Acknowledgments

The California Legislature, through Assembly Bill 599 (AB 599, the "Ground-Water Quality Monitoring Act of 2001") recognizes the importance of maintaining and monitoring the quality of California's ground water. The U.S. Geological Survey's report, "Framework for a Ground-Water Quality Monitoring and Assessment Program for California," is submitted as part of this larger effort. The preparation of this report was greatly aided by the input of a number of water resources professionals who served as members of two important committees that were established by AB 599: the Public Advisory Committee and the Interagency Task Force. The preparation of this report also was greatly aided by the support and collaboration of staff from the State Water Resources Control Board.

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Framework for a Ground-Water Quality Monitoring and Assessment Program for California

By Kenneth Belitz, Neil M. Dubrovsky, Karen Burow, Bryant Jurgens, *and* Tyler Johnson

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U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 03-4166

Prepared in cooperation with the

CALIFORNIA STATE WATER RESOURCES CONTROL BOARD

Sacramento, California
2003

U.S. DEPARTMENT OF THE INTERIOR

GALE A. NORTON, *Secretary*

U.S. GEOLOGICAL SURVEY

Charles G. Groat, *Director*

For additional information write to:

District Chief
U.S. Geological Survey
Placer Hall, Suite 2012
6000 J Street
Sacramento, CA 95819-6129
http://ca.water.usgs.gov

Copies of this report can be purchased from:

U.S. Geological Survey
Information Services
Building 810
Box 25286, Federal Center
Denver, CO 80225-0286

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CONVERSION FACTORS, DATUM, AND ABBREVIATIONS

CONVERSION FACTORS

Multiply	By	To obtain
kilometer (km)	0.6214	mile
square kilometer (km^2)	247.1	acre
square kilometer (km^2)	0.3861	square mile
liter (L)	33.82	ounce, fluid
cubic hectometer per year (hm^3/yr)	811.03	acre-foot per year

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

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

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

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L). One thousand micrograms per liter is equivalent to 1 milligram per liter. Milligrams per liter is equivalent to parts per million (ppm) and micrograms per liter is equivalent to parts per billion (ppb).

DATUM

Vertical coordinate information was referenced to the National Geodetic Vertical Datum of 1988 (NGVD88).

Horizontal coordinate information was referenced to the North American Datum of 1983 (NAD83).

ABBREVIATIONS

CAS	California Aquifer Susceptibility program
CFCs	chlorofluorocarbons
GAMA	Groundwater Ambient Monitoring and Assessment program
ID	identification
ITF	interagency task force
LUFTs	leaking underground fuel tanks
MTBE	methyl *tert*-butyl ether
NAWQA	National Water-Quality Assessment program
NWIS	National Water Information System
PAC	public advisory committee
PCE	tetrachloroethylene
PPCP	pharmaceuticals and personal care products
PSW	public-supply wells
QAQC	quality assurance and quality control
SacV	subbasin of Sacramento Valley
SJV	subbasin of San Joaquin Valley
TSPR	Transverse and Selected Peninsular Ranges
VOCs	volatile organic compounds

Organizations

DHS	Department of Health Services
DTSC	Department of Toxic Substances Control
DWR	Department of Water Resources
SWRCB	State Water Resources Control Board
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey

Framework for a Ground-Water Quality Monitoring and Assessment Program for California

By Kenneth Belitz, Neil M. Dubrovsky, Karen Burow, Bryant Jurgens, *and* Tyler Johnson

EXECUTIVE SUMMARY

The State of California uses more ground water than any other State in the Nation. With a population of over 30 million people, an agricultural economy based on intensive irrigation, large urban industrial areas, and naturally elevated concentrations of some trace elements, there is a wide range of contaminant sources that have the potential to contaminate ground water and limit its beneficial uses. In response to the many—and different—potential sources of ground-water contamination, the State of California has evolved an extensive set of rules and programs to protect ground-water quality, and agencies to implement the rules and programs. These programs have in common a focus on compliance with regulations governing chemical use and (or) ground-water quality. Although appropriate for, and successful at, their specific missions, these programs do not at present provide a comprehensive view of ground-water quality in the State of California.

In October 2001, The California Assembly passed a bill, AB 599, establishing the "Ground-Water Quality Monitoring Act of 2001." The goal of AB 599 is to improve statewide comprehensive ground-water monitoring and increase availability of information about ground-water quality to the public. AB 599 requires the State Water Resources Control Board (SWRCB), in collaboration with an interagency task force (ITF) and a public advisory committee (PAC), to develop a plan for a comprehensive ground-water monitoring program. AB 599 specifies that the comprehensive program should be capable of assessing each ground-water basin in the State through direct and other statistically reliable sampling approaches, and that the program should integrate existing monitoring programs and design new program elements, as necessary. AB 599 also stresses the importance of prioritizing ground-water basins that provide drinking water.

The United States Geological Survey (USGS), in cooperation with the SWRCB, and in coordination with the ITF and PAC, has developed a framework for a comprehensive ground-water quality monitoring and assessment program for California. The proposed framework relies extensively on previous work conducted by the USGS through its National Water-Quality Assessment (NAWQA) program. In particular, the NAWQA program defines three types of ground-water assessment: (1) status, the assessment of the current quality of the ground-water resource; (2) trends, the detection of changes in water quality, and (3) understanding, assessing the human and natural factors that affect ground-water quality.

A statewide, comprehensive ground-water quality-monitoring and assessment program is most efficiently accomplished by applying uniform and consistent study-design and data-collection protocols to the entire State. At the same time, a comprehensive program should be relevant at a variety of scales, and therefore needs to retain flexibility to address regional and local issues. Consequently, many of the program components include a predominant element that will be consistently applied in all basins, and a secondary element that may be applied in specific basins where local conditions warrant attention.

Hydrogeologic Provinces of California

A comprehensive monitoring and assessment program should be representative of the range of hydrologic, geologic, and climatic conditions in California. To achieve this goal, the State of California was divided into 10 hydrogeologic provinces. Within each province one can identify ground-water basins, which are areas mapped by the California Department of Water Resources (DWR). As mapped by DWR, ground-water basins are generally underlain by unconsolidated alluvial deposits, or by volcanic deposits. About 80 percent of California's public-supply wells are located in ground-water basins. The hydrogeologic provinces also include areas that are outside the mapped ground-water basins. Although the areas outside of basins are generally underlain by rocks of low permeability, about 20 percent of the State's public-supply wells are in these areas. Given that a substantial proportion of public-supply wells are in areas outside basins, it is important to use a classification system that both includes ground-water basins and areas outside basins.

Ancillary Data

Any water-quality assessment will be limited if no ancillary (that, is additional) data are available to use in the assessment. The most critical ancillary data describe the location and characteristics of the sampling point, including well depth, screen (open interval) length, and other pertinent information. A second category of ancillary information provides hydrogeologic context for the water-quality sample, including data on sediment or rock type and water levels. A third category of ancillary data provides information on sources and potential sources of contamination.

In some cases, statewide digital data are currently (2003) available to support a comprehensive monitoring and assessment program. Examples include the locations of leaking underground fuel tanks and application of pesticides. In other cases, statewide data are available only in paper copy; these data need to be compiled into digital databases if they are to be systematically used for basin assessment. Examples include drillers' logs collected by the DWR and the locations of point sources of contaminants collected by the Department of Toxic Substances Control. Other data sets are maintained, either in paper or digital formats, by local water agencies; these data also can be utilized for basin assessments. Newly acquired data sets will be most useful if they are compatible with the existing database-support systems developed by the SWRCB.

Utility of Existing Data for Ground-Water-Quality Assessment

A review of existing data is usually a recommended first step in a water-quality assessment, and AB 599 requires that existing resources be used as appropriate. Toward that end, the water-quality database assembled by the California Department of Health Services (DHS) will be used to support the basin assessments. The DHS database is assembled for the purposes of regulatory compliance, and therefore has some limitations for other uses. These limitations include the use of analytical methods with relatively high detection limits; detections of constituents at low concentrations can provide an “early warning” for constituents of concern. These limitations also include the general absence of analyses for constituents that can be used as “environmental tracers”; environmental tracers can provide a basis for assessment of the human and natural factors that affect water quality.

The DHS data set on water quality for public-supply wells is currently (2003) the only statewide, digital water-quality database that is available. Although there may be a large amount of other Federal, State, and local water-quality data relevant to basin assessment, these data have not yet been centralized into a digital database. In some cases, it may be possible to incorporate additional data into the basin assessments. In other cases, it will be difficult to identify or obtain additional data.

Network Design

The monitoring network should allow for assessment of the ground-water resource at a variety of scales. To achieve this goal, the statewide monitoring program will use a consistent study design in all study areas. The basic monitoring network will be established using an approach that selects wells that are spatially distributed across a study area, but that also incorporates an element of randomization in the selection process. Establishment of a spatially distributed, randomized monitoring network in each study area will produce data sets that address the basic objectives at the basin scale but, most importantly, can be aggregated and compared to produce regional and statewide assessments. However, sampling need not be limited to the basic network; additional wells can be sampled to address additional issues related to local concerns or to achieve better understanding of the factors that affect water quality.

AB 599 specifically focuses on ground water used for drinking water. Given this focus, the monitoring network will rely primarily on existing public-supply wells for sampling the major aquifers. Public-supply wells, in addition to sampling the drinking-water resource, are appropriate because they generally have long well screens and high pumping capacities, and therefore sample a larger volume of the aquifer than do wells with shorter screened intervals (domestic and monitoring wells). Equally important, public-supply wells are widely distributed wherever there are population centers; have their locations entered into an electronic database administered by the State DHS; and have historical water-quality data from previous drinking-water quality compliance monitoring available in the DHS database. In some basins, public-supply wells might not provide sufficient spatial coverage; in these basins, other types of wells (irrigation, domestic supply, or monitoring wells) will need to be sampled. In many basins, local water agencies are a valuable source of information on water wells.

Target Constituents

The selection of target constituents should be based on relevance to important water-quality issues. Given the focus of AB 599 on ground water as a source of drinking water, three important goals have been identified: (1) protection of the beneficial use of ground water; (2) understanding the human and natural factors that affect ground-water quality; and (3) detection of unregulated compounds that have been identified as potential concerns, the so-called “emerging contaminants.” To support achievement of these goals, an approach is proposed that is “tiered” to balance spatial coverage with analytical intensity (number of different constituents analyzed for), and iterative to allow reconsideration of the analytical objectives.

The broadest spatial coverage, or first tier, will be provided by the existing DHS database; these data can be used to characterize water quality relative to beneficial use. The second tier will be provided by sampling a network of wells for a “relatively reduced” list of constituents. The reduced list of constituents are those used by the SWRCB for assessing the susceptibility of aquifers to contamination, and include age-dating, stable isotopes, and low-level analyses of organic compounds. The third tier will sample for a larger number of constituents, but at fewer wells than the second tier. The “relatively expanded” list of constituents would include constituents covered by the USGS NAWQA program, as well as emerging contaminants. About 25 percent of the wells sampled for the relatively-reduced list also will be sampled for the relatively-expanded list.

Trend Assessment

A comprehensive monitoring program should provide an assessment of trends, or changes in ground-water quality with time. Resampling of the well network 10 years after the first sampling would help achieve this goal. For this to be efficient, it is imperative that the same wells be sampled, not just the same number of wells. The decadal-scale sampling of the entire network should be supplemented by triennial sampling at 10 percent of the wells. The triennial sampling will provide two sets of data between the decadal samples, which will provide context and confidence that any change seen in the two decadal samples is part of a pattern; and it will provide earlier warning of the presence of a new contaminant. More frequent sampling should be considered in areas of concern.

Many ground-water basins are already intensively monitored and have been studied in detail. Many of these studies are conducted by local water agencies. This ongoing monitoring should be taken into account, and a portion of the resources of the trends assessment should be adapted to take advantage of the existing knowledge and data networks. In particular, where there is reason to believe that change might be rapid in specific areas, concentrating some effort to do annual sampling should be considered.

Assessment for Understanding

A comprehensive monitoring program should allow for an assessment of the human and natural factors that affect water quality. In particular, one would like to answer the question of why a specific constituent is, or is not, observed in a ground-water basin. An assessment of the factors that affect water quality generally will be addressed through the systematic sampling for environmental tracers and indicators of water and contaminant sources, and by targeting sampling of wells chosen for that purpose. It is anticipated that in many of the basins as much as 25 percent of the data collection will be designed to improve the understanding of basin-specific issues.

Prioritization of Basins and Other Study Areas

AB 599 requires that the comprehensive monitoring program prioritize ground-water basins that are a source of drinking water. In recognition of this goal, four categories of priority basins (Categories 1 to 4) were identified. The primary criterion used for identifying priority basins was the number of public-supply wells in a basin. Secondary criteria included municipal ground-water use, agricultural pumping, number of leaking underground fuel tanks (LUFTs), and pesticide applications. In addition to the four categories of priority basins, two other categories were identified to account for areas outside basins (Category 5) and for “low use” ground-water basins (Category 6).

Categories 1 to 4 include 116 basins. These basins account for 76 percent of California's public-supply wells. If one excludes wells located outside mapped basins, then Categories 1 to 4 account for 95 percent of the public-supply wells. The basins in categories 1 to 4 also account for most of California's municipal ground-water use (98 percent), agricultural pumping (88 percent), LUFTs (74 percent), and square-mile sections of land with pesticide applications (71 percent). If one accounts only for ground-water basins, then categories 1 to 4 account for about 90 percent of the LUFTs and about 90 percent of the sections with pesticide applications. For the purposes of efficiency, some of the basins can be grouped with neighboring basins; therefore, study areas can consist of a single basin or a group of basins.

Category 5 accounts for those areas of the State that are outside mapped ground-water basins. These areas are important because 19 percent of the public-supply wells, 16 percent of the leaking underground fuel tanks, and 21 percent of the sections of land with pesticide applications occur in areas outside basins. One or more pilot studies can be implemented to monitor and assess these areas.

Category 6 includes 356 ground-water basins with relatively little ground-water use. These low-use basins account for 43 percent of the total area mapped as ground-water basins, but account for only 5 percent of the public-supply wells and less than 1 percent of the municipal ground-water users. About one-half of the Category 6 basins have no public-supply wells.

A statewide monitoring and assessment program that focuses on basins in Categories 1 to 4 and on selected areas of Category 5 will provide substantial coverage of the ground-water resource that is used for public supply, and also will provide substantial coverage of the ground-water resource that is potentially threatened by contamination.

Scope of the Proposed Comprehensive Monitoring and Assessment Program

The proposed comprehensive ground-water monitoring and assessment program will focus primarily on public-supply wells that are located in basins where ground water is an important source of drinking supply. The program will utilize water-quality data assembled for the purposes of regulatory compliance (DHS database), and will collect additional water samples from public-supply wells and other types of wells as needed (domestic supply, irrigation and monitoring). About 3,200 to 3,500 wells need to be sampled to provide complete spatial coverage of the priority basins (Categories 1 to 4). The proposed network of wells will be used for assessing the status of the ground-water resource and assessing trends in water quality, and will provide a basis for understanding the factors that affect water quality.

Although AB 599 specifies a focus on ground-water basins, the results of the present study indicate that 19 percent of the public-supply wells in California are in areas outside the basins. Given that AB 599 also seeks to protect the beneficial use of ground water, particularly as a source of drinking supply, it is important to include some portion of these areas. One or more pilot studies could be implemented in one, or more, of the hydrogeologic provinces where there are a relatively large number of public-supply wells located outside basins. About two-thirds of these wells are located in either the Sierra Nevada province or the Transverse and Selected Peninsular Ranges province.

Extension of the comprehensive program to low-use ground-water basins would require substantial investment in identifying, and perhaps drilling and installation of, additional wells. At the present time, the low-use ground-water basins are not a priority for inclusion in the proposed comprehensive monitoring and assessment program.

Information from other types of wells—in particular, monitoring wells and domestic supply wells—also is important and should be reviewed as it becomes available. A statewide digital database could be developed for these wells, as has been done for monitoring wells for underground storage tanks under SWRCB regulation. This is especially true for domestic wells because they are sources of drinking water.

INTRODUCTION

The State of California uses about 16 million acre-feet of ground water each year, more than any other State in the Nation (Solley and others, 1998). With a population of over 30 million people, an agricultural economy based on intensive irrigation, and large urban industrial areas, there is a wide range of human activities that have the potential to contaminate ground water in California. In addition, there are also a number of naturally occurring constituents that can limit the use of ground water for drinking water, agriculture, support of aquatic communities in rivers, and other beneficial uses.

In response to the many—and different—potential sources of ground-water contamination, the State of California has evolved an extensive set of rules and programs to protect ground-water quality, as well as agencies to implement the rules and programs. The great complexity of this effort is reflected in the numerous and varied programs concerned with managing ground water. Sarna (1990), in a compilation of public agencies that are involved in some facet of ground-water management or study, lists 1,436 individual ground-water activities and 1,037 individual databases. Some agencies protect ground-water resources from point sources of contamination (California Department of Toxic Substances Control, 2003), some address both point sources and nonpoint sources, and some have a mission targeted to protect a specific beneficial use (California Department of Health Services, 2003). What all of these programs have in common is a focus on compliance with a set of rules and regulations governing chemical use and (or) ground-water quality, and hence on specific contaminant sources (or class of sources) or on protecting a specific beneficial use.

What has been absent is a program designed to systematically assess the quality of all of the State's ground-water resources. In October 2001, The California Assembly passed a bill, AB 599, establishing the “Ground-Water Quality Monitoring Act of 2001." The goal of AB 599 is to improve comprehensive ground-water monitoring and increase the availability of ground-water-quality information to the public. AB 599 requires the State Water Resources Control Board (SWRCB), in collaboration with an interagency task force (ITF) and a public advisory committee (PAC), to develop a plan for a comprehensive ground-water monitoring program. AB 599 specifies that the comprehensive program should be capable of assessing each ground-water basin in the State through direct and other statistically reliable sampling approaches, and that the program should integrate existing monitoring programs and design new program elements, as necessary. AB 599 also stresses the importance of prioritizing ground-water basins that provide drinking water.

The United States Geological Survey (USGS), in cooperation with the SWRCB, and in coordination with the ITF and PAC, has developed a plan, or framework, for a comprehensive ground-water quality monitoring and assessment program for California. The proposed framework relies extensively upon previous work conducted by the USGS through its National Water-Quality Assessment (NAWQA) program (Hirsch and others, 1988; Gilliom and others, 1995). The goal of the proposed program is to provide assessments of water quality in basins and other areas where ground water is an important source of drinking supply. The assessments should be multi-purpose and useful at various scales—local, regional, and statewide.

In addition, the proposed program should be able to make various ground-water-quality assessments including assessments of:

- **Status**: Assess the current quality of the ground-water resource;
- **Trends:** Detect changes in water quality; and
- **Understanding:** Relate human and natural factors to ground-water quality.

An important aspect of a comprehensive ground-water quality monitoring and assessment program, and one required by AB 599, is to provide ground-water-quality information to the public. In response to AB 599, the SWRCB has taken responsibility for this important goal.

OBJECTIVES AND OVERVIEW OF THE PROPOSED PROGRAM

The purpose of this report is to present a framework for a comprehensive ground-water quality monitoring and assessment program for California. The objectives of this framework are consistent with the goals of AB 599:

- Provide assessments of ground-water quality at multiple scales;
- Prioritize ground-water basins that provide drinking water;
- Utilize existing resources, where appropriate; and
- Design new program elements, as needed.

To achieve these objectives, this report includes several chapters and appendixes. Each chapter focuses on a specific aspect of the comprehensive monitoring and assessment program. In many of the chapters and in Appendix A, case studies (fig. 1) are used to illustrate selected points:

- **Hydrogeologic provinces**—Hydrogeologic provinces are large regions with relatively similar geologic, climatic, and hydrologic characteristics. The delineation of provinces provides a context for identifying priority basins, and for evaluating the ground-water resource that occurs outside mapped ground-water basins. Delineation of provinces also provides a context for evaluating water quality at regional and statewide scales.
- **Ancillary data**—Ancillary data are required for an assessment of the ground-water resource. The most critical ancillary data describe the location and characteristics of the sampling point. A case study from Modesto illustrates how lithologic information from drillers' logs can be utilized as part of an assessment.

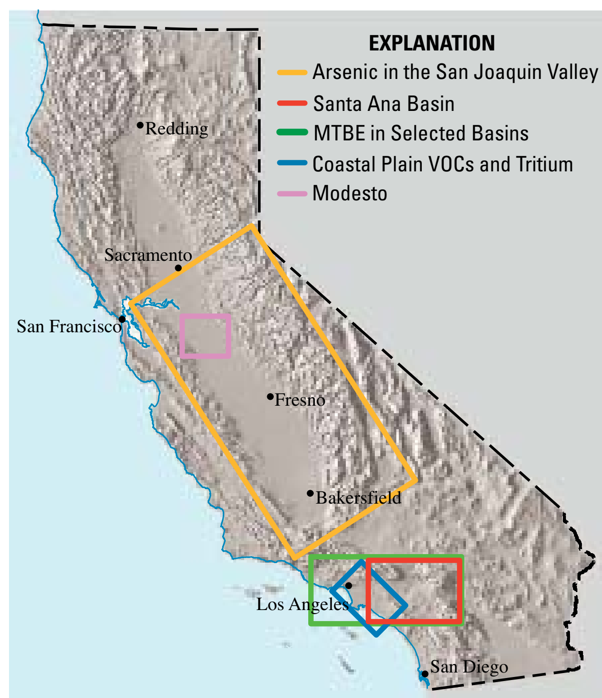


Figure 1. Location of selected case studies.

- **Utility of existing data for ground-water-quality assessment**—AB 599 requires that existing data be used as appropriate. The Department of Health Services (DHS) maintains a database of water-quality analyses obtained from about 16,000 public-supply wells. Presently, this is the only statewide database for water quality. Although these data are useful for assessment, there are some limitations to their utility for other purposes. A case study from several ground-water basins in southern California illustrates how the occurrence and distribution of methyl *tert*-butyl ether (MTBE) can be underestimated if DHS data were the only data available. A second case study focusing on arsenic in the San Joaquin Valley (Appendix A) illustrates the extent to which the DHS database can and cannot be used for assessment of status, trends, and understanding.
- **Network design**—In order to collect data that will allow the various assessments to be made at multiple scales, the statewide monitoring program will employ an approach that selects wells that are spatially distributed across a basin, but that also incorporates an element of randomization in the selection process. Deviating from a randomized selection approach will compromise the ability to do assessments on groups of basins, and hence sacrifice the ability to answer questions of regional and statewide importance. In addition to the basic network, additional wells should be sampled to address issues of particular concern, or to identify the human and natural factors that affect water quality. The monitoring network will rely primarily on public-supply wells. A case study from the Santa Ana Basin, conducted by the USGS NAWQA program, illustrates implementation of this approach.
- **Target constituents**—Broadly defined, three types of constituents can be analyzed for in a comprehensive ground-water monitoring program: constituents that are regulated for the protection of beneficial use; constituents that can be used as indicators of water and contaminant source ("environmental tracers"); and emerging contaminants, such as pharmaceuticals and personal care products. Regulated constituents are already sampled for at public-supply wells. Environmental tracers can be sampled for at all wells in the proposed network. Emerging contaminants and other selected constituents can be sampled for at a subset of the well network. These analyses would provide the basis for conducting the three types of assessment: status, trends, and understanding. The list of target constituents can be reassessed for each basin as needed.
- **Trend assessment**—An important objective of the proposed program is detection of important changes in water quality, including the detection of emerging contaminants. It is proposed that the entire network be sampled on a decadal scale with triennial sampling at a subset of the wells. A case study of nitrate in the eastern San Joaquin Valley illustrates the importance of resampling the same wells for detection of trends.
- **Assessment for understanding**—Another important objective of the proposed program is to provide information that can help answer the question of why a specific constituent is, or is not, found in a ground-water basin. These questions can be addressed by sampling for environmental tracers, and by sampling additional wells. A case study of tritium, chloroform, and MTBE in the southern California coastal plain is presented to illustrate the influence of human activity on the distribution of contaminants in the subsurface.
- **Basin prioritization**—AB 599 requires that the comprehensive monitoring program prioritize ground-water basins that provide drinking water. The number of public-supply wells in a basin is therefore used as the primary factor for ranking basins. Secondary factors include municipal ground-water use, agricultural pumping, the number of leaking underground fuel tanks, and pesticide applications. Given these factors, four categories of priority basins are identified. A fifth category is proposed to account for areas

outside mapped basins; about 20 percent of California's public-supply wells are in these areas. A sixth category includes basins with low use of ground water; these basins are not considered a priority for monitoring and assessment at this time.

- **Scope of the proposed program**—The proposed comprehensive ground-water monitoring and assessment program will focus primarily on sampling public-supply wells that are located in basins and other areas where ground water is an important source of drinking supply. In many basins, public-supply wells do not provide complete spatial coverage of the basin; other types of wells (domestic supply, irrigation, or monitoring wells) will need to be identified for the purposes of monitoring and assessment. In general, the proposed program will focus primarily on those parts of the ground-water basins used for public supply; other depth intervals generally will not be evaluated.
- **Appendix A (Arsenic in the San Joaquin Valley)**—The objective of this case study is to examine whether existing data on arsenic in ground water can adequately support the assessments required by the statewide comprehensive ground-water monitoring program. Arsenic was selected as a case study because the drinking-water limit for arsenic has recently been lowered from 50 to 10 µg/L (U.S. Environmental Protection Agency, 2001). The San Joaquin Valley was selected because there are a large amount of data on arsenic concentrations in ground water from previous studies.
- **Appendix B (Digital Map of Hydrogeologic Provinces)**—A digital map of hydrogeologic provinces was developed to support the analyses and identification of priority basins and other study areas.
- **Appendixes C to F**—A compilation of ground-water basins, and related data, corresponding to the four categories of priority basins.
- **Appendix G** —A compilation of low-use ground-water basins and related data.

HYDROGEOLOGIC PROVINCES OF CALIFORNIA

A comprehensive monitoring and assessment program should be representative of the range of hydrologic, geologic, and climatic conditions in California. To achieve this goal, the State of California was divided into 10 hydrogeologic provinces (fig. 2), which can be defined as large areas with relatively similar geologic, climatic, and hydrologic characteristics. These provinces, and the boundaries between them, are based partly on the generalized geology and geomorphology of California (Norris and Webb, 1990; Saucedo and others, 2000; California Geological Survey, 2002), and partly on a nationwide map of principal aquifers (Miller, 2000). A digital map for these provinces was developed and is described in Appendix B.

Each of the 10 hydrogeologic provinces includes ground-water basins (California Department of Water Resources, 2002), which are areas underlain by relatively permeable materials, as well as areas of relatively low permeability (fig. 3*A*). As mapped by California Department of Water Resources (DWR), ground-water basins are generally underlain by unconsolidated alluvial deposits or volcanic deposits. About 80 percent of California's 16,000 public-supply wells are located in ground-water basins (table 1; fig. 3*B*). Although the areas outside basins consist primarily of relatively low permeability rocks, these areas include nearly 20 percent of California's public-supply wells (table 1; fig. 3*B*). Inclusion of the areas outside basins in the delineation of provinces, along with the ground-water basins, provides a context for assessing all of California's ground-water resources.

The Northern Coast Ranges hydrogeologic province corresponds to the northern half of the Coast Ranges geomorphic province. The hydrogeologic province is bounded to the west by the Pacific Ocean, to the north by the Oregon border, to the south by San Francisco Bay, and to the east by the Klamath Mountains and Central Valley hydrogeologic provinces. The Northern Coast Ranges province consists primarily of relatively low-permeability rocks; ground-water basins account for about 15 percent of the total area (table 1).

Digital relief based upon USGS digital elevation model (DEM)

Albers Equal-Area Conic Projection
Standard parallels 29°30′ and 45°30′,
Central meridian - 120°, projection origin 23°

Figure 2. Hydrogeologic Provinces of California.

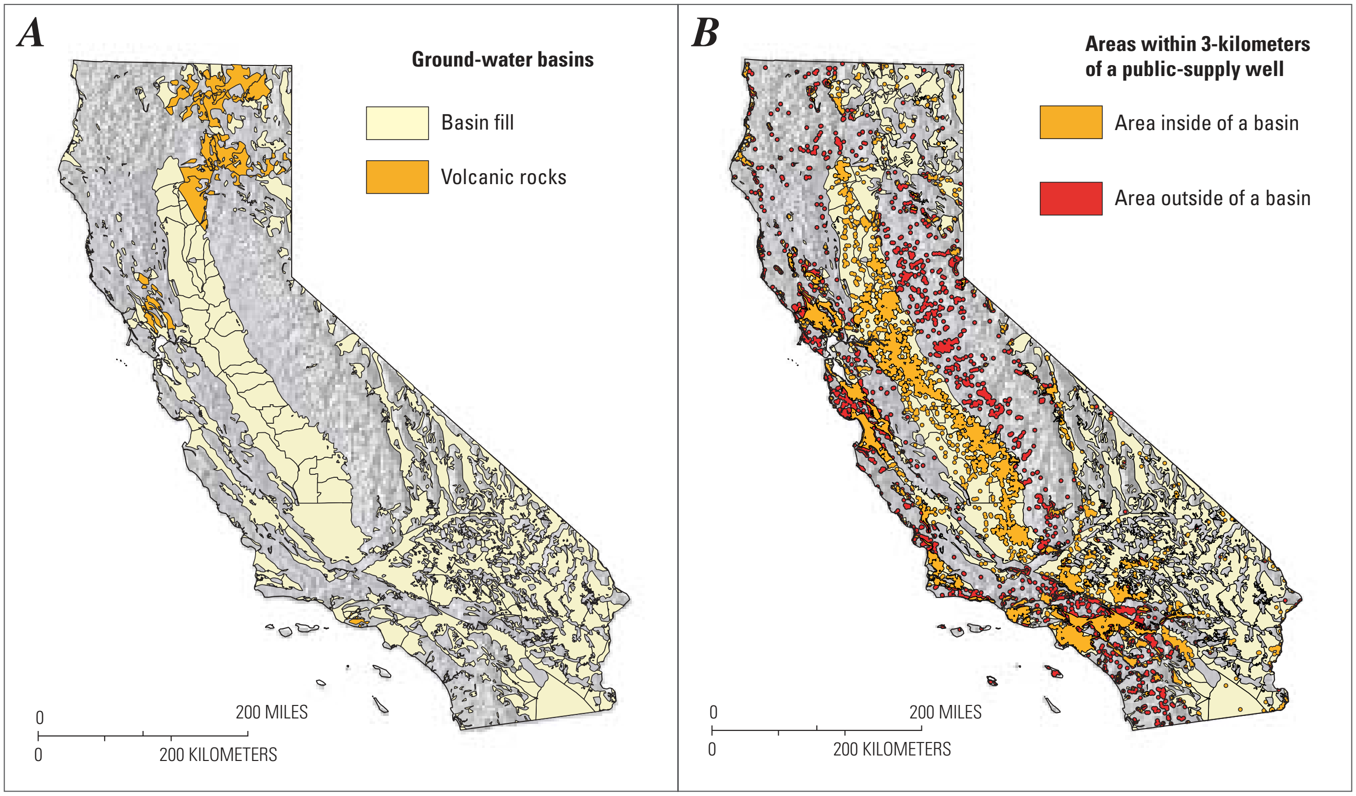


Figure 3. Ground-water basins and public-supply wells in California.

(*A*) Basins and subbasins identified by the Department of Water Resources (California Department of Water Resources, 2002), and (*B*) Areas within 3 kilometers of a public-supply well (active and inactive wells included). Location of public-supply wells from California Department of Health Services (written commun., 2001)

Table 1. Public-supply wells located inside and outside of mapped ground-water basins, California

[Based on data from California Department of Health Services (written commun., 2001) and California Department of Water Resources (2002). km^2, square kilometer]

Province	Total area of province (km^2)	Number of ground-water basins in province	Total area of basins (km^2)	Number of public-supply wells inside basins	Number of public-supply wells outside basins
Northern Coast Ranges	38,000	79	6,000	770	280
Southern Coast Ranges	42,000	74	13,000	1,740	480
Klamath Mountains	23,000	7	300	20	110
Modoc Plateau and Cascades	39,000	55	21,000	240	40
Central Valley	53,000	36	53,000	5,360	0
Sierra Nevada	66,000	22	2,000	330	1,170
Basin and Range	36,000	45	16,000	260	20
Transverse and Selected Peninsular Ranges	22,000	33	8,000	2,720	800
San Diego Drainages	10,000	25	1,000	180	120
Desert	81,000	96	56,000	1,240	60
California	*410,000*	*472*	*176,000*	*12,860*	*3,080*

The Southern Coast Ranges hydrogeologic province corresponds to the southern half of the Coast Ranges geomorphic province. The hydrogeologic province is bounded to the west by the Pacific Ocean, to the north by San Francisco Bay, to the south by the Transverse and Selected Peninsular Ranges province, and to the east by the Central Valley province. Ground-water basins account for about 30 percent of the total area of the province (table 1).

The Klamath Mountains hydrogeologic province consists almost entirely of relatively low-permeability rocks; ground-water basins account for about 1 percent of the total province area (table 1). The Klamath Mountains province is bounded on the west and south by the Northern Coast Ranges province; on the north by the Oregon border; and on the east by the Modoc Plateau and Cascades province. Of the 10 provinces, the Klamath Mountains province has the fewest number of public-supply wells (table 1).

The Modoc Plateau and Cascades hydrogeologic province includes two geomorphic provinces (Modoc Plateau and Cascades) and part of another (Basin and Range). The inclusion of a part of the Basin and Range in this province is consistent with a previous nationwide classification of principal aquifers (Miller, 2000). The hydrogeologic province is bounded to the west by the Klamath Mountains and Central Valley provinces, to the north by the Oregon border, to the east by the Nevada border, and to the south by the Sierra Nevada province. Ground-water basins account for about half of the total province area (table 1); most of the aquifers underlying the ground-water basins are volcanic rocks.

The Central Valley hydrogeologic province consists of the Sacramento and San Joaquin ground-water basins. These two basins include 36 relatively large subbasins (California Department of Water Resources, 2002), which for the purposes of this study are recognized as individual ground-water basins. In contrast, subbasins in other hydrogeologic provinces are not recognized as individual basins. The subbasins of the Sacramento and San Joaquin ground-water basins generally are larger (greater area) than the ground-water basins located in other provinces. The Central Valley province includes Sutter Buttes, a relatively small area of relatively low-permeability volcanic deposits. The Central Valley province has more public-supply wells than any other hydrogeologic province (table 1).

The Sierra Nevada hydrogeologic province consists primarily of areas not mapped as ground-water basins (California Department of Water Resources, 2002); isolated ground-water basins account for about 3 percent of the total area (table 1). The Sierra Nevada province is bounded to the west by the Central Valley province; to the north by the Modoc Plateau and Cascades province; to the east by the Nevada border and the Basin and Range province; and to the south by the Transverse and Selected Peninsular Ranges province. Of the 10 provinces, the Sierra Nevada has the largest number of public-supply wells that are located in areas outside of mapped basins (table 1).

The Basin and Range hydrogeologic province is bounded to the west by the Sierra Nevada province, to east by the Nevada border, and to the south by the Desert province. Ground-water basins account for about one-half of the total province area (table 1).

The Transverse and Selected Peninsular Ranges hydrogeologic province is one of the smallest provinces by area (table 1), but it includes the heavily populated southern California coastal plain and adjacent inland valleys. The province also includes the Santa Ynez, Santa Monica, San Gabriel, and San Bernardino Mountains. The ground-water basins of the Transverse and Selected Peninsular Ranges province contain the highest density of public-supply wells in California (number of wells divided by area). The mountain areas of the province also contain a disproportionately large number of public-supply wells (table 1).

The San Diego Drainages hydrogeologic province corresponds to the southern three-quarters of the Peninsular Ranges geomorphic province. The hydrogeologic province is bounded to the west by the Pacific Ocean, to the north by the Transverse and Selected Peninsular Ranges province, to the east by the Desert province, and to the south by the Mexican border. The province includes the drainage areas of the Santa Margarita, San Luis Rey, San Dieguito, and San Diego Rivers. In contrast to the Transverse and Selected Peninsular Ranges province, the ground-water basins of the San Diego Drainages province do not include a large number of public-supply wells (table 1).

The Desert hydrogeologic province corresponds to the Mojave Desert and Colorado Desert geomorphic provinces. This hydrogeologic province is bounded to the west by the Transverse and Selected Peninsular Ranges and San Diego Drainages provinces; to the north by the Basin and Range province; to the east by the Nevada and Arizona borders; and to the south by the Mexican border. The Desert province is the largest of the 10 provinces, and ground-water basins account for about 70 percent of the total area (table 1).

ANCILLARY DATA NEEDED FOR A COMPREHENSIVE ASSESSMENT

The questions that a water-quality assessment can address can be limited by the availability of ancillary (that is, additional) data. Ancillary data are necessary to describe the type of sampling point and its location in space; the hydrogeologic context for the sampling location; and its location in relation to potential sources of contamination. Franke and others (1997, table 12) provide a list of information useful for water-quality assessment. These ancillary data are needed to help delineate the lateral and vertical extent of ground water of different quality, and to explain the observed patterns of contaminant occurrence, distribution, and change with time.

The most critical ancillary data describe the location and characteristics of the sampling point. A summary of useful information on well characteristics is given in the protocols for ground-water data collection for the USGS NAWQA program (Lapham and others, 1997). Critical information includes the latitude, longitude, and land-surface altitude of the well location, along with the depth of the screened (open) interval. Data on the location of public-supply wells are collected by DHS, and characteristics of public-supply wells are being added to the DHS database as part of the Drinking Water Source Assessment and Protection Program (California Department of Health Services, 1999). Data on well construction are collected and stored by DWR. In addition, many local water agencies maintain databases that include well-location and well-construction information. These data are needed to delineate the spatial and vertical extent of ground water of different quality.

The second category of ancillary information provides hydrogeologic context for the water-quality sample. Geologic information that will be useful includes surficial materials (soils), unsaturated-zone properties, type and texture of sediment or rock, and aquifer structure. Hydrologic information that will be useful includes ground-water levels, recharge mechanisms and locations, and water use (pumpage). Much of this information has been summarized at a basin scale in DWR Bulletin 118, *California's Ground water* (California Department of Water Resources, 1980, 2003a). This type of information also is available in the published literature (for example, USGS Water-Resources Investigations Reports) and in unpublished reports (for example, consultant and staff reports prepared for local water agencies). These data are needed to help identify the sources and processes affecting water quality.

Drillers' logs required by DWR contain important ancillary information including well location, well construction, and descriptions of rock and sediment encountered during drilling. Recent efforts by DWR to electronically scan well drillers' logs is an important first step toward making this information available for use in assessments. A critical next step would be creation and maintenance of a digital database of well locations and characteristics, as well as a systematic digital representation of the scanned lithologic logs. This will be time consuming and should be prioritized to support the sequence of basin assessments.

Information on the location of potential contaminant sources would be useful for the assessment. Data on the location of point sources are currently collected by State regulatory programs, and these data could be made digitally available. For example, the SWRCB maintains a comprehensive digital database on the location of leaking underground storage tanks (see California State Water Resources Control Board, 2003a). One recent source of information on potential sources is the inventories of “possible contaminating activities” in the vicinity of public-supply wells that are collected by the DHS Drinking Water Source Assessment and Protection Program (California Department of Health Services, 1999). Information on local contaminant sources can also be obtained from Regional Water Quality Control Boards and from local water agencies.

The spatial distribution of nonpoint sources of ground-water contamination has been difficult to quantify in the past. An exception to this is the database on pesticide application created by the California Department of Pesticide (DPR) regulation, which has proved to be of value to investigators in a wide variety of environmental fields (see California Department of Pesticide Regulation, 2003). The location of other nonpoint source contaminants is usually inferred from land use, and the current digital maps of field-scale agricultural land use created by DWR are invaluable (see California Department of Water Resources, 2003b). Because past agricultural practices may have had a lasting impact on ground-water quality, it would also be useful to have digital historical land-use information. An important caveat to bear in mind is that associating contamination in a specific well with a specific source is difficult because ground-water flow paths are complex, transient, and difficult to quantify with certainty (Franke and others, 1999).

Case Study: Using Drillers' Logs from the Modesto Area

Drillers' logs include descriptions of the grain size, or texture, of the sediments encountered, as well as other characteristics such as rock type, color, or structure. This information can be used for a number of purposes including development of quantitative models of ground-water flow (Belitz and Phillips, 1995) and to define the hydrogeologic framework for interpreting water-quality data. A recent example of the latter is the coding of drillers' logs in the Modesto area (fig. 1).

In the Modesto area, and other parts of the San Joaquin Valley, the Corcoran Clay separates ground water with distinctly different ages, histories, and water quality (Davis and Coplen, 1989; Bertoldi and others, 1991; Dubrovsky and others, 1991). In addition, ground water above the Corcoran Clay is more susceptible to contamination from land surface activities than is ground water below the clay. The Corcoran Clay has a characteristic blue color, and it is therefore readily identified from drill cuttings and drillers’ logs.

The USGS, in cooperation with the Modesto Irrigation District, is using data from drillers' logs to provide an improved framework for water management and for interpreting water quality (see U.S. Geological Survey, 2003b). Lithologic and well-construction data from 3,500 wells were digitized to describe the texture and spatial distribution of specific hydrogeologic units, including the Corcoran Clay (fig. 4). Sixty-one percent of the logs were from domestic wells, 27 percent were from irrigation wells, and 4 percent were from public-supply wells. A preliminary evaluation of the distribution of blue clay in the drillers' logs shows areas northwest of the city of Modesto where blue clay was observed beyond the previously mapped extent of the Corcoran Clay (Page, 1986) (fig. 5). This type of analysis requires an initial investment of resources, but can produce a digital data set of lasting impact: the lithologic description of hydraulic properties produced by Laudon and Belitz (1991) has been used repeatedly in subsequent major modeling efforts in the western San Joaquin Valley.

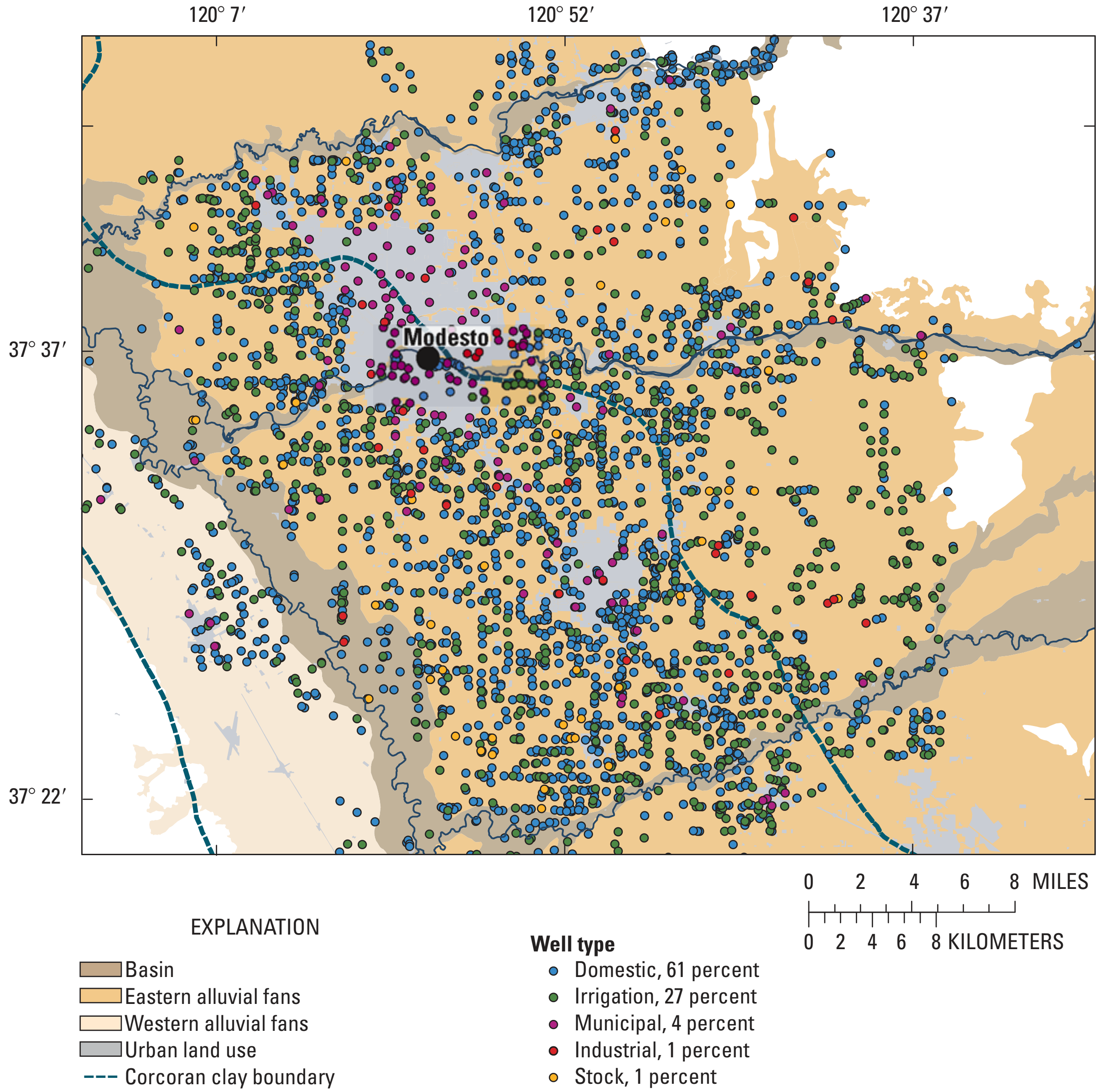


Figure 4. Locations of selected wells in the Modesto and Turlock ground-water basins.

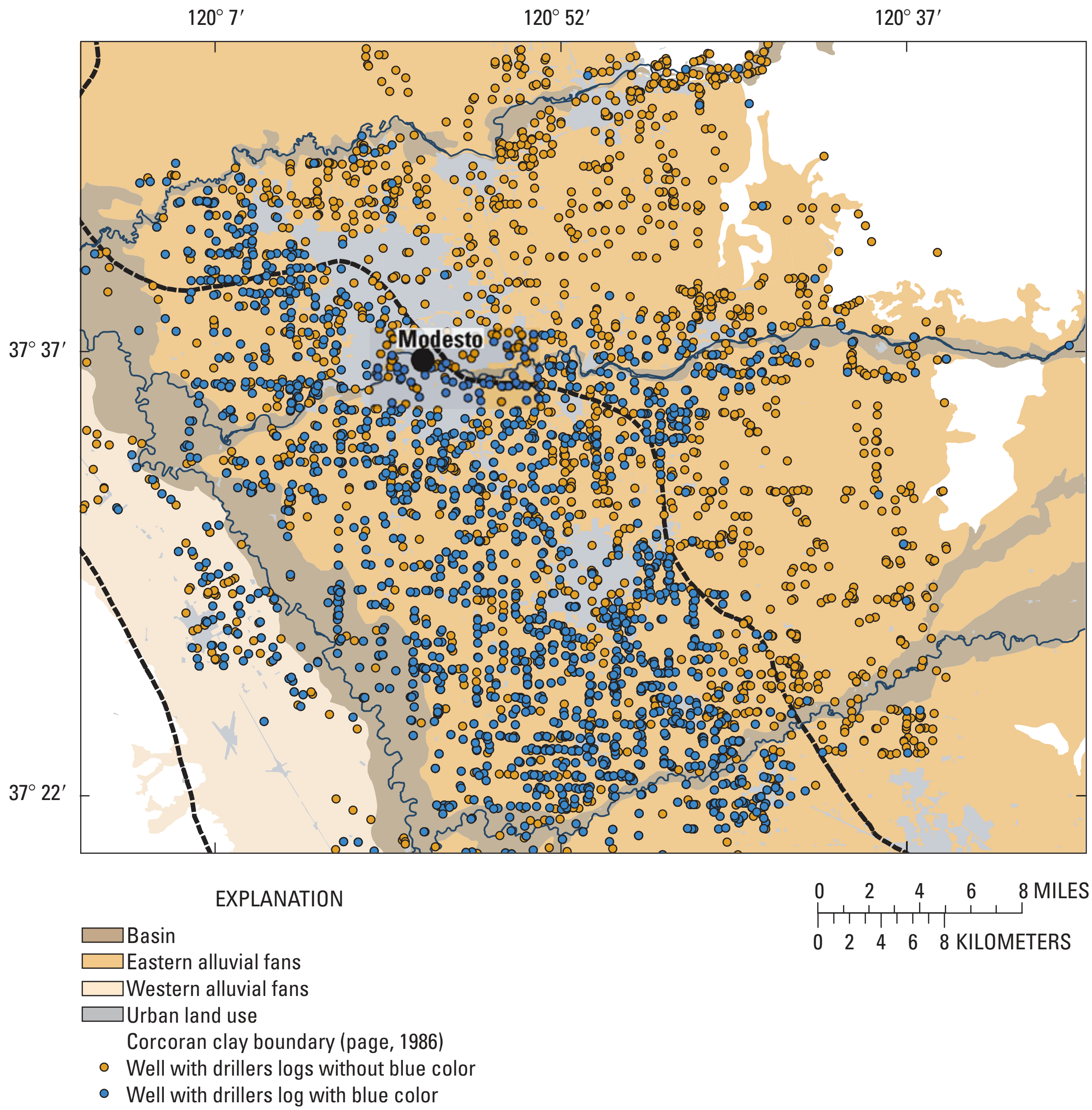


Figure 5. Locations of wells with blue clay indicated in drillers' logs in the Modesto and Turlock ground-water basins.

UTILITY OF EXISTING DATA FOR GROUND-WATER-QUALITY ASSESSMENT

A review of existing data is a recommended first step in a water-quality assessment, and AB 599 requires that existing resources be used as appropriate. Toward that end, the water-quality database assembled by the DHS will be used to support the basin assessments. The DHS database is assembled for the purposes of regulatory compliance, and therefore has some limitations for other uses. These limitations include the use of analytical methods with relatively high detection limits, the general absence of analyses for environmental tracers, and the lack of ancillary data. A case study from selected southern California basins, discussed in the following section, illustrates the potential significance of these limitations. A second case study, which examines arsenic in the San Joaquin Valley, is presented in Appendix A.

The DHS database on water quality for public-supply wells is currently (2003) the only statewide, digital water-quality database that is available. Although there is a large amount of Federal, State, and local water-quality data relevant to basin assessment, these data have not yet been centralized into a digital database. In some cases, it may be possible to incorporate additional data into the basin assessments. In other cases, it will be difficult to accomplish (Hirsch and others, 1988).

Case Study: MTBE Occurrence in Several Southern California Ground-Water Basins

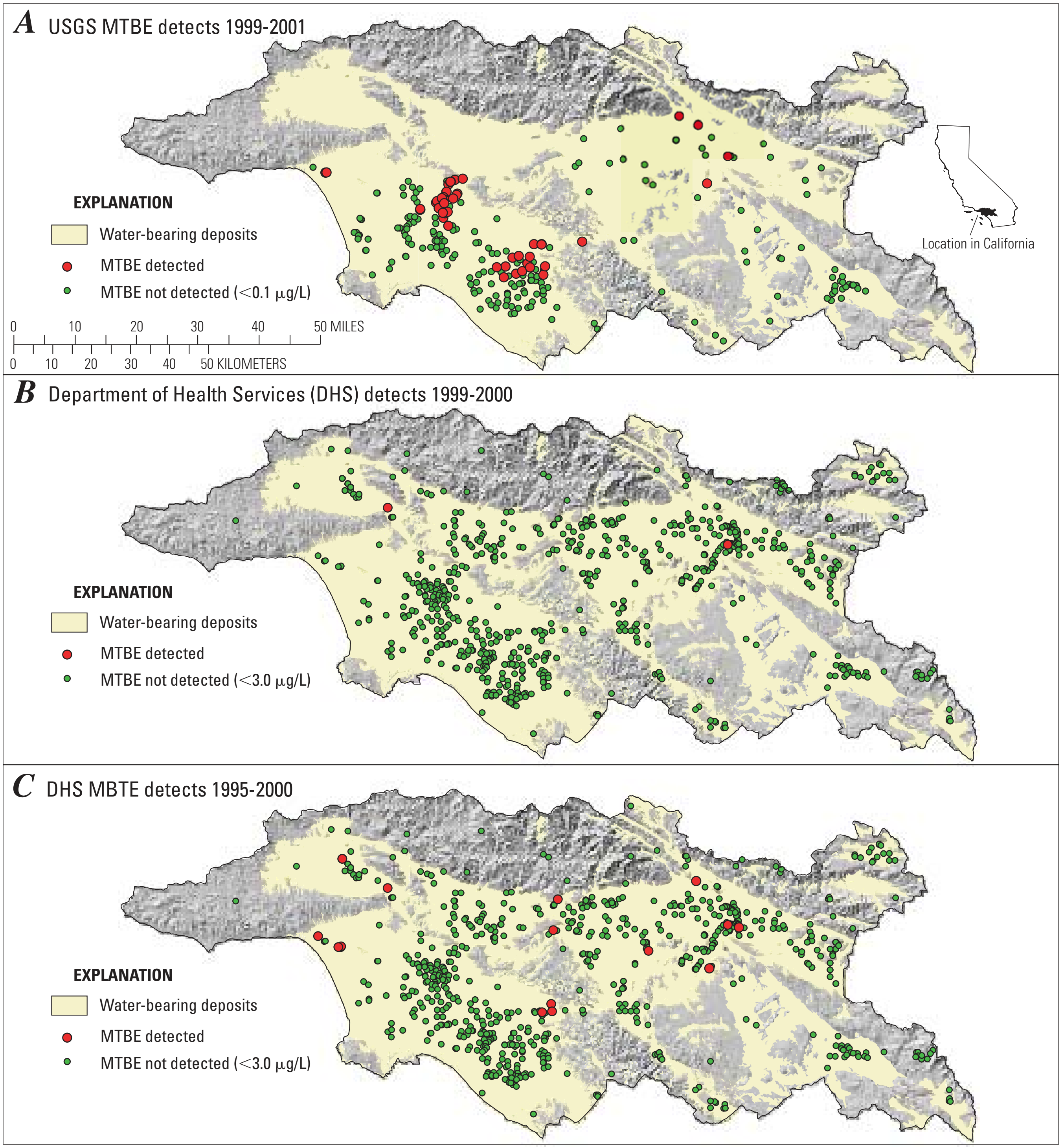
The ability to assess water quality, and the factors that affect water quality, can be limited by the laboratory methods used to analyze samples. For example, the USGS National Water Quality Laboratory uses methods that can detect the presence of MTBE at concentrations less than 0.1 µg//L. In contrast, the DHS requires reporting of detections greater than 3 µg/L. The use of data based on analytical methods with low detection limits indicates that MTBE occurs more frequently and is more widespread in ground water than does the use of data based solely on analytical methods with relatively high detection limits.

From March 1999 to July 2001, the USGS NAWQA and SWRCB GAMA (Groundwater Ambient Monitoring and Assessment) programs sampled 272 wells in several ground-water basins in southern California (fig. 6*A*). The identification and sampling of these wells was facilitated by several local agencies including the Orange County Water District and the Los Angeles Water Replenishment District. MTBE was detected in 51 wells, or 19 percent of the wells sampled. Many of the detections were in the coastal plain; the distribution of these detections is consistent with the distribution of water associated with artificial-recharge operations along the San Gabriel River, Rio Hondo, Santa Ana River, and Santiago Creek. MTBE, at concentrations below drinking water standards, is present in surface water in southern California (Belitz and others, 2003). Where this surface water is used to recharge ground-water flow systems, the MTBE serves as a "tracer" for the presence of that water in the subsurface.

For the period January 1999 to June 2000, which corresponds to the time period of the USGS and SWRCB studies, the DHS database includes analyses for MTBE at 697 wells (fig. 6*B*). MTBE was detected at two wells, or less than 1 percent of the wells sampled. None of the detections were in the coastal plain. If these were the only data available, one would underestimate the frequency that MTBE is present in ground water in these southern California basins.

If one extends the time period to include the entire DHS database (January 1995 to June 2000), then the DHS database includes analyses for MTBE at 868 wells (fig. 6*C*). MTBE was detected at 15 wells, or about 2 percent of the wells sampled. MTBE was detected in the coastal plain, but the distribution of detections does not readily illustrate the relation between the recharge operations and the occurrence of MTBE in ground water. Even with the use of all available DHS data, the frequency of occurrence is underestimated. In addition, the available DHS data are insufficient for identifying the importance of the recharge facilities as an explanatory factor for the distribution of MTBE in the aquifer system.

It is important to note that the concentrations of MTBE in ground water in the coastal plain are generally much lower than drinking-water standards. However, these detections provide a potential "early warning" for a constituent of concern. These detections at low concentrations also provide a basis for assessing the human and natural factors that affect water quality.



Digital relief based upon USGS digital elevation model (DEM)

Geology based used California Department of Conservation, 1962, 1965, 1969a, 1969b, 1981, and Southern California Mapping Project, 1999.

Albers Equal-Area Conic Projection
Standard parallels 29°30′ and 45°30′,
Central meridian - 120°, projection origin 23°

Figure 6. Detection of methyl *tert*-butyl ether (MTBE) using USGS and State Water Resources Control Board data.

NETWORK DESIGN

The monitoring network should allow for assessment of the ground-water resource at a variety of scales. To achieve this goal, the statewide monitoring program will employ a consistent study design in all basins. This consistency will permit assessment at a variety of scales by producing data sets that address the basic objectives at the basin scale, but equally important, can be aggregated to produce regional and statewide assessments.

The basic monitoring network will be established using an approach that selects wells that are spatially distributed across a basin, but which also incorporates an element of randomization in the selection process (Scott, 1990). A spatially distributed, randomized set of wells provides a statistical representation of the resource, and sampling of these wells provides water-quality data that can be taken as representative of the water quality of that resource. Data from several basins can then be aggregated or compared to produce regional and statewide assessments. Deviating from a randomized selection approach will compromise the ability to do assessments on groups of basins, and hence sacrifice the ability to answer questions of regional and statewide importance.

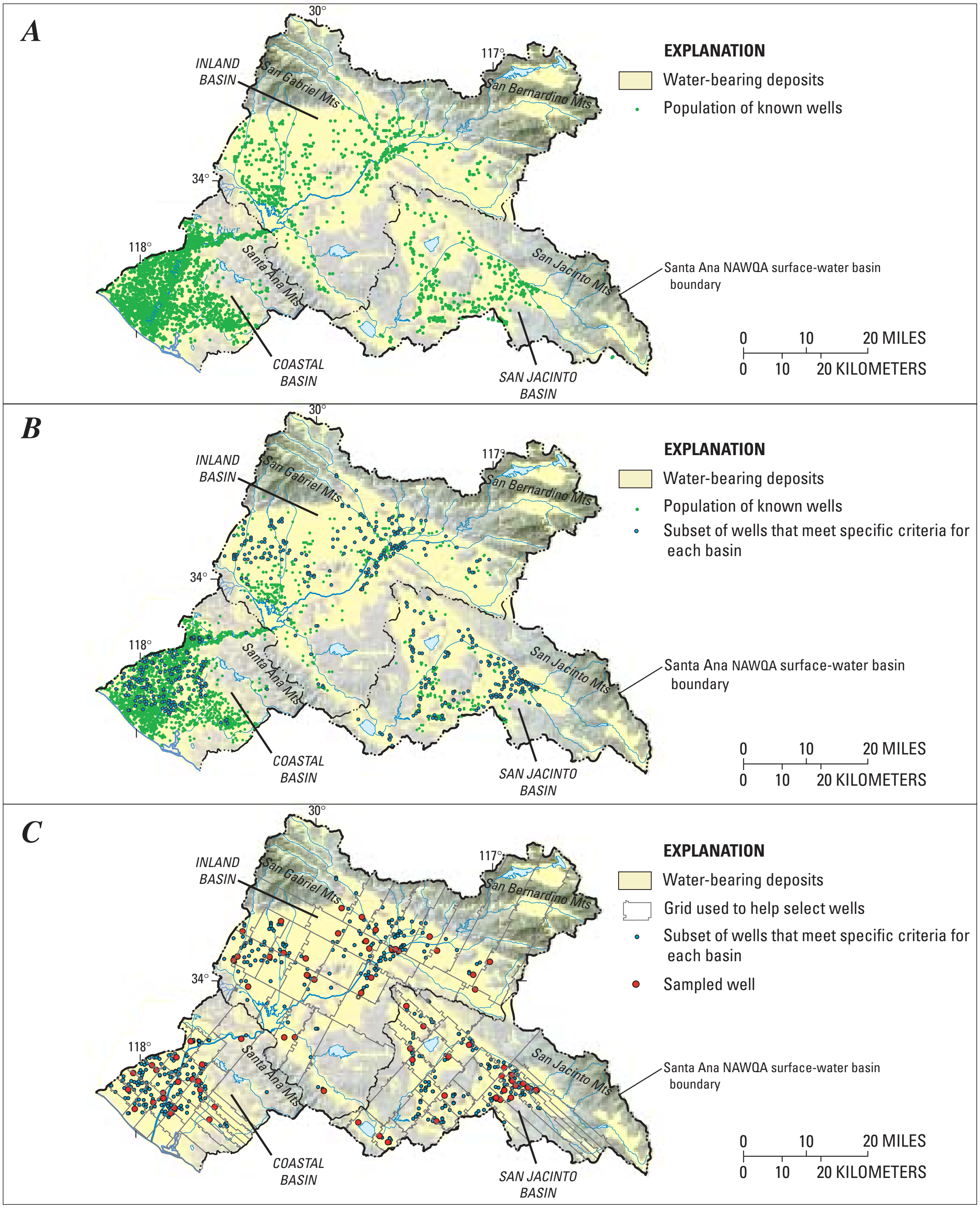
The basic monitoring network can be supplemented by the sampling of additional wells to provide additional information. Justifications for additional sampling include addressing issues of local concern, detecting the presence of emerging contaminants, or obtaining information relevant to understanding the factors that affect water quality. It is anticipated that as much as 25 percent of the sampling effort could be directed toward these additional efforts.

AB 599 specifically focuses on ground water used for drinking water. Given this focus, the monitoring and assessment program will rely primarily on existing public-supply wells for sampling the major aquifers. Public-supply wells, in addition to sampling the drinking-water resource, are appropriate because they generally have long well screens and high pumping capacities, and sample a larger volume of the aquifer than do wells with shorter screened intervals (domestic and monitoring wells). Equally important, public-supply wells have wide areal distribution wherever there are population centers; have their locations entered into an electronic database administered by the DHS; and have historical water-quality data from previous drinking-water-quality compliance monitoring available in the DHS database.

There are limitations to relying primarily on public-supply wells for the monitoring network. These limitations include: (1) The relatively long screen length of public-supply wells can result in dilution of the maximum concentration of a constituent of concern, which can result in underestimation of the maximum concentration present in the aquifer. (2) The relatively long screen length can sometimes obscure the source of contamination to a well (Izbicki, 1991). (3) Public-supply wells can draw water from more than one aquifer, thus complicating interpretation of water quality data. (4) Public-supply wells tend to be located away from areas with impaired water quality, and therefore a statistical summary of data from public-supply wells can underestimate the extent of contamination in an aquifer. (5) Public-supply wells in some basins do not provide sufficient spatial coverage, either in terms of area or in terms of depth; in these basins other types of wells (domestic supply, irrigation, monitoring) will need to be sampled. Many local water agencies maintain databases that will be helpful for identifying suitable wells.

Case Study: Spatially Distributed, Randomized Well Selection in the Santa Ana Basin

The Santa Ana study area, located in southern California (fig. 1), is one of the areas being studied by the USGS NAWQA program. The NAWQA program conducted three major aquifer-system studies in the Santa Ana Basin, corresponding to the major subunits: the Coastal basin, the Inland basin, and the San Jacinto basin. Collectively, there are about 3,000 wells in these three subunits (fig. 7*A*). A subset of 72 wells was identified for the purposes of assessing water quality in each of the three basins. The subset of wells was chosen so that they could provide an unbiased sampling of water-quality conditions in these three basins.



Digital relief based upon USGS digital elevation model (DEM)

Geology based used California Department of Conservation, 1965, 1969a, 1981, and Southern California Mapping Project, 1999.

Albers Equal-Area Conic Projection
Standard parallels 29°30′ and 45°30′,
Central meridian - 120°, projection origin 23°

Figure 7. Well selection for Santa Ana NAWQA major aquifer studies.

(*A*) Population of known wells; (*B*) Wells where extensive data are available; (*C*) Wells selected for sampling using a spatially distributed, randomized approach.

In each of the subunits in the Santa Ana Basin, the map of water-bearing deposits was divided into cells of equal area, and within each cell, wells were selected at random for sampling. In all three subunits, only wells with well-ownership and well-construction information (well depth, well-screen interval) were targeted (fig. 7*B*). In the Coastal basin, wells also had to be screened in the main zone of production; this reduced the number of target wells for the basin from about 2,200 to about 200. In the Inland basin, wells also had to have been previously sampled; this reduced the number of target wells from about 600 to about 300 wells. No additional constraints beyond well-ownership and well-construction information were imposed on wells in the San Jacinto basin; there were about 200 target wells.

In the Inland and San Jacinto basins, an additional step was added to the well-selection process. After each well in a cell was selected, the screened interval (interval open to the aquifer) was compared with the screened interval of the other wells in the cell. If the selected well was representative of the other wells, then it was sampled. If it was not representative, then another well was selected; the process was repeated until the selected well was representative of the other wells. If there were only a few wells in a cell, or if no one well was representative of the others, then the first well selected was sampled.

A total of 72 wells out of about 700 were selected for sampling using the spatially distributed, randomized approach in the three subunits of the Santa Ana study area (fig. 7*C*). Water-quality analyses of samples from these wells were used as the basis for assessment of ground-water quality in the Santa Ana study area (Hamlin and others, 2002), and allow for a comparison with other aquifers sampled by NAWQA in other parts of the country (Belitz and others, 2003). Because each NAWQA well network was established in a similar manner, the results from different aquifer-system studies in different parts of the Nation are directly comparable. In addition, because the well networks are spatially distributed in each aquifer system, each network can be taken as statistically representative of the resource. For example, the aquifers in the Santa Ana Basin generally have higher concentrations of radon than do aquifers sampled by NAWQA in other parts of the country (fig. 8). In the Santa Ana Basin, about 80 percent of the wells have concentrations of radon higher than the regulatory threshold, proposed by the U.S. Environmental Protection Agency (EPA). In addition, volatile organic compounds and pesticides are detected more frequently in the aquifers of the Santa Ana Basin than in aquifers sampled by NAWQA in other parts of the country (fig. 9). The higher detection frequencies are notable because the wells in the Santa Ana Basin tend to be deeper than other wells sampled by NAWQA. The higher detection frequencies in the Santa Ana Basin are likely a consequence of the relatively intensive use of ground water for water supply. If the data were not collected in a uniform manner in each part of the Nation, then these comparisons—and interpretations based on these comparisons—would be more difficult.

The use of a consistent method of well selection in the proposed comprehensive program will allow for an unbiased sampling of water-quality conditions in individual basins in California, will allow for systematic comparison between basins, and will allow for aggregation of data for assessment of the natural and human factors that affect water quality.

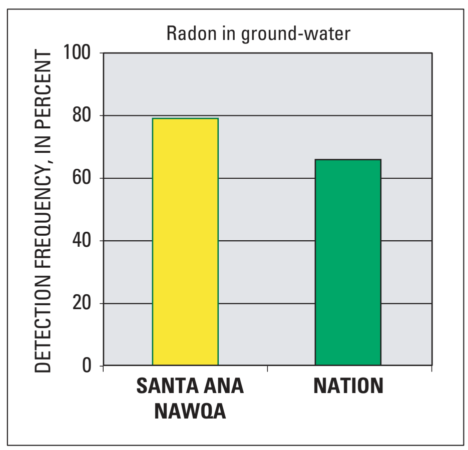


Figure 8. Radon concentrations above proposed drinking-water standards in the Santa Ana NAWQA study area versus aquifers sampled by NAWQA nationwide (from Belitz and others, 2003).

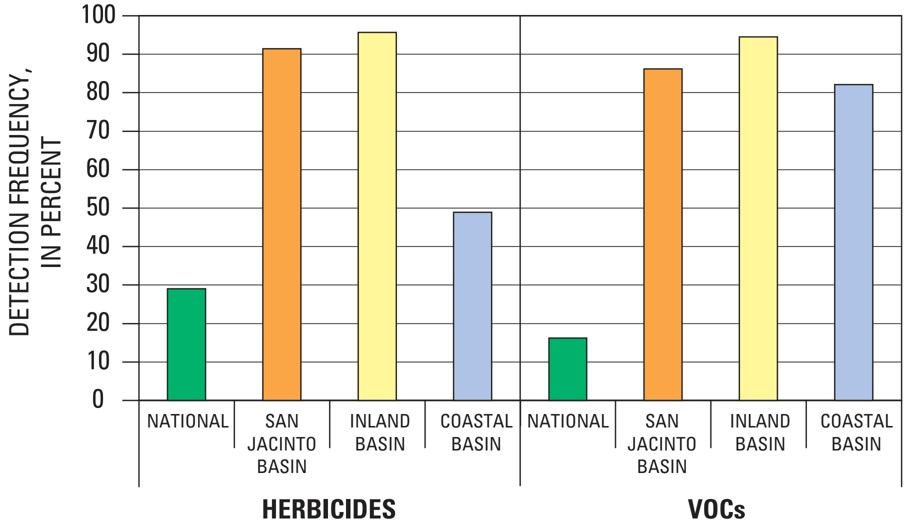


Figure 9. Herbicides and VOCs in ground water in three basins in the Santa Ana NAWQA study area versus aquifers sampled by NAWQA nationwide (from Belitz and others, 2003).

SELECTION OF TARGET CONSTITUENTS

Broadly defined, there are three types of constituents that can be included in a comprehensive ground-water quality monitoring and assessment program. First, there are those constituents that need to be monitored for protection of beneficial uses, especially drinking-water supply. Second, there are constituents that provide information on the sources of water and sources of contamination; these constituents can be used for understanding the natural and human factors that affect water quality. Third, there are constituents that are presently unregulated but that are of potential concern; these “emerging contaminants” include pharmaceuticals and personal care products (U.S. Environmental Protection Agency, 2003). Some of these constituents are already included in existing statewide monitoring programs; others have been included only on a limited basis. Given the availability of different types of data, it is proposed that the comprehensive program implement a “tiered” approach that balances spatial coverage and analytical intensity (number of different constituents analyzed for). In addition, it is proposed that the list of analytes be reviewed as new findings and concerns arise.

Data Collected by Existing Programs

Most of the existing data have been collected for regulatory purposes, and focus on constituents monitored for the protection of beneficial uses. The DHS collects data on an ongoing basis for the protection of public drinking-water supply. Other data collection for regulatory purposes is conducted by the Department of Toxic Substances Control (http://www.dtsc.ca.gov/), the Department of Pesticide Regulation (http://www.cdpr.ca.gov/), and the State and Regional Water Quality Control Boards. The DWR and the USGS have also collected water-quality data related to beneficial use of water, including the suitability for agriculture. For example, Bertoldi and others (1991) discuss the distribution of boron, which is potentially limiting for irrigation, in the Central Valley. Presently (2003), there is no statewide program to assess water characteristics that are limiting for agriculture.

Sampling for constituents that provide information on the sources of water and contaminants has been less common than sampling for regulatory compliance. The SWRCB, through its California Aquifer Susceptibility (CAS) program, is using environmental tracers to assess the susceptibility of public-supply wells to contamination (California State Water Resources Control Board, 2003b). These environmental tracers include age-dating (Ekwurzel and others, 1994), stable isotopes of water, and low-level analyses (part per trillion) of volatile organic compounds (VOCs). These methods have been applied in southern and northern California (Shelton and others, 2001; Hudson and others, 2002; Moran and others, 2002; Dawson and others, 2003).

Other studies utilizing environmental tracers have generally been site specific or focused on particular issues. Such studies include tracking of water at recharge facilities (Davisson and others, 1998;1999a;1999b), identification of salinity in both agricultural and urban areas (Izbicki, 1991; Deverel and others, 1994), and pesticide movement from nonpoint sources (Spurlock and others, 2000; Dawson, 2001).

Sampling for currently unregulated constituents such as emerging contaminants has been limited. At present, the DHS is sampling for a small number of emerging contaminants in public-supply wells as required by Federal and State programs (California Department of Health Services, 2001). A recent national reconnaissance for these emerging contaminants in surface water has increased awareness of the possible transport of these constituents into ground water (Kolpin and others, 2002).

There are a number of different studies that provide guidance for selecting chemical constituents that should be included in water-quality assessments. For example, the National Research Council published recommendations of methods to help the EPA identify potential drinking-water contaminants among the thousands of candidate chemicals (National Research Council, 2001). In a more narrowly focused example, the USGS NAWQA program conducted a systematic evaluation of candidate VOCs for inclusion in the national sampling program; the systematic evaluation considered several factors including chemical properties, human cancer rating, toxicity to aquatic organisms, and availability of occurrence data (Bender and others, 1999).

Balancing Spatial Coverage and Analytical Intensity

Owing to the high cost of laboratory analyses for some environmental tracers and emerging contaminants, it is not feasible to be comprehensive for both spatial and analytical intensity. An approach is proposed that is tiered to balance spatial coverage and analytical intensity (number of different constituents analyzed for). The broadest spatial coverage, or first tier, will be provided by the existing DHS database; these data can be used to characterize water quality relative to beneficial use. The second tier will be provided by sampling a network of wells for a "relatively reduced" list of constituents. The second tier would focus primarily on public-supply wells and would include constituents currently included in the SWRCB CAS program. The third tier will sample for a larger number of constituents, but at fewer wells than the second tier. The "relatively expanded" list of constituents would include constituents covered by the USGS NAWQA program (U.S. Geological Survey, 2003a), as well as emerging contaminants. About 25 percent of the wells sampled for the relatively reduced list will also be sampled for the relatively expanded list.

This tiering will result in spatially comprehensive data for DHS constituents, which are already being analyzed for at public-supply wells, and somewhat decreased spatial coverage for the second and third tiers. As a result, data necessary for protection of beneficial uses will be spatially the most comprehensive; data for environmental tracers will be sufficiently dense to develop an understanding of the natural and human factors affecting water quality at the basin and regional scale; and data for identifying emerging threats to ground-water quality will be available at the regional scale. A comparison of constituent coverage of the DHS and NAWQA lists by general chemical category is given in table 2.

Table 2. Comparison of the number of constituents analyzed for by the California Department of Health Services (DHS) Drinking Water Program and the U.S. Geological Survey National Water-Quality Assessment (NAWQA) program

[Based on data from DHS (written commun., 2001) and California Department of Water Resources (2002). PPCP, pharmaceuticals and personal care products; MTBE, methyl *tert*-butyl ether; PCE, tetrachloroethylene; km^2, square kilometer; —, no data]

Class	Example	DHS	NAWQA
Pesticides	Simazine	34	194
VOCs	MTBE, PCE	33	103
Trace elements	Arsenic	20	22
Nutrients	Nitrate	3	5
Major inorganics	Fluoride	5	15
PPCP	Caffeine	—	67

Iterative Analytical Strategy

An iterative strategy is recommended for the statewide program. In an iterative approach, analytical objectives are reviewed in response to findings from previous studies (Franke and others, 1997; see figure 3). In addition, the comprehensive program is built on the conservative assumption that contaminants may be found where one would not expect them to occur. In California, this can happen not just because of the complexity of contaminant transport in the subsurface, but also because the sources of some contamination may result from the interbasin transfers of water over long distances. This approach runs counter to the tendency to try to reduce cost by looking only for contaminants that one would expect on the basis of the location of current local sources. For that reason, more intensive analytical coverage is proposed in subsets of wells during the first iteration. Constituent distributions can then be evaluated and hypotheses about the relation between occurrence and local sources can be tested. On the basis of these findings, the list of analytes can be decreased or increased in subsequent iterations. As discussed earlier, in addition to the basic consistent approach, the program should have a flexible component that considers issues that may be specific to a particular basin or basins.

Quality Assurance and Quality Control

Consistent procedures for quality assurance and quality control (QAQC) are essential for ensuring the accuracy and precision of water-quality data. QAQC procedures need to be well documented and to encompass all field and laboratory activities related to the collection, analysis, and interpretation of water-quality data (Alley, 1993).

Field QAQC procedures include the cleaning and handling of equipment, as well as the collection, processing, and transport of water samples (U.S. Geological Survey, 1997 to present). Field procedures also include the collection of replicates, spikes, and blanks, at a frequency dictated by the data-quality objectives of the program. The field procedures are normally completed at pre-planned intervals throughout the sampling program and data are interpreted immediately so that corrective actions, if any are required, can be completed. Each analyzed constituent or group of constituent will have a specified performance measure for blanks, replicates, or spikes. Failure to meet those performance measures will require corrective action. The USGS NAWQA program provides guidance on the number and types of replicates, spikes, and blanks to be collected in the field (U.S. Geological Survey, 2003c).

Laboratory QAQC procedures include analysis of replicates, spikes, and blanks that have been prepared in the laboratory, and are used to document that the laboratory analysis is performing according to the specifications of the standard operating procedures for each constituent or constituent group. The USGS National Water Quality Laboratory evaluates laboratory QAQC data to assess potential analytical bias and contamination, and documents these procedures through a series of annual reports (U.S. Geological Survey, 2003d). Laboratory QAQC procedures can also include the “blind-testing of samples” by personnel who make field measurements (U.S. Geological Survey, 2003e).

Successful implementation of the statewide, comprehensive ground-water-monitoring program will require application of well-documented QAQC procedures to ensure the integrity and credibility of the data. It is anticipated that USGS NAWQA guidelines (Koterba and others, 1995) will provide the basis and structure for the statewide QAQC program. Reports based on water-quality data collected for the statewide program will include analysis of the QAQC data.

TREND ASSESSMENT

A comprehensive ground-water monitoring program must be capable of detecting important changes in water quality, including systematic directional changes in quality ("trends"), and the appearance of new contaminants in ground water that were previously not sampled for (that is, "emerging contaminants"). Although this topic covers a wide range of changes, for simplicity it will be referred to as a "Trend Assessment." This assessment is important because the California landscape, as well as natural-resource management, is rapidly changing. Undeveloped lands with native vegetation are being converted to agricultural land use, and agricultural land is being converted to urban land use. An assessment of trends in ground-water quality is challenging because changes in ground-water quality may be the result of natural as well as anthropogenic factors. It is therefore important that natural-resource managers have the data that will permit assessment of the impact or efficacy of various changes.

The goal of the trend assessment is to collect sufficient data to identify broad patterns in change in ground-water quality over time. Because of the focus of AB 599, the objective may be more specifically stated to identify decadal-scale change in selected chemicals in aquifers used as drinking-water supply, and to warn of new occurrences.

The shape of a trend or change may take any number of forms including simple monotonic increases, step functions, and oscillations. In fact, because of the wide variety of factors that affect ground-water quality, the variability in a particular constituent may include combinations of these patterns, such as a step function (due to regulation of a source) imposed on an oscillation (due to climate-driven variations in recharge).

Designing a strategy for assessing trends in ground-water quality contains a central paradox: specification of a frequency of sampling to obtain a desired statistical power to detect a change requires data that do not exist for many of the target constituents. That is, there may be insufficient data to describe the rate and magnitude of the expected change, or the shape of the trend, for most target constituents. Finally, the trends and changes in different classes of target constituents may be different, not just because of differences in sources but also because of differences in the chemical properties that govern transport in ground water.

In some hydrogeologic settings, contaminant concentrations increase more rapidly in shallow wells than in deeper wells (Kolpin and others, 1997; Alley, 1993, p.12). The trends assessment would be greatly enhanced if shallow wells were systematically sampled, and the resulting water-quality data made available digitally; existing shallow wells are typically used for domestic supply or monitoring.

Approach—For the purpose of a statewide assessment, the objective of the trend assessment needs to be further constrained to make it tractable. Most importantly, although there is the potential for seasonal variability in shallow systems that have rapid transport, this scale of temporal variability is beyond the scope of the statewide assessment. Therefore, the working hypothesis for the design is that seasonal variability will generally be small in public-supply wells because of the relatively large depth and length of the well screen. An additional major working hypothesis is that because of the relatively slow rate of ground-water movement in most basins—usually on the order of tens to hundreds of feet per year in major aquifers—frequent sampling is unnecessary. This last hypothesis will likely not hold in some basins, especially those with high lateral gradients produced by large amounts of artificial recharge and pumpage; the design may need to be modified in these areas.

Because of the complexity of the objective, the trends assessment will adopt a multi-tiered approach: retrospective analysis, a systematic decadal-scale sampling of the entire well network, more frequent sampling (every 3 years) of a subset of the well network, complementary assessments to help link the decadal and triennial sampling, and coordination with other monitoring programs. This approach is modeled after the decadal-scale assessment implemented by the USGS National Water Quality Assessment program for trends assessment in the Nation's ground water (Gilliom and others, 1995; 2001; Mueller and others, 2002).

Analysis of existing data—Standard practice for the water-quality assessment in each basin should be a review of existing data, or a *retrospective assessment*. There are variable, but sometimes large, amounts of existing data for public-supply wells. However, as shown in the case study of arsenic in the San Joaquin Valley (Appendix A), the utility of existing data for assessing trends for some classes of constituents can be limited. Therefore, the proposed monitoring and assessment program will include sampling and analyses.

Decadal-scale sampling—The well network sampled during the first phase of the comprehensive program could be resampled 10 years after the first sampling. Resampling on a decadal time scale is generally consistent with rates of ground-water flow in most large aquifers. To maximize the utility of the data, it is imperative that the same wells be sampled, not just the same number of wells. Sampling the same wells allows use of pair-wise statistical comparisons, which have much greater power to detect change than do comparisons of the same number of samples from different wells. Confronted with the same challenge of describing long-term trends in ground-water quality, the USGS NAWQA program is resampling 69 of 225 ground-water networks across the nation at a decadal scale (Mueller and others, 2002).

More frequent sampling of a subset of the network—Sampling wells decadally will provide information as to whether or not water quality has changed in this time frame, but more frequent sampling is necessary to determine if the change in fact constitutes a trend. The NAWQA program requires biennial sampling of 17 percent of the wells in a typical network (Mueller and others, 2002): typically 5 of 30 wells. Because biennual sampling in a large number of wells is not feasible, and because California's ground-water basins are much smaller than NAWQA study areas, sampling 10 per cent of the wells in each priority basin once every 3 years (triennially) can be considered. This approach would provide two sets of data between the decadal samples. The resulting data will (1) provide context and confidence that any change seen in the two decadal samples is part of a persistent pattern, and (2) provide earlier warning if a new contaminant that is rapidly transported is introduced into the system. Depending on the rate of change of each specific chemical constituent, the triennial sampling may not reveal significant trends in individual wells for two or more decades. More frequent sampling should be considered in areas of concern.

Complementary trends assessments—The trends assessment should make extensive use of the second tier of analytical intensity: constituents analyzed to aid in interpretation of chemical processes and ground-water flow. The simplest way to use these data is to identify constituents that date ground water by serving as "event markers"; these are environmental tracers that mark the occurrence of a particular event, such as the use of a chemical—be it household use, industrial use, or agricultural use—confined to a specific and relatively brief window of time (Plummer and others, 1993). The SWRCB GAMA program has made extensive use of VOCs (Shelton and others, 2001) and radiochemical event markers (Hudson and others, 2002; Moran and others, 2002) to help determine the susceptibility of aquifers to contamination. Other examples include the now-banned rice herbicide bentazon in ground water in the Sacramento Valley (Dawson, 2001, p. 25), and different types of chlorofluorocarbons (CFCs) that have a known history of occurrence in the atmosphere (Plummer and others, 1993). Spurlock and others (2000) applied CFC age-dating to help explain the relation between pesticide-application practice and occurrence in the San Joaquin Valley.

A more specific application of environmental tracers is to age-date ground water from a set of wells along a ground-water flowpath. These flow-system studies allow inferences to be drawn about the change in chemical input over time by examining the current distribution of chemical concentration along the flowpath. Because the age of the ground water increases downgradient from the recharge area, these studies are said to exchange "space for time." Puckett and others (2002) present an example of the application of CFC age-dating for evaluating how time-dependent nitrate input and in-situ nitrate-removal processes control nitrate transport to a stream.

Adapt the design for basins of high concern—Many of the highly engineered ground-water basins in California are already intensively monitored and have been studied in detail, including the evaluation of environmental tracers. This ongoing monitoring should be taken into account, and a portion of the resources of the trends assessment should be adapted to take advantage of the existing knowledge and data networks. Many of these studies are conducted by State and local water agencies. For example, sampling in eastern Fresno County can be coordinated with the ongoing DPR program investigating the effectiveness of best management practices on pesticide occurrence in domestic wells (Troiano and others, 2001). In particular, where there is reason to believe that change might be rapid, concentrating some effort to conduct annual sampling in specific areas should be considered.

Case Study: Nitrate Concentrations in the San Joaquin Valley

The San Joaquin Valley (fig. 1) was 1 of 60 large hydrologic areas selected for study by the USGS NAWQA program. The results of the ground-water-quality investigations, and for nitrate in particular, were reported by Burow and others (1998a,b, 1999), and are summarized in Dubrovsky and others (1998). Prior to new sample collection, thousands of existing analyses for nitrate concentration were reviewed. These data showed that long-term changes in nitrate concentrations in existing wells are consistent with increases in fertilizer use during the same period (fig. 10).

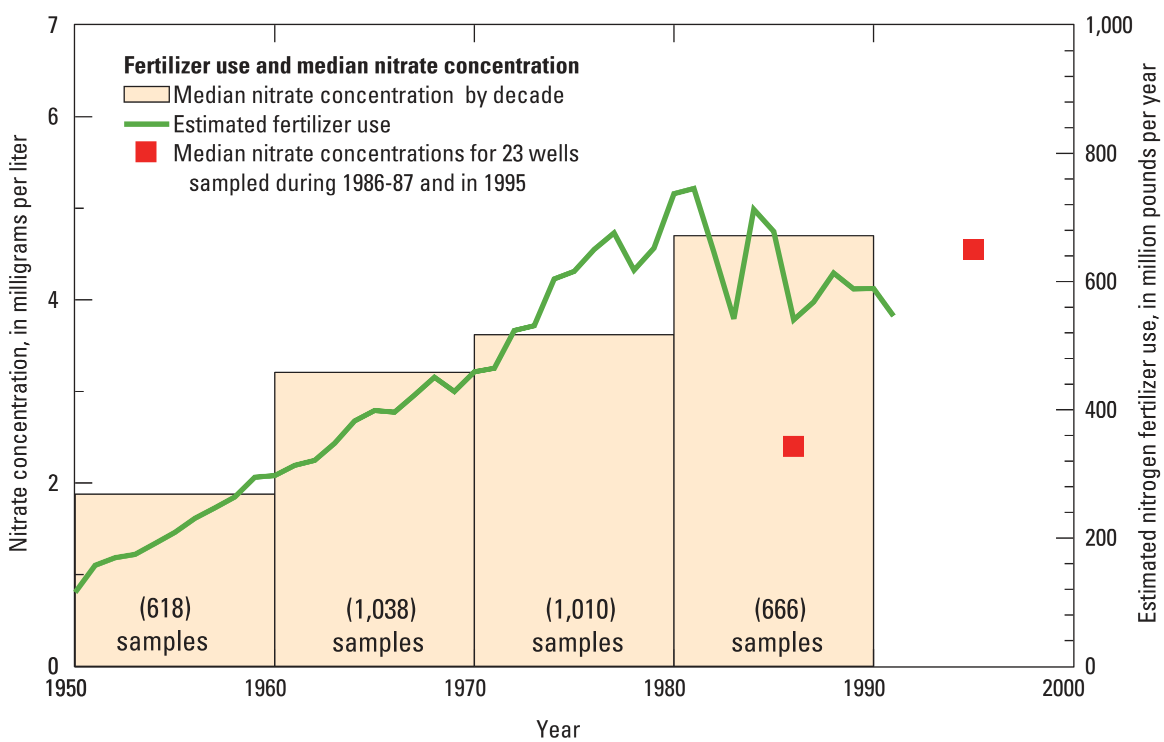


Figure 10. Nitrate concentrations in ground water in the San Joaquin Valley have increased over the last four decades (from Dubrovsky and others, 1998).

This observation of increasing nitrate concentration with time in ground water was supported by analyses of new data. In 1995, NAWQA resampled 23 domestic supply wells in the eastern San Joaquin Valley that had previously been sampled by the USGS between 1986 and 1987 (Burow and others, 1998b). The median nitrate concentration for the 23 wells in 1986–87 was 2.4 mg/L, and in 1995 the median concentration was 4.8 mg/L. Taking into account the fact that the data are paired analyses from the same wells (fig. 11) allows the use of a paired-sample test, the Wilcoxon signed-rank test (Helsel and Hirsch, 1992). The Wilcoxon signed-rank test indicates that the two sets of nitrate analyses are statistically different (p=0.05), and therefore nitrate concentrations in this network of domestic wells increased in the intervening 8 to 9 years. If these data sets were assumed to be independent of one another, which is a classic statistical assumption, then a parametric t-test would show that they are not significantly different (p=0.528). This example illustrates the importance of retaining a consistent set of wells in a network to maximize the statistical power for determining change with the least number of samples.

Burow and others (1999) also used CFC age-dating to help assess changes in the concentrations of nitrate and the banned fumigant DBCP along a ground-water flowpath in the eastern San Joaquin Valley. Data for 20 monitoring wells east of Fresno, California, indicate that nitrate concentrations are highest in the shallow portion of the aquifer with young CFC age-dates, and generally decrease with increasing depth and increasing CFC age in the aquifer (fig. 12).

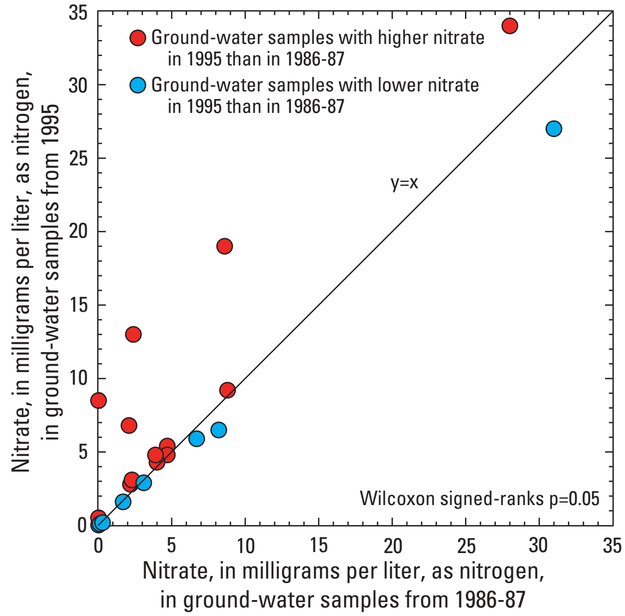


Figure 11. Increased nitrate concentrations in the eastern San Joaquin Valley from 1985-86 to 1995 (from Burow and others, 1998b).

The highest nitrate concentrations occurred in shallow ground water recharged during 1977 to 1992. These findings, taken along with the analysis of the retrospective nitrate data and the decadal sampling, provide three complementary lines of evidence that increase our confidence that nitrate in ground water in the eastern San Joaquin Valley has increased during the last few decades.

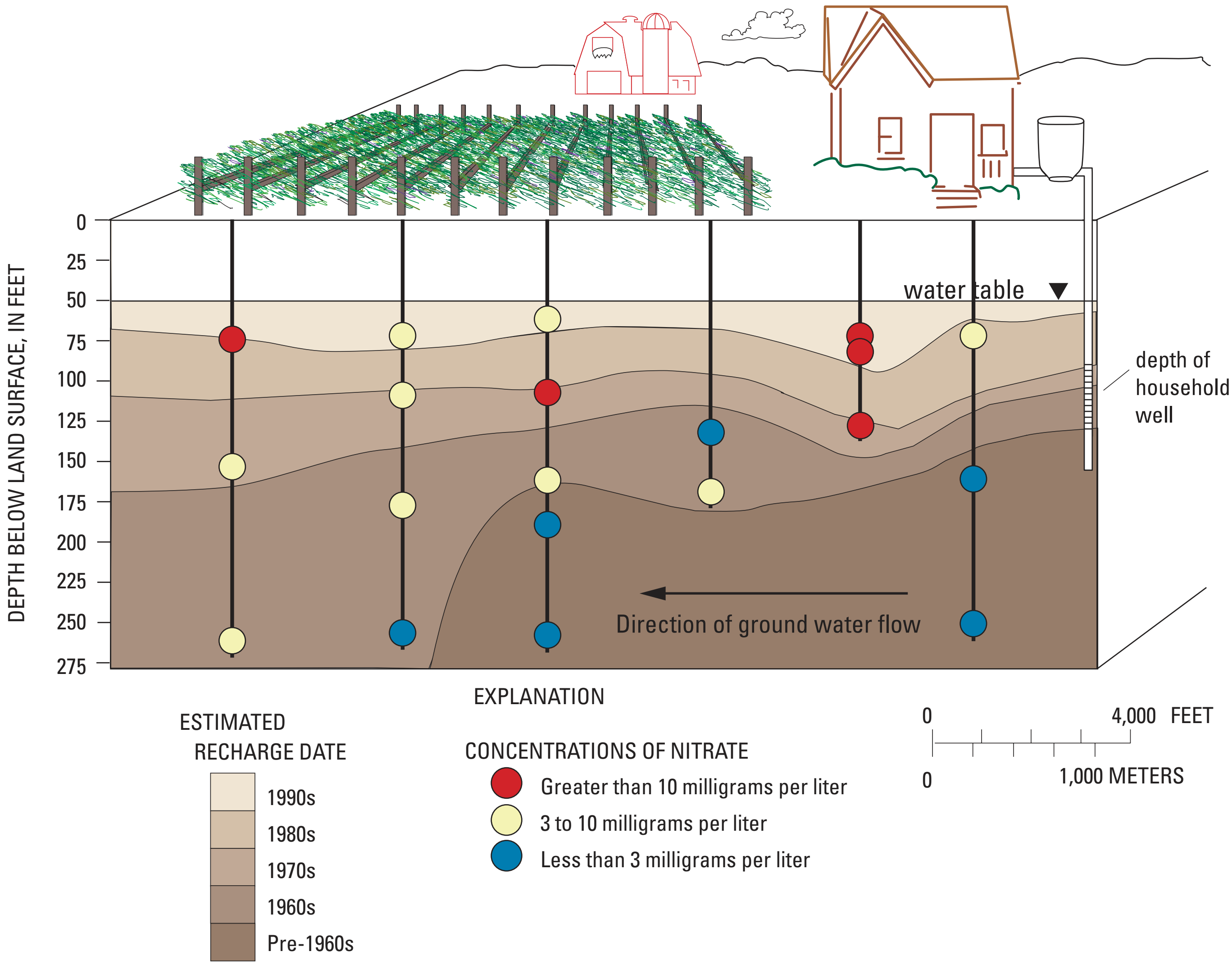


Figure 12. Nitrate concentrations decreasing with depth, suggesting that nitrate entering the ground-water system has increased in the past few decades, east of Fresno (from Dubrovsky and others, 1998)

ASSESSMENT FOR UNDERSTANDING: RELATING WATER QUALITY TO HUMAN AND NATURAL FACTORS

A ground-water-quality assessment needs to provide information that can help answer the question of why a specific constituent is, or is not, observed in a ground-water basin. Answering this question requires identification of the source(s) of a constituent and an understanding of the processes that govern its transport through the aquifer. Ultimately the assessment will seek to improve our understanding of how human and natural sources of contaminants impact ground-water quality. This information can then support management decisions on how to mitigate an existing, or avoid a potential, ground-water-quality problem. It is anticipated that in many of the basins as much as 25 percent of the data-collection effort will be designed to improve the understanding of basin-specific issues.

Determination of how a constituent is transported from a source to a well may be simple or difficult. The simplest cases are when a contaminant is derived from a single source, and the physical and chemical processes that govern transport are well defined. In reality, many contaminants have a variety of potential sources, their chemical behavior is complex, and the hydrogeological system is variable in space and time. Some contaminants may appear in wells many years or decades after their release from a source.

Because of these potentially confounding complexities, an understanding of why a contaminant occurs at a certain level is usually accomplished by coupling high-quality ancillary data on source and hydrogeologic factors, with multiple lines of evidence—often at multiple scales. Much of the evidence is derived from analyzing the relations among the various constituents along with the data on environmental tracers. Application of a variety of interpretative methods (deterministic, statistical, empirical, modeling) increases the confidence in identifying a suitable explanation. Although a comprehensive discussion of approaches to analyzing water-quality data is beyond the scope of this report, a few examples from the literature on regional-scale water-quality assessment in California are offered.

- Sources of some contaminants may be obscure and (or) remote, and contamination may result from the inter-basin transfers of water over long distances. Perchlorate is an example of a contaminant that originated in a watershed outside of California, but was introduced from imported surface water into ground water in some parts of southern California.
- Multiple sources and processes may contribute to increasing dissolved solids concentrations. In coastal parts of southern California, ratios among major and minor elements along with environmental tracers have been used to discriminate among multiple sources of salinity (Izbicki, 1991). Because the sources are such radically different processes—seawater intrusion, evaporative concentration of young shallow ground water, and upwelling of old connate saline water—very different management approaches need to be considered.
- Trace-element transport in ground water is commonly microbially mediated and governed by complex processes such as adsorption and oxidation/reduction (redox) reactions. An understanding of factors controlling the regional distribution of selenium in San Joaquin Valley ground water required the integration of an understanding of the redox chemistry of selenium (White and Dubrovsky, 1994); laboratory studies of microbial processing of selenium (Oremland, 1994); and the valleywide distribution of natural selenium sources, selenium concentrations, and redox conditions (Dubrovsky and others, 1993).

Case Study: Tritium, Chloroform and MTBE in the Southern California Coastal Plain

In the southern California coastal plain (fig. 13), ground-water recharge facilities are used to enhance replenishment of aquifers used for public supply. These facilities are located along the San Gabriel River and Rio Hondo in the Los Angeles part of the coastal plain, and along the Santa Ana River and Santiago Creek in the Orange County part of the coastal plain. These facilities have been used for more than 5 decades. In addition to the recharge facilities, ground-water injection wells, located along the coast, are used to help prevent seawater from entering the aquifer system.

From 1999 to 2001, about 200 wells were sampled in the southern California coastal plain as part of the USGS NAWQA and SWRCB GAMA programs (fig. 13). Analyses of these samples included tritium, chloroform, and MTBE. Tritium, an isotope of hydrogen that is incorporated into the water molecule, is an indicator of ground water recharged since the early 1950s. Tritium is widespread in the aquifer system, indicating the replacement of older ground-water by water recharged during the past 50 years (fig. 13*A*). Chloroform, a VOC that is primarily a byproduct of water disinfection, is also widely distributed in the aquifer system (fig. 13*B*), although not as widespread as tritium. MTBE, a compound added to gasoline to reduce air pollution, has been used extensively since the early 1990s. MTBE is not as widespread (fig. 13*C*) in the aquifer system as is chloroform, which has been generated for a longer period of time. Although the concentrations of chloroform and MTBE are below regulatory and advisory levels set for drinking water, the distribution of these compounds indicates the extent to which human activity may affect water quality. In particular, the distribution of these compounds illustrates relatively rapid transport from the land surface into aquifers, and therefore relatively high susceptibility of these aquifers to contamination that occurs in the unconfined, or forebay, areas.

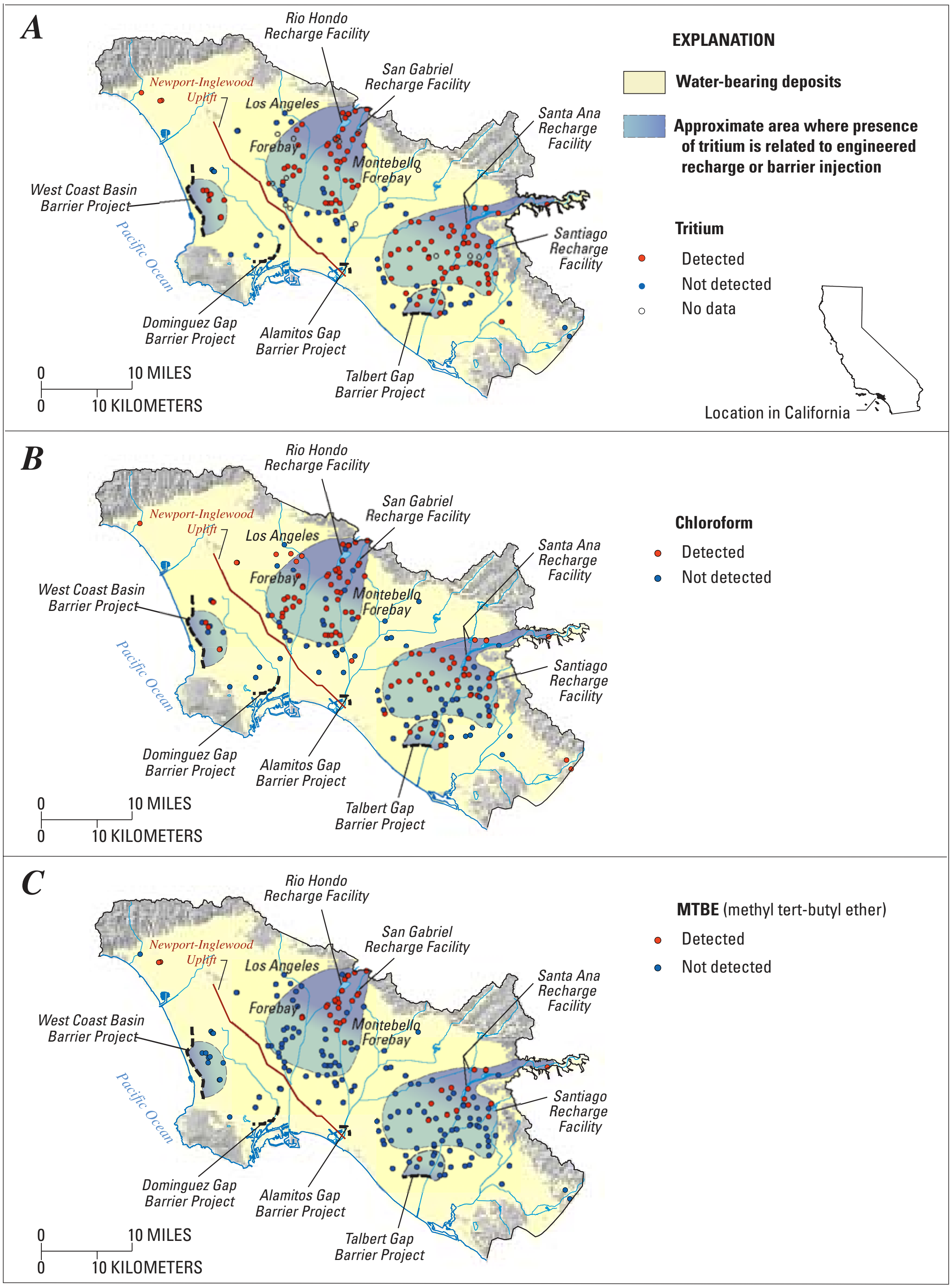


Figure 13. Distribution of (*A*) tritium, (*B*) chloroform, and (*C*) methyl *tert*-butyl ether (MTBE) in the southern California coastal plain, 1999-2001.

PRIORITIZATION OF BASINS AND OTHER STUDY AREAS

Previous sections of this report have focused on how a comprehensive ground-water quality monitoring and assessment program might be implemented in individual basins. This section focuses on where the monitoring program should be implemented. AB 599 requires that the monitoring program prioritize ground-water basins that provide drinking water. Given this requirement, we distinguish between “priority basins” and “low use” ground-water basins.

The four sections that follow describe how priority basins were identified. In the first section, each basin in the State is ranked relative to the others using several factors related to reliance on ground water and to potential sources of contamination. These rankings provide perspective on the number of basins that need to be included in a comprehensive monitoring and assessment program. In the second section, the locations of basins that rank highly with respect to drinking-water supply are compared to the locations of basins that rank highly with respect to other factors. These comparisons suggest that basins highly ranked for drinking-water supply are also highly ranked for the other factors, thus allowing identification of a relatively simple set of criteria for identifying priority basins. These criteria are described in the third section. In the fourth section, the criteria are used to identify four categories of priority basins; some ground-water basins were grouped with other basins for the purposes of prioritization. Because some basins are grouped with others, “single-basin study areas” can be differentiated from “grouped basin study areas”; the term study area can refer to either.

The fifth and final section of this chapter describes two additional categories. One additional category is proposed to account for areas outside basins. It is important to include these areas because nearly 20 percent of the public-supply wells in California are located in areas outside mapped ground-water basins (fig. 3*B*; table 1). Another category is proposed to account for basins that are identified as “low use ground-water” basins. Altogether, there are six categories.

Ranking the Basins

Ranking of ground-water basins is an important step in establishing priorities for the comprehensive ground-water-monitoring and assessment plan. In this section, six individual factors are used to rank ground-water basins: (1) area, (2) number of public-supply wells, (3) municipal ground-water use, (4) agricultural ground-water use, (5) number of leaking underground fuel tanks, and (6) number of square-mile sections with registered use of pesticides. For the purposes of analyses, areas mapped as ground-water subbasins in the San Joaquin and Sacramento Valleys (California Department of Water Resources, 2002) are considered as basins. Elsewhere in the State, subbasins are not considered separately. Ranking of basins for each of the six factors provides perspective on the number of basins that should be included in a comprehensive ground-water monitoring and assessment program.

The six factors chosen for ranking basins were chosen because each one relates to some aspect of ground-water use, and because digital data are available for each on a statewide basis. It is important to use data with statewide coverage to ensure that all basins in the State can be considered; digital data permits efficient evaluation. Other factors, such as the number of domestic wells or domestic well users, were not considered because there is presently (2003) no statewide digital database available for them.

For each factor, the ground-water basins were ranked from largest to smallest. After the basins were ranked, the numbers of basins needed to account for specified percentages of each factor was determined (table 3). For example, there are 472 ground-water basins with a total area of 176,000 km^2; these 472 basins account for 100 percent of the area. The 34 largest basins account for 50 percent of the total area; each of these basins is larger than 1,470 km^2. The largest 136 basins (those that are larger than 300 km^2) account for 90 percent of the total area.

Given the example of area, other factors relevant to ground-water use and potentially contaminating activities can be examined. Table 3 includes a compilation of the number of basins needed to account for specified percentages of the individual factors (for example, number of public-supply wells). Table 3 also includes a compilation of the amount of a factor, or threshold, needed for a basin to be included in a specified category.

Table 3. Number of basins, and associated thresholds, needed to account for specified percentages of water supply and potential sources of pollution

[Based on data from California Department of Health Services (written commun., 2001); California State Water Resources Control Board (2001), Joe Marade, California Department of Pesticide Regulation (written commun., 2002) and California Department of Water Resources (2002); km^2, square kilometer; acre-ft/yr, acre-feet per year, —, no data]

Factor	Total amount of factor for all basins	Number of basins needed to account for specified percentage of factor					Threshold values for each factor associated with percentiles			
		50 percent	75 percent	90 percent	95 percent	100 percent	50 percent	75 percent	90 percent	95 percent
Area (km^2)	176,000	34	80	136	—	472	1,470	710	300	—
Public-supply wells	13,000	14	33	71	114	267	260	100	25	12
Municipal ground-water users	10.8 million	4	10	28	—	126	695,000	210,000	50,000	—
Agricultural pumping (acre-ft/yr)	18 million	6	18	37	—	360	625,000	225,000	85,000	—
Leaking underground fuel tanks	30,000	9	29	67	—	244	700	180	70	—
Pesticide applications (sections)	22,000	12	29	55	—	253	650	195	70	—

The number of public-supply wells in a ground-water basin is a direct indicator of the extent to which ground water is used for public supply. The DHS database (California Department of Health Services, written commun., 2001) includes 13,000 public-supply wells that are located in areas mapped as ground-water basins (California Department of Water Resources, 2002). An additional 3,000 public-supply wells are located outside areas mapped as basins (table 1; fig. 3). Of the 472 ground-water basins in California, only 267 have public-supply wells (table 3). Fourteen of these basins account for 50 percent of the 13,000 wells located in basins, and 71 basins account for 90 percent (table 3). These results indicate that a substantial proportion of the used ground-water resource in California can be evaluated by focusing on relatively few basins.

Municipal ground-water use is also a direct indicator of ground water used for public supply. For the purposes of ranking basins, municipalities that rely entirely or partly on ground water were assumed to be located within a single ground-water basin. The municipal-use database (William Templin, U.S. Geological Survey, written commun., 2002) estimates the number of "equivalent people" relying on ground water. For example, if a city of 2 million people relies on ground water for 50 percent of the total water demand, then the number of ground-water users would be 1 million. Given this approach, there are about 10.8 million municipal ground-water users located in 126 basins (table 3); an additional 0.1 million are located outside areas mapped as basins. Of the 10.8 million municipal ground-water users located in basins, 50 percent are located in 4 basins and 90 percent are located in 28 basins. The 28 basins that account for 90 percent of the municipal ground-water users also tend to have a large number of public-supply wells. The relation between factors is discussed in more detail in the next section.

Agricultural pumping is a direct measure of ground-water use, albeit not of ground water used for public supply. Given the possibility of conversion of agricultural land use to urban land use, the volume of agricultural pumping can be viewed as an indicator of ground water that might be used in the future as a source of public supply. In addition, basins with large amounts of agricultural pumping may be indicative of basins in which there are a large number of domestic wells. The database for agricultural pumping (William Templin, U.S. Geological Survey, written commun., 2002) provides estimates for surface-water watersheds rather than ground-water basins. For the purposes of ranking basins, pumping in each watershed was distributed among ground-water basins located within that watershed. The distribution between basins was based on area. If a ground-water basin was located in more than one watershed, then the pumping from that basin was the sum of the distributions from each of the watersheds. Given this approach, 6 of California's 472 ground-water basins account for 50 percent of the agricultural pumping (table 3). Thirty-seven of the basins account for 90 percent. As with public-supply wells and municipal ground-water users, relatively few basins account for a predominance of the used ground-water resource.

The number of leaking underground fuel tanks [LUFTs] (California State Water Resources Control Board, 2001) in a ground-water basin is an indicator of potential ground-water contamination. The California EPA database includes 30,000 LUFTs that are located in basins; an additional 6,000 LUFTS are located in areas outside basins. Of the 30,000 leaking tanks that are located in ground-water basins, 50 percent are located in just nine basins, and 90 percent are located in 67 basins (table 3). Of the 472 basins in California, about half have no reported leaking tanks. As with factors related to ground-water supply, one can account for a substantial proportion of potential contaminant sources by focusing on a disproportionately small number of basins.

The number of square-mile sections with registered use of pesticides (Joe Marade, California Department of Pesticide Regulation, written commun., 2002) also is an indicator of potential ground-water contamination. The DPR database includes 22,000 sections that are located in basins; an additional 6,000 sections are located in areas outside basins. Of the 22,000 sections with registered pesticide use, 50 percent of the sections are located in 12 basins, and 90 percent are located in 55 basins (table 3). Of the 472 basins in the State, 219 basins have no sections with registered pesticide application. Again, one can account for a substantial proportion of the potential contaminant sources by focusing on a disproportionately small number of basins.

Examine the Location of Highly Ranked Basins

This section examines the locations of basins that are highly ranked for each of the factors relating to ground-water use and potential sources of contamination. This examination provides perspective on where in California the ground-water monitoring and assessment program should be implemented. In addition, the locations of basins that rank highly on the basis of drinking water supply are compared to the locations of basins that rank highly on the basis of other factors. As a measure of drinking-water supply, the number of public-supply wells is used rather than municipal ground-water use because public-supply wells include, but are not limited to, wells used for municipal supply. The purpose of the comparison is to determine the extent to which basins that are highly ranked for public-supply wells also are highly ranked for the other factors. If there is a general correspondence, then a program that prioritizes the basins with a relatively large number of public-supply wells will tend to be inclusive of other factors as well.

The locations of basins classified by the number of public-supply wells are shown in figures 14*A* and 14*B*. For the purposes of illustration, six classifications are shown in figure 14*A*: basins that collectively account for 50 percent of the wells, additional basins needed to account for 75 percent of the wells, additional basins needed to account for 90 percent of the wells, additional basins needed to account for 95 percent of the wells, additional basins needed to account for 100 percent of the wells, and basins with no wells. Basins that account for 50 percent of all public-supply wells are located in just four hydrogeologic provinces: Southern Coast Ranges, Central Valley, Desert, and Transverse and Selected Peninsular Ranges. Most of the basins with relatively few public-supply wells are located in the Desert province, Basin and Range province, and Modoc Plateau and Cascades province.

Two classifications are shown in figure 14*B*: basins that collectively account for 95 percent of the public-supply wells, and remaining basins. For the purposes of discussion, the basins that account for 95 percent of the wells are defined as “highly ranked for wells.” This map is useful for examining the relation between basins that are highly ranked for wells and basins that are highly ranked for the other factors. The 95-percent threshold was chosen for two reasons: (1) to identify basins that are inclusive of a large percentage of wells; and (2) to identify basins that are inclusive of other factors. Of the 472 basins in California, 114 are highly ranked on the basis of public-supply wells.

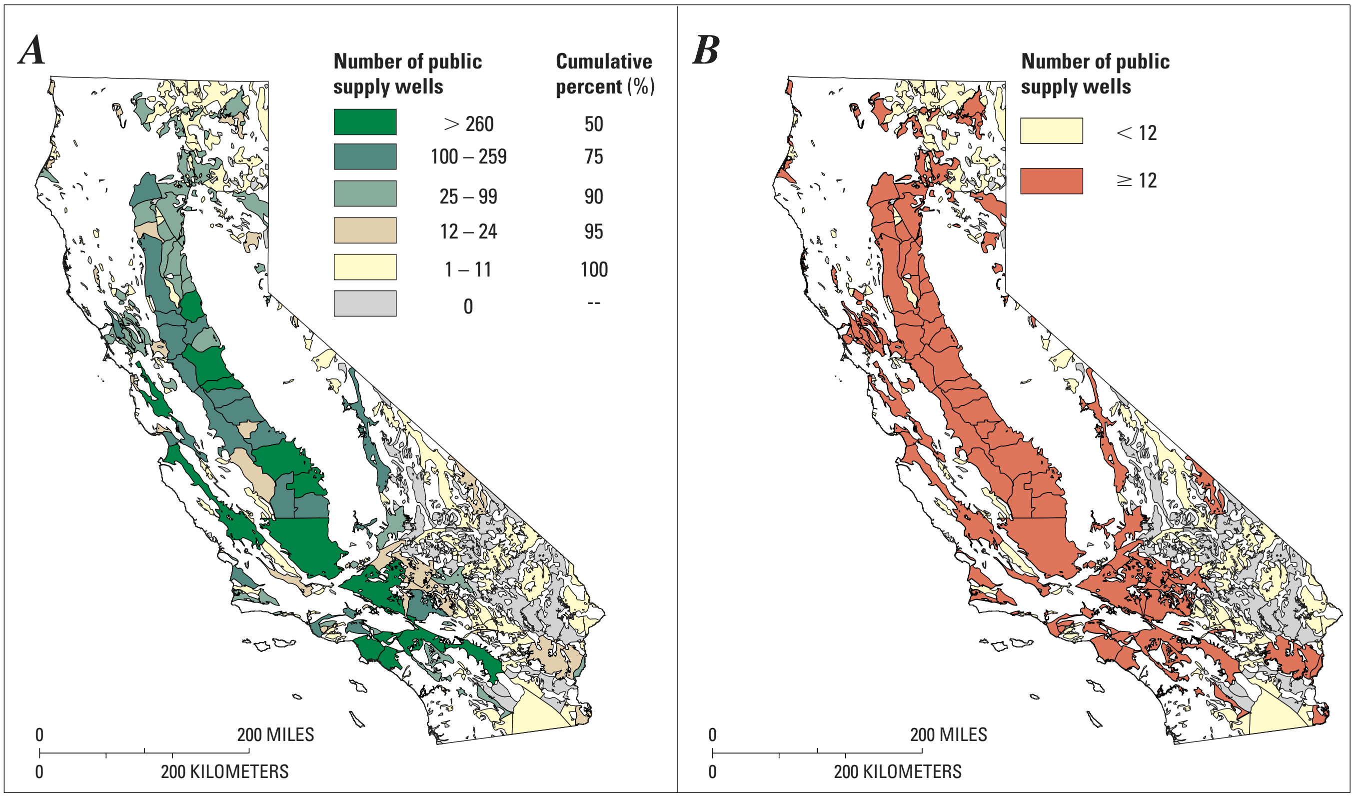


Figure 14. Ground-water basins categorized by number of public-supply wells.

(A) Six categories based on cumulative percent of wells that are located in basins. (B) Basins that account for 95 percent of public-supply wells are shaded in red. Location of public-supply wells from California Department of Health Services (written commun., 2001). Location of ground-water basin boundaries from California Department of Water Resources (2002).

For the purposes of mapping the other factors (figs. 15 to 19, below), five groups of basins were recognized: basins that collectively account for 50 percent of the factor, additional basins needed to account for 75 percent of the factor, additional basins needed to account for 90 percent of the factor, additional basins needed to account for 100 percent of the factor, and basins with none of the factor. The number of basins associated with these percentiles is compiled in table 3. For the purposes of discussion, the basins that collectively account for 90 percent of a factor, other than public-supply wells, are defined as "highly ranked" for that factor. The 90 percent threshold was chosen to identify basins that are inclusive of a large percentage of the selected factor.

The locations of basins classified by area are shown in figure 15*A*. In figure 15*B*, the locations of basins highly ranked for public-supply wells are superimposed over the locations of basins classified by area. Comparison of the two figures indicates that many of the larger basins (greater than 300 km^2) are not highly ranked for wells. Most of these basins are located in the Desert, Basin and Range, and Modoc Plateau and Cascades provinces. Comparison of the two figures also indicates that many of the smaller basins (less than 300 km^2) are highly ranked for wells. Most of these basins are located in the Northern Coast Ranges, Southern Coast Ranges, and Transverse and Selected Peninsular Ranges hydrogeologic provinces. These results reflect the fact that more people in California live along or near the coast, rather than in the arid areas of eastern California. These results also suggest that if the number of public-supply wells is used as the primary factor for prioritizing basins, some of the larger basins in the State might not be included in the comprehensive monitoring and assessment program.

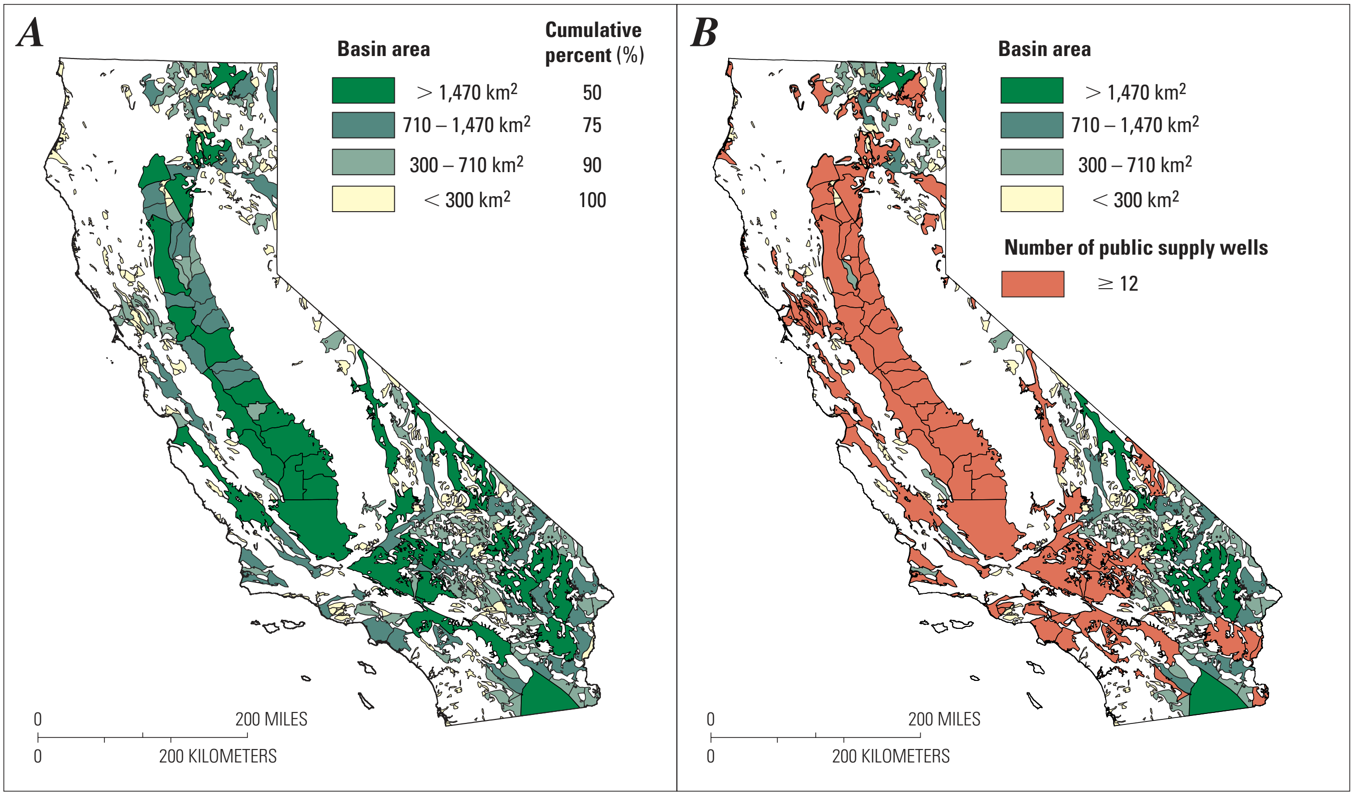


Figure 15. Ground-water basins categorized by area.
(*A*) Four categories based on cumulative percent of area. (*B*) Basins that account for 95 percent of public-supply wells are shaded in red, and are superimposed over map (*A*). Location of ground-water basin boundaries from California Department of Water Resources (2002).

The locations of basins classified by municipal ground-water use are shown in figure 16*A*. In figure 16*B*, the locations of basins highly ranked for public-supply wells are superimposed over them. Comparison of the two figures indicates that the basins highly ranked for wells are completely inclusive of the basins highly ranked for municipal ground-water use. The basins highly ranked for wells also include basins that are not highly ranked for municipal ground-water use. Alternatively stated, the basins that are highly ranked for municipal ground-water users are a subset of the basins that are highly ranked for number of public-supply wells.

The locations of basins classified by agricultural pumping are shown in figure 17*A*. In figure 17*B*, the locations of basins highly ranked for public wells are superimposed over them. Most of the basins that are highly ranked for pumping (more than 85,000 acre-ft/yr) are located in the Central Valley and Modoc Plateau and Cascades provinces. Other basins highly ranked for agricultural pumping are located in the Desert and Southern Coast Ranges provinces. Comparison of figure 17*A* and 17*B* indicates that, with the exception of the Modoc Plateau and Cascades province, the basins highly ranked for wells are generally inclusive of the basins that are highly ranked for agricultural pumping. This result suggests that if public-supply wells are used as the primary factor for basin prioritization, basins that are highly ranked for agricultural pumping will be generally included in the comprehensive monitoring program.

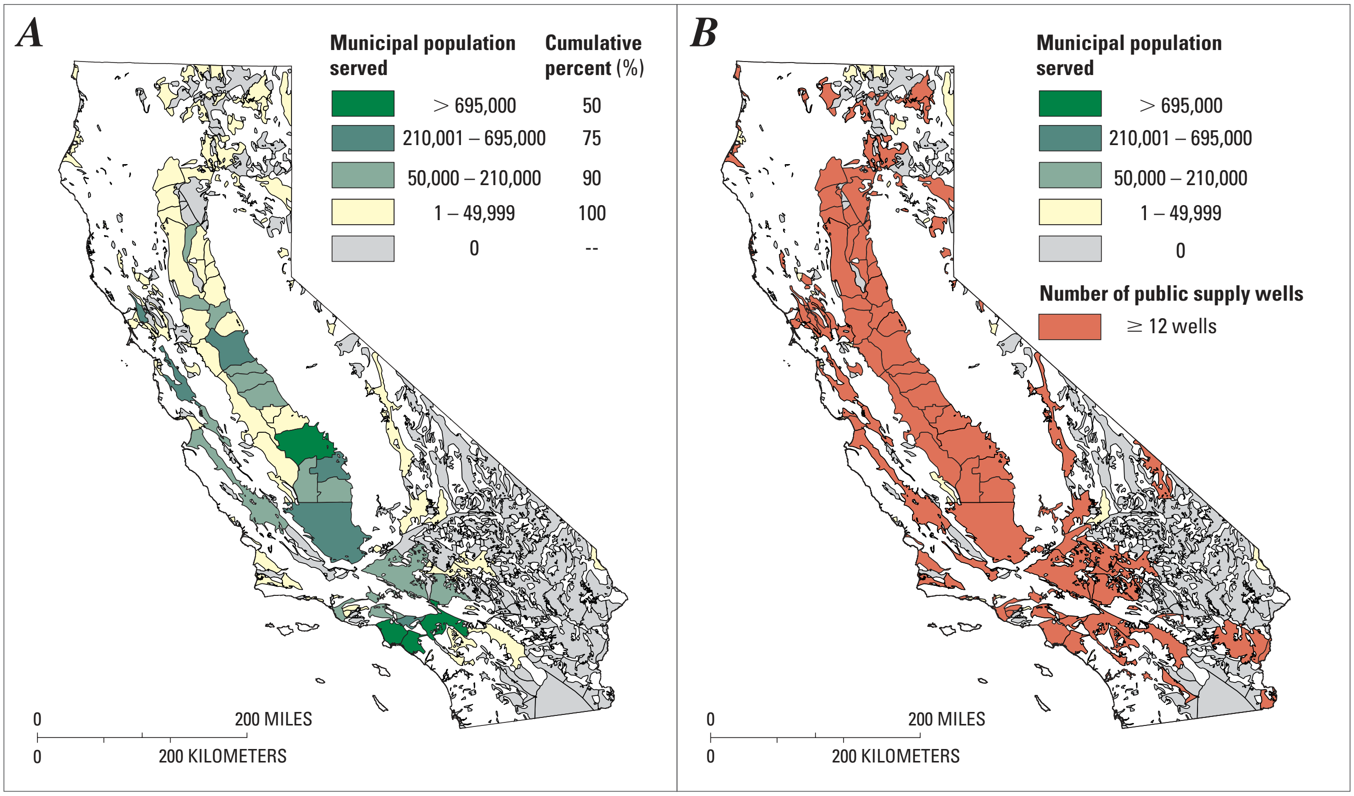


Figure 16. Ground-water basins categorized by municipal population using ground water.
(*A*) Five categories based on cumulative number of people using ground water. (*B*) Basins that account for 95 percent of public-supply wells are shaded in red, and are superimposed over map (*A*). Location of ground-water basin boundaries from California Department of Water Resources (2002).

The locations of basins classified by the number of LUFTs are shown in figure 18*A*. In figure 18*B*, the locations of basins highly ranked for public-supply wells are superimposed over them. Basins that are highly ranked for LUFTs (more than 70 tanks) occur in 7 of the 10 hydrogeologic provinces; the exceptions are the Klamath Mountains, Modoc Plateau and Cascades, and Sierra Nevada provinces. Comparison of figures 18*A* and 18*B* indicate that, with a few notable exceptions, the basins highly ranked for wells are inclusive of the basins that are highly ranked for LUFTs. The notable exceptions are basins in the San Francisco Bay, San Diego, and the Imperial Valley areas; these areas generally are served by surface water sources rather than ground-water sources. The basins in the San Francisco Bay and San Diego areas are small, and therefore difficult to see in figure 18. The general correspondence between basins highly ranked for public-supply wells and basins highly ranked for LUFTs supports the use of public-supply wells as the primary factor for basin prioritization.

The locations of basins classified by the number of square-mile sections with registered pesticide applications (sometime between 1995 and 1999) are shown in figure 19*A*. In figure 19*B*, the locations of basins highly ranked for wells are superimposed over them. Basins that are highly ranked for pesticide application (more than 70 sections) occur in 7 of the 10 hydrogeologic provinces; the exceptions are the Klamath Mountains, Basin and Range, and Sierra Nevada provinces. Comparison of figures 19*A* and 19*B* indicate that the basins highly ranked for wells, with a few notable exceptions, are generally inclusive of the basins that are highly ranked for pesticide applications.

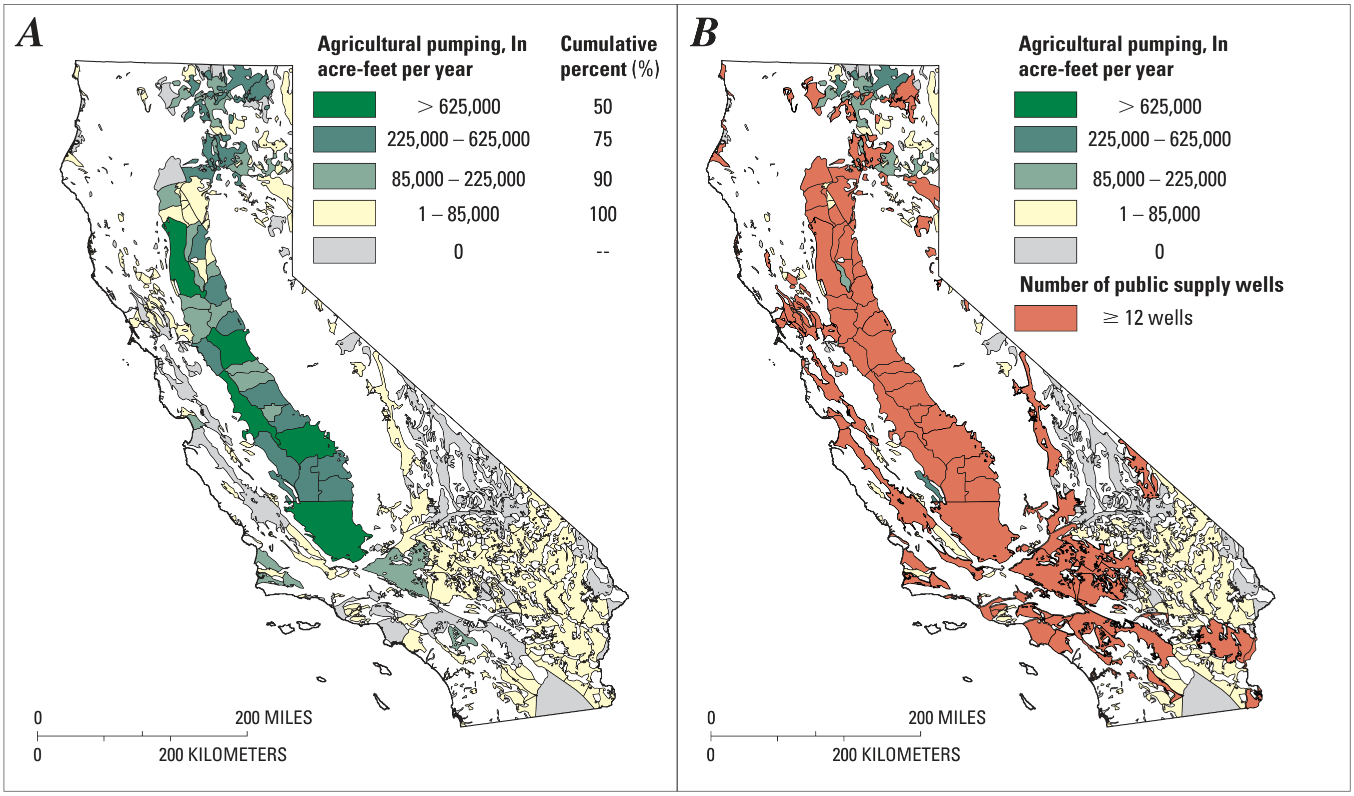


Figure 17. Ground-water basins categorized by agricultural pumping.

(*A*) Five categories based on cumulative pumping. (*B*) Basins that account for 95 percent of public-supply wells are shaded in red, and are superimposed over map (A). Location of ground-water basin boundaries from California Department of Water Resources (2002).

As illustrated in figures 14 to 19, there is a general correspondence, with the exception of area, between basins highly ranked for public-supply wells and basins highly ranked for the other factors. This suggests that a comprehensive monitoring program that prioritizes ground-water basins with a large number of public-supply wells will tend to be inclusive of other factors as well.

Define the Criteria for Identifying Four Categories of Priority Basins

This section presents the criteria used for identifying four categories of priority basins. The choice of four categories was recommended by the California State Water Resources Control Board and the Interagency Task Force, which was created as part of AB 599. Although the number of categories is subjective, categorization provides a method for broadly separating those basins that are more important from those basins that are less important. In addition, categorization helps to eliminate small differences in rankings between basins.

The primary factor used in developing the four categories was the number of public-supply wells in a basin. In addition to the primary criteria, four secondary factors were used: municipal pumping, agricultural pumping, LUFTs, and pesticide applications. Representation of hydrogeologic provinces and efficiencies associated with sampling groups of neighboring basins were also considered in the identification of priority basins.

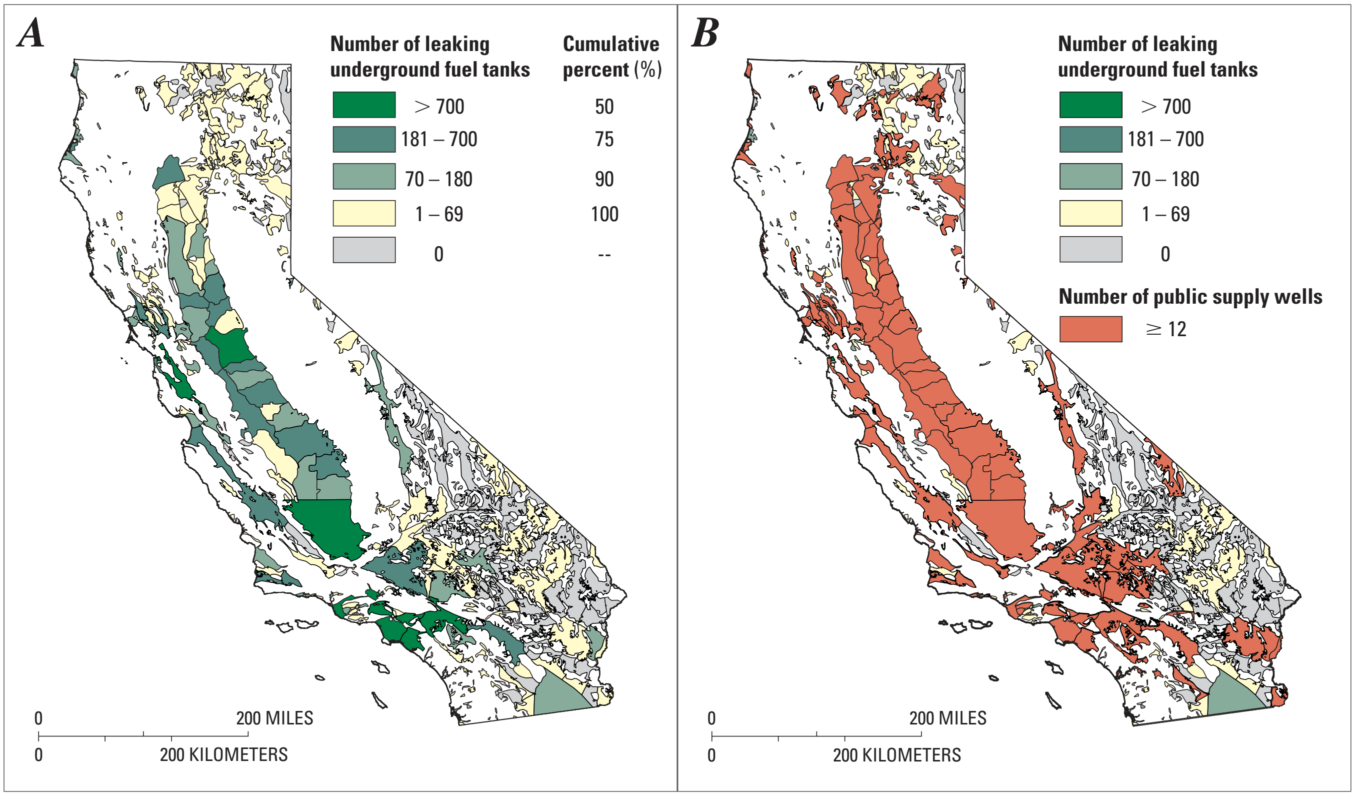


Figure 18. Ground-water basins categorized by leaking underground fuel tanks (LUFTs).

(A) Five categories based on cumulative number of LUFTs. (B) Basins that account for 95 percent of public supply wells are shaded in red, and are superimposed over map (A). Location of LUFTs from California State Water Resources Control Board (2001). Location of ground-water basin boundaries from California Department of Water Resources (2002).

In some areas, individual basins may not have a large number of pubic supply wells or secondary factors. In the interests of efficiency, some of these basins were grouped with neighboring basins that do have relatively large numbers, and in other cases, several basins were grouped so that the group would have sufficiently large numbers. Because some basins are grouped with others, we differentiate between “single-basin study areas” and “grouped-basin study areas”; the term “study area” can refer to either.

Selection of public-supply wells as the primary factor is consistent with AB 599, which requires prioritization of basins that provide drinking water. For this factor, four thresholds of significance were identified: 260 wells, 100 wells, 25 wells, and 12 wells. These thresholds correspond to the 50th, 75th, 90th, and 95th percentiles for the number of public-supply wells located in basins (table 3). Categorization based on these thresholds separates those study areas that have the most wells from those study areas that have the fewest wells.

For each of the secondary factors, a single threshold of significance was identified: 50,000 ground-water users (or equivalent users), 85,000 acre-ft/yr pumped for irrigation, 70 LUFTs, and 70 sections with pesticide application. These thresholds correspond to the 90th percentile for each of the factors (table 3). If a study area has more of a factor than the relevant threshold, then that study area is “highly ranked” for that factor. Recognition of highly ranked study areas for the secondary factors allows for prioritization of study areas that might have relatively few public-supply wells, but that are important for other reasons.

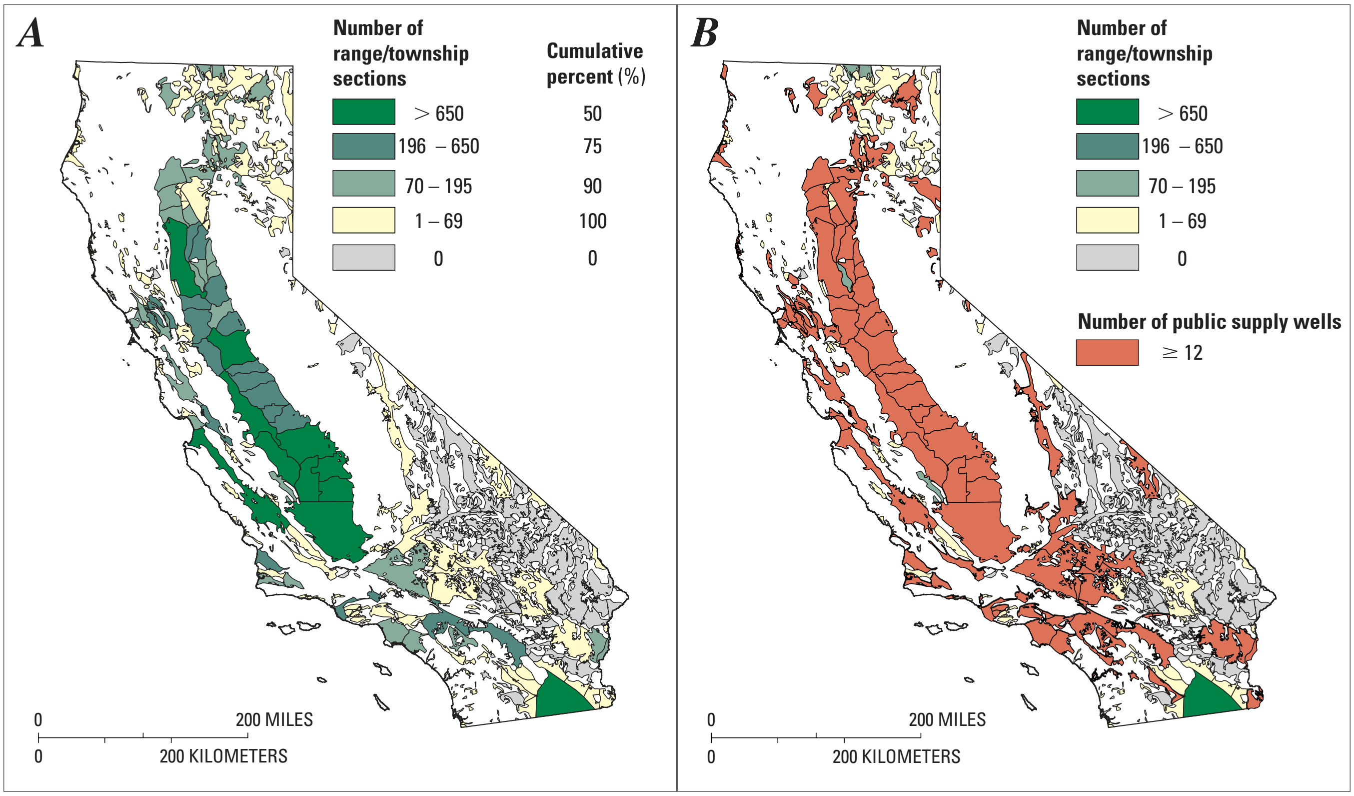


Figure 19. Ground-water basins with registered pesticide applications (sometime between 1995 and 1999) categorized by number of square-mile sections.

(A) Five categories based on cumulative number of sections. (*B*) Basins that account for 95 percent of public-supply wells are shaded in red, and are superimposed over map (*A*). Location of sections with pesticide applications from Joe Marade, California Department of Pesticide Regulation (written commun., 2002). Location of ground-water basin boundaries from California Department of Water Resources (2002).

Given the specified thresholds for public-supply wells and the secondary factors, four categories of prioritization were identified (table 4). Categories 1 and 2 were established to include study areas with a large number of public-supply wells. Categories 3 and 4 were established to include study areas that have lesser numbers of wells, but are highly ranked for one or more secondary factors. These four categories are discussed in more detail in the next section.

Table 4. Criteria for inclusion of a study area in Categories 1 to 4 (priority ground-water basins, California)

Category	Criteria for inclusion
1	More than 260 public-supply wells
2	100 to 259 public-supply wells
3	25 to 99 public-supply wells and highly ranked for at least two secondary factors
4	25 to 99 public-supply wells, but not highly ranked for at least two secondary factors; or12 to 24 public-supply wells and highly ranked for at least 1 secondary factor

Apply the Criteria: Priority Study Areas Consisting of Basins

Four categories of "priority basins" were identified using the criteria described in the previous section (table 4). Collectively, the four categories include 82 study areas (and 116 basins; table 5) representing all 10 hydrogeologic provinces (fig. 20). Collectively, the basins in Categories 1 to 4 account for about three-quarters of California's 16,000 public-supply wells (table 6). If one excludes wells located outside of basins, then Categories 1 to 4 account for 94 percent of the public-supply wells (table 7).

Table 5. Number of study areas and basins, and total area for Categories 1 to 6

[Based on data from California Department of Health Services (written commun., 2001) and California Department of Water Resources (2002). km^2, square kilometer; na, not applicable]

Category	Description	Number of study areas	Number of basins	Total area (km^2)
1	Priority basins	22	29	45,400
2	Priority basins	19	30	30,300
3	Priority basins	23	31	11,300
4	Priority basins	18	26	15,000
5	Areas outside basins	na	na	234,000
6	Low-use basins	na	356	74,500

Table 6. Number of public-supply wells, municipal ground-water users, agricultural pumping, leaking underground fuel tanks, and sections of land with pesticide application for Categories 1-6

[Based on data from California Department of Health Services (written commun., 2001); California State Water Resources Control Board (2001); Joe Marade, California Department of Pesticide Regulation (written commun., 2002); and California Department of Water Resources (2002)]

Category	Description	Public-supply wells	Municipal ground-water users (millions)	Agricultural pumping (millions of acre-feet per year)	Leaking underground fuel and storage tanks	Pesticide application (sections)
1	Priority basins	7,700	9	6.6	18,100	8,100
2	Priority basins	2,900	1.3	6.4	5,000	7,600
3	Priority basins	1,000	.3	1.6	1,900	2,000
4	Priority basins	600	.1	1.6	1,100	2,000
5	Areas outside basins	3,100	.1	0	5,800	6,000
6	Low-use basins	800	.1	2.2	3,500	1,400

Table 7. Priority basins (Categories 1 to 4) account for a relatively high percentage of public-supply wells, municipal ground-water users, agricultural pumping, leaking underground fuel tanks, sections of land with pesticide application, and area

[Percentages are based on total amount of each factor located in basins (see table 6)]

Category	Description	Public-supply wells	Municipal ground-water users	Agricultural pumping	Leaking underground fuel and storage tanks	Pesticide application	Area
1	Priority basins	60	84	36	61	36	26
2	Priority basins	22	12	35	17	35	17
3	Priority basins	8	3	8	6	9	6
4	Priority basins	5	1	8	4	9	8
1–4	All priority basins	95	99	88	88	90	58
6	Low-use basins	5	1	12	12	10	42
1–4, 6	All basins	100	100	100	100	100	100

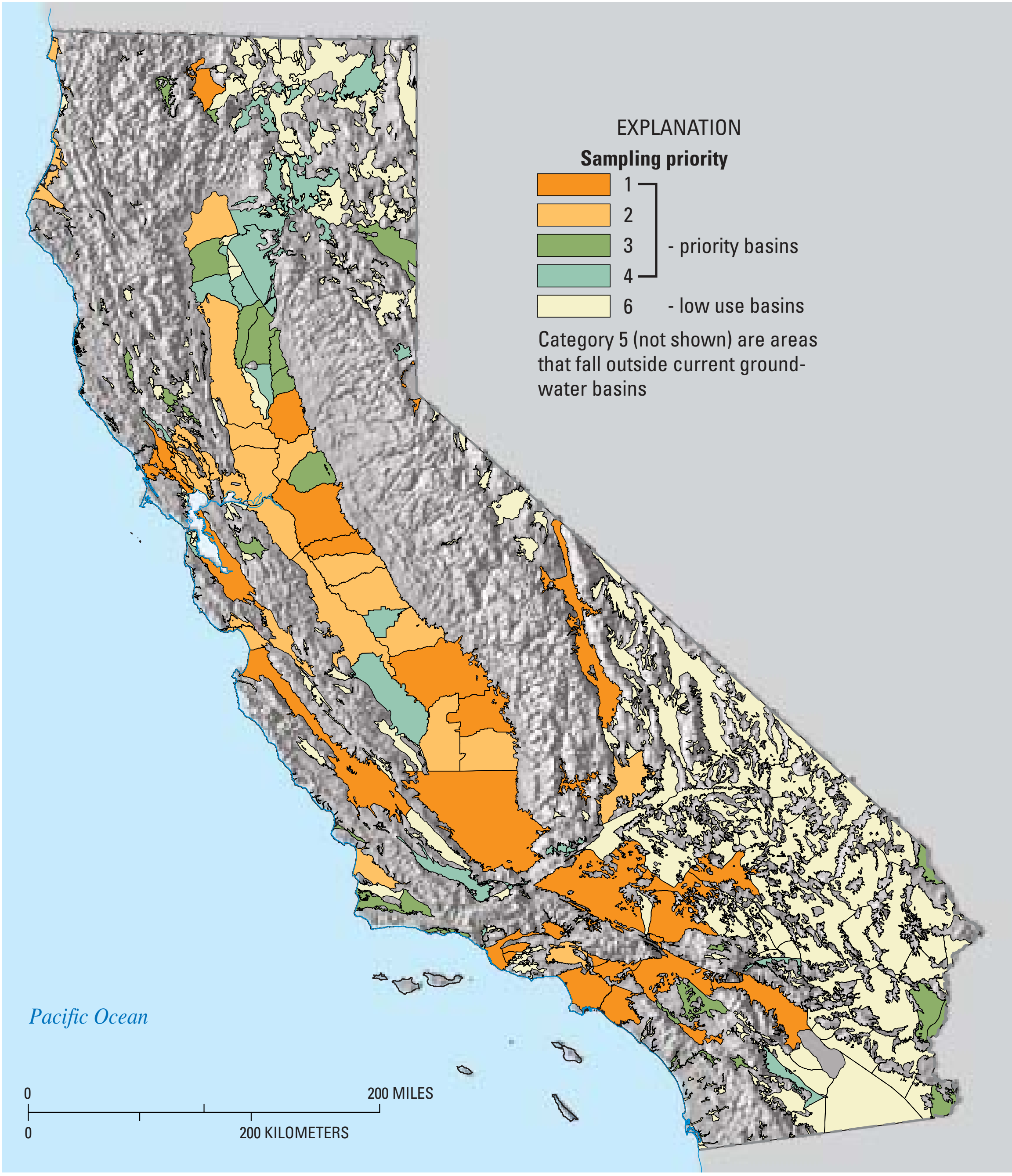


Figure 20. Ground-water basins categorized by sampling priority.

Location of ground-water basin boundaries from California Department of Water Resources (2002).

The basins in Categories 1 to 4 also account for most of California's municipal ground-water use, agricultural pumping, LUFTs, and square mile sections of land with pesticide applications (table 6). If one excludes areas outside of basins, then Categories 1 to 4 account for 99 percent of the municipal ground-water users, 88 percent of the agricultural pumping, 88 percent of the LUFTs, and 90 percent of the sections with pesticide applications (table 7). In this section, additional information about each of the four categories is presented.

Category 1 includes 22 study areas (table 5; Appendix C). These 22 study areas include 29 ground-water basins that are distributed among 9 of the 10 hydrogeologic provinces. Seventeen of the study areas meet the criteria for Category 1 (more than 260 public-supply wells); these study areas represent only 5 of the 10 hydrogeologic provinces. Therefore, an additional five study areas were included to provide representation for four additional hydrogeologic provinces. The Klamath Mountains Hydrogeologic Province is not represented in Category 1; the basin in this province with the largest number of wells is Scott's Valley, which has only 12 public-supply wells.

Category 1 includes about 7,700 public-supply wells (table 6), or about 60 percent of all the public-supply wells located in basins (table 7). Given the percentage of public-supply wells as a benchmark (60 percent), the percentage of municipal ground-water users (84 percent) is disproportionately high; the percentages of agricultural pumping (36 percent) and sections with pesticide applications (36 percent) are disproportionately low. These results suggest that the basins in Category 1 are primarily urban.

Category 2 includes 19 study areas (table 5; Appendix D). These study areas include 30 basins that are distributed among five hydrogeologic provinces. Eighteen of the study areas, representing four provinces, meet the criteria for Category 2 (more than 100 public-supply wells). One study area was added to provide representation for an additional hydrogeologic province.

Category 2 includes about 2,900 public-supply wells (table 6), or 22 percent of all the public- supply wells located in one of California's ground-water basins (table 7). Given the percentage of public- supply wells as a benchmark (22 percent), the percentage of municipal ground-water users (12 percent) is disproportionately low; the percentages of agricultural pumping (35 percent) and sections with pesticide applications (35 percent) are disproportionately high. These results suggest that the Category 2 basins are primarily agricultural.

Category 3 includes 23 study areas (table 5; Appendix E). These study areas include 31 basins that are distributed among nine hydrogeologic provinces, including the Klamath Mountains, which was not represented in either Categories 1 or 2. Eleven of the study areas meet the criteria for Category 3 (table 4); these basins represent 5 of the 10 hydrogeologic provinces. An additional 12 study areas were included in Category 3 to provide representation of an additional four provinces or to provide additional spatial coverage within a province. The basins of Category 3 account for 8 percent of the public-supply wells that are located in basins, and less than 10 percent of the secondary factors (table 7).

Category 4 includes 18 study areas (table 5; Appendix F). These study areas include 26 basins that are distributed among seven hydrogeologic provinces. Seventeen of the study areas meet the criteria for Category 4 (table 4). One of the 18, the Modoc Plateau Pleistocene Volcanic Area, meets the criteria for inclusion in Category 3, but it has relatively few wells (27 wells) given its relatively large area (5,010 km^2). The basins of Category 4 account for 5 percent of the public-supply wells that are located in basins, and less than 10 percent of the secondary factors (table 7).

Two Additional Categories Are Identified

In the previous section, four categories of priority basins were identified. In this section, two additional categories are identified (table 5). Category 5 accounts for areas outside basins, and Category 6 accounts for “low use” ground-water basins.

Category 5 includes areas outside basins. The areas outside ground-water basins are important because about 3,100 of California's 16,000 public-supply wells, or nearly 20 percent, are located in these areas (table 6; fig. 3*B*). In addition, 16 percent of the leaking underground fuel tanks and 21 percent of the square-mile sections of land with pesticide applications are located in areas outside mapped basins (table 8; fig. 21). Given these relatively large proportions, a comprehensive ground-water monitoring and assessment plan should include areas outside mapped ground-water basins.

Table 8. Number of leaking underground fuel tanks (LUFTs) and square-mile sections (township-range sections) with pesticide applications that are located inside and outside basins

[Based on data from California State Water Resources Control Board (2001); Joe Marade, California Department of Pesticide Regulation (written commun., 2002) and California Department of Water Resources (2002). km^2, square kilometer]

Province	Total area (km^2)	Area outside basins	LUFTs		Sections with pesticide application	
			Inside basins	Outside basins	Inside basins	Outside basins
Northern Coast Ranges	38,000	32,000	2,430	580	940	1,490
Southern Coast Ranges	42,000	29,000	8,300	760	1,920	1,100
Klamath Mountains	23,000	22,700	20	200	60	260
Modoc Plateau & Cascades	39,000	18,000	190	30	770	410
Central Valley	53,000	0	6,400	0	15,080	0
Sierra Nevada	66,000	64,000	190	990	60	1,600
Basin & Range	36,000	20,000	190	40	100	10
Transverse & Peninsular Ranges	22,000	14,000	9,650	560	1,260	480
San Diego Drainages	10,000	9,000	920	2590	140	640
Desert	81,000	25,000	1300	80	1,720	20
California	*410,000*	*234,000*	*29,590*	*5,830*	*22,050*	*6,010*

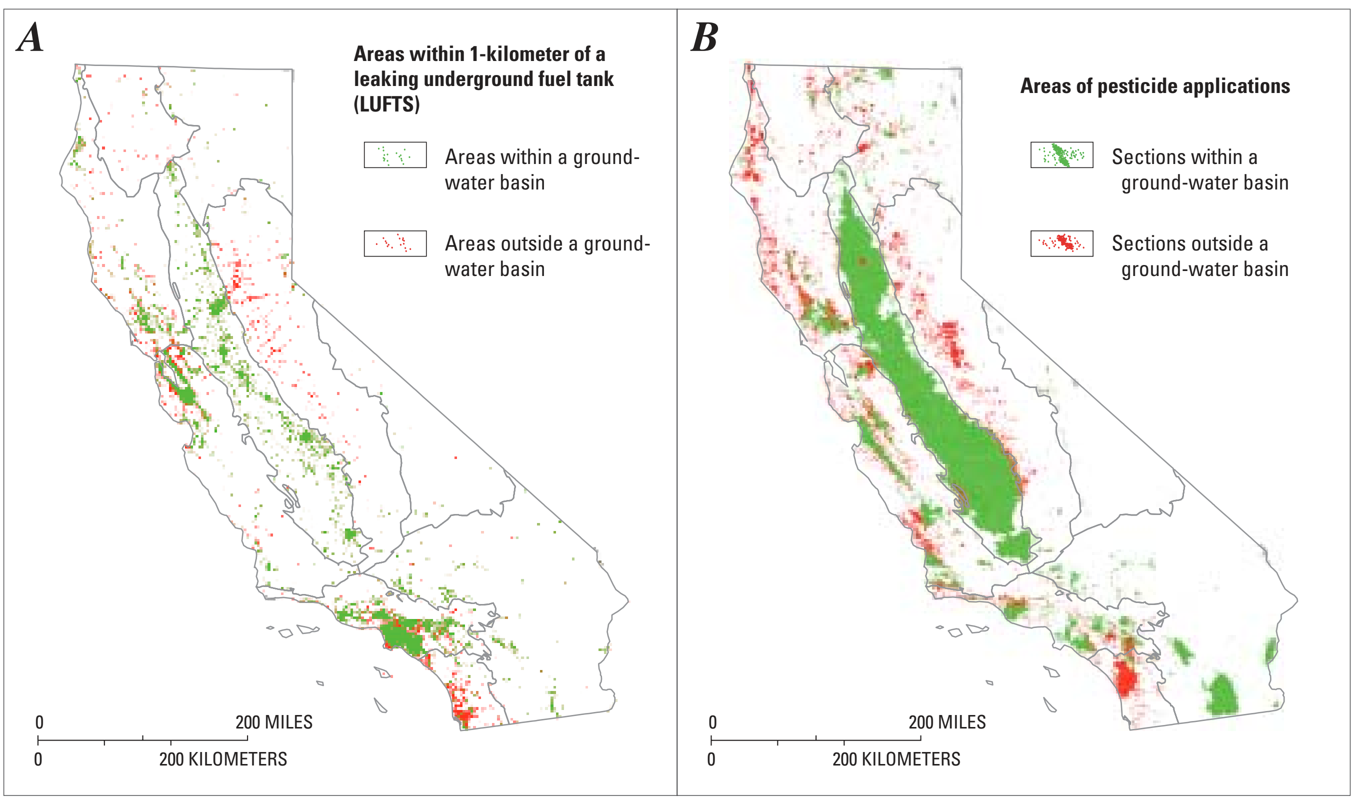


Figure 21. Leaking underground fuel tanks (LUFTs) and areas of pesticide application in California.

(*A*) Areas within 1 kilometer of a LUFT, inside and outside of ground-water basins. (*B*) Square-mile sections (township-range sections) where pesticides were applied sometime between 1995-2000, inside and outside of ground-water basins. Location of LUFTs from California State Water Resources Control Board (2001). Location of sections with pesticide applications from Joe Marade, California Department of Pesticide Regulation (written commun., 2002). Location of ground-water basin boundaries from California Department of Water Resources (2002).

The comprehensive ground-water monitoring and assessment program can include one or more pilot studies in areas outside mapped ground-water basins. Nearly 90 percent of the public-supply wells not located in basins are located in four hydrogeologic provinces (table 1): the Sierra Nevada, the Transverse and Selected Peninsular Ranges, the Northern Coast Ranges, and the Southern Coast Ranges provinces. Therefore, the proposed pilot studies could be implemented in one or more of these provinces.

Category 6 includes the 356 ground-water basins that do not rank highly for public-supply wells and other factors (Appendix G). Although these basins account for about 75 percent of California's ground-water basins and about 40 percent of the total area mapped as basins (table 5), they account for only 5 percent of the public-supply wells (table 7). In addition, these basins account for less than 1 percent of the municipal ground-water users, 12 percent of the agricultural pumping, 12 percent of the LUFTs, and 10 percent of the square-mile sections with pesticide applications (table 7). Given the relatively large number of basins and low proportion of public-supply wells, these basins are not identified as priority basins.

Although the basins of Category 6 are not "priority basins," additional distinctions can be made among them (Appendix G). These additional distinctions provide some perspective on the types of basins that are not included in the four categories of priority basins. The primary criterion for distinguishing within Category 6 was the number of public-supply wells, and the secondary criteria were the number of secondary factors.

SCOPE OF THE PROPOSED COMPREHENSIVE MONITORING AND ASSESSMENT PROGRAM

Implementation of the comprehensive ground-water monitoring plan requires sampling of wells, and analyses of those samples for selected constituents. This chapter focuses primarily on the number of wells that need to be sampled on a statewide basis. In the first section that follows, estimates are provided for the total number of wells that would be sampled if the monitoring program were to be implemented in the four categories of priority basins (Categories 1 to 4). In the section after that, estimates are provided for the total number of wells that would be sampled if the monitoring program were extended to the low-use ground-water basins (Category 6). In each section, estimates are provided for the amount of analytical effort that might be required. The third section of this chapter briefly discusses the types of additional wells that could be included in a statewide monitoring program.

For the purposes of estimating the number of wells to be sampled, public-supply wells registered with DHS are differentiated from other types of wells. Other types of wells include those used for domestic supply, irrigation, and monitoring. This distinction is made because the location of public-supply wells is included in the DHS database, and because the DHS requires that water samples from these wells be analyzed on a regular basis for compliance with drinking-water regulations. Where public-supply wells are present, they will be used for the comprehensive ground-water monitoring program. Where public-supply wells are not present, additional effort will be required to locate other types of wells that could be used for implementation of the monitoring program.

Also for the purposes of estimation, a distinction is recognized between samples that would be analyzed for a relatively reduced list of constituents and samples that would be analyzed for a relatively expanded list. The relatively reduced list would include environmental tracers (for example, stable isotopes of water, tritium/helium age-dating) and low-level concentrations of volatile organic compounds; these constituents are the same as those included in the SWRCB CAS studies. The relatively expanded list would include field parameters (including pH, electrical conductance, dissolved oxygen, alkalinity, and temperature), major ions, trace elements, pesticides, and emerging contaminants, as well as the constituents on the reduced list. The expanded list of constituents is similar to that used by the USGS NAWQA program. Sampling and analysis for the relatively expanded list will require additional costs, both field and laboratory, in comparison with the relatively reduced list.

In general, public-supply wells will be sampled for the reduced list of constituents, and other types of wells will be sampled for the expanded list. This distinction reflects the general availability of water-quality data for public-supply wells, and the general lack of availability for other types of wells. In addition, it is proposed that 25 percent of the public-supply wells be analyzed for the expanded list. The additional sampling of public-supply wells will provide data not otherwise available at these wells (for example, low-level concentrations of pesticides and emerging contaminants), and will also provide data for quality assurance of the existing data in the DHS database.

Estimate the Total Number of Samples to be Collected in Priority Basins

The number and density of wells to be sampled in the priority basins needs to be sufficient to allow for assessment of water quality in each basin. The USGS NAWQA program provides guidelines for broad-scale assessments of ground-water quality and for detailed studies of the effects of land-use on ground-water quality. For both types of studies, the guidelines suggest that 20 to 30 wells be sampled to provide statistical confidence (Gilliom and others, 1995). The USGS NAWQA program also provides guidelines for well density: no less than 1 well per 100 km^2 for a broad-scale assessment (Gilliom and others, 1995), and no greater than 1 well per 1 km^2 for a detailed assessment (Squillace and others, 1996). These densities correspond to a spacing between wells of 10 and 1 km, respectively.

Several assumptions are made for the purposes of estimating how many wells might be sampled in the priority basins. The first assumption is that the density of sampling will be 1 well per 25 km^2. This density corresponds to a spacing between wells of 5 km, which is midway between the two spacings recommended by NAWQA for broad-scale and detailed assessments. The second assumption is that in each study area there will be lower and upper bounds for the number of wells to be sampled. A lower bound is considered so that there are enough wells to provide statistical confidence. An upper bound is considered to constrain costs. The third assumption is that if the number of public-supply wells in a study area is equal to or larger than the number of wells estimated for that study area, then no other types of wells would need to be identified in those study areas.

The numbers of wells to be sampled, statewide, in each of the four categories of priority basins are tabulated in tables 9*A*, *B*. Estimates are given if a minimum of 30 wells is sampled in each study area (table 9*A*), and if the minimum is reduced to 20 wells (table 9*B*). For each minimum, three upper bounds are considered: no limit, 60-well limit, and 50-well limit. The estimated number of wells to be sampled ranges from about 2,900 wells (20-well minimum, 50-well maximum, table 9*B*) to about 4,800 wells (30-well minimum, no upper limit, table 9*A*).

Of the six estimates of the total number of wells to be sampled (tables 9*A*, *B*), the middle two values are the computations for which the lower bound is 30 wells and the upper bound is either 50 wells or 60 wells per study area. The largest two estimates are the computations where no upper limit is assumed. The smallest two estimates are the computations for which the lower bound is 20 wells. If the middle two estimates are taken as a probable range, then the total number of wells to be sampled would range from 3,200 to 3,500 wells. Of these, about 3,000 to 3,200 wells would be public-supply wells and about 200 to 300 would be other types of wells (domestic supply, irrigation, or monitoring wells).

The results of these computations suggest that 3,000 to 3,200 public-supply wells would be sampled as part of the statewide comprehensive monitoring and assessment program. However, if some of the public-supply wells were not available at the time of sampling, then other types of wells would need to be substituted for them. In addition, if the available public-supply wells were not distributed across an entire basin, then other types of wells would need to be substituted for them. Alternatively, one could identify a subarea of a basin as the “used resource” and limit an assessment to that part of the basin.

Table 9. Total number of wells to be sampled statewide in each of the four categories of priority basins (study areas), California

[(A) Using a lower limit of 30 wells per study area. (B) Using a lower limit of 20 wells per study area. Total: Number of wells needed for each category. PSW: Number of public-supply wells that can be used. Other: Other types of wells that need to be identified]

***A*. Using a lower limit of 30 wells per study area**

Category	No upper limit			Upper limit of 60 wells per study area			Upper limit of 50 wells per study area		
	Total	PSW	Other	Total	PSW	Other	Total	PSW	Other
1	1,888	1,888	0	1,074	1,074	0	958	958	0
2	1,235	1,194	41	981	981	0	868	868	0
3	752	630	122	752	630	122	751	630	121
4	884	515	369	676	515	161	646	515	131
Priority basins (study areas)	*4,759*	*4,227*	*532*	*3,483*	*3,200*	*283*	*3,223*	*2,971*	*252*

***B*. Using a lower limit of 20 wells per study area**

Category	No upper limit			Upper limit of 60 wells per study area			Upper limit of 50 wells per study area		
	Total	PSW	Other	Total	PSW	Other	Total	PSW	Other
1	1,853	1,853	0	1039	1,039	0	923	923	0
2	1,222	1,181	41	968	968	0	855	855	0
3	613	542	71	613	542	71	612	542	70
4	758	424	334	550	424	126	520	424	96
Priority basins (study areas)	*4,446*	*4,000*	*446*	*3,170*	*2,973*	*197*	*2,910*	*2,744*	*166*

In addition to estimating the number of wells to be sampled, it is important to estimate the number of different chemical analyses that may need to be conducted. Of the 3,000 to 3,200 samples obtained from public-supply wells, 75 percent would be analyzed for a relatively reduced list of constituents and 25 percent would be analyzed for a relatively expanded list. Of the 200 to 300 wells of other types to be sampled, 100 percent would be sampled for a relatively expanded list. Therefore, the number of wells to be sampled for a relatively reduced list would range from about 2,200 to 2,400, and the number to be sampled for a relatively extended list would be about 800.

Estimate the Total Number of Samples to be Collected in Low-Use Ground-Water Basins

The basins identified as low-use ground-water basins (Category 6) contain relatively few public-supply wells, and therefore substantial numbers of other types of wells (domestic supply, irrigation, and monitoring) would be needed to allow for an assessment of water quality. In many areas, this would require drilling and installation of new wells.

Given that there are relatively few public-supply wells in these basins, the number of wells to be sampled is estimated by using a density of 1 well per 100 km^2, with at least one well sampled in each basin. Given these sampling criteria, a total of about 990 wells would need to be sampled. Of these, about 320 public-supply wells would be included in the monitoring network, and about 670 wells of other types would need to be identified. In many basins, it is likely that new wells would need to be installed.

The 356 basins in category 6 can be divided into three groups: (a) basins with sufficient number of public-supply wells that meet the specified density; (b) basins that have public-supply wells, but not enough to meet the specified density; and (c) basins with no public-supply wells. Category 6(a) includes 112 basins; about 200 public-supply wells would be sampled. Category 6(b) includes 39 basins; about 120 public-supply wells and 270 wells of other types would need to be sampled. Category 6(c) includes 205 basins; about 400 wells of other types would be needed.

As with the priority basins (Categories 1 to 4), it is important to estimate the number of different chemical analyses that may need to be conducted in the low-use basins (Category 6). If 75 percent of the public-supply wells in the Category 6 basins were sampled for a reduced list of constituents, and if 25 percent of the public-supply wells and all of the other types of wells were sampled for an expanded list, then a total of 240 wells would be sampled on a reduced list and 750 wells would be sampled on an expanded list. These wells would be distributed across a wider area than would the wells to be sampled in Categories 1 to 4, and additional expense would therefore be incurred in obtaining samples.

Sampling of the Category 6 basins at the specified density would permit assessment at a regional scale, but would not permit assessment of individual basins owing to the relatively low number of wells that would be sampled in many of these basins.

Other Types of Wells that Might be Sampled

Information from other types of wells, in particular monitoring wells and domestic water-supply wells, is also important and should be reviewed as it becomes available. A statewide digital database could be developed for these wells, as has been done for monitoring wells for underground storage tanks under SWRCB regulation (see California State Water Resources Control Board, 2003c). This is especially true for domestic wells because they are sources of drinking water. Past investigations have shown that data from domestic wells can be used to make meaningful assessments, and examination of the DHS public-supply wells database has shown the value of a statewide digital database. The current domestic well sampling being done by the SWRCB GAMA program (see California State Water Resources Control Board, 2003d), combined with existing data on thousands of domestic wells in the USGS and Department of Pesticide Regulation databases, is an excellent start. These data will be particularly important in ground-water basins where the DHS wells are not present in all areas of the basin.

SUMMARY

Although there are many State agencies addressing specific—and different—ground-water-quality issues, these programs do not at present offer a comprehensive view of ground-water quality in the State. State Assembly Bill 599 (AB 599), the "Ground-Water Quality Monitoring Act of 2001," requires the design of a comprehensive statewide ground-water quality monitoring program. The comprehensive program is needed to protect the beneficial use of water, particularly for drinking-water supply. The USGS, as part of a cooperative effort with the State Water Resources Control Board (SWRCB), has prepared this report to address part of this need.

This report presents a framework for a comprehensive ground-water quality monitoring and assessment program for California. The proposed program prioritizes ground-water basins that are a source of drinking-water supply. The objectives of the program are to provide assessments of ground-water quality including a broad characterization of the current condition of the ground water (*Status Assessment)*, an assessment of the change in ground-water quality with time (*Trend Assessment*), and an assessment that strives to relate ground-water quality to human and natural sources of contaminants (*Assessment for Understanding*).

In this report, the State is divided into 10 hydrogeologic provinces to represent the range of hydrologic, geologic, and climatic conditions in California. The delineation of provinces provides a context for identifying priority ground-water basins, and for evaluating the ground-water resource in areas outside mapped ground-water basins. Within each province one can identify ground-water basins, which are the primary source of ground-water supply, and areas outside the basins. Ground-water basins account for about 80 percent of the State's public-supply wells, and the areas outside basins account for about 20 percent.

The program described in this report will allow assessment at various scales—local (ground-water basin), regional, and statewide. To facilitate assessment at different scales, the program will employ a consistent study design: a spatially distributed, randomized set of wells for each study area.

Consistency will allow aggregation of data from adjacent, or similar, basins, which is critical because resource-planning issues are commonly regional in nature. Deviating from a spatially distributed randomized selection approach would compromise the ability to answer questions of regional and statewide importance.

In selected basins, additional wells can be sampled to address important local issues, or to provide additional understanding of the human and natural factors that affect water quality. These additional wells would supplement the wells selected using the spatially distributed, randomized approach. It is anticipated that as much as 25 percent of the sampling effort could be associated with these efforts. Local water agencies will be an important resource for identifying these issues and for providing information on suitable wells for sampling.

At a statewide level, and within each province, basins were prioritized by considering a number of factors that describe the reliance on ground-water resources and potential sources of contamination in each basin. Four categories of priority basins were identified. Categories 1 to 4 include 116 basins that collectively account for more than 90 percent of the public-supply wells, municipal ground-water users, agricultural pumping, leaking underground fuel tanks, and pesticide applications that are located in ground-water basins.

A tiered approach is proposed to balance spatial coverage and analytical intensity (number of different constituents to be analyzed for). The broadest spatial coverage, or first tier, will be provided by the existing DHS water-quality data. The second tier will consist of sampling the proposed network of wells for a "relatively reduced" list of constituents; these constituents are the same as those used by the SWRCB for evaluating the susceptibility of aquifers to contamination. The third tier will consist of sampling a subset of wells in the proposed network for a "relatively expanded" list of constituents; these constituents are the same as those used by the USGS NAWQA program, with the addition of emerging contaminants. Sampling for the different constituents will also be iterative in time to allow for reconsideration of objectives.

AB 599 specifically focuses on assessing the quality of ground water used for drinking supply. The proposed program relies primarily on existing public-supply wells to meet this charge because both well-location and historical water-quality data are available in a digital database administered by the DHS. These wells are also widely distributed where there are population centers, and they sample a relatively large volume of the aquifer. Where public-supply wells are not available, other types of wells (domestic supply, irrigation, monitoring) will need to be identified. The program can work with local agencies to identify suitable wells.

The proposed program is comprehensive in the sense that basins representing the entire range of conditions, as well as most of the water use and potential contaminating activities, in the State will be assessed. The program is not literally comprehensive because information from other types of wells—domestic supply, irrigation, and monitoring—is not broadly included. These additional wells can provide additional access to the ground-water resource, both in terms of area and in terms of depth. At present (2003), there is no comprehensive digital database for these wells, and therefore there is no practical way to systematically assess that portion of the resource. As these databases are developed, a more expansive comprehensive monitoring and assessment program can be developed.

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APPENDIX A. ARSENIC IN THE SAN JOAQUIN VALLEY: EVALUATING THE UTILITY OF EXISTING DATA

Maximizing the use of existing data, and in particular the large amount of data collected from public-supply wells, for assessing ground-water quality is a specific objective of the comprehensive statewide program. The feasibility of using existing data on naturally occurring contaminants for assessing ground-water quality is illustrated for the trace-element arsenic in one of the major physiographic regions in the State, the San Joaquin Valley (fig. 1). Arsenic was selected as a case study because the drinking-water limit for arsenic has recently been lowered from 50 to 10 μg/L (U.S. Environmental Protection Agency, 2001); there is a large amount of data on arsenic concentrations in ground water for the San Joaquin Valley; and studies in other areas have shown that the large-scale distribution of arsenic in regional aquifers can be systematically related to the geochemistry and hydrology of the aquifers (Hull, 1984; Welch and Lico, 1998).

The objective of the case study is to examine whether existing data on arsenic in ground water can adequately support the assessments required by the statewide comprehensive ground-water monitoring program: assessing the occurrence and spatial distribution of arsenic concentrations (*Status Assessment*); detecting changes in arsenic concentration in time (*Trend Assessment*); and understanding the relations between arsenic concentrations and human and natural sources (*Assessment for Understanding*). Addressing this question requires comparing the primary source of existing data—data collected from public-supply wells for drinking-water compliance monitoring—with other data sets. This comparison is possible in the San Joaquin Valley because the USGS database (the National Water Information System, or NWIS) contains a large number of arsenic analyses on ground-water samples. These data were collected as part of various water-resource investigations, and most recently by the San Joaquin Valley Drainage Program (Gilliom and others, 1989), the Regional Aquifer Systems Analysis program (Sun and Weeks, 1991), and the National Water Quality Assessement Program (NAWQA) (Gilliom and others, 1995; Dubrovsky and others, 1998; Focazio and others, 1999).

Available Data

Existing data were compiled from the USGS National Water Information System (NWIS) and the California Department of Health Services (DHS) database. These retrievals yielded analyses for 1,595 public-supply wells from the DHS database, and 1,042 domestic, irrigation, observation, and public-supply wells from NWIS (fig. A1*A*, A1*B*). Although the DHS data were collected for one purpose (compliance monitoring of drinking-water supplies), the sources of the USGS data ranged from local studies of processes that control trace-element mobility to regional-scale studies of trace-element occurrence and distribution. For the purposes of this broad assessment, data from all the wells were used. A rigorous assessment should take into account factors such as over-representation of the major urban areas owing to the dense clustering of wells there, and the differing spatial distributions of the different well types in the USGS database. Although these issues could be accommodated by more sophisticated methods, such treatment of the data is beyond the scope of this report.

Because many of the wells in the databases have more than one arsenic analysis, a median arsenic concentration was determined for each well. In the NWIS data set, the median was computed from all samples collected from 1970 to 2001. In the DHS data set, the median was computed only from samples collected in the 1990s because analyses of samples collected prior to 1990 had higher detection limits (commonly 50 μg/L). Because most of the DHS data in the 1990s have a detection limit of 10 μg/L, whereas the USGS data usually has a detection limit of 1 μg/L, all samples were censored at a common detection limit of 10 μg/L for statistical comparisons. Nonparametric statistical methods were used in the analysis because they do not require that the data be normally distributed and generally are unaffected by outliers (Helsel and Hirsch, 1992).

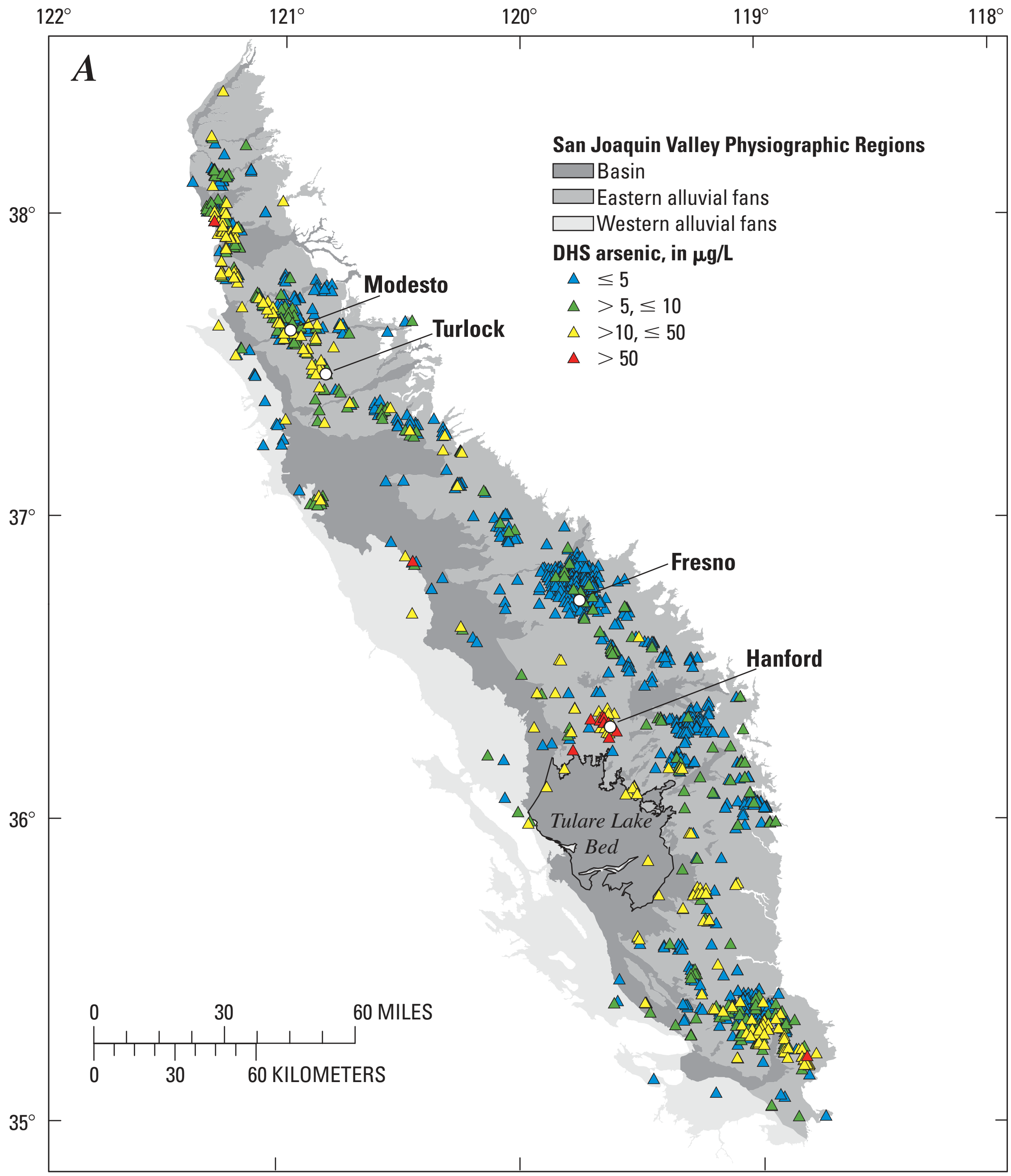

Figure A1. Distribution of arsenic concentrations in ground water in the San Joaquin Valley for public-supply wells from the Department of Health Services database (*A*), and from the USGS database (*B*).

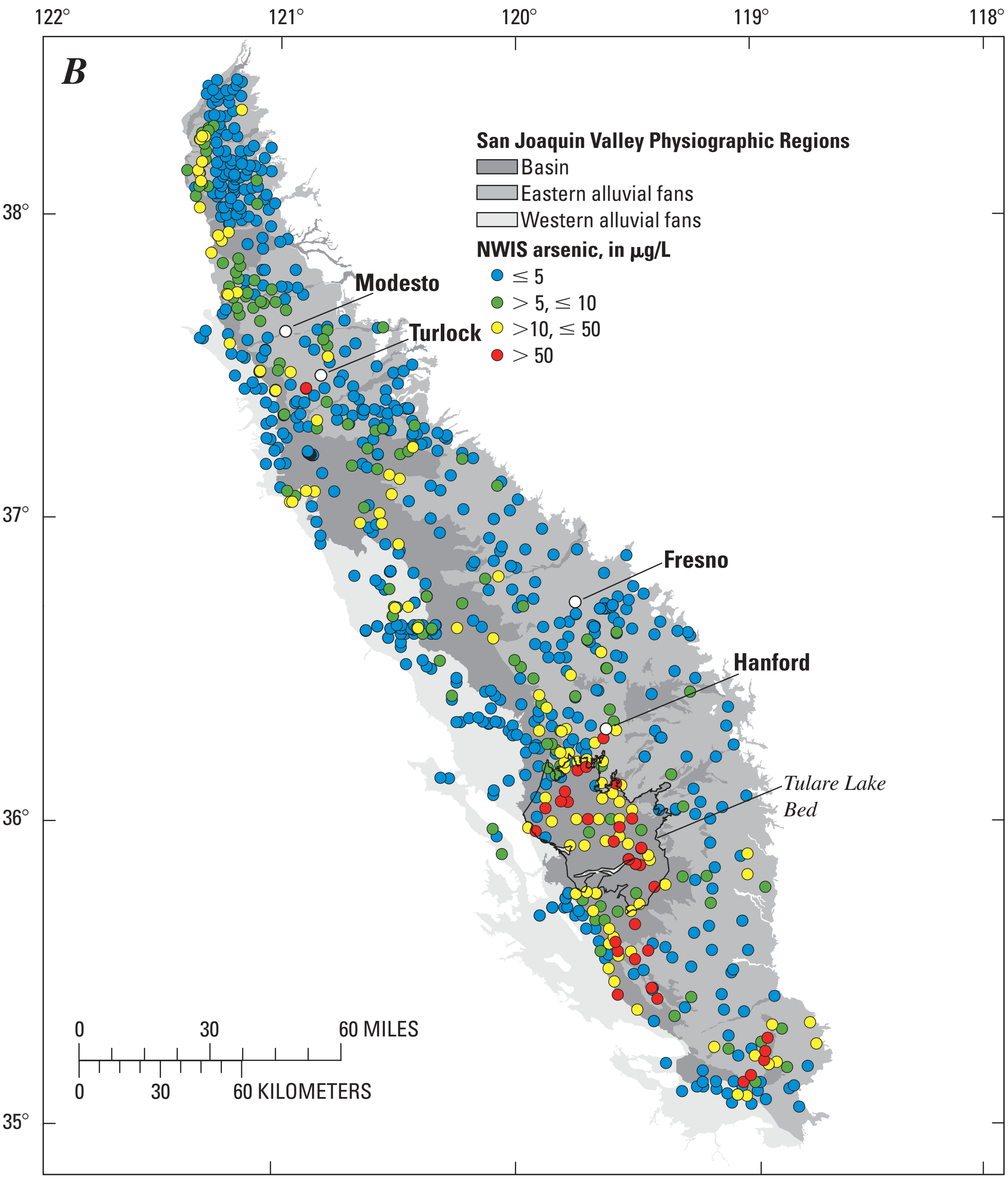

Figure A1.—*Continued.*

Data Quality

The first task in any assessment is to ensure that the quality of the data is sufficient to address the assessment questions. Although there was no specific data-collection effort to address this question, a small set of wells was identified for which data were present in both the USGS and DHS data sets. Forty-nine samples from public-supply wells in the Modesto area were analyzed by both agencies within 5 years, and usually within 1 year. Arsenic concentrations were significantly higher in the DHS data than in the USGS data (p=0.017, Sign-rank test). Examination of the data shows that about one-half of the analyses are within 1 µg/L, and only two differ by as much as 5 µg/L (fig. A2). Slightly higher arsenic concentrations in the DHS data are consistent with the use of unfiltered samples for analysis for the public-supply wells (DHS), and analysis of filtered samples (0.45 micron filters) by the USGS. Unfiltered samples could contain small amounts of solids that could contribute to higher arsenic concentrations. These results indicate that the DHS arsenic concentrations have a slightly high bias relative to the USGS samples, but they are adequate for an assessment of broad, regional patterns.

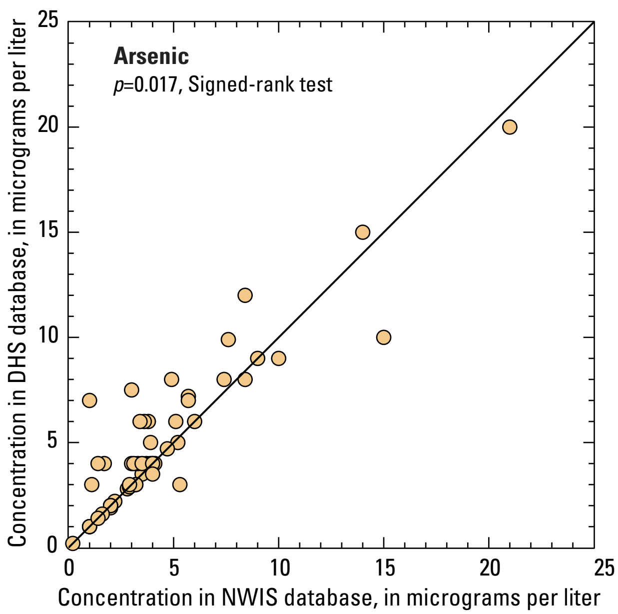

Figure A2. Comparison of arsenic data from the Department of Health Services and USGS databases for 49 wells in the vicinity of Modesto, California.

Status Assessment: The Occurrence and Distribution of Arsenic in the San Joaquin Valley

Data on arsenic concentrations in public-supply wells from the DHS database are not uniformly distributed across the San Joaquin Valley (fig. A1*A*). Rather, the data are clustered in the larger cities, and along the major transportation corridor (State Route 99), in the eastern San Joaquin Valley. The data show that arsenic concentrations are generally low in the eastern San Joaquin Valley, and especially in the central part of the valley in the vicinity of Fresno. Ground water in this area rarely contains more than 5 µg/L. Arsenic concentrations are somewhat higher in the northeastern and southeastern part of the valley, with concentrations usually greater than 5 µg/L and commonly more than the drinking-water limit of 10 µg/L. The exception is a prominent cluster of high arsenic concentrations in the vicinity of the city of Hanford, where several wells contain arsenic that exceeds the previous drinking-water limit of 50 µg/L (California Department of Water Resources, 1970). Overall, about 13 percent of the samples from the DHS database had concentrations greater than the new drinking-water limit of 10 µg/L.

Although there are sufficient public-supply wells with samples in the eastern part of the valley to characterize the broad patterns of occurrence and distribution of arsenic, the same cannot be said of the central and western portions of the valley. These parts of the valley are sparsely populated, and ground water in these areas generally have higher concentrations of dissolved solids than does the eastern part (Bertoldi and others, 1991). These factors result in fewer public-supply wells, and hence the DHS data in the central and western parts of the valley are insufficient for characterizing the occurrence and distribution of arsenic. The DHS data set is therefore inadequate for describing the regional pattern of arsenic distribution in the San Joaquin Valley.

The data on arsenic concentrations in ground water from the USGS are much more uniformly distributed (fig. A1*B*). The USGS and DHS data are in general agreement for most of the eastern part of the valley. For example, the USGS data contain a group of wells with arsenic concentrations above 50 µg/L south of Bakersfield; the corresponding wells in the DHS database have arsenic concentrations in the 10 to 50 µg/L range, and the occurrence of elevated arsenic concentrations in this area has been documented in the past (Swartz, 1995). The locally high arsenic concentrations in the Hanford area also are discernible in the USGS data.

The USGS data provide additional detail in some areas. Specifically, the USGS data show that the area with slightly elevated arsenic concentrations (5 to 50 µg/L) in the northeastern part of the valley is actually confined to a narrow zone along the western margin of the valley adjacent to the Sacramento-San Joaquin Delta. East of this zone, samples from a large number of domestic wells show arsenic concentrations consistently below 5 µg/L (Sorenson, 1981). Domestic wells are generally shallower than public-supply wells, and part of the contrast may be due to higher arsenic concentrations at greater depth in the aquifer. One of the only potential points of disagreement between the DHS and USGS data sets is the presence of arsenic concentrations greater than 10 µg/L in public-supply wells in the Modesto area (DHS data), whereas concentrations in samples from domestic wells in the vicinity are usually less than 5 µg/L (USGS data). This difference may be due in part to differences between the depth, construction, operation, or other characteristics of public-supply and domestic wells.

The USGS data for the central and western parts of the valley allow a characterization of the spatial patterns in arsenic distribution that could not be made with the DHS data alone. The USGS data shows that with the above-noted exceptions, most of the samples with arsenic concentrations greater than 10 µg/L in the USGS data set are located in the central part of the valley. In addition, samples from wells in alluvial fans on the western side of the valley usually have arsenic concentrations less than 5 µg/L.

In summary, analyses of samples from public-supply wells in the DHS database provide a sufficient characterization of the spatial distribution of arsenic in ground water, but the characterization is limited to areas where the population density is relatively high and ground water is used for drinking supply: that is, the eastern San Joaquin Valley. In the absence of these conditions, there are insufficient data to assess arsenic distribution using the DHS database alone; data collected from other sources—domestic supply, monitoring, and irrigation wells—are required.

Trend Assessment: Detecting Changes in Arsenic Concentration with Time

Evaluation of trends in arsenic concentration is limited by high (and changing) analytical detection limits, particularly in the DHS data set. Two different approaches were attempted for determining whether arsenic concentrations have changed as a function of time. These approaches are comparisons of large groups of data collected at different points in time; and comparisons between two data sets consisting of pairs of samples collected at two different times from the same well. None of the wells had been sampled often enough to evaluate the change in arsenic concentration in a single well using time-series analysis.

Data on arsenic concentrations for wells in the USGS database collected during the 1980s were compared with data for samples collected in the 1990s (fig. A3). Arsenic concentrations were not significantly different between the 1980s and the 1990s (p=0.831, Mann-Whitney test), although the median arsenic concentration in the 1990s is slightly higher than in the 1980s. Conversely, the DHS data for the 1980s appear to indicate higher concentrations than in the 1990s (p<0.001, Mann-Whitney test); however, this apparent trend is an artifact of the change in the detection limit between the two decades and the large number of samples with concentrations below the detection limit. During the 1980s, the arsenic concentration in many of the samples was below the detection limit, which was often 10 µg/L. The values for these samples were set to one-half of the detection limit, or 5 µg/L, for the statistical analysis (Helsel and Hirsch, 1992). In comparison, the generally lower detection limits in the 1990s resulted in more frequent low arsenic concentrations (less than 5 µg/L) in the 1990s than in the 1980s. In short, the high rate of non-detections in the 1980s invalidates the use of this statistical comparison.

One way to circumvent this problem is to identify individual wells that were sampled in the 1980s and 1990s and analyzed using a similar detection limit. This process yields a set of wells in which each well has a pair of analyses: one sample from the 1980s and one sample from the 1990s. This data set of paired samples can be tested to determine whether concentrations have increased or decreased.

Results of pair-wise analyses on the DHS and USGS data sets indicate that there has been no significant change in arsenic concentrations over the last decade (*p*=0.968, Signed-rank test). This test for change is, however, somewhat insensitive because of the large proportion of non-detections in both data sets (about 90 and 85 percent respectively, in the DHS and USGS data).

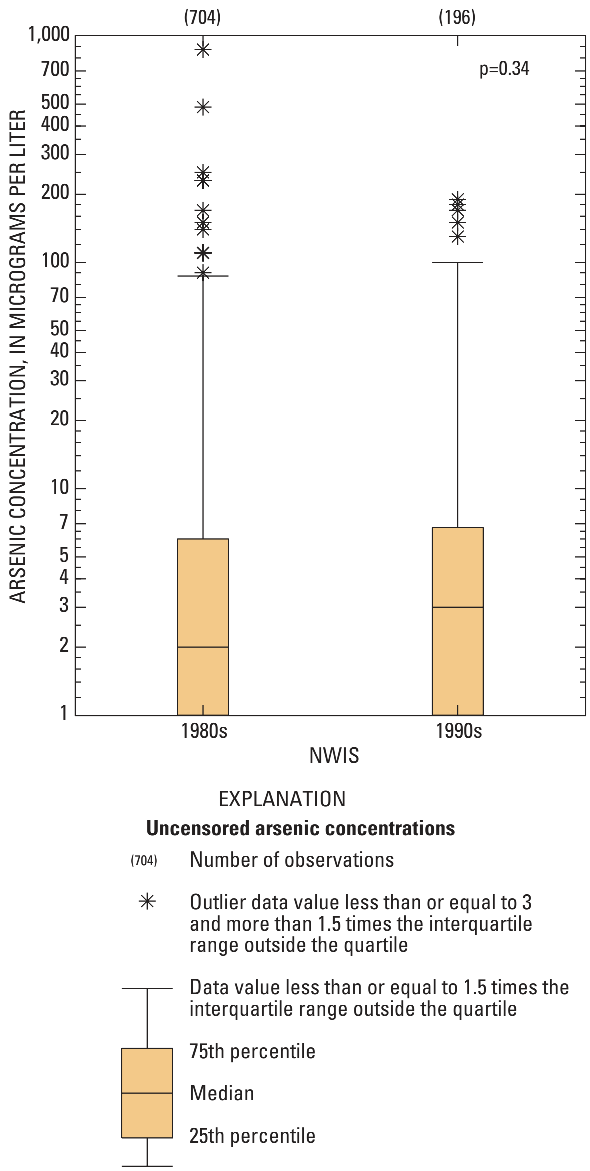

Figure A3. Boxplots of USGS data for arsenic concentrations in ground water for the 1980s and 1990s.

Assessment for Understanding: Relations Between Arsenic Concentrations and Sources

The distribution of a contaminant in ground water is related to both the presence of a source, natural or human, as well as the physical and chemical processes that govern the mobility and persistence of the contaminant in the subsurface environment. The relative strength of the natural arsenic sources can be assessed using a data set on the arsenic concentration in soil in the San Joaquin Valley collected by the USGS (Tidball and others, 1986a,b).

A contour map of arsenic concentrations in soil shows that concentrations are high in the western part of the valley as well as the southernmost part (fig. A4). The highest concentrations—greater than 8 to 10 parts per million (ppm)—occur in isolated areas in the central west side, south of the Tulare Lake bed, and in the extreme southern end of the valley. The arsenic concentrations in the soils of the eastern part of the valley are consistently lower—generally less than 6 ppm, and less than 4 ppm in the vicinity of Fresno (fig.A4). This asymmetry in arsenic concentrations is consistent with the contrasts in the geological sources of soils on the east and west sides of the valley, as has been observed for other elements as well (Bertoldi and others, 1991; Dubrovsky and others, 1991; Tidball and others, 1986a,b).

The data show that high soil arsenic concentrations are not sufficient to cause high arsenic concentrations in ground water. This is especially evident in the central west side, where ground-water samples in the lowest concentration class (less than 5 µg/L) are associated with soils in the highest concentration classes (8 to more than 10 ppm) (fig. A4). Similarly, low soil arsenic concentration is not always associated with low ground-water concentration: in fact, the highest arsenic concentration in a DHS public-supply well (75 µg/L) was from the Hanford area where soil arsenic concentration is less than 6 ppm. In addition, high arsenic concentrations in ground water from the central part of the valley are associated with moderate soil arsenic concentrations of 4 to 8 ppm. Two areas where high soil arsenic concentrations do co-occur with high arsenic concentrations in ground water are immediately south of the Tulare Lake bed, and at the southern limit of the valley.

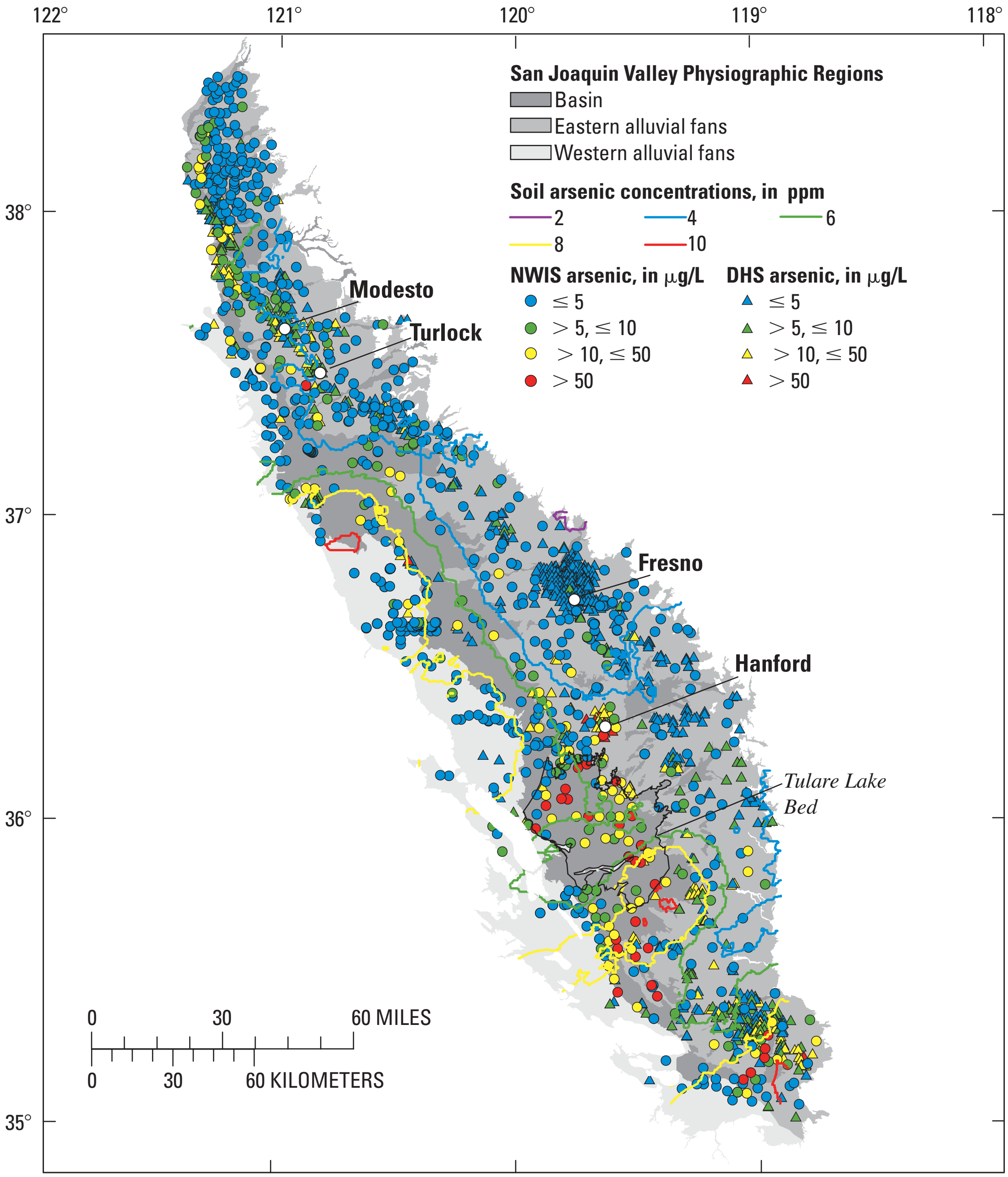

Figure A4. Concentrations of arsenic in soils and ground waters of the San Joaquin Valley.

While acknowledging the limitations of the soil arsenic data—which provide only a surficial depiction of what is really a three-dimensional distribution—the data indicate that the concentrations of arsenic in ground water are influenced by factors other than its availability in surficial soils.

Much of the arsenic in the solid phase in an aquifer is commonly associated with the iron hydroxides that coat grain surfaces in the sediments under oxidizing conditions. Two major chemical processes known to mobilize arsenic in ground water are release of arsenic associated with the iron hydroxides owing to the reductive dissolution of the iron mineral, and release of arsenic adsorbed on iron hydroxides by high-pH conditions (Welch and Lico, 1998; Welch and others, 2000). Both of these processes can be evaluated using existing data.

Reducing chemical conditions in the ground-water samples were inferred from the concentrations of redox-sensitive species (nitrate, iron, manganese, and sulfate), and low concentrations of dissolved oxygen. Shown in figure A5 are all wells with arsenic concentrations greater than 10 µg/L classified by whether the samples are oxidized or reduced, and whether the pH of the water is greater or less than 8. Samples from about 47 percent of the wells with arsenic greater than 10 µg/L also are chemically reduced, and arsenic is positively correlated with manganese concentrations (p<0.001, Spearman's rank correlation). The association of arsenic with chemically reducing conditions is supported by a negative correlation between arsenic and nitrate because nitrate is mobile and persistent under oxidizing conditions and removed under reducing conditions (p<0.001, Spearman's rank correlation).

The association of arsenic with chemically reducing conditions is also consistent with the spatial distribution of the high arsenic concentrations. The samples with high arsenic and a reduced chemistry are generally restricted to the basin physiographic province (figs. A1,A5), and arsenic concentrations in the basin are significantly higher than in the eastern and western alluvial fans (p<0.001, multiple stage Kruskal-Wallis test). The basin physiographic province is that part of the valley that was historically the discharge zone for regional ground-water flow and also subject to frequent flooding. The basin physiographic province is characterized by fine-grained, water-logged soils with a high organic carbon content—characteristics conducive to the consumption of dissolved oxygen and evolution of chemically reduced conditions.

Forty-two percent of the wells with arsenic concentrations greater than 10 µg/L have an elevated pH of greater than 8 (fig. A5), and high arsenic is positively correlated with pH (p<0.001, Spearman's rank correlation). These observations indicate that release of arsenic adsorbed on iron hydroxides by high-pH conditions may account for some of the samples with elevated arsenic concentrations. An association of high pH and arsenic in ground water in the southern part of the valley has been noted previously (Swartz, 1995). Some of the same hydrogeochemical processes that generate high pHs also generate reducing conditions, and the coincidence of chemically reduced conditions with high pH conditions (fig. A5) makes it difficult to resolve the relative contributions of these two processes. Furthermore, some of the high arsenic concentrations in shallow wells in the Tulare Lake Bed have been attributed to a different mechanism, evaporative concentration (Fujii and Swain, 1995).

These proposed mechanisms warrant more thorough evaluation, but the findings shed light on the cause of the current spatial distribution of arsenic in ground water, suggest possible ways to remediate or avoid high-arsenic ground water, and have important implications for the location of conjunctive-use projects. As with the status question, this evaluation could not have been done with the limited spatial coverage of the DHS data. This conclusion highlights the importance of acquiring additional data sets in ground-water quality in different types of wells (domestic supply, irrigation, and monitoring wells) to support the statewide assessment as soon as they are electronically available.

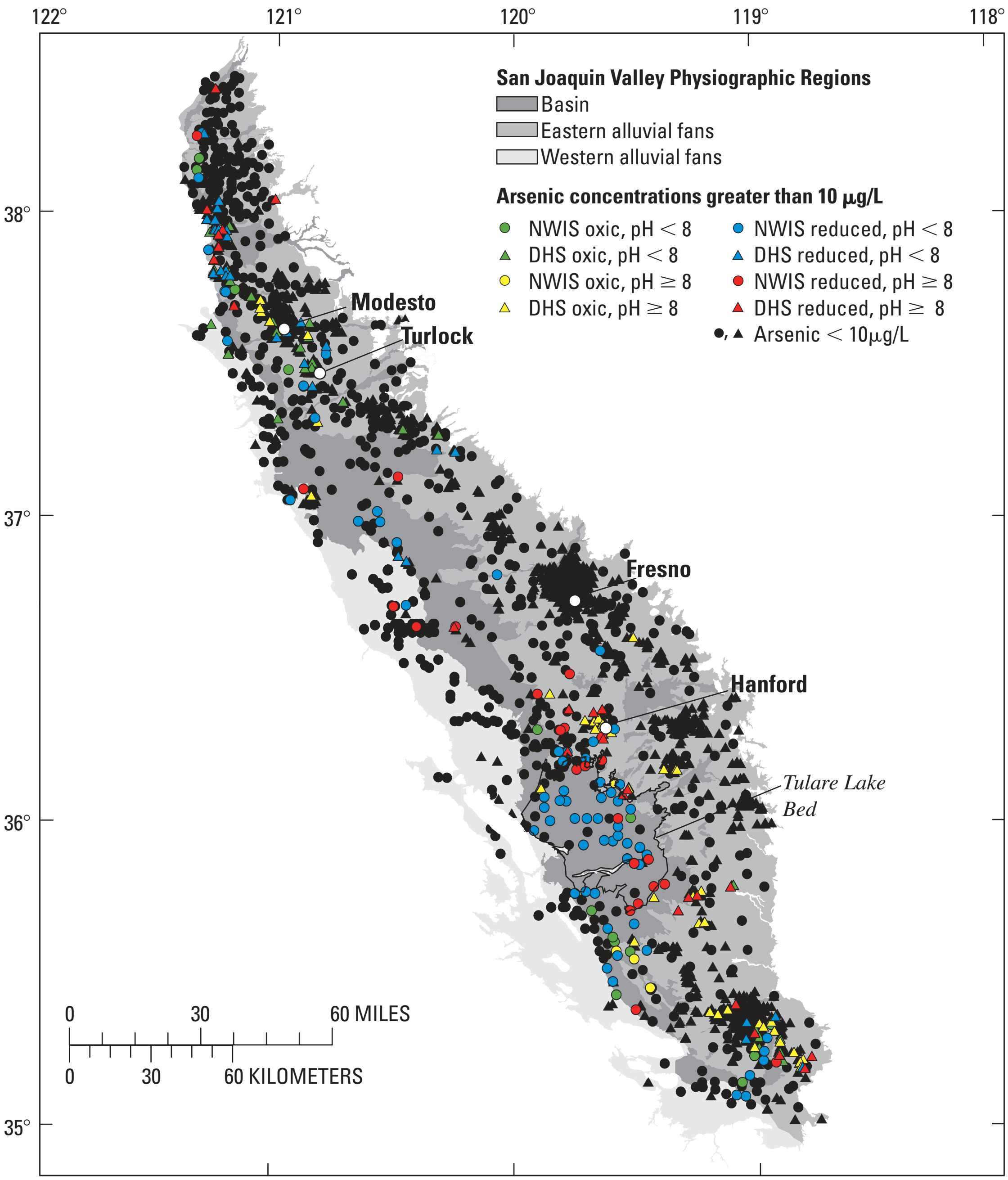

Figure A5. Arsenic concentrations in ground water classified by redox and pH status.

Assessment for Understanding: Subregional-Scale Analysis of Arsenic Occurrence and Dominant Factors Controlling Concentrations

The results of the assessment of the valleywide data set suggest that at the scale of the San Joaquin Valley (about 80,000 km^2), existing water-quality data are adequate to describe arsenic occurrence and the dominant processes affecting mobilization. In addition, the assessment also shows that at the next smaller spatial scale—the alluvial fans of the eastern San Joaquin Valley—the DHS data are consistent with the USGS data. The smallest scale that assessments will be done in the proposed statewide program is that of individual DWR ground-water basins (500 to 5,000 km^2). At this scale, the spatial bias in well locations, the limited number of sampling points in some basins, and the overall lower variability in concentrations of arsenic and other explanatory variables may influence the analysis.

A subset of 219 public supply, 48 domestic, 14 irrigation, and 29 observation wells was selected from the regional data set and used in an analysis of arsenic occurrence in the northern San Joaquin Valley near Modesto and Turlock (fig. A6). In addition, 40 public-supply wells sampled by the USGS in 2001 as part of the Groundwater Ambient Monitoring and Assessment program (see California State Water Resources Control Board, 2003d) were included in the statistical analyses. The public-supply wells are clustered in the urban areas, whereas the irrigation and domestic wells are distributed throughout the area. Twelve percent of the wells in the Modesto/Turlock area had concentrations greater than 10 µg/L, whereas only one well (an observation well) had a concentration greater than 50 µg/L. The concentrations were not significantly different among the well types (p=0.769; Kruskal-Wallis test), although the median concentration of arsenic was slightly higher in the public-supply wells than in the other well types.

Elevated arsenic concentrations (greater than 10 µg/L) were generally widely distributed across the Modesto/Turlock area (fig. A6). The greater number of public-supply wells with elevated concentrations suggests that high arsenic concentrations may be associated with parts of the aquifer screened by public-supply wells. However, the public-supply and irrigation wells are screened at similar depths in the aquifer (multiple-stage Kruskal-Wallis test); yet none of the 14 irrigation wells had an arsenic concentration greater than 10 µg/L. Another possibility is that the slight high bias for DHS arsenic concentrations relative to the USGS sample concentrations noted earlier contributes to the small difference in concentrations between these two well types.

Arsenic concentrations in the Modesto/Turlock area are not significantly correlated with pH or reduced chemical conditions (as indicated by elevated manganese concentrations). Arsenic was negatively correlated with nitrate (p=0.028, Spearman's rank correlation); this finding is consistent with elevated arsenic concentrations in slightly reduced conditions as determined using the valleywide data set. However, without correlation to other redox variables, the relation between arsenic concentrations and reduced conditions in the Modesto/Turlock area is weak.

This evaluation illustrates that at the scale of an individual ground-water basin, the assessment of processes that influence arsenic concentration—and hence possibly other naturally occurring trace-element concentrations—becomes problematic. This is due in part to the overall lower variability in arsenic concentrations in the smaller, more geologically homogeneous area. Other factors that will make the assessment more difficult at the smaller scale include the limited number of sampling points in some basins, and spatial bias in well locations owing to clustering in urban areas.

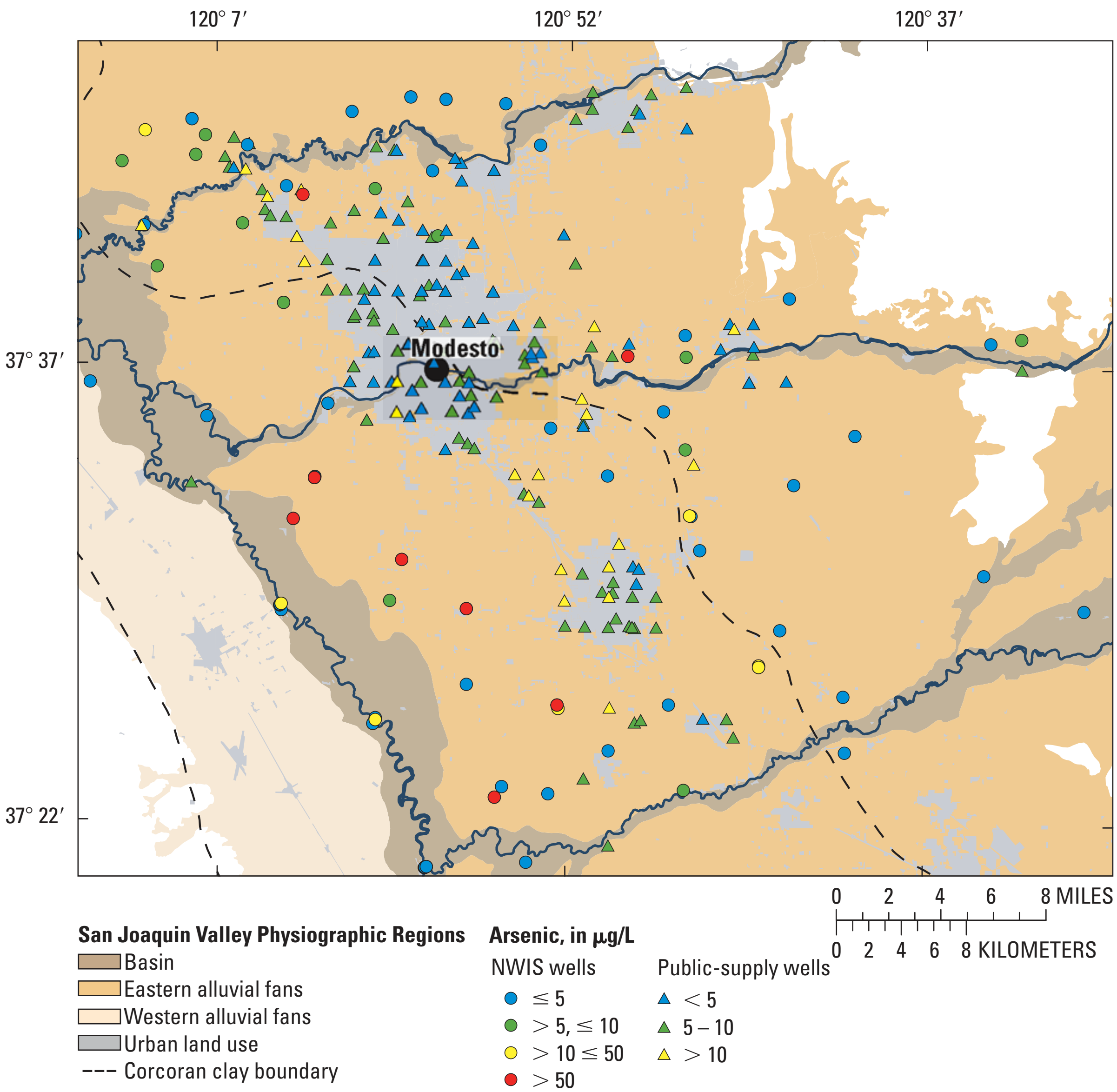

Figure A6. Arsenic in the Modesto and Turlock ground-water basins.

Adequacy of the Arsenic Data for Assessment

In summary, the DHS data were found to be inadequate for most of the assessment questions owing to a lack of spatial coverage in the valley, and high (and changing) detection limits.

- A direct comparison of the data from a small number of wells indicated that the DHS and USGS arsenic analytical results were similar; the DHS concentratons were slightly higher because they are for unfiltered samples, whereas the USGS data were for filtered samples.
- The spatial distribution of arsenic in ground water can be assessed using samples from public-supply wells in the DHS data set, but the characterization is limited to areas where the population density is relatively high and ground water is used for drinking supply. In the absence of these conditions in much of the central and western San Joaquin Valley, there are insufficient data to assess arsenic distribution in the DHS database.
- Changes in arsenic concentrations in time could not be thoroughly assessed because of limitations imposed on data interpretation by high (and changing) analytical detection limits in the DHS data set.
- Processes controlling arsenic concentrations could not have been—or would have been very difficult—to evaluate with the limited spatial coverage of the DHS data.
- At the scale of an individual ground-water basin, the assessment of processes that influence arsenic concentration—and hence possibly other naturally occurring trace elements—is made problematic for either data set by the overall low variability in arsenic concentrations, the limited number of sampling points in some basins, and spatial bias in well locations owing to clustering in urban areas.

These conclusions highlight the importance of acquiring additional data sets on ground-water quality in different types of wells (domestic supply, irrigation, and monitoring wells) to support the statewide assessment as soon as they are electronically available to supplement the DHS data. This is especially true for the more sparsely populated agricultural basins. These results also show the importance of using consistent analytical methods with the lowest detection limit feasible at the time of sampling.

APPENDIX B. DIGITAL MAP OF HYDROGEOLOGIC PROVINCES

In this study, 10 hydrogeologic provinces were defined to provide a context for developing a statewide, comprehensive ground-water monitoring and assessment program (see section titled “Hydrogeologic Provinces of California”). A digital map of these 10 provinces was developed from previously developed digital maps of ground-water basins (California Department of Water Resources, 2002) and watersheds (California Department of Forestry and Fire Protection, 1999). The development of a digital map facilitated analysis and identification of the priority basins and areas outside basins (see section titled “Prioritization of Basins and Other Study Areas”). The previously developed digital maps were used to maintain consistency with boundaries recognized by State agencies.

The boundaries between hydrogeologic provinces generally correspond with the boundaries between major geomorphic and geologic provinces (Norris and Webb, 1990; Saucedo and others, 2000; California Geological Survey, 2002). However, the specific locations are based on ground-water basin boundaries (California Department of Water Resources, 2002) and on watershed boundaries (California Department of Forestry and Fire Protection, 1999). In areas where ground-water basin boundaries approximate province boundaries, ground-water basin boundaries were used; therefore, ground-water basins are always contained within a single province. In other areas, the watershed boundaries that most closely approximated the province boundaries were used. In a few instances, the boundary between hydrogeologic provinces is not approximated by either a ground-water basin boundary or a watershed boundary. In those instances, watersheds were divided between hydrogeologic provinces.

The Northern Coast Ranges hydrogeologic province includes 79 ground-water basins and 126 watersheds. The boundary with the Klamath Mountain province is primarily defined by watersheds that approximate the Coast Range Fault; one watershed (Klamath Glen hydrologic subarea) extends to both sides of the fault and was divided between the two provinces. Two other watersheds (Platina and Ono hydrologic subareas) were also divided between the two provinces to better approximate the contact between Cretaceous sedimentary rocks of the Coast Ranges from the Paleozoic and Mesozoic metamorphic rocks of the Klamath Mountains. The boundary between the Northern Coast Ranges and Central Valley provinces is defined by the boundary of the Sacramento ground-water basin.

The Southern Coast Ranges hydrogeologic province includes 74 ground-water basins and 89 watersheds. The western part of the boundary with the Transverse and selected Peninsular Ranges province is defined by ground-water basin boundaries that approximate the Santa Ynez Fault; the eastern part of the boundary is defined by watershed boundaries that approximate the Santa Ynez and Big Pine Faults. The boundary with the Central Valley province is defined by the boundary of the San Joaquin ground-water basin.

The Klamath Mountains hydrogeologic province includes 7 ground-water basins and 51 watersheds. The boundary with the Northern Coast Ranges province is defined by watershed boundaries that approximate geologic boundaries; three watersheds (Klamath Glen, Platina, and Ono hydrologic subareas) are divided between the two provinces. The boundary with the Modoc Plateau and Cascades province is defined by ground-water basin and watershed boundaries that approximate geologic boundaries; three watersheds (Hornbrook, Squaw Valley, and Big Bend hydrologic subareas) are divided between the two provinces. The boundary with the Central Valley province is defined by the boundary of the Sacramento ground-water basin.

The Modoc Plateau and Cascades hydrogeologic province includes 55 ground-water basins and 70 watersheds. The boundary with the Klamath Mountains province is defined by ground-water basin and watershed boundaries that approximate geologic boundaries; three watersheds (Hornbrook, Squaw Valley, and Big Bend hydrologic subareas) are divided between the two provinces. The boundary with the Sierra Nevada province is also defined by ground-water basin and watershed boundaries that approximate geologic boundaries; three watersheds (Upper Little

Chico hydrologic area, West Branch North Folk hydrologic area, and Butt Valley hydrologic subarea) were divided between the two provinces. The boundary with the Central Valley province is defined by the boundary of the Sacramento ground-water basin

The Central Valley hydrogeologic province consists of the Sacramento and San Joaquin ground-water basins, and includes eight watersheds. These two ground-water basins include 36 relatively large ground-water subbasins, which for the purposes of this study are recognized as individual ground-water basins. The boundaries of the Central Valley hydrogeologic province are entirely defined by ground-water basin boundaries. The province includes a few areas of relatively low permeability areas that are surrounded by ground-water subbasins.

The Sierra Nevada hydrogeologic province includes 22 ground-water basins and 161 watersheds. The boundary with the Central Valley Province is defined by the boundaries of the Sacramento and San Joaquin ground-water basins. The boundary with the Modoc Plateau and Cascades province is defined by ground-water basin and watershed boundaries that approximate geologic boundaries; three watersheds (Upper Little Chico hydrologic area, West Branch North Folk hydrologic area, and Butt Valley hydrologic subarea) were divided between the two provinces. The boundary with the Basin and Range province is also defined by ground-water basin and watershed boundaries that approximate geologic boundaries; one watershed (Upper Owens hydrologic area) was divided between the two provinces. An additional watershed (Neenach hydrologic area) was divided between the Sierra Nevada province and Transverse and Selected Peninsular Ranges province.

The Basin and Range hydrogeologic province includes 45 ground-water basins and 56 watersheds. The boundary with the Sierra Nevada province is defined by ground-water basin and watershed boundaries that approximate geologic boundaries; only one watershed (Upper Owens hydrologic area) was divided between the two provinces. Most of the boundary with the Desert province is defined by ground-water basin boundaries that approximate the Garlock Fault. The easternmost part of the boundary is defined by ground-water basin boundaries that approximate the geomorphic boundary between the north-south trending mountains of the Basin and Range province and the broader, more widely-spaced mountains of the Desert province.

The Transverse and selected Peninsular Ranges hydrogeologic province includes 33 ground-water basins and 167 watersheds. The boundaries with the Southern Coast Range, Sierra Nevada, and Desert provinces are defined by ground-water basin and watershed boundaries that approximate geologic boundaries, including the Santa Ynez, Big Pine, and San Andreas Faults. Mountain areas along the boundaries, other than the Sierra Nevadas, are generally included in the Transverse and selected Peninsular Ranges province. Only one watershed (Neenach hydrologic area) was divided between provinces. The boundary with the San Diego Drainages province is defined by boundaries between relatively large watersheds defined as “hydrologic units” (California Department of Forestry and Fire Protection, 1999). The boundaries between the large-scale watersheds (hydrologic units) also correspond to the boundaries between ground-water basins, including the Santa Ana, Elsinore, and San Jacinto ground-water basins, which are included in the Transverse and selected Peninsular Ranges province.

The San Diego Drainages province includes 25 ground-water basins and 163 watersheds. The boundary with the Transverse and Selected Peninsular Ranges to the north is defined by the boundaries of hydrologic units, which are relatively large watersheds. The boundary with the Desert province to the east is defined by the boundaries of hydrologic regions, which are the largest scale watershed identified by the State Water Resources Control Board (California Department of Forestry and Fire Protection, 1999). No watersheds, including relatively small-scale hydrologic subareas, were divided along any of the boundaries of the San Diego Drainages province.

The Desert hydrogeologic province includes 96 ground-water basins and 110 watersheds. The boundary with the Transverse and Selected Peninsular Ranges province is primarily defined by ground-water basin boundaries that delineate the San Gabriel and San Bernardino Mountains, which are part of the Transverse and Selected Peninsular Ranges province, from ground-water basins that are a part of the Desert province. Ground-water basins along the boundary include the Antelope, Mojave, and Coachella basins. The boundary with the Basin and Range province is defined by ground-water basin boundaries, as noted previously. The boundary with the San Diego Province is defined by a major watershed divide demarcating the South Coastal and Colorado River hydrologic regions.

APPENDIX C. CATEGORY 1 PRIORITY GROUND-WATER BASINS, CALIFORNIA

[TSPR, Transverse and selected Peninsular Ranges; DWR, California Department of Water Resources; SacV, subbasin of Sacramento Valley; SJV, subbasin of San Joaquin Valley; LUFT, leaking underground fuel and storage tanks; ID, identification; km^2, square kilometer; acre-ft/yr, acre-feet per year]

DWR basin ID	Ground-water basin	Province	Public supply wells	Municipal population served	Agricultural pumping (acre-ft/yr)	LUFTs	Sections with pesticide application	Area (km^2)
Single-basin study areas with more than 260 public-supply wells								
8-2	Upper Santa Ana Valley	TSPR	788	883,891	0	972	270	1,932
5-22.01	Eastern San Joaquin (SJV)	Central Valley	750	224,431	642,537	745	813	2,862
5-22.08	Kings (SJV)	Central Valley	692	695,806	989,034	660	1,419	3,949
5-22.14	Kern County (SJV)	Central Valley	552	369,175	3,649,345	708	1,878	7,872
3-4	Salinas Valley	Southern Coast Ranges	511	129,158	0	297	777	4,025
4-11	Coastal Plain of Los Angeles	TSPR	478	3,578,031	0	3,223	112	1,274
5-22.02	Modesto (SJV)	Central Valley	353	135,552	170,160	222	257	998
2-9	Santa Clara Valley	Southern Coast Ranges	351	588,085	0	4,663	113	1,470
5-22.11	Kaweah (SJV)	Central Valley	327	213,101	568,118	257	679	1,803
5-21.64	North American (SacV)	Central Valley	326	25,482	345,845	524	289	1,377
7-21	Coachella Valley	Desert	324	46,097	0	306	231	1,964
6-44	Antelope Valley	Desert	313	100,243	95,388	282	169	4,488
8-1	Coastal Plain of Orange County	TSPR	269	839,857	32,602	2,242	182	899
Grouped-basin study areas with more than 260 public-supply wells								
4-13	San Gabriel Valley	TSPR	365	474,266	2,983	795	59	513
4-23	Raymond	TSPR	79	78,180	0	65	8	106
	Study area total		444	552,446	2,983	860	67	619
1-55	Santa Rosa Valley	Northern Coast Ranges	200	227,480	0	535	107	409
1-59	Wilson Grove Formation Highlands	Northern Coast Ranges	56	10,274	1,889	89	75	350
2-1	Petaluma Valley	Northern Coast Ranges	25	49,957	287	129	28	186
	Study area total		281	287,711	2,176	753	210	946
6-42	Upper Mojave River Valley	Desert	193	91,090	11,645	118	30	1,671
6-40	Lower Mojave River Valley	Desert	55	850	8,496	111	49	1,155
6-41	Middle Mojave River Valley	Desert	16	3,988	14,186	21	13	855
	Study area total		264	95,928	34,326	250	92	3,681
4-4	Santa Clara River Valley	TSPR	216	64,006	0	702	200	775
4-6	Pleasant Valley	TSPR	14	25,986	8,452	85	29	87
4-8	Las Posas Valley	TSPR	30	8,790	16,539	46	63	171
	Study area total		260	98,782	24,990	833	292	1,034
Single-basin study areas with less than 260 public-supply wells but in category 1 because of province representation								
6-12	Owens Valley	Basin and Range	115	6,052	73,082	85	63	2,675
5-25	Kern River Valley	Sierras	110	0	2,187	14	12	321
6-5	Tahoe Valley	Sierras	80	32,240	0	87	1	93
9-5	Temecula Valley	San Diego	68	49,160	3,403	27	69	355
1-4	Shasta Valley	Modoc Plateau and Cascades	43	1,363	0	42	79	793

APPENDIX D. CATEGORY 2 PRIORITY GROUND-WATER BASINS, CALIFORNIA

[TSPR, Transverse and selected Peninsular Ranges; DWR, California Department of Water Resources; SacV, subbasin of Sacramento Valley; SJV, subbasin of San Joaquin Valley; LUFT, leaking underground fuel and storage tanks; ID, identification; km^2, square kilometer; acre-ft/yr, acre-feet per year]

DWR basin ID	Ground-water basin	Province	Public supply wells	Municipal population served	Agricultural pumping (acre-ft/yr)	LUFTs	Sections with pesticide application	Area (km^2)
Single-basin study areas with 100 to 259 public-supply wells								
5-22.03	Turlock (SJV)	Central Valley	251	109,398	223,770	173	458	1,405
5-21.65	South American (SacV)	Central Valley	211	107,720	137,060	664	168	1,003
5-22.15	Tracy (SJV)	Central Valley	209	35,408	259,951	223	413	1,396
3-3	Gilroy-Hollister Valley	Southern Coast Ranges	187	113,714	0	179	199	745
5-22.13	Tule (SJV)	Central Valley	184	57,698	453,600	123	657	1,898
4-12	San Fernando Valley	TSPR	180	123,352	0	704	28	586
5-22.04	Merced (SJV)	Central Valley	172	110,738	297,386	240	536	1,987
3-12	Santa Maria	Southern Coast Ranges	142	14,643	213,678	105	197	745
5-21.67	Yolo (SacV)	Central Valley	140	99,823	97,754	224	320	914
5-21.66	Solano (SacV)	Central Valley	125	34,245	175,638	166	584	1,720
5-22.07	Delta-Mendota (SJV)	Central Valley	123	29,559	1,416,583	188	931	3,021
5-6	Redding Area	Central Valley	123	41,794	0	212	95	1,579
5-22.06	Madera (SJV)	Central Valley	110	45,986	254,204	127	498	1,591
5-21.52	Colusa (SacV)	Central Valley	108	25,717	2,133,561	88	1,216	3,717
5-22.12	Tulare Lake (SacV)	Central Valley	100	82,728	502,931	136	701	2,120
Grouped-basin study areas with 100 to 259 public-supply wells								
3-2	Pajaro Valley	Southern Coast Ranges	146	49,310	103,893	148	119	357
3-21	Santa Cruz Purisima Formation	Southern Coast Ranges	23	0	29,818	6	29	163
3-1	Soquel Valley	Southern Coast Ranges	13	45,000	0	27	1	10
3-26	West Santa Cruz Terrace	Southern Coast Ranges	10	1,988	1,568	109	4	32
	Study area total		*192*	*96,298*	*135,279*	*290*	*153*	*561*
2-23	Napa-Sonoma Volcanic Highlands	Northern Coast Ranges	76	0	43,069	57	224	1,010
2-2	Napa-Sonoma Valley	Northern Coast Ranges	52	9,860	0	441	140	530
2-3	Suisun-Fairfield Valley	Northern Coast Ranges	15	0	3,562	127	56	541
2-19	Kenwood Valley	Northern Coast Ranges	9	0	146	6	7	21
	Study area total		*152*	*9,860*	*46,777*	*631*	*427*	*2,101*
1-10	Eel River Valley	Northern Coast Ranges	30	14,075	6,810	88	30	298
1-1	Smith River Plain	Northern Coast Ranges	22	15,316	8,838	80	12	164
1-14	Lower Klamath River Valley	Northern Coast Ranges	20	0	10,014	9	3	28
1-9	Eureka Plain	Northern Coast Ranges	13	28,234	22	188	13	151
1-27	Big Lagoon Area	Northern Coast Ranges	12	0	0	12	2	54
1-8	Mad River Valley	Northern Coast Ranges	10	42,500	0	107	8	160
	Study area total		*107*	*100,125*	*25,685*	*484*	*68*	*856*
Single-basin study areas with less than 100 public-supply wells but in category 2 because of province representation								
6-54	Indian Wells Valley	Basin and Range	81	36,319	4,391	59	7	1,545

APPENDIX E. CATEGORY 3 PRIORITY GROUND-WATER BASINS, CALIFORNIA

[TSPR, Transverse and selected Peninsular Ranges; DWR, California Department of Water Resources; SacV, subbasin of Sacramento Valley; SJV, subbasin of San Joaquin Valley; LUFT, leaking underground fuel and storage tanks; ID, identification; km^2, square kilometer; acre-ft/yr, acre-feet per year]

DWR basin ID	Ground-water basin	Province	Public supply wells	Municipal population served	Agricultural pumping (acre-ft/yr)	LUFTs	Sections with pesticide application	Area (km^2)
Single-basin study areas with 25 to 99 public-supply wells and highly ranked for two or more other factors								
3-15	Santa Ynez River Valley	Southern Coast Ranges	95	46,938	162,836	280	146	828
5-22.16	Cosumnes (SJV)	Central Valley	69	8,500	277,690	52	236	1,135
5-21.61	South Yuba (SacV)	Central Valley	53	11,513	88,063	141	115	423
5-21.59	East Butte (SacV)	Central Valley	44	8,007	336,995	71	307	1,074
5-21.60	North Yuba (SacV)	Central Valley	36	12,320	54,853	69	124	418
5-21.50	Red Bluff (SacV)	Central Valley	35	14,347	112,037	59	106	1,079
5-21.58	West Butte (SacV)	Central Valley	32	81,515	122,102	46	237	735
2-10	Livermore Valley	Southern Coast Ranges	31	43,628	110	162	65	282
Grouped-basin study areas with 25 to 99 public-supply wells and highly ranked for two or more other factors								
8-5	San Jacinto	TSPR	70	4,200	173,254	138	192	758
8-4	Elsinore	TSPR	27	0	10,915	15	7	104
	Study area total		*97*	*4,200*	*184,169*	*153*	*199*	*862*
3-16	Goleta	TSPR	47	0	7,568	73	9	37
3-49	Montecito	TSPR	19	2,658	0	15	11	25
3-53	Foothill	TSPR	13	0	2,563	25	2	13
3-17	Santa Barbara	TSPR	11	1,901	0	120	5	25
3-18	Carpinteria	TSPR	5	14,600	88	17	14	33
	Study area total		*95*	*19,159*	*10,219*	*250*	*41*	*133*
7-38	Palo Verde Valley	Desert	25	0	0	27	117	295
7-39	Palo Verde Mesa	Desert	14	0	4,828	134	94	910
	Study area total		*39*	*0*	*4,828*	*161*	*211*	*1,205*
Single-basin study areas in category 3 because of province representation								
8-9	Bear Valley	TSPR	52	7,000	2,221	31	1	79
6-4	Honey Lake Valley	Modoc Plateau and Cascades	38	2,741	33,000	16	51	1,261
5-34	Mount Shasta Volcanic Area	Modoc Plateau and Cascades	31	3,680	110	26	1	85
9-8	Warner Valley	San Diego	29	0	8,407	4	0	97
5-67	Clear Lake Pleistocene Volcanic Area	Northern Coast Ranges	27	2,000	82,716	8	16	280
1-52	Ukiah Valley	Northern Coast Ranges	22	12,289	2,552	115	52	152
1-5	Scott River Valley	Klamath Mountains	12	0	31,045	19	56	258
7-36	Yuma Valley	Desert	12	0	1,447	11	37	502
7-44	Needles Valley	Desert	9	6,000	0	26	9	356
9-17	Sweetwater Valley	San Diego	9	0	541	152	2	24
Grouped-basin study areas in category 3 because of province representation								
3-9	San Luis Obispo Valley	Southern Coast Ranges	39	1,018	32,558	46	17	51
3-8	Los Osos Valley	Southern Coast Ranges	18	0	0	1	9	28
	Study area total		*57*	*1,018*	*32,558*	*47*	*26*	*80*
9-7	San Luis Rey Valley	San Diego	17	0	20,814	18	38	120
9-4	Santa Margarita Valley	San Diego	15	0	652	0	4	32
	Study area total		*32*	*0*	*21,466*	*18*	*42*	*152*

APPENDIX F. CATEGORY 4 PRIORITY GROUND-WATER BASINS, CALIFORNIA

[TSPR, Transverse and selected Peninsular Ranges; DWR, California Department of Water Resources; SacV, subbasin of Sacramento Valley; SJV, subbasin of San Joaquin Valley; LUFT, leaking underground fuel and storage tanks; ID, identification; km^2, square kilometer; acre-ft/yr, acre-feet per year]

DWR basin ID	Ground-water Basin	Province	Public supply wells	Municipal population served	Agricultural pumping (acre-ft/yr)	LUFTs	Sections with pesticide application	Area (km^2)
Single-basin study areas with 25 to 99 public-supply wells and highly ranked for one other factor								
5-21.62	East Sutter (SacV)	Central Valley	63	135	74,052	60	193	532
5-21.57	Vina (SacV)	Central Valley	61	0	52,490	51	114	504
1-21	Fort Bragg Terrace Area	Northern Coast Ranges	31	0	30,401	69	13	98
5-55	Sacramento Valley Eastside	Modoc Plateau and Cascades	27	0	76,192	44	58	2,052
Grouped-basin study areas with 25 to 99 public-supply wells and highly ranked for one other factor								
7-12	Warren Valley	Desert	18	0	280	9	0	96
7-62	Joshua Tree	Desert	18	0	246	0	1	110
7-20	Morongo Valley	Desert	6	0	381	1	0	29
	Study area total		*42*	*0*	*907*	*10*	*1*	*235*
3-13	Cuyama Valley	Southern Coast Ranges	14	0	63,758	5	56	978
5-82	Cuddy Canyon Valley	Southern Coast Ranges	8	2,365	78	1	0	13
5-84	Cuddy Valley	Southern Coast Ranges	8	0	90	7	1	14
5-29	Castac Lake Valley	Southern Coast Ranges	6	624	90	20	0	14
5-83	Cuddy Ranch Area	Southern Coast Ranges	6	0	101	0	0	17
	Study area total		*42*	*2,989*	*64,117*	*33*	*57*	*1,037*
Single-basin study areas with 25 to 99 public-supply wells and not highly ranked for any other factor								
1-60	Lower Russian River Valley	Northern Coast Ranges	31	0	459	20	5	27
1-54	Alexander Valley	Northern Coast Ranges	29	7,750	0	53	38	126
7-24	Borrego Valley	Desert	27	0	8,099	9	11	617
5-21.54	Antelope (SacV)	Central Valley	26	0	7,987	17	23	76
6-67	Martis Valley	Sierras	25	12,800	0	40	0	147
Grouped-basin study areas with 25 to 99 public-supply wells and not highly ranked for any other factor								
5-28	Tehachapi Valley West	Sierras	33	10,337	437	9	10	73
5-27	Cummings Valley	Sierras	18	0	246	0	9	41
6-45	Tehachapi Valley East	Sierras	11	0	806	0	4	97
	Study area total		*62*	*10,337*	*1,490*	*9*	*23*	*210*
Single-basin study areas with 12 to 24 public-supply wells and highly ranked for two or more other factors								
5-22.05	Chowchilla (SJV)	Central Valley	22	6,800	97,284	28	234	644
5-22.09	Westside (SJV)	Central Valley	18	8,000	622,831	30	935	2,590
Single-basin study areas with 12 to 24 public-supply wells and highly ranked for one other factor								
4-3	Ventura River Valley	TSPR	22	0	0	84	13	51
5-21.51	Corning (SacV)	Central Valley	21	6,272	77,850	36	162	832
2-35	Westside	Southern Coast Ranges	19	14,820	168	473	4	103
Basins with priority lowered due to low density of public-supply wells								
5-33	Modoc Plateau Pleistocene Volcanic Area	Modoc Plateau and Cascades	27	3,040	394,053	9	94	5,010

APPENDIX G. CATEGORY 6 LOW-USE GROUND-WATER BASINS, CALIFORNIA

[TSPR, Transverse and selected Peninsular Ranges; DWR, California Department of Water Resources; SacV, subbasin of Sacramento Valley; SJV, subbasin of San Joaquin Valley; LUFT, leaking underground fuel and storage tanks; ID, identification; km^2, square kilometer; acre-ft/yr, acre-feet per year]

DWR basin ID	Ground-water basin	Province	Public-supply wells	Municipal population served	Agricultural pumping (acre-ft/yr)	LUFTs	Pesticide application	Area (km^2)
Single-basin study areas with 11 to 23 public-supply wells but not highly ranked for any other factor								
6-43	El Mirage Valley	Desert	22	0	2,240	11	4	307
7-19	Lucerne Valley	Desert	21	0	1,344	4	13	597
5-2	Alturas Area	Modoc Plateau and Cascades	18	2,982	0	6	31	737
6-7	Antelope Valley	Basin and Range	18	0	11,269	2	6	81
6-47	Harper Valley	Desert	16	0	29,168	7	13	1,657
4-5	Acton Valley	Desert	15	0	2,363	1	1	33
5-12	Sierra Valley	Sierras	14	0	0	2	11	515
6-46	Fremont Valley	Desert	14	0	7,931	3	1	957
5-10	American Valley	Sierras	13	6,228	840	17	3	28
6-20	Middle Amargosa Valley	Basin and Range	13	0	11	2	1	1,577
7-5	Chuckwalla Valley	Desert	13	0	5,858	2	2	2,434
3-27	Scotts Valley	Southern Coast Ranges	12	0	269	13	0	3
Single-basin study areas with 1 to 11 public-supply wells and highly ranked for one or more significant factors								
1-2	Klamath River Valley	Modoc Plateau and Cascades	10	1,500	0	8	154	653
1-3	Butte Valley	Modoc Plateau and Cascades	10	886	6,127	2	59	323
5-21.63	West Sutter (SacV)	Central Valley	6	0	93,442	13	160	417
1-24	Modoc Plateau Pleistocene Volcanic Area	Modoc Plateau and Cascades	5	0	431,242	1	38	2,107
2-33	Islais Valley	Southern Coast Ranges	4	45,616	11	162	0	24
4-10	Conejo	TSPR	4	0	7,438	69	4	76
4-9	Simi Valley	TSPR	4	2,612	4,828	93	7	49
1-23	Modoc Plateau Recent Volcanic Area	Modoc Plateau and Cascades	3	0	110,602	0	29	1,194
6-103	Modoc Plateau Pleistocene Vocanic Area	Modoc Plateau and Cascades	3	0	223,277	6	7	1,505
7-30	Imperial Valley	Desert	3	0	0	164	831	3,876
5-32	Modoc Plateau Recent Volcanic Area	Modoc Plateau and Cascades	2	0	165,176	1	7	1,376
5-22.10	Pleasant Valley (SJV)	Central Valley	1	15,400	278,332	38	151	589
Basins with 1 to 11 public-supply wells, not highly ranked for any other significant factor, but with a non-zero entry for one or more other factors								
1-19	Anderson Valley	Northern Coast Ranges	11	0	202	13	8	20
3-14	San Antonio Creek Valley	Southern Coast Ranges	11	0	48,905	7	35	331
3-7	Carmel Valley	Southern Coast Ranges	11	0	0	8	3	21
7-16	Ames Valley	Desert	11	0	986	0	0	439
2-22	Half Moon Bay Terrace	Southern Coast Ranges	10	0	0	40	9	37
5-14	Scotts Valley	Northern Coast Ranges	10	4,486	2,207	22	9	30
5-15	Big Valley	Northern Coast Ranges	10	2,588	7,292	8	28	98
5-21.56	Los Molinos (SacV)	Central Valley	10	0	13,968	0	21	134
5-4	Big Valley	Modoc Plateau and Cascades	9	442	10,597	5	30	373
7-13	Deadman Valley	Desert	9	0	0	0	0	479
7-41	Calzona Valley	Desert	9	0	0	0	0	326
2-26	Pescadero Valley	Southern Coast Ranges	8	0	0	6	4	12
3-6	Lockwood Valley	Southern Coast Ranges	8	0	38,499	7	11	243
4-2	Ojai Valley	TSPR	8	5,690	2,845	32	10	28
5-60	Humbug Valley	Sierras	8	2,200	1,456	12	0	40
5-9	Indian Valley	Sierras	8	0	10,888	9	1	119

[TSPR, Transverse and selected Peninsular Ranges; DWR, California Department of Water Resources; SacV, subbasin of Sacramento Valley; SJV, subbasin of San Joaquin Valley; LUFT, leaking underground fuel and storage tanks; ID, identification; km², square kilometer; acre-ft/yr, acre-feet per year]

DWR basin ID	Ground-water basin	Province	Public-supply wells	Municipal population served	Agricultural pumping (acre-ft/yr)	LUFTs	Pesticide application	Area (km²)
Basins with 1 to 11 public-supply wells, not highly ranked for any other significant factor, but with a non-zero entry for one or more other factors—*Cont.*								
6-8	Bridgeport Valley	Basin and Range	8	600	13,935	0	5	131
9-11	Santa Maria Valley	San Diego	8	0	1,165	25	4	50
9-15	San Diego River Valley	San Diego	8	0	930	54	3	40
1-57	Bodega Bay Area	Northern Coast Ranges	7	0	0	0	0	11
3-42	Chorro Valley	Southern Coast Ranges	7	0	0	0	2	6
6-11	Long Valley	Basin and Range	7	0	13,408	30	0	291
7-29	Coyote Wells Valley	Desert	7	0	7,729	2	1	589
1-53	Sanel Valley	Northern Coast Ranges	6	0	381	11	10	23
2-27	Sand Point Area	Northern Coast Ranges	6	0	0	0	0	6
2-4	Pittsburg Plain	Southern Coast Ranges	6	6,660	224	53	1	47
2-5	Clayton Valley	Southern Coast Ranges	6	0	347	37	3	72
4-7	Arroyo Santa Rosa Valley	TSPR	6	0	1,479	2	6	15
5-11	Mohawk Valley	Sierras	6	0	2,778	0	1	77
5-85	Mil Potrero Area	Southern Coast Ranges	6	0	56	1	0	9
6-18	Death Valley	Basin and Range	6	0	0	0	0	3,725
6-25	Bicycle Valley	Desert	6	0	2,453	0	0	362
6-30	Ivanpah Valley	Desert	6	0	5,690	3	0	801
6-36	Langford Valley	Desert	6	0	0	0	0	121
9-1	San Juan Valley	San Diego	6	3,250	0	49	8	68
1-11	Covelo Round Valley	Northern Coast Ranges	5	0	10,048	8	5	66
1-61	Fort Ross Terrace Deposits	Northern Coast Ranges	5	0	314	23	0	34
5-63	Stonyford Town Area	Northern Coast Ranges	5	0	0	0	2	26
6-38	Caves Canyon Valley	Desert	5	0	2,083	0	0	295
8-6	Hemet Lake Valley	T notDesert Mountains	5	0	10,294	2	1	68
9-2	San Mateo Valley	San Diego	5	0	168	0	1	12
1-16	Seiad Valley	Klamath Mountains	4	0	0	1	0	9
1-26	Redwood Creek Area	Northern Coast Ranges	4	650	2,285	0	0	8
1-7	Hoopa Valley	Klamath Mountains	4	0	0	0	1	16
3-25	Tres Pinos Valley	Southern Coast Ranges	4	0	2,991	0	5	14
3-41	Morro Valley	Southern Coast Ranges	4	0	1,669	3	1	3
4-21	Conejo-Tierra Rejada Volcanic	TSPR	4	0	37,704	11	16	232
5-21.55	Dye Creek (SacV)	Central Valley	4	0	11,481	5	13	112
6-2	Madeline Plains	Modoc Plateau and Cascades	4	0	4,604	1	16	632
6-33	Soda Lake Valley	Desert	4	0	10,854	8	0	1,538
7-11	Copper Mountain Valley	Desert	4	0	280	0	0	123
9-3	San Onofre Valley	San Diego	4	0	67	0	0	5
1-31	Weott Town Area	Northern Coast Ranges	3	0	2,386	0	1	15
2-7	San Ramon Valley	Southern Coast Ranges	3	0	134	35	1	29
3-28	San Benito River Valley	Southern Coast Ranges	3	0	17,474	0	10	98
5-18	Coyote Valley	Northern Coast Ranges	3	0	1,512	2	4	26
5-21.68	Capay Valley (SacV)	Central Valley	3	0	23,187	0	31	101
5-30	Lower Lake Valley	Northern Coast Ranges	3	0	728	2	1	10
5-69	Yosemite Valley	Sierras	3	0	0	0	1	30
6-1	Surprise Valley	Modoc Plateau and Cascades	3	650	84,380	0	37	924
7-2	Fenner Valley	Desert	3	0	4,122	2	0	1,831
7-35	Ogilby Valley	Desert	3	0	15,884	0	1	539

APPENDIX G. CATEGORY 6 LOW-USE GROUND-WATER BASINS, CALIFORNIA—*CONTINUED*

[TSPR, Transverse and selected Peninsular Ranges; DWR, California Department of Water Resources; SacV, subbasin of Sacramento Valley; SJV, subbasin of San Joaquin Valley; LUFT, leaking underground fuel and storage tanks; ID, identification; km^2, square kilometer; acre-ft/yr, acre-feet per year]

DWR basin ID	Ground-water basin	Province	Public-supply wells	Municipal population served	Agricultural pumping (acre-ft/yr)	LUFTs	Pesticide application	Area (km^2)
Basins with 1 to 11 public-supply wells, not highly ranked for any other significant factor, but with a non-zero entry for one or more other factors—*Cont.*								
7-40	Quien Sabe Point Valley	Desert	3	0	0	0	2	102
7-47	Jacumba Valley	Desert	3	0	134	4	0	10
7-9	Dale Valley	Desert	3	0	1,938	0	1	860
9-10	San Pasqual Valley	San Diego	3	0	426	0	4	18
1-28	Mattole River Valley	Northern Coast Ranges	2	0	0	0	0	13
1-32	Garberville Town Area	Northern Coast Ranges	2	0	0	7	0	9
1-35	Hyampom Valley	Klamath Mountains	2	0	0	0	0	5
1-49	Anapolis Ohlson Ranch Farm Highlands	Northern Coast Ranges	2	0	0	9	2	35
1-51	Potter Valley	Northern Coast Ranges	2	0	571	9	10	33
3-19	Carrizo Plain	Southern Coast Ranges	2	0	1,490	0	27	852
3-20	Ano Nuevo Area	Southern Coast Ranges	2	0	190	0	2	8
4-16	Hidden Valley	TSPR	2	0	67	4	1	9
4-17	Lockwood Valley	Southern Coast Ranges	2	0	11,325	0	0	88
5-13	Upper Lake Valley	Northern Coast Ranges	2	0	2,184	4	6	29
5-19	Collayomi Valley	Northern Coast Ranges	2	5,766	1,501	5	3	26
5-35	Mccloud Area	Modoc Plateau and Cascades	2	0	0	6	1	86
5-48	Burney Creek Valley	Modoc Plateau and Cascades	2	5,240	78	9	0	10
5-5	Fall River Valley	Modoc Plateau and Cascades	2	0	1,725	6	51	219
5-7	Lake Almanor Valley	Modoc Plateau and Cascades	2	2,600	526	4	1	29
5-87	Middle Fork Feather River	Sierras	2	0	1,243	0	0	18
6-16	Eureka Valley	Basin and Range	2	0	0	0	0	521
6-51	Pilot Knob Valley	Desert	2	0	0	0	0	561
6-56	Rose Valley	Basin and Range	2	0	22	0	0	172
6-6	Carson Valley	Sierras	2	0	21,215	4	0	43
7-10	Twentynine Palms Valley	Desert	2	0	571	6	0	252
7-28	Vallecito-carrizo Valley	Desert	2	0	6,463	0	0	493
7-42	Vidal Valley	Desert	2	0	5,847	0	0	557
1-12	Laytonville Valley	Northern Coast Ranges	1	1,000	0	5	0	20
1-25	Prairie Creek Area	Northern Coast Ranges	1	0	0	0	0	81
1-30	Pepperwood Town Area	Northern Coast Ranges	1	0	8,334	5	8	25
1-34	Dinsmores Town Area	Northern Coast Ranges	1	0	3,013	0	1	9
1-37	Cottoneva Creek Valley	Northern Coast Ranges	1	0	34	2	0	3
1-50	Knights Valley	Northern Coast Ranges	1	0	280	0	4	17
2-11	Sunol Valley	Southern Coast Ranges	1	0	22	6	15	67
2-30	Novato Valley	Northern Coast Ranges	1	43,450	112	56	2	83
3-29	Dry Lake Valley	Southern Coast Ranges	1	0	1,255	1	1	6
3-30	Bitter Water Valley	Southern Coast Ranges	1	0	21,171	0	14	130
3-32	Peach Tree Valley	Southern Coast Ranges	1	0	6,284	0	5	40
3-5	Cholame Valley	Southern Coast Ranges	1	0	1,848	0	4	161
4-1	Upper Ojai Valley	TSPR	1	0	1,389	1	3	15
4-15	Tierra Rejada	TSPR	1	0	7,303	4	2	19
5-1	Goose Lake	Modoc Plateau and Cascades	1	0	0	0	4	220
5-23	Panoche Valley	Southern Coast Ranges	1	0	2,599	0	1	134
5-50	North Fork Battle Creek	Modoc Plateau and Cascades	1	0	101	0	1	52
5-66	Clear Lake Cache Formation	Northern Coast Ranges	1	0	8,961	4	0	120
5-95	Meadow Valley	Sierras	1	0	706	0	0	23

APPENDIX G. CATEGORY 6 LOW-USE GROUND-WATER BASINS, CALIFORNIA—*CONTINUED*

[TSPR, Transverse and selected Peninsular Ranges; DWR, California Department of Water Resources; SacV, subbasin of Sacramento Valley; SJV, subbasin of San Joaquin Valley; LUFT, leaking underground fuel and storage tanks; ID, identification; km^2, square kilometer; acre-ft/yr, acre-feet per year]

DWR basin ID	Ground-water basin	Province	Public-supply wells	Municipal population served	Agricultural pumping (acre-ft/yr)	LUFTs	Pesticide application	Area (km^2)
Basins with 1 to 11 public-supply wells, not highly ranked for any other significant factor, but with a non-zero entry for one or more other factors—*Cont.*								
6-15	Deep Springs Valley	Basin and Range	1	0	0	0	0	121
6-22	Upper Kingston Valley	Desert	1	0	1,613	1	0	715
6-32	Broadwell Valley	Desert	1	0	2,722	0	0	372
6-74	Harrisburg Flats	Basin and Range	1	0	0	0	0	101
6-75	Wildrose Canyon	Basin and Range	1	0	0	0	0	21
6-9	Mono Valley	Basin and Range	1	0	0	3	0	700
7-18	Johnson Valley	Desert	1	0	0	0	0	453
7-26	Terwilliger Valley	Desert	1	0	426	0	5	32
7-31	Orocopia Valley	Desert	1	0	4,794	0	0	389
7-33	East Salton Sea	Desert	1	0	10,339	3	31	789
7-43	Chemehuevi Valley	Desert	1	0	67	0	0	1,101
7-51	Lost Horse Valley	Desert	1	0	157	0	0	70
7-59	Mason Valley	Desert	1	0	291	0	0	22
7-6	Pinto Valley	Desert	1	0	1,983	0	0	738
8-7	Big Meadows Valley	TSPR	1	0	1,680	3	0	57
9-22	Batiquitos Lagoon Valley	San Diego	1	0	269	4	1	3
9-28	Campo Valley	San Diego	1	0	280	4	0	14
9-29	Potrero Valley	San Diego	1	0	157	0	0	8
9-6	Cahuilla Valley	Desert	1	0	683	1	12	74
Single-basin study areas with zero public-supply wells and highly ranked for one or more other factors								
2-39	Marina	Southern Coast Ranges	0	0	11	190	0	9
2-40	Downtown	Southern Coast Ranges	0	0	11	780	0	31
2-6	Ygnacio Valley	Southern Coast Ranges	0	0	302	148	1	63
9-14	Mission Valley	San Diego	0	0	0	208	0	30
9-16	El Cajon Valley	San Diego	0	0	672	167	1	29
Single-basin study areas with zero public-supply wells, not highly ranked for any other factor, but with a non-zero entry for either LUFTs or pesticide applications								
1-13	Little Lake Valley	Northern Coast Ranges	0	0	0	28	1	41
1-15	Happy Camp Town Area	Klamath Mountains	0	0	0	2	0	11
1-18	Red Rock Valley	Modoc Plateau and Cascades	0	0	694	1	7	36
1-20	Garcia River Valley	Northern Coast Ranges	0	0	90	0	1	9
1-38	Lower Laytonville Valley	Northern Coast Ranges	0	0	0	6	1	9
1-41	Little Valley	Northern Coast Ranges	0	0	34	0	1	3
1-43	Williams Valley	Northern Coast Ranges	0	0	1,008	0	1	7
1-46	Navarro River Valley	Northern Coast Ranges	0	0	34	4	0	3
1-56	Mcdowell Valley	Northern Coast Ranges	0	0	101	0	3	6
1-6	Hayfork Valley	Klamath Mountains	0	0	0	1	0	13
2-28	Ross Valley	Northern Coast Ranges	0	0	11	22	0	7
2-29	San Rafael Valley	Northern Coast Ranges	0	0	0	37	0	4
2-31	Arroyo Del Hambre Valley	Southern Coast Ranges	0	0	11	11	0	3
2-32	Visitacion Valley	Southern Coast Ranges	0	0	11	52	3	24
2-36	San Pedro Valley	Southern Coast Ranges	0	0	0	9	0	3
2-37	South San Francisco	Southern Coast Ranges	0	0	0	60	0	9
2-38	Lobos	Southern Coast Ranges	0	0	11	68	0	10
2-8	Castro Valley	Southern Coast Ranges	0	0	0	58	0	7
3-22	Santa Ana Valley	Southern Coast Ranges	0	0	2,408	0	4	11
3-24	Quien Sabe Valley	Southern Coast Ranges	0	0	4,156	0	3	19

APPENDIX G. CATEGORY 6 LOW-USE GROUND-WATER BASINS, CALIFORNIA—*CONTINUED*

[TSPR, Transverse and selected Peninsular Ranges; DWR, California Department of Water Resources; SacV, subbasin of Sacramento Valley; SJV, subbasin of San Joaquin Valley; LUFT, leaking underground fuel and storage tanks; ID, identification; km^2, square kilometer; acre-ft/yr, acre-feet per year]

DWR basin ID	Ground-water basin	Province	Public-supply wells	Municipal population served	Agricultural pumping (acre-ft/yr)	LUFTs	Pesticide application	Area (km^2)
Single-basin study areas with zero public-supply wells, not highly ranked for any other factor, but with a non-zero entry for either LUFTs or pesticide applications—*Cont.*								
3-34	Arroyo De La Cruz Valley	Southern Coast Ranges	0	0	0	0	1	4
3-36	Santa Rosa Valley	Southern Coast Ranges	0	6,100	9,129	5	3	14
3-39	Old Valley	Southern Coast Ranges	0	0	3,058	3	2	5
3-43	Rinconada Valley	Southern Coast Ranges	0	0	1,658	0	3	10
3-44	Pozo Valley	Southern Coast Ranges	0	0	4,402	0	3	28
3-45	Huasna Valley	Southern Coast Ranges	0	0	1,255	0	5	19
3-47	Big Spring Area	Southern Coast Ranges	0	0	336	0	1	30
3-50	Felton Area	Southern Coast Ranges	0	2,222	403	9	0	5
3-51	Majors Creek	Southern Coast Ranges	0	0	11	0	1	1
3-52	Needle Rock Point	Southern Coast Ranges	0	0	45	1	1	2
4-19	Thousand Oaks Area	TSPR	0	0	650	58	2	13
4-20	Russell Valley	TSPR	0	0	90	12	1	12
4-22	Malibu Valley	TSPR	0	0	22	7	0	2
5-17	Burns Valley	Northern Coast Ranges	0	0	863	9	0	12
5-21.53	Bend (SacV)	Central Valley	0	0	4,805	1	5	84
5-26	Walker Basin Creek Valley	Sierras	0	0	190	0	1	31
5-36	Round Valley	Modoc Plateau and Cascades	0	0	840	0	1	29
5-40	Hot Springs Valley	Modoc Plateau and Cascades	0	0	78	0	1	10
5-45	Cayton Valley	Modoc Plateau and Cascades	0	0	45	0	1	5
5-47	Goose Valley	Modoc Plateau and Cascades	0	0	134	0	6	17
5-62	Elk Creek Area	Northern Coast Ranges	0	0	0	0	2	6
5-64	Bear Valley	Northern Coast Ranges	0	0	2,744	1	0	37
5-68	Pope Valley	Northern Coast Ranges	0	0	1,658	2	6	29
5-86	Joseph Creek	Modoc Plateau and Cascades	0	0	515	0	1	18
5-91	Antelope Creek	Northern Coast Ranges	0	0	1,624	0	1	8
5-92	Blanchard Valley	Northern Coast Ranges	0	0	3,540	0	1	9
6-104	Long Valley	Sierras	0	0	5,029	0	1	189
6-14	Fish Lake Valley	Basin and Range	0	0	0	0	16	195
6-24	Red Pass Valley	Desert	0	0	90	13	0	390
6-28	Pahrump Valley	Desert	0	0	2,621	2	0	376
6-29	Mesquite Valley	Desert	0	0	2,487	0	8	357
6-3	Willow Creek Valley	Modoc Plateau and Cascades	0	0	1,255	0	3	47
6-52	Searles Valley	Basin and Range	0	4,000	45	7	0	797
6-95	Dry Valley	Modoc Plateau and Cascades	0	0	190	0	1	26
7-22	West Salton Sea	Desert	0	0	5,589	1	1	426
7-25	Ocotillo-clark Valley	Desert	0	0	11,795	0	28	899
7-27	San Felipe Valley	Desert	0	0	1,243	1	2	95
7-34	Amos Valley	Desert	0	0	6,889	4	2	526
7-8	Bristol Valley	Desert	0	0	9,790	3	3	2,011
9-12	San Dieguito Creek	San Diego	0	0	336	7	3	14
9-13	Poway Valley	San Diego	0	0	235	25	0	10
9-18	Otay Valley	San Diego	0	0	672	46	3	28
9-19	Tia Juana	San Diego	0	0	594	14	1	30
9-23	San Elijo Valley	San Diego	0	0	314	0	2	4
9-25	Ranchita Town Area	Desert	0	0	952	1	0	13
9-32	San Marcos Area	San Diego	0	0	762	56	0	9
9-9	Escondido Valley	San Diego	0	0	1,031	64	0	12

APPENDIX G. CATEGORY 6 LOW-USE GROUND-WATER BASINS, CALIFORNIA—*CONTINUED*

[TSPR, Transverse and selected Peninsular Ranges; DWR, California Department of Water Resources; SacV, subbasin of Sacramento Valley; SJV, subbasin of San Joaquin Valley; LUFT, leaking underground fuel and storage tanks; ID, identification; km^2, square kilometer; acre-ft/yr, acre-feet per year]

DWR basin ID	Ground-water basin	Province	Public-supply wells	Municipal population served	Agricultural pumping (acre-ft/yr)	LUFTs	Pesticide application	Area (km^2)
Single-basin study areas with zero public-supply wells, zero LUFTs and zero pesticide applications, but non-zero entry for agricultural pumping								
1-17	Bray Town Area	Modoc Plateau and Cascades	0	0	616	0	0	33
1-22	Fairchild Swamp Valley	Modoc Plateau and Cascades	0	0	314	0	0	13
1-33	Larabee Valley	Northern Coast Ranges	0	0	1,277	0	0	4
1-36	Hettenshaw Valley	Northern Coast Ranges	0	0	1,120	0	0	3
1-44	Eden Valley	Northern Coast Ranges	0	0	840	0	0	6
1-45	Big River Valley	Northern Coast Ranges	0	0	134	0	0	7
3-23	Upper Santa Ana Valley	Southern Coast Ranges	0	0	1,266	0	0	6
3-31	Hernandez Valley	Southern Coast Ranges	0	0	2,532	0	0	12
3-33	San Carpoforo Valley	Southern Coast Ranges	0	0	2,733	0	0	4
3-35	San Simeon Valley	Southern Coast Ranges	0	0	1,434	0	0	2
3-37	Villa Valley	Southern Coast Ranges	0	0	3,517	0	0	5
3-38	Cayucos Valley	Southern Coast Ranges	0	0	851	0	0	1
3-40	Toro Valley	Southern Coast Ranges	0	0	1,871	0	0	3
3-46	Rafael Valley	Southern Coast Ranges	0	0	134	0	0	12
4-18	Hungry Valley	TSPR	0	0	1,512	0	0	21
5-16	High Valley	Northern Coast Ranges	0	0	706	0	0	10
5-20	Berryessa Valley	Northern Coast Ranges	0	0	627	0	0	6
5-3	Jess Valley	Modoc Plateau and Cascades	0	0	773	0	0	27
5-31	Long Valley	Northern Coast Ranges	0	0	840	0	0	11
5-37	Toad Well Area	Modoc Plateau and Cascades	0	0	112	0	0	14
5-38	Pondosa Town Area	Modoc Plateau and Cascades	0	0	67	0	0	8
5-41	Egg Lake Valley	Modoc Plateau and Cascades	0	0	470	0	0	17
5-43	Rock Prairie Valley	Modoc Plateau and Cascades	0	0	661	0	0	23
5-44	Long Valley	Modoc Plateau and Cascades	0	0	123	0	0	4
5-46	Lake Britton Area	Modoc Plateau and Cascades	0	0	448	0	0	57
5-49	Dry Burney Creek Valley	Modoc Plateau and Cascades	0	0	101	0	0	12
5-51	Butte Creek Valley	Modoc Plateau and Cascades	0	0	101	0	0	13
5-52	Grays Valley	Modoc Plateau and Cascades	0	0	179	0	0	22
5-53	Dixie Valley	Modoc Plateau and Cascades	0	0	157	0	0	20
5-54	Ash Valley	Modoc Plateau and Cascades	0	0	694	0	0	24
5-56	Yellow Creek Valley	Sierras	0	0	168	0	0	9
5-57	Last Chance Creek Valley	Sierras	0	0	571	0	0	19
5-58	Clover Valley	Sierras	0	0	2,072	0	0	68
5-59	Grizzly Valley	Sierras	0	0	1,938	0	0	54
5-70	Los Banos Creek Valley	Southern Coast Ranges	0	0	370	0	0	20
5-71	Vallecitos Creek Valley	Southern Coast Ranges	0	0	1,165	0	0	61
5-8	Mountain Meadows Valley	Modoc Plateau and Cascades	0	0	1,187	0	0	33
5-89	Squaw Flat	Northern Coast Ranges	0	0	1,031	0	0	5
5-90	Funks Creek	Northern Coast Ranges	0	0	2,397	0	0	12
5-93	North Fork Cache Creek	Northern Coast Ranges	0	0	1,042	0	0	14
5-94	Middle Creek	Northern Coast Ranges	0	0	213	0	0	3
6-100	Secret Valley	Modoc Plateau and Cascades	0	0	3,618	0	0	136
6-101	Bull Flat	Modoc Plateau and Cascades	0	0	739	0	0	73
6-102	Modoc Plateau Recent Volcanic Area	Modoc Plateau and Cascades	0	0	213	0	0	8
6-105	Slinkard Valley	Basin and Range	0	0	2,532	0	0	18
6-106	Little Antelope Valley	Basin and Range	0	0	1,400	0	0	10

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DWR basin ID	Ground-water basin	Province	Public-supply wells	Municipal population served	Agricultural pumping (acre-ft/yr)	LUFTs	Pesticide application	Area (km^2)
Single-basin study areas with zero public-supply wells, zero LUFTs and zero pesticide applications, but non-zero entry for agricultural pumping—*Cont.*								
6-107	Sweetwater Flat	Basin and Range	0	0	2,016	0	0	19
6-13	Black Springs Valley	Basin and Range	0	0	1,770	0	0	125
6-23	Riggs Valley	Desert	0	0	202	0	0	354
6-31	Kelso Valley	Desert	0	0	7,281	0	0	1,031
6-34	Silver Lake Valley	Desert	0	0	997	0	0	142
6-35	Cronise Valley	Desert	0	0	3,607	0	0	511
6-37	Coyote Lake Valley	Desert	0	0	2,778	0	0	357
6-48	Goldstone Valley	Desert	0	0	863	0	0	114
6-49	Superior Valley	Desert	0	0	3,685	0	0	487
6-50	Cuddeback Valley	Desert	0	0	2,700	0	0	384
6-68	Santa Rosa Flat	Basin and Range	0	0	202	0	0	68
6-69	Kelso Lander Valley	Sierras	0	0	370	0	0	45
6-70	Cactus Flat	Basin and Range	0	0	414	0	0	28
6-79	California Valley	Desert	0	0	504	0	0	235
6-89	Kane Wash Area	Desert	0	0	168	0	0	24
6-90	Cady Fault Area	Desert	0	0	224	0	0	32
6-91	Cow Head Lake Valley	Modoc Plateau and Cascades	0	0	3,551	0	0	23
6-92	Pine Creek Valley	Modoc Plateau and Cascades	0	0	1,109	0	0	39
6-93	Harvey Valley	Modoc Plateau and Cascades	0	0	482	0	0	18
6-94	Grasshopper Valley	Modoc Plateau and Cascades	0	0	515	0	0	71
6-96	Eagle Lake Area	Modoc Plateau and Cascades	0	0	1,367	0	0	51
6-97	Horse Lake Valley	Modoc Plateau and Cascades	0	0	1,243	0	0	15
6-99	Painters Flat	Modoc Plateau and Cascades	0	0	190	0	0	26
7-1	Lanfair Valley	Desert	0	0	739	0	0	633
7-14	Lavic Valley	Desert	0	0	6,654	0	0	414
7-15	Bessemer Valley	Desert	0	0	717	0	0	158
7-17	Means Valley	Desert	0	0	134	0	0	60
7-3	Ward Valley	Desert	0	0	5,085	0	0	2,256
7-32	Chocolate Valley	Desert	0	0	6,799	0	0	522
7-37	Arroyo Seco Valley	Desert	0	0	15,323	0	0	1,038
7-4	Rice Valley	Desert	0	0	1,579	0	0	761
7-46	Canebrake Valley	Desert	0	0	291	0	0	22
7-48	Helendale Fault Valley		0	0	22	0	0	11
7-49	Pipes Canyon Fault Valley		0	0	34	0	0	14
7-50	Iron Ridge Area	Desert	0	0	45	0	0	21
7-52	Pleasant Valley	Desert	0	0	90	0	0	39
7-53	Hexie Mountain Area	Desert	0	0	101	0	0	45
7-54	Buck Ridge Fault Valley	Desert	0	0	370	0	0	28
7-55	Collins Valley	Desert	0	0	370	0	0	29
7-56	Yaqui Well Area	Desert	0	0	795	0	0	61
7-61	Davies Valley	Desert	0	0	190	0	0	14
7-63	Vandeventer Flat	Desert	0	0	358	0	0	27
7-7	Cadiz Valley	Desert	0	0	2,464	0	0	1,092
8-8	Seven Oaks Valley	TSPR	0	0	482	0	0	16
9-24	Pamo Valley	San Diego	0	0	146	0	0	6
9-27	Cottonwood Valley	San Diego	0	0	302	0	0	16

APPENDIX G. CATEGORY 6 LOW-USE GROUND-WATER BASINS, CALIFORNIA—*CONTINUED*

[TSPR, Transverse and selected Peninsular Ranges; DWR, California Department of Water Resources; SacV, subbasin of Sacramento Valley; SJV, subbasin of San Joaquin Valley; LUFT, leaking underground fuel and storage tanks; ID, identification; km^2, square kilometer; acre-ft/yr, acre-feet per year]

DWR basin ID	Ground-water basin	Province	Public-supply wells	Municipal population served	Agricultural pumping (acre-ft/yr)	LUFTs	Pesticide application	Area (km^2)
Single-basin study areas with no entries								
1-29	Honeydew Town Area	Northern Coast Ranges	0	0	0	0	0	10
1-39	Branscomb Town Area	Northern Coast Ranges	0	0	0	0	0	6
1-40	Ten Mile River Valley	Northern Coast Ranges	0	0	0	0	0	6
1-42	Sherwood Valley	Northern Coast Ranges	0	0	0	0	0	5
1-48	Gravelly Valley	Northern Coast Ranges	0	0	0	0	0	12
1-62	Wilson Point Area	Klamath Mountains	0	0	0	0	0	3
2-24	San Gregorio Valley	Southern Coast Ranges	0	0	0	0	0	4
5-61	Chrome Town Area	Northern Coast Ranges	0	0	0	0	0	6
5-65	Little Indian Valley	Northern Coast Ranges	0	0	0	0	0	5
5-88	Stony Gorge Reservoir	Northern Coast Ranges	0	0	0	0	0	4
6-10	Adobe Lake Valley	Basin and Range	0	0	0	0	0	161
6-17	Saline Valley	Basin and Range	0	0	0	0	0	592
6-19	Wingate Valley	Basin and Range	0	0	0	0	0	288
6-21	Lower Kingston Valley	Desert	0	0	0	0	0	970
6-26	Avawatz Valley	Desert	0	0	0	0	0	112
6-27	Leach Valley	Desert	0	0	0	0	0	248
6-53	Salt Wells Valley	Basin and Range	0	0	0	0	0	119
6-55	Coso Valley	Basin and Range	0	0	0	0	0	103
6-57	Darwin Valley	Basin and Range	0	0	0	0	0	179
6-58	Panamint Valley	Basin and Range	0	0	0	0	0	1,049
6-61	Cameo Area	Basin and Range	0	0	0	0	0	38
6-62	Race Track Valley	Basin and Range	0	0	0	0	0	57
6-63	Hidden Valley	Basin and Range	0	0	0	0	0	73
6-64	Marble Canyon Area	Basin and Range	0	0	0	0	0	42
6-65	Cottonwood Spring Area	Basin and Range	0	0	0	0	0	16
6-66	Lee Flat	Basin and Range	0	0	0	0	0	82
6-71	Lost Lake Valley	Basin and Range	0	0	0	0	0	94
6-72	Coles Flat	Basin and Range	0	0	0	0	0	12
6-73	Wild Horse Mesa Area	Basin and Range	0	0	0	0	0	13
6-76	Brown Mountain Valley	Basin and Range	0	0	0	0	0	88
6-77	Grass Valley	Desert	0	0	0	0	0	40
6-78	Denning Spring Valley	Desert	0	0	0	0	0	29
6-80	Middle Park Canyon	Basin and Range	0	0	0	0	0	7
6-81	Butte Valley	Basin and Range	0	0	0	0	0	36
6-82	Spring Canyon Valley	Basin and Range	0	0	0	0	0	19
6-84	Greenwater Valley	Basin and Range	0	0	0	0	0	242
6-85	Gold Valley	Basin and Range	0	0	0	0	0	13
6-86	Rhodes Hill Area	Basin and Range	0	0	0	0	0	63
6-88	Owl Lake Valley	Basin and Range	0	0	0	0	0	90
6-98	Tuledad Canyon Valley	Modoc Plateau and Cascades	0	0	0	0	0	21
7-45	Piute Valley	Desert	0	0	0	0	0	709

Belitz and others—Framework for a Ground-Water Quality Monitoring and Assessment Program for California—WRIR 03–4166