasts with national findings (Squillace and others, 2002). This contrast may reflect the relatively recent urbanization of agricultural land; the time since land-use conversion may be an additional factor to consider in the evaluation of VOC occurrence. The contrast with national findings may also reflect the relatively large depth of wells sampled in the San Jacinto Basin, which generally have large contributing areas influenced by land use beyond a 500-m radius.

VOC detection frequency was lower in wells classified as more agricultural (55 percent) than in wells classified as less agricultural (91 percent). This result is consistent with national findings (Squillace and others, 2002). However, the number of VOCs detected per well was not statistically different between the two groups (*table 3*; *fig. 18B*). These results may reflect the long history of agricultural land use; agricultural land use has had a relatively widespread impact on ground-water quality in the basin over a relatively long period of time.

The relationship between pesticide occurrence and land use within 500 m of wells sampled in the San Jacinto Basin contrasts with national findings. Nationally, pesticide occurrence directly correlated with urban and agricultural land use (Squillace and others, 2002). In the San Jacinto Basin, pesticide detection frequency was lower in wells classified as more urban (42 percent) than in wells classified as less urban (82 percent). In addition, the number of pesticides detected per well was significantly higher in the wells classified as less urban (*table 3*; *fig. 18C*), and was inversely correlated with percentage urbanization (*table 3*; Kendall's test). The inverse correlation is the opposite of national findings (Squillace and others, 2002). In addition, pesticide detection frequencies were the same for wells classified as more and less agricultural (58 percent). Similarly, the number of pesticides detected per well was not statistically different between the two groups (*table 3*; *fig. 18D*). These results indicate that current land use near the sampled wells is not an important factor for explaining pesticide occurrence in the San Jacinto Basin.

The number of VOCs detected per well was not significantly different when wells were classified by higher and lower population density (*table 3*). This result contrasts with national findings (Squillace and others, 2002). In addition, the number of pesticides detected per well was significantly lower for wells in areas classified as having higher population density than in areas of lower population density, and the number of pesticides was negatively correlated to population density near the sampled wells (*table 3*). These results contrast with national findings (Squillace and others, 2002). The contrasts may reflect contribution of pesticides from agricultural land that has been recently urbanized.

Occurrence and Distribution of VOCs and Pesticides in the Inland Basin

Detection Frequencies of Tritium, VOCs, and Pesticides

Tritium was detected somewhat more frequently (90 percent) than VOCs (86 percent) or pesticides (83 percent) in the Inland Basin (*fig. 10*). The detection frequencies of tritium, VOCs, and pesticides were higher in the Inland Basin than the corresponding frequencies in the San Jacinto Basin (*fig. 10*). The higher detection frequencies reflect the more intense utilization of the ground-water resource (pumping and engineered recharge) and longer history of urbanization in the Inland Basin than in the San Jacinto Basin. At the basin scale, the percentage of urbanization in the Inland Basin has been higher than in the San Jacinto Basin and therefore may be a useful surrogate for the intense utilization of the resource. In contrast, the percentage of land use around the sampled wells was not significantly different in these basins. The detection frequencies of tritium, VOCs, and pesticides were also higher in the Inland Basin than the corresponding frequencies in the Coastal Basin (*fig. 10*). The higher detection frequencies probably reflect the generally unconfined conditions in the Inland Basin as compared to the more widespread confined conditions in the Coastal Basin. Although the Coastal Basin is more urbanized on a basin scale and near the sampled wells, detection frequencies were lower reflecting the predominance of confined conditions.

The most commonly detected VOCs in the Inland Basin were the disinfection byproducts chloroform and bromodichloromethane and the solvents PCE, TCE, DCE, cis-1,2-dichloroethene, TCA, and 1,1-dichloroethane (*fig. 11B*). The number of VOCs detected per well was significantly higher in the Inland Basin than in the San Jacinto Basin, but not different from the Coastal Basin (*table 1*; *fig. 12A*). The greater number of VOCs detected per well in the Inland Basin compared with that in the San Jacinto Basin likely reflects a higher percentage of urban land use, for a longer period of time, in the Inland Basin than in the San Jacinto Basin.

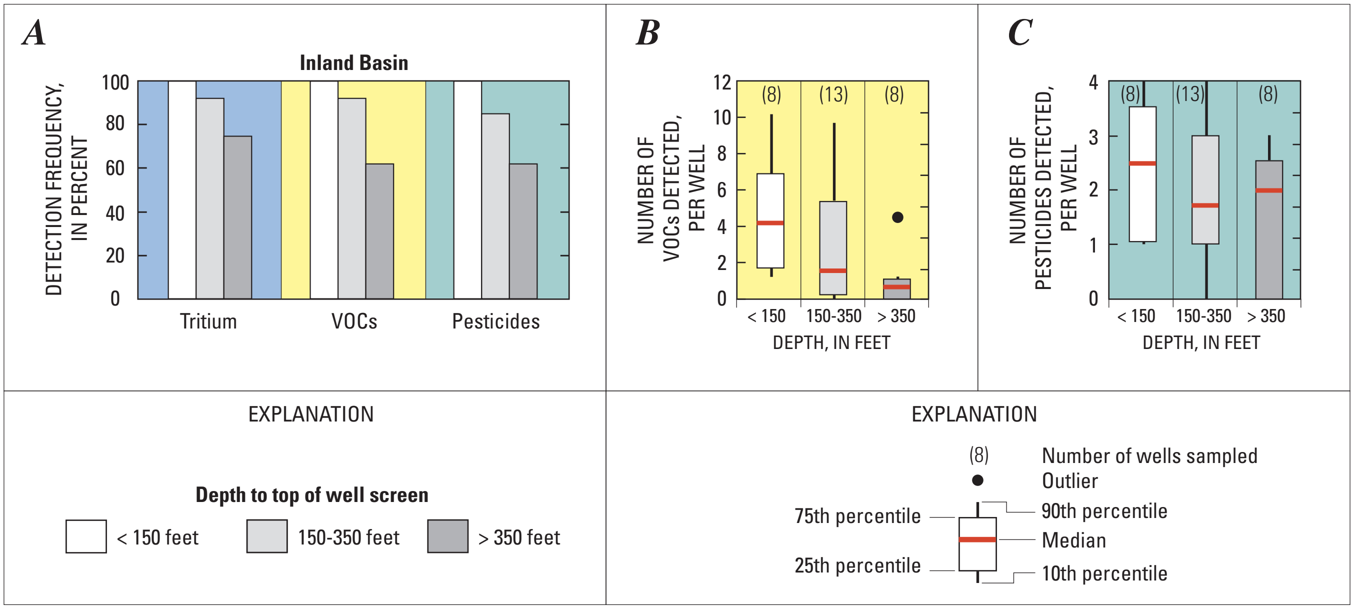


Figure 19. (*A*) Detection frequencies for tritium, volatile organic compounds (VOCs), and pesticides; (*B*) number of VOCs detected, and (*C*) number of pesticides detected grouped by depth to the top of the well screen in the Inland Basin of the Santa Ana Basin, southern California

Solvents were detected more frequently in the Inland Basin (75 percent) than in the San Jacinto (35 percent) and Coastal (35 percent) Basins (Hamlin and others, 2002). The higher detection frequency in the Inland Basin may reflect a greater percentage of industrial and military land use near the sampled wells; the median value was 14 percent in the Inland Basin, but only 3 percent in the San Jacinto Basin and 2 percent in the Coastal Basin (Appendixes A1–A3). Numerous solvent plumes associated with industrial and military facilities have been documented in the Inland Basin (Hamlin and others, 2002; Dawson and others, 2003).

The most commonly detected pesticides in the Inland Basin were the herbicides atrazine, simazine, bromacil, and diuron, and the atrazine degradation products deethylatrazine, deethyldeisopropylatrazine, and deisopropylatrazine (*fig. 13B*).

Pesticides were detected more frequently in the Inland Basin than in the San Jacinto Basin (*fig. 10*), even though both basins are unconfined and the Inland Basin has a lower percentage of agricultural land use. In addition, the number of pesticides detected per well was significantly higher in the Inland Basin (*table 1*; *fig. 12B*). The higher detection frequency and the higher number of pesticides detected per well may reflect the higher use of ground water (more pumping and engineered recharge) and consequently the higher flow (and transport) rates in the Inland Basin than in the San Jacinto Basin. Pesticides were also detected more frequently in the Inland Basin than in the Coastal Basin (*fig. 10*). Additionally, the number of pesticides detected per well was significantly higher in the Inland Basin (*table 1*; *fig. 12B*). These results are consistent with the higher percentage of agricultural land in the Inland Basin than in the Coastal Basin and with the confined nature of the Coastal Basin.

Relation to Ground-Water Age and Depth to the Top of the Well Screen

In the Inland Basin, VOCs and pesticides were detected more frequently in younger water than in older ground water (*table 2*). VOCs were detected in 92 percent of the younger samples and in 33 percent of the older samples. Similarly, pesticides were detected in 88 percent of the younger samples and in 33 percent of the older samples. As in the San Jacinto Basin, the higher detection frequencies in younger ground suggest that these compounds have generally entered the aquifer system since the early 1950s. The detection of VOCs and pesticides in older ground water may reflect use prior to this period. Alternatively, these compounds may have been introduced into older ground water from sources at or near land surface via well-bore leakage.

Tritium was detected more frequently in shallower wells than in deeper wells in the Inland Basin, 93 and 86 percent, respectively. To better define the distribution of younger water, the data were grouped into three depth intervals, rather than two, and a greater contrast in detection frequency is seen: 100 percent in wells with the depth to the top of the screen within 150 ft of land surface, 92 percent in wells with the top of the screen between 150 and 350 ft, and 75 percent in wells with the top of the screen more than 350 ft deep (*fig. 19A*). The trend in detection frequency of tritium with depth suggests that recharge to the ground-water flow system is primarily from above.

The trend in VOC detection frequency with depth is nearly the same as the trend for tritium: 100 percent in the shallowest wells, 92 percent in intermediate-depth wells, and 62 percent in the deepest wells (*fig. 19A*). In addition, the number of VOCs detected per well was significantly higher in the shallowest wells than in the deepest wells (*table 3*; *fig. 18B*). The number of VOCs detected per well was inversely correlated with screen depth (*table 3*). These results indicate that VOCs are transported downward from the overlying landscape to aquifers in the Inland Basin.

Pesticide detection frequency also decreases with depth: 100 percent in the shallowest wells, 85 percent in intermediate-depth wells, and 62 percent in the deepest wells (*fig. 19A*). However, the number of pesticides detected per well was not significantly different in the shallowest and the deepest wells (*table 3*; *fig. 19C*), nor correlated with screen depth (*table 3*). The trend in pesticide detection frequency indicates downward transport from the overlying landscape in the Inland Basin, but the number of compounds detected per well does not show a trend with depth.

In the Inland Basin, in contrast to the other basins, pesticides were detected nearly as frequently as VOCs, in both shallow and deep wells. The similar detection frequencies probably reflect intense use of the ground-water resource. The intense use of ground water has accelerated the movement of recharge water that might contain trace amounts of VOCs and pesticides through the flow system. Consequently, widespread distribution of pesticides may result from high flow rates and relatively short residence time in ground water, allowing less time for degradation and attenuation.

Relation to Land Use and Population Density

The Inland Basin as a whole has intermediate percentages of urban (58 percent) and agricultural (13 percent) land compared with that in the San Jacinto and Coastal Basins. The median percentage of urbanized land within 500 m (1,640 ft) of the sampled wells was higher than for the basin as a whole—75 percent. The amount of urbanization in the Inland Basin has been consistently higher than that in the San Jacinto Basin and consistently lower than that in the Coastal Basin (*fig. 9A*). The median percentage of agricultural land use near the sampled wells (1 percent) is intermediate between the San Jacinto (6 percent) and Coastal (0 percent) Basins, and is much lower than for the basin as a whole.

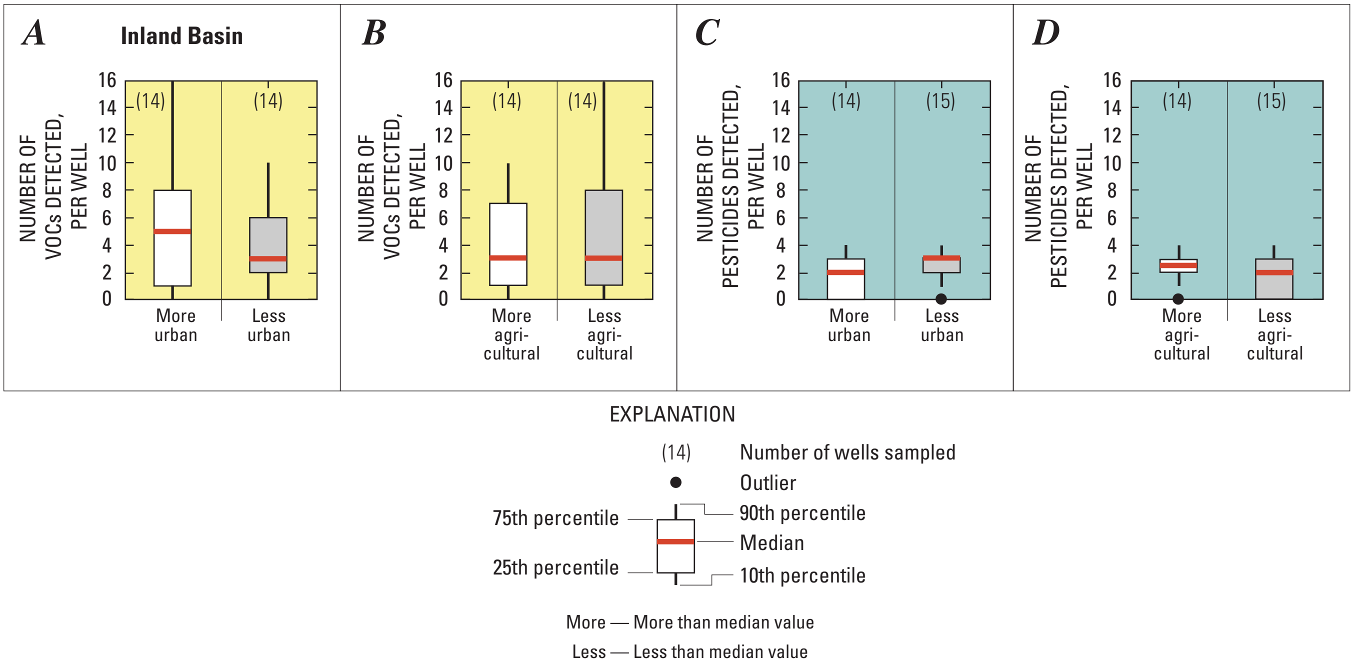


Figure 20. Number of volatile organic compounds (VOCs) and pesticides detected in agricultural and urban areas of the Inland Basin of the Santa Ana Basin, southern California. A, Number of VOCs detected per well for urban use. B, Number of VOCs detected per well for agricultural land use. C, Number of pesticides detected per well for urban use. D, Number of pesticides detected per well for agricultural land use.

VOC detection frequencies in the Inland Basin were lower in wells classified as more urban than in wells classified as less urban, 79 percent compared with 93 percent. In addition, the number of VOCs detected per well was not statistically different (table 3) between the two groups (*fig. 20A*). The lack of direct correlation between VOCs and urban land use within a 500-m radius of sampled wells contrasts with national findings (Squillace and others, 2002). These results suggest that ground-water quality in the Inland Basin was not significantly affected by urban land use near the sampled wells. Several VOC plumes extend from 3 to 6 mi (5 to 10 km) in the aquifer system, illustrating the large extent that contaminants have been distributed in ground water (Hamlin and others, 2002; Dawson and others, 2003). The sources of these VOC plumes, and elevated VOC concentrations in general, are associated with military and industrial land uses.

VOC detection frequencies were somewhat lower for wells classified as more agricultural than in wells classified as less agricultural, 79 percent compared with 87 percent. This result is consistent with national findings (Squillace and others, 2002). However, the number of VOCs detected per well was not statistically different between the two groups (*table 3*; *fig. 20B*). This absence of correlation suggests that current agricultural land use within a 500-m radius of the well is not related to VOC occurrence in the Inland Basin; military, industrial, and urban land uses at distances beyond 500 m have a broader impact on VOC occurrence.

Pesticide detection frequencies were lower in wells classified as more urban than in wells classified as less urban, 71 percent compared with 93 percent. This contrasts with national findings (Squillace and others, 2002). In addition, the number of pesticides detected per well was not statistically different between the two groups (*table 3*; *fig. 20C*). The current urban land use near the sampled wells is not an explanatory factor for pesticide occurrence in the Inland Basin.

Pesticide detection frequencies were higher in wells classified as more agricultural than in wells classified as less agricultural, 93 percent compared with 73 percent. This is consistent with national findings (Squillace and others, 2002). However, the number of pesticides detected per well was not statistically different between the two groups (*table 3*; *fig. 20D*). Although not statistically correlated with agricultural land use, pesticide occurrence may be related to pesticide usage in the basin.

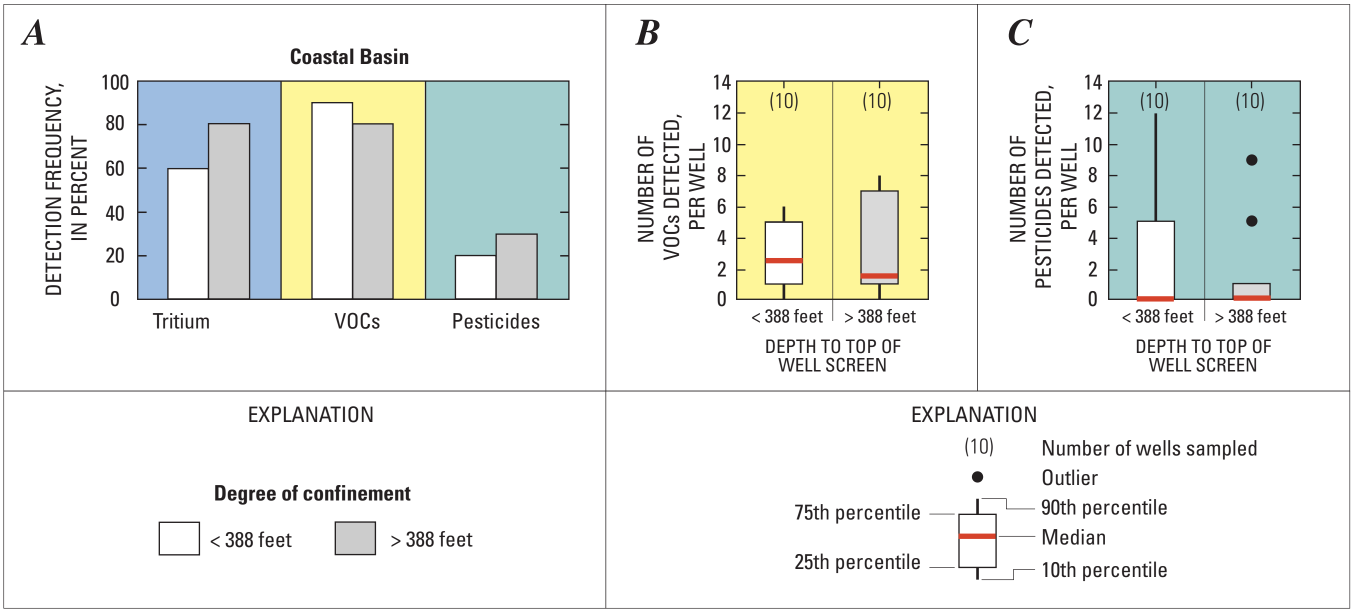


Figure 21. (*A*) Detection frequencies for tritium, volatile organic compounds (VOCs), and pesticides, and number of (*B*) VOCs and (*C*) pesticides detected by depth to the top of the well screen in the Coastal Basin of the Santa Ana Basin, southern California.

In the Inland Basin, the number of VOCs and pesticides detected per well was not significantly different for wells classified by higher and lower population density (*table 3*). This is in contrast to national findings (Squillace and others, 1999; Squillace and others, 2002). Population density near the sampled wells is not an explanatory factor for VOC and pesticide occurrence in the Inland Basin.

The lack of correlation of land use with VOCs and pesticides could be related to the relatively large depth of wells sampled in the Inland Basin and to intense use of ground water. The basin has been highly urbanized for a relatively long period of time and has a high population density that relies primarily on ground water for supply. As a consequence, ground-water flow rates have increased substantially, which has resulted in widespread occurrence of VOCs and pesticides in the basin.

Occurrence and Distribution of VOCs and Pesticides in the Coastal Basin

Detection Frequencies of Tritium, VOCs, and Pesticides

The Coastal Basin differs from the San Jacinto and Inland Basins in that VOCs were detected more frequently than tritium (85 percent as compared with 70 percent; *fig. 10*). However, many of the detections were at concentrations below the laboratory reporting limit (LRL; see "Approach" section for explanation of LRL); the detection frequency of VOCs at concentrations above the LRL was lower than the detection frequency of tritium. In the Coastal Basin, as in the other basins, pesticides were detected less frequently (25 percent) than tritium or VOCs.

In the Coastal Basin, the most commonly detected VOCs were the disinfection byproduct chloroform, the refrigerants CFC-113 and CFC-11, and the gasoline additive MTBE (*fig. 11C*). The number of VOCs detected per well in the Coastal Basin was not statistically different from the numbers detected per well in the San Jacinto and Inland Basins (*table 1*; *fig. 12A*). If the analysis is restricted to detections above the LRL, then the number of VOCs detected per well in the Coastal Basin was significantly lower than the number detected per well in the Inland Basin ($p = 0.08$, Wilcoxon test); the number of VOCs detected per well was not statistically different from the number detected per well in the San Jacinto Basin ($p = 0.80$, Wilcoxon test).

The most commonly detected pesticide compounds in the Coastal Basin were the herbicide atrazine and its degradation product deethylatrazine (*fig. 13C*). Pesticides were detected less frequently in the Coastal Basin than in the San Jacinto and Inland Basins (*fig. 10*). The number of pesticides detected per well was not significantly different from detections in the San Jacinto Basin, but was significantly lower than that in the Inland Basin (*table 1*; *fig. 12B*). The lower detection frequency, and lower number of pesticides detected per well, probably reflects the degree of aquifer confinement—mostly confined in the Coastal Basin and generally unconfined in the San Jacinto and Inland Basins.

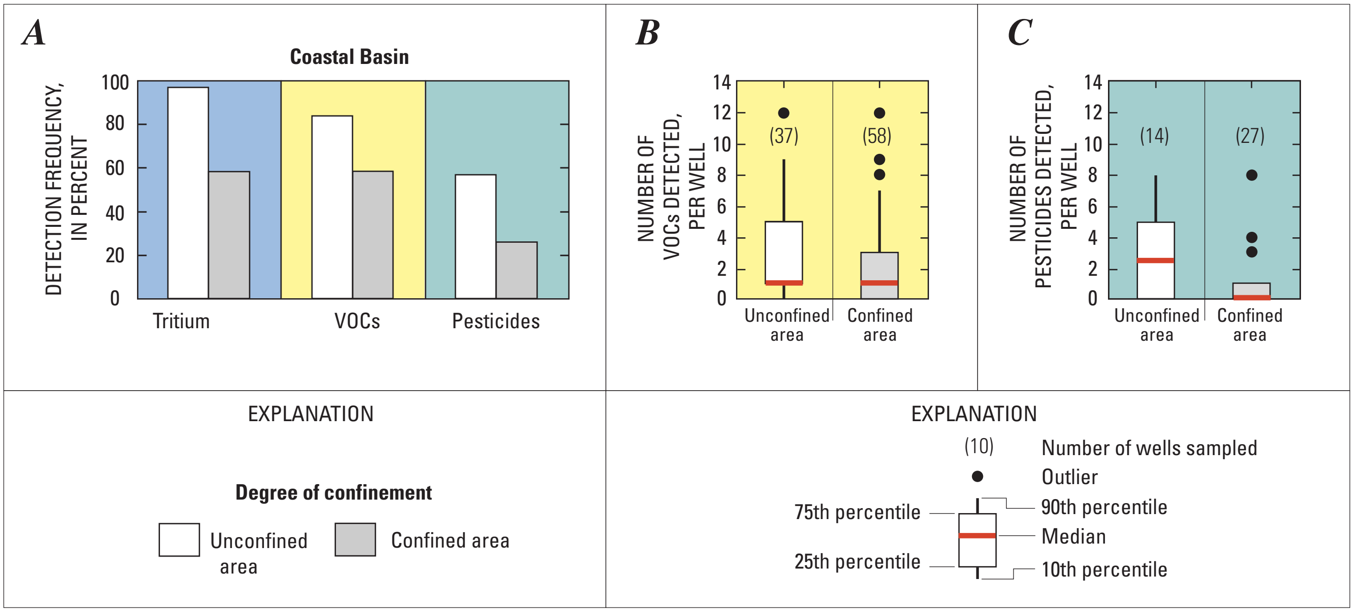


Figure 22. (*A*) Detection frequencies for tritium, volatile organic compounds (VOCs), and pesticides, and number of (*B*) VOCs and (*C*) pesticides detected in unconfined and confined areas of the Coastal Basin of the Santa Ana Basin, southern California.

Relation to Ground-Water Age and Depth to the Top of the Well Screen

VOCs and pesticides were detected more frequently in younger water (recharged since the early 1950s) than in older ground water in the Coastal Basin (*table 2*). VOCs were detected in more than 90 percent of the younger samples, but in only 50 percent of the older samples. Pesticides were detected in 36 percent of the younger samples, but in none of the older samples.

In the Coastal Basin, tritium was detected less frequently in wells with shallower screens than in wells with deeper screens (60 percent compared with 80 percent; *fig. 21A*), in contrast to that for wells in the San Jacinto and Inland Basins. Tritium was detected less frequently than VOCs in shallower wells, also in contrast to that for the other basins, with the exception of the Hemet area of the San Jacinto Basin. These results likely result from the predominance of lateral transport in the mostly confined aquifers in the Coastal Basin; the distribution of tritium was not related to well-screen depth.

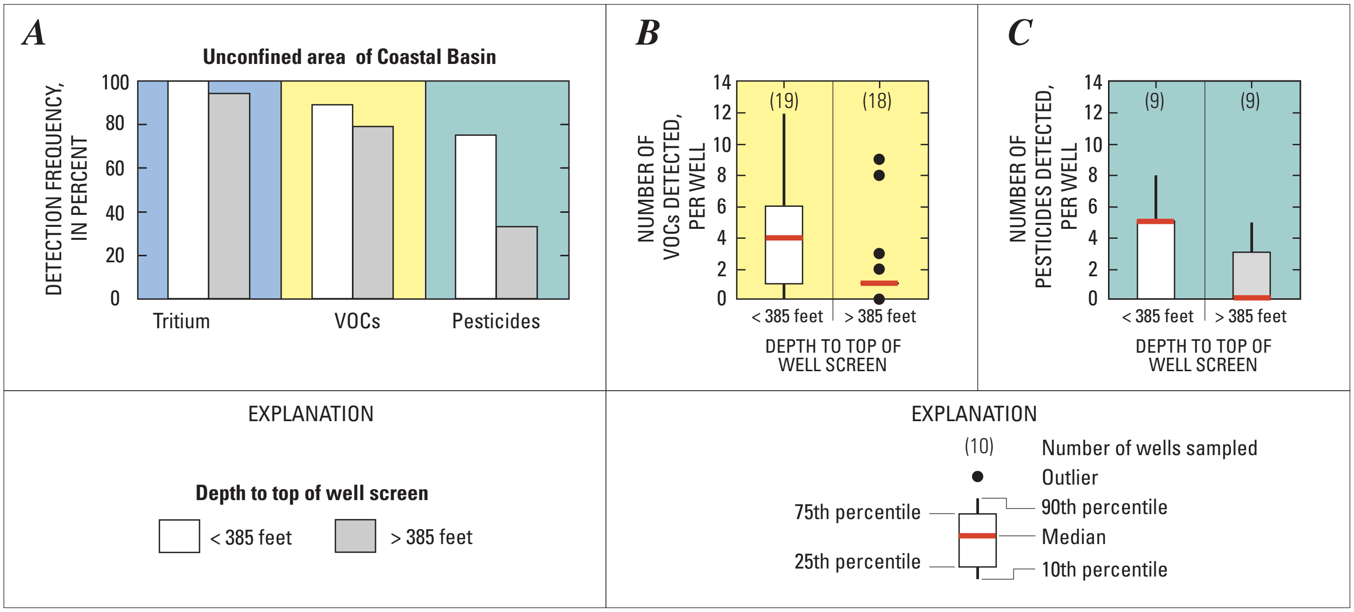


Figure 23. (*A*) Detection frequencies for tritium, volatile organic compounds (VOCs), and pesticides in unconfined areas, and number of (*B*) VOCs and (*C*) pesticides detected by depth to the top of the well screen in the Coastal Basin of the Santa Ana Basin, southern California.

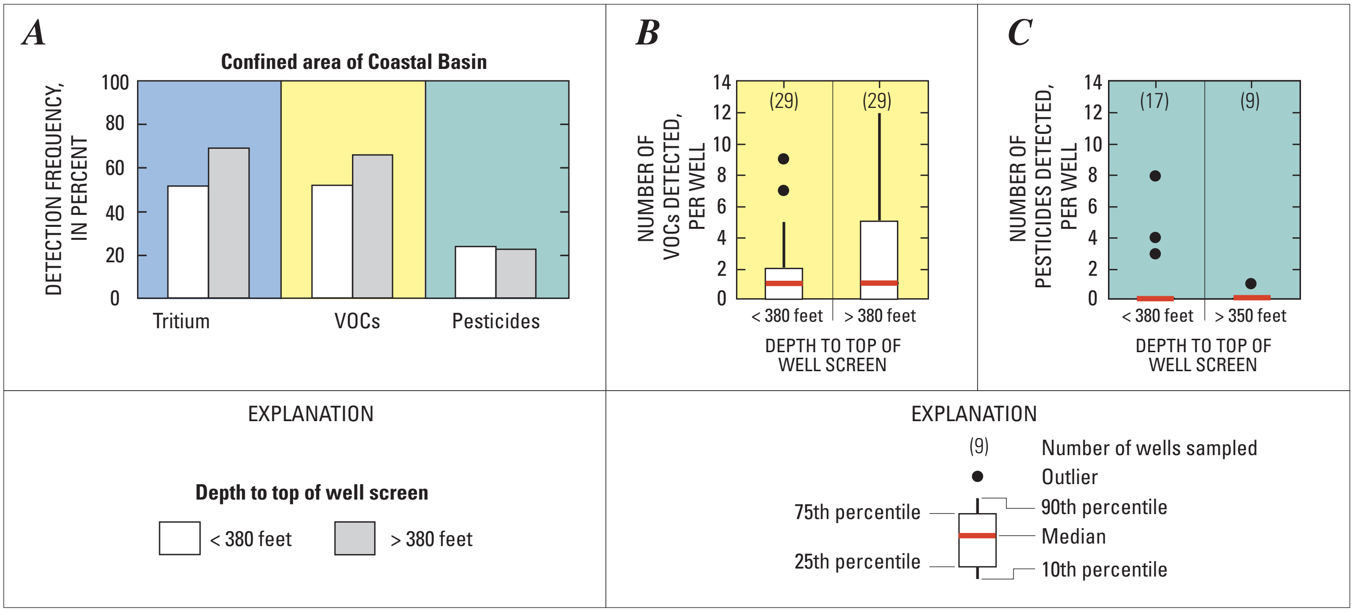


Figure 24. (*A*) Detection frequencies for tritium, volatile organic compounds (VOCs), and pesticides in confined areas and number of (*B*) VOCs and (*C*) pesticides detected by depth to the top of the well screen in the Coastal Basin of the Santa Ana Basin, southern California.

VOC detection frequencies in the Coastal Basin followed a pattern similar to that for the other basins: higher in shallower wells than in deeper wells (90 percent compared with 80 percent; *fig. 21A*). However, the number of VOCs detected per well was not significantly different in the shallower and deeper wells (*fig. 21B*). The lack of correlation suggests that well-screen depth is not explanatory for VOC occurrence in the Coastal Basin.

Pesticides were detected less frequently in shallower wells than in deeper wells (20 percent compared with 30 percent; *fig. 21A*), and, like tritium, contrasted with detection frequencies observed in the San Jacinto and Inland Basins (*figs. 14A* and *19A*). The number of pesticides detected per well was not significantly different in the shallower and deeper wells (*fig. 21C*). These results suggest that well-screen depth is not explanatory for pesticide occurrence in the Coastal Basin.

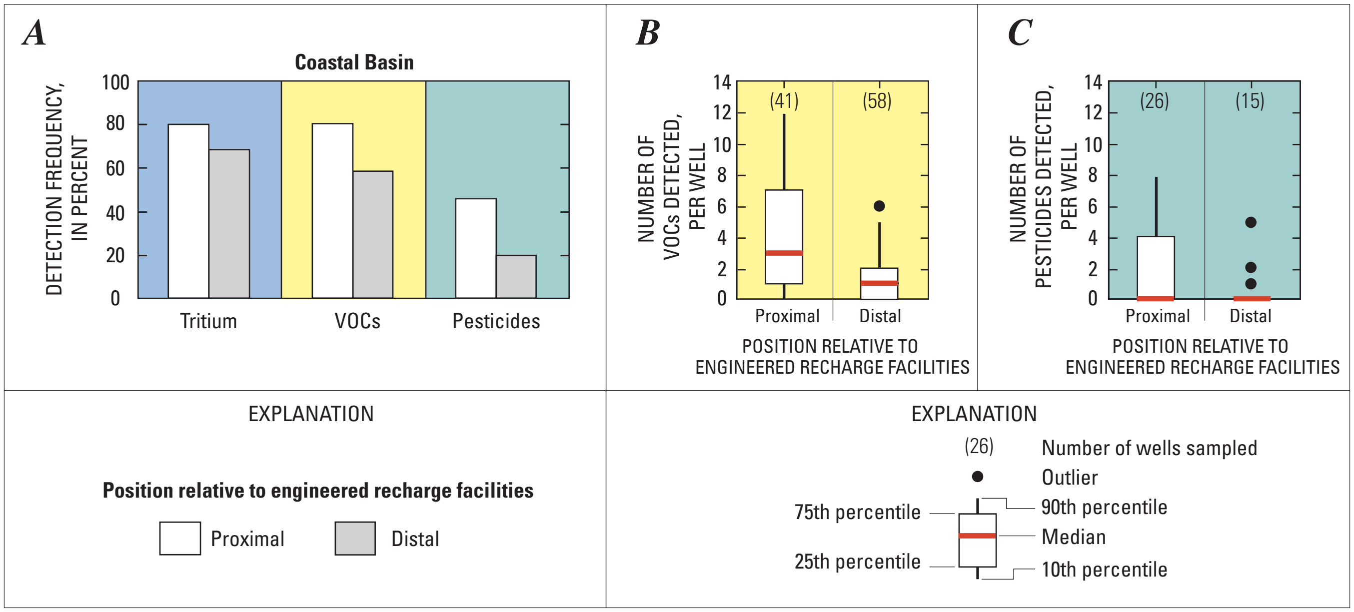


Figure 25. (*A*) Detection frequencies for tritium, volatile organic compounds (VOCs), and pesticides, and number of (*B*) VOCs and (*C*) pesticides detected by position relative to engineered recharge facilities in the Coastal Basin of the Santa Ana Basin, southern California.

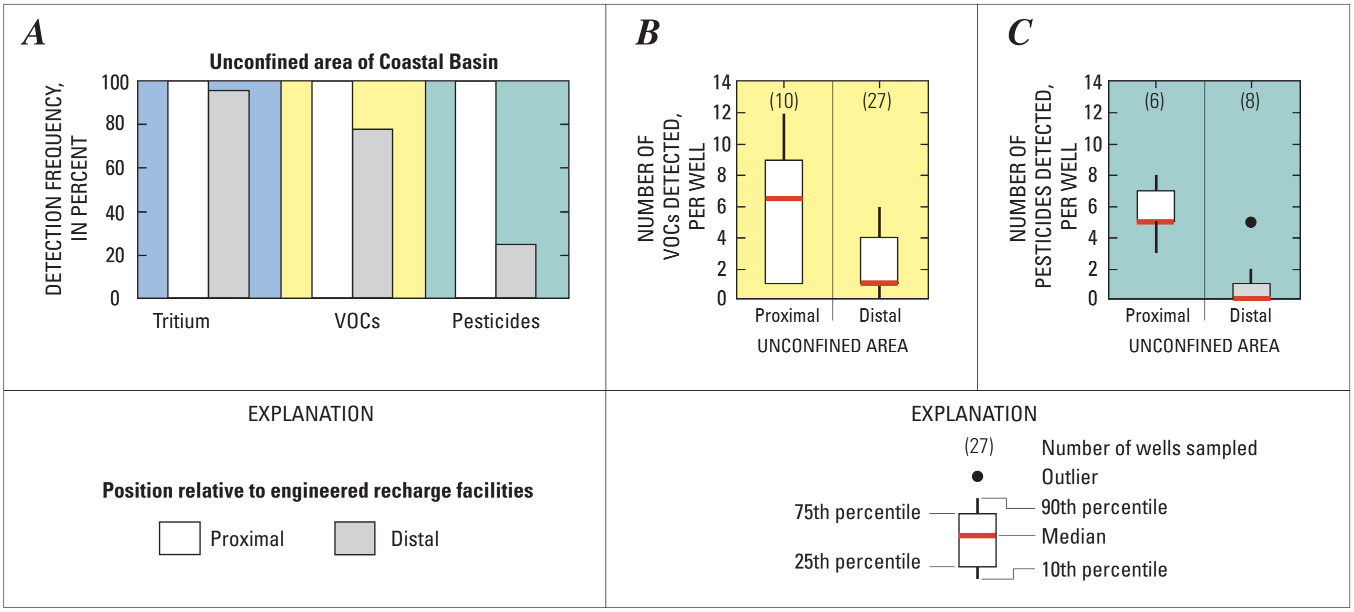


Figure 26. (*A*) Detection frequencies for tritium, volatile organic compounds (VOCs), and pesticides in unconfined areas, and number of (*B*) VOCs and (*C*) pesticides detected grouped by position relative to engineered recharge facilities in the Coastal Basin of the Santa Ana Basin, southern California.

Relation to Hydrogeologic Setting

The hydrogeologic setting (unconfined versus confined) is an important explanatory factor for the distribution of tritium, VOCs, and pesticides in the Coastal Basin. Tritium was detected more frequently in the unconfined area (97 percent of sampled wells) than in the confined area (59 percent of sampled wells; *fig. 22A*), indicating that ground water is younger in the unconfined area than in the confined area, and flows laterally from the unconfined to the confined area (Belitz and others, 2004).

VOC detection frequencies are similar to those observed for tritium (*fig. 22A*): higher in the unconfined area than in the confined area (84 percent versus 59 percent). In addition, the number of VOCs detected per well was significantly higher in the unconfined area than in the confined area (*table 3*; *fig. 22B*).

Pesticide detection frequencies are also similar to those observed for tritium (*fig. 22A*): higher in the unconfined area than in the confined area (57 percent versus 26 percent). And like VOCs, the number of pesticides detected per well was significantly higher in the unconfined area than in the confined area (*table 3*; *fig. 22C*).

The distribution of tritium, VOCs, and pesticides is consistent with the dynamics of the flow system. Ground water recharged in the unconfined area since the early 1950s contains trace amounts of VOCs and pesticides and flows laterally into the confined area.

In the unconfined area of the Coastal Basin, tritium was detected in all (100 percent) of the shallower wells and in 94 percent of the deeper wells (*fig. 23A*). The higher detection frequency in the shallower wells is consistent with downward movement of recharge in the unconfined area.

VOCs were also detected more frequently in shallower wells (89 percent) than in deeper wells (79 percent) in the unconfined area (*fig. 23A*). In addition, the number of VOCs detected per well was significantly higher in the shallower wells than in the deeper wells, and was inversely correlated with depth to the top of the well screen (*table 3*; *fig. 23B*). These results indicate downward movement of ground water in the unconfined area of the Coastal Basin.

Pesticides were also detected more frequently in shallower wells (75 percent) than in deeper wells (33 percent) in the unconfined area (*fig. 23A*). In addition, the number of pesticides detected per well was significantly higher in shallower wells than in deeper wells (*table 3*; *fig. 23C*). These results are consistent with downward movement of ground water in the unconfined area of the basin.

In the confined area of the Coastal Basin, tritium was detected less frequently in shallower wells than in deeper wells (52 versus 69 percent; *fig. 24A*). VOCs were also detected less frequently in shallower wells than in deeper wells: 52 percent compared to 66 percent (*fig. 23A*). However, the number of VOCs detected per well was not significantly different in shallower and deeper wells (*table 3*; *fig. 24B*). The detection frequencies are the opposite of what one would expect in a system where recharge is from above. Instead, recharge in the confined area of the aquifer system occurs primarily by lateral flow from the unconfined area.

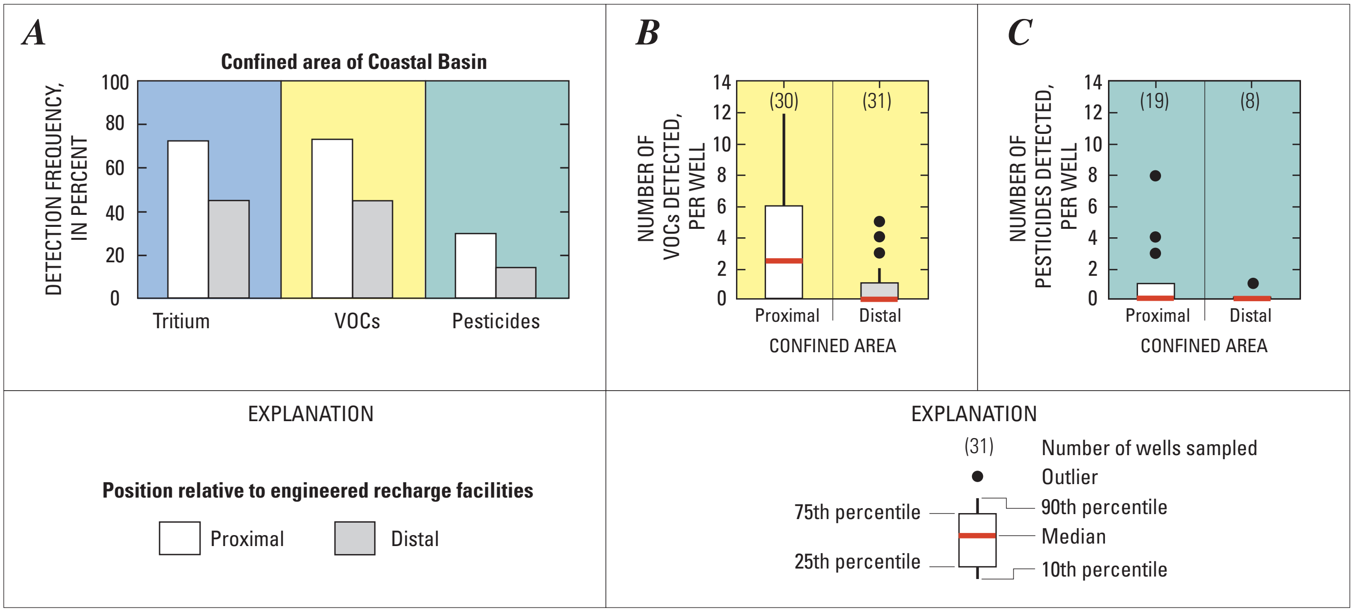


Figure 27. (*A*) Detection frequencies for tritium, volatile organic compounds (VOCs), and pesticides in confined areas, and number of (*B*) VOCs and (*C*) pesticides detected by position relative to engineered recharge facilities in the Coastal Basin of the Santa Ana Basin, southern California.

Pesticides were detected at about the same frequency in shallower and deeper wells in the confined area (24 and 22 percent, respectively; *fig. 24A*). The number of pesticides detected per well was not significantly different in shallower and deeper wells (*table 3*; *fig. 24C*). The median number of pesticides detected in both shallower and deeper wells was zero; only 4 of 26 wells sampled for pesticides in the confined area had detections (*fig. 24C*). These results reflect relatively low stability and low mobility of pesticides, which are lost during transport to, and through, the confined aquifer system.

Relation to Proximity to Engineered Recharge Facilities Along the Santa Ana River

Within the Coastal Basin, the ground-water flow system is dominated by high rates of recharge from engineered recharge facilities along the Santa Ana River (*fig. 4*). Tritium and VOCs define the “Santa Ana River flow path,” which extends more than 12 mi (20 km) from the recharge facilities in the unconfined area into the confined area (Dawson and others, 2003); the distribution of these compounds reflects a relatively long history of intense, focused recharge. In the flow path, the importance of the recharge facilities is reflected in the distribution of anthropogenic compounds; tritium, VOCs, and pesticides occur more frequently in wells that are proximal to the engineered recharge facilities than in wells that are more distal (*fig. 25A*). The numbers of VOCs and pesticides detected were significantly higher in the proximal wells than in wells further from the recharge facilities (*table 3*; *fig. 25B,C*). These results are consistent with increased ground-water flow (and transport of anthropogenic compounds) in response to recharge from engineered facilities.

If the comparison is restricted to wells in the unconfined area, the same relations are observed: higher detection frequencies in the proximal wells than in distal wells (*fig. 26A*). Indeed, tritium, VOCs, and pesticides were detected in all (100 percent) of the proximal wells. The numbers of VOCs and pesticides detected per well were both significantly higher in the proximal wells than in the distal wells sampled in the Coastal Basin (*table 3*; *fig. 26B,C*).

If the comparison is restricted to wells in the confined area, the same relations are again observed: higher detection frequencies in the proximal wells than in the distal wells (*fig. 27A*). The number of VOCs detected per well was significantly higher in the proximal wells than in the distal wells (*table 3*; *fig. 27B*). However, the number of pesticides detected per well was not significantly different for the two groups of wells (*table 3*; *fig. 27C*). The median number of pesticide detections for both groups of wells was zero, reflecting loss during transport.

The more frequent occurrence and greater number of VOCs and pesticides in wells located in proximity to the engineered recharge facilities reflects the displacement of native ground water by water introduced to the flow system since the early 1950s; large-scale recharge of imported water began at that time.

Relation to Land Use and Population Density

The Coastal Basin is the most highly urbanized of the three basins; 80 percent of the land overlying the aquifer system is urban. The basin also has a longer history of urbanization, as indicated by historical trends in population density, than the other ground-water basins (*fig. 9A*). However, the aquifer system is confined in most of the Coastal Basin; therefore overlying land use is not expected to have a significant correlation with the general occurrence of anthropogenic compounds. The quality of water used in engineered recharge facilities and land use in the unconfined (recharge) area of the Coastal Basin are primary factors affecting the occurrence and distribution of VOCs and pesticides in the aquifer system.

The numbers of VOCs and pesticides detected per well were not significantly different when compared by the percentage of urbanization near the wells sampled in the Coastal Basin (*table 3*). Correlation of VOC and pesticide detections with urban land use would be more likely in the unconfined area of the basin. However, VOC and pesticide detections were not significantly different when grouped by percentage of urbanization in the unconfined area (*table 3*). The absence of correlation in both cases can be attributed to several factors: (1) uniformly high urban land use near the wells (appendix table A3), (2) use of large amounts of imported water (containing VOCs and pesticides) for recharge in the basin (from the Inland Basin, the Colorado River, and Northern California), and (3) widespread distribution of point sources of VOCs.

Similarly, the number of VOCs and pesticides detected per well were not significantly different when compared by population density near the wells sampled in the Coastal Basin (*table 3*). In addition, VOC and pesticide detections were not significantly different when grouped by population density in the unconfined area (*table 3*). Population density follows similar trends to, and may be considered a surrogate for, urbanization. The absence of correlation of VOCs and pesticides with population density near the sampled wells can be attributed to the same factors as that for percentage of urbanization.

Summary and Conclusions

The Santa Ana Basin can be subdivided into three primary ground-water basins: the San Jacinto, Inland, and Coastal Basins. Aquifers in the San Jacinto Basin are unconfined and land use in the basin is primarily agricultural (37 percent), with lesser amounts of urban (33 percent) and undeveloped (25 percent) land use. Population density in the basin increased from 188 people per km^2 in 1970 to 558 people per km^2 in 2000. Aquifers in the Inland Basin are also unconfined and land use in the basin is primarily urban (58 percent), with lesser amounts of agricultural (13 percent) and undeveloped land (28 percent). Population density in the basin increased from 925 people per km^2 in 1970 to 1,620 people per km^2 in 2000. The Coastal Basin includes a relatively small unconfined area (28 percent) and a relatively large confined area (72 percent). Recharge is primarily from engineered facilities in the unconfined area. The Coastal Basin is the most urbanized (80 percent) of the three ground-water basins. Population density in the basin increased from 1,800 people per km^2 in 1970 to 3,160 people per km^2 in 2000.

Data from two different types of studies were used in this report. Subunit surveys (SUS) were designed to obtain a statistical characterization of the basins as a whole. Data from special studies (flow path and aquifer susceptibility) were used, along with SUS data, to evaluate explanatory factors affecting water quality within individual basins. The wells sampled in these studies were primarily deep production wells, mostly used for public supply. The total depths of these wells ranged from 98 to 1,720 ft. The depths to the tops of the well screens ranged from 26 to 818 ft. Land use near the wells (within 500 m) was more urban than land use in the basins as a whole; public-supply wells tend to be located in urban areas in proximity to highest demand.

The most frequently detected VOCs in the San Jacinto, Inland, and Coastal Basins (occurring in more than 20 percent of the wells in any one basin) were disinfection byproducts (chloroform and bromodichloromethane), solvents (PCE, TCE, DCE, *cis*-1,2-dichloroethene, TCA, and 1,1-dichloroethane), refrigerants (CFC-113 and CFC-11), and the gasoline additive MTBE. The most frequently detected pesticide compounds were the herbicides atrazine and simazine and the atrazine degradation products deethylatrazine, deisopropylatrazine, and deethyldeisopropylatrazine.

The occurrence and distribution of VOCs and pesticides in the Santa Ana ground-water basins were evaluated in relation to two types of explanatory factors: hydrogeologic characteristics and land use. Hydrogeologic characteristics evaluated were setting (unconfined or confined), ground-water age, depth to the top of well perforations, and proximity to engineered recharge. Land-use factors evaluated were the percentage of urban and agricultural land and population density. Population density can be considered a surrogate for the relative degree of urbanization.

Anthropogenic compounds were detected more frequently in unconfined aquifers than in confined aquifers in the Santa Ana ground-water basins. In the mostly unconfined Inland and San Jacinto Basins and in the unconfined part of the Coastal Basin, tritium was detected in 90, 78, and 97 percent of the wells sampled, respectively. In contrast, tritium was detected in 59 percent of the wells sampled in the confined area of the Coastal Basin. Similarly, VOCs were detected in more than 70 percent of the wells sampled in the unconfined areas, but in only 59 percent of the wells sampled in the confined area. Pesticides were detected in 83 and 48 percent of the wells sampled in the unconfined Inland and San Jacinto Basins, respectively. In the unconfined part of the Coastal Basin, pesticides were detected in 57 percent of the wells sampled, but in only 26 percent of the wells sampled in the confined area.

VOCs and pesticides were detected more frequently in younger ground water (recharged since the early 1950s) than older ground water. In the three ground-water basins, VOCs were detected in 88 percent of the younger samples and in 36 percent of the older samples. Pesticides were detected in 72 percent of the younger samples and in 14 percent of the older samples. In addition, more compounds (both VOCs and pesticides) were detected in younger samples. Water from shallow wells and wells proximal to recharge facilities is generally younger than water from deep wells and wells distal from recharge facilities.

VOCs and pesticides were detected more frequently in shallower wells than in deeper wells in the unconfined San Jacinto and Inland Basins, and in the unconfined area of the Coastal Basin. In addition, the number of compounds detected per well was inversely correlated with depth to the top of the well screen. These correlations reflect the presence of younger ground water in shallower wells as compared to deeper wells, and proximity to sources of contamination from the overlying landscape. VOC and pesticide occurrence were not correlated with depth to the top of the well screen in confined aquifers of the Coastal Basin; the lack of correlation reflects the dominance of lateral flow and insulation from the overlying landscape.

Proximity to engineered recharge facilities is an important explanatory factor for the distribution of anthropogenic compounds in the Coastal Basin and in the Hemet area of the San Jacinto Basin. VOCs and pesticides were detected more frequently in wells near engineered recharge facilities than in more distal wells. In addition, the number of VOCs and pesticides detected per well was significantly higher in proximal wells than distal wells in the Coastal Basin. In the Hemet area, the number of pesticides detected per well was significantly higher in proximal wells. In the Coastal Basin, anthropogenic compounds (tritium, VOCs, and pesticides) are present in ground water as much as 16 mi (25 km) from the recharge facilities, illustrating the large-scale displacement of native water by water recharged since the early 1950s.

On a national basis, land use within 500 m of shallow wells was an explanatory factor for the occurrence of VOCs and pesticides. A national evaluation of NAWQA data found that urban land use was positively correlated with VOC and pesticide occurrence. Similarly, on a national basis, population density showed a positive correlation with VOCs and pesticides, and agricultural land use was positively correlated with pesticide occurrence. In contrast, land use within 500 m of wells sampled in the Santa Ana ground-water basins was not an explanatory factor for the occurrence of VOCs and pesticides.

The absence of correlation between land use near wells (urban, agricultural, and population density) and the occurrence of VOCs and pesticides in the Santa Ana ground-water basins is due to a number of factors. In the Coastal Basin, most of the wells sampled are relatively deep and insulated from the overlying landscape by a thick confining layer. In the unconfined Inland and San Jacinto Basins, the absence of correlation is likely due to the large depth of the wells sampled; the capture zones for these deep wells likely extend beyond 500 m. As evidence, there are solvent plumes in the Inland Basin that extend up to 10 km from the points of entry into the system. Another explanation for the lack of correlation between land use and the occurrence of VOCs and pesticides is that the current land use commonly differs from land use at the time of recharge; in the unconfined San Jacinto and Inland basins, population density has increased substantially since 1970.

Qualitatively, there was a relationship between basin-scale land use and basin-scale detection frequencies of VOCs and pesticides in the unconfined aquifers of the Santa Ana ground-water basins. Urban land uses and population density are higher in the Inland Basin than in the San Jacinto Basin, and VOCs and pesticides were detected more frequently in the Inland Basin. In addition, urbanization in the Inland Basin has led to more intense use of ground water and increased transport rates of these compounds.

The distribution of anthropogenic compounds in the Santa Ana ground-water basins illustrates the extensive influence of human activities on water quality. These compounds are widely distributed in ground water in the Santa Ana Basin, both laterally and vertically. Engineered recharge, irrigation return flow (both agricultural and landscape), and intensive municipal pumping have accelerated the movement of ground water, and have widely distributed anthropogenic compounds in the aquifer systems. The distribution of anthropogenic compounds, generally in trace amounts, refines our understanding of the aquifer systems; this knowledge can be used to better manage the ground-water resource.

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Appendix : Classification of Wells in the San Jacinto, Inland, and Coastal Basins

Table A1. San Jacinto Basin explanatory factors for the occurrence and distribution of volatile organic compounds (VOCs) and pesticides within the Santa Ana Basin, southern California.

[Proximal wells are near recharge facilities; distal wells are more distant; —, no data; n/a, not applicable; mi^2, square mile; m, meter]

NAWQA ID[1]	Depth to top of well screen relative to median value	Location of well relative to engineered recharge facilities in the Hemet area	Percent agricultural land within 500 m of well	Percent urban land within 500 m of well	Percent undeveloped land within 500 m of well	Population density within 500 m of well, people per mi^2
SAS-1	Deeper	Proximal	0	100	0	1,070
SAS-2	—	N/a	0	100	0	1,486
SAS-3	Deeper	Distal	9	89	0	1,724
SAS-4	Shallower	Proximal	0	100	0	1,568
SAS-5	—	N/a	6	80	14	529
SAS-6	Deeper	Distal	0	51	0	615
SAS-7	—	N/a	15	78	6	1,518
SAS-8	Deeper	Proximal	33	67	0	1,848
SAS-9	Deeper	N/a	0	87	6	2,277
SAS-10	Deeper	N/a	0	0	100	408
SAS-11	Deeper	N/a	2	20	74	785
SAS-12	Shallower	N/a	81	16	3	331
SAS-13	Shallower	N/a	12	62	26	88
SAS-14	Shallower	N/a	0	100	0	196
SAS-15	Shallower	N/a	74	5	20	85
SAS-16	Shallower	N/a	0	80	0	352
SAS-17	Shallower	N/a	52	41	6	85
SAS-18	Deeper	Distal	8	77	0	93
SAS-19	Shallower	Proximal	0	81	19	189
SAS-20	Deeper	N/a	43	8	50	12
SAS-21	Shallower	Proximal	35	18	47	281
SAS-22	Shallower	N/a	75	5	20	310
SAS-23	Deeper	Distal	0	100	0	345
SAC-1	Deeper	N/a	69	12	19	159
SAC-2	Shallower	Distal	11	89	0	886
SAC-3	Deeper	Proximal	26	57	14	513
SAC-4	Deeper	Distal	32	61	0	690
SAC-5	Deeper	Distal	7	48	1	1,068
SAC-6	Shallower	Distal	0	100	0	1,930
SAC-7	Deeper	Proximal	0	100	0	1,040
SAC-8	Deeper	Distal	9	86	4	778
SAC-9	Shallower	Distal	42	17	41	363
SAC-10	Shallower	Proximal	9	45	45	339
SAC-11	Shallower	Proximal	6	48	46	405

[1] Wells are described and water-quality data are summarized in a report by Hamlin and others (2002).

Table A2. Inland Basin explanatory factors for the occurrence of compounds within the Santa Ana Basin, southern California.

[mi^2, square mile]

NAWQA ID[1]	Depth to top of well screen relative to median value	Percent agricultural land within 500 meters of well	Percent urban land within 500 meters of well	Percent vacant land within 500 meters of well	Population density within 500 meters of well, people per mi^2
INS-1	Deeper	1	99	0	1,034
INS-2	Deeper	9	74	18	84
INS-3	Deeper	18	59	21	169
INS-4	Shallower	0	100	0	2,491
INS-5	Shallower	0	82	10	1,531
INS-6	Deeper	5	95	0	1,617
INS-7	Deeper	0	100	0	1,887
INS-8	Shallower	0	55	45	20
INS-9	Deeper	0	99	0	2,150
INS-10	Deeper	2	98	0	1,622
INS-11	Deeper	0	40	43	1,790
INS-12	Deeper	61	37	0	441
INS-13	Shallower	0	90	0	1,826
INS-14	Shallower	40	58	3	539
INS-15	Shallower	0	58	42	435
INS-16	Deeper	0	17	66	48
INS-17	Shallower	4	84	7	1,148
INS-18	Shallower	2	21	62	254
INS-19	Shallower	0	98	2	302
INS-20	Deeper	43	55	1	869
INS-21	Shallower	43	25	32	133
INS-22	Deeper	7	76	17	1,194
INS-23	Shallower	3	34	63	421
INS-24	Shallower	1	94	6	794
INS-25	Deeper	18	71	6	25
INS-26	Shallower	0	97	0	1,965
INS-27	Shallower	0	83	0	93
INS-28	Deeper	14	66	19	306
INS-29	Shallower	0	100	0	3,139

[1] Wells are described and water-quality data are summarized in a report by Hamlin and others (2002).

Table A3. Coastal Basin explanatory factors for occurrence of compounds within the Coastal Basin of the Santa Ana Basin, southern California.

[m, meters; mi^2, square mile]

NAWQA ID[1]	Hydrogeologic setting (aquifer type)	Depth to top of well screen relative to median value	Location of well relative to engineered recharge facilities	Percent agricultural land within 500 m of well	Percent urban land within 500 m of well	Percent vacant land within 500 m of well	Population density within 500 m of well, people per mi^2
COS-1	Confined	Shallow	Proximal	0	52	0	1,835
COS-2	Confined	Deep	Proximal	0	96	0	2,993
COS-3	Confined	Shallow	Proximal	0	90	0	1,498
COS-4	Confined	Shallow	Distal	0	77	0	3,180
COS-5	Confined	Shallow	Distal	4	93	0	2,103
COS-6	Unconfined	Deep	Distal	0	93	0	1,942
COS-7	Unconfined	Shallow	Distal	0	100	0	2,499
COS-8	Unconfined	Shallow	Distal	0	100	0	1,510
COS-9	Unconfined	Shallow	Distal	2	32	51	201
COS-10	Confined	Deep	Distal	0	100	0	6,106
COS-11	Unconfined	Deep	Distal	0	100	0	2,711
COS-12	Unconfined	Deep	Distal	6	69	10	1,881
COS-13	Confined	Shallow	Distal	32	66	0	1,762
COS-14	Confined	Shallow	Proximal	29	68	0	2,112
COS-15	Confined	Deep	Distal	0	84	0	3,367
COS-16	Confined	Deep	Proximal	0	52	0	1,397
COS-17	Confined	Shallow	Distal	0	100	0	3,720
COS-18	Unconfined	Deep	Proximal	0	91	0	2,706
COS-19	Unconfined	Deep	Proximal	0	62	0	56
COS-20	Confined	Deep	Proximal	8	92	0	3,021
COF-1	Confined	Shallow	Proximal	7	93	0	3,065
COF-2	Confined	Shallow	Proximal	0	98	0	1,834
COF-3	Confined	Deep	Proximal	0	99	0	3,058
COF-4	Confined	Shallow	Proximal	1	93	0	2,984
COF-5	Confined	Deep	Proximal	0	100	0	3,542
COF-6	Confined	Shallow	Proximal	1	99	0	4,113
COF-7	Confined	Deep	Proximal	9	91	0	1,955
COF-8	Unconfined	Deep	Distal	0	100	0	2,711
COF-9	Confined	Shallow	Proximal	0	99	0	2,263
COF-10	Confined	Shallow	Proximal	0	96	0	4,256
COF-11	Confined	Shallow	Proximal	3	96	0	2,263
COF-12	Unconfined	Shallow	Proximal	6	90	0	919
COF-13	Confined	Deep	Proximal	0	90	0	3,204
COF-14	Unconfined	Shallow	Distal	0	100	0	2,593
COF-15	Confined	Shallow	Distal	6	94	0	3,093
COF-16	Unconfined	Shallow	Distal	0	73	16	2,669
COF-17	Confined	Shallow	Proximal	0	100	0	279
COF-18	Unconfined	Shallow	Proximal	0	100	0	988
COF-19	Unconfined	Shallow	Proximal	1	99	0	2,582

See footnote at end of table.

Table A3. Coastal Basin explanatory factors for occurrence of compounds withint eh Coastal Basin of the Santa Ana Basin, southern California—Continued.

[m, meters; mi², square mile]

NAWQA ID[1]	Hydrogeologic setting (aquifer type)	Depth to top of well screen relative to median value	Location of well relative to engineered recharge facilities	Percent agricultural land within 500 m of well	Percent urban land within 500 m of well	Percent vacant land within 500 m of well	Population density within 500 m of well, people per mi²
COF-20	Confined	Shallow	Proximal	3	97	0	6,749
COF-21	Unconfined	Shallow	Proximal	0	78	0	1,018
COF-22	Unconfined	Shallow	Distal	6	62	0	2,058
COF-23	Confined	Shallow	Distal	0	47	0	4,779
OCC-1	Confined	Deep	Proximal	3	94	0	2,578
OCC-2	Confined	Deep	Proximal	0	97	0	2,711
OCC-3	Confined	Deep	Proximal	0	96	0	2,993
OCC-4	Confined	Deep	Distal	0	98	0	1,555
OCC-5	Confined	Deep	Distal	0	100	0	1,270
OCC-6	Confined	Shallow	Distal	13	84	0	2,081
OCC-7	Confined	Deep	Proximal	8	92	0	3,021
OCC-8	Confined	Deep	Proximal	0	98	0	2,744
OCC-9	Unconfined	Shallow	Proximal	0	96	0	5,296
OCC-10	Confined	Deep	Proximal	0	84	0	3,492
OCC-11	Confined	Deep	Proximal	0	92	0	5,589
OCC-12	Unconfined	Deep	Distal	0	91	0	3,825
OCC-13	Confined	Deep	Proximal	1	86	0	4,073
OCC-14	Confined	Shallow	Distal	4	93	0	2,103
OCC-15	Confined	Deep	Distal	6	82	0	1,472
OCC-16	Confined	Shallow	Distal	0	100	0	1,165
OCC-17	Unconfined	Deep	Proximal	0	91	0	2,706
OCC-18	Confined	Shallow	Distal	0	92	0	1,165
OCC-19	Unconfined	Shallow	Proximal	0	99	0	3,431
OCC-20	Unconfined	Deep	Proximal	0	62	0	56
OCC-21	Confined	Shallow	Distal	0	98	0	3,516
OCC-22	Confined	Shallow	Distal	0	92	0	8,807
OCC-23	Confined	Deep	Distal	0	100	0	6,214
OCC-24	Confined	Deep	Distal	0	100	0	6,106
OCC-25	Confined	Deep	Distal	0	100	0	1,540
OCC-26	Unconfined	Deep	Distal	0	93	0	1,942
OCC-27	Unconfined	Shallow	Distal	0	100	0	1,380
OCC-28	Confined	Deep	Distal	2	97	0	4,271
OCC-29	Confined	Shallow	Distal	0	98	0	2,212
OCC-30	Confined	Shallow	Proximal	0	95	0	3,236
OCC-31	Unconfined	Shallow	Distal	4	93	0	823
OCC-32	Unconfined	Shallow	Distal	5	94	0	726
OCC-33	Confined	Shallow	Distal	28	72	0	544
OCC-34	Confined	Shallow	Distal	0	60	40	1,669
OCC-35	Unconfined	Deep	Distal	0	100	0	3,728
OCC-36	Confined	Deep	Distal	41	16	44	496
OCC-37	Unconfined	Deep	Distal	0	100	0	2,543

See footnote at end of table.

Table A3. Coastal Basin explanatory factors for occurrence of compounds withint eh Coastal Basin of the Santa Ana Basin, southern California—Continued.

[m, meters; mi^2, square mile]

NAWQA ID[1]	Hydrogeologic setting (aquifer type)	Depth to top of well screen relative to median value	Location of well relative to engineered recharge facilities	Percent agricultural land within 500 m of well	Percent urban land within 500 m of well	Percent vacant land within 500 m of well	Population density within 500 m of well, people per mi^2
OCC-38	Confined	Deep	Distal	0	100	0	1,600
OCC-39	Unconfined	Shallow	Distal	0	100	0	2,632
OCC-40	Unconfined	Deep	Distal	3	94	0	1,421
OCC-41	Unconfined	Deep	Distal	10	81	0	722
OCC-42	Unconfined	Deep	Distal	6	85	0	762
OCC-43	Confined	Deep	Distal	0	96	0	7,682
OCC-44	Confined	Shallow	Distal	0	98	0	3,704
OCC-45	Confined	Shallow	Distal	0	99	0	6,402
OCC-46	Unconfined	Shallow	Distal	0	64	0	3,264
OCC-47	Unconfined	Shallow	Distal	0	84	0	2,354
OCC-48	Unconfined	Deep	Distal	0	86	0	2,108
OCC-49	Confined	Deep	Distal	3	87	0	3,614
OCC-50	Confined	Deep	Distal	0	100	0	5,863
OCC-51	Confined	Deep	Distal	0	100	0	5,801
OCC-52	Unconfined	Shallow	Distal	0	100	0	4,425
OCC-53	Confined	Deep	Distal	14	86	0	1,548
OCC-54	Unconfined	Deep	Distal	5	95	0	642
OCC-55	Unconfined	Shallow	Proximal	0	100	0	1,947
OCC-56	Unconfined	Deep	Distal	0	100	0	2,019

[1] Wells are described and water-quality data are summarized in a report by Hamlin and others (2002).